Green Energy and Technology

Yaşar Demirel

Energy

Production, Conversion, Storage, Conservation, and Coupling

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Resources including the solution manual for this textbook are available for instructors on sending a request to Dr. Yaşar Demirel at ydemirel2@unl.edu.

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Preface

This book is a first effort to fill the need for a comprehensive text on energy. The importance of energy and its effects on everyday life is undisputable. Consequently, many institutions today offer either minor or major degree programs on energy. This undergraduate textbook is prepared for students with diverse backgrounds who are interested to know more on energy and pursue a degree on energy. Although, it is naturally connected to thermodynamics through the energy balance, the new textbook covers many aspects of energy in systems with rate and transport processes.

This new textbook discusses five major aspects of energy in an introductory manner in separate chapters. The major aspects are energy production, conversion, storage, conservation, and coupling. Before discussing these aspects of energy, the textbook starts with an introduction and basic definitions in Chap. 1. In Chap. 2, the primary and the secondary energy types are discussed. Chapter 3 discusses mechanical and electrical energies. Chapter 4 discusses internal energy, enthalpy, heat of reaction, and heat transfer, while Chap. 5 discusses energy balance. Chapter 6 discusses energy production by mainly cyclic processes. Chapter 7 discusses energy conversion with an emphasis on thermal efficiency of these conversions. Chapter 8 discusses energy storage techniques including thermal energy storage by sensible and latent heats. Chapter 9 discusses energy conservation, while energy coupling in biological systems is discussed briefly in Chap. 10. There are 130 fully solved example problems throughout the chapters, and 642 practice problems listed at the end of ten chapters. The examples and practice problems provide the students with an opportunity towards a deep understanding of the concepts and aspects of energy.

I want to thank all those who helped me in preparing, developing, and improving the text. I especially thank Brad Hailey and Nghi Nguyen for their help in preparing the figures, checking the problems, and reading the text over and over again. It is obvious that this textbook will mature in reoccurring prints and reprints based on suggestions from the students and colleagues. I very much want to encourage those using this textbook to contact me with suggestions and corrections for possible future prints and editions.

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Abbreviations

ATP	Adenosine triphosphate
ADP	Adenosine diphosphate
ASHRAE	American society of heating, refrigerating and air conditioning engineers
AUFE	Annual fuel utilization efficiency
CAES	Compressed air energy storage
COP	Coefficient of performance
DOE	Department of energy
EER	Energy efficiency ratio
EIA	Energy information administration
EPA	Environmental protection agency
ETB	Engineering tool box
HP	Heat pump
HVAC	Heating ventilation and air conditioning
NREL	National renewable energy laboratory
PCM	Phase changing material
SEER	Seasonal energy efficiency ratio

Chapter 1
Introduction: Basic Definitions

1.1 System

System is a quantity of matter or a region with its boundary in space chosen for study as seen in Fig. 1.1a. *Boundary* is a surface separating the system from its surroundings. In *simple systems* there are no electrical, magnetic, gravitational, motion, and surface tension effects. These effects are due to external force fields and are negligible for most engineering problems. The boundary may be fixed or moving as seen in Fig. 1.1b. The universe outside the system's boundary is systems' *surroundings*. *Environment* refers to the region beyond the immediate surroundings whose properties are not affected by the process at any point. *Control volume* is any arbitrary region in space through which mass and energy can pass across the boundary as seen in Fig. 1.1c. A control volume may involve heat, work, and material flow interactions with its surroundings.

There are various types of systems with the following brief definitions:

- *Open systems* are arbitrary regions in space through which mass and energy can pass across the boundary as seen in Fig. 1.1c.
- *Closed systems* consist of a fixed amount of mass, and no mass can cross its boundary. But energy, in the form of heat or work, can cross the boundary as seen in Fig. 1.1d.
- *Isolated systems* do not exchange mass and energy with their surroundings.
- *Adiabatic systems* do not exchange heat with their surroundings.
- *Isothermal systems* have a uniform temperature everywhere within the systems boundary.
- *Isobaric systems* have a uniform pressure everywhere within the systems boundary.
- *Isochoric systems* have a constant volume within the systems boundary.
- *Steady state systems* have properties, which are independent of time; for example, amount of energy in the systems does not change with time.

Y. Demirel, *Energy*, Green Energy and Technology,
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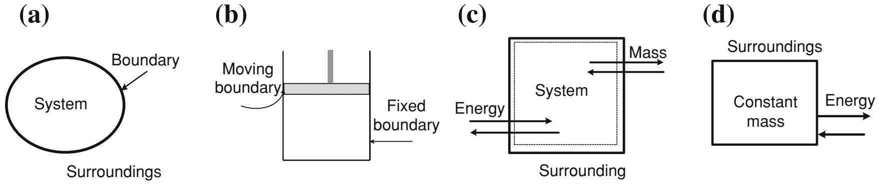


Fig. 1.1 **a** Boundary separates system from its surroundings, **b** a closed system with moving and fixed boundaries, **c** an open system with a control volume; an open system can exchange mass and energy with its surroundings, **d** a closed system does not exchange material with its surroundings, while it can exchange energy

1.2 Property and Variables

Property is an observable characteristic of a system, such as temperature or pressure. Two types of commonly used properties are *state properties* and *path variables*. The values of *state properties* depend on the state of the system. Temperature, pressure, and volume are examples of state properties. On the other hand, changes in *path variables* depend on the path a system undertakes when it changes from one state to another. For example, work and heat are path variables and occur when a system goes through a change in state with a specified path. Therefore, change of heat in a process that proceeds first at constant pressure and then at constant volume will be different from the one that proceeds first at constant volume and then at constant pressure from states 1 to 2.

- An *extensive property*, such as volume, depends on the size of the system. If the system consists of several parts, the volume of the systems is the sum of the volumes of its parts, and therefore, extensive properties are additive.
- An *intensive property* does not depend on the size of the system. Some examples of intensive properties are temperature, pressure, and density (specific volume). For a homogeneous system, an intensive property can be calculated by dividing an extensive property by the total quantity of the system such as specific volume m^3/kg or molar volume m^3/mol.

1.3 Dimensions and Units

Dimensions are basic concepts of measurements such as mass, length, temperature, and time. Units are the means of expressing the dimensions, such as feet or meter for length. Energy has been expressed in several different units. Scientific and engineering quantifications are based on the "International Systems of Units" commonly abbreviated as SI units, which was adopted in 1960 [1]. Table 1.1 shows the seven fundamental measures: length, mass, time, electric current,

Table 1.1 Fundamental measures and units

Measure	Symbol	Unit name and abbreviation
Length	l	Meter (m), foot (ft)
Mass	m	Kilogram (kg), pound (lb)
Time	t	Second (s)
Current	I	Amper (A)
Temperature	T	Kelvin (K), Rankine (R)
Luminous intensity	I	Candela (cd)

Table 1.2 Mass and length units and their definitions

Measure	Symbol	Unit name and Abbreviation
Kilogram	kg	1000 g = 2.204 lb = 32.17 oz
Ounce	oz	28.35 g = 6.25×10^{-2} lb
Pound	lb	0.453 kg = 453 g = 16 oz
Ton, long	ton	2240 lb = 1016.046 kg
Ton, short	sh ton	2000 lb = 907.184 kg
Tonne	t	1000 kg
Ångstrőm	Å	1×10^{-10} m = 0.1 nm
Foot	ft	1/3 yd = 0.3048 m = 12 inches
Inch	in	1/36 yd = 1/12 ft = 0.0254 m
Micron	μ	1×10^{-6} m
Mile	mi	5280 ft = 1760 yd = 1609.344 m
Yard	yd	0.9144 m = 3 ft = 36 in

temperature, amount of substance, and luminous intensity. American Engineering system units, on the other hand, use English system units that are length in foot ft, mass in pound lb_m, and temperature in degree Fahrenheit °F. At present, the widely accepted unit of measurement for energy is the SI unit of energy, the joule. Some other units of energy include the kilowatt hour (kWh) and the British thermal unit Btu. One kWh is equivalent to exactly 3.6×10^6 J, and one Btu is equivalent to about 1055 J. The candela is the luminous intensity of a surface of a black body at 1 atm and temperature of freezing platinum. Table 1.2 shows the various units of mass and length.

The fundamental measures may be used to derive other quantities and variables called the *derived units*, such as area, volume, density, pressure, force, speed, acceleration, energy, and power. For example, speed is length/time: l/t, acceleration is l/t^2, and force is ml/t^2. Table 1.3 shows some derived variables from fundamental measures, while Table 1.4 shows the prefix system for very small and large magnitudes using metric units.

1.4 Measures of Amounts and Fractions

Common measurements for amount are mass *m*, number of moles *n*, or total volume *V*. Two common fractions are the mass fractions and mole fractions.

Table 1.3 Some derived measures and variables

Measure	Symbol	Unit name and abbreviation
Area	A	m^2, ft^2
Volume	V	m^3, ft^3
Density	ρ	kg/m^3, lb/ft^3
Pressure	P	Pascal (Pa), psi
Velocity	v	m/s, ft/s
Acceleration	a	m/s^2 ft/s^2
Volume flow	Q	m^3/s, ft^3/s
Mass flow	m	kg/s, lb/s
Mass flux	m	kg/m^2 s, lb/ft^2 s
Force	F	Newton (N), kg m/s^2
Energy	E	Joule (J), Btu (1055.05 J)
Power	P	Watt (W), (W = J/s), Btu/s
Energy flux	E	J/m^2 s, Btu/ft^2 s
Potential difference	ψ	Volt (V)
Resistance	R	Ohm (Ω)
Electric charge	C	Coulomb (C)
Frequency	f	Hertz (Hz)
Electric flux	e	C/m^2

- Number of moles n is the ratio of a substance mass m to its molecular weight MW, and calculated by

$$n = \frac{m}{MW} \tag{1.1}$$

- *Mass fraction* is the mass of a substance divided by the total mass of all the substances in the mixture or solution. Mass fraction w_i for a substance i is calculated by

$$w_i = \frac{m_i}{m_{\text{total}}} \tag{1.2}$$

- *Mole fraction* x is the ratio of moles of a substance in a mixture or solution divided by the total number of moles in the mixture or solution. Mole fraction x_i for a substance i is calculated by

$$x_i = \frac{n_i}{n_{\text{total}}} \tag{1.3}$$

For example, assuming that the mole fraction of nitrogen is 79% and of oxygen is 21% in air, then the mass fractions of nitrogen and oxygen are 76.83 and 23.17%, respectively. Here, the molecular weight of nitrogen is 28.2 g/gmol and oxygen 32 g/gmol.

Table 1.4 Prefixes for SI units

Prefix	Symbol	Factor	Example
Peta	P	10^{15}	Petameter, Pm = 10^{15} m
Tera	T	10^{12}	Terabyte, TB = 10^{12} byte
Giga	G	10^{9}	Gigajoule, GJ = 10^{9} J
Mega	M	10^{6}	Megawatt, MW = 10^{6} W
Kilo	K	10^{3}	Kilojoule, kJ = 10^{3} J
Hecto	H	10^{2}	Hectometer, hm = 10^{2} m
Deka	Da	10^{1}	Decaliter, dal = 10^{1} l
Deci	D	10^{-1}	Deciliter, dl = 10^{-1} l
Centi	C	10^{-2}	Centimeter, cm = 10^{-2} m
Milli	M	10^{-3}	Milligram, mg = 10^{-3} g
Micro	μ	10^{-6}	Microvolt, μV = 10^{-6} V
Nano	N	10^{-9}	Nanometer, nm = 10^{-9} m
Pico	P	10^{-12}	Picometer, pm = 10^{-12} m
Femto	F	10^{-15}	Femtometer, fm = 10^{-15} m

1.5 Force

Force F is defined as the product of mass m and acceleration a, according to the Newton's second law, and expressed by

$$F = ma \tag{1.4}$$

The SI unit of force is the newton defined by (1 kg)(m/s^2). One kg of mass can be accelerated 1 m/s^2 by a force of 1 N.

The English engineering system of unit of force is the pound force lb$_\mathrm{f}$, which can accelerate one pound of mass 32.174 ft/s^2. For the consistency of units, one pound force is expressed by

$$F = \frac{1}{g_c} ma = \frac{1}{g_c} \mathrm{lb}\ 32.174 \frac{\mathrm{ft}}{\mathrm{s}^2} \tag{1.5}$$

where g_c is the proportionality constant

$$g_c = 32.174 \frac{\mathrm{lb\,ft}}{\mathrm{lb_f} s^2}$$

A pound force and a pound mass are different quantities. If an equation contains both the pound force and pound mass, the proportionality constant g_c is necessary for the equation to have correct dimensions.

Weight is the force of gravity acting on a body, and is expressed in newton or in pound force. Since the acceleration of gravity is $g = 9.8$ m/s^2, the weight in the SI unit is estimated by

$$F = mg \tag{1.6}$$

In the English engineering system, the weight is expressed by

$$F = m\frac{g}{g_c} \tag{1.7}$$

Since the gravitational force is different at different elevations, the weight is a function of elevation. Therefore, the weight for the same mass of a body would vary at different elevations.

1.6 Temperature

Temperature is a physical property that underlies the common notions of hot and cold. Something that feels hotter generally has a higher temperature. Heat flows from a matter with the higher temperature to a matter with the lower temperature. If no net heat flow occurs between two matters, then they have the same temperatures. Statistical physics describe matter as a collection of a large number of particles, and define temperature as a measure of the average energy in each degree of freedom of the particles in the matter. For a solid, this energy is found primarily in the vibrations of its atoms. In an ideal monatomic gas, energy is found in the translational motions resulting in changes in position of the particles; with molecular gases, vibrational and rotational motions also provide thermodynamic degrees of freedom.

Temperature is measured with thermometers that may be calibrated to a variety of scales as seen in Fig. 1.2a. Common temperature scales are:

- On the *Celsius scale*, the freezing point of water is 0°C and the boiling point of water is 100°C (at standard atmospheric pressure). Celsius scale is used in the SI system and named after A. Celcius.
- On the *Fahrenheit scale*, the freezing point of water is 32°F and the boiling point is 212°F (at standard atmospheric pressure). The Fahrenheit scale is used in the English engineering units system and named after D.G. Fahrenheit.
- *Thermodynamic temperature* scale is a scale that is independent of the properties of the substances and is called the *Kelvin scale* or *Rankine scale*. The temperature on this scale is called the *absolute temperature.*
- *Kelvin scale* is the thermodynamic temperature scale in the SI units. The lowest temperature on the Kelvin scale is −273.15°C as seen in Fig. 1.2b. The Kelvin temperature scale matches the Celsius scale: 1 K = 1°C. The Kelvin temperature scale is named after Lord Kelvin.
- *Rankine scale* is the thermodynamic temperature scale in the English engineering system units. The lowest temperature on the Rankine scale is −459.67°F. Rankine and Fahrenheit temperature scales have the same degree intervals: 1 R = 1°F. The Rankine temperature scale is named after W. Rankine.

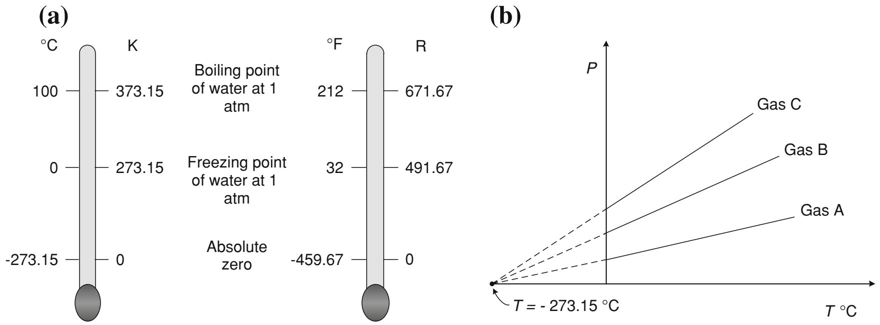


Fig. 1.2 **a** Comparison of different temperature scales; **b** Using three different gases in a constant-volume gas thermometer, all the straight lines, showing the change of pressure with temperature, will intersect the temperature axis at −273.15°C after extrapolation of measurements at low pressures. This is the lowest temperature that can be obtained regardless the nature of gases. So the absolute gas temperature scale, called the Kelvin scale, is obtained by assigning a value of 0 K to this lowest temperature of −273.15°C

Table 1.5 Temperature units and their definitions

Unit	Symbol	Definition	Conversion	Equation
degree Celsius	°C	°C = K − 273.15	°C = (°F − 32)/1.8	(1.8)
degree Fahrenheit	°F	°F = R – 459.67	°F = °C × 1.8 + 32	(1.9)
degree Rankine	R	R = °F + 459.67	R = K × 1.8	(1.10)
degree Kelvin	K	K = °C + 273.15	K = R/1.8	(1.11)

Table 1.5 summarizes the units, definitions, and conversions of temperature to each other.

Example 1.1 Conversion of temperature units

(a) Convert 27°C to °F, K, and R.

(b) Express a change of 25°C in K and a change of 70°F in R.

Solution:

(a) $T(\mathrm{K}) = T(°\mathrm{C}) + 273.15°\mathrm{C} = 27°\mathrm{C} + 273.15°\mathrm{C} = \mathbf{300.15\ K}$

$T(°\mathrm{F}) = 1.8\mathrm{T}(°\mathrm{C}) + 32 = (1.8)(27)°\mathrm{F} + 32°\mathrm{F} = \mathbf{80.6°F}$

$T(\mathrm{R}) = T(°\mathrm{F}) + 460°\mathrm{F} = 80.6°\mathrm{F} + 460°\mathrm{F} = \mathbf{540.6\ R}$

(b) A change of 25°C in K is: $\Delta T(\mathrm{K}) = \Delta T(°\mathrm{C}) = 25$ K as Kelvin and Celsius scales are identical.

A change 70°F in R is: $\Delta T(\mathrm{R}) = \Delta T(°\mathrm{F}) = 70$ R as Rankine and Fahrenheit scales are identical.

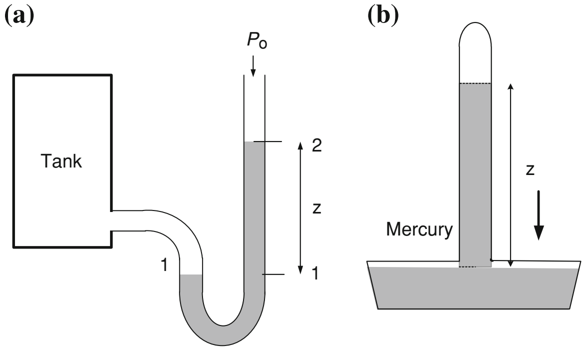


Fig. 1.3 **a** Basic manometer: $P = \rho g z + P_o$, **b** basic mercury barometer to measure atmospheric pressure. The length or the cross-sectional area of the tube has no effect on the height of the fluid in the barometer

1.7 Pressure

Pressure P is the force per unit cross-sectional area applied in a direction perpendicular to the surface of an object. Pressure is calculated by

$$P = \frac{F}{A} \tag{1.12}$$

where F is the component of the force that is perpendicular (normal) and A is the cross-sectional area. The SI unit for pressure is the Pascal (Pa) defined as 1 Pa = 1 N/m^2 = (1 kg m/s^2)/m^2. Two common units for pressure are the pounds force per square inch abbreviated as 'psi' and atmosphere abbreviated as 'atm', and they are related by 1 atm = 14.659 psi. The atmospheric pressure is variable, while the standard atmosphere is the pressure in a standard gravitational field and is equal to 1 atm, or 101.32 kPa, or 14.69 psi. Pressure is measured by a manometer. Figure 1.3a shows a basic manometer. Atmospheric pressure is measured by barometer as seen in Fig. 1.3b. The pressure at the bottom of the static column of mercury in Fig. 1.3b is

$$P = \rho g z + P_o \tag{1.13}$$

where P is the pressure at the bottom of the column of the fluid, ρ is the density of the fluid, g is the acceleration of gravity, z is the height of the fluid column, and P_o is the pressure at the top of the column of the fluid.

- According to the measuring device, we can measure *relative* or *absolute* pressures. *Gauge pressure*, psig, is the pressure relative to the local atmospheric or ambient pressure. Gauge pressure is measured by an open-end manometer as seen in Fig. 1.3a. If the open end of the manometer is closed and a vacuum is created in that end, then we measure *absolute pressure*, psia. For example, the standard atmosphere is absolute pressure. The relationship between absolute and relative pressures is

$$\text{Absolute pressure} = \text{Gauge pressure} + \text{Atmospheric pressure} \tag{1.14}$$

Table 1.6 Pressure conversion factors [2]

	kPa	Bar	Atm	mm Hg	Psi
kPa	1	10^{-2}	9.869×10^{-3}	7.50	145.04×10^{-3}
Bar	100	1	0.987	750.06	14.503
Atm	101.32	1.013	1	760	14.696
mm Hg	0.133	1.333×10^{-3}	1.316×10^{-3}	1	19.337×10^{-3}
Psi	6.894×10^{3}	68.948×10^{-3}	68.046×10^{-3}	51.715	1

1 Pa = 1 N/m^2 = 10^{-5} bar = 10.197×10^{-6} at = 9.8692×10^{-6} atm = 7.5006×10^{-3} torr = 145.04×10^{-6} psi

- In common usage, pressure is frequently called as *technical atmosphere*, at (kilogram-force per square centimeter) (kg$_f$/cm^2), and kg$_f$/cm^2 = 9.8 10^4 Pa. Table 1.6 shows some conversion factors among the common pressure units.

Example 1.2 Pressure calculations

Consider a column of mercury, Hg, that has an area of 1 cm^2 and a height of 20 cm. The top of the column is open to atmosphere. The density of mercury at 20°C is 13.55 g/cm^3. Estimate the pressure exerted by the column of mercury on the sealing plate.

Solution:

Data: $A = 1$ cm^2; $z = 20$ cm; $g = 980$ cm/s^2; $\rho = 13.55$ g/cm^3 at 20°C, $P_o = 101.32$ kPa.

$$P = \rho g z + P_o = \left(\frac{13.55\,\mathrm{g}}{\mathrm{cm}^3}\right)\left(\frac{980\,\mathrm{cm}}{\mathrm{s}^2}\right)(20\,\mathrm{cm})\left(\frac{\mathrm{kg}}{1000\,\mathrm{g}}\right)\left(\frac{\mathrm{N\,s}^2}{\mathrm{kg\,m}}\right)\left(\frac{100\,\mathrm{cm}}{1\,\mathrm{m}}\right)\left(\frac{\mathrm{m}^2\,\mathrm{Pa}}{\mathrm{N}}\right)\left(\frac{\mathrm{kPa}}{1000\,\mathrm{Pa}}\right)$$
$$+101.32\,\mathrm{kPa} = 26.56\,\mathrm{kPa} + 101.32\,\mathrm{kPa} = 127.88\,\mathrm{kPa}$$

P = **127.88 kPa**

In English engineering units, we have the density of mercury

$$\rho = \left(\frac{13.55\,\mathrm{g}}{\mathrm{cm}^3}\right)\left(\frac{62.4\,\mathrm{lb_m}}{\mathrm{ft}^3}\right) = 845\,\mathrm{lb_m}/\mathrm{ft}^3$$

The pressure in English units becomes:

$$P = \rho g z + P_o = \left(\frac{845.5\,\mathrm{lb_m}}{\mathrm{ft}^3}\right)\left(\frac{32.2\,\mathrm{ft}}{\mathrm{s}^2}\right)(20\,\mathrm{cm})\left(\frac{\mathrm{in.}}{2.54\,\mathrm{cm}}\right)\left(\frac{\mathrm{ft.}}{12\,\mathrm{in.}}\right)\left(\frac{\mathrm{s}^2\,\mathrm{lb_f}}{32.174\,\mathrm{ft\,lb_m}}\right)\left(\frac{\mathrm{ft}^2}{144\,\mathrm{in}^2}\right)$$
$$+14.69\,\mathrm{psi} = 3.85\,\mathrm{psi} + 14.69\,\mathrm{psi} = 18.54\,\mathrm{psi}$$

P = **18.54 psi**

In practice, the height of a liquid column is referred to as *head* of liquid. Therefore, the pressure of the column of mercury is expressed as 20 cm Hg, while the pressure on the sealing plate at the bottom becomes 20 cm Hg + 76 cm Hg (1 atm) = 96 cm Hg.

Example 1.3 Pressure conversions

Convert the pressure of 10 GPa to (a) psia, (b) atm, and (c) bar.

Solution:

$$\frac{10\,\text{GPa}}{1}\left(\frac{10^9\,\text{Pa}}{\text{GPa}}\right)\left(\frac{14.69\,\text{psia}}{101.32\times 10^3\,\text{Pa}}\right) = 1.45\times 10^6\,\text{psia}$$

$$\frac{10\,\text{GPa}}{1}\left(\frac{10^9\text{Pa}}{\text{GPa}}\right)\left(\frac{\text{atm}}{101.32\times 10^3\text{Pa}}\right) = 0.098\times 10^6\,\text{atm}$$

$$\frac{10\,\text{GPa}}{1}\left(\frac{10^9\text{Pa}}{\text{GPa}}\right)\left(\frac{\text{bar}}{100.0\times 10^3\text{Pa}}\right) = 0.1\times 10^6\,\text{atm}$$

Example 1.4 Absolute pressure estimations

A gauge connected to a chamber kept under vacuum reads 7.6 psig. The atmospheric pressure at the location is 14.3 psi. Estimate the absolute pressure in the chamber.

Solution:

Absolute pressure shows the actual pressure at a given point. Pressures below atmospheric pressure are called vacuum pressure, and the gauges measuring it indicate the difference between atmospheric pressure and absolute pressure.

$P_{\text{gauge}} = P_{\text{abs}} - P_{\text{atm}}$ (For pressures above atmospheric pressure)

$P_{\text{gauge}} = P_{\text{vacuum}} = P_{\text{atm}} - P_{\text{abs}}$ (For pressures below atmospheric pressure)

$P_{\text{abs}} = P_{\text{atm}} - P_{\text{gauge}} = 14.3\text{ psi} - 7.6\text{ psig} = \mathbf{6.7\ psia}$

1.8 Volume

Volume is how much three-dimensional space occupies or contains a substance. The substance may be one or more of solid, liquid, gas, or plasma states. The units of volume depend on the units of length. If the lengths are in meters, the volume will be in *cubic* meters, m^3; if they are in feet the volume is in cubic feet, ft^3. Table 1.7 shows common units and their definitions for volume. Table 1.8 shows the conversion factor between the various volume units. Volume-related derivative properties are:

- Total volume V_t of a system may be divided by the mass to calculate *specific volume* v. Specific volume is the inverse of density, such as m^3/kg of ft^3/lb

$$\text{specific volume}\,(v) = \frac{1}{\rho} = \frac{V}{m} \tag{1.15}$$

- Total volume may be divided by number of moles n to calculate *molar volume*

Table 1.7 Volume units and their definitions

Name of unit	Symbol	Definitions
Barrel (Imperial)	bl (Imp)	36 gal (Imp) = 0.163 m^3
Barrel	bl; bbl	42 gal (US) = 0.158 m^3
Cubic foot	cu ft	0.028 m^3
Cubic inch	cu in	16.387×10^{-6} m^3
Cubic meter	m^3	1 m^3 = 1000 l
Cubic yard	cu yd	27 cu ft = 0.764 m^3
Gallon (U.S.)	gal (US)	3.785×10^{-3} m^3 = 3.785 l
Ounce	US fl oz	1/128 gal (US) = 29.573×10^{-6} m^3
Pint	pt (US dry)	$1/8\,\text{gal(US dry)} = 550.610 \times 10^{-6}\text{m}^3$
Quart	qt (US)	¼ gal (US dry) = 1.101×10^{-3} m^3
Liter	l	1000 cm^3 = 10^{-3} m^3

[1, 4]

Table 1.8 Volume conversion factors [2]

	in^3	ft^3	U.S. gal	Liters	m^3
in^3	1	5.787×10^{-4}	4.329×10^{-3}	1.639×10^{-2}	1.639×10^{-5}
ft^3	1.728×10^{3}	1	7.481	28.32	2.832×10^{-2}
U.S. gal	231	0.133	1	3.785	3.785×10^{-3}
Liters	61.03	3.531×10^{-2}	0.264	1	1.000×10^{-3}
m^3	6.102×10^{4}	35.31	264.2	1000	1

$$V_m = \frac{V_t}{n} \tag{1.16}$$

- *Density* ρ is the ratio of mass per unit volume, such as lb/ft^3, or g/cm^3, and estimated by

  $$\text{density}(\rho) = \frac{\text{mass}}{\text{volume}} = \frac{m}{V} \tag{1.17}$$

  Densities of liquids and solids do not change significantly with pressure at ordinary conditions. However, densities of liquids and solids change with temperature. Densities of gases change with pressure and temperature. For example, the density of ethanol is 0.790 g/cm^3 and the volume of 1 lb of ethanol is (454 g/lb) (cm^3/0.790 g) = 574.7 cm^3.
- *Specific gravity* is ratio of densities of the substance to density of a reference substance

  $$\text{specific gravity (sp. gr.)} = \frac{\rho}{\rho_{\text{H}_2\text{O at } 4°\text{C}}} \tag{1.18}$$

  In specific gravity, the reference substance usually is water at 4°C, with density of 1 g/cm^3, or 62.43 lb/ft^3. The specific gravity of gases frequently is referred to air. Therefore, the data for specific gravity is expressed by both the temperature of the substance considered and the temperature of the reference density measured. For example, sp. gr. = 0.82 at $25^o/4^o$ means the substance is at 20°C and the reference substance is at 4°C. As the density of water at 4°C is 1 g/cm^3, the numerical values of the specific gravity and density are the same in the SI unit system.

In the petroleum industry the specific gravity of petroleum products is often reported in terms of a hydrometer scale called API *gravity*, and expressed with a standard temperature of 60°F

$$^o\text{API gravity} = \frac{141.5}{\text{sp. gr.} \frac{60^o\text{F}}{60^o\text{F}}} - 131.5 \tag{1.19}$$

Concentration usually refers to the quantity of a substance per unit volume. Some common concentrations are:

- *Mass concentration* is the mass per unit volume such as lb solute/ft^3 or g solute/l.
- *Molar concentration* is the moles per unit volume, such as lb mol/ft^3 or gmol/l.
- *Molarity* = gmol of solute/l of solution.
- *Molality* = gmol of solute/kg of solvent.
- *Normality* = equivalents of solute/l of solution.
- *Parts per million*, ppm, or *parts per billion*, ppb, expresses the concentration of extremely dilute solutions or mixtures

$$\text{ppm} = \frac{\text{part}}{10^6 \text{parts}} \tag{1.20}$$

  They are dimensionless and equivalent to a mass fraction for solids and liquids, and a mole fraction for gases. For example, about 9 ppm carbon monoxide means that 9 parts (mass or mole unit) per million part of air.
- *Parts per million by volume*, ppmv, or *parts per billion by volume*, ppbv.

1.9 State

State is a set of properties that completely describes the condition of that system. At this point, all the properties can be measured or calculated.

- *Reference state* is mainly chosen to assign a value of zero for a convenient property or properties at that state.
- *Standard reference state* for the properties of chemical components is chosen as 25°C (77°F) and 1 atm. Property values at the standard reference state are indicated by a superscript (°).

- *In steady state,* any kind of accumulation within the system is zero. The flows in and out remain constant in time, and the properties of the system do not change in time.
- The value of a *state variable*, such as internal energy, depends only on the state of the system and not on its previous history.
- *Gas* and *vapor states* are often used as synonymous words. Gas state of a substance is above its critical temperature. Vapor, on the other hand, implies a gas state that is not far from its condensation temperature.

1.9.1 Thermodynamic Equilibrium State

A system in *thermodynamic equilibrium* state experiences no changes when it is isolated from its surroundings. *Thermal equilibrium*, for example, means that the temperature is the same throughout the entire system. A system is in *mechanical equilibrium* if there is no change in pressure at any point of the system with time. In *chemical equilibrium*, the reaction rates in forward and backward directions become equal to each other.

1.9.2 Ideal-Gas Equation of State

An equation of state relates the pressure, temperature, and volume of a substance. At low pressures and high temperature the density of a gas decreases and the volume of a gas becomes proportional to its temperature

$$PV = nRT \tag{1.21}$$

where P is the absolute pressure, T is the absolute temperature, n is the number of moles of a substance, and R is called the universal gas constant, which is the same for all substances:

$R = 8.314$ J/mol K $= 8.314$ Pa m^3/mol K
$R = 1.986$ Btu/lbmol R $= 10.73$ psia ft^3/lbmol R

Equation (1.21) is called ideal-gas equation of state, and any gas that obeys this relation is known as ideal gas. The ideal-gas relation approximately represents the P–V–T behavior of real gases only at low densities. For a constant mass, the properties of an ideal gas at two different states are related to each other by

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \tag{1.22}$$

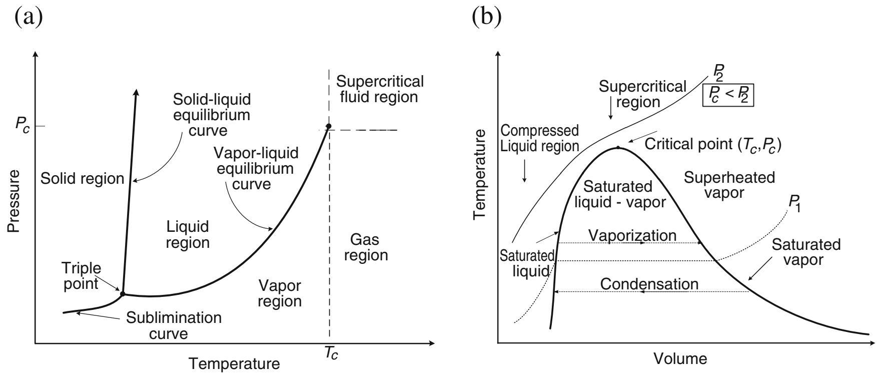


Fig. 1.4 **a** Pressure-temperature diagram of a pure component; **b** temperature-volume diagram of a pure substance. At critical point, saturate liquid line and saturated vapor lines merge. Within the saturation curves, a mixture of vapor and liquid phases exist. Super critical region represents a state of matter for temperature and pressure above P_c and T_c that are the critical pressure and temperature

1.9.3 Saturated Liquid and Saturated Vapor State

A pure substance will start to boil when its vapor pressure is equal to atmospheric pressure. The saturation temperature or boiling temperature of a pure substance depends on pressure; at higher pressure boiling point will be higher. Figure 1.4a shows a typical phase diagram for a pure substance. Between the solid and liquid phases, there is a solid–liquid equilibrium curve; between liquid and vapor phases there is a liquid–vapor equilibrium curve. The temperature and pressures on the liquid–vapor equilibrium curve are the saturation (boiling temperatures) and pressures. At critical point, the saturated liquid state and saturated vapor state are identical. At triple point, the three phases of a pure substance coexist in equilibrium. The isotherm at $T = T_c$, in Fig. 1.4b, has a point of inflexion (change of curvature) at the critical point (P_c, T_c). The zone where the isobars become flat shows the two-phase region, which is enveloped by saturated liquid and saturated vapor lines. At the supercritical region: $T > T_c$ and $P > P_c$.

1.9.4 Steam Tables

Steam tables tabulate the properties of saturated and superheated vapor and liquid water as shown in Appendix F. The properties of saturated steam are shown in Table F1 in English units and in Table F3 in SI units. Tables 1.9 and 1.10 show part of Tables F1 and F3 in Appendix F. Saturated water vapor and liquid properties are fully defined by either its temperature or by its pressure. For example, at

Table 1.9 Saturated water in English engineering units

T (°F)	P^{sat} (psia)	V (ft^3/lbm)		U (Btu/lb)		Enthalpy H (Btu/lb)		Entropy S (Btu/lb R)	
		V_l	V_g	U_l	U_g	H_l	H_g	S_l	S_g
132	2.345	0.01626	149.66	99,95	1053.7	99.95	1118.6	0.1851	1.9068
134	2.472	0.01626	142.41	101.94	1054.3	101.95	1119.5	0.1884	1.9024
136	2.605	0.01627	135.57	103.94	1055.0	103.95	1120.3	0.1918	1.8980
138	2.744	0.01628	129.11	105.94	1055.6	105.95	1121.1	0.1951	1.8937
140	2.889	0.01629	123.00	107.94	1056.2	107.95	1122.0	0.1985	1.8895
142	3.041	0.01630	117.22	109.94	1056.8	109.95	1122.8	0.2018	1.8852
144	3.200	0.01631	111.76	111.94	1057.5	111.95	1123.6	0.2051	1.8810

Table 1.10 Saturated water in SI units

T (K)	P^{sat} (kPa)	V (cm^3/g)		U (kJ/kg)		Enthalpy H (kJ/kg)		Entropy S (kJ/kg K)	
		V_l	V_g	U_l	U_g	H_l	H_g	V_l	V_g
372.15	97.76	1.043	1730.0	414.7	2505.3	414.8	2674.4	1.2956	7.3675
373.15	101.33	1.044	1673.0	419.0	2506.5	419.1	2676.0	1.3069	7.3554
375.15	108.78	1.045	1565.5	427.4	2508.8	427.5	2679.1	1.3294	7.3315
377.15	116.68	1.047	1466.2	435.8	2511.1	435.9	2682.2	1.3518	7.3078
379.15	125.04	1.049	1374.2	444.3	2513.4	444.4	2685.3	1.3742	7.2845
381.15	133.90	1.050	1288.9	452.7	2515.7	452.9	2688.3	1.3964	7.2615
383.15	143.27	1.052	1209.9	461.2	2518.0	461.3	2691.3	1.4185	7.2388

Table 1.11 Superheated steam in English engineering units

T (°F)	V (ft^3/lb).	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
	$P = 250$ psia, $T^{sat} = 400.97$°F				$P = 255$ psia, $T^{sat} = 402.72$°F			
Sat. liq.	0.019	375.3	376.1	0.5679	0.019	377.2	378.0	0.5701
Sat. vap.	1.843	1115.8	1201.1	1.5264	1.808	1116.0	1201.3	1.5247
420	1.907	1125.8	1214.0	1.5413	1.865	1125.1	1213.1	1.5383
440	1.970	1135.9	1227.1	1.5559	1.928	1135.3	1226.3	1.5530
460	2.032	1145.6	1239.6	1.5697	1.989	1145.0	1238.9	1.5669
480	2.092	1154.9	1251.7	1.5827	2.048	1154.5	1251.1	1.5800
500	2.150	1164.0	1263.5	1.5951	2.105	1163.6	1262.9	1.5925

140°F liquid water has the value of enthalpy of 107.95 Btu/lb and water vapor of 1122.0 Btu/lb. The difference would be the heat of vaporization at 140°F.

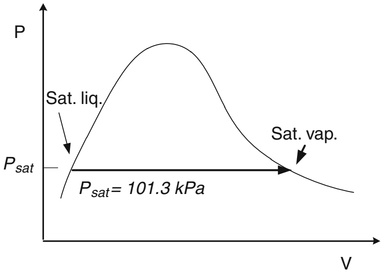
The properties of superheated steam tables are tabulated in Appendix F in Tables F2 and F4 for English and for SI units, respectively. Tables 1.11 and 1.12 show part of Tables F2 and F4 in Appendix F. The properties of superheated steam are determined fully by the values of temperature and pressure jointly.

Table 1.12 Superheated steam in SI units

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
	P = 1200 kPa, T^{sat} = 187.96°C				P = 1250 kPa, T^{sat} = 189.81°C			
Sat. liq.	1.139	797.1	798.4	2.2161	1.141	805.3	806.7	2.2338
Sat. vap.	163.20	2586.9	2782.7	6.5194	156.93	2588.0	2784.1	6.5050
200	169.23	2611.3	2814.4	6.5872	161.88	2608.9	2811.2	6.5630
220	178.80	2650.0	2864.5	6.6909	171.17	2648.0	2861.9	6.6680
240	187.95	2686.7	2912.2	6.7858	180.02	2685.1	2910.1	6.7637
260	196.79	2722.1	2958.2	6.8738	188.56	2720.8	2956.5	6.8523
280	205.40	2756.5	3003.0	6.9562	196.88	2755.4	3001.5	6.9353
300	213.85	2790.3	3046.9	7.0342	205.02	2789.3	3045.6	7.0136

Example 1.5 Energy change during evaporation

A mass of 22 kg of saturated liquid water at 101.3 kPa is evaporated completely at constant pressure and produced saturated vapor. Estimate the temperature of the vapor and amount of energy added to the water.



Solution:

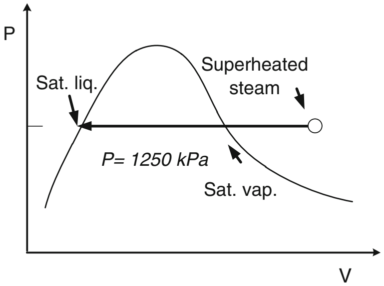
From Table F3: $P_{\text{sat}} = 101.3$ kPa and $T_{\text{sat}} = 100°\text{C}$.
$H_{\text{sat liq}} = 419.1$ kJ/kg and $H_{\text{sat vap}} = 2676.0$ kJ/kg

$\Delta H_{\text{vap}} = H_{\text{sat vap}} - H_{\text{sat liq}} = (2676.0 - 419.1)$ kJ/kg $= 2256.9$ kJ/kg

Total amount of heat added = (2256.9 kJ/kg)(22 kg) = **49,651.8 kJ**

Example 1.6 Energy change during condensation

A mass of 22 kg of superheated steam at 1250 kPa and 220°C condenses completely to saturated liquid state at constant pressure. Estimate the temperature of the saturated vapor and heat removed from the steam.



Solution:
From Tables F4 and F3

Superheated steam: $P = 1250$ kPa and $T = 220°C$, $H_{\text{superheat vap}} = 2861.9$ kJ/kg

Saturated steam and liquid is at $T_{\text{sat}} = 189.8°C$ (Table F3)
Saturated liquid water at 1250 kPa, and $H_{\text{sat liq}} = 806.7$ kJ/kg, $\boldsymbol{T_{\text{sat}}}$ **= 189.8°C**

$\Delta H_{\text{cond}} = H_{\text{sat liq}} - H_{\text{superheat vap}} = (806.7 - 2861.9)$ kJ/kg $= -\ 2055.2$ kJ/kg
Total amount of heat removed = – (2055.2 kJ/kg)(22 kg) = **– 45,214.4 kJ**

The removed heat has the negative sign as the heat leaving the system of superheated steam after condensation process as seen in the figure above.

1.9.5 Saturated Liquid–Vapor Mixture

The proportions of vapor and liquids phases in the saturated mixture is called the *quality x,* which is the ratio of mass of vapor to the total mass of the mixture

$$\text{quality}(x) = \frac{\text{mass of vapor}}{\text{total mass of mixture}} \tag{1.23}$$

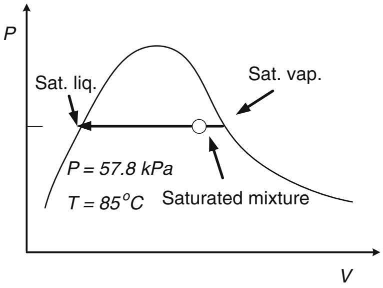
Average values of specific volume, enthalpy, and internal energy of a saturated liquid–vapor mixture are estimated by

$$V = (1 - x)V_{\text{liq sat}} + xV_{\text{vap sat}} \tag{1.24}$$

$$H = (1 - x)H_{\text{liq sat}} + xH_{\text{vap sat}} \tag{1.25}$$

$$U = (1 - x)U_{\text{liq sat}} + xU_{\text{vap sat}} \tag{1.26}$$

Example 1.7 Quality of a saturated liquid and vapor mixture of a steam
A rigid tank contains 15 kg of saturated liquid and vapor water at 85°C. Only 2 kg of the water is in liquid state. Estimate the enthalpy of the saturated mixture and the volume of the tank.



Solution:
From Table F3
Saturated liquid–vapor water mixture at 57.8 kPa and $T_{\text{sat}} = 85°C$,

Saturated vapor: $P = 57.8$ kPa, $H_{\text{sat vap}} = 2652.0$ kJ/kg, $V_{\text{vap}} = 2828.8$ cm^3/g

Saturated liquid water : $P = 57.8$ kPa, $H_{\text{sat liq}} = 355.9$ kJ/kg, $V_{\text{liq}} = 1.003$ cm^3/g
Amount of liquid water = 2 kg
Amount of vapor = 15 – 2 = 13 kg

Quality x of the saturated mixture: $x = \dfrac{m_{\text{vap}}}{m_{\text{total}}} = \dfrac{13\,\text{kg}}{15\,\text{kg}} = 0.87$

Enthalpy of the mixture, Eq. (1.25):

$$H_{\text{mix}} = (1-x)H_{\text{sat liq}} + xH_{\text{sat vap}} = (1-0.87)355.9\,\text{kJ/kg} + (0.87)2652.0\,\text{kJ/kg} \\ = \mathbf{2353.5\,kJ/kg}$$

Volume of the mixture, Eq. (1.24):

$$V_{\text{mix}} = (1-x)V_{\text{sat liq}} + xV_{\text{sat vap}} = (1-0.87)0.001003\,\text{m}^3/\text{kg} + (0.87)2.828\,\text{m}^3/\text{kg} \\ = 2.46\,\text{m}^3/\text{kg}$$

$V_{\text{tank}} = 15$ kg (2.46 m^3/kg) = **36.9 m^3**

Enthalpy of the saturated mixture depends on the quality of the mixture x and will be
$H_{\text{sat vap}} > H_{\text{mix}} > H_{\text{sat liq}}$

1.9.6 Partial Pressure and Saturation Pressure

Partial pressure is the pressure exerted by a single component in a gaseous mixture if it existed alone in the same volume occupied by the mixture and at the same temperature and pressure of the mixture. Partial pressure depends on the pressure and temperature. On the other hand, *saturation pressure* is the pressure at which liquid and vapor phases are at equilibrium at a given temperature. Saturation pressure depends only on the temperature. When a saturation pressure of a pure component reaches the atmospheric pressure the liquid starts to boil. For example, water boils at 100°C when its saturation pressure equals to the atmospheric pressure of 1 atm. The Antoine equation may be used to estimate the saturation pressure

$$\ln P_{\text{sat}} = A - \frac{B}{T+C} \quad (P \text{ in kPa and } T \text{ in } ^\circ\text{C}) \tag{1.27}$$

where A, B, and C are the Antoine constants. Table 1.13 lists the Antoine constants for some substances.

Example 1.8 Estimation of saturated vapor pressure

(a) Estimate the saturation vapor pressure of water and acetone 50°C, (b) Estimate the boiling point temperature of water and acetone at $P = 101.32$ kPa.

Solution:

The Antoine constants from Table 1.13:

Table 1.13 Antoine constants[a] for some components: P is in kPa and T is in °C

Species	A	B	C	Range (°C)
Acetone	14.314	2756.22	228.06	−26 to −77
Acetic acid	15.071	3580.80	224.65	24 to −142
Benzene	13.782	2726.81	217.57	6 to −104
1-Butanol	15.314	3212.43	182.73	37 to −138
iso-Butanol	14.604	2740.95	166.67	30 to −128
Carbon tetrachloride	14.057	2914.23	232.15	−14 to −101
Chloroform	13.732	2548.74	218.55	−23 to −84
Ethanol	16.895	3795.17	230.92	3 to −96
Ethyl benzene	13.972	3259.93	212.30	33 to −163
Methanol	16.578	3638.27	239.50	−11 to −83
Methyl acetate	14.245	2662.78	219.69	−23 to −78
1-propanol	16.115	3483.67	205.81	20 to −116
2-propanol	16.679	3640.20	219.61	8 to −100
Toluene	13.932	3056.96	217.62	13 to −136
Water	16.387	3885.70	230.17	0 to −200

[a] [3]

Water: $A = 16.3872$; $B = 3885.70$; $C = 230.17$
Acetone: $A = 14.3145$; $B = 2756.22$; $C = 228.06$

(a) $T = 50°\text{C}$ use $\ln P_{\text{sat}} = A - \dfrac{B}{T + C}$

$\boldsymbol{P_{\text{w,sat}}}$ **= 12.33 kPa at $\boldsymbol{T}$ = 50°C** (This value is very close to the tabulated value in Table F3)

$\boldsymbol{P_{\text{a,sat}}}$ **= 82.1 kPa at $\boldsymbol{T}$ = 50°C**

(b) Boiling point, T_{b}, of water at 101.32 kPa

$$T_b = \frac{B}{A - \ln P} - C$$

$\boldsymbol{T_{\text{w,b}}}$ **= 100°C and $\boldsymbol{T_{\text{a,b}}}$ = 56.4°C at 101.32 kPa**

1.10 Process

Process is any change that a system undergoes from one equilibrium state to another. To describe a process completely, one should specify the initial and final states of the process, as well as the *path* it follows during its progress, and the interactions with the surroundings. There are several types of processes:

- *Adiabatic process* occurs in either open or closed system without exchanging heat with the surroundings. This is an ideal concept as it implies a perfect insulation against the flow of heat, which is impossible in the strict sense.
- In an *isothermal* process, the temperature remains constant. In an *isobaric* process, the pressure remains constant. In an *isochoric* process the volume remains constant.

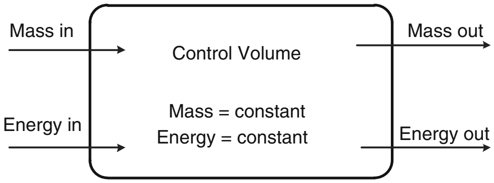


Fig. 1.5 Steady-flow system with mass and energy flow interactions with the surroundings. Mass and energy flows do not change with time in a steady-flow system

- In a *batch process*, material is neither added to nor removed from the process during its operation. In a *semi-batch process*, material may be added but product is not removed during the operation.
- In a *steady-flow (uniform-flow) process*, a fluid flows through a control volume steadily and no intensive or extensive properties within the control volume change with time. The fluid properties can change from point to point within the control volume, but at any point, they remain constant during the entire process. Figure 1.5 shows a steady-flow system with mass and energy interactions with the surroundings.
- In an *unsteady-flow*, or *transient-flow* process, properties change within a control volume with time.
- *Reversible process* can be reversed without leaving any trace on the surroundings. Reversible processes are idealized processes, and they can be approached but never reached in reality. In *reversible adiabatic compression* a working fluid decreases in volume reversibly and adiabatically. In *reversible adiabatic expansion* a working fluid expands and increases in volume reversibly and adiabatically. *Reversible isothermal compression* takes place at constant temperature while a working fluid decreases in volume reversibly. In r*eversible isothermal expansion* the temperature is held constant while a working fluid expands reversibly.
- *Irreversible processes* cannot spontaneously reverse themselves and restore the system to its initial state. They are also called as natural process because all the processes occurring in the nature are irreversible processes. For instance, as a natural process, heat flows from a system at higher temperature to a system at lower temperature; similarly, water flows from high level to low level. *Irreversibility* can be viewed as the wasted work potential or the lost opportunity to do work. Some of the factors causing *irreversibility* are friction, unrestrained expansion, mixing of two gases, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions. *Friction* is a familiar form of irreversibility associated with bodies in motion which results from the force that opposes the motion developed at the interface of the two bodies in contact when the two bodies are forced to move relative to each other.
- *Cyclic process*, or series of processes, allows a system to undergo various state changes and return the system to the initial state at the end of the processes. For a cycle the initial and final states are identical. *Ideal cycle* consists of internally reversible processes.

- *Isentropic process* is an internally reversible and adiabatic process. In such a process the entropy remains constant.
- *Quasi-static, or quasi-equilibrium, process* is a process which proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times. A quasi-equilibrium process can be viewed as a sufficiently slow process that allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts.

Problems

1.1. Temperature units are Celsius and Kelvin (K) in the SI units, and Fahrenheit and Rankine (R) in the English engineering system. At what temperature the values of the temperatures in Celsius (°C) and in Fahrenheit (°F) scales become equal to each other?

1.2. In a cooling process, the temperature of a system drops by 36°F. Express this drop in Celsius (°C), Kelvin (K), and Rankin (R).

1.3. In a heating process, the temperature of a system increases by 110°C. Express this increase in Fahrenheit (°F), Kelvin (K), and Rankin (R).

1.4. The temperature of a steam is 420°C. Express the temperature of steam in Fahrenheit (°F), Kelvin (K), and Rankin (R).

1.5. Convert the following units: (a) atm to bar, (b) Btu to J, (c) hp to kW; (d) quad to kJ, (e) $\mathrm{lb_m}$ to tonne, (f) quart to liter.

1.6. Convert the following units: (a) 4 km to miles, (b) 100 $\mathrm{ft^3}$/day to $\mathrm{cm^3}$/h, (c) 10 miles to ft, (d) 1000 l to gal.

1.7. Convert the following units: (a) 40 km to miles, (b) 10 $\mathrm{ft^3}$/day to $\mathrm{cm^3}$/h, (c) 100 miles to ft, (d) 10 l to gal.

1.8. Convert the following units: (a) 1000 miles to km, (b) 2000 $\mathrm{ft^3}$/day to gal/h, (c) 50000 ft to miles, (d) 1000 gal to $\mathrm{m^3}$.

1.9. Convert the following units: (a) 550 miles to km, (b) 500 $\mathrm{ft^3}$/day to gal/min, (c) 10000 ft to miles, (d) 150 gal to liters.

1.10. Convert the following units: (a) 1200 miles to meters, (b) 1500 $\mathrm{ft^3}$/day to gal/s, (c) 2000 ft to meters, (d) 500 gal to liters.

1.11. Convert the following units: (a) 200 miles to inches, (b) 2500 $\mathrm{ft^3}$/h to gal/s, (c) 600 nm to inches, (d) 300 gal to $\mathrm{in^3}$.

1.12. A heat capacity equation for acetylene is given by

$$C_p = 9.89 + 0.827 \times 10^{-2} T - 0.378 \times 10^{-5} T^2$$

where T is in °F and C_p is in Btu/lbmol °F. Convert the equation for C_p in J/gmol °C.

1.13. Parameters in Table B1 require use of temperatures in Kelvin and from that table the molar heat capacity of ethylene in ideal-gas state is

$$\frac{C_p^{ig}}{R} = 1.424 + 14.394 \times 10^{-3}T - 4.392 \times 10^{-6}T^2$$

Develop an equation for C_p^{ig} in J/gmol °C.

1.14. Parameters in Table B1 require use of temperatures in Kelvin and from that table the molar heat capacity of propylene in ideal-gas state is

$$\frac{C_p^{ig}}{R} = 1.637 + 22.706 \times 10^{-3}T - 6.915 \times 10^{-6}T^2$$

Develop an equation for C_p^{ig} in cal/gmol °C.

1.15. Parameters in Table B1 require use of temperatures in Kelvin and from that table the molar heat capacity of methane in ideal-gas state is

$$\frac{C_p^{ig}}{R} = 1.702 + 9.081 \times 10^{-3}T - 2.164 \times 10^{-6}T^2$$

Develop an equation for C_p^{ig} in cal/gmol °C.

1.16. Parameters in Table B2 require use of temperatures in Kelvin and from that table the molar heat capacity of liquid ethanol is

$$\frac{C_p}{R} = 33.866 - 172.60 \times 10^{-3}T + 349.17 \times 10^{-6}T^2$$

Develop an equation for C_p in J/gmol °C.

1.17. Parameters in Table B2 require use of temperatures in Kelvin and from that table the molar heat capacity of liquid methanol is

$$\frac{C_p}{R} = 13.431 - 51.28 \times 10^{-3}T + 131.13 \times 10^{-6}T^2$$

Develop an equation for C_p in J/gmol °C.

1.18. Parameters in Table B3 require use of temperatures in Kelvin and from that table the molar heat capacity of solid $NaHCO_3$ is

$$\frac{C_p}{R} = 5.128 + 18.148 \times 10^{-3}T$$

Develop an equation for C_p in Btu/lbmol R.

1.19. Experimental values for the heat capacity, C_p, in J/gmol °C of air from temperature, T, interval of 0 to 900°C are:

T, °C	0	25	100	200	300	400	500	600	700	800	900
C_p J/gmol °C	29.062	29.075	29.142	29.292	29.514	29.782	30.083	30.401	30.711	31.020	31.317

Use the least square method to estimate the values of the coefficients in the following form: $C_p = A + BT + CT^2$

1.20. The heat capacity of ethanol is expressed by $C_p = 61.34 + 0.1572T$ where T is in °C and C_p is in J/g mol °C. Modify the expression so that the unit for C_p would be Btu/lbmol R.

1.21. Express 30 GPa in: (a) atmosphere, (b) psia, (c) inches of Hg, (d) mm of Hg.

1.22. A gauge connected to a chamber kept under vacuum reads 4.5 psi. The atmospheric pressure at the location is 14.6 psi. Estimate the absolute pressure in the chamber.

1.23. A gauge connected to a chamber kept under vacuum reads 75 kPa. The atmospheric pressure at the location is 101.2 kPa psi. Estimate the absolute pressure in the chamber.

1.24. A gauge connected to a chamber reads 24.8 psi. The atmospheric pressure at the location is 14.2 psi. Estimate the absolute pressure in the chamber.

1.25. Estimate the atmospheric pressure at a location where the temperature is 25°C and the barometric reading is 755 mm Hg.

1.26. A dead-weight gauge uses a piston with diameter, D, of 3 mm. If the piston is pressed by a 50 kg of the weight, determine the pressure reading on the gauge.

1.27. A pressure reading by a dead-weight gauge is 30 bar. The piston of the gauge has diameter of 4 mm. Determine the approximate mass in kg of the weights required for the pressure reading.

1.28. The pressure reading on a dead-weight gauge is 3 atm. The piston diameter of the gauge is 0.2 in. Determine the approximate mass in $\mathrm{lb_m}$ of the weights required.

1.29. The reading on a mercury open manometer (open to the atmosphere at one end) is 15.5 cm. The local acceleration of gravity is 9.832 m/s^2. Atmospheric pressure is 101.75 kPa. Determine the absolute pressure in kPa being measured. The density of mercury at 25°C is 13.534 g/cm^3.

1.30. The reading on a mercury open manometer at 70°F (open to the atmosphere at one end) is 10.25 in. The local acceleration of gravity is 32.243 ft/s^2. Atmospheric pressure is 29.86 Hg. Estimate the measured absolute pressure in psia. The density of mercury at 70°F is 13.543 g/cm^3.

1.31. At 300 K the reading on a manometer filled with mercury is 65.7 cm. The local acceleration of gravity is 9.785 m/s^2. What is the pressure in atmosphere that corresponds to this height of mercury?

1.32. The pressure gauge on a tank filled with carbon dioxide reads 45 psi. The barometer reading is 28.5 in Hg. Estimate the absolute pressure in the tank in psia and atmosphere.

1.33. Complete the following table if $P_{\text{atm}} = 100$ kPa and $\rho_{\text{Hg}} = 13.6$ g/cm^3

P_{Gauge}(kPa)	P_{abs}(kPa)	P_{abs}(mmHg)	P_{Gauge}(m H_2O)
5			
	150		
		30	
			30

1.34. Estimate the mass of the air in a room with dimensions of (4)(5)(5)m^3 at 20°C and 1 atm.

1.35. Estimate the temperature of 68.2 kg of carbon dioxide gas in a tank with a volume of 20 m^3 and pressure of 250 kPa.

1.36. Estimate the temperature of 12 kg of propane gas in a tank with a volume of 1.6 m^3 and pressure of 400 kPa.

1.37. Estimate the temperature of 6.8 kg of hydrogen gas in a tank with a volume of 40 m^3 and pressure of 300 kPa.

1.38. Estimate the temperature of 12.6 lb of nitrogen gas in a tank with a volume of 150 ft^3 and pressure of 27 psia.

1.39. Estimate the pressure of 2.2 kg of carbon dioxide (CO_2) gas at $T = 350$ K and $V = 0.5$ m^3.

1.40. Estimate the pressure of 0.6 kg of hydrogen gas at $T = 400$ K and $V = 1.0$ m^3.

1.41. A tank has been filled with 240 lb of propane (C_3H_8). The volume of the tank is 150 ft^3 and the temperature is 80°F. Estimate the pressure of propane using the ideal-gas equation of state.

1.42. Estimate the molar volume and specific volume of nitrogen (N_2) at 20 psia and 180°F using the ideal-gas equation of state.

1.43. Estimate the molar volume and specific volume of propane C_3H_8 at 15 psia and 100°F using the ideal-gas equation of state.

1.44. Convert 2.5 μg mol/ml min to lb mol/ft^3 h.

1.45. The current Operational Safety and Healy Administration (OSHA) 8-hour limit for carbon monoxide (CO) in air is 9 ppm. How many grams carbon monoxide/kg air is 9 ppm?

1.46. (a) Estimate the saturation vapor pressure of water and acetone at 40°C, (b) Estimate the boiling point temperature of water and acetone at 98 kPa.

1.47. (a) Estimate saturation pressures for methanol and ethanol at 40°C, (b) Estimate boiling points for methanol and ethanol at 101.33 kPa.

1.48. (a) Estimate saturation pressures for methanol and ethanol at 40°C, (b) Estimate boiling points for methanol and ethanol at 101.33 kPa.

1.49. A tank filled with 10 lb of air is heated. The air originally is at 40 psia and 100°F. After heating, the air pressure becomes 60 psia. Estimate the final temperature of the air.

1.50. A 2.0 m^3 tank filled with hydrogen (H_2) at 200 kPa and 500 K. The hydrogen is cooled until its temperature drops to 300 K. Estimate the amount of hydrogen and the final pressure in the tank after cooling.

1.51. Determine the number of grams of ethanol vapor within a volume of 500 cm^3 at a pressure of 500 kPa and a temperature of 100°C.

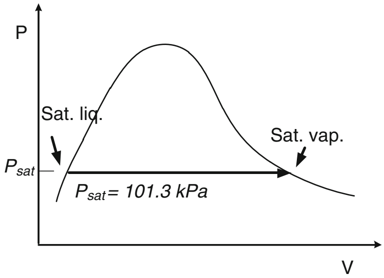
1.52. A cylinder of a fixed volume of 15 m^3 containing CO_2 is initially at a temperature of 100°C and a pressure of 101 kPa. When the temperature rises to 150°C find the final pressure.

1.53. A piston cylinder system is under isothermal conditions is at a temperature of 15°C with a volume of 37 cm^3 and a pressure of 120 kPa. The piston moves creating a pressure of 260 kPa within the system. What is the change of volume after the piston has reached its final position?

1.54. Determine the volume occupied by 10 kg of water at a pressure of 10 MPa and the following temperatures: 400 and 600°C.

1.55. Determine the volume occupied by 3.5 kg of water vapor at a pressure of 260 psia and the following temperatures of 480 and 1100°F.

1.56. A mass of 10 kg of saturated liquid water at 101.3 kPa is evaporated completely at constant pressure and produced saturated vapor. Estimate the temperature of the vapor and amount of energy added to the water.



1.57. A mass of 25 lb of saturated liquid water at 3.2 psia is evaporated completely at constant pressure and produced saturated vapor. Estimate the temperature of the vapor and amount of energy added to the water.

1.58. A mass of 100 lb of saturated liquid water at 132°F is evaporated completely at constant pressure and produced saturated vapor. Estimate the temperature of the vapor and amount of energy added to the water.

1.59. A mass of 10 kg of superheated steam at 1250 kPa and 220°C condenses completely to saturated liquid state at constant pressure. Estimate the temperature of the saturated vapor and heat removed from the steam.

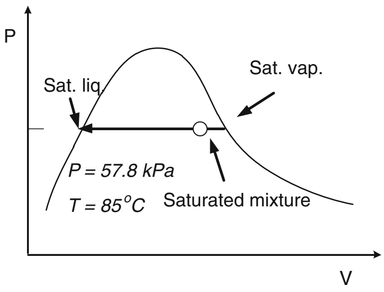
1.60. A mass of 150 kg of superheated steam at 500 kPa and 200°C condenses completely to saturated liquid state at constant pressure. Estimate the temperature of the saturated vapor and heat removed from the steam.

1.61. A mass of 25 kg of superheated steam at 470 kPa and 240°C condenses completely to saturated liquid state at constant pressure. Estimate the temperature of the saturated vapor and heat removed from the steam.

1.62. A mass of 150 lb of superheated steam at 250 psia and 440°F condenses completely to saturated liquid state at constant pressure. Estimate the temperature of the saturated vapor and heat removed from the steam.

1.63. A mass of 50 lb of superheated steam at 255 psia and 500°F condenses completely to saturated liquid state at constant pressure. Estimate the temperature of the saturated vapor and heat removed from the steam.

1.64. A rigid tank contains 30 kg of saturated liquid and vapor water at 85°C. Only 4 kg of the water is in liquid state. Estimate the enthalpy of the saturated mixture and the volume of the tank.



1.65. A rigid tank contains 10 kg of saturated liquid and vapor water at 326.15 K. Only 1.5 kg of the water is in liquid state. Estimate the enthalpy of the mixture and the volume of the tank.

1.66. A rigid tank contains 100 lb of saturated liquid and vapor water at 140°F. Only 8.0 lb of the water is in liquid state. Estimate the enthalpy of the saturated mixture and the volume of the tank.

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Chapter 2
Energy and Energy Types

2.1 Energy

Energy is the capacity to do work. Energy comes in various forms, such as motion, heat, light, electrical, chemical, nuclear energy, and gravitational. *Total energy* is the sum of all forms of the energy a system possesses. In the absence of magnetic, electrical and surface tension effects, the total energy of a system consists of the *kinetic, potential, and internal energies*. The *internal energy* of a system is made up of sensible, latent, chemical, and nuclear energies. The sensible internal energy is due to translational, rotational, and vibrational effects of atoms and molecules. *Thermal energy* is the sensible and latent forms of internal energy. The classification of energy into different "types" often follows the boundaries of the fields of study in the natural sciences. For example, c*hemical energy* is the kind of potential energy stored in chemical bonds, and *nuclear energy* is the energy stored in interactions between the particles in the atomic nucleus. *Microscopic forms of energy* are related to the molecular structure of a system and they are independent of outside reference frames.

Hydrogen represents a store of potential energy that can be released by fusion of hydrogen in the Sun. Some of the fusion energy is then transformed into sunlight, which may again be stored as gravitational potential energy after it strikes the earth. For example, water evaporates from the oceans, may be deposited on elevated parts of the earth, and after being released at a hydroelectric dam, it can drive turbines to produce energy in the form of electricity. Atmospheric phenomena like wind, rain, snow, and hurricanes, are all a result of energy transformations brought about by solar energy on the atmosphere of the earth. Sunlight is also captured by plants as *chemical potential energy* in photosynthesis, when carbon dioxide and water are converted into carbohydrates, lipids, and proteins. This chemical potential energy is responsible for growth and development of a biological cell.

British thermal unit (Btu) is the energy unit in the English system needed to raise the temperature of 1 lb_m of water at 68°F by 1°F. *Calorie* (cal) is the amount

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Table 2.1 Some energy units and definitions

Name of unit	Symbol	Definitions
British thermal unit	Btu	1055 J = 5.4039 psia ft^3
Btu/lb_m	Btu/lb_m	2.326 kJ/kg
Joule	J	$\text{J} = \text{m}\cdot\text{N} = 1\ \text{kg}\cdot\text{m}^2/\text{s}^2$
Calorie	Cal	4.1868 J
kJ	kJ	$\text{kPa m}^3 = 1000\ \text{J}$
kJ/kg	kJ/kg	$0.43\ \text{Btu/lb}_\text{m}$
Erg	erg	$\text{g}\cdot\text{cm}^2/\text{s}^2 = 10^{-7}\ \text{J}$
Foot pound force	ft lb_f	$g \times \text{lb} \times \text{ft} = 1.355\ \text{J}$
Horsepower hour	hph	$\text{hp} \times \text{h} = 2.684 \times 10^6\ \text{J}$
Kilowatt hour	kWh	$\text{kW} \times \text{h} = 3.6 \times 10^6\ \text{J}$
Quad	quad	$10^{15}\ \text{Btu} = 1.055 \times 10^{18}\ \text{J}$
Atmosphere liter	atml	$\text{atm} \times \text{l} = 101.325\ \text{J}$
kW	kW	3412 Btu/h
Horsepower	hp	2545 Btu/h
Therm	therm	29.3 kWh
Electronvolt	eV	$\approx 1.602\ 17 \times 10^{-19} \pm 4.9 \times 10^{-26}\ \text{J}$

of energy in the metric system needed to raise the temperature of 1 g of water at 15°C by 1°C. Table 2.1 displays some of the important energy units and their definitions.

2.2 Energy Types

Primary and secondary types of energy are the two main types as shown in Fig. 2.1. Primary energy is extracted or captured directly from the environment, while the secondary energy is converted from the primary energy in the form of electricity or fuel. Distinguising the primary and secondary energy sources are important in the energy balances to count and record energy supply, transformations, and losses. These energy types are discussed in the next sections.

2.2.1 Primary Energy

Primary energy is the energy extracted or captured directly from the environment. Three distinctive groups of primary energy are:

- Nonrenewable energy (fossil fuels): coal, crude oil, natural gas, nuclear fuel.
- Renewable energy: hydropower, biomass, solar energy, wind, geothermal, and ocean energy.
- Waste.

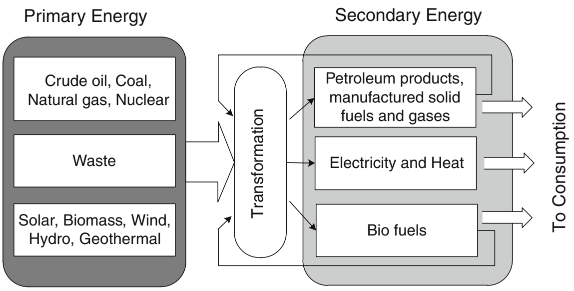


Fig. 2.1 Primary and secondary energy types. To separate primary and secondary energy is important in energy balances for energy supply, transformation, and losses [33]

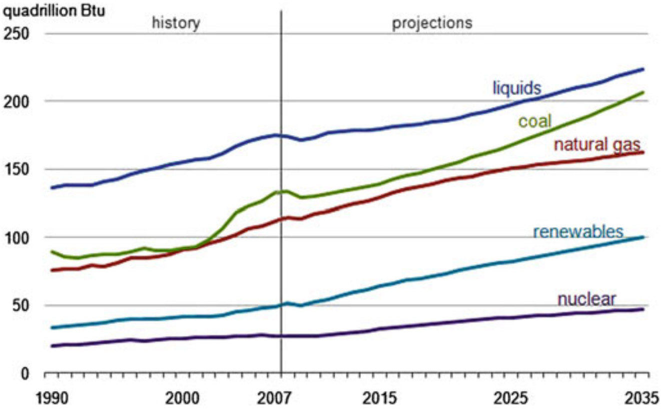


Fig. 2.2 History and projections of energy use by fuel type in the world (Quad = 10^{15} Btu) [13]

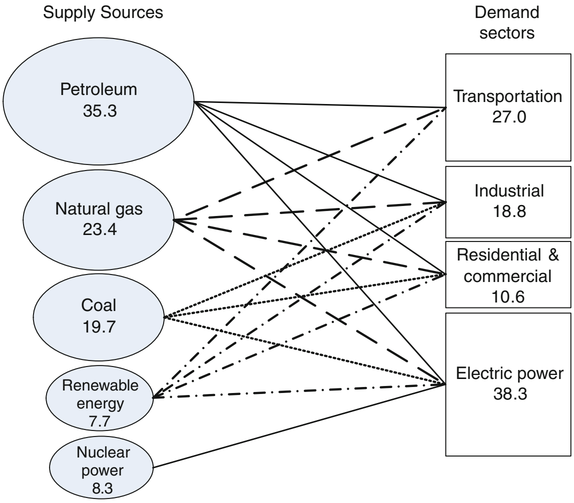
Primary sources of energy consisting of petroleum, coal, and natural gas amount to about 85% of the fossil fuels in primary energy consumption in the world [13, 37]. Projected energy use in the world shows that petroleum, coal, and natural gas will still be the dominant energy sources by 2035 (Fig. 2.2). The principle of supply and demand suggests that as fossil fuels diminish, their prices will rise and renewable energy supplies, particularly biomass, solar, and wind resources, will become sufficiently economical to exploit [13, 37]. Figure 2.3 shows the primary energy flow in the US.

The energy content may be converted to ton of oil equivalent (TOE): 1 TOE = 11630 kWh = 41870 MJ.

2.2.2 Secondary Energy

The primary energy is transformed to *secondary energy* in the form of electrical energy or fuel, such as gasoline, fuel oil, methanol, ethanol, and hydrogen [3]. The

Fig. 2.3 US primary energy flow by source and sector in 2009 in quadrillion Btu- quad = 10^{15} Btu. Sum of components may not be equal to total due to independent rounding [14]



primary energy of *renewable energy* sources, such as sun, wind, biomass, geothermal energy, and flowing water is usually equated with either electrical or thermal energy produced from them. Final energy is often electrical energy and fuel, which is referred to as *useful energy*. The selected four types of final energy are electrical, thermal, mechanical, and chemical energy. These types of final energy set a boundary between the energy production and the consumption sectors [7, 14, 33].

2.3 Non Renewable Energy Sources

It is generally accepted that nonrenewable energy sources or *fossil fuels* are formed from the remains of dead plants and animals by exposure to heat and pressure in the earth's crust over the millions of years. Major nonrenewable energy sources are:

- Coal
- Petroleum
- Natural gas
- Nuclear

Fossil fuels contain high percentages of carbon and include mainly coal, petroleum, and natural gas. Natural gas, for example, contains only very low boiling point and gaseous components, while gasoline contains much higher boiling point components. The specific mixture of hydrocarbons gives a fuel its characteristic properties, such as boiling point, melting point, density, and viscosity. These types

Table 2.2 Typical properties of various coals

	Anthracite coal	Bituminous coal	Lignite coal
Fixed carbon, weight%	80.5–85.7	44.9–78.2	31.4
Moisture, weight%	2.8–16.3	2.2–15.9	39
Bulk density, lb/ft^3	50–58	42–57	40–54
Ash, weight%	9.7–20.2	3.3–11.7	3.3–11.7
Sulfur, weight%	0.6–0.77	0.7–4.0	0.4

ETB [18], Gaur and Reed [15]

of fuels are known as nonrenewable energy sources. The following sections discuss some important nonrenewable energy sources.

2.3.1 Coal

Coals are sedimentary rocks containing combustible and incombustible matters as well as water. Coal comes in various composition and energy content depending on the source and type. Table 2.2 shows some typical properties of various coals. The poorest lignite has less than 50% carbon and an energy density lower than wood. Anthracites have more than 90% carbon, while bituminous coals mostly between 70 and 75%. Bituminous coal ignites easily and burns with a relatively long flame [35]. If improperly fired, bituminous coal is characterized with excess smoke and soot. Anthracite coal is very hard and shiny and the ultimate maturation. Anthracite coal creates a steady and clean flame and is preferred for domestic heating. Furthermore it burns longer with more heat than the other types. For countries with rising oil prices coal may become a cheaper source of energy. It was in the 1880s when coal was first used to generate electricity for homes and factories. Since then coal played a major role as source of energy in the industrial revolution.

Coal has impurities like sulfur and nitrogen and when it burns the released impurities can combine with water vapor in the air to form droplets that fall to earth as weak forms of sulfuric and nitric acid as acid rain. Coal also contains minerals, which do not burn and make up the ash left behind in a coal combustor. Carbon dioxide is one of several gases that can help trap the earth's heat and, as many scientists believe, cause the earth's temperature to rise and alter the earth's climate. Because of high carbon content, coals generate more CO_2 per unit of released energy than any other fossil fuel such as crude oil. Sulfur content of coal is also a drawback. Sulfur makes up, typically, about 2% of bitumen coals. However, advanced coal technology can filter out 99% of the tiny particles, remove more than 95% of the acid rain pollutants, and reduce the release of carbon dioxide by burning coal more efficiently. Many new plants are required to have flue gas desulfurization units called *scrubbers* [7, 27].

Table 2.3 Typical elemental composition by weight of crude oil [17]

Element	Percent range (%)
Carbon	83–87
Hydrogen	10–14
Nitrogen	0.1–2
Oxygen	0.1–1.5
Sulfur	0.5–6
Metals	<0.1

Table 2.4 Composition by weight of hydrocarbons in petroleum

Hydrocarbon	Average (%)	Range (%)
Paraffins (alkanes)	30	15–60
Naphtanes (cycloalkanes)	49	30–60
Aromatics	15	3–30
Asphaltics	6	Remainder

2.3.2 Petroleum (Crude Oil)

Oil is a naturally occurring flammable liquid consisting of a complex mixture of hydrocarbons of various molecular weights, which define its physical and chemical properties, like heating value, color, and viscosity. The composition of hydrocarbons ranges from as much as 97% by weight in the lighter oils to as little as 50% in the heavier oils. The proportion of chemical elements varies over fairly narrow limits as seen in Table 2.3. The hydrocarbons in crude oil are mostly alkanes, cycloalkanes and various aromatic hydrocarbons while the other organic compounds contain nitrogen, oxygen, sulfur, and trace amounts of metals. The relative percentage of each varies and determines the properties of oil (see Table 2.4).

- *Alkanes*, also known as *paraffin*, are saturated hydrocarbons with straight or branched chains containing only carbon and hydrogen and have the general formula C_nH_{2n+2}. They generally have from 5 to 40 carbon atoms per molecule. For example, CH_4 represents the methane, which is a major component of natural gas. The propane (C_3H_8) and butane (C_4H_{10}) are known as petroleum gases. At the heavier end of the range, *paraffin wax* is an alkane with approximately 25 carbon atoms, while *asphalt* has 35 and up. These long chain alkanes are usually cracked by modern refineries into lighter and more valuable products.
- *Cycloalkanes*, also known as *naphthenes*, are saturated hydrocarbons which have one or more carbon rings to which hydrogen atoms are attached according to the formula C_nH_{2n}. Cycloalkanes have similar properties to alkanes but have higher boiling points.
- *Aromatic hydrocarbons* are unsaturated hydrocarbons which have one or more six-carbon rings called benzene rings with double and single bonds and hydrogen atoms attached according to the formula C_nH_n.

Oil currently supplies more than 40% of our total energy demands and more than 99% of the fuel are used in transportation. Known oil reserves are typically estimated at around 1.2 trillion barrels without oil sands, or 3.74 trillion barrels with oil sands [3, 26].

2.3.3 Petroleum Fractions

Oil is refined and separated into a large number of commodity products, from gasoline and kerosene to asphalt and chemical reagents used to make plastics and pharmaceuticals. Figure 2.4 shows a part of a typical refinery processing crude oil to produce various fuels. 84% by volume of the hydrocarbons present in petroleum is converted into energy-rich fuels, including gasoline, diesel, jet fuel, heating, and other fuel oil and liquefied petroleum gases. The remaining oil is converted to pharmaceuticals, solvents, fertilizers, pesticides, and plastics [22]. Therefore, petroleum is vital to many industries, and thus is a critical concern to many nations.

Some common fractions from petroleum refining are:

- *Liquefied petroleum gas* (LPG) is a flammable mixture of propane (C_3H_8) (about 38% by volume and more in winter) and butane (C_4H_{10}) (about 60% by volume and more in summer) used as a fuel in heating appliances and vehicles. Energy content of liquefied petroleum gas per kilogram is higher than for gasoline because of higher hydrogen to carbon ratio. Liquefied petroleum gas emits 81% of the CO_2 per kWh produced by oil and 70% of that of coal. Liquefied petroleum gas has a typical specific heat of 46.1 MJ/kg compared with 43.5 MJ/kg for gasoline. However, its energy density of 26 MJ/l is lower than either that of gasoline. Pure *n*-butane is liquefied at around 220 kPa (2.2 bar), while pure propane (C_3H_8) at 2200 kPa (22 bar). At liquid state, the vapor pressure of liquefied petroleum gas is about 550 kPa (5.5 bar).
- *Gasoline* is primarily used as a fuel in internal combustion engines. A typical gasoline consists of hydrocarbons with between 4 and 12 carbon atoms per molecule. It consists mostly of aliphatic hydrocarbons obtained by the fractional distillation of petroleum, enhanced with iso-octane or the aromatic hydrocarbons toluene and benzene to increase its octane rating. The specific density of gasoline ranges from 0.71 to 0.77 (6.175 lb/US gal) higher densities having a greater volume of aromatics. Gasoline contains about 132 MJ/US gal (higher heating value), while its blends differ by up to 4% more or less than the average. The emission of CO_2 from gasoline is around 73.38 g/MJ.
- *Petroleum diesel* contains 8–21 carbon atoms per molecule with a boiling point in the range of 180–360°C (360–680°F). The density of petroleum diesel is about 6.943 lb/gal. About 86.1% of the fuel mass is carbon and it offers a net heating value of around 43.1 MJ/kg. However, due to the higher density, diesel

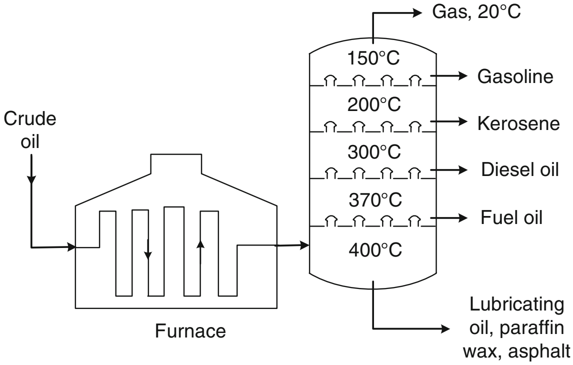


Fig. 2.4 A distillation tower showing the differing weights of various products produced from petroleum

offers a higher volumetric energy density at 128,700 Btu/gal versus 115,500 Btu/gal for gasoline, some 11% higher (see Table 2.7). The CO_2 emissions from diesel are 73.25 g/MJ, (similar to gasoline). Because of quality regulations, additional refining is required to remove sulfur which may contribute to a higher cost.

- *Kerosene* is a thin, clear liquid formed containing between 6 and 16 carbon atoms per molecule, with density of 0.78–0.81 g/cm^3. The flash point of kerosene is between 37 and 65°C (100 and 150°F) and its autoignition temperature is 220°C (428 F). The heat of combustion of kerosene is similar to that of diesel: its lower heating value is around 18,500 Btu/lb, (43.1 MJ/kg), and its higher heating value is 46.2 MJ/kg (19,861 Btu/lb).
- *Jet fuel* is a type of aviation fuel designed for use in aircraft powered by gas-turbine engines. The commonly used fuels are Jet A and Jet A-1 which are produced to a standardised international specification. Jet B is used for its enhanced cold-weather performance. Jet fuel is a mixture of a large number of different hydrocarbons with density of 0.775−0.840 kg/l at 15°C (59°F). The range is restricted by the requirements for the product, for example, the freezing point or smoke point. Kerosene-type jet fuel (including Jet A and Jet A-1) has a carbon number between about 8 and 16; wide-cut or naphtha-type jet fuel (including Jet B), between about 5 and 15.
- *Fuel oil* is made of long hydrocarbon chains, particularly alkanes, cycloalkanes, and aromatics and heavier than gasoline and naphtha. Fuel oil is classified into six classes, numbered 1 through 6, according to its boiling point, composition, and purpose. The boiling point, ranging from 175 to 600°C, and carbon chain length, 9–70 atoms. Viscosity also increases with number, and the heaviest oil has to be heated to get it to flow. Price usually decreases as the fuel number increases. Number 1 is similar to kerosene, number 2 is the diesel fuel that trucks and some cars run on, leading to the name “road diesel”. Number 4 fuel oil is usually a blend of heavy distillate and residual fuel oils. Number 5 and 6 fuel oils are called residual fuel oils or heavy fuel oils. Table 2.5 shows the heating values of various fuel oils per gallon.

Table 2.5 Typical heating values of various fuel oils

Type	Unit	Btu
No. 1 Oil	Gallon	137400
No. 2 Oil	Gallon	139600
No. 3 Oil	Gallon	141800
No. 4 Oil	Gallon	145100
No. 5 Oil	Gallon	148800
No. 6 Oil	Gallon	152400

ETB [15] with permission

Carbon fuels contain sulfur and impurities. Combustion of such fuels eventually leads to producing sulfur monoxides (SO) and sulfur dioxide (SO_2) in the exhaust which promotes acid rain. One final element in exhaust pollution is ozone (O_3). This is not emitted directly but made in the air by the action of sunlight on other pollutants to form *ground level ozone*, which is harmful on the respiratory systems if the levels are too high. However, the *ozone layer* in the high atmosphere is useful in blocking the harmful rays from the sun. Ozone is broken down by nitrogen oxides. For the nitrogen oxides, carbon monoxide, sulfur dioxide, and ozone, there are accepted levels that are set by legislation to which no harmful effects are observed.

2.3.4 Natural Gas

Natural gas is a naturally occurring mixture, consisting mainly of methane. Table 2.6 shows the typical components of natural gas. Natural gas provides 23% of all energy consumed in the world. The International Energy Agency predicts that the demand for natural gas will grow by more than 67% through 2030. Natural gas is becoming increasingly popular as an alternative transportation fuel. Typical theoretical flame temperature of natural gas is 1960°C (3562°F), ignition point is 593°C.

Natural gas is a major source of electricity production through the use of gas turbines and steam turbines. It burns more cleanly and produces about 30% less carbon dioxide than burning petroleum and about 45% less than burning coal for an equivalent amount of heat produced. Combined cycle power generation using natural gas is thus the cleanest source of power available using fossil fuels, and this technology is widely used wherever gas can be obtained at a reasonable cost. The gross heat of combustion of one cubic meter of natural gas is around 39 MJ and the typical caloric value is roughly 1,000 Btu per cubic foot, depending on gas composition.

Liquefied natural gas exists at −161°C (−258°F). Impurities and heavy hydrocarbons from the gaseous fossil fuel are removed before the cooling process. The density of liquefied natural gas is in the range 410–500 kg/m^3. The volume of the liquid is approximately 1/600 of the gaseous volume at atmospheric conditions.

Table 2.6 Typical composition in mole % and heating value of a natural gas

Component	Composition	Range
Methane	95.2	87.0–96.0
Ethane	2.5	1.5−5.1
Propane	0.2	0.1−1.5
Butane, *n*-butane	0.03	0.01−0.3
Iso-pentane, *n*-pentane, hexane plus	0.01	Trace−0.14
Nitrogen	1.3	0.7−5.6
Carbon dioxide	0.7	0.1−1.0
Oxygen	0.02	0.01−0.1
Hydrogen	Trace	Trace−0.02
Specific gravity	0.58	0.57−0.62
Gross heating value (MJ/m^3), dry basis	37.8	36.0−40.2

2.3.5 Nuclear Energy

Nuclear energy plants produce electricity through the fission of nuclear fuel, such as uranium, so they do not pollute the air with harmful gases. *Nuclear fission* is a nuclear reaction in which the nucleus of an atom splits into smaller parts, often producing free neutrons and photons in the form of gamma rays and releasing large amounts of energy. Nuclear fuels undergo fission when struck by free neutrons and generate neutrons leading to a self-sustaining chain reaction that releases energy at a controlled rate in a nuclear reactor [5, 7]. This heat is used to produce steam to be used in a turbine to produce electricity. This is similar to most coal, oil, and gas-fired power plants.

Typical fission release about two hundred million eV (200 MeV) of energy, which is much higher than most chemical oxidation reactions. For example, complete fission energy of uranium-235 isotope is 6.73×10^{10} kJ/kg [8]. The energy of nuclear fission is released as kinetic energy of the fission products and fragments, and as electromagnetic radiation in the form of gamma rays in a nuclear reactor. The energy is converted to heat as the particles and gamma rays collide with the atoms that make up the reactor and its working fluid, usually water or occasionally heavy water. The products of nuclear fission, however, are far more radioactive than the heavy elements which are normally fissioned as fuel, and remain so for a significant amount of time, giving rise to a nuclear waste problem. More than 400 nuclear power plants operating in 25 countries supply almost 17% of the world's electricity.

Nuclear power is essentially carbon-free. However, the electricity from new nuclear power plants would be relatively expensive, and nuclear energy faces a number of significant obstacles. The biggest challenges are the disposal of radioactive waste and the threat of nuclear proliferation. New plants would also require long licensing times, and it would likely be at least a decade before nuclear energy could be brought to bear on the climate change problem.

2.4 Heating Value of Fuels

The heating value of a fuel is the quantity of heat produced by its combustion at constant pressure and under “normal” conditions (i.e. to 25°C and under a pressure of 1 atm). The combustion process generates water. Various heating values are:

- The *higher heating value* (HHV) consists of the combustion product of water condensed and that the heat of vaporization contained in the water vapor is recovered. So the all the water produced in the combustion is in liquid state.
- The *lower heating value* (LHV) assumes that the water product of combustion is at vapor state and the heat of vaporization is not recovered.
- *Net heating value* is the same with lower heating value and is obtained by subtracting the latent heat of vaporization of the water vapor formed by the combustion from the gross or higher heating value.
- *The gross heating value* is the total heat obtained by complete combustion at constant pressure including the heat released by condensing the water vapor in the combustion products. Gross heating value accounts liquid water in the fuel prior to combustion, and valuable for fuels containing water, such as wood and coal. If a fuel has no water prior to combustion then the gross heating value is equal to higher heating value. A common method of relating HHV to LHV per unit mass of a fuel is

  $$\mathrm{HHV} = \mathrm{LHV} + \Delta H_{\mathrm{vap}}\left[\left(MW_{\mathrm{H_2O}} n_{\mathrm{H_2O,out}}\right)/\left(MW_{\mathrm{Fuel}} n_{\mathrm{Fuel,in}}\right)\right] \tag{2.1}$$

  where ΔH_{vap} is the heat of vaporization per mole of water (kJ/kg or Btu/lb), $n_{\mathrm{H_2O,out}}$ is the moles of water vaporized, $n_{\mathrm{fuel,in}}$ is the number of moles of fuel combusted, and MW is the molecular weight.

Tables 2.7 and 2.8 show the properties and heating values of some common fuels. The heating value of fossil fuels may vary depending on the source and composition.

2.4.1 Energy Density

Energy density is the amount of energy per unit volume. *Specific energy* is the amount of energy per unit amount. Comparing, for example, the effectiveness of hydrogen fuel to gasoline, hydrogen has a higher specific energy than gasoline but a much lower energy density even in liquid form. Energy per unit volume has the same physical units as pressure. Table 2.9 lists energy densities of some fuel and fuel mixtures.

Table 2.7 Properties heating values of some common fuels and hydrocarbons at 1 atm and 20°C; at 25°C for liquid fuels, and 1 atm and normal boiling temperature for gaseous fuels

Fuel (phase)	Formula	MW (kg/kmol)	ρ (kg/l)	ΔH_v (kJ/kg)	T_b (°F)	C_p (kJ/kg °C)	HHV[a] (kJ/kg)	LHV[a] (kJ/kg)
Carbon (s)	C	12.01	2.000	–		0.71	32,800	32,800
Hydrogen (g)	H_2	2.01	–	–		14.40	141,800	120,000
Methane (g)	CH_4	16.04	–	509	−258.7	2.20	55,530	50,050
Methanol (l)	CH_3OH	32.04	0.790	1168	149.0	2.53	22,660	19,920
Ethane (g)	C_2H_6	30.07	–	172	−127.5	1.75	51,900	47,520
Ethanol (l)	C_2H_5OH	46.07	0.790	919	172.0	2.44	29,670	26,810
Propane(g)	C_3H_8	44.09	0.500	420	−43.8	2.77	50,330	46,340
Butane (l)	C_4H_{10}	58.12	0.579	362	31.1	2.42	49,150	45,370
Isopentane (l)	C_5H_{12}	72.15	0.626	–	82.2	2.32	48,570	44,910
Benzene (l)	C_6H_6	78.11	0.877	433	176.2	1.72	41,800	40,100
Hexane (l)	C_6H_{14}	86.18	0.660	366	155.7	2.27	48,310	44,740
Toluene (l)	C_7H_8	92.14	0.867	412	231.1	1.71	42,400	40,500
Heptane (l)	C_7H_{16}	100.204	0.684	365	209.1	2.24	48,100	44,600
Octane (l)	C_8H_{18}	114.23	0.703	363	258.3	2.23	47,890	44,430
Decane (l)	$C_{10}H_{22}$	142.28	0.730	361		2.21	47,640	44,240
Gasoline (l)	$C_nH_{1.87n}$	100–110	0.72−0.78	350		2.40	47,300	44,000
Light diesel (l)	$C_nH_{1.8n}$	170.00	0.78−0.84	270		2.20	46,100	43,200
Heavy diesel (l)	$C_nH_{1.7n}$	200.00	0.82-0.88	230		1.90	45,500	42,800
Natural gas (g)		~18.00	–	–		2.00	50,000	45,000

ETB [15] with permission

[a] HHV, LHV; higher heating value and lower heating value, respectively; (s): solid; (l): liquid; (g): gas

Example 2.1 Energy consumption by a car

An average car consumes 50 gallons gasoline per month. Estimate the energy consumed by the car per year.

Solution:

Assume that gasoline has an average density of 0.72 g/cm^3 and the heating value of 47.3 MJ/kg (Table 2.7).

Data: $V = 50$ gallons/month $=$ 189.25 l/month, 2271.01/year (3.785 l $=$ 1 gallon)

$\rho_{\text{gas}} = 0.72\ \text{g/cm}^3 = 0.72\ \text{kg/l}$

Mass of gasoline: $m_{\text{gas}} = \rho V = 1635.1$ kg/year

Energy consumed per year:

$E_{\text{gas}} = 1635.1$ kg/year (47,300 kJ/kg) $=$ **77,340,230 kJ/year**

$=$ **77,340.2 MJ/year**

Example 2.2 Fuel consumption by a low and a high-mileage car

An average daily traveling distance is about 40 miles/day. A car has a city-mileage of 20 miles/gal. If the car is replaced with a new car with a city-mileage of 30 miles/gal and the average cost of gasoline is $3.50/gal, estimate the amount of fuel, energy, and money conserved with the new car per year.

Assume: The gasoline is incompressible with $\rho_{av} = 0.75$ kg/l.

Table 2.8 Higher heating values (gross calorific value) of some common fuels

Fuel	Higher heating value	
	kJ/kg	Btu/lb
Anthracite	32,500–34,000	14,000–14,500
Bituminous coal	17,000–23,250	7,300–10,000
Butane	49,510	20,900
Charcoal	29,600	12,800
Coal(anthracite)	30,200	13,000
Coal(bituminous)	27,900	12,000
Coke	28,000–31,000	12,000–13,500
Diesel	44,800	19,300
Ether	43,000	
Gasoline	47,300	20,400
Glycerin	19,000	
Hydrogen	141,790	61,000
Lignite	16,300	7,000
Methane	55,530	
Oils, vegetable	39,000–48,000	
Peat	13,800–20,500	5,500–8,800
Petroleum	43,000	
Propane	50,350	
Semi anthracite	26,700–32,500	11,500–14,000
Wood (dry)	14,400–17,400	6,200–7,500
	kJ/m^3	Btu/ft^3
Acetylene	56,000	
Butane C_4H_{10}	133,000	3200
Hydrogen	13,000	
Natural gas	43,000	950–1,150
Methane CH_4	39,820	
Propane C_3H_8	101,000	2550
Butane C_4H_{10}		3200
	kJ/l	Btu/gal
Gasoline	32,000	115,000
Heavy fuel oil #6	42,600	153,000
Kerosene	37,600	135,000
Diesel	36,300	130,500
Biodiesel	33,500	120,000
Butane C_4H_{10}	36,200	130,000
Methanol	15,900	57,000
Ethanol	21,100	76,000

Gaur and Reed [18]; ETB [15] with permission

1 kJ/kg = 1 J/g = 0.43 Btu/lb$_m$ = 0.239 kcal/kg

1 Btu/lb$_m$ = 2.326 kJ/kg = 0.55 kcal/kg

1 kcal/kg = 4.187 kJ/kg = 1.8 Btu/lb$_m$

Table 2.9 Energy densities of some fuels

Fuel type	Gross (HHV)			Net (LHV)
	MJ/l	MJ/kg	Btu/gal	Btu/gal
Conventional gasoline	34.8	44.4	125,000	115,400
High octane gasoline	33.5	46.8	120,200	112,000
LPG (60%Pr. + 40%Bu.)	26.8	46.0		
Ethanol	24.0	30.0	84,600	75,700
Methanol	17.9	19.9	64,600	56,600
Butanol	29.2	36.6		
Gasohol E10 (ethanol 10% vol.)	33.2	43.5	120,900	112,400
Gasohol E85 (ethanol 85% vol.)	25.6	33.1		
Gasoline (petrol)	34.2	46.4		115,500
Diesel	38.6	45.4	138,700	128,700
Biodiesel	33.5	42.2	126,200	117,100
Jet fuel (kerosene based)	35.1	43.8	125,935	
Jet fuel (naphtha)	42.8	33.0	127,500	118,700
Liquefied natural gas (160°C)	22.2	53.6	90,800	
Liquefied petroleum gas	26.8	46.0	91,300	83,500
Hydrogen (liquid at 20 K)	10.1	142.0		130
Hydrogen gas	0.0108	143.0		
Methane (1 atm, 15°C)	0.0378	55.6		
Natural gas	0.0364	53.6		
LPG propane	25.3	49.6		
LPG butane	27.7	49.1		
Crude oil	37.0	46.3		
Coal, anthracite	72.4	32.5		
Coal, lignite		14.0		
Coal, bituminous	20.0	24.0		
Wood		18.0		

Gaur and Reed [18], ETB [15]

Lower heating value (LHV) = 44000 kJ/kg; 44,000 kJ of heat is released when 1 kg of gasoline is completely burned and the produced water is in vapor state (Table 2.7).

Fuel needed for the old car: (40 miles/day)/(20 miles/gal) = 2 gal/day
Fuel needed for the new car: (40 miles/day)/(30 miles/gal) = 1.34 gal/day

Old car:
Mass of gasoline:
$m_{gas} = \rho_{av}$ (Volume) = (0.75 kg/l)(2.0gal/day)(3.785 l/gal) = **5.7 kg/day**

Energy of gasoline:
E_{gas} (LHV) = (5.7 kg/day) (44000 kJ/kg) = 250800 kJ/day (365 day/year)
= 91542,000 kJ/year = **91,542 MJ/year**
Cost: ($3.50/gal)(2 gal/day)(365 day/year) = $2555/year

New car:
Mass of gasoline:
$m_{gas} = \rho_{av}$ (Volume) = (0.75 kg/l)(1.34gal/day)(3.785 l/gal) = **3.8 kg/day**
Energy of gasoline:
E_{gas} (LHV) = (3.8 kg/day) (44000 kJ/kg) = 167,200 kJ/day (365 day/year)
= 61,028,000 kJ/year = **61,028 MJ/year**
Cost: (\$3.50/gal)(1.34 gal/day)(365 day/year) = \$1712/year

The new car reduces the fuel consumption by around 33%, which is significiant.

Example 2.3 Daily consumption of natural gas by a city
The new car reduces the fuel consumption by around 33%, which is significant. A city consumes natural gas at a rate of 500 × 10^6 ft^3/day. The volumetric flow is at standard conditions of 60°F and 1 atm = 14.7 psia. If the natural gas is costing \$6/GJ of higher heating value what is the daily cost of the gas for the city.

Solution:
Q = 500 × 10^6 ft^3/day at 60°F and 1 atm = 14.7 psia.

The higher heating value is the heat of combustion of the natural gas when the water product is at liquid state. From Table 2.7, the value of HHV is: 1,030 Btu/ft^3 (Table 2.8)

Heating value: 1030 Btu/ft^3 (500 × 10^6 ft^3/day) = 515.0 × 10^9 Btu/day
(515.0 ×10^9 Btu/day) (1055 J/Btu) = 543,325 GJ/day

Daily cost: (543,325 GJ/day) (\$6/GJ) = **\$32.6 × 10^5/day**

Example 2.4 Energy consumed by a car
An average car consumes about 2 gallons (US gallon = 3.785 l) a day, and the capacity of the fule tank is about 15 gallon. Therefore, a car needs to be refueled once every week. The density of gasoline ranges from 0.72 to 0.78 kg/l (Table 2.7). The lower heating value of gasoline is about 44,000 kJ/kg. Assume that the average density of gasoline is 0.75 kg/l. If the car was able to use 0.2 kg of nuclear fuel of uranium-235, estimate the time in years for refueling.

Solution:
Assume: The gasoline is incompressible with ρ_{av} = 0.75 kg/l.
Lower heating value (LHV) = 44,000 kJ/kg; 44,000 kJ of heat is released when 1 kg of gasoline is completely burned and the produced water is in vapor state.

Complete fission energy of U-235 = 6.73 × 10^{10} kJ/kg
Mass of gasoline per day:
$m_{gas} = \rho_{av}\, V$ = (0.75 kg/l)(2gal/day)(3.785 l/gal) = 5.67 kg/day

Energy of gasoline per day :
$E_{gas} = m_{gas}\, (LHV)$ = (5.67 kg/day)(44,000 kJ/kg) = 249,480 kJ/day

Energy released by the complete fission of 0.2 kg U-235:
$E_{\text{U-235}} = (6.73\ 10^{10}\ \text{kJ/kg})(0.2\ \text{kg}) = 1.346\ 10^{10}\ \text{kJ}$

Time for refueling: $(1.346\ 10^{10}\ \text{kJ})/(249{,}480\ \text{kJ/day}) =$ **53952 days = 148 years**
Therefore, the car will not need refueling for about 148 years.

2.5 Renewable Energy Resources

Renewable energy comes from natural resources and are naturally replenished. Major renewable energy sources are:

- Hydroelectric
- Solar energy
- Biomass
- Wind
- Geothermal heat
- Ocean

In its various forms, renewable energy comes directly from the sun, or from heat generated deep within the earth. In 2008, about 19% of global final energy consumption came from renewables, with 13% coming from traditional biomass, which is mainly used for heating, and 3.2% from hydroelectricity. Other renewables, such as small hydro, biomass, wind, solar, geothermal, and biofuels contributed around 2.7% and are growing rapidly. The share of renewables in electricity generation is around 18%, with 15% of global electricity coming from hydroelectricity and 3% from new renewables. Climate change concerns, high oil prices, and government support are leading to increase in renewable energy usage and commercialization [14]. Consequently, between 2004 and 2009, worldwide renewable energy capacity grew at rates of 10–60% annually creating businesses and employment. Renewable energy replaces conventional fuels in four distinct areas: power generation, hot water/space heating, transport fuels, and rural (off-grid) energy services [6, 7]:

- *Renewable power generation* provides 18% of total electricity generation worldwide. Renewable power generators are spread across many countries, and wind power alone already provides a significant share of electricity in some areas.
- *Solar hot water* contributes a portion of the water heating needs of over 70 million households in many countries.
- *Renewable biofuels* have contributed to a decline in oil consumption in Brazil, the United States and many other countries. The 93 billion liters of biofuels produced worldwide in 2009 displaced the equivalent of an estimated 68 billion liters of gasoline, equal to about 5% of world gasoline production.

New and emerging renewable energy technologies are still under development and include cellulosic ethanol, hot-dry-rock geothermal power, and ocean energy. Renewable energy generally gets cheaper in the long term, while fossil fuels generally get more expensive. Fossil fuel technologies are more mature, while renewable energy technologies are being rapidly improved to increase the efficiency of renewable energy and reduce its cost. In rural and remote areas, transmission and distribution of energy generated from fossil fuels can be difficult and expensive; therefore producing renewable energy locally can offer a viable alternative.

The International Renewable Energy Agency (IRENA) promotes the adoption of renewable energy worldwide. As of March 2010, IRENA has 143 member states. Renewable energy policy targets exist in some 73 countries around the world, and public policies to promote renewable energy use have become more common in recent years. Mandates for blending biofuels into vehicle fuels have been enacted in 17 countries. The shift from food crop feedstock to waste residues and native grasses offers significant opportunities for farmers and investors [30].

2.5.1 Hydroenergy

Hydroenergy is derived from the force or energy of moving water. Most hydroelectric energy comes from the potential energy of dammed water driving a water turbine and generator. The power extracted from the water depends on the volume and on the difference in height between the source and the water's outflow. This height difference is called the head. The amount of potential energy in water is proportional to the head. To deliver water to a turbine while maintaining pressure arising from the head, a large pipe called a penstock may be used. In 1878, the world's first house to be powered with hydroelectricity was in Northumberland, England. The old Schoelkopf Power Station near Niagara Falls in the US began to produce electricity in 1881.

One of the major advantages of hydroelectricity is the elimination of fuel. Because there is no fuel combustion, there is little air pollution in comparison with fossil fuel plants and limited thermal pollution compared with nuclear plants. Hydroelectric plants also tend to have longer economic lives than fuel-fired power generation, with some plants now in service which were built 50–100 years ago. Operating labor cost is also usually low, as plants are automated and need few personnel on site during normal operation. The sale of electricity from the station may cover the construction costs after 5–8 years of full operation.

Hydroelectric usually refers to large-scale hydroelectric dams. Micro hydro systems typically produce up to 100 kW of power. Hydro systems without dam derive kinetic energy from rivers and oceans. Ocean energy includes marine current power, ocean thermal energy conversion, and tidal power. Figure 2.5 shows the Ice Harbor dam in the US.

2.5.2 Solar Energy

Solar energy is derived from the sun through the form of solar radiation. Solar powered electrical generation relies on photovoltaics and heat engines. Other solar applications

Fig. 2.5 Ice Harbor Dam. Hydroelectric plants operate where suitable waterways are available. Water may be a source of cheap and relatively clean power. In addition, because there is no fuel combustion, there is little air pollution in comparison with fossil fuel plants and limited thermal pollution compared with nuclear plants. The use of water for power generation has environmental impacts caused by damming rivers and streams, which affects the habitats of the local plant, fish, and animal life [14]

includes space heating and cooling through solar architecture, daylighting, solar hot water, solar cooking, and high temperature process heat for industrial purposes. Solar technologies are broadly characterized as either passive solar or active solar depending on the way they capture, convert and distribute solar energy:

- *Active solar techniques* include the use of solar thermal collectors to harness the energy. Some active solar techniques include s*olar process heat* by commercial and industrial buildings, *space heating/cooling*, and water heating. A typical water heating system includes solar collectors that work along with a pump, heat exchanger, and one or more large heat storage tanks. The most common collector is called a *flat-plate collector*. Mounted on a roof, it consists of a thin, flat, rectangular box with a transparent cover that faces the sun (see Fig. 2.6a). Small tubes run through the box and carry the heat transfer fluid mainly water or air to be heated. The tubes are attached to an absorber plate, which is painted black to absorb the heat. As heat builds up in the collector, it heats the fluid passing through the tubes. The storage tank then holds the hot liquid. It can be just a modified water heater, but it is usually larger and very well-insulated. Systems that use fluids other than water usually heat the water by passing it through a coil of tubing in the storage tank, which is full of hot fluid.
- *Passive solar systems* rely on gravity and the tendency for water to naturally circulate as it is heated. *Passive solar techniques* orient buildings to the Sun, select materials with favorable thermal mass or light dispersing properties, and design spaces that naturally circulate air. Figure 2.6a shows solar hot water systems and Fig. 2.6b a house with passive solar design.

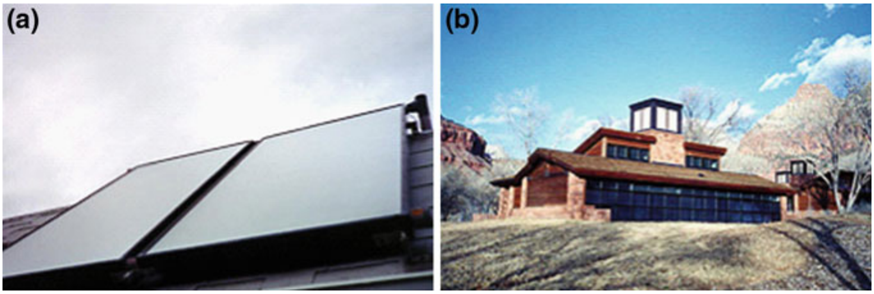


Fig. 2.6 **a** For solar hot water systems, flat-plate solar collectors are typically installed facing south on a rooftop; **b** the Zion National Park Visitor Center incorporates passive solar design features, including clerestory windows for daylighting and Trombe walls that absorb heat during the day and give off heat at night [32]

2.5.2.1 Nonresidential Solar Collectors

The two main types of solar collectors used for nonresidential buildings are an *evacuated-tube collector* and a *linear concentrator*. They can operate at high temperatures with high efficiency. An evacuated-tube collector is a set of many double-walled, glass tubes and reflectors to heat the fluid inside the tubes. A vacuum between the two walls insulates the inner tube, retaining the heat. Linear concentrators use long, rectangular, U-shaped mirrors tilted to focus sunlight on tubes that run along the length of the mirrors. The concentrated sunlight heats the fluid within the tubes. Solar absorption systems use thermal energy to evaporate a refrigerant fluid to cool the air. In contrast, solar desiccant systems use thermal energy to regenerate desiccants that dry the air, thereby cooling the air [4, 14].

2.5.2.2 Solar Electric Generating Systems

Solar electric generating system use parabolic trough collectors to collect the sun's energy to generate steam to drive a conventional steam turbine [4]. The parabolic mirrors automatically track the sun throughout the day. The sun light is directed to central tube carrying synthetic oil, which heats around 400°C. The heat is used to convert water to steam to drive a steam turbine and produce electricity. The largest solar thermal power station is in the Mojave Desert in the US with a power output of 354 MW (see Fig. 2.7).

2.5.2.3 Photovoltaic

Solar photovoltaic (PV) convert light into electricity using semiconductor materials. Photovoltaic cell is a *solar cell*, which is a solid state electrical device that converts the energy of light directly into electricity. Assemblies of cells are known

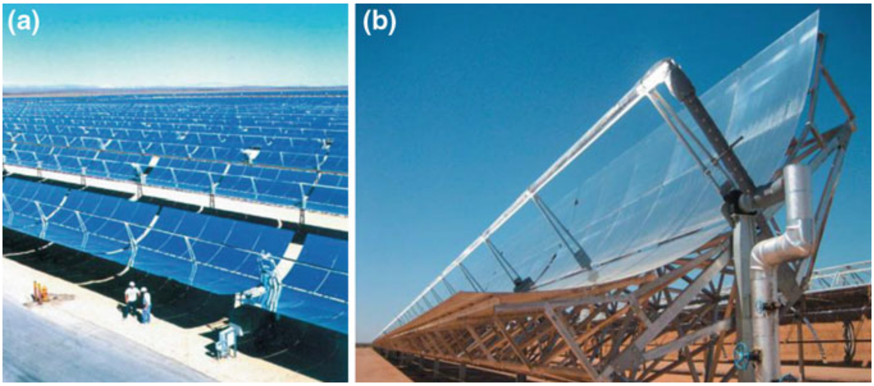


Fig. 2.7 **a** The 150-MW Kramer Junction plants shown here are part of a 354 MW series of SEGS (solar electric generating system) facilities, each using parabolic trough collectors to collect the sun's energy to generate steam to drive a conventional steam turbine. The plants have been operating in the California Mojave Desert for two decades [32]; **b** parabolic trough solar collectors at the recently dedicated 1-MW Saguaro power plant outside Tucson concentrate sunlight onto a receiver tube located along the trough's focal line. The solar energy heats the working fluid in the receiver tube, which vaporizes a secondary fluid to power a turbine. A next-generation version of this collector is being installed at a new 64-MW plant in Nevada [25]

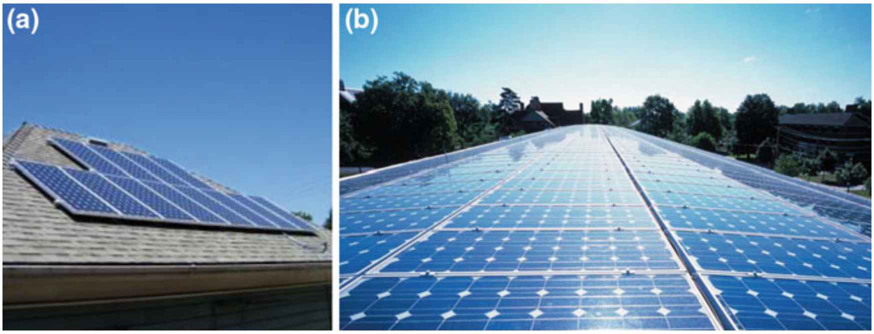


Fig. 2.8 **a** Photovoltaic systems are typically sited on roofs and may be connected to the electrical grid. Photovoltaic modules can compete against the retail price of electricity, offsetting the technology's high cost; **b** rooftop photovoltaic module (Oberlin College's Adam Joseph Lewis Center for Environmental Studies features a south-facing curved roof covered in Williamson) [25]

as *solar modules* or *solar panels*. Solar modules are typically deployed as an array of individual modules on rooftops, building facades, or in large-scale ground-based arrays (see Fig. 2.8). A module consists of many jointly connected solar cells. Most crystalline modules usually consist of 60–72 cells. Photovoltaic cell and modules use various semiconductors; they have three types (1) crystalline silicon, (2) thin-film, and (3) concentrator. Photovoltaic systems produce direct

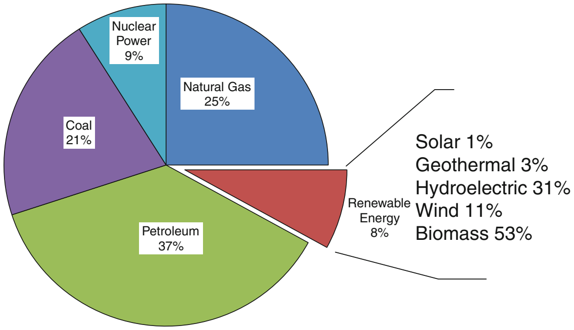


Fig. 2.9 Renewable energy consumption in the U.S.'s energy supply in 2009. (quad = 10^{15} Btu): Total; 97892 quadrillion Btu, Total renewables: 8049 quadrillion Btu [14]

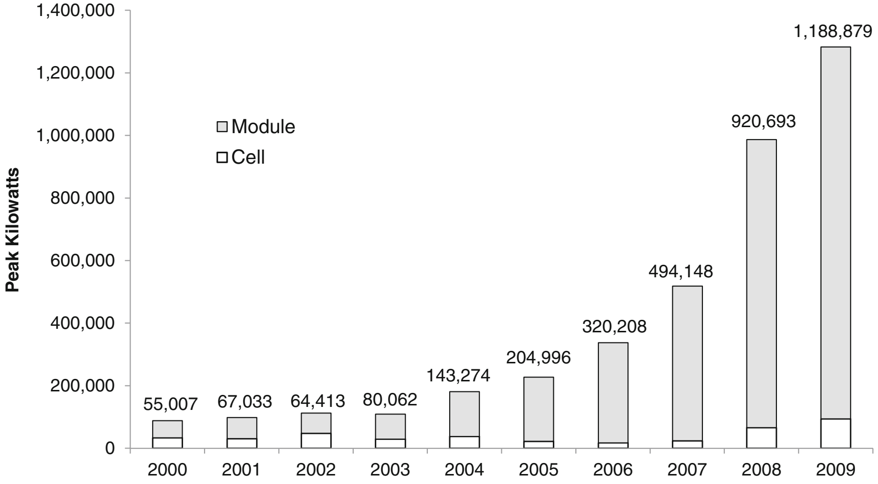


Fig. 2.10 Growth of US photovoltaic industry between 2000 and 2009. Assemblies of cells are known as solar modules or solar panels. Photovoltaic cell and modules use various semiconductors; they have three types (1) crystalline silicon, (2) thin-film, and (3) concentrator [14]

current, which must be converted to alternating current via an inverter if the output from the system is to be used in the grid. Annual production of photovoltaic modules in 2005 was about 150 MW in the US and about 1.7 gigawatts (GW) worldwide [11].

A major goal is to increase solar photovoltaic efficiency and decrease costs. Current efficiencies for crystalline silicon cells equal to about 15–20%. The total costs of photovoltaic systems are currently in the \$6 to \$9 per peak watt range. Component costs include the photovoltaic modules at about \$3–\$4/W (direct current), with another \$3–\$5/W for the inverter, installation, and balance of system. The cost of residential electricity from solar photovoltaic should be around 10–12 cents/kWh by 2015 and 6–8 cents/kWh by 2030. Figure 2.9 shows the renewable energy consumption in the U.S. energy supply in 2009. Figure 2.10 shows the use of photovoltaic in kW in the U.S. between 2000 and 2009.

Fig. 2.11 **a** Photosynthesis; in the photosynthesis plants convert solar energy into chemical energy in the form of glucose: Water + Carbon dioxide + Sunlight → Glucose + Oxygen and $H_2O + CO_2 + \text{Sunlight} \rightarrow C_6H_{12}O_6 + 6O_2$; **b** biomass growth; **c** the 21 MW Tracy Biomass Plant uses wood residues discarded from agricultural and industrial operations to provide the San Francisco Bay Area with base load capacity [32]

2.5.3 Biomass and Bioenergy

Biomass is organic material made from plants including microorganisms and animals. Plants absorb the sun's energy in photosynthesis and store the energy as biomass (see Fig. 2.11). Therefore, biomass is a renewable energy source based on the carbon cycle. Some examples of biomass fuels include wood, crops, and algae. When burned, the chemical energy in biomass is released as heat. Biomass can be converted to other biofuels, such as ethanol and biodiesel. Biomass grown for biofuel includes corn, soybeans, willow switch grass, rapeseed, sugar beet, palm oil, and sorghum [30]. Cellulosic biomass, such as corn stover, straw, timber, rice husks can also be used for biofuel production (see Fig. 2.11). Anaerobic digestion of biomass produces biogas, while gasification produces syngas, which is the mixture of hydrogen and carbon dioxide to be converted to liquid fuels. Cellulosic ethanol can also be created by a thermo-chemical process, which uses various combinations of temperature, pressure, water, oxygen or air, and catalysts to convert biomass to cellulosic ethanol. Table 2.10 shows lower heating values, moisture, and ash content of some biomass.

As Fig. 2.12 indicates that between years 2006 and 2010 the use of wind power and biomass increased, while the hydropower share decreased; the use of solar and geothermal sources remained the same [14].

2.5.3.1 Carbon Cycle

In the carbon cycle, carbon in various forms is transported between the various components of the Earth's biosphere, between the atmosphere, hydrosphere (seas and oceans), lithosphere (rocks, soils and mineral deposits, including fossil fuels) and biological material including plants and animals. Carbon cycle maintains a state of dynamic equilibrium. Other forms, most notably fossil fuels, can potentially store carbon indefinitely, however if they are burned the carbon is released and makes a net addition to the carbon cycle and raising the total free carbon. If

Table 2.10 Lower heating values (LHV) for selected biomass

Product	Moisture (%)	Ash content[a] (%)	LHV (MJ/kg)
Bagasse sugarcane	18	4	17–18
Coconut husks	5–10	6	16,7
Coffee husks	13	8–10	16,7
Corn stover	5–6	8	17–19
Corncobs	15	1–2	19,3
Cotton husks	5–10	3	16,7
Oil-palm fibers	55	10	7–8
Oil-palm husks	55	5	7–8
Poplar wood	5–15	1.2	17–19
Rice hulls	9–11	15–20	13–15
Rice straw and husk	15–30	15–20	17–18
Switchgrass	8–15	6	18–20
Wheat straw and husk	7–15	8–9	17–19
Willow wood	12	1–5	17–19

[a] Approximate [15]

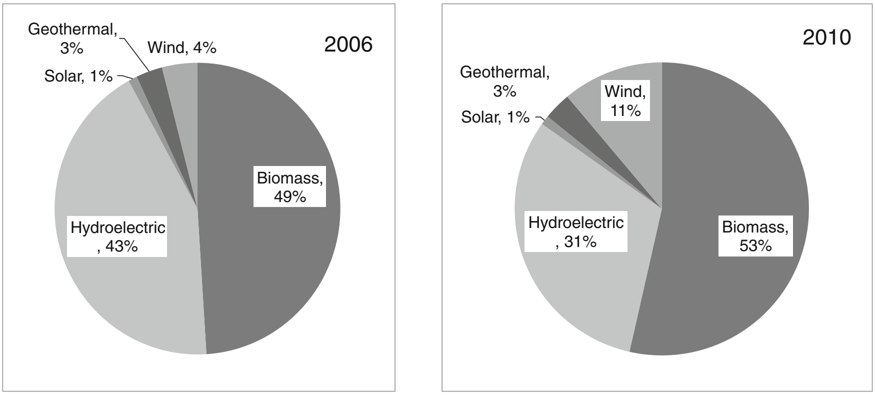


Fig. 2.12 Use of renewable energy in the US; the use of wind power and biomass increased, while the hydropower share decreased; the use of solar and geothermal sources remained the same [14]

biomass is used without replacement, for example in the case of forest clearance, this too can make a net addition to the carbon cycle. As growing plant absorbs the carbon released by the harvested biomass, sustainable use of biomass makes no direct net contribution [19, 20].

2.5.3.2 Gross Heating Values of Biomass Fuels

Biomass fuels are usually characterized by the *proximate* and *ultimate analyses*.

Table 2.11 Proximate and ultimate analyses of biomass fuels in weight percentage

Name	Fixed Carbon	Volatiles %	Ash %	C %	H %	O %	N %	S %	HHV$_m$ kJ/g	HHV$_{est}$ kJ/g
Douglas Fir	17.70	81.50	0.80	52.30	6.30	40.50	0.10	0.00	21.05	21.48
Hickory	–	–	0.73	47.67	6.49	43.11	0.00	0.00	20.17	19.82
Maple	–	–	1.35	50.64	6.02	41.74	0.25	0.00	19.96	20.42
Ponderosa Pine	17.17	82.54	0.29	49.25	5.99	44.36	0.06	0.03	20.02	19.66
Poplar	–	–	0.65	51.64	6.26	41.45	0.00	0.00	20.75	21.10
Redwood	16.10	83.50	0.40	53.50	5.90	40.30	0.10	0.00	21.03	21.45
Western Hemlock	15.20	84.80	2.20	50.40	5.80	41.10	0.10	0.10	20.05	20.14
Yellow Pine	–	–	1.31	52.60	7.00	40.10	0.00	0.00	22.30	22.44
White Fir	16.58	83.17	0.25	49.00	5.98	44.75	0.05	0.01	19.95	19.52
White Oak	17.20	81.28	1.52	49.48	5.38	43.13	0.35	0.01	19.42	19.12
Douglas Fir bark	25.80	73.00	1.20	56.20	5.90	36.70	0.00	0.00	22.10	22.75
Loblolly Pine bark	33.90	54.70	0.40	56.30	5.60	37.70	0.00	0.00	21.78	22.35
Peach Pits	19.85	79.12	1.03	53.00	5.90	39.14	0.32	0.05	20.82	21.39
Walnut Shells	21.16	78.28	0.56	49.98	5.71	43.35	0.21	0.01	20.18	19.68
Almond Prunings	21.54	76.83	1.63	51.30	5.29	40.90	0.66	0.01	20.01	19.87
Black Walnut Prunings	18.56	80.69	0.78	49.80	5.82	43.25	0.22	0.01	19.83	19.75
Corncobs	18.54	80.10	1.36	46.58	5.87	45.46	0.47	0.01	18.77	18.44
Wheat Straw	19.80	71.30	8.90	43.20	5.00	39.40	0.61	0.11	17.51	16.71
Cotton Stalk	22.43	70.89	6.68	43.64	5.81	43.87	0.00	0.00	18.26	17.40
Corn Stover	19.25	75.17	5.58	43.65	5.56	43.31	0.61	0.01	17.65	17.19
Sugarcane Bagasse	14.95	73.78	11.27	44.80	5.35	39.55	0.38	0.01	17.33	17.61
Rice Hulls	15.80	63.60	20.60	38.30	4.36	35.45	0.83	0.06	14.89	14.40
Pine needles	26.12	72.38	1.50	48.21	6.57	43.72			20.12	20.02
Cotton gin trash	15.10	67.30	17.60	39.59	5.26	36.38	2.09	0.00	16.42	15.85
Cellulose	–	–	162	44.44	6.17	49.38	–	–	–	17.68
Lignin (Softwood)	–	–	–	63.8	6.30	29.90	–	–	–	26.60
Lignin (Hardwood)	–	–	–	59.8	6.40	33.70	–	–	–	24.93

Gaur and Reed [18]

- The *proximate analysis* gives moisture content, volatile content (when heated to 950°C), the free carbon remaining at that point, the ash (mineral) in the sample, and the higher heating value based on the complete combustion of the sample to carbon dioxide and liquid water.
- The *ultimate analysis* is the elemental analysis and provides the composition of the biomass in wt% of carbon, hydrogen, oxygen, sulfur, and nitrogen.

Table 2.11 shows measured and estimated gross heating values as well as the proximate and ultimate analyses of some selected fuels, including biomass components, natural biomass (woods, agricultural products), processed biomass, and other solid and liquid fuels.

A relationship between the high heating value, HHV and the elemental composition is given by

$$\begin{aligned}\mathrm{HHV}(\mathrm{in\,kJ/g}) = {} & 0.3491\mathrm{C} + 1.1783\mathrm{H} - 0.1034\mathrm{O} - 0.0211\mathrm{A} + 0.1005\mathrm{S} \\ & - 0.0151\,\mathrm{N}\end{aligned} \tag{2.2}$$

where C is the weight fraction of carbon, H of hydrogen, O of oxygen, A of ash, S of sulfur, and N of nitrogen appearing in the ultimate analysis. This equation represents the experimental data with an average error of 1.45% and can be used in estimating heat values and modeling of biomass processes [18].

Based on chemical functional groups of the fuels, the heating values may vary. When the oxygen percentage is higher in a fuel, the percentages of carbon and hydrogen available for combustion are reduced. This leads to the lower heating values. By using the values of fixed carbon (FC, wt%), the higher heating value of the biomass samples can be estimated by

$$\mathrm{HHV}(\mathrm{MJ/kg}) = 0.196(\mathrm{FC}) + 14.119 \tag{2.3}$$

The heating values calculated from Eq. (2.3) shows a mean difference of 2.2% between estimated and measured values [10]. Another correlation between the HHV and dry ash content from proximate analysis of biomass (in weight percent) is expressed by

$$\mathrm{HHV}(\mathrm{MJ/kg}) = 19.914 - 0.2324\mathrm{Ash} \tag{2.4}$$

Based on the composition of main elements (in wt%) C, H, and O, the heating value is estimated by

$$\mathrm{HHV}(\mathrm{MJ/kg}) = 0.3137\mathrm{C} + 0.7009\mathrm{H} + 0.0318\mathrm{O} - 1.3675 \tag{2.5}$$

with more than 90% predictions in the range of ±5% error [34].

Example 2.5 Gross heating value estimations

Using data in Table 2.11, estimate the gross heating values in kJ/kg for the biomass redwood from: (a) ultimate analysis, (b) fixed carbon, (c) dry ash content, and (d) carbon (C), hydrogen (H), and oxygen (O) compositions.

Name	Fixed Carbon	Volatiles (%)	Ash (%)	C (%)	H (%)	O (%)	N (%)	S (%)	$\mathrm{HHV_m}$ (kJ/g)	$\mathrm{HHV_{est}}$ (kJ/g)
Redwood	16.10	83.50	0.40	53.50	5.90	40.30	0.10	0.00	21.03	21.45

Solution:

(a) From ultimate analysis

HHV (in MJ/kg)

$= 0.3491\mathrm{C} + 1.1783\ \mathrm{H} - 0.1034\ \mathrm{O} - 0.0211\ \mathrm{A} + 0.1005\ \mathrm{S} - 0.0151\ \mathrm{N}$

HHV (in MJ/kg) = 0.3491(53.50) + 1.1783 (5.90) − 0.1034 (40.3) − 0.0211 (0.0040) + 0.1005 (0.0) −0.0151 (0.0010) = 21.44 MJ/kg = **21,440 kJ/kg**

(b) From fixed carbon percentage
HHV (MJ/kg) = 0.196(FC) + 14.119
HHV (MJ/kg) = 0.196(16.10) + 14.119 = 17.3 MJ/kg = **17,300 kJ/kg**

(c) From dry ash content
HHV (MJ/kg) = 19.914 – 0.2324 Ash
HHV (MJ/kg) = 19.914 – 0.2324 (0.0040) = 19.914 MJ/kg = **19,914 kJ/kg**

(d) From the main elements (in wt%) C, H, and O
HHV (MJ/kg) = 0.3137 C + 0.7009 H + 0.0318 O−1.3675
HHV (MJ/kg) = 0.3137 (53.50) + 0.7009 (5.9) + 0.0318 (40.3)−1.3675 = 20.83 MJ/kg = **20,830 kJ/kg**

Estimation from Eq. (2.5), used in part (d), is the closest to the measured value of 21.03 MJ/kg (21,030 kJ/kg)

2.5.3.3 Bioenergy

Biological fuels produced from photosynthesis can be categorized in three groups:

- *Carbohydrates*, representing a mixture of mono-di-and poly-saccharides (4 kcal/g or 17 kJ/g).
- *Fats*, unsaturated and saturated fatty acids (triacylglycerol or triglyceride) (9 kcal/g or 39 kJ/g).
- *Proteins*, used partly as fuel source (4 kcal/g or 17 kJ/g).

Carbohydrates are straight-chain aldehydes or ketones with many hydroxyl groups that can exist as straight chains or rings. Carbohydrates such as starch are the most abundant biological molecules, and play numerous roles, such as the storage and transport of energy, and structural components such as cellulose in plants. Triglycerides and fatty free acids both contain long, linear aliphatic hydrocarbon chains, which are partially unsaturated and have a carbon number range. The fuel value is equal to the heat of combustion (oxidation) of fuel. Carbohydrates and fats can be completely oxidized while proteins can only be partially oxidized and hence has lower fuel values [28].

Synthetic biofuels are:

- Bioethanol—In the United States, corn-based ethanol is currently the largest source of biofuel as a gasoline substitute or additive. The gasoline sold in the United States today is mixed with 10% ethanol, a mix known as E10 (or gasohol). Only specific types of vehicles named as flexible fuel vehicles can use mixtures with greater than 10% ethanol. E85 is an alternative fuel that contains up to 85% ethanol (see Fig. 2.13; [16]).

Fig. 2.13 Biofuels can displace imported oil for transportation. This triple biofuels dispenser at the Baca Street Biofuels Station in Santa Fe, New Mexico, offers consumers a choice of renewable transportation fuels [32]

- Biodiesel—Biodiesel is most often blended with petroleum diesel in ratios of 2% (B2), 5% (B5), or 20% (B20). It can also be used as pure biodiesel (B100). Biodiesel can be produced from various feedstock [2] and used in regular diesel vehicles without making any changes to the engines [24].
- Green diesel—Green diesel is produced by removing the oxygen by catalytic reaction with hydrogen from renewable feedstock containing triglycerides and fatty acids, producing a paraffin-rich product, water, and carbon oxides. Therefore, green diesel has a heating value equal to conventional diesel and is fully compatible for blending with the standard mix of petroleum-derived diesel fuels [9, 23]. Biodiesel has around 11% oxygen, whereas petroleum-based diesel and green diesel have no oxygen.

Bioethanol and biodiesel provided 1.8% of the world's transport fuel in 2008 and provided about 4% of the energy used in the United States [14]. Using biomass as a feedstock for liquid fuels production may cut back on waste and greenhouse gas emissions, and can offset the use of fossil fuels in heat and power generation. The total worldwide biomass electrical capacity is on the order of 40 GW. The current global growth rate for biomass-based transportation fuels is more than 10% per year.

2.5.4 Wind Energy

The Earth is unevenly heated by the sun and the differential heating drives a global atmospheric convection system reaching from the earth's surface to the


(a) (b)

Fig. 2.14 **a** Each 1.65 MW wind turbine at the Maple Ridge Wind Farm near Lowville, New York, generates enough electricity to power about 500 homes. Jennifer Harvey, NYSERDA, NREL PIX 14399; **b** offshore wind resources. Currently, the US has more than 35,000 MW of land-based installed wind power capacity. That is enough to serve more than 9 million homes and avoid the annual emissions of 62 million tons of carbon dioxide [13]

stratosphere. Most of the energy stored in these wind movements can be found at high altitudes where continuous wind speeds of over 160 km/h (99 mph) occur (see Fig. 2.14). To assess the frequency of wind speeds at a particular location, a probability distribution function is often fitted to the observed data. Wind power is a totally renewable energy source with no greenhouse gas emissions, but due to its unpredictability, has problems integrating with national grids. At the end of 2009, worldwide wind farm capacity was 157,900 MW, representing an increase of 31% during the year, and *wind power* supplied some 1.3% of global electricity consumption. Installed US wind power capacity reached 25,170 MW at the end of 2008 and still growing (15% in cumulative wind power capacity in 2010) [1, 39].

The potential for wind to supply a significant quantity of energy is considerable (see Fig. 2.15). Availability of transmission capacity helps large-scale deployment by reducing the cost of delivered wind energy.

2.5.5 Geothermal Energy

Geothermal energy is the heat originating from the original formation of the planet, from radioactive decay of minerals, from volcanic activity, and from solar energy absorbed at the surface (see Fig. 2.16). The geothermal gradient, which is the difference in temperature between the core of the planet and its surface, drives a continuous conduction of thermal energy in the form of heat from the core to the surface. Geothermal power is cost effective, reliable, sustainable, and environmentally friendly. The world's largest geothermal power installation is The Geysers in California, with a rated capacity of 750 MW. Worldwide, about 10,715 MW of geothermal power is produced. An additional 28 GW of direct geothermal heating capacity is installed for district heating, space heating, spas, industrial processes, desalination, and agricultural applications.

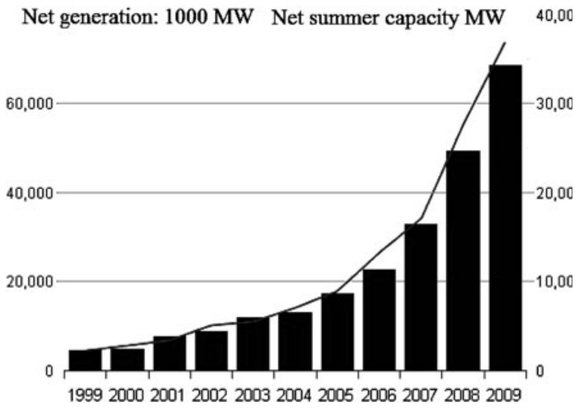


Fig. 2.15 Wind generation versus capacity; growth of wind power [14]


(a) (b)

Fig. 2.16 **a** The Earth's heat—called geothermal energy—escapes as steam at a hot springs in Nevada; **b** the Mammoth Lakes power plant is located in a picturesque area of northern California. Binary-cycle geothermal power plants release no carbon dioxide or water vapor plumes and blend into the environment [32]

Hot water or steam reservoirs deep in the earth are accessed by drilling. Geothermal reservoirs located near the earth's surface maintain a relatively constant temperature of 50°–60°F. The hot water and steam from reservoirs can be used to drive generators and produce electricity. In other applications, the heat produced from geothermal is used directly in heating buildings and industrial plants. As in the case of biomass electricity, a geothermal plant runs 24 hours per day, 7 days per week and can provide base load power, thus competing against coal plants.

2.5.6 Ocean Energy

Systems to harvest electrical power from ocean waves have recently been gaining momentum as a viable technology. The potential for this technology is considered promising. The world's first commercial tidal power station was installed in 2007

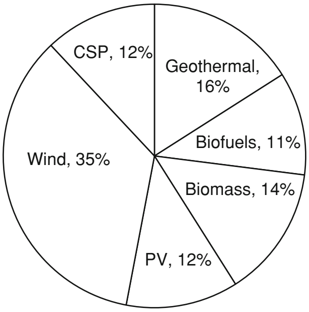


Fig. 2.17 Pie chart showing future projections of relative contributions of the various renewables in 2030 [14]. *PV* Photovoltaic; *CSP* Concentrated solar power

in the narrows of Strangford Lough in Ireland. Although the generator is powerful enough to power a thousand homes, the turbine has minimal environmental impact, as it is almost entirely submerged, and the rotors pose no danger to wildlife as they turn quite slowly. Ocean thermal energy conversion uses the temperature difference that exists between deep and shallow waters to run a heat engine (see Sect 7.16).

2.5.7 Projection on Renewable Energy Contributions

The pie chart in Fig. 2.17 shows the relative contributions of different renewable energy technologies. *Hybrid renewable energy systems* usually consist of two or more renewable energy sources used together to provide increased system efficiency as well as greater balance in energy supply. For example, consider a load of 100% power supply and there is no renewable system to fulfill this need, so two or more renewable energy systems can be combined. For example, 60% from a biomass system, 20% from a wind energy system and the remainder from fuel cells. Thus combining all these renewable energy systems may provide 100% of the power and energy requirements for the load, such as a home or business. Another example is the combination of a photovoltaic array coupled with a wind turbine. This would create more output from the wind turbine during the winter, whereas during the summer, the solar panels would produce their peak output.

2.6 Hydrogen

Hydrogen is the simplest element. Each atom of hydrogen has only one proton. The sun is basically a giant ball of hydrogen and helium gases. In the sun's core, hydrogen atoms combine to form helium atoms (called fusion process) and gives off *radiant energy*. This radiant energy sustains life on earth as it drives the photosynthesis in plants and other living systems, and is stored as chemical energy in fossil fuels.

Hydrogen does not exist on earth as a gas and is found only in compound form with other elements, such as water H_2O and methane CH_4. Hydrogen is produced from other resources including natural gas, coal, biomass, and even water. The two most common production methods are steam reforming and electrolysis in which the water is split into oxygen and hydrogen. Steam reforming is currently the least expensive and most common method of producing hydrogen. Electrolysis is currently an expensive process. Currently, global hydrogen production is 48% from natural gas, 30% from oil, 18% from coal, and 4% from water electrolysis.

Hydrogen has the highest energy content of any common fuel by weight (about three times more than gasoline), but the lowest energy content by volume (see Table 2.9). Hydrogen transports energy in a useable form from one place to another. Like electricity, hydrogen is an energy carrier. Hydrogen burns cleanly, producing water H_2O. When burned in an engine or; used a fuel cell, it is converted to water only. To make hydrogen a renewable fuel it should use renewable energy, such as wind power or solar power, for production.

There are two primary uses for hydrogen today. About half of hydrogen is used to produce ammonia (NH_3) via the Haber process. Ammonia, in turn, is used directly or indirectly as fertilizer. The other half of current hydrogen production is used in hydrocracking process to convert heavy petroleum sources into lighter fractions suitable for use as fuels. Hydrogen fuel cells produce electricity. They are very efficient, but expensive to build. Small fuel cells can power electric cars, while large fuel cells can provide electricity in remote places with no power lines.

2.7 Electric Energy

The protons and electrons of an atom carry an *electrical charge*. Protons have a positive charge (+) and electrons have a negative charge (−). Opposite charges attract each other. The electrons in an atom's outermost shells do not attract strongly to the protons and can move from one atom to another and create electricity. The amount of electricity a power plant generates or a customer uses over a period of time is measured in kilowatt hours (kWh), which is equal to the energy of 1,000 watts working for 1 h. For example, if you use a 100-W light bulb for 7 h, you have used 700 Wh or 0.7 kWh of electrical energy. Figure 2.18 shows the resources for electricity, while Fig. 2.19 shows how the electricity is used in US.

Most of the electricity used in the residential sector is for air conditioning, refrigerators, space and water heating, lighting, and powering appliances and equipment. Electricity is the fastest growing form of end-use energy worldwide through 2030, as it has been over the past several decades. Electricity is the most well-known energy carrier to transfer the energy in coal, natural gas, uranium, wind power, and other energy sources to homes, businesses, and industry. We also use electricity to transfer the energy in flowing water from hydropower dams to consumers. For many energy needs, it is much easier to use electricity than the energy sources themselves.

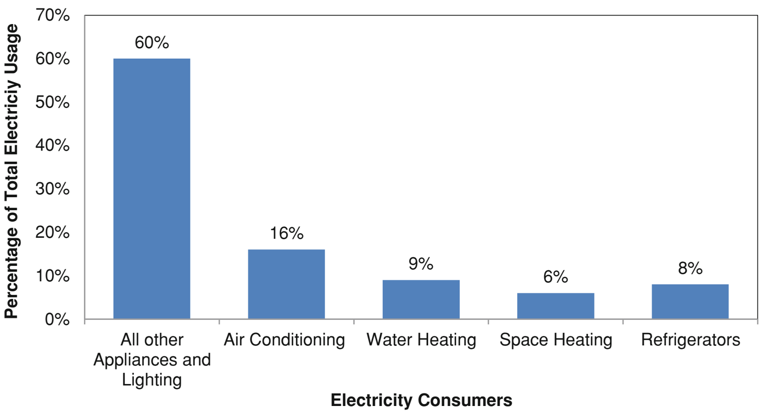


Fig. 2.18 Usage of electricity in homes in 2008 in the US [14]

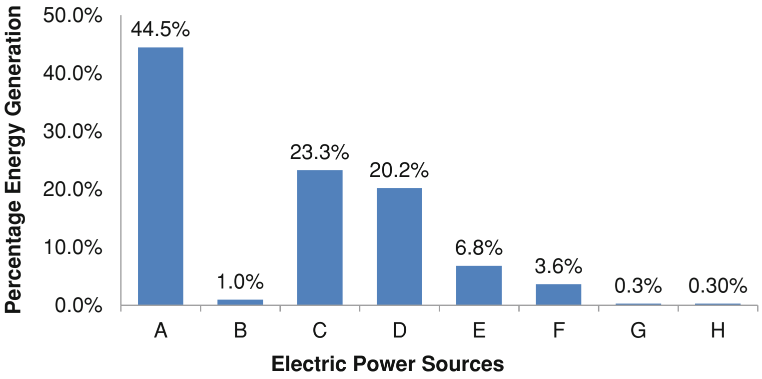


Fig. 2.19 US electric power industry net production by fuel [13]. *A* Coal, *B* Petroleum, *C* Natural gas, *D* Nuclear, *E* Hydroelectric, *F* Other renewables, *G* Other gases, *H* Other [14]

If the current passes through an electric appliance, some of the electric energy will be converted into other forms of energy (although some will always be lost as heat). The amount of electric energy, E_e, due to an electric current can be expressed in a number of different ways:

$$E_e = VIt = I^2Rt \tag{2.6}$$

where V is the electric potential difference (in volts), I is the current (in amperes), t is the time for which the current flows (in seconds), and R is the electric resistance (in ohms).

In *alternating current* (AC) the direction of the flow of electrons switches back and forth at regular intervals or cycles. Current flowing in power lines and normal household electricity that comes from a wall outlet is alternating current. The standard current used in the US is 60 cycles per second (i.e. a frequency of 60 Hz); in Europe and most other parts of the world it is 50 cycles per second (i.e. a frequency of 50 Hz.). In *Direct current* (DC)**,** on the other hand, electrical current flows consistently in one direction. The current that flows in a flashlight is direct current. One advantage of alternating current is that it is relatively cheap to change the voltage of the current. Furthermore, the inevitable loss of energy that occurs when current is carried over long distances is far smaller with alternating current than with direct current.

Example 2.6 Electricity consumption of a laptop computer

A laptop consuming 90 Watt is used on average 10 h per day. The laptop costs $500 and will be used for 4 years. Electricity cost is $0.15/kWh. Estimate the total electricity cost in four years for the laptop.

Solution:

$$\mathrm{Cost}_{\mathrm{laptop}} = \frac{\$500}{4\,\mathrm{year}} = \$125/\mathrm{year}$$

$$\mathrm{Cost}_{\mathrm{electricity}} = \frac{\$0.15}{\mathrm{kWh}}\frac{10\,\mathrm{h}}{\mathrm{day}}\frac{365\,\mathrm{days}}{\mathrm{year}}90\,\mathrm{W}\frac{\mathrm{kW}}{1000\,\mathrm{W}} = \$49.3/\mathrm{year}$$

$$\mathrm{Cost}_{\mathrm{total}} = \mathrm{Cost}_{\mathrm{laptop}} + \mathrm{Cost}_{\mathrm{electricity}} = (\$125/\mathrm{year} + \$49.3/\mathrm{year})4\,\mathrm{years} = \$\mathbf{697.2}$$

2.8 Magnetic Energy

There is no fundamental difference between magnetic energy and electric energy: the two phenomena are related by Maxwell's equations. The potential energy of a magnet of magnetic moment m in a magnetic field B is defined as the work of magnetic force (magnetic torque), and is estimated by

$$E_m = -mB \tag{2.7}$$

Calculating work needed to create an electric or magnetic field in unit volume results in the electric and magnetic fields energy densities. Electromagnetic radiation, such as microwaves, visible light, or gamma rays, represents a flow of electromagnetic energy. The energy of electromagnetic radiation has discrete energy levels. The spacing between these levels is equal to $E = hv$ where h is the

Planck constant, 6.626×10^{-34} Js [31], and v is the frequency of the radiation. This quantity of electromagnetic energy is usually called a photon. The photons which make up visible light have energies of 160 − 310 kJ/mol.

2.9 Chemical Energy

Chemical energy results from the associations of atoms in molecules and various other kinds of aggregates of matter. It may be defined as a work done by electric forces that is electrostatic potential energy of electric charges. If the chemical energy of a system decreases during a chemical reaction, the difference is transferred to the surroundings in the form of heat or light. On the other hand, if the chemical energy of a system increases as a result of a chemical reaction, the difference then is supplied by the surroundings in form of heat or light. Typical values for the change in molar chemical energy during a chemical reaction range from tens to hundreds of kilojoules per mole. For example, 2,2,4-trimethylpentane (isooctane), widely used in petrol, has a chemical formula of C_8H_{18} and it reacts with oxygen exothermically and produces 10.86 MJ per mole of isooctane

$$C_8H_{18}(l) + 25/2\ O_2(g) \rightarrow 8CO_2(g) + 9H_2O(g) + 10.86\,\text{MJ/mole} \tag{2.8}$$

When two hydrogen atoms react to form a hydrogen molecule, the chemical energy decreases by the bond energy of the H–H. When the electron is completely removed from a hydrogen atom, forming a hydrogen ion, the chemical energy called the ionization energy increases.

2.10 Energy and Global Warming

The burning of fossil fuels produces around 21.3 Gigatons of carbon dioxide per year, and natural processes can only absorb about half of that amount, so there is a net increase of 10.65 billion tons of atmospheric carbon dioxide per year [21].

One tonne of carbon is equivalent to: $MW_{CO_2}/MW_C = 44/12 = 3.7$ tons of carbon dioxide

Carbon dioxide emission can be calculated as

$$e_{CO_2} = \left(C_f/E_f\right)\left(MW_{CO_2}/MW_C\right) \tag{2.9}$$

where e_{CO_2} is the CO_2 emission in kgCO_2/kWh, C_f is the carbon content in the fuel (kg$_C$/kg$_{fuel}$) and E_f is the energy content of the fuel (kWh/kg$_{fuel}$).

Table 2.12 shows typical emission of carbon dioxide from the combustion of various fuels. An average car traveling 10,000 miles per year and consuming an average 25 miles per gallon emits about 1.2 tons of carbon dioxide per year. Since the early 1800s, it is known that various atmospheric gases, acting like the glass in

Table 2.12 Emission of carbon dioxide from the combustion of various fuels

Fuel	Specific carbon (kg_c/kg_{fuel})	Specific energy (kWh/kg_{fuel})	Specific CO_2 emission (kg_{CO_2}/kg_{fuel})	Specific CO_2 emission (kg_{CO_2}/kWh)
Coal (bituminous/anthracite)	0.75	7.5	2.3	0.37
Gasoline	0.9	12.5	3.3	0.27
Light oil	0.7	11.7	2.6	0.26
Diesel	0.86	11.8	3.2	0.24
LPG—liquid petroleum gas	0.82	12.3	3.0	0.24
Natural gas, methane	0.75	12	2.8	0.23
Crude oil				0.26
Kerosene				0.26
Wood[a]				0.39
Peat[a]				0.38
Lignite				0.36

(ETB [15] with permission)

[a] Commonly viewed as a biofuel

a greenhouse, transmit incoming sunlight but absorb outgoing infrared radiation, thus raising the average air temperature at the earth's surface. Carbon dioxide is clearly the most influential greenhouse gas. The most compelling evidence we have for climate change lies in the so-called paleoclimatic data obtained from ancient ice core samples in Greenland and Antarctica. By analyzing air bubbles that were trapped in the ice when it formed, scientists are able to determine the content of greenhouse gases and even the average temperature at each point in time. Figure 2.20 shows that over the past 420,000 years, the CO_2 content in the atmosphere has varied cyclically between about 180 and 290 ppm by volume with a period of about 100,000 years in conjunction with variations in the Earth's orbit. The earth's temperature has closely followed the greenhouse gas concentration.

Around 1850, when the CO_2 level was about 280 ppm, the level began to increase and now reached the value of 380 ppm, which indicates a 36% increase over the pre-industrial value (see Fig. 2.20). Increase in temperature can release CO_2 from the ground and seawater so the two effects reinforce each other. The possible consequences of these increases include ice melts, sea level rises, and severe storms because of the additional energy in the atmosphere. As the ice melts, the resulting darker water and ground absorb more sunlight, thus exacerbating the warming. The melt water flows like a river, causing rapid heat transfer and erosion.

The *global warming potential* is a measure of how much a given mass of a chemical substance contributes to global warming over a given period of time. The global warming potential is the ratio of the warming potential caused by a substance to the warming potential caused by a similar mass of carbon dioxide. Various hydrochlorofluorocarbons (HCFC) and hydrofluorocarbons (HFC) have

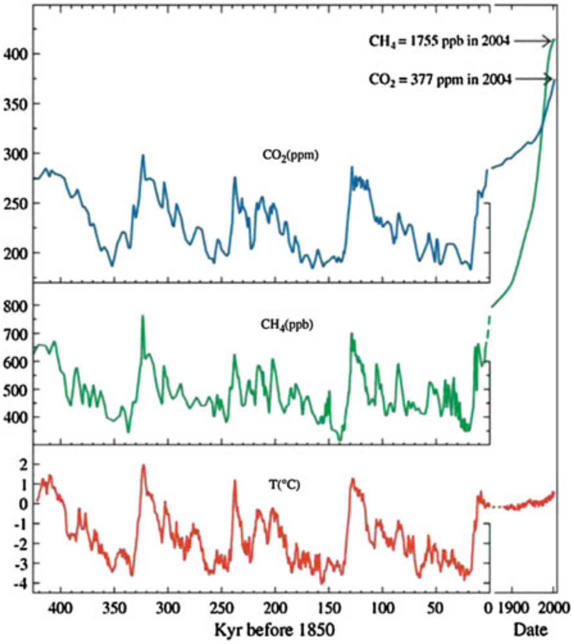


Fig. 2.20 Paleoclimatic data from ice cores shows recent increases in carbon dioxide and methane. The temperature, though increasing, has not yet reached record levels but will likely do so by midcentury [38]

global warming potentials ranging from 93 to 12100. These values are calculated over a 100-year period of time [12, 36].

Example 2.7 Carbon dioxide emission from natural gas combustion
When a hydrocarbon fuel is burned, almost all of the carbon in the fuel burns completely to form carbon dioxide CO_2, which is causes the greenhouse effect. On average, 0.59 kg of CO_2 is produced for each kWh of electricity generated from a power plant that burns natural gas. A typical new household uses about 7,000 kWh of electricity per year. Determine the amount of CO_2 production that is due to the refrigerators in a city with 200,000 households.

Solution:

Carbon dioxide emission from natural gas combustion A kWh is kW times hours. It is the amount of energy consumed in an hour by a device that uses 1 kW of power (1 kJ/s for 3,600 s), so you are left with units of energy.

Data: $m_{CO2} = 0.59$ kg CO_2/kWh, 200,000 houses, power 7,000 kWh/house per year
The total mass of CO_2 produced per year is the product of the rate of CO_2 production per kWh and the number of houses:

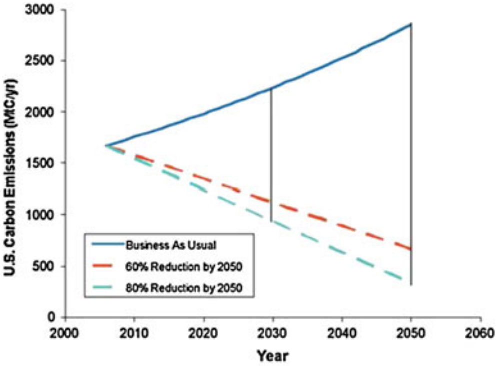


Fig. 2.21 Triangle of US fossil fuel carbon reductions needed by 2030 for a 60–80% reduction from today's levels by 2050 [25]

$$m_{\text{total}\,\text{CO}_2} = \text{Power}(m\text{CO}_2)(\text{Number of houses}) = \left(\frac{\text{kWh}}{\text{house year}}\right)\left(\frac{\text{kg}\,\text{CO}_2}{\text{kWh}}\right)(\text{Houses})$$

$$m_{\text{total CO}_2} = \mathbf{8.26 \times 10^8\ kg\ CO_2/year = 826.0\ Mton\ CO_2/year}$$

2.11 Tackling the Global Warming

Electricity production (~40%) and transportation fuels (~30%) accounts a large part of total carbon dioxide emissions (see Fig. 2.21). Therefore, targeting electricity generation and transportation fuels will address about 70% of the carbon dioxide emissions. For example, the use of renewable energy for electricity generation does not cause additional carbon dioxide emissions, and is sustainable into the future. The major challenges with greatly expanded use of renewables are the cost, intermittency of supply, and distance between the resources and the end use. Some possible renewable energy sources are concentrating solar power, geothermal electric plants, wind power, distributed rooftop photovoltaic, and solar hot water heaters. Hybrid electric vehicles represent an important advance. A hybrid electric vehicle can cover a distance of about 10 to 20 miles, and if it can be plugged into the grid to be recharged, it is possible to greatly reduce the amount of gasoline the vehicle uses. Using E85 (85% and 15% blend of ethanol and gasoline, respectively) may help reducing carbon dioxide emission [29].

Example 2.8 Consumption of coal and emission of carbon dioxide from coal
A large public computer lab runs six days per week from Monday through Saturday. Each computer uses a power of around 240 W. If the computer lab contains 45 computers and each is on for 12 hours a day, during the course of the year how much CO_2 will the local coal power plant have to release to the atmosphere in kg and kmol to keep these computers running?

Solution:
Data: Coal(bituminous/anthracite): 0.37 kg of CO_2/kWh. Data from Table 2.12.

$$\left(\frac{240\,\mathrm{W}}{\text{computer}}\right)\left(\frac{\mathrm{kW}}{1,000\,\mathrm{W}}\right)\left(\frac{52\,\text{weeks}}{\text{year}}\right)\left(\frac{6\,\text{days}}{\text{week}}\right)\left(\frac{12\,\mathrm{h}}{\text{day}}\right)\left(\frac{45\,\text{computers}}{\text{lab}}\right)$$
$$= 40,435.2\,\mathrm{kWh}$$

We know that 40,435.2 kWh is needed from the lab per year and since the power plant is coal we can use its emission value of 0.37 kg of CO_2/kWh.
(40435.2 kWh) (0.37 kg CO_2/kWh) = **14,961 kg CO_2 released**
or
14,962 kg/(44.01 kg/mole) = **339.9 kmols CO_2 released**

Example 2.9 Reducing air pollution by geothermal heating
A district uses natural gas for heating. Assume that average NO_x and CO_2 emissions from a gas furnace are 0.0045 kg/therm and 6.4 kg/therm, respectively. It is considered to replace the gas heating system with a geothermal heating system. The projected saving by the geothermal heating system would be 20×10^6 therms of natural gas per year. Determine the amount of NO_x and CO_2 emissions the geothermal heating system would save every year.

Solution:
therm = 29.3 kWh (Table 2.1)
Reduction in NO_x emission = (0.0045 kg/therm) (20×10^6 therm/year)
= **9.0×10^4 kg/year**
Reduction in CO_2 emission = (6.4 kg/therm) (20×10^6 therm/year)
= **$12.8.0 \times 10^7$ kg/year**

Atypical car produces about 8.5 kg NO_x and 6000 kg of CO_2 per year. Replacing the gas heating system by the geothermal heating system is equivalent to taking 10600 cars off the road for NO_x emission and taking 21000 cars of the road for CO_2 emission. Therefore, the proposed geothermal heating would have a positive impact on the air pollution [8].

Student Concern of Global Warming

Each generation has its own crisis, in which people are gravely affected. Some generations have wars or famine, however my generation will certainly have both if our energy crisis is not addressed. Our reliance on fossil fuels has become an addiction. We enjoy many luxuries such as air conditioning, television, and the ability to surf the web or make a call across the country. All of these luxuries are telling of the modernized society we live in, but sadly in times where energy is scarce, we are hardest hit. It would be hard to believe that the generation following the greatest rise in human ingenuity could be blind to such an issue. Our fossil fuel energy resources are limited and many scientists say the expiration date is within our lifetime. We need to better understand the basic principles of energy and its usage so that we can make better choices and change the direction we are currently heading.—Brad Healey-Senior UNL-2012

Problems

2.1. What are the advantages and disadvantages of using coal?
2.2. Does an electric car reduce the use of fossil fuels?
2.3. Is a fuel oil heater or an electric resistance heater the best for the environment?
2.4. Is a natural gas heater or a geothermal heating system the best for the house?
2.5. Why is electrical energy so useful?
2.6. How can the energy in the wind be used?
2.7. 2.7. How can wind power help conserve our oil supplies?
2.8. How might using wind energy help reduce the air pollution?
2.9. What is the best energy source to convert to electricity?
2.10. Do the white-colored roof tiles keep houses cool?
2.11. How can energy from the sun be used to heat water?
2.12. With the clear advantages of nuclear power, why is it not more commonly used?
2.13. How can using solar energy help reduce pollution in the atmosphere and help conserve our oil supplies?
2.14. Why is the process of photosynthesis so valuable?
2.15. Name some foods that are known to be high energy foods.
2.16. Why are battery-powered vehicles considered to be the transport of the future?
2.17. Why is chemical energy useful to us?
2.18. What other forms of energy can be produced from chemical energy?
2.19. Name three examples of other fuels that contain chemical energy.
2.20. An over used car may consume around 250 gallons of gasoline per month. Estimate the energy consumed by the car per year.
2.21. An over used car may consume around 150 gallons gasoline per month. Estimate the energy consumed by the car per year.
2.22. A car's daily travelling distance is about 80 miles/day. A car has a city-mileage of 20 miles/gal. If the car is replaced with a new car with a city-mileage of 30 miles/gal and the average cost of gasoline is $4.50/gal, estimate (a) the amount of fuel, energy, and money conserved with the new car per year, (b) reduction in CO_2 emission.
2.23. A car's daily travelling distance is about 80 miles/day. A car has a city-mileage of 10 miles/gal. If the car is replaced with a new car with a city-mileage of 32 miles/gal and the average cost of gasoline is $4.50/gal, estimate (a) the amount of fuel, energy, and money conserved with the new car per year, (b) reduction in CO_2 emission.
2.24. A city consumes natural gas at a rate of 500 10^6 ft^3/day. The volumetric flow is at standard conditions of 60°F and 1 atm = 14.7 psia. If the natural is costing $12/GJ of higher heating value what is the daily cost of the gas for the city.
2.25. A city consumes natural gas at a rate of 800 × 10^6 ft^3/day. The volumetric flow is at standard conditions of 60°F and 1 atm = 14.7 psia. If the natural

is costing \$10/GJ of higher heating value what is the daily cost of the gas for the city.

2.26. A car consumes about 6 gallons a day, and the capacity of a full tank is about 15 gallons. The density of gasoline ranges from 0.72 to 0.78 kg/l (Table 2.2). The lower heating value of gasoline is about 44,000 kJ/kg. Assume that the average density of gasoline is 0.75 kg/l. If the car was able to use 0.2 kg of nuclear fuel of uranium-235, estimate the time in years for refueling.

2.27. A car consumes about 3 gallons a day, and the capacity of the full tank is about 11 gallon. The density of gasoline ranges from 0.72 to 0.78 kg/l (Table 2.2). The lower heating value of gasoline is about 44,000 kJ/kg. Assume that the average density of gasoline is 0.75 kg/l. If the car was able to use 0.1 kg of nuclear fuel of uranium-235, estimate the time in years for refueling.

2.28. Using data in Table 2.11 and ultimate analysis, fixed carbon, dry ash content, C, H, and O compositions estimate the gross heating values in kJ/kg for the biomass white oak.

2.29. Using data in Table 2.11 and ultimate analysis, fixed carbon, dry ash content, and C, H, and O compositions only estimate the gross heating values in kJ/kg for the biomass corn stover and wheat straw.

2.30. When a hydrocarbon fuel is burned, almost all of the carbon in the fuel burns completely to form CO_2 (carbon dioxide), which is the principle gas causing the greenhouse effect and thus global climate change. On average, 0.59 kg of CO_2 is produced for each kWh of electricity generated from a power plant that burns natural gas. A typical new household uses about 7,000 kWh of electricity per year. Determine the amount of CO_2 production that is due to the refrigerators in a city with 100,000 households

2.31. When a hydrocarbon fuel is burned, almost all of the carbon in the fuel burns completely to form CO_2 (carbon dioxide), which is the principle gas causing the greenhouse effect and thus global climate change. On average, 0.59 kg of CO_2 is produced for each kWh of electricity generated from a power plant that burns natural gas. A typical new household uses about 10,000 kWh of electricity per year. Determine the amount of CO_2 production that is due to the refrigerators in a city with 250,000 households

2.32. A large public computer lab operates Monday through Saturday. There the computers are either being used constantly or remain on until the next user comes. Each computer needs around 240 W. If the computer lab contains 53 computers and each is on for 12 h a day, during the course of the year how much CO_2 will the local coal power plant have to release to the atmosphere in gram moles to keep these computers running?

2.33. The average university will have a large public computer lab open Monday through Saturday. There the computers are either being used constantly or remain on until the next user comes. Each computer needs around 240 W. If the computer lab contains 53 computers and each is on for 12 h a day, during the course of the year how much coal will the local coal power plant have to consume to keep these computers running?

2.34. A large public computer lab runs six days per week from Monday through Saturday. Each computer uses a power of around 120 W. If the computer lab contains 45 computers and each is on for 12 h a day, during the course of the year how much CO_2 will the local coal power plant have to release to the atmosphere in gram moles to keep these computers running?

2.35. If a car consumes 60 gallons gasoline per month. Estimate the energy consumed by the car per year.

2.36. A car having an average 22 miles/gal is used 32 miles every day. If the cost of a gallon fuel is $3.8 estimate the yearly cost of fuel.

2.37. A car having an average 22 miles/gal is used 32 miles every day. Estimate the yearly energy usage.

2.38. How can you control your carbon footprint?

2.39. A 150-W electric light bulb is used on average 10 h per day. A new bulb costs $2.0 and lasts about 5,000 h. If electricity cost is $0.15/kWh, estimate the yearly cost of the bulb.

2.40. A laptop consuming 90 Watt is used on average 5 h per day. If a laptop costs $500 and will be used for four years estimate the total electricity cost in four years for the laptop. Electricity cost is $0.15/kWh.

2.41. A laptop consuming 90 Watt is used on average 7 h per day. If a laptop costs $500 and will be used for four years estimate the total electricity cost in four years for the laptop. Electricity cost is $0.10/kWh.

2.42. A 20-hp electric motor is used to pump ground water into a storage tank 4 h every day. Estimate the work done by the pump in kW every year and the cost of electricity every year. Assume that the electricity unit cost is $0.1/kWh.

2.43. A city consumes natural gas at a rate of 250×10^6 ft^3/day. The volumetric flow is at standard conditions of 60°F and 1 atm = 14.7 psia. If the natural gas is costing $6/GJ of higher heating value what is the daily cost of the gas for the city.

2.44. A home consumes natural gas at a rate of 4.3ft^3/day to heat the home. The volumetric flow is at standard conditions of 60°F and 1 atm = 14.7 psia. If the natural gas is costing $0.67/MJ of higher heating value what is the daily cost of the gas for the home?

2.45. A district uses natural gas for heating. Assume that average NO_x and CO_2 emissions from a gas furnace are 0.0045 kg/therm and 6.4 kg/therm, respectively. The district wants to replace the gas heating system with a geothermal heating system. The projected saving by the geothermal heating system would be 40×10^6 therms of natural gas per year. Determine the amount of NO_x and CO_2 emissions the geothermal heating system would save every year.

2.46. A water heater consumes propane, which is providing 80% of the standard heat of combustion when the water produced after combustion is vapor. If the price of propane is \$2.2/gal measured at 25°C. What is the heating cost in \$ per million Btu and in \$ per MJ?

2.47. An average video games system consumes 170 W of power during gameplay. If a person were to play an hour a day for 80% of the year how many liters of gasoline would the person have burned? (Evaluated at HHV)

2.48. A competitive road cyclist can hold an average of 300W of power during a 4 h race. During long races he must do this each day for three weeks. How many protein bars will the cyclist have to eat at 184 calories per bar to just make up the calories lost during the race?

2.49. Describe the process of how natural gas goes from its natural state to the market?

2.50. Some people like to have background noise when they are falling asleep. Many choose to listen to their television. The television will usually run on about 340 W and will run during the 8 h that you are asleep. With electricity costing \$0.20/kWh, calculate how much this will cost you if you do this for five days a week for an entire year.

2.51. What are the advantages and disadvantages of electrical energy in an alternating current?

2.52. What are the advantages and disadvantages of electrical energy flowing in direct current?

2.53. In the search for new sources of energy that are renewable and emit less greenhouse gases, carbon-based biofuels are of major interest. These fuels are still carbon-based and must undergo combustion to release the chemical energy. Why is this process being looked at as a reasonable energy source?

2.54. While fixing wiring in a house, an electrician aims to deliver the same amount of electric energy to a devise at the same rate it is currently coming in. The wiring he is replacing runs at has 2 ohms of resistance and has a 20 A current. To deliver the same amount of electric energy how many amps will be needed if the resistance is changed to 4 ohms?

2.55. Calculate the yearly dollar savings if you cut down from a daily 9 min shower to a 6 min shower. The shower volumetric flow rate is 3.2 gpm and the amount of energy used per gallon is 440 Btu and energy costs \$0.13/kWh.

2.56. Rank the following carbon-based fuels in order of lowest to highest gross energy density; diesel, ethanol, conventional gasoline, and kerosene-based jet fuel.

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Chapter 3
Mechanical Energy and Electrical Energy

3.1 Mechanical Energy

There are two large forces that we can experience: gravitational forces and electromagnetic forces. Both of these forces act through space. *Mechanical energy* describes the sum of potential energy and kinetic energy present in the components of a *mechanical system*. Mechanical energy is the energy associated with the motion or position of an object under gravitational force. Mass causes gravitational attraction. Charge and mass obey an inverse square law, which states that a specified physical quantity or strength is inversely proportional to the square of the distance from the source of that physical quantity. The gravitational force law depends inversely upon the square of the distance between two masses, so mass plays a role somewhat similar to the role charge plays in the force law. Charged particles exhibit non-gravitational forces between them. The force of attraction or repulsion between two electrically charged particles is directly proportional to the product of the electric charges and is inversely proportional to the square of the distance between them. This is known as Coulomb's law. The law of conservation of mechanical energy states that if a body or system is subjected only to conservative forces the total mechanical energy of that body or system remains constant.

The mechanical energy is the form of energy that can be converted to mechanical work completely and directly by a mechanical device such as a turbine. Thermal energy cannot be converted to work directly and completely, therefore thermal energy is not mechanical energy. The familiar forms of mechanical energy are kinetic and potential energy. Pressure energy is also another form of mechanical energy due to the pressure of a fluid. Therefore, mechanical energy for a unit mass can be defined by

$$\left(\frac{\Delta P}{\rho}+\frac{\Delta v^2}{2}+g\Delta z\right)=W_{\text{shaft}}+W_{\text{loss}} \tag{3.1}$$

Pressure energy + Kinetic energy + Potential energy = Mechanical energy + Work loss

Y. Demirel, *Energy*, Green Energy and Technology,
DOI: 10.1007/978-1-4471-2372-9_3,

where P is the pressure, ρ is the density, v is the flow velocity, g is the acceleration of gravity, z is the elevation height, W_{shaft} net shaft energy in per unit mass for a pump, fan, or similar equipment, and W_{loss} represents the energy loss due to friction and other nonidealities. The mechanical energy equation for a pump, a fan, or a turbine can be written in terms of energy per unit mass (ft^2/s^2 or m^2/s^2 = N m/kg). Equation (3.1) is often used for incompressible flow problems and is called the *mechanical energy equation* [7].

3.2 Kinetic Energy

Kinetic energy KE is the energy that a system or a material possesses because of its velocity relative to the surroundings. The kinetic energy of a flowing fluid relative to stationary surroundings is estimated by

$$KE = \frac{1}{2} m v^2 \tag{3.2}$$

where m is the mass and v is the average velocity. The value of a change in the kinetic energy occurs in a specified time interval, and depends only on the mass and the initial and final values of the average velocities of the material.

$$\Delta KE = \frac{1}{2} m \left(v_2^2 - v_1^2\right) \tag{3.3}$$

Mass flow rate $\dot{m}$ is related to the density, cross-sectional area A, and average velocity v by

$$\dot{m} = \rho A v \tag{3.4}$$

In the English engineering units, for the unit consistency g_c (g_c= 32.174 lb_m ft/lb_f s^2) is included and the unit of kinetic energy becomes

$$KE = \frac{mv^2}{2g_c} = \frac{\text{lb}_\text{m}\,\text{ft}^2\,\text{s}^{-2}}{\text{lb}_\text{m}\,\text{ft}\,(\text{lb}_\text{f})^{-1}\,\text{s}^{-2}} = \text{ft lb}_\text{f} \tag{3.5}$$

Example 3.1 Calculation of the kinetic energy for a flowing fluid
Water with a flow rate of 2.0 kg/s is pumped from a storage tank through a tube of 2.5 cm inner diameter. Calculate the kinetic energy of the water in the tube.

Solution:
Assume the density of the water to be ρ = 1,000 kg/m^3.
Basis is 2.0 kg/s.
Radius of the tube (r) = 2.5/2 = 1.25 cm

Cross sectional area of the tube:
$A = \pi r^2 = 3.14(2.5\,\text{cm}/2)^2(1\,\text{m}/100\ \text{cm})^2 = 4.906 \times 10^{-4}\,\text{m}^2$
The average velocity of the water:

$$v = \frac{\dot{m}}{\rho A} = \frac{2.0\,\text{kg/s}}{(1000\,\text{kg/m}^3)(4.906\ \times\ 10^{-4}\,\text{m}^2)} = 4.076\,\text{m/s}$$

The kinetic energy of the water in the tube:

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}(2.0\ \text{kg/s})(4.076\ \text{m/s})^2\left(\frac{\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = \mathbf{0.0166\,kJ/s} = \mathbf{16.6\,W}$$

J = N m, where N is the Newton.

Example 3.2 Kinetic energy of a car
A car having a mass of 2750 lb is traveling at 55 miles/h. Estimate: (a) the kinetic energy of the car in kJ, (b) the work necessary to stop the car.

Solution:
Equation: $KE = \frac{1}{2}mv^2$
Data: m = 2750 lb (kg/2.2 lb) = 1250 kg;

$$v = 55\ \ \text{miles/h} \rightarrow v = \left(\frac{55\ \text{miles}}{\text{h}}\right)\left(\frac{1609.34\ \text{m}}{\text{mile}}\right)\left(\frac{\text{h}}{3600\ \text{s}}\right) = 24.58\,\text{m/s}$$

(a) $KE = \frac{1}{2}(1250\,\text{kg})(24.58\,\text{m/s})^2\left(\frac{\text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = \mathbf{377.6\ kJ}$
(b) $W = KE =$ **377.6 kJ**

3.3 Potential Energy

Potential energy exists whenever an object has a position within a force field. The gravitational force near the Earth's surface varies very little with the height z and is equal to the mass m multiplied by the gravitational acceleration $g = 9.81\ \text{m/s}^2$. When the force field is the earth's gravitational field, then the potential energy of an object is:

$$PE = mgz \tag{3.6}$$

where z is the height above the earth's surface or a reference surface. Potential energy is stored within a system and is activated when a restoring force tends to pull an object back towards some lower energy position. For example, when a mass is lifted up, the force of gravity will act so as to bring it back down. The energy that went into lifting up the mass is stored in its position in the gravitational field. Therefore, the potential energy is the energy difference between the energy of an object in a given position and its energy at a reference position Δz, and is expressed by

$$\Delta PE = mg\Delta z \tag{3.7}$$

In the English units, potential energy is expressed as

$$\Delta PE = \frac{mg\Delta z}{g_c} = \frac{\text{lb}_\text{m}\,\text{ft}\,\text{ft}\,\text{s}^{-2}}{\text{lb}_\text{m}\,\text{ft}\,(\text{lb}_\text{f})^{-1}\,\text{s}^{-2}} = \text{lb}_\text{f}\,\text{ft} \tag{3.8}$$

For the unit consistency, g_c (g_c= 32.174 lb_m ft/lb_f s^2) is included and the unit of potential energy becomes lb_f ft

Various types of potential energy are associated with a particular type of force:

- *Gravitational potential energy* is the work of the gravitational force. If an object falls from one point to another inside a gravitational field, the force of gravity will do positive work on the object, such as the production of hydroelectricity by falling water.
- *Elastic potential energy* is the work of an elastic force. Elastic potential energy arises as a consequence of a force that tries to restore the object to its original shape, which is most often the electromagnetic force between the atoms and molecules that constitute the object.
- *Chemical potential energy* is related to the structural arrangement of atoms or molecules. For example, chemical potential energy is the energy stored in fossil fuels and when a fuel is burned the chemical energy is converted to heat. Green plants convert solar energy to chemical energy through the process called photosynthesis. Electrical energy can be converted to chemical energy through electrochemical reactions.
- *Nuclear potential energy* is the potential energy of the particles inside an atomic nucleus. The nuclear particles are bound together by the strong nuclear force.

Example 3.3 Potential energy change of water

Water is pumped from one reservoir to another. The water level in the second reservoir is 30 ft above the water level of the first reservoir. What is increase in specific potential energy of one pound of water in Btu?

Solution:

The problem requires the change of potential energy of 1 lb_m of water. The difference between the water levels of the two reservoirs is Δz = 30 ft. The Eq. (3.8) yields

$$\Delta PE = \left(\frac{32.2\text{ft}}{s^2}\right)\left(\frac{\text{lb}_\text{f} s^2}{32.2\,\text{lb}_\text{m}\,\text{ft}}\right)(30\,\text{ft})\left(\frac{\text{Btu}}{778.2\,\text{ft lb}_\text{f}}\right) = \mathbf{0.0385\,Btu/lb}$$

Example 3.4 Energy of an elevator

An elevator with a mass of 1,500 kg rests at a level of 3 m above the base of an elevator shaft. The elevator has travelled to 30 m above the base. The elevator falls from this height freely to the base and strikes a strong spring. Assume that the entire process is frictionless. Estimate:

(a) The potential energy of the elevator at its original position relative to the base of the shaft.
(b) The work done travelling the elevator.
(c) The potential energy of the elevator at its highest position relative to the base of the shaft.
(d) The velocity and kinetic energy of the elevator just before it strikes the spring.

Solution:
Assume g = 9.8 m/s^2
Data: m = 1500 kg, z_1= 3 m, z_2= 30 m

(a) $PE_1 = mgz_1 = (1500)(9.8)(3) = \mathbf{44100\,J} = \mathbf{44.1\,kJ}$

(b) $W = \int_{z_1}^{z_2} Fdz = \int_{z_1}^{z_2} mgdz = mg(z_1 - z_2) = (1500)(9.8)(30 - 3) = \mathbf{396.9\,kJ}$

(c) $PE_2 = mgz_2 = (1500)(9.8)(30) = \mathbf{441.0\,kJ}$
So $W = PE_2 - PE_1 = (441.0 - 44.1)$ kJ = 396.9 kJ

(d) $KE = PE_2 =$ **441.0 kJ**

$$KE = \frac{mv^2}{2} \rightarrow v = \sqrt{\frac{2KE}{m}} = \sqrt{\frac{2(441{,}000)}{1500}} = \mathbf{24.25\,m/s}$$

3.4 Pressure Energy

The pressure unit Pa is defined as: Pa = N/m^2 = N m/m^3 = J/m^3, which becomes energy per unit volume. The product of pressure with volume $P(1/\rho)$ leads to J/kg that is the energy per unit mass. Therefore, the mechanical energy due to the pressure of the fluid is known as pressure energy PV and is expressed by

$$PV = \frac{P}{\rho} \tag{3.9}$$

where ρ is the density. Pressure energy P/ρ can be converted to mechanical energy completely, for example, by a reversible turbine. Transferring of mechanical energy is usually accomplished through a rotating shaft, and mechanical work is usually referred to as shaft work. A turbine, for example, converts the mechanical energy of a fluid to shaft work. Only the frictional effects cause the loss of mechanical energy in the form of heat. Consider a tank filled with water, as shown in Fig. 3.1.

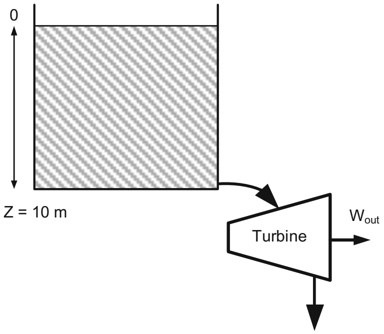


Fig. 3.1 Pressure energy P/ρ can be converted to mechanical energy completely by a reversible turbine

$$\dot{W}_{\max} = \dot{m}\frac{P}{\rho} = \dot{m}\frac{\rho g z}{\rho} = \dot{m}gz \tag{3.10}$$

For example, for a water mass flow rate of 10 kg/s, the maximum work would be

$$\dot{W}_{\max} = \dot{m}gz = (10\ \text{kg/s})(9.81\ \text{m/s}^2)(10\ \text{m}) = 981\ \text{W}$$

For a flowing fluid, pressure energy is the same with the flow energy using the gauge pressure instead of absolute pressure.

Example 3.5 Pressure energy of a hydraulic turbine

Electricity is produced by a hydraulic turbine installed near a large lake. Average depth of the water in the lake is 45 m. The water mass flow rate is 600 kg/s. Determine the work output of the turbine.

Solution:

Assume: The mechanical energy of water at the turbine exit is small and negligible. The density of the water is 1,000 kg/m^3.

$$W_{out} = PE = \dot{m}gz = (600\text{kg/s})\left(9.81\text{m/s}^2\right)(45\text{m}) = \mathbf{264.9kW}\ \left(\text{kJ/kg} = 1000\text{m}^2/\text{s}^2\right)$$

The lake supplies 264.9 kW of mechanical energy to the turbine.

3.4.1 Pressure Head

For an incompressible fluid, such as liquids, the pressure difference between two elevations can be expressed as *static pressure difference*: $P_2 - P_1 = -\rho\, g\, (z_2 - z_1)$. The *pressure head h* is estimated by the static pressure difference

$$h = \frac{P_2 - P_1}{\rho g} \text{ (in m or ft)} \tag{3.11}$$

The pressure head is related to the height of a column of fluid required to give a pressure difference of $\Delta P = P_2 - P_1$.

The mechanical energy equation (Eq. 3.1) can also be written in terms of head

$$\left(\frac{\Delta P}{\rho g} + \frac{\Delta v^2}{2g} + \Delta h\right) + h_{\text{shaft}} = h_{\text{loss}} \tag{3.12}$$

where $h_{\text{shaft}} = W_{\text{shaft}}/g$ is the net shaft energy head in per unit mass and the head loss due to friction is estimated by

$$h_{\text{loss}} = W_{\text{loss}}/g = \text{loss head due to friction} \tag{3.13}$$

Example 3.6 Pumping water

Water is pumped from an open tank at level zero to an open tank at level 12 ft. The pump adds 6 hp to the water when pumping a volumetric flow rate of 3 ft^3/s. Estimate the loss energy in head.

Solution:
Data: $Q = 3\ \text{ft}^3/\text{s}$, $W_{\text{shaft}} = 6$ hp
Since $v_{\text{in}} = v_{\text{out}} = 0$, $P_{\text{in}} = P_{\text{out}} = 0$ and $h_{\text{in}} = 0$ then Eq. (3.12) becomes $g = 32.2\ \text{ft/s}^2$.
Density of water = 62.4 lb/ft^3
The special conversion factor with symbol $g_c = 32.174\ \text{ft lb}_\text{m}/(\text{s}^2\ \text{lb}_\text{f})$.

$$h_{\text{shaft}} = h_{\text{loss}} + h_{\text{out}}$$

$$h_{\text{shaft}} = \frac{W_{\text{shaft}}}{\rho(g/g_c)Q} = \frac{(6\,\text{hp})\left(\frac{550\,\text{ft lb}_\text{f}/\text{s}}{\text{hp}}\right)(32.174\ \text{ft lb}_\text{m}/\text{s}^2\ \text{lb}_\text{f})}{\left(62.4\,\text{lb}_\text{m}/\text{ft}^3\right)(32.2\ \text{ft/s}^2)\left(3\,\text{ft}^3/\text{s}\right)} = 17.6\,\text{ft}$$

where, specific weight of water is 62.4 $\text{lb}_\text{m}/\text{ft}^3$ and 1 hp (English horse power) = 550 ft lb_f/s

h_{loss} = (17.6 − 12) ft = **5.6 ft**

Example 3.7 Calculation of the power needed to pump water

A pump draws water from a 10 feet deep well and discharges into a tank, which is 2 feet above the ground level. The discharge rate of water is 0.25 ft^3/s. Calculate the power needed by the pump.

Solution:
Assume that negligible heat dissipation due to friction occurs within the pipe and the pump.
The power needed can be calculated from: $\dot{W} = \dot{m}g(z_{\text{out}} - z_{\text{in}})$
where g is the standard gravity $g = 9.806\ \text{m/s}^2 = 32.2\ \text{ft/s}^2$.

The special conversion factor with symbol $g_c = 32.174\ \text{ft lb}_\text{m}/(\text{s}^2\ \text{lb}_\text{f})$.

Density of water = 62.4 lb/ft^3
With a basis of lb$_\text{m}$/s, the mass flow rate of water is

$$\dot{m} = (0.25\ \text{ft}^3/\text{s})\ (62.4\ \text{lb/ft}^3) = 15.6\,\text{lb}_\text{m}/\text{s}$$

Using the conversion of 1.0 kW = 737.56 lb$_\text{f}$ ft/s (Table 3.1)

$$\text{Power: } W = \frac{(15.6\,\text{lb}_\text{m}/\text{s})(32.2\,\text{ft}^2/\text{s})(12\,\text{ft})}{32.2\,\text{ft}\,\text{lb}_\text{m}/(\text{s}^2\,\text{lb}_\text{f})}\left(\frac{1.0\,\text{kW}}{737.56\,\text{lb}_\text{f}\ \text{ft/s}}\right) = \mathbf{0.253\,kW} = \mathbf{0.340\,hp}$$

3.5 Surface Energy

Surface energy is a measure of intermolecular forces that occur when a surface is created. The surface energy is the excess energy at the surface of a material compared to the bulk. For a liquid, the surface tension (surface energy density) is defined as the force per unit length. Water has a surface energy density of 0.072 J/m^2 and a surface tension of 0.072 N/m. Raindrops are spherically shaped because of surface tension or surface energy. Surface energy is a characteristic property of a liquid and is directly related to the liquid's surface area. High surface area geometries contain high surface energy, while low surface area geometries contain low surface energy levels. Liquids form themselves into spherical shapes to lower their overall energy state since the sphere has the smallest surface area and also has the lowest energy state. The driving force behind spherically shaped liquids involves cohesive forces, which are the attractive forces that a liquid's molecules have to one another [8].

3.6 Sound Energy

Sound energy is the energy produced by an object's vibrations. Sound energy E results from the integral of the acoustic pressure P times the particle velocity v over a surface A, and is given by the integral

$$E = \int (Pv) \cdot dA \tag{3.14}$$

The sound energy flux is the average rate of flow of sound energy through any specified area A and is usually referred to as acoustic intensity. Sound energy is, therefore, a form of mechanical energy and is related to the pressure that sound vibrations produce. Sound energy is typically not used for electrical power or for other human energy needs because the amount of energy that can be gained from sound is quite small.

Ultrasound is cyclic sound pressure with a frequency greater than the upper limit of human hearing, which is approximately 20 kHz. For a sound wave, the

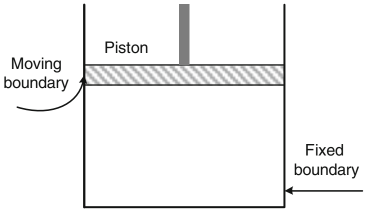


Fig. 3.2 Mechanical work for a mechanical force moving the boundary of a system

hertz (Hz) is equal to cycles of the sound wave per second. Ultrasound is used typically to penetrate a medium and measure the reflection signals or supply focused energy. The reflection signals can reveal details about the inner structure of the medium. In ultrasonic welding of plastics, high frequency (15–40 kHz) low amplitude vibration is used to create heat by way of friction between the materials to be joined. Also, ultrasonic testing is used to find flaws in materials and to measure the thickness of objects [4].

3.7 Mechanical Work

When a force acts on a system through a distance, then energy is transferred as work. Mechanical work is performed when a mechanical force moves the boundary of a system. For example, in a compression work, a piston representing surroundings performs work on the gas (see Fig. 3.2) so that the initial boundary changes and the final volume of the gas is less than the initial volume of the gas. The net amount of mechanical work done over a period of time is

$$W = -\int_{\text{state}1}^{\text{state}2} \mathbf{F} \cdot d\mathbf{l} \tag{3.15}$$

where **F** is an external force vector acting on the system boundary, and **l** is the displacement or pathway vector. Some common types of work are summarized in the following sections:

3.7.1 Power

Power is the energy exchanged in time. For example, Watt (W) gives rise to one joule of energy in one second of time. Table 3.1 displays some of the power definitions and their conversions. The rate of work that is the work per unit time is called the *power*. In SI units, power is defined as W = J/s = N·m/s = kg·m^2/s^3. In English units power is in Btu/s = 778.1 ft lb_f/s = 1.415 hp; mechanical hp = 550 ft lb_f/s = 746 W = (electrical hp).

Table 3.1 Power conversions

	hp	kW	ft $\mathrm{lb_f}$/s	Btu/s	J/s
hp	1	0.745	550	0.707	745.7
kW	1.341	1	737.56	0.948	1,000
ft $\mathrm{lb_f}$/s	1.818×10^{-3}	1.356×10^{-3}	1	1.285×10^{-3}	1.356
Btu/s	1.415	1.055	778.16	1	1,055
J/s	1.341×10^{-3}	1,000	0.737	9.478×10^{-3}	1

Himmeblau and Riggs [3]

- *Horsepower* is the imperial (British) unit of power. A horsepower is the ability to do work at the rate of 33,000 $\mathrm{lb_f}$ ft/min or 550 $\mathrm{lb_f}$ ft/s. For example, the total horsepower developed by water falling from a given height is

$$P_{hp} = \frac{\dot{m}gz}{550} \tag{3.16}$$

  Or in terms of volumetric flow rate, horsepower is estimated by

$$P_{hp} = \frac{\dot{Q}\rho gz}{550} \tag{3.17}$$

  where P_{hp} is the horsepower hp, $\dot{m}$ is the mass flow rate (lb/s), z is the head or height (ft), g is the acceleration of gravity (32 ft/s^2), and $\dot{Q}$ is the volumetric flow rate (ft^3/s).

- *The brake horsepower* is the amount of real horsepower going to the pump, and not the horsepower used by the motor. Due to hydraulic, mechanical, and volumetric losses in a pump or turbine the actual horsepower available for work is less than the total horsepower supplied.

Example 3.8 Power conversions

A 20 kW electric motor is used to pump groundwater into a storage tank. Estimate the work done by the pump in (a) Btu/h, (b) hp, (c) J/s, and (d) ft $\mathrm{lb_f}$/h.

Solution:

(a) $$(20\,\mathrm{kW})\left(\frac{0.948\,\mathrm{Btu/s}}{\mathrm{kW}}\right)\left(\frac{3600\,\mathrm{s}}{\mathrm{h}}\right) = 6.825\times10^4\,\mathrm{Btu/h}$$

(b) $$(20\,\mathrm{kW})\left(\frac{1.341\,\mathrm{hp}}{\mathrm{kW}}\right) = 26.82\,\mathrm{hp}$$

(c) $$(20\,\mathrm{kW})(\frac{1000\,\mathrm{J/s}}{\mathrm{kW}}) = 2\times10^4\,\mathrm{J/s}$$

(d) $$(20\,\mathrm{kW})\left(\frac{737.5\,\mathrm{ft\,lb_f/s}}{\mathrm{kW}}\right)\left(\frac{3600\,\mathrm{s}}{\mathrm{h}}\right) = 53.1\times10^6\,\mathrm{ft\ lb_f/h}$$

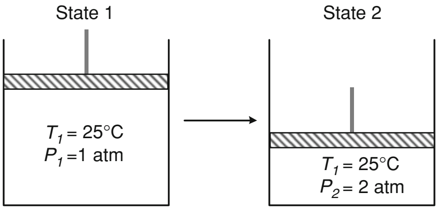


Fig. 3.3 Example of a boundary work: compression at constant temperature

3.7.2 Boundary Work

The most common form of mechanical work is boundary work. Boundary work is a mechanism for energy interaction between a system and its surroundings. *Boundary work at constant pressure* is the total boundary work done during the entire constant pressure process obtained by adding all the differential works from initial state to final state

$$W = -\int_{\text{state1}}^{\text{state2}} PdV \tag{3.18}$$

For example, during an expansion process, the boundary work represents the energy transferred from the system to its surroundings. Therefore, for the sign convention adapted here, the expansion work is negative. For a compression process, the boundary work represents the energy transferred from the surroundings to the system as seen in Fig. 3.3. Therefore, the compression work is positive according to the sign convention. If the boundary is fixed between states 1 and 2, there would be no work performed on the system. For example, if a gas in a fixed volume container is heated and its initial temperature changed, there would be no work performed associated with the gas because the boundary of the system has not changed. Work calculated by Eq. (3.18) may be any value depending on the pathway taken between states 1 and 2. This means that work is a path-dependent function [1].

At constant pressure, Eq. (3.18) becomes

$$W = -P(V_2 - V_1) \tag{3.19}$$

For an ideal gas, *boundary work at constant temperature* is formulated by using $PV = nRT =$ constant $= C$ and $P = C/V$, which may be substituted into Eq. 3.18, and the work is estimated by

$$W = -\int_{\text{state1}}^{\text{state2}} PdV = -\int_{\text{state1}}^{\text{state2}} \frac{C}{V} dV = -C \ln\frac{V_2}{V_1} = -P_1 V_1 \ln\frac{V_2}{V_1} \tag{3.20}$$

The above equation may be modified by using: $P_1V_1 = P_2V_2$ or $V_2/V_1 = P_1/P_2$. For example, if a piston-cylinder device contains 0.5 m^3 of air at 120 kPa and 100°C, and the air is compressed to 0.2 m^3 at constant temperature, then the work done would be

$$W = -P_1 V_1 \ln \frac{V_2}{V_1} = -(120\,\text{kPa})(0.5\ \text{m}^3)\ln\left(\frac{0.2}{0.5}\right)\left(\frac{\text{kJ}}{\text{kPa m}^3}\right) = 54.97\,\text{kJ}$$

As the work done by the surrounding on the system the work is positive according to the sign convention adopted in this book.

By using $PV = nRT$ and $P = nRT/V$ in Eq. (3.20), the isothermal boundary work is also estimated by

$$W = -\int_1^2 PdV = -\int_1^2 \left(\frac{nRT}{V}\right)dV = -nRT\ln\left(\frac{V_2}{V_1}\right) = -nRT\ln\left(\frac{P_1}{P_2}\right) \quad (3.21)$$

Example 3.9 Expansion and compression work of an ideal gas

Estimate the work during: (a) an expansion of a gas from 1 to 7 m^3 at constant pressure of 120 kPa, (b) a compression of a gas when pressure changes from 100 to 80 kPa and volume changes from 7 to 5 m^3.

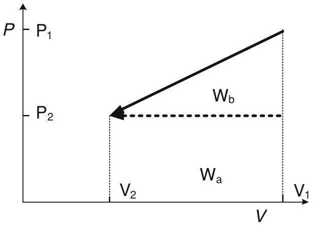
Solution:
Assume that the work done by, or on, an ideal gas is computed by taking the product of the pressure and the change in volume.
Data:
(a) P = 120 kPa, V_1 = 1 m^3, V_2 = 7 m^3,

$$W = -P(V_2 - V_1) = -\mathbf{720\,kJ}$$

Note that the work is negative and done by the gas.

(b) When pressure and volume change at the same time, we calculate the work underneath the P vs V diagram with two parts: a rectangle and a triangle:
P_1 = 100 kPa, P_2 = 80 kPa, V_1 = 7 m^3, V_2 = 5 m^3

The "area" of the rectangular region: $W_a = -P_2(V_2 - V_1) = 160\,\text{kJ}$
The "area" of the triangular region: $W_b = (1/2)(P_1 - P_2)(V_2 - V_1) = 20\,\text{kJ}$
Total work done on the gas = (160 + 20) = **180 kJ**



Example 3.10 Isothermal compression work

Estimate the boundary work when $V_1 = 0.5\ \text{m}^3$ of carbon dioxide at $P_1 = 110$ kPa and $T_1 = 27°\text{C}$ is compressed isothermally to $P_2 = 750$ kPa.

Solution:

Assume that the carbon dioxide is ideal gas.

Data: $V_1 = 0.5\ \text{m}^3$, $P_1 = 110$ kPa, $T_1 = 27°\text{C}$, $P_2 = 750$ kPa

Isothermal system: $\Delta H = \Delta U = 0$

Ideal gas: $PV = nRT$ and $P = \frac{nRT}{V}$

$$W = -\int_1^2 PdV = -\int_1^2 \left(\frac{nRT}{V}\right) dV = -P_1 V_1 \ln\left(\frac{V_2}{V_1}\right)$$

$$W = -P_1 V_1 \ln\frac{V_2}{V_1} = -P_1 V_1 \ln\frac{P_1}{P_2} = -(110\text{kPa})(0.5\text{m}^3)\ln\left(\frac{110}{750}\right)\left(\frac{\text{kJ}}{\text{kPa}\,\text{m}^3}\right) = \mathbf{105.6kJ}$$

The positive sign indicates that the work is done on the system.

3.7.3 Isentropic Process Work

Isentropic process work occurs at isentropic entropy: $S_1 = S_2$. For isentropic process of ideal gas with constant C_v and C_p, we have the following relations:

$$S_2 - S_1 = C_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right) = 0 \tag{3.22}$$

Using the following relationships from the ideal gas equation

$$\frac{T_2}{T_1} = \frac{P_2 V_2}{P_1 V_1} \text{ and } C_p - C_v = R \text{ or } R/C_p = (\gamma - 1)/\gamma \tag{3.23}$$

in Eq. (3.22) yield

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma} \text{ and } \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{3.24}$$

where γ is ratio heat capacities ($\gamma = C_p/C_v$). For an ideal gas, the heat capacity depends only on temperature. The values of R at various units are:

$R = 10.73$ psia ft^3/lbmol R = 0.7302 atm ft^3/lbmol R = 83.14 bar cm^3/gmol K
$R = 1.987$ cal/gmol K = 1.986 Btu/lbmol R
$R = 8.314$ J/gmol K = 8.314 Pa m^3/gmol K = 8314 kPa cm^3/gmol K
$R = 0.082$ atm l/gmol K = 82.06 atm cm^3/gmol K

For the isentropic process (reversible, adiabatic); the heat transfer is zero and using the ideal gas relations, the work is estimated by

$$W_s = \dot{m}C_v(T_2 - T_1) = \dot{m}(U_2 - U_1) \tag{3.25}$$

Example 3.11 Isentropic compression of air

A tank filled with air at 1 bar and 20°C is compressed adiabatically (isentropic) to 4 bar. Estimate the compression work in kJ/mol. Constant heat capacities for the air are $C_{v,av}$ = 20.8 J/mol K and $C_{p,av}$ = 29.1 J/mol K.

Solution:
Assume that the air is ideal gas.
Basis: 1 mol of ideal gas.
Data:
T_1 = 20°C (293 K); P_1 = 1 bar; P_2 = 4 bar; R = 8.314 J/mol K
$C_{v,av}$ = 20.8 J/mol K and $C_{p,av}$ = 29.1 J/mol K, $\gamma = C_{p,av}/C_{v,av} = 1.4$

For adiabatic expansion: $T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 435\ \text{K}$

$W = C_{v,av}(T_2 - T_1) = \mathbf{2953.9\ J/mol}$

The positive sign of the work shows that the work is done on the air.

3.7.4 Polytropic Process Work

In *polytropic process work*, pressure and volume are related by

$$P_1V_1^{\gamma} = P_2V_2^{\gamma} = C \tag{3.26}$$

and the pressure is expressed by

$$P = CV^{-\gamma} \tag{3.27}$$

where γ and C are constants. By using this newly derived pressure in Eq. (3.18), we obtain the polytropic work by [1]

$$W = -\int_{\text{state1}}^{\text{state2}} PdV = -\int_{\text{state1}}^{\text{state2}} CV^{-\gamma}dV = -C\frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{1-\gamma} = -\frac{P_2V_2 - P_1V_1}{1-\gamma} \tag{3.28}$$

Example 3.12 Calculation of work done by a piston on an ideal gas

A piston does a compression work on an ideal gas. The ideal gas is initially at 400 K and 300 kPa. The volume of the gas is compressed to 0.1 from 0.3 m^3. Calculate the work done by the piston on the gas by two different paths.

Path A: Isobaric compression at constant pressure P = 300 kPa.
Path B: Isothermal compression at constant temperature T = 400 K.

Solution:
Assume that the piston is frictionless, an ideal compression (occur very slowly), the ideal gas is the system.
Basis is the amount of the ideal gas.
From ideal gas law: $PV = nRT$, where R = 8.314 kPa m^3/kmol K

Moles of the gas: $n = PV/(RT)$
= (300 kPa) (0.3 m^3)/[(8.314 kPa m^3/kmol K)(400 K)] = 0.027 kmol.

Path A: isobaric compression at P = 300 kPa:

$(V_2 - V_1) = (0.1 - 0.3)\text{m}^3 = -0.2\ \text{m}^3$;

$$W = -\int_{V_1}^{V_2} PdV = -P(V_2 - V_1) = -300 \times 10^3\,\text{Pa}\frac{\text{N}}{\text{m}^2\,\text{Pa}}(-0.2\,\text{m}^3)\frac{\text{J}}{\text{N m}} = \mathbf{60\,kJ}$$

Path B: isothermal compression at T = 400 K:

$$\begin{aligned} W &= -\int_{V_1}^{V_2} PdV = -\int_{V_1}^{V_2} \frac{nRT}{V} dV = -nRT \ln\left(\frac{V_2}{V_1}\right) \\ &= -(0.027\ \text{kmol})\left(\frac{8.314\text{kJ}}{\text{kmol K}}\right)(400\,\text{K})\ln\left(\frac{0.1\ \text{m}^3}{0.3\ \text{m}^3}\right) \\ &= \mathbf{98.65\,kJ} \end{aligned}$$

As the work is a path-dependent variable the work done by the following different paths are different from each other.

Example 3.13 Polytropic expansion of air
Air in a cylinder is at 110 kPa and expands polytropically from 0.01 to 0.05 m^3. The exponent $\gamma = 1.3$ in the pressure volume relation (PV^γ = constant) in polytropic process. Estimate the work done during the process.

Solution:
Assume that the air is ideal gas. $PV = RT$ (for one mole of gas).
Data:
$V_1 = 0.01\,\text{m}^3,\ V_2 = 0.05\,\text{m}^3,\ P_1 = 110\,\text{kPa, and}\,\gamma = 1.3$

$$P_1 V_1^\gamma = P_2 V_2^\gamma = C = \text{constant}$$

$$P_2 = P_1 \frac{V_1^\gamma}{V_2^\gamma} = (110\,\text{kPa})\left(\frac{0.01}{0.05}\right)^{1.3} = 13.6\ \text{kPa}$$

$$W_b = \int_1^2 CV^{-\gamma} dV = \frac{R\Delta T}{\gamma - 1} = \frac{P_2 V_2 - P_1 V_1}{\gamma - 1}\left(\frac{\text{kJ}}{\text{kPa m}^3}\right) = -\mathbf{1.4\,kJ}$$

The negative sign indicates that the work is done on the surroundings.

3.7.5 Shaft Work

Shaft work is the energy transmitted by a rotating shaft and is related to the torque **T** applied to the shaft and the number of revolutions of the shaft per unit time. Shaft work occurs by force acting on a shaft to turn the shaft against a mechanical resistance. A shaft work performed by a pump transferring a liquid body over a distance is positive. On the other hand, the shaft work is negative if a fluid in the system turns a shaft that performs work on the surroundings [5].

A force F acting through a moment arm r produces a torque **T**.

$$\mathbf{T} = Fr \,\text{and}\, F = \frac{\mathbf{T}}{r} \tag{3.29}$$

This force acts through a distance of $2\pi rN$, where N is the number of revolutions. The work done during N revolution becomes

$$W_s = F(2\pi rN) = \frac{\mathbf{T}}{r} 2\pi rN = 2\pi N\mathbf{T} \tag{3.30}$$

A rotating shaft can transmit power. The power transmitted through the shaft is

$$\dot{W}_s = 2\pi\dot{N}\mathbf{T} \tag{3.31}$$

where $\dot{N}$ is the number of revolutions per unit time.

Example 3.14 Estimation of shaft power

Estimate the power transmitted through the shaft of a car when the torque applied is 100 N m. The shaft rotates at a rate of 2,000 revolutions per minute.

Solution:

$\dot{N} = 2000/\text{min}, \mathbf{T} = 100\,\text{Nm}$

$$\dot{W}_s = 2\pi\dot{N}\mathbf{T} = 2\pi\left(2000\frac{1}{\text{min}}\right)\left(\frac{\text{min}}{60\,\text{s}}\right)(100\,\text{Nm})\left(\frac{\text{kJ}}{1000\ \text{Nm}}\right) = \mathbf{20.9\,kW} = \mathbf{28.1\,hp}$$

3.7.6 Spring Work

The length of a spring changes when a force is applied. For a change of length of dx after applying a force F, the work done becomes

$$\delta W_{sp} = Fdx \tag{3.32}$$

For linear elastic springs, the change in length is proportional to the force applied: $F = kx$, where k is the spring constant with unit kN/m. Therefore, for an initial x_1 and final x_2 displacements the work done becomes

$$W_{sp} = \frac{1}{2}k(x_2^2 - x_1^2)\ (\text{kJ}) \tag{3.33}$$

Example 3.15 Estimation of spring work

A piston cylinder system is attached a spring with a spring constant of 110 kN/m. At state 1 there is no displacement on the spring. At state 2, the piston cylinder system performs a compression work and due to the decrease in volume underneath the piston, the spring changes its length by 0.12 m. Estimate the spring work.

Solution:

$k = 110\,\text{kN/m}, \quad x_1 = 0, \quad x_2 = 0.12\ \text{m}$

$W_{sp} = \frac{1}{2}k(x_2^2 - x_1^2) = \mathbf{792\,J} = \mathbf{0.792\,kJ}$

3.8 Electric Energy

Electricity starts with *charge* that produces electrical forces. When, for example, a light bulb is turned on, charge flows from the wall plug through the bulb and heats up the filament in the bulb generating light. There are two large forces: gravitational forces and electromagnetic forces. Both these forces act through space. Mass causes the gravitational forces and two masses always attract each other. Some particles possess a charge and may be subject to electromagnetic forces. Charge may be positive or negative and two positive charges or two negative charges will repel each other, whereas the positive and negative charges attract each other. Charge is measured in Coulombs (C) named after Charles Augustin Coulomb who was the first scientist to formulate the force law for charges. A Farad (F) is the charge in Coulombs. The Coulomb's law is given by

$$F = k_e \frac{Q_1 Q_2}{r^2} \tag{3.34}$$

where k_e is the Coulomb's constant and given by $k_e = 1/(4\pi\varepsilon_0) = 8.987 \times 10^9\,\text{Nm}^2/\text{C}^2$, ε_0 is the electric constant and in the SI system $\varepsilon_0 \sim 8.885419 \times 10^{-12}$ F/m. For the two charges, $\mathbf{Q_1}$ and $\mathbf{Q_2}$, the force between them is proportional to the product of the two charges and inversely proportional to the square of the distance r (in meters) between them. The *electric charge* Coulomb (C) is the amount of electricity carried in one second of time by one ampere of current (C = As). One Faraday is 96,485 C. A positive force implies it is repulsive, while a negative force implies it is attractive. Charge comes in discrete sizes. Electrons and protons have the charge of magnitude 1.6×10^{-19} C that are negative for electrons and positive for protons. The charge on an electron is a fundamental constant of nature. For one electron and one proton the two charges cancel and no net charge appears [2].

When charge flows in a wire it is called current (I), which is measured in coulombs/second and called amperes (A). For example, for a current of 4 A and time interval of 15 s, the total charge is: (current)(time) = (4 A)(15 s) = 60 C. Current can also flow through an ionic solution and through the ground. Current is measured by a device called *ammeter*.

3.8.1 Electric Potential Energy

Electric potential energy is the work of the Coulomb force. Work of intermolecular forces is called *intermolecular potential energy*. There are two main types of electric potential energy: electrostatic potential energy and electrodynamics potential energy (or magnetic potential energy). The *electrostatic potential energy* is the energy of an electrically charged particle in an electric field. It is defined as the work that must be done to move it from an infinite distance away to its present location, in the absence of any non-electrical forces [2]. Consider two point-like objects A_1 and A_2 with electrical charges Q_1 and Q_2. The work W required to move A_1 from an infinite distance to a distance r away from A_2 is given by:

$$W = \frac{1}{4\pi\varepsilon_0}\frac{Q_1 Q_2}{r} \tag{3.35}$$

Electric potential known as *voltage* is equal to the electric potential energy per unit charge. Voltage is the driving force behind current. When the charged particles are in motion, they generate *magnetic potential energy*. This kind of potential energy is a result of the magnetism having the potential to move other similar objects. Magnetic objects are said to have some *magnetic moment*.

Figure 3.4 shows a simple circuit with a battery and two other components. A battery will supply charge at some specified voltage to an applied electrical load. When the charge flows through the load it gives up the potential energy to the load. If the load is a motor that energy might be transformed into mechanical energy. If the load is a light bulb, the energy is transformed into light and heat.

Here, V_B, represents the voltage across the battery. Considering the circuit in Fig. 3.4, the energy added to a charge Q would be:

- When charge moves from the bottom of the battery to the top of the battery the charge gains an amount of energy: QV_B.
- As a charge Q moves from the top of element 1 to the bottom of element 1, the charge loses an amount of energy $QV_\mathbf{1}$.
- As a charge Q moves from the top of element 2 to the bottom of element 2, the charge loses an amount of energy $QV_\mathbf{2}$.

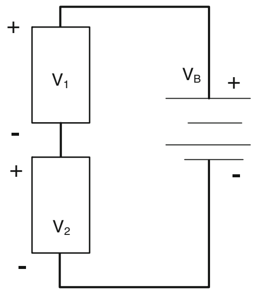


Fig. 3.4 Electrical circuit; V_B represents the voltage across the battery

Like mechanical potential energy, electrical potential energy and voltage are measured from a reference usually chosen as ground. That means the reference is the earth or ground itself. A voltage level of 120 V means that the voltage difference between that point and ground is 120 V. To measure voltage differences in circuits a *voltmeter* is used.

3.8.2 Estimation of Electrical Energy

Figure 3.5 shows a circuit with a resistance R, which determines how much current will flow through a component. Resistors control voltage and current levels. A high resistance allows a small amount of current to flow. A low resistance allows a large amount of current to flow. Resistance is measured in ohms Ω. One ohm is the resistance through which one volt will maintain a current of one ampere. In a resistor, the voltage and the current is related to each other by the Ohm's law

$$I = V/R \,\text{or}\, V_{\mathbf{r}} = RI_{\mathbf{r}} \tag{3.36}$$

Ohm's Law defines the relationships among voltage V, current I, and resistance R. If both V and I remain constant during the time t then electrical energy becomes

$$W_e = VIt \tag{3.37}$$

3.8.3 Electric Power

Electric power P is the rate at which electrical energy is transferred by an electric circuit

$$P = VI \tag{3.38}$$

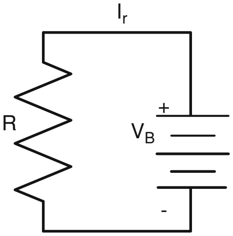


Fig. 3.5 A circuit diagram; battery voltage, V_b, current I_r through a resistance R

where P is the electric power, V is the potential difference, and I is the electric current. Electric power is measured in watts in SI units. The power flowing into the battery is negative, and the power flowing out of the battery is positive. The power delivered to the resistor is the product of the voltage across the resistor and the current through the resistor: VI_r.

In the case of resistive loads (see Fig. 3.5), using the Ohm's law, the following alternative expression for the dissipated power is given by

$$P = I^2R = V^2/R \tag{3.39}$$

where R is the electrical resistance.

Electrical work occurs when an electrical current passes through an electrical resistance in the circuit. Electrical work in the rate form is the same as power

$$\dot{W}_e = VI = I^2R \tag{3.40}$$

3.8.4 Capacitance

A capacitor's ability to store charge is called the capacitance, which is measured by *Farad* (F). One Farad is the capacitance between two parallel plates that results in one volt of potential difference when charged by one coulomb of electricity ($F = C/V$) [6].

In *alternating current* circuits, energy storage elements such as inductance and capacitance may result in periodic reversals of the direction of energy flow. The portion of power flow that, averaged over a complete cycle of the alternating current waveform, results in net transfer of energy in one direction is known as real power or active power. That portion of power flow due to stored energy, which returns to the source in each cycle and is known as reactive power as seen in Fig. 3.6

The relationship among real power, reactive power, and apparent power can be expressed by representing the quantities as vectors. Real power is represented as a horizontal vector and reactive power is represented as a vertical vector. The apparent power vector is the hypotenuse of a right triangle formed by connecting the real and reactive power vectors. This representation is often called the *power*

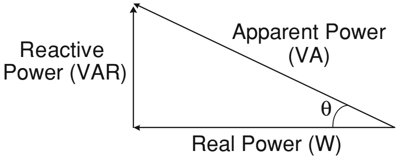


Fig. 3.6 Power triangle and the components of AC power

triangle. Using the Pythagorean theorem, the relationship among real, reactive, and apparent powers is:

$$(\text{Apparent power})^2 = (\text{Real power})^2 + (\text{Reactive power})^2 \tag{3.41}$$

Real and reactive powers can also be calculated directly from the apparent power, when the current and voltage are both sinusoids with a known phase angle between them:

$$(\text{Real power}) = (\text{Apparent power})\cos(\theta) \tag{3.42}$$

$$(\text{Reactive power}) = (\text{Apparent power})\sin(\theta) \tag{3.43}$$

The ratio of real power to apparent power is called power factor and is always a number between 0 and 1. Where the currents and voltages have non-sinusoidal forms, power factor is generalized to include the effects of distortion.

Example 3.16 Estimation of electrical work

A resistance heater within a well-insulated tank is used to heat 12 kg of water. The heater passes a current of 0.6 Amper (A) for 4 h from a 120-V source. Estimate the electric energy used after 4 h of heating.

Solution:
V = 120 V, I = 0.6 A, t = 4 h
Electrical energy received by the water:

$$W_e = VIt = 120\,V(0.6\,A)(4\,\text{h})(3600\,\text{s/h})\left(\frac{\text{kJ/s}}{1000\,VA}\right) = \mathbf{1036.8\,kJ}$$

3.9 Other Forms of Work

Nonmechanical forms of work are formulated in terms of generalized force, F, and generalized displacement, x

$$W_{\text{other}} = Fx \tag{3.44}$$

Table 3.2 Some common forms of work formulations

Boundary work	Equation
General	$W = -\int_{\text{state1}}^{\text{state2}} PdV$
Isobaric work P = constant	$W = -P(V_2 - V_1)$
Isothermal T = constant	$W = -P_1 V_1 \ln \frac{V_2}{V_1}$
Isentropic work S = constant For ideal gases	$W_s = \dot{m} C_v (T_2 - T_1) = \dot{m}(U_2 - U_1)$
Polytropic work PV^{γ}= constant	$W = -\frac{P_2 V_2 - P_1 V_1}{1 - \gamma}$
Shaft work	$W_s = 2\pi N\mathbf{T}$
Spring work	$W_{sp} = \frac{1}{2} k(x_2^2 - x_1^2)$
Electrical work	$W_e = VIt$
Non mechanical forms of work	$W_{\text{other}} = Fx$

- *Magnetic work*: (magnetic field strength) (total magnetic dipole moment)
- *Electric polarization work*: (electric field strength) (polarization of the medium)

Polarization of the medium is the sum of the electric dipole rotation moments of the molecules. Some common forms of work and their formulations are summarized in Table 3.2.

Problems

3.1. Determine the SI units and English units of kinetic and potential energy.

3.2. A one lb_m glass cup is at rest initially, and dropped onto a solid surface: (a) What is the kinetic energy change, (b) What is the sign of potential energy change? (c) What is the work?

3.3. A 50-hp electric motor is used to pump groundwater into a storage tank. Estimate the work done by the pump in Btu/h, kW, and J/s.

3.4. A water pumping process consumes 200 hp. Estimate the pump work in Btu/h and in kW.

3.5. A 25-hp electric motor is used to pump groundwater into a storage tank. Estimate the work done by the pump in Btu/h, MW, and J/s.

3.6. An 85-hp electric motor is used to pump groundwater into a storage tank. Estimate the work done by the pump in Btu/h, kW, and kcal/s.

3.7. A 40 kW electric motor is used to pump groundwater into a storage tank. Estimate the work done by the pump in Btu/h, hp, J/s, and ft lb_f/h.

3.8. A car having a mass of 1,500 kg is initially traveling with a speed of 80 km/h. It slows down at a constant rate, coming to a stop at a distance of 90 m. (a) What is the change in the car's kinetic energy over the 90 m distance it travels while coming to a stop? (b) What is the net force on the car while it is coming to a stop?

3.9. A truck weighing 5,000 lb is travelling at 55 miles/h. The brakes are suddenly applied to stop the car completely. Estimate the energy transfer through the brakes.

3.10. A car having a mass of 1,000 kg is initially at rest. A constant 1,000 N net force acts on the car over a distance of 50 m, causing the car to speed up. (a) Estimate the total work done on the car over the 50 m distance it travels, (b) Estimate the speed of the car after 50 m.

3.11. Calculate the kinetic energy (KE) of a 1,500-kg automobile with a speed of 30 m/s. If it accelerates to this speed in 20 s, what average power has been developed?

3.12. A load with mass of 200 kg is pushed a horizontal distance of 20.0 m by a force of 60.0 N. For a frictionless surface, estimate the kinetic energy of the load when the work is finished, (b) estimate the speed of the load.

3.13. Estimate the power needed to accelerate a 1,400-kg car from rest to a speed of 60 km/h in 10 s on a level road.

3.14. Estimate the power needed to accelerate a 2,000-kg car from rest to a speed of 70 km/h in 5 s on a level road.

3.15. A car having a mass of 1,300 kg is travelling at 55 miles/h. Estimate: (a) the kinetic energy of the car in kJ, (b) the work necessary to stop the car.

3.16. A car having a mass of 1,450 kg is travelling at 65 miles/h. Estimate: (a) the kinetic energy of the car in kWh, (b) the work necessary to stop the car.

3.17. A car having a mass of 1,800 kg is travelling at 40 miles/h. Estimate: (a) the kinetic energy of the car in Btu, (b) the work necessary to stop the car.

3.18. A car having a mass of 2,250 kg is travelling at 65 miles/h. Estimate (a) the kinetic energy of the car in kJ, (b) the work necessary to stop the car.

3.19. A car weighing 2,700 lb is travelling at 60 miles/h. Estimate (a) the kinetic energy of the car in Btu, (b) the work necessary to stop the car.

3.20. A car having a mass of 3,000 lb is travelling at 50 miles/h. Estimate: (a) the kinetic energy of the car in kJ, (b) the work necessary to stop the car.

3.21. A car having a mass of 4,200 lb is travelling at 70 miles/h. Estimate: (a) the kinetic energy of the car in ft lb_f, (b) the work necessary to stop the car.

3.22. A box has a mass of 6 kg. The box is lifted from the garage floor and placed on a shelf. If the box gains 200 J of potential energy estimate the height of the shelf.

3.23. A man climbs on to a wall that is 3.4 m high and gains 2,400 J of potential energy. Estimate the mass of the man.

3.24. A 1 kg ball is dropped from the top of a cliff and falls with a constant acceleration due to gravity (9.8 m/s^2). Assume that effects of air resistance can be ignored. (a) Estimate the ball's gravitational potential energy change, (b) How much work has been done on the ball?

3.25. Estimate the potential energy of 1,000 kg of water at the surface of a lake that is 50 m above a water turbine, which is used to generate electricity.

3.27. Consider a 1,200-kg car travelling at 25 km/h. If the car has to climb a hill with a slope of 30° from the horizontal road, estimate the additional power needed for the speed of the car to remain the same.

3.28. Estimate the potential energy of 10 kg of water at the surface of a lake that is 50 m above a water turbine, which is used to generate electricity.

3.29. Estimate the potential energy of 350 lb of water at the surface of a lake that is 200 ft above a water turbine, which is used to generate electricity.

3.30. Water is flowing over a waterfall 80 m in height. Assume 1 kg of the water as the system. Also assume that the system does not exchange energy with its surroundings. (a) What is the potential energy of the water at the top of the falls with respect to the base of the falls? (b) What is the kinetic energy of the water just before it strikes bottom?

3.31. Estimate the potential energy of 1,000 lb of water at the surface of a lake that is 100 ft above a water turbine, which is used to generate electricity.

3.32. An elevator with a mass of 3,000 kg rests at a level of 3 m above the base of an elevator shaft. The elevator has travelled to 30 m above the base. The elevator falls from this height freely to the base and strikes a strong spring. Assume that the entire process is frictionless. Estimate:

(a) The potential energy of the elevator in its original position relative to the base of the shaft.
(b) The work done travelling the elevator.
(c) The potential energy of the elevator in its highest position relative to the base of the shaft.
(d) The velocity and kinetic energy of the elevator just before it strikes the spring.

3.33. An elevator with a mass of 2,000 kg rests at a level of 2 m above the base of an elevator shaft. The elevator has travelled to 20 m above the base. The elevator falls from this height freely to the base and strikes a strong spring. Assume that the entire process is frictionless. Estimate:

(a) The potential energy of the elevator in its original position relative to the base of the shaft.
(b) The work done travelling the elevator.
(c) The potential energy of the elevator in its highest position relative to the base of the shaft.
(d) The velocity and kinetic energy of the elevator just before it strikes the spring.

3.34. An elevator with a mass of 4,000 lb rests at a level of 5 ft above the base of an elevator shaft. The elevator has travelled to 100 ft above the base. The elevator falls from this height freely to the base and strikes a strong spring.

Assume that the entire process is frictionless. Estimate:

(a) The potential energy of the elevator in its original position relative to the base of the shaft.
(b) The work done travelling the elevator
(c) The potential energy of the elevator in its highest position relative to the base of the shaft.
(d) The velocity and kinetic energy of the elevator just before it strikes the spring.

3.35. An elevator with a mass of 5,000 lb rests at a level of 10 ft above the base of an elevator shaft. The elevator has travelled to 150 ft above the base. The elevator falls from this height freely to the base and strikes a strong spring. Assume that the entire process is frictionless. Estimate:

(a) The potential energy of the elevator in its original position relative to the base of the shaft.
(b) The work done travelling the elevator.
(c) The potential energy of the elevator in its highest position relative to the base of the shaft.
(d) The velocity and kinetic energy of the elevator just before it strikes the spring.

3.36. Water is pumped from an open tank at level zero to an open tank at level 14 ft The pump adds 7.5 hp to the water when pumping a volumetric flow rate of 3.6 ft^3/s. Estimate the loss energy in head.

3.37. Water is pumped from an open tank at level zero to an open tank at a level of 24 ft The pump adds 16 hp to the water when pumping a volumetric flow rate of 5 ft^3/s. Estimate the loss energy in head.

3.38. Estimate the head equivalent of a pressure difference of 12 psi (lbf/in^2) in ft of water and in ft of mercury.

3.39. Estimate the head equivalent of a pressure difference of 20 psi (lbf/in.^{2}) in ft of water and in ft of mercury.

3.40. Estimate the compression work done by a gas during a process with the following recorded data obtained that relates pressure and volume:

P, kPa	100	200	300	400	500
V, L	1.1	0.8	0.55	0.4	0.3

3.41. A saturated steam is expanded inside a cylinder. The steam is initially at 151.8°C and 500 kPa. The final pressure is 200 kPa. Determine the work produced by the steam.

P, kPa	500	450	400	350	300	250	200
V, cm^3	374	413	462	524	605	718	885

3.42. Find the work during (a) an expansion of a gas from 1to 8 m^3 at constant pressure of 120 kPa, (b) a compression of a gas when pressure changes from 140 to 80 kPa and volume changes from 7 to 2 m^3.

3.43. Calculate the boundary work when $V_1 = 1.5$ m^3 of carbon dioxide at $P_1 =$ 110 kPa and $T_1 = 27$°C is compressed isothermally to $P_2 = 750$ kPa.

3.44. A tank filled with an ideal gas at 200°C and 100 kPa is compressed isothermally to 500 kPa. Estimate the compression work in kJ/mol.

3.45. Air undergoes a constant temperature compression from 100 kPa and 100°C to 200 kPa. Find the net work done for 4 kg of air.

3.46. A tank filled with air at 6 bar and 20°C is expanded isothermally to 2 bar. Estimate the expansion work in kJ/mol.

3.47. A tank filled with 10 mol of air at 2 bar and 20°C is compressed adiabatically (isentropic) to 8 bar. Estimate the compression work in kJ/mol. Constant heat capacities for the air are $C_{v,av} = 20.8$ J/mol K and $C_{p,av} =$ 29.1 J/mol K.

3.48. A piston cylinder device contains 2 kg steam at 2 MPa and 450°C. (a) If the steam is cooled to 225°C at constant pressure, estimate the compression work the system performs, (b) if the volume of the cylinder at the final state has the saturated vapor, estimate the work and the temperature at the final state.

3.49. Saturated ammonia vapor enters a compressor at −10°C and leaves at 76.2°C. Determine the work requirement per 0.4 kg of ammonia for the compressor if the process is adiabatic and reversible. Constant heat capacity is $C_{p,av} = 2.64$ kJ/kg K.

3.50. Air in a cylinder is at 110 kPa and expands polytropically from 0.02 to 0.1 m^3. The exponent $\gamma = 1.3$ in the pressure volume relation ($PV^\gamma =$ constant) in polytropic process. Estimate the work done during the process.

3.51. 1 kg of air in a cylinder is at 100 kPa and 30°C. After a polytropic compression the temperature of air reaches 62°C. The constant $\gamma = 1.25$ in the pressure volume relation ($PV^\gamma =$ constant) in polytropic process. Estimate the work done during the process.

3.52. Calculate the boundary work when 1.0 m^3 of air at 25°C is compressed to a final volume of 0.8 m^3 of air at a constant temperature process.

3.53. Calculate the boundary work when 60 ft^3 of nitrogen gas at 80 psia and 150°F is expanded to 40 psia at a constant temperature process.

3.54. Estimate the boundary work when 500 ft^3 of hydrogen gas at 30 psia and 150°F is compressed to 150 psia at a constant temperature process.

3.55. Superheated vapor at 45 psia and 500°F in a piston cylinder system is cooled at constant pressure until 80% of it condenses. Calculate the boundary work per pound of steam.

3.56. Calculate the boundary work when 150 ft^3 of carbon dioxide at 20 psia and 100°F is compressed to 70 psia at a constant temperature process.

3.57. A piston cylinder device has a 10 kg of saturated vapor at 350 kPa. The vapor is heated to 150°C at constant pressure. Estimate the work done by the steam.

3.58. Superheated vapor at 800 kPa and 200°C in a piston cylinder system is cooled at constant pressure until 70% of it condenses. Calculate the boundary work per kg of steam.

3.59. A piston cylinder device contains 0.5 kg of air at 1,000 kPa and 400 K. The air undergoes an isothermal expansion to 300 kPa. Estimate the boundary work for this expansion process.

3.60. A piston cylinder device contains 10 lb of air at 20 psia and 500 R. The air undergoes a polytropic compression to 100 psia. Estimate the boundary work for the compression process.

3.61. A piston cylinder device contains 10 lb of air at 100 psia and 500 R. The air undergoes an isothermal expansion to 20 psia. Estimate the boundary work for the expansion process.

3.62. A piston cylinder device contains 0.5 kg steam at 1 MPa and 400°C. (a) If the steam is cooled to 250°C at constant pressure, estimate the compression work the system performs, (b) if the volume of the cylinder at the final state is 50% of the initial volume and the pressure in the final state is 0.5 MPa, estimate the work and the temperature at the final state.

3.63. A piston cylinder device has a volume of 0.5 m^3 and contains carbon dioxide (CO_2) at 140 kPa and 100°C. At the final state pressure is 90 kPa. Estimate the isentropic expansion work and value of temperature at the final state.

3.64. A piston cylinder device has a volume of 0.5 m^3 and contains carbon dioxide (CO_2) at 140 kPa and 400 K. At the final state pressure is 90 kPa. Estimate the isentropic expansion work and value of temperature at the final state.

3.65. A piston cylinder device has a volume of 1.5 m^3 and contains carbon dioxide (CO_2) at 100 kPa and 300 K. At the final state pressure is 200 kPa. Estimate the isentropic compression work and value of temperature at the final state.

3.66. A car creates a torque of 400 Nm. This torque is transmitted through a shaft which rotates at a rate of 3,000 revolution per minute. Estimate the power transmitted through the shaft.

3.67. A car creates a torque of 500 Nm. This torque is transmitted through a shaft which rotates at a rate of 3,200 revolution per minute. Estimate the power transmitted through the shaft.

3.68. A 180-hp car creates a rotation rate of 2,600 revolution/min. Estimate the torque the car creates at this revolution rate.

3.69. A 210-hp car creates a rotation rate of 3,000 revolution/min. Estimate the torque the car creates at this revolution rate.

3.70. Determine the SI system units of (a) electric power; (b) electric charge; (c) electric potential difference, and (d) electric resistance

3.71. A 2 kW resistance heater is used within a water tank of a shower. If you use the shower for half an hour every day, estimate the cost of electricity per month. The unit cost of electricity is $0.10/kWh.

3.72. A 5 kW resistance heater is used within a room with floor heating systems. If you use the heating system for an average of 8 h everyday, estimate the cost of electricity per year. The unit cost of electricity is \$0.10/kWh.

3.73. A 120 W laptop is used an average of 12 h everyday. Estimate the cost of electricity per year. The unit cost of electricity is \$0.15/kWh.

3.74. A resistance heater is used within a well-insulated water tank. The heater passes a current of 1.2 A from a 120-V source. Estimate the electric energy after 4 h of heating.

3.75. A resistance heater is used within a room. The heater passes a current of 0.2 A from a 120-V source. Estimate the electric energy used after 30 min of heating.

3.76. A resistance heater passes a current of 0.4 A from a 120-V source. Estimate the electric energy if the heater is used for 10 h.

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Chapter 4
Internal Energy and Enthalpy

4.1 Internal Energy

Internal energy U of a system or a body with well-defined boundaries is the total of the kinetic energy due to the motion of molecules (translational, rotational, and vibrational) and the potential energy associated with the vibrational motion and electric energy of atoms within molecules. Internal energy also includes the energy in all the chemical bonds. From a microscopic point of view, the internal energy may be found in many different forms. For a gas it may consist almost entirely of the kinetic energy of the molecules and the potential energy of these molecules in a gravitational, electric, or magnetic field. For any material, solid, liquid, or gaseous, it may also consist of the potential energy of attraction or repulsion between the individual molecules.

Internal energy is a state function of a system and is an extensive quantity. One can have a corresponding intensive thermodynamic property called *specific internal energy*, commonly symbolized by the lower-case letter u, which is internal energy per mass of the substance in question. As such, the SI unit of specific internal energy would be the J/g. If intensive internal energy is expressed on an amount of substance basis, then it could be referred to as *molar internal energy* and the unit would be the J/mol. Table 4.1 shows the different components of internal energy of a system, while Table 4.2 shows the changes in internal energy. Non-mechanical work, such as external electric field, or adding energy through stirring, can change the internal energy.

For a closed system the internal energy is essentially defined by

$$\Delta U = q + W \tag{4.1}$$

where ΔU is the change in internal energy of a system during a process, q is the heat, and W is the mechanical work. If an energy exchange occurs because of temperature difference between a system and its surroundings, this energy appears as *heat* otherwise it appears as *work*. When a force acts on a system through a distance, then energy is transferred as work. Equation 4.1 shows that energy is

Y. Demirel, *Energy*, Green Energy and Technology,
DOI: 10.1007/978-1-4471-2372-9_4,

Table 4.1 Components of internal energy

Thermal energy	Sensible heat	Energy change of a system associated with: (a) Molecular translation, rotation, vibration, (b) Electron translation and spin, (c) Nuclear spin of molecules.
	Latent heat	Energy required or released for phase change; change from liquid to vapor phase requires heat of vaporization.
Chemical energy	Energy associated with the chemical bonds in a molecule.	
Nuclear energy	The large amount of energy associated with the bonds within the nucleus of the atom.	

Table 4.2 Physical and chemical processes that can change the internal energy of a system

Transferring energy across the system boundary by	Heat transfer	Energy transfer from a high temperature to low temperature state.
	Work transfer	Energy transfer driven by changes in macroscopic physical properties of a system, such as compression or expansion work.
	Mass transfer	Energy transfer by mass flowing across a system boundary.
Change through internal processes	Mixing	Heat releases upon components mixing that may lead to lower internal energy
	Chemical reaction	Heat required or released during a chemical reaction that changes chemical energy.
	Nuclear reaction	Heat released during a nuclear reaction that changes nuclear energy.

conserved. According to the sign convention adopted here, the value of heat is positive when transferred to the system and negative when it is transferred from the system to its surroundings. Similarly, the value of work is positive when transferred to the system and negative when transferred from the system to its surroundings. Equation 4.1 in infinitesimal terms is given by

$$\mathrm{d}U = \delta q + \delta W \tag{4.2}$$

where the operator d before the internal energy function indicates that it is an exact differential as it is a state function. On the other hand, the δ*'s* before the other terms describe increments of energy which are not state functions but both the heat and work depend on the path taken between the initial and final states of system.

The change in internal energy in terms of temperature and volume is

$$\mathrm{d}U = C_v \mathrm{d}T + \left(\frac{\partial U}{\partial V}\right)_T \mathrm{d}V \tag{4.3}$$

where C_v is the heat capacity at constant volume. The value of C_v is the amount of heat required to raise the temperature of one gram of a substance by one degree

Celsius at a constant volume process. C_v is a temperature-dependent quantity. A gas becomes ideal in the limit as pressure approaches zero, where the interactions between the gas particles will be small enough to neglect. For ideal gases the internal energy is independent of volume. Therefore, the second term on the right-hand side of Eq. 4.3 may be zero for a constant volume process, for ideal gases, and for incompressible fluids. This term would be approximately zero for low-pressure gases. Whenever the internal energy is independent of volume or at constant volume, the change of internal energy is estimated by

$$\Delta U = U_2 - U_1 = \int_{T_1}^{T_2} C_v \mathrm{d}T \tag{4.4}$$

If the value of the C_v is constant, such as an average value, $C_{v,av}$, within the temperature interval $(T_2 - T_1)$ considered, then integration in Eq. 4.4 yields

$$\Delta U = U_2 - U_1 = C_{v,av}(T_2 - T_1) \tag{4.5}$$

However, if the C_v is expressed by $C_v = A + BT + CT^2$, we have the change of internal energy in terms of temperature estimated by

$$\Delta U = \int_{T_1}^{T_2} C_v dT = A(T_2 - T_1) + \frac{1}{2}B(T_2^2 - T_1^2) + \frac{1}{3}C(T_2^3 - T_1^3) \tag{4.6}$$

The total internal energy U of a system cannot be measured directly. Thus, change in internal energy, $\Delta U = U_{\text{final}} - U_{\text{initial}}$, is a more useful value than U itself. The U_{final} is the final value of the internal energy, while U_{initial} is the initial value of the internal energy of the system.

4.2 Enthalpy

Enthalpy H of a system is defined by

$$H = U + PV \tag{4.7}$$

where U is the internal energy, P is the pressure at the boundary of the system and its environment, and V is the volume of the system. The PV term is equivalent to the energy which would be required to make the pressure of the environment remained constant. For example, a gas changing its volume can maintain a constant pressure P. This may be possible, for example, by a chemical reaction that causes the change in volume of a gas in a cylinder and pushes a piston. The SI unit of enthalpy is the joule. The SI unit for specific enthalpy is joules per kilogram. Enthalpy is a state function of a system and is an extensive quantity.

The total enthalpy of a system cannot be measured directly; the *enthalpy change* of a system is measured instead. Enthalpy change is defined by: $\Delta H = H_{\text{final}} - H_{\text{initial}}$, where H_{final} is the final value and H_{initial} is the initial value of the enthalpy of the system. When enthalpy is expressed in terms of T and P, we have the change of enthalpy given by

$$\mathrm{d}H = C_p \mathrm{d}T + \left(\frac{\partial H}{\partial P}\right)_T \mathrm{d}P \tag{4.8}$$

where C_p is the heat capacity at constant pressure. The value of C_p is the amount of heat required to raise the temperature of one gram of a substance by one degree Celsius at a constant pressure process. The value of C_p is a temperature-dependent quantity. The second term on the right-hand side of Eq. 4.8 may be zero for a constant-pressure process and approximately zero for low-pressure gases. For ideal gases the enthalpy of a matter is independent of pressure. For low-pressure gases and incompressible fluids the enthalpy of a matter is approximately independent of pressure. Whenever the enthalpy of a matter is independent of pressure, regardless of the process, or at constant pressure, the change of enthalpy is estimated by

$$\Delta H = H_2 - H_1 = \int_{T_1}^{T_2} C_p \mathrm{d}T \tag{4.9}$$

If the value of the C_p is constant, such as an average value, $C_{p,av}$, within the temperature interval $(T_2 - T_1)$ considered, then integration in Eq. 4.9 yields

$$\Delta H = H_2 - H_1 = C_{p,av}(T_2 - T_1) \tag{4.10}$$

ΔH of a system is equal to the sum of non-mechanical work done on it and the heat supplied to it. The increase in enthalpy of a system is exactly equal to the energy added through heat, provided that the system is under constant pressure: $\Delta H = q$. Therefore, enthalpy is sometimes described as the *"heat content"* of a system under a given pressure.

Calculation of the enthalpy by the integral in Eq. 4.9 requires an expression for the temperature dependence of heat capacity. Such expressions of practical value are

$$C_p = A + BT + CT^2 \tag{4.11}$$

Ideal-gas-state heat capacities are functions of temperature only designated by C_p^{ig} and C_v^{ig}. The temperature dependence of an ideal gas may be expressed by

$$C_v^{ig}/R = A + BT + CT^2. \tag{4.12}$$

The ratio C_p/R is dimensionless and the units of C_p are governed by the units of R chosen. In Appendix B, Table B1 lists the parameters used in Eq. 4.12 for various chemical species. The two ideal gas heat capacities, C_p^{ig} and C_v^{ig}, are related by:

$$\frac{C_p^{ig}}{R} - \frac{C_v^{ig}}{R} = 1 \text{ or } C_p^{ig} - C_v^{ig} = R \tag{4.13}$$

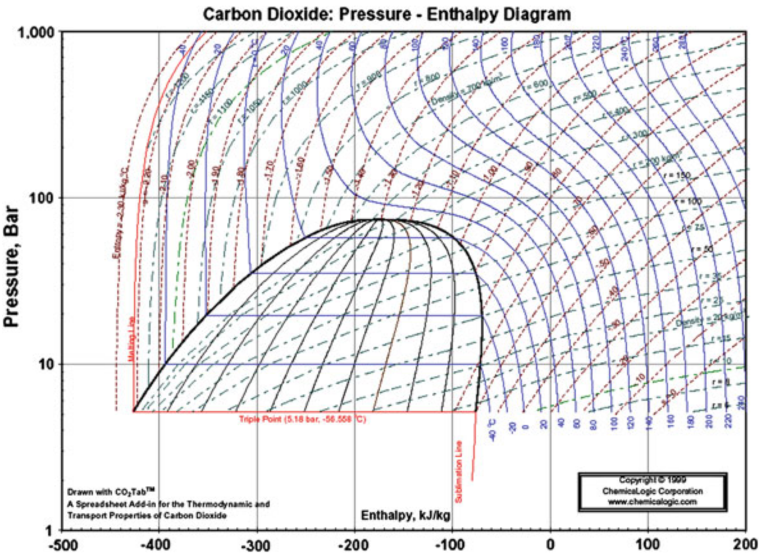


Fig. 4.1 Pressure- enthalpy diagram for carbon dioxide (With permission from Chemicalogic Corporation)

The departure of real gases from ideal behavior is seldom significant at pressures of several bars, and C_p^{ig} and C_v^{ig} are usually good approximations to their true heat capacities [10].

Figure 4.1 shows the change of enthalpy with pressure and temperature for carbon dioxide. At high pressures, the interactions between the molecules will be considerable and the behavior of carbon dioxide will be nonideal. Figure 4.2 shows the values of enthalpy for water at various temperature and pressure. The values of enthalpy at as high as 1,000 bar can be obtained from these pressure-enthalpy diagrams as they represent the non-ideal behavior of carbon dioxide and water. Therefore, they are useful in industrial design of compression and expansion processes.

Example 4.1 Unit conversions of heat capacity

The parameters in Table B1 require the use of temperatures in Kelvin. Dimensionless heat capacity of propane in ideal-gas state in Table B1 is given by

$$\frac{C_p^{ig}}{R} = 1.213 + 28.785 \times 10^{-3}T - 8.824 \times 10^{-6}T^2$$

Develop an equation for C_p^{ig} in J/gmol °C.

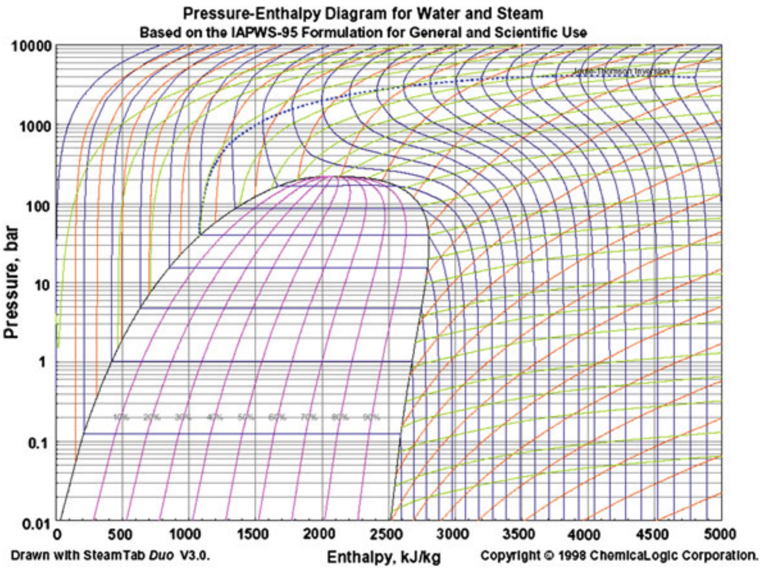


Fig. 4.2 Pressure-enthalpy diagram for water (With permission from Chemicalogic Corporation)

Solution:
The relation between the two temperature scales: $T\,\mathrm{K} = T°\mathrm{C} + 273.15$
The gas constant: R = 8.314 J/gmol K = 8.314 J/gmol °C

$$C_p^{ig} = R\left(1.213 + 28.785 \times 10^{-3}(T + 273.15) - 8.824 \times 10^{-6}(T + 273.15)^2\right)$$

$$C_p^{ig} = 69.981 + 199.24 \times 10^{-3}\,T - 73.362 \times 10^{-6}\,T^2 \text{ in J/gmol °C}$$

Example 4.2 Calculation of internal energy change
Calculate the change in internal energy when 0.5 m^3 of air at 200 kPa is heated from 25 to 120°C in a constant volume process.

Solution:
Assume that the system will remain as nearly ideal gas during the process.
Data: V = 0.5 m^3, P = 200 kPa, T_1 = 25°C (298.15 K); T_2 = 120°C (393.15 K),

The relation between the two temperature scales: $T\,\mathrm{K} = T°\mathrm{C} + 273.15$,
R = 8.314 Pa m^3/gmol K

Moles of air:

$$n_{\text{air}} = \frac{PV}{RT} = \frac{(200 \times 10^3\,\text{Pa})(0.5\,\text{m}^3)}{8.314(\text{Pa m}^3/\text{gmol K})(298.15\ \text{K})} = 40.3\ \text{gmol}$$

The heat capacity parameters in Table B1 require use of temperatures in Kelvin.

Heat capacity at constant pressure of air in ideal-gas state: (Table B1)

$$\frac{C_p^{ig}}{R} = 3.355 + 0.575 \times 10^{-3} \qquad T(T\,\text{in K})$$

From Eq. 4.12, we have

$$\frac{C_v^{ig}}{R} = \frac{C_p^{ig}}{R} - 1 \text{ or } C_v^{ig} = C_p^{ig} - R$$

$$\frac{C_v^{ig}}{R} = (3.355 + 0.575 \times 10^{-3}\,T) - 1$$

The gas constant: R = 8.314 J/gmol K = 8.314 J/gmol °C

$$\begin{aligned}\Delta U &= n_{\text{air}} R \int_{298\text{K}}^{393\text{K}} C_v^{ig} dT \\ &= (40.3\,\text{gmol})(8.314\,\text{J/gmol K})\left(2.355(T_2 - T_1) + \frac{1}{2}0.575 \times 10^{-3}(T_2^2 - T_1^2)\right) \\ &= \mathbf{78.10\ kJ}\end{aligned}$$

The change in internal energy is positive as the heat is transferred to the system (air).

Example 4.3 Determination of state properties

Complete the following table for water with the missing state properties.

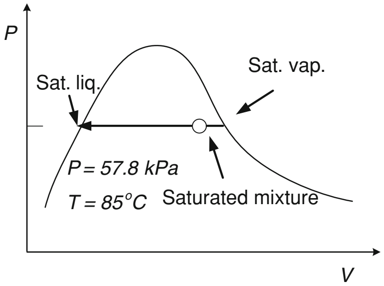
Solution:

T (°F)	P (psia)	ΔU (Btu/lb)	State
250	27	550	
213.03		181.16	Saturated liquid
213.03	15	1,077.9	
350	30	1,125.5	
298	100		Compressed liquid

Properties are from Tables F1 and F2:

T (°F)	P (psia)	ΔU (Btu/lb)	State
250	27	550	Saturated mixture
213.03	15	181.16	Saturated liquid
213.03	15	1,077.9	Saturated vapor
350	30	1,125.5	Superheated vapor
298	100	267.42	Compressed liquid

Example 4.4 Heat value of a saturated liquid and vapor mixture of a steam
A rigid tank contains 15 kg of saturated vapor water at 85°C. If the vapor partially condenses and 2 kg of the liquid water is formed estimate the enthalpy of the saturated liquid-vapor mixture and the amount of heat lost through the condensation.



Solution:
Saturated liquid–vapor water mixture at T_{sat} = 85°C (57.8 kPa) (Table F3)
Saturated vapor: $H_{sat\ vap}$ = 2652.0 kJ/kg
Saturated liquid water: $H_{sat\ liq}$ = 355.9 kJ/kg

Amount of liquid water = 2 kg
Amount of vapor = 15 – 2 = 13 kg

Quality x of the saturated mixture: $x = \frac{m_{vap}}{m_{total}} = \frac{13\,\mathrm{kg}}{15\,\mathrm{kg}} = 0.87$
Enthalpy of the liquid-vapor mixture:

$$H_{mix} = (1-x)H_{sat\,liq} + xH_{sat\,vap} = (1-0.87)355.9\ \mathrm{kJ/kg} + (0.87)2652.0\ \mathrm{kJ/kg}$$

$$= \mathbf{2353.5\,kJ/kg}$$

Heat of condensation at 85°C:
$\Delta H_{cond} = H_{sat\ vap} - H_{sat\ liq}$ = (2652.0 – 355.9) kJ/kg = 2296.1 kJ/kg
Heat lost after forming 2 kg of liquid water: (2 kg) (ΔH_{cond}) = 4592.2 kJ
Enthalpy of the saturated mixture depends on the quality of the mixture x and will be $H_{sat\ vap} > H_{mix} > H_{sat\ liq}$

4.3 Heat

Heat is part of the total energy flow across a system boundary that is caused by a temperature difference between the system and its surroundings or between two systems. Heat flows from high temperature region to cold temperature region. Therefore, heat is not stored and defined as thermal energy in transit. The unit for heat in the SI system is joule, J, though Btu and calorie are still used. When heat capacity is constant, such as $C_{p,av}$, the amount of heat changed when a substance changed its temperature from T_1 to another temperature T_2 is estimated by

$$q = mC_{p,av}(T_2 - T_1) \tag{4.14}$$

where q is the heat, and m is the mass. For processes taking place at constant volume, the specific heat capacity is denoted by C_v. The values of specific heat capacity at constant pressure, C_p, for various substances are shown in Appendix B. For a fluid flow, the heat in the rate form becomes

$$\dot{q} = \dot{m}C_{p,av}(T_2 - T_1) \tag{4.15}$$

where $\dot{q}$ is the rate of heat transfer (J/s or Btu/s), and $\dot{m}$ is the rate of mass flow (kg/s or lb/s). The sign of heat is positive when transferred to the system and negative when transferred from the system to its surroundings. There is no heat flow through the boundary in an *adiabatic process* as the system and its surroundings have the same temperatures.

If an amount of mass, m, is heated from T_1 to T_2, it will gain the heat. For example, the energy needed to heat 1.0 kg of water from 0°C to 100°C when the specific heat of water is 4.18 kJ/kg K becomes q = (1.0 kg) (4.18 kJ/kg K) (100 − 0)°C = 418 kJ. However, if an amount of mass, m, is cooled from T_1 to T_2, it will lose the heat. The value of heat is a path-dependent function. For example, the value of heat at constant pressure process will be different from the value required at a constant volume process.

When there is no work interaction between a closed system and its surroundings the amount of heat is estimated by

$$q = \int_{T_1}^{T_2} C_p dT \tag{4.16}$$

Using the expression for the temperature dependence of the heat capacity, given in Eq. 4.11, the change of heat between T_1 and T_2 is estimated by

$$q = \int_{T_1}^{T_2} C_p dT = A(T_2 - T_1) + \frac{1}{2}B\left(T_2^2 - T_1^2\right) + \frac{1}{3}C\left(T_2^3 - T_1^3\right) \tag{4.17}$$

Table 4.3 Heat, energy, or work conversions

	ft lb	kWh	hp h	Btu	Calorie	Joule
ft lb	1	3.766×10^{-7}	5.050×10^{-7}	1.285×10^{-3}	0.324	1.356
kWh	2.655×10^{6}	1	1.341	3.413×10^{3}	8.606×10^{5}	3.6×10^{6}
hp h	1.98×10^{6}	0.745	1	2.545×10^{3}	6.416×10^{5}	2.684×10^{6}
Btu	778.16	2.930×10^{-4}	3.930×10^{-4}	1	252	1.055×10^{3}
Calorie	3.086	1.162×10^{-6}	1.558×10^{-6}	3.97×10^{-3}	1	4.184
Joule	0.737	2.773×10^{-7}	3.725×10^{-7}	9.484×10^{-4}	0.2390	1

(Himmelblau and Riggs [5])

Thermal equilibrium is achieved when two systems in thermal contact with each other cease to exchange energy by heat.

- If two systems are in thermal equilibrium, then their temperatures are the same.
- For an *isolated system* no energy must is transferred to or from the system.
- A *perfectly insulated* system experiences no heat exchange through the boundary.

4.3.1 Sensible Heat

Sensible heat effects calculate the quantity of heat transfer causing the temperature change of a system in which there is no phase transition, no chemical reaction, and no change in composition. For mechanically reversible, constant pressure, and closed systems, the amount of total heat transferred would be

$$q = \Delta H = \int_{T_1}^{T_2} C_p \mathrm{d}T \tag{4.18}$$

When $C_{p,av}$ = constant, we have

$$q = \Delta H = C_{p,av}(T_2 - T_1) \tag{4.19}$$

According to the sign convention used here, the sign of heat is negative when heat is transferred from the system and positive when heat is transferred to the system.

In a wide variety of situations, it is possible to raise the temperature of a system by the energy released from another system. The calorie was originally defined as the amount of energy required to raise the temperature of one gram of water by 1°C (approximately 4.1855 J), and the British thermal unit was defined as the energy required to heat one pound of water by 1°F (later fixed as 1,055.06 J). Tables 4.3 and 4.4 list the conversion coefficients between various units of energy and power, respectively.

Table 4.4 Power conversions

	hp	kW	ft lb_f/s	Btu/s	J/s
hp	1	0.745	550	0.707	745.7
kW	1.341	1	737.56	0.948	1,000
ft lb_f/s	1.818×10^{-3}	1.356×10^{-3}	1	1.285×10^{-3}	1.356
Btu/s	1.415	1.055	778.16	1	1,055
J/s	1.341×10^{-3}	1,000	0.737	9.478×10^{-3}	1

(Himmelblau and Riggs [5])

4.3.2 Latent Heat

Consider the heat needed for liquefaction of a pure substance from the solid state or vaporization from the liquid state at constant pressure. These

heat effects are called the *latent heat of fusion* and *latent heat of vaporization*, respectively. In either case, no change in temperature occurs but the transfer of a finite amount of heat into the system is required. Similarly, a substance state may change from liquid to solid state if a finite amount of heat is transferred from the liquid state to the surroundings. This heat is called the *latent heat of freezing*. The state of a substance changes from vapor to liquid state when a finite amount of heat is transferred from the vapor state to the surroundings. This heat is called the *latent heat of condensation*. There are also heats of transitions accompanying the change of a substance from one solid state to another; for example, when rhombic crystalline sulfur changes to monoclinic structure at 95°C and 1 bar, the heat of transition is 360 J per gram-atom.

For a pure substance, heat of vaporization ΔH_{vap} is a function of temperature only, and is related to other system properties of an ideal gas at temperature T by the *Clausius-Clapeyron* equation

$$\frac{d \ln P_{\text{sat}}}{\mathrm{d}T} \simeq \frac{\Delta H_{\text{vap}}}{RT^2} \tag{4.20}$$

where P_{sat} is the saturation pressure of the pure substance. The value of saturation pressure P_{sat} can be calculated from the Antoine equation, given in Eq. (1.14). The Antoine parameters A, B, and C are listed in Table 1.15. When ΔH_{vap} can be assumed to be constant within the temperature interval of $(T_2 - T_1)$, Eq. (4.20) can be integrated as follows

$$\ln\left(\frac{P_{2\text{sat}}}{P_{1\text{sat}}}\right) = -\frac{\Delta H_{\text{vap}}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{4.21}$$

Equation 4.21 relates the fluid saturation pressures at two different temperatures to the heat of vaporization. Here the heat of vaporization is assumed to be temperature independent when the temperature difference of $(T_2 - T_1)$ is small [10].

Latent heats may also be measured using a calorimeter, and experimental values are available for many substances (see Table A1). *Trouton's rule* predicts the heat of vaporization at normal boiling point, ΔH_n, that is at a pressure of 1 standard atm (101.32 kPa).

$$\frac{\Delta H_n}{RT_n} \simeq 10 \tag{4.22}$$

where T_n is the absolute temperature of the normal boiling point and R is the gas constant. The units of ΔH_n, T_n, and R must be chosen to yield a dimensionless value for the ratio in Eq. 4.22. Another approximate model is proposed by Riedel [9], and is given by

$$\frac{\Delta H_n}{RT_n} \simeq \frac{1.092(\ln P_c - 1.013)}{0.930 - T_n/T_c} \tag{4.23}$$

where P_c and T_c are the critical pressure and critical temperature, respectively. Predictions by this equation are quite satisfactory [11]. For example, application of Eq. 4.23 for water is

$$\frac{\Delta H_n}{RT_n} \simeq \frac{1.092(\ln 220.55 - 1.013)}{0.930 - 0.577} = 13.56$$
$$\Delta H_n = 13.56(8.314)(373.15) = 42.065\,\text{kJ/mol}$$

where R = 8.134 J/mol K, T_n = 373.15 K, P_c = 220.55 bar, and T_c = 646.71 K (Table A2). The experimental value from Table A1 is 40.65 kJ, which is lower by only 3.4%

The method proposed by Watson [12] estimates the latent heat of vaporization of a pure substance at any temperature from a known value of the latent heat at another temperature

$$\frac{\Delta H_2}{\Delta H_1} \simeq \left(\frac{1 - T_{r_2}}{1 - T_{r_1}}\right)^{0.38} \tag{4.24}$$

where T_{ri} is the reduced temperature obtained from the ratio of T_i/T_c. This equation is fairly accurate.

4.3.3 Heating with Phase Change

The heating processes for the water between 25 and 200°C are illustrated on a temperature-volume diagram in Fig. 4.3.

The heating with phase change has the following sub processes of sensible and latent heating:

Process a: sensible heating of liquid water between 25°C (298 K) and 100°C (373 K):
Process b: latent heating of vaporization at 100°C (373 K)
Process c: sensible heating of water vapor between 100°C (373 K) and 200°C (473 K)

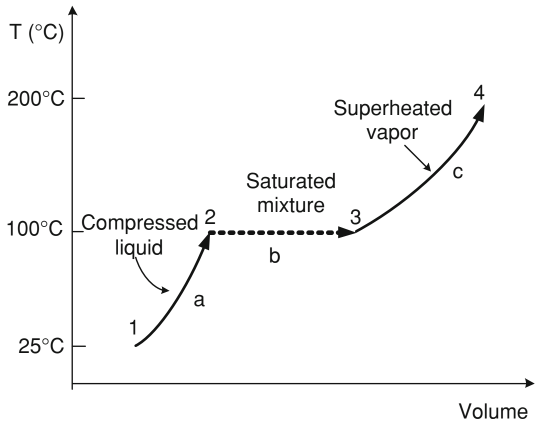


Fig. 4.3 Temperature-volume diagram for heating water with phase change between 25 and 200°C

The total heat per unit amount of water is calculated by

$$\Delta H_{\text{total}} = \Delta H_{\text{a}} + \Delta H_{\text{b}} + \Delta H_{\text{c}} = \left(\int_{298K}^{373K} C_{p,liq}\text{d}T + \Delta H_{\text{vap}} + \int_{373K}^{473K} C_{p,vap}^{ig}\text{d}T\right) \tag{4.25}$$

The equations of temperature-dependent heat capacities are needed within the integrals to estimate the sensible heating at liquid and vapor states.

Example 4.5 Calculation of heat of vaporization using Antoine equation and Clasius-Clapeyron equation

Determine the heat of vaporization of benzene at its normal boiling point T_{b} by using the Antoine equation and compare with the experimental value.

Solution:

Vapor pressure of benzene from the Antoine equation with the constants from $T = T_{\text{b}}$ = 80.11°C = 353.26 K (from Table A1), $R = 8.314$ J/gmol K

Table 1.13:

A = 13.7819, B = 2726.81, C = 217.57

$\ln P_{\text{sat}} = 13.7819 - \dfrac{2726.81}{T + 217.57}$ (P_{sat} is in kPa and T in °C) (Eq. 1.27).

The Clausius-Clapeyron equation: $\dfrac{d\ln P_{\text{sat}}}{\text{d}T} \simeq \dfrac{\Delta H_{\text{vap}}}{RT^2}$

Differentiation of the Antoine equation with respect to temperature T yields

$$\frac{d\ln P_{\text{sat}}}{\text{d}T} = -\frac{2726.81}{(80 + 217.57)^2} \simeq \frac{\Delta H_{\text{vap}}}{8.314(353.15)^2}$$

ΔH_{vap} = **31.95 kJ/gmol**

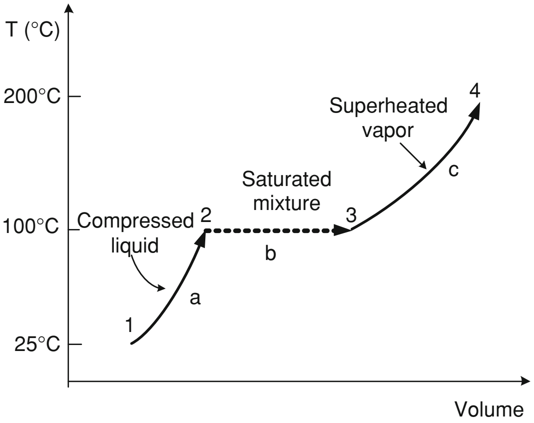
The experimental data from Table A1 is 30.76 kJ/mol and the deviation:

$\dfrac{31.95 - 30.76}{30.76} = 0.038 = 3.8\%$ (small enough for many engineering calculations).

Example 4.6 Estimation of change of enthalpy with sensible and latent heat
Estimate the change of enthalpy of a water flowing at a rate of 4.5 kg/s and heated from 25 to 200°C at atmospheric pressure.

Solution:
Assume that the water will remain in ideal state from the initial and the final temperatures.

The heating processes are shown below on a temperature versus volume diagram:



T_1 = 298 K, T_{sat} = 373 K, T_2 = 473 K
The total heat is calculated by

$$\Delta H_{\text{total}} = \Delta H_{\text{a}} + \Delta H_{\text{b}} + \Delta H_{\text{c}} = \dot{m}\left(\int_{298K}^{373K} C_{p,\text{liq}}dT + \Delta H_{\text{vap}} + \int_{373K}^{473K} C_{p,\text{vap}}dT\right)$$

where $\dot{m}$ is mass flow rate of water: 4.5 kg/s
R = 8.314 J/gmol K, MW = 18.02 g/gmol, R = 0.4615 kJ/kg K.
At T_{sat} = 373 K: $\Delta H_{vap} = \Delta H_{sat\ vap} - \Delta H_{sat\ liq}$ = 2257 kJ/kg (Table F3)
From Table B1 the dimensionless heat capacities at constant pressure are:

$$C_{p,\text{liq}} = R(A + BT) = R(8.712 + 1.25 \times 10^{-3}\, T) \qquad \text{(T in K)}$$

$$C_{p,\text{vap}} = C_p^{ig} = R(A + BT) = R(3.47 + 1.45 \times 10^{-3}\, T) \qquad \text{(T in K)}$$

Process a: $\dot{m}\left(\int_{298K}^{373K} C_{p,\text{liq}}dT\right) = \dot{m}R[8.712(373 - 298) + \frac{1}{2}1.25 \times 10^{-3}(373^2 - 298^2)]$
= 1422.3 kJ/s = 1422.3 kW

Process b: $\dot{m}(\Delta H_{\text{vap}}) = 10256.3\ \text{kJ/s} = 10256.3\,\text{kW}$

Process c: $\dot{m}\left(\int_{373K}^{473K} C_{p,\text{liq}}dT\right) = \dot{m}R[3.47(473-373) + \frac{1}{2}1.45 \times 10^{-3}(473^2 - 373^2)]$
$= 848.0$ kJ/s $= 848$ kW

Total amount of energy (power) needed = 12,426.8 kJ/s = **12,426.8 kW**

Using the steam tables of Table F3 and Table F4:

Process a: $\dot{m}(H_2 - H_1)$ = (4.5 kg/s)(419.06 − 104.8) kJ/kg = 1417.5 kW
Process b: $\dot{m}\Delta H_{\text{vap}}$ (4.5 kg/s)(2676.0 − 419.06) kJ/kg = 10156.5 kW
Process c: $\dot{m}(H_4 - H_3)$ (4.5 kg/s)(2875.3 − 2676.0) kJ/kg = 898.8 kW

Total = 1,417.5 + 10,156.5 + 898.8 = **12,470.8 kW**

The results from the steam tables are slightly different from the estimated results because of the nonideal behavior of water at high temperatures and pressures.

Example 4.7 Estimation of heat of vaporization at another temperature
The latent heat of vaporization of water at 100°C is 2,253.0 kJ/kg (Table A1). Estimate the latent heat of water at 150°C.

Solution:
For water: T_c = 646.71 K; ΔH_1 = 2,253.0 kJ/kg (From Tables A1)
T_1 = 373.15 K, T_2 = 423.15 K

Reduced temperatures to be used in Eq. 4.24:
T_{r1} = 373.15/647.1 = 0.577
T_{r2} = 423.15/647.1= 0.654

$$\Delta H_2 \simeq (2253.0\,\text{kJ/kg})\left(\frac{1-0.654}{1-0.577}\right)^{0.38} = \mathbf{2087.4\,kJ/kg}$$

The value given in the steam table is 2,113.2 kJ/kg (From Table F3)
Deviation:

$$\frac{2{,}113.2 - 2{,}087.4}{2{,}113.2} = 0.012 \text{ or } 1.2\%$$

Deviation of the estimated value from the tabulated value is low.

4.3.4 Heat of Reaction

Systems with chemical reactions exchange heat with the surroundings and the temperature may change. These effects result because of the differences in molecular structure and therefore in energy of the products and reactants. The heat associated with a specific chemical reaction depends on the temperatures of reactants and products. A general chemical reaction may be written as follows

$$v_A \mathrm{A} + v_B \mathrm{B} \rightarrow v_C \mathrm{C} + v_D \mathrm{D} \tag{4.26}$$

where v_i is the stoichiometric coefficient for the substance A, B, C and D, which is positive for a product and negative for a reactant.

A standard basis for estimation of reaction heat effects results when the reactants and products are at the same temperature. For the reaction given in Eq. 4.26, the standard heat of reaction is the enthalpy change when v_A moles of A and v_B moles of B in their standard states at temperature T react to form v_C moles of C and v_D moles of D in their standard states at the same temperature T. Standard state for gases is the pure substance in the ideal-gas state at 1 atm. For liquids and solids, the standard state is the real pure liquid or solid at 1 atm. Standard state properties are therefore functions of temperature. Based on this sign convention, a standard heat of reaction is expressed by

$$\Delta H_r^o = \sum_i v_i \Delta H_{fi}^\mathrm{o} \tag{4.27}$$

where H_{fi}^o is the *standard heat of formation*. Some values of standard heats of formation are tabulated at 298.15 K or 25°C in Table C1, and are shown as $\Delta H_{f298}^\mathrm{o}$.

A formation reaction is defined as a reaction which forms 1 mol of a single compound from its constituent elements with each substance in its standard state at 298.15 K (25°C). Standard states are: (i) gases (g); pure ideal gas at 1 atm and 25°C. (b) liquids (l) and solids (s); (ii) pure substance at 1 atm and 25°C; (iii) solutes in aqueous 1-molal ideal solution at 1 atm and 25°C. Standard heats of formation for stable elements in their standard states are zero, since they are naturally exist. For example, the formation reaction for ammonia is $N_2 + 3H_2 \rightarrow NH_3$ since all the reactants are elements. However the reaction $H_2O + SO_3 \rightarrow H_2SO_4$ is not a formation reaction, since it forms sulfuric acid not from elements but from other compounds.

The summation in Eq. 4.27 is over all products and reactants. For example, for the reaction

$$4\mathrm{HCl(g)} + \mathrm{O_2}(g) \rightarrow 2\mathrm{H_2O(g)} + 2\mathrm{Cl_2}(g) \tag{4.28}$$

the stoichiometric coefficients are $v_\mathrm{HCl} = -4$, $v_\mathrm{O2} = -1$, $v_\mathrm{H2O} = 2$, $v_\mathrm{Cl2} = 2$ and the standard heat of reaction using Eq. 4.27 becomes

$$\Delta H_r^o = \sum_i v_i \Delta H_{fi}^\mathrm{o} = v_{H_2O} \Delta H_{fH_2O}^\mathrm{o} + v_{Cl_2} \Delta H_{fCl_2}^\mathrm{o} + v_{HCl} \Delta H_{fHCl}^\mathrm{o} + v_{O_2} \Delta H_{fO_2}^\mathrm{o} \tag{4.29}$$

where $\Delta H_{f\mathrm{Cl_2}}^\mathrm{o} = 0$ and $\Delta H_{f\mathrm{O_2}}^\mathrm{o} = 0$ as they are naturally occurring stable elements.

Heat effects change according to the nature of chemical reactions. Reactions that release heat are called *exothermic reactions* and reactions that require heat are called *endothermic reactions*. For an exothermic reaction at constant pressure, the

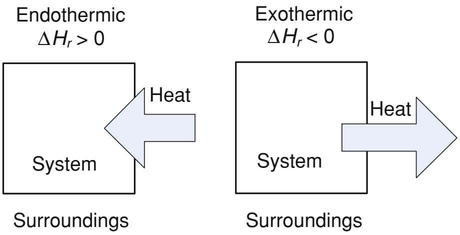


Fig. 4.4 Heat interactions in chemical reactions: endothermic reaction needs energy from outside and exothermic reactions release energy to the surroundings

system's change in enthalpy equals the energy released in the reaction, including the energy retained in the system and lost through expansion against its surroundings. In a similar manner, for an endothermic reaction, the system's change in enthalpy is equal to the energy *absorbed* in the reaction. If ΔH_r is positive, the reaction is endothermic, that is heat is absorbed by the system due to the products of the reaction having a greater enthalpy than the reactants. On the other hand, if ΔH_r is negative, the reaction is exothermic, that is the overall decrease in enthalpy is achieved by the generation of heat (Fig 4.4).

When a heat of reaction is given for a particular reaction, this applies for the current stoichiometric coefficients. If the stoichiometric coefficients are doubled, the heat of reaction is doubled. For example, consider the following reactions:

$$\frac{1}{2}N_2 + \frac{3}{2}H_2 \rightarrow NH_3 \quad \Delta H_{\mathrm{r}}^{\mathrm{o}} = -46.11\,\mathrm{kJ}$$

$$N_2 + 3H_2 \rightarrow 2NH_3 \quad \Delta H_{\mathrm{r}}^{\mathrm{o}} = -92.22\,\mathrm{kJ}$$

When chemical reactions are combined by addition, the standard heats reaction may also be added to estimate the standard heats of the resulting reaction. This is possible since the enthalpy is a state function and, for a given initial and final states, its value is independent of path. Chemical reaction equations considered for this purpose often include an indication of the physical state of each reactant and product; the symbol g, l, or s indicates gas, liquid, or solid states, respectively.

Example 4.8 Estimation of standard heat of reaction

Estimate the heat of reaction at 298.15 K for the reaction $4HCl(g) + O_2(g) \rightarrow 2H_2O(g) + 2Cl_2(g)$

Solution:

$4HCl(g) + O_2(g) \rightarrow 2H_2O(g) + 2Cl_2(g)$

Stoichiometric coefficients v_i are positive for a product and negative for a reactant. The stoichiometric coefficients for the reaction are $v_{\mathrm{HCl}} = -4$, $v_{\mathrm{O_2}} = -1$, $v_{\mathrm{H_2O}} = 2$, $v_{\mathrm{Cl_2}} = 2$.

Based on this sign convention, a standard heat of reaction is expressed by $\Delta H_r^o = \sum_i v_i \Delta H_{fi}^{\mathrm{o}}$

where H_{fi}^{o} is the standard heat of formation. The summation is over all the products and the reactants using the standard heat of formations from Table C1.

$$\Delta H_r^o = 2\Delta H_{f\mathrm{H2O}}^{\mathrm{o}} - 4\Delta H_{f\mathrm{HCl}}^{\mathrm{o}} = (2)(-241.82) + (-4)(-92.31) = \mathbf{-114.41\,kJ/mol}$$

The heats of formations for the stable and naturally occurring elements of O_2 and Cl_2 are zero.

Example 4.9 Estimation of standard heats of reaction from standard heats of formation

Estimate standard heats of reaction for the water–gas shift reaction:

$$CO_2(g) + H_2(g) \rightarrow CO(g) + H_2O(g)$$

Solution:

Although this reaction takes place at temperatures well above 25°C, standard heats of reaction is calculated at 25°C.

Stoichiometric coefficients v_i are positive for a product and negative for a reactant. The pertinent formation reactions and their heats of formation from Table C1 are:

$$CO_2 : C(s) + O_2(g) \rightarrow CO_2(g) \qquad \Delta H_{f298}^{\mathrm{o}} = -393.51 \text{ kJ/mol}, v = -1$$

$$H_2 : H_2(g) \qquad \Delta H_{f298}^{\mathrm{o}} = 0 \text{ because hydrogen is a stable element}$$

$$CO : C(s) + \frac{1}{2}O_2(g) \rightarrow CO(g) \qquad \Delta H_{f298}^{\mathrm{o}} = -110.52 \text{ kJ/mol}, v = 1$$

$$H_2O : H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(g) \quad \Delta H_{f298}^{\mathrm{o}} = -241.82 \text{ kJ/mol}, v = 1$$

Here all the products and reactants are at their standard states: ideal gas state at 1 atm and 25°C.

Based on this sign convention, the standard heat of reaction is expressed by Eq. 4.27

$$\Delta H_r^o = \sum_i v_i \Delta H_{fi}^{\mathrm{o}} = -110.52 - 241.82 - (-393.51) = \mathbf{41.16\,kJ/mol}$$

This result shows that the enthalpy of 1 mol of CO plus 1 mol of H_2O is greater than the enthalpy of 1 mol of CO_2 plus 1 mol of H_2 by 41.16 kJ when all the components are at their standard states. Therefore, the water–gas-shift reaction is an endothermic reaction and requires heat from the surroundings to occur.

4.3.5 Standard Heat of Combustion

Consider the reaction for the combustion of coal: C(s) + $O_2(g) \rightarrow CO_2(\mathrm{g}) + \Delta H_r$, here the pure carbon representing the coal is in solid state, while oxygen and carbon dioxide are both in gas state. The reactants in a combustion reaction possess greater energy than do the products, and this energy is transferred to the surroundings as heat so the reaction is exothermic. The *heats of combustion* of fuel may be measured by a flow-calorimeter. The fuel is mixed with air at ambient temperature and mixture flows into a combustion chamber of the calorimeter where reaction occurs. The combustion products enter a water-cooled section and are cooled to the temperature of the reactants. As there is no shaft work produced in the process and potential and kinetic energies are negligible, the change in enthalpy caused by the combustion reaction becomes the heat flowing from the calorimeter

$$q = \Delta H = \text{heat of reaction} \tag{4.30}$$

For example, 2,2,4-trimethylpentane (isooctane), widely used in petrol, has a chemical formula of C_8H_{18}, and it reacts with oxygen exothermically and produces 10.86 MJ per mole of isooctane

$$2\mathrm{C_8H_{18}}(l) + 25\mathrm{O_2}(g) \rightarrow 16\mathrm{CO_2}(g) + 18\mathrm{H_2O}(g) + 10.86\ \mathrm{MJ/mol} \tag{4.31}$$

Incomplete combustion of petroleum or petrol products results in carbon monoxide. At a constant volume the heat of combustion of a petroleum product can be approximated by:

$$q_v = 12{,}400 - 2{,}100d^2 \tag{4.32}$$

where q_v is measured in cal/gram and d is the specific gravity at 60°F (16°C). Ethane C_2H_6 is an aliphatic hydrocarbon. The complete combustion of ethane releases 1,561 kJ/gmol, or 51.9 kJ/g, of heat, and produces carbon dioxide and water according to the chemical equation

$$\mathrm{C_2H_6} + 3/2\mathrm{O_2} \rightarrow 2\mathrm{CO_2} + 3\mathrm{H_2O} + 1{,}561\,\mathrm{kJ/gmol} \tag{4.33}$$

Gasoline contains about 35MJ/l (132 MJ/US gal) (higher heating value). This is an average value. Gasoline blends differ; therefore actual energy content varies from season to season and from batch to batch, by up to 4% more or less than the average value.

Example 4.10 Determination of standard heats of reaction

Determine the standard heat of formation for n-pentane: $5C(s) + 6H_2 \rightarrow C_5H_{12}\,(g)$.

Solution:

Many standard heats of formation come from *standard heats of combustion* measurements in a calorimeter. A combustion reaction occurs between an element or compound and oxygen to form specified combustion products. When organic compounds are made up of carbon, hydrogen, and oxygen only, the combustion products are carbon dioxide and water. The state of the water produced may be either vapor or liquid.

The reaction for formation of n-pentane may result from combination of the following combustion reactions in practice.

Stoichiometric coefficients v_i are positive for a product and negative for a reactant.

$$\begin{array}{ll} 5C(s) + 5O_2(g) \rightarrow 5CO_2(g) & \Delta H^{o}_{f298} = (5)(-393.51)\text{kJ/mol} \\ 6H_2(g) + 3O_2(g) \rightarrow 6H_2O(l) & \Delta H^{o}_{f298} = (6)(-285.83)\text{kJ/mol} \\ 5CO_2(g) + 6H_2O(l) \rightarrow C_5H_{12}(g) + 8O_2(g) & \Delta H^{o}_{f298} = 3{,}535.77\ \text{kJ/mol} \\ 5C(s) + 6H_2 \rightarrow C_5H_{12} & \Delta H^{o}_{f298} = \mathbf{-146.76\,kJ/mol} \end{array}$$

The net reaction is obtained from the summation of the first three equations by considering that the value of stoichiometric coefficients, v_i, are positive for the products and negative for the reactants. This result is the standard heat of formation of n-pentane listed in Table C1.

Example 4.11 Estimation of standard heats of combustion from standard heats of formation

Estimate standard heats of reaction for the combustion of methane:

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$$

Solution:

The pertinent formation reactions and their heats of formation from Table C1 are:

$$\begin{array}{ll} CH_4 : C(s) + 2H_2(g) \rightarrow CH_4(g) & \Delta H^{o}_{f298} = -74.52\ \text{kJ/mol}, v = -1 \\ O_2 : O_2(g) & \Delta H^{o}_{f298} = 0 \text{ because oxygen is a stable element} \\ CO_2 : C(s) + O_2(g) \rightarrow CO_2(g) & \Delta H^{o}_{f298} = -393.51\ \text{kJ/mol}, v = 1 \\ H_2O : H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l) & \Delta H^{o}_{f298} = -285.83\ \text{kJ/mol}, v = 2 \end{array}$$

Stoichiometric coefficients v_i are positive for a product and negative for a reactant. A standard heat of reaction is expressed by: $\Delta H^{o}_{r} = \sum_i v_i \Delta H^{o}_{fi}$

$\Delta H^{\circ}_{298} = -393.51 + 2(-285.83) - (-74.52) = \mathbf{-890.65\,kJ/mol}$

This result shows that the enthalpy of 1 mol of CH_4 plus 2 mol of O_2 is less than the enthalpy of 1 mol of CO_2 plus 2 mol of H_2O by 890.65 kJ when all the components are at their standard states. Therefore, the reaction is an exothermic reaction and emits heat to the surroundings.

4.4 Effect of Temperature on the Heat of Reaction

Standard-state of formation enthalpies are function of temperature only

$$\mathrm{d}H^{\circ}_{fi} = C^{o}_{pi}\mathrm{d}T \tag{4.34}$$

Multiplying by v_i and summing over all products and reactants gives

$$\mathrm{d}\Delta H^{o} = \sum_i \mathrm{d}v_i H^{\circ}_{fi} = \sum_i v_i C^{o}_{pi}\mathrm{d}T \tag{4.35}$$

The standard heat capacity change of a reaction is

$$\Delta C^{o}_{p} = \sum_i v_i C^{o}_{pi} \tag{4.36}$$

or

$$\Delta C^{o}_{p} = \Delta A + \Delta B \times 10^{-3}T + \Delta C \times 10^{-6}T^{2}$$

where $\Delta A = \sum_i v_i A_i; \Delta B = \sum_i v_i B_i; \Delta C = \sum_i v_i C_i$

As a result, the effect of temperature on heats of reaction is obtained from

$$\begin{aligned}\Delta H^{o}_{r2} &= \Delta H^{o}_{r1} + \int_{T_1}^{T_2} \Delta C^{o}_{p} dT \\ &= \Delta H^{o}_{r1} + \int_{T_1}^{T_2} (\Delta A + \Delta B \times 10^{-3}T + \Delta C \times 10^{-6}T^{2}) dT\end{aligned} \tag{4.37}$$

where ΔH^{o}_{1} is the known value, such as the standard heat of reaction (T_1 = 25°C) and ΔH^{o}_{2} is the standard heat of reaction at another temperature T_2.

Industrial reactions are usually are not carried out at standard-state conditions. In real applications, several reactions may occur simultaneously, actual reactions may also not go to completion, and the final temperature may differ from the initial temperature. Also, some inert components may be present in the reactions. Still, calculations of the heat effects will be based on the principles outlined above.

Example 4.12 Estimation of standard heat of reaction at a temperature other than 298 K

Estimate the standard heat of reaction for the methanol synthesis at 800°C.

$CO(g) + 2H_2(g) \rightarrow CH_3OH(g)$

Solution:

By using standard heat of formation data in Eq. 4.27, we have

Stoichiometric coefficients v_i are positive for a product and negative for a reactant.

$$\Delta H^{\mathrm{o}}_{r,298} = -200.66 - (-110.52) = -90.13\mathrm{kJ} = -110.52\ \mathrm{kJ/mol}$$

Heat of formation for hydrogen is zero as it is naturally occurring stable element. The ideal gas heat capacity parameters for all the components from Table B1 are:

Components	v_i	A	$10^3\ B$	$10^6\ C$
CO	−1	3.376	0.557	0.0
H_2	−2	3.249	0.422	0.0
CH_3OH	1	2.211	12.216	−3.45

$\Delta A = (1)(2.211)+(-1)(3.376)+(-2)(3.249) = -7.663$
$\Delta B = [(1)(12.216)+(-1)(0.557)+(-2)(0.422)]\times10^{-3} = 10.815\times10^{-3}$
$\Delta C = [(1)(-3.45)+(-1)(0.0)+(-2)(0.0)]\times10^{-6} = -3.45\times10^{-6}$

$T_1 = 298.15$ K
$T_2 = (800 + 273.15)^{\mathrm{o}}\mathrm{C} = 1{,}073.15$ K
$R = 8.314$ J/gmol K

$$\begin{aligned}\Delta H^o_{r2} &= \Delta H^o_{r1} + R\int_{T_1}^{T_2} (\Delta A + \Delta B \times 10^{-3}T + \Delta C \times 10^{-6}T^2)\mathrm{d}T \\ &= -90.13 + R\int_{298.15}^{1073.15} (-7.663 + 10.815 \times 10^{-3}T - 3.45 \times 10^{-6}T^2)\mathrm{d}T \\ &= \mathbf{-13,249.2kJ}\end{aligned}$$

The reaction is exothermic and releases energy. The heat of reaction increased with increased temperature.

Stable combustion reactions require the right amounts of fuels and oxygen. In theory, there is a theoretical amount of oxygen needed (known as stoichiometric amount) to completely burn a given amount of fuel. In practice, burning conditions are never ideal. Therefore, more air than that of stoichiometric amount must be supplied to burn all fuel completely. The amount of air that is more than the theoretical requirement is referred to as *excess air*. Power plant boilers, for example, normally run with about 10 to 20% excess air. Natural gas-fired boilers may run as low as 5% excess air. Pulverized coal-fired boilers may run with 20% excess air. Gas turbines run very lean with up to 300% excess air. If insufficient amount of air is supplied to the burner, unburned fuel, soot, smoke, and carbon monoxide are exhausted from the boiler. The result is heat transfer surface fouling, pollution, lower combustion efficiency, flame instability and a potential for explosion. To avoid inefficient and unsafe conditions, boilers normally operate at an excess air level.

4.5 Standard Enthalpy Changes

Standard enthalpy changes describe the change in enthalpy observed in a system when going between different states under standard conditions. Some of the standard enthalpy changes are:

- *Standard enthalpy of formation* is the enthalpy observed when one mole of a compound is formed from its elementary antecedents under standard conditions. The enthalpy change of any reaction under any conditions can be computed using the standard enthalpy of formation of all of the reactants and products.
- *Standard enthalpy of reaction*, defined as the enthalpy observed when one mole of substance reacts completely under standard conditions.
- *Standard enthalpy of combustion* is the enthalpy observed when one mole of a substance combusts completely with oxygen under standard conditions.
- *Standard enthalpy of neutralization* is the enthalpy observed when one mole of water is produced when an acid and a base react under standard conditions.
- *Standard enthalpy of fusion* is the enthalpy required to completely change the state of one mole of substance between solid and liquid states under standard conditions.
- *Standard enthalpy of vaporization* is the enthalpy required to completely change the state of one mole of substance between liquid and gaseous states under standard conditions.
- *Standard enthalpy of sublimation* is the enthalpy required to completely change the state of one mole of substance between solid and gaseous states under standard conditions.
- *Enthalpy of hydration* is the enthalpy observed when one mole of gaseous ions is completely dissolved in water forming one mole of aqueous ions.

4.6 Adiabatic Flame Temperature

There are two types of *adiabatic flame temperatures*: at constant volume and at constant pressure, describing the temperature of a combustion reaction products theoretically reaching if no energy is lost to the outside environment. Constant pressure adiabatic flame temperature results from a complete combustion process

Table 4.5 Adiabatic constant pressure flame temperature T_{ad} of common gases/materials

Fuel	T_{ad} (°C)	T_{ad} (°F)
Acetylene (C_2H_2)	2,500	4,532
Butane (C_4H_{10})	1,970	3,578
Ethane (C_2H_6)	1,955	3,551
Hydrogen (H_2)	2,210	4,010
Methane (CH_4)	1,950	3,542
Natural gas	1,960	3,562
Propane (C_3H_8)	1,980	3,596
Wood	1,980	3,596
Kerosine	2,093	3,801
Light fuel oil	2,104	3,820
Medium fuel oil	2,101	3,815
Heavy fuel oil	2,102	3,817
Bituminous coal	2,172	3,943
Anthracite	2,180	3,957

(Jarosinski and Veyssiere [7]; Griffiths and Barnard [3])

that occurs without any heat transfer or changes in kinetic or potential energy. The adiabatic flame temperature of the constant pressure process is lower than that of the constant volume process. This is because some of the energy released during combustion goes into changing the volume of the control system. The constant pressure adiabatic flame temperature for many fuels, such as wood, propane, and gasoline in air is around 1,950°C [7, 10]. Assuming initial atmospheric conditions (1 atm and 25°C), Table 4.5 lists the adiabatic flame temperatures for various gases for a stoichiometric fuel–air mixture.

Example 4.13 Maximum flame temperature

Estimate the maximum temperature that can be reached by the combustion of methane with air at constant pressure. Both the methane and air enter the combustion chamber at 25°C and 1 atm. The combustion reaction is

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

Solution:

Stoichiometric coefficients v_i are positive for a product and negative for a reactant. The heats of formation from Table C1 are:

$\Delta H^{o}_{f298}(CH_4) = -74.52$ kJ/mol, $v = -1$

$\Delta H^{o}_{f298}(O_2) = 0$ because oxygen is an element, $v = -2$

$\Delta H^{o}_{f298}(CO_2) = -393.51$ kJ/mol, $v = 1$

$\Delta H^{o}_{f298}(H_2O) = -241.82$ kJ/mol (vapor state), $v = 2$

$R = 8.314$ J/gmol K

A standard heat of reaction is expressed by: $\Delta H^{o}_{r} = \sum_i v_i \Delta H^{o}_{fi}$

$$\Delta H^{\text{o}}_{f298} = -393.51 + 2(-241.82) - (-74.52) = -802.62\ \text{kJ/mol}$$

Burning one mole of methane releases 802.62 kJ. There is 3.76 mol of N_2 for one mole of O_2 in air. The heat released by the combustion reaction will only be used to heat the products of 1 mol of carbon dioxide, 2 mol of water vapor, and 7.52 mol of nitrogen:

$$\Delta H^{o}_{r298} = \int_{298.15}^{T} C_{p,\text{mix}}\text{d}T$$

Where n_i is the number of moles of component i, T is the maximum flame temperature in K.

$C_{p,\text{mix}} = \sum n_i C^{\text{o}}_{pi}$, estimated by

$$\frac{C^{o}_{pi}}{R} = A_i + B_i \times 10^{-3} T \text{ and } \frac{C^{o}_{p,\text{mix}}}{R} = A' + BA' \times 10^{-3}\, T$$

Heat capacities are from Table B1:

	CO_2	H_2O(g)	N_2
A	5.457	3.47	3.280
B 10^{-3}	1.045	1.450	0.593
n_i	1	2	7.52

$$A' = \sum_i n_i A_i = 5.457 + 2(3.47) + 7.52(3.280) = 37.06$$

$$B' = \sum_i n_i B_i\, [1.045 + 2(1.45) + 7.52(0.593)]10^{-3} = 8.40 \times 10^{-3}$$

$$802{,}620\,\text{J/mol} = R\int_{298.15}^{T} C^{o}_{p,mix} dT = 8.314[37.06(T - 298.15) + (1/2)8.40 \times 10^{-3}(T^2 - 298.15^2)]$$

***T* = 2309 K**

4.7 Air Pollution from Combustion Processes

Emissions from combustion of carbon fuels processes lead to air pollution. The main derivatives of the process are carbon dioxide CO_2, water, particulate matter, nitrogen oxides, sulfur oxides, and some uncombusted hydrocarbons, depending on the operating conditions and the fuel–air ratio. Not all of the fuel will be completely consumed by the combustion process; a small amount of fuel will be present after combustion, some of which can react to form oxygenates or hydrocarbons not initially present in the fuel mixture. Increasing the amount of air in the combustion process reduces the amount of the first two pollutants, but tends to increase nitrogen oxides (NO_x) that has been demonstrated to be hazardous to both plant and animal health. Further chemicals released are benzene and 1,3-butadiene that are also particularly harmful. When incomplete burning occurs carbon monoxide (CO) may also be produced [6, 8].

4.8 Heat of Mixing

Upon mixing of pure components, the thermodynamic properties change as shown by the symbol Δ. Figure 4.5 shows the heat of mixing and vapor-liquid equilibrium in ethanol-water mixture. Enthalpy of the mixture is composition dependent. As Fig. 4.5 shows that, at 197.2°F (isotherm), $H_{\text{sat liq}} \cong 155$ Btu/lb, while $H_{\text{sat vap}} \cong 775$ Btu/lb. When the ethanol mass fraction is $w_e = 0.4$ at 197.2°F, the enthalpy of mixture is around 600 Btu/lb. The property change of mixing is

$$\Delta H = H - \sum_i x_i H_i \tag{4.38}$$

The partial enthalpies are obtained from the following relationships

$$\Delta H_1 = \Delta H + (1 - x_1)\frac{\mathrm{d}\Delta H}{\mathrm{d}x_1} \tag{4.39}$$

$$\Delta H_2 = \Delta H - x_1\frac{\mathrm{d}\Delta H}{\mathrm{d}x_1} \tag{4.40}$$

Example 4.14 Estimation of partial enthalpies

The heat of mixing (excess enthalpy) for a binary mixture is $H = x_1x_2(2ax_1 + ax_2)$, where a is the parameter in J/mol, x_1 and x_2 are the mole fractions of components 1 and 2, respectively. Derive equations for the partial enthalpies of H_1 and H_2 in terms of x_1.

Solution:

The partial properties from Eqs. 4.35 and 4.36:

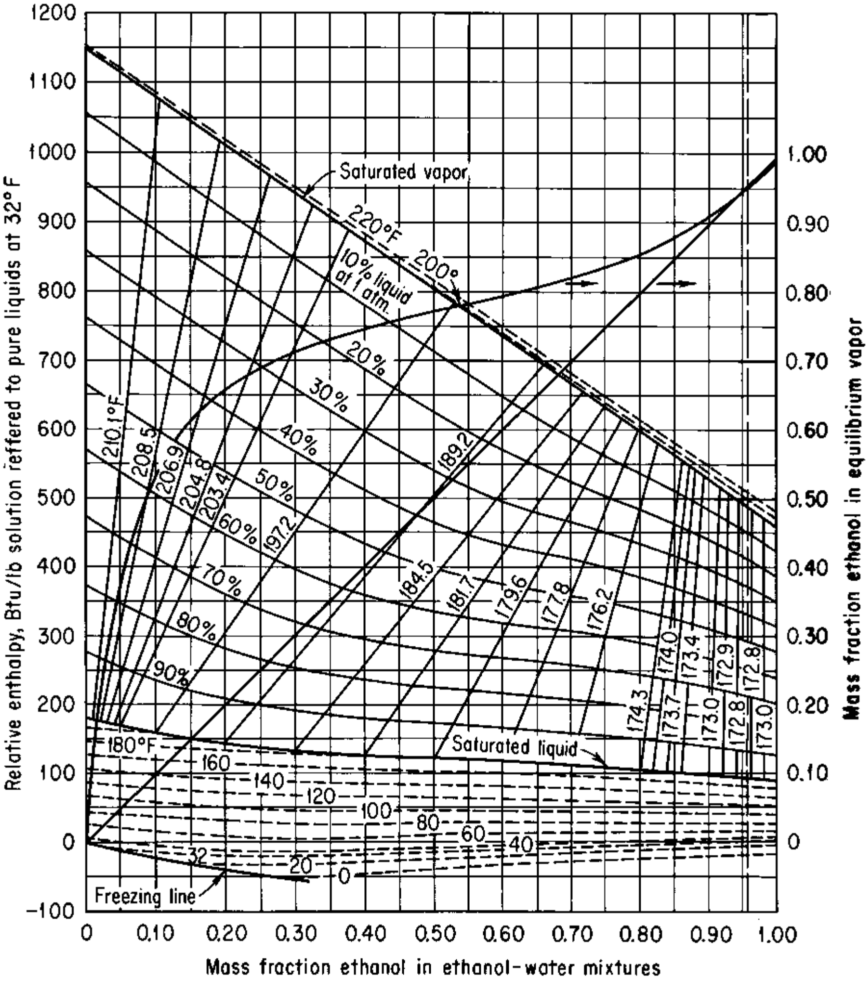


Fig. 4.5 Heat of mixing [5]

$$H_1 = H + (1 - x_1)\frac{\mathrm{d}H}{\mathrm{d}x_1}$$

$$H_2 = H - x_1\frac{\mathrm{d}H}{\mathrm{d}x_1}$$

With $\sum x_i = 1$: $x_2 = 1 - x_1$, and the equation for the heat of mixing H becomes: $H = ax_1 - ax_1^3$

The differentiation: $\frac{dH}{dx_1} = a - 3ax_1^2$

Therefore, the partial molar excess enthalpies:

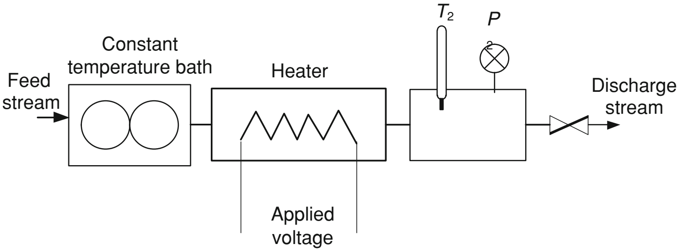


Fig. 4.6 Typical flow-calorimeter

$$H_1 = ax_1 - ax_1^3 + (1 - x_1)(a - 3ax_1^2) = a - 3ax_1^2 + 2ax_1^3$$

$$H_2 = ax_1 - ax_1^3 - x_1(a - 3ax_1^2) = 2ax_1^3$$

and

$$H = x_1H_1 + x_2H_2$$

4.9 Heat Measurements by Calorimeter

Only the energy change during transition of a system from one state into another can be defined and thus measured. Conventionally, this heat is measured by calorimeter. Figure 4.6 shows a typical flow-calorimeter in which the change of temperature is related to the electrical energy supplied through the heater. The heat lost by the system would be equal to the heat gained by the surroundings in an exothermic system. Similarly, heat gained by the system from the surroundings would be equal to heat lost by the surroundings in an endothermic process. In a typical calorimeter, a hot substance (the system) and its surroundings are allowed to reach equilibrium at some final temperature. The heat flows from the system (hot) to the surroundings (cold). The heat lost by the system must be equal to the heat gained by the surroundings if there is no heat loss from the surroundings. No calorimeter is perfectly insulating to heat loss. Once the calorimeter has been calibrated to determine the calorimeter constant, we can use it to determine the specific heat effect

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Example 4.15 Measurement of heat capacity of a metal in a calorimeter 28.2 g of an unknown metal is heated to 99.8°C and placed into a calorimeter containing 150.0 g of water at a temperature of 23.5°C. The temperature is allowed to equilibrate, and a final temperature is measured as 25°C. The calorimeter constant has been determined to be 19.2 J/°C. Estimate the specific heat capacity of the metal

Solution:
Heat transfer is represented by:
Heat lost by the hot metal = heat gained by the water + heat gained by the calorimeter

$$(28.2\ \text{g})(C_{p,m})(99.8 - 25.0)^\circ\text{C} = (150.0\ \text{g})(4.184\ \text{J/g}^\circ\text{C})(25.0 - 23.5)\ ^\circ\text{C} + 19.2\ \text{J}/^\circ\text{C}(25.0 - 23.5)\ ^\circ\text{C}$$

Solving for specific heat capacity:

$$C_{p,m} = 969\,\text{J}/(2.11 \times 10^3 g^\circ\text{C}) = \mathbf{0.459\,J/g^oC}$$

Metals tend to have low specific heat capacities, while water has a relatively high heat capacity.

A bomb calorimeter is a well-insulated tank containing a small combustion chamber in a water bath to measure the heat of combustion of a particular reaction. Bomb calorimeters have to withstand the large pressure within the calorimeter as the heat of reaction is being measured. Electrical energy is used to ignite the fuel. The energy released by the combustion raises the temperature of the steel bomb, its contents, and the surrounding water jacket. The temperature change in the water is then accurately measured. This temperature rise, along with a bomb calorimeter constant (which is dependent on the heat capacity of the metal bomb parts) is used to calculate the energy given out by the sample.

In a *differential scanning calorimeter*, conduction heat flows into a sample contained in a small aluminum capsule or a 'pan', and is measured by comparing it to the flow into an empty reference pan. The flow of heat into the sample is larger because of its heat capacity C_p of that sample. The difference in the heat flows induces a small temperature difference ΔT across the slab, which is measured using a thermocouple. Similarly, heat of melting of a sample substance can also be measured in such a calorimeter.

4.10 Psychrometric Diagram

Figure 4.7 shows a psychrometric diagram representing physical and thermal properties of moist air in a graphical form. Psychrometric diagrams help determining of environmental control concepts such as humidity of air and change of enthalpy resulting in condensation of the moisture.

- The *dry-bulb temperature* T_{db} is the ambient air temperature, which can be measured using a normal thermometer freely exposed to the air but shielded from radiation and moisture. The dry-bulb temperature appears as vertical lines in the psychrometric chart.

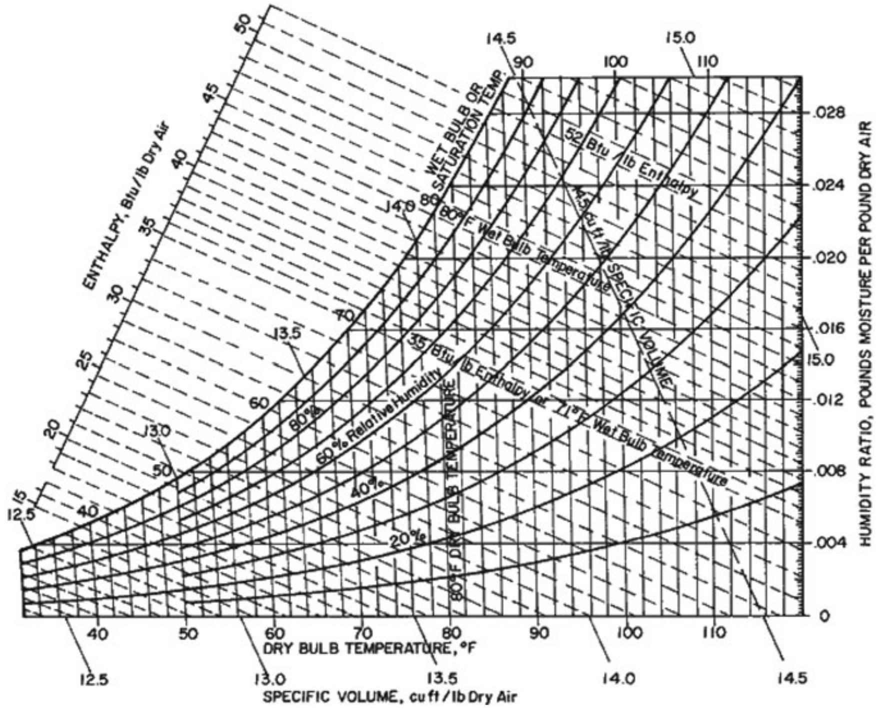


Fig. 4.7 Psychrometric diagram [2] with permission)

- The *wet-bulb temperature* T_{wb} is indicated by a moistened thermometer bulb exposed to the air flow. Wet-bulb temperature can be measured by using a thermometer with the bulb of thermometer wrapped in wet cloth. The adiabatic evaporation of water from the thermometer and the cooling effect is indicated by a "wet-bulb temperature" which is lower than the "dry bulb temperature" in the air.

The rate of evaporation from a wet bandage on the bulb depends on the humidity of the air. The evaporation is reduced when the air contains more water vapor. The wet-bulb temperature and the dry-bulb temperature are identical at 100% relative humidity of the air (the air humidity is at the saturation line). Combining the dry-bulb and wet-bulb temperature in a psychrometric diagram (also called Mollier diagram) determines the state of the humid air. Lines of constant wet-bulb temperatures run diagonally from the upper left to the lower right on the psychrometric diagram.

The *dew point* is the temperature at which water vapor starts to condense out of the air (the temperature at which air becomes completely saturated). Above this temperature the moisture will stay in the air. For example, if moisture condensates on a cold bottle taken from the refrigerator, the dew-point temperature of the air is above the temperature in the refrigerator. The dew point is given by the saturation line in the psychorometric diagram.

The Mollier diagram is a variant of the psychrometric diagram and graphic representation of the relationship between air temperature, moisture content, and enthalpy. The Mollier diagram is a basic design tool for engineers and designers [2]. Figure 4.8 shows the Mollier diagram.

Example 4.16 Determination of air properties on a psychrometric chart

For a dry-bulb temperature of 74°F and a wet-bulb temperature of 67°F:

(a) Estimate the air properties and its enthalpy.

(b) Estimate the heat to be added if the air is heated to 84°F dry-bulb temperature at constant humidity ratio.

(c) Estimate the dry-bulb temperature for an evaporative cooling starting from the state point reached in part (b).

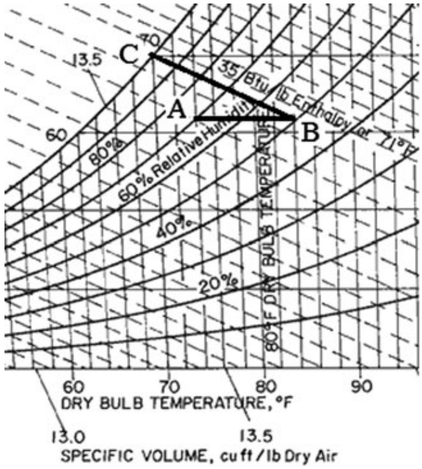
Solution:

(a) Find the intersection (A) of the dry-bulb temperature of 74°F and wet-bulb temperature of 67°F on the psychrometric chart as shown on the figure below. This intersection (A) is a "state point" for the air.

We read relative humidity as 70% and dew point temperature as approximately 63.2°F (follow horizontal line, moving left, toward the curved upper boundary of saturation temperatures). The enthalpy is 31.7 Btu/lb dry air.

(b) The heating process moves horizontally to the right along a line of constant humidity ratio (B), and we read the enthalpy as approximately 34.2 Btu/lb Dry air and the relative humidity as 50%.

The heat necessary: q = (34.2 – 31.7) Btu/lb dry air = 2.5 Btu/lb dry air.



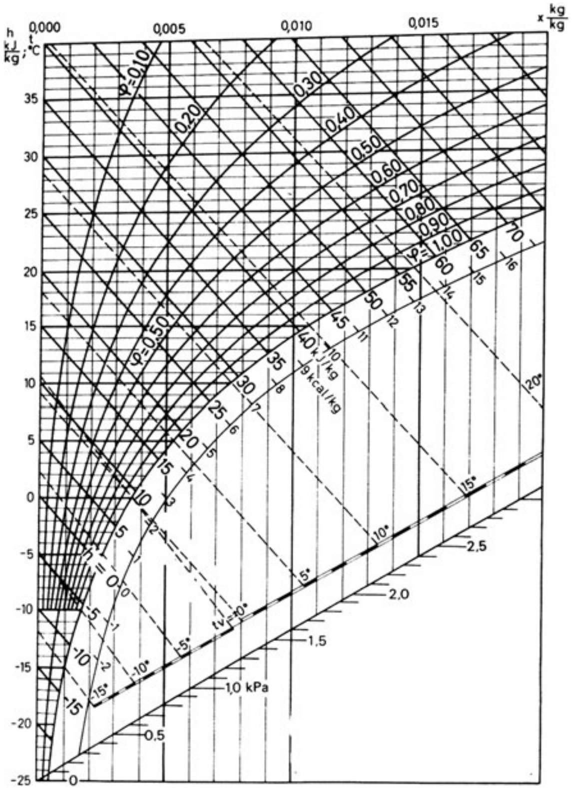


Fig. 4.8 The Mollier diagram. The Mollier diagram is a variant of the psychrometric diagram and graphic representation of the relationship between air temperature, moisture content and enthalpy (ETB [2] with permission)

(c) During the evaporative cooling heat contained in the air evaporates water. The process moves upward along the line of constant enthalpy or constant web-bulb temperature. Air temperature (dry-bulb) drops to 70°F while water content (humidity) rises to the saturation point (C) with a relative humidity of 100%. Evaporation is often used in hot weather to cool ventilation air.

4.11 Heat Transfer

During the transfer of energy in the form of work, some energy involved may be dissipated as heat. Heat and work are the two mechanisms by which energy can be transferred. Work performed on a body is, by definition, an energy transfer to the body that is due to a change to external parameters of the body, such as the volume, magnetization, and center of mass in a gravitational field. Heat is the energy transferred to the body in any other way.

Heat is transferred by conduction, convection, and radiation. The heat transfer by conduction is based on direct molecular contact, most commonly in solids, while the convection is based on moving particles of liquids and gases. The heat

Table 4.6 Thermal conductivities and heat capacities of some gases(at 1 atm), liquids and solids

Substance	T (K)	k (W/m K)
Gases		
Hydrogen, H_2	300	0.1779
Oxygen, O_2	300	0.0265
Carbon dioxide, CO_2	300	0.0166
Methane, CH_4	300	0.0342
NO	300	0.0259
Liquids		
Water, H_2O	300	0.6089
	350	0.6622
Ethanol, C_2H_5OH	300	0.1676
Carbon tetrachloride, CCl_4	350	0.0893
Acetone, $(CH_3)_2CO$	300	0.1274
Mercury, Hg	372.2	10.50
Solids		
Lead, Pb	977.2	15.1
Aluminum, Al	373.2	205.9
Copper, Cu	291.2	384.1
Cast iron, Fe	373.2	51.9
Steel	291.2	46.9
Silver	373.2	411.9

(Bird et al. [1]; Griskey [4])

transfer by radiation is based on the emission of electromagnetic waves from warm bodies to their surroundings.

Rate of heat transfer by conduction is estimated by

$$\dot{q} = -kA\frac{(T_2 - T_1)}{\Delta x} \tag{4.41}$$

where $\dot{q}$ is the rate of heat transfer, J/s (Watt, W) or Btu/h, k is the thermal conductivity in J/m s °C or Btu/ft s °F, A is the area for heat transfer, $(T_2 - T_1)$ is the temperature difference between state 2 and state 1, and Δx is the distance. As the heat flows from high to low temperature the value of $(T_2 - T_1)$ is negative. The values of thermal conductivity for various substances are tabulated in Table A1. Table 4.6 shows the thermal conductivities and heat capacities of some gases at 1 atm and some liquids and solids.

Rate of heat transfer by convection is estimated by

$$\dot{q} = hA(T_2 - T_1) \tag{4.42}$$

where h is the heat transfer coefficient in J/m^2 s °C or Btu/ft^2 s °F, and. *Heat flux*, $\dot{q}/A$, is the rate of heat transfer per unit cross-sectional area.

All bodies radiate energy in the form of photons moving in a random direction and frequency. When photons reach another surface, they may either be absorbed, reflected or transmitted:

α = absorptance—fraction of incident radiation absorbed
τ = transmittance—fraction of incident radiation transmitted
ρ = reflectance—fraction of incident radiation reflected

From energy considerations, the three coefficients must sum to unity: $\alpha + \tau + \rho = 1$. Real bodies radiate less effectively than black bodies. The measurement of this is the emittance ε defined by

$$\varepsilon = \frac{E}{E_b} \tag{4.43}$$

where E is radiation from the real body, and E_b is radiation from a black body at temperature T. Values of emittance are near unity for rough surfaces such as ceramics or oxidized metals, and roughly 0.02 for polished metals or silvered reflectors. The energy radiated per unit area of a black body is estimated by: $E_b = \sigma T^4$ where σ is the Stefan–Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W/m^2 K^4. The level of emittance can be related to absorptance by

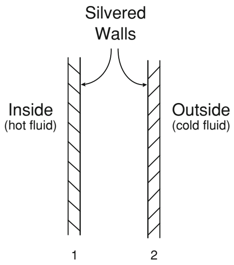
$$\frac{E}{E_b} = \varepsilon = \alpha \tag{4.44}$$

The relation $\varepsilon = \alpha$ is known as Kirchhoff's Law. It implies that good radiators are good absorbers. Heat transfer between gray and planar surfaces is estimated by

$$\dot{q} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \tag{4.45}$$

Example 4.17 Estimation of radiation heat transfer

Use a thermos bottle to estimate the heat transfer between thermos silver walls. The temperature of silver wall is T_1 = 100°C = 373 K and the surroundings temperature is T_2 = 20°C = 293 K. The values of the emittances are $\varepsilon_1 = \varepsilon_2 = 0.02$.



Solution:

The Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W/m^2 K^4,
T_1 = 100°C = 373 K, T_2 = 20°C = 293.15 K, and $\varepsilon_1 = \varepsilon_2 = 0.02$.

From Eq. 4.45: $\dot{q} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} = \mathbf{6.9\,W/m^2}$

The thermos is a good insulator as the heat transfer is very small from the hot wall to cold wall.

4.12 Entropy

Entropy change is determined by the following equation

$$\mathrm{d}S = \frac{\delta q_{\mathrm{rev}}}{T} \tag{4.46}$$

where δq_{rev} is the reversible heat flow. In an integrated form, the reversible change of heat flow is estimated by

$$q_{\mathrm{rev}} = T\Delta S \tag{4.47}$$

When a fluid system changes from state A to state B by an irreversible process, then the change of its entropy is $\Delta S = S_B - S_A$. Some important properties of entropy are:

- Entropy is a state function and an extensive property.
- $dS \geq q/T$: the inequality is for a natural (irreversible) change, while the equality is for a reversible change.
- The total change of entropy is expressed by: $\Delta S = \Delta S_{\mathrm{boundary}} + \Delta S_{\mathrm{internal}}$, where $\Delta S_{\mathrm{boundary}}$ is the change due to the interaction of a system with its surroundings, and $\Delta S_{\mathrm{internal}}$ is the increase due to a natural change within the system, such as a chemical reaction, and is always positive for irreversible changes and zero at equilibrium.
- The entropy of a system is the sum of the entropies of all changes within the system.
- The entropy of an insulated closed system remains constant in any reversible change, increases in any natural change, and reaches a maximum at equilibrium.
- Entropy remains constant for any reversible adiabatic change so that $\Delta S = 0$.
- For any complete cycle, the change of entropy is zero.

The change of entropy in terms of temperature and pressure is estimated by

$$\mathrm{d}S = \left(\frac{\partial S}{\partial T}\right)_P \mathrm{d}T + \left(\frac{\partial S}{\partial P}\right)_T \mathrm{d}P = C_p \frac{\mathrm{d}T}{T} - \left(\frac{\partial V}{\partial T}\right)_P \mathrm{d}P \tag{4.48}$$

For ideal gases ($PV = RT$, and $dV/dT = R/P$), Eq. 4.48 becomes

$$\mathrm{d}S = C_p \frac{\mathrm{d}T}{T} - R\frac{\mathrm{d}P}{P} \tag{4.49}$$

The change of entropy of an ideal gas may be estimated by integration of Eq. 4.49 using a constant heat capacity $C_{p,av}$

$$\Delta S = \int_1^2 C_{p,av}\frac{dT}{T} - R\ln\frac{P_2}{P_1} = C_{p,av}\ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right) \tag{4.50}$$

For incompressible fluids, Eq. 4.49 becomes

$$dS = C_{p,av}\frac{dT}{T} \tag{4.51}$$

Energy exchange accompanied by entropy transfer is the heat transfer, and energy exchange that is not accompanied by entropy transfer is the work transfer.

4.13 Exergy

An energy source comes with its amount of energy, and its work potential that is the useful energy. Amount and quality of energy in a source can be distinguished by the concept of exergy, *Ex*. Exergy is the maximum amount of work theoretically available by bringing a resource into equilibrium with its surrounding through a reversible process. Exergy is also known as availability. Quality of energy is the ability to produce work under the conditions determined by the *natural environment* called *the reference state*. The temperature and pressure of the natural environment are usually the standard-state values, such as 298.15 K and 101.31 kPa.

The work done during a process depends on the initial state, final state, and the process path chosen between these initial and final states. The initial state is not a variable in an exergy analysis. In the final state, a process reaches thermodynamic equilibrium with the environment and the system's temperature and pressure become the same with the values of temperature and pressure of the environment. So the system has no kinetic and potential energy relative to the environment. The work output is maximized when the process takes place between the initial and final states in a reversible manner. In practical processes, this means that work output is maximized when the process proceeds through a path with the lowest possible *entropy production* between the initial and final states.

Kinetic and potential energies can be converted to work completely. Therefore, exergy of the kinetic energy and potential energy of a system are equal to the kinetic energy and potential energy

$$\Delta Ex_{\mathrm{KE}} = m\frac{\Delta v^2}{2} \tag{4.52}$$

$$\Delta Ex_{\mathrm{PE}} = mg\Delta z \tag{4.53}$$

However, the enthalpy *H* and internal energy *U* of a system are not completely available. The exergy change of a closed system during a process is

$$\Delta Ex = \Delta H - T_o\Delta S \tag{4.54}$$

Here the Δ denotes the difference between the initial and final state (reference state), and T_{o} is the reference temperature. The fluid-flow exergy is

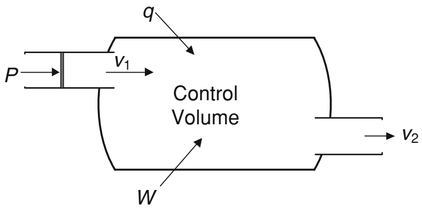


Fig. 4.9 Fluid flow with heat and work interactions between the control volume and surroundings: $\dot{m}\left(\Delta H + \frac{\Delta v^2}{2} + g\Delta z\right) = \dot{q} + \dot{W}_s$ at constant pressure

$$\dot{E}x = \dot{m}\left((H - H_o) - T_o(S - S_o) + \frac{\Delta v^2}{2} + g\Delta z\right) \tag{4.55}$$

Exergy change of a fluid flow in an open system is given by

$$\Delta\dot{E}x = \dot{m}\left(\Delta H - T_o\Delta S + \frac{\Delta v^2}{2} + g\Delta z\right) \tag{4.56}$$

Here, as before, the dot over a symbol indicates a quantity per unit time. If the changes in kinetic and potential energy are neglected then Eq. 4.56 becomes

$$\Delta\dot{E}x = \dot{m}(\Delta H - T_o\Delta S) \tag{4.57}$$

Heat (especially at low temperature) is much lower in exergy due to its low efficiency in its conversion to other forms of energy. The useful (available) work content of the heat is limited by the Carnot factor, η_{Carnot}; therefore, the available heat $q_{\text{available}}$ becomes

$$Ex_{\text{heat}} = q_{\text{available}} = q\eta_{\text{Carnot}} = q\left(1 - \frac{T_C}{T_H}\right) \tag{4.58}$$

where T_H and T_C are the temperatures for the hot and cold regions, respectively. Equation 4.58 means that a power generator based on heat cannot have efficiency greater than that of a Carnot cycle working between the hot source with T_{H} and cold source with T_{C}. It is possible to increase or lower exergy as exergy is not a conserved property.

4.14 Fluid-Flow Work

Open systems involve mass flows across their boundaries. The work required to maintain a continuous flow into or out of the control volume is called the fluid-flow work. If the fluid pressure is P and the cross-sectional area is A as seen in Fig. 4.9, the force applied on the fluid element becomes

$$F = PA \tag{4.59}$$

When the force acts through a distance L, the fluid-flow work becomes

$$W_f = FL = PAL = PV \tag{4.60}$$

In most practical processes, flow can be approximated as steady state and one-dimensional, then the total energy of a fluid, E_{fluid}, entering or leaving a system at steady state is estimated by

$$\dot{E}_{\text{fluid}} = \dot{m}\left(\Delta U + PV + \frac{\Delta v^2}{2} + g\Delta z\right) \tag{4.61}$$

The dot over a symbol indicates a quantity per unit time. After the combination of $U + PV$ as enthalpy H, as given by Eq. 4.7

$$\Delta H = \Delta U + PV$$

Equation 4.61 becomes

$$\dot{E}_{\text{fluid}} = \dot{m}\left(\Delta H + \frac{\Delta v^2}{2} + g\Delta z\right) \tag{4.62}$$

For fluid-flow systems, enthalpy rather than the internal energy is important in engineering since the fluid-flow work is taken into account within the enthalpy. The general relation between the heat and work for a fluid flow is estimated by

$$\dot{m}\left(\Delta H + \frac{\Delta v^2}{2} + g\Delta z\right) = \dot{q} + \dot{W}_s \tag{4.63}$$

Problems

4.1. Determine the states of the system containing water under the following conditions by using the steam tables.

T (°C)	P (kPa)	H_{vap} (kJ/kg)	U_{vap} (kJ/kg)	State
175	30	2,830.0	2,623.6	
45.83	10	2,584.8	2,438.0	
450	2,400	3,352.6	3,027.1	
100	98	2,676.0	2,506.5	

4.2. Determine the states of the system containing water under the following conditions by using the steam tables.

T (°F)	P (psia)	H_{vap} (Btu/lb)	U_{vap} (Btu/lb)	State
164	5.99	1,134.2	1,065.4	
500	20	1,286.9	1,181.6	
600	1,000	1,517.4	1,360.9	
331.37	105	1,188.0	1,105.8	

4.3. Determine the states of the system containing water under the following conditions by using the steam tables.

T (°C)	*P* (kPa)	*V* (m^3/kg)	$H_{\text{sat vap}}$ (kJ/kg)	State
60	19.92	5.50	2,609.7	
110	143.27	1.21	2,691.3	
340	8,200	0.0280	–	
40	47.36	0.001	–	

4.4. Determine the states of the system containing water under the following conditions by using the steam tables.

T (°C)	*P* (kPa)	*x*	*H* (kJ/kg)	State
120.2	200	0.7	2,045.8	
80	47.36	1	2,643.8	
150	476	0	632.1	
325	500	–	3,116.4	

4.5. Determine the states of the system containing refrigerant-134a under the following conditions.

T (°F)	*P* (psia)	*H* (Btu/lbm)	State
-10	16.67	95.0	
5	23.8	102.47	
30	40.78	20.87	
60	70	110.23	

4.6. Determine the states of the system containing water under the following conditions by using the steam tables.

T (°C)	*P* (kPa)	*V* (m^3/kg)	*U* (kJ/kg)	State
133.5	300	0.50	2,196.4	
300	725	0.358	2,799.3	
400	6,500	0.043	2,888.9	
211.1	1,950	0.001	900,46	

4.7. Determine the missing property values in the table below for a system that contains water.

P (kPa)	*V* (m^3/kg)	*U* (kJ/kg)	*H* (kJ/kg)	*x* (kg vap/kg tot)	State
9.1		2250			
200				0.85	

4.8. Determine the missing property values in the table below for a system that contains pure R-134a.

T (°C)	P (kPa)	V (m^3/kg)	U (kJ/kg)	H (kJ/kg)	x
30	836				
-45			204.51		
	300	0.054			
	1,124			244.0	
65	1,550				

4.9. A 50 kg block of copper (Cu) at 0°C and a 100 kg block of iron (Fe) at 200°C are brought into contact in an insulated space. Predict the final equilibrium temperature.

4.10. Estimate the internal energy and enthalpy of 100 lb of water at 220 psia and 500 °F.

4.11. A rigid tank contains 500 lb of saturated steam at 230°F. Estimate the internal energy and enthalpy.

4.12. Determine the specific internal energy of 100 L of hydrogen gas at 600 K and 1 atm. The hydrogen gas has a total enthalpy of 19416 J. Assume that the hydrogen gas is an ideal gas.

4.13. Calculate the change in internal energy when 0.75 m^3 of air at 200 kPa is heated from 20 to 250°C in a constant volume process.

4.14. Calculate the change in internal energy when 15 m^3 of air at 110 kPa is heated from 30 to 400°C in a constant volume process.

4.15. Calculate the change in internal energy when 1.5 m^3 of air at 275 kPa is cooled from 150 to 20°C in a constant volume process.

4.16. Calculate the change in internal energy when 10 m^3 of air at 150 kPa is cooled from 300 to 50°C in a constant volume process.

4.17. Calculate the change in internal energy when 25.1 m^3 of carbon dioxide at 250 kPa is heated from 30 to 350°C in a constant volume process.

4.18. Calculate the change in internal energy when 100 m^3 of carbon dioxide at 150 kPa is heated from 0 to 500°C in a constant volume process.

4.19. Calculate the change in internal energy when 5 m^3 of carbon dioxide at 250 kPa is cooled from 270 to 20°C in a constant volume process.

4.20. Calculate the change in internal energy when 52.8 m^3 of nitrogen at 200 kPa is heated from 15 to 700°C in a constant volume process.

4.21. Calculate the change in internal energy when 0.92 m^3 of nitrogen at 200 kPa is cooled from 300 to 30°C in a constant volume process.

4.22. Calculate the change in internal energy when 32.5 ft^3 of nitrogen at 20 psia is heated from 75 to 300°F in a constant volume process.

4.23. Superheated water vapor at 400°C expands isothermally in a piston-and-cylinder device from 1350 to 770 kPa. Calculate the change in the molar enthalpy and molar internal energy in units of kJ/mol.

4.24. One mole of gas is undergoing an expansion processes, in which it expands from 0.03 to 0.06 m^3 at constant pressure of 2 atm. Estimate the change in internal energy if $C_{v,av}$ = 12.5 J/mol K.

4.25. A one mole of gas at 300 K expands from 0.03 to 0.06 m^3 at constant temperature. Estimate the change in internal energy of the gas.

4.26. A large rigid tank contains 70 kg of water at 80°C. If 14 kg of the water is in the liquid state estimate the pressure and enthalpy of the water in the tank.

4.27. A large rigid tank contains 40 lb of water at 200°F. If 2.8 lb of the water is in the liquid state estimate the internal energy and enthalpy of the water in the tank.

4.28. A rigid tank is filled with 0.5 lb of refrigerant-134a at T = 79.2°F. If 0.06 lb of the refrigerant is in the liquid state estimate the internal energy and enthalpy of the refrigerant.

4.29. Heat capacity of toluene in Btu/lbmol °F is given by $C_p = 20.869 + 5.293 \times 10^{-2}\,T$. Estimate the heat capacity in cal/gmol K and estimate the heat necessary if 400 g toluene is heated from 17°C to 48°C.

4.30. Determine the enthalpy change and internal energy change of ammonia in J/gmol, as it is heated from 30 to 150°C, using the ideal gas heat capacity given by the following equation: $C_p^{ig} = R(3.578 + 3.02 \times 10^{-3}\,T)$ T in K (Table B1)

4.31. Determine the enthalpy change and internal energy change of air in kJ/kg, as it is heated from 300 to 750 K, using the following equation for C_p. $C_p^{ig} = R(3.355 + 0.575 \times 10^{-3}\,T)$ T in K (Table B1)

4.32. An ideal gases mixture of carbon dioxide (CO_2), nitrogen (N_2), and Oxygen (O_2) at 200 kPa and 300°C contains 10 mole% CO_2, 60 mole% N_2, and 30 mole% O_2. The mixture is heated to 600°C. Calculate the change in the molar internal energy of the mixture.

4.33. 12 kg of benzene is heated from a subcooled liquid at P_1 = 100 kPa and T_1 = 300 K to a superheated vapor at T_2 = 450 K and P_2 = 100 kPa. The heating process is at constant pressure. Calculate the total enthalpy, ΔH, in kJ/kg. Assume the n-heptane vapor behave as an ideal gas and a constant heat capacity of 85.29 J/gmol K. Use the Antoine and Clausius-Clapeyron equations to estimate the heat of vaporization of n-heptane at T_1.

4.34. Water is heated from a subcooled liquid at P_1 = 200 kPa and T_1 = 300 K to a superheated vapor at P_2 = 2400 kPa and T_2 = 573 K. Calculate the molar ΔH for each step in the path in kJ/kg.

4.35. Water is cooled from a superheated vapor at P_1 = 250 psia and T_1 = 460°F to a subcooled liquid at P_2 = 15 psia and T_2 = 140°F. Calculate the molar ΔH for each step in the path in Btu/lb.

4.36. In a steady-state flow heating process, 50 k mol of methanol is heated from subcooled liquid at 300 K and 3 bar to superheated state at 500 kPa. Estimate the heat flow rate for the process. The saturation temperature for methanol at 3 bar is 368.0 K.

4.37. A one mole of gas at 300 K expands from 0.03 to 0.06 m^3 at adiabatic conditions. Estimate the change in internal energy of the gas. $C_{v.av}$ = 12.5 J/mol K

4.38. A piston-and-cylinder device contains 0.3 kg refrigerant R-134a vapor at 12°C. This vapor is expanded in an internally reversible, adiabatic process until the temperature is −3°C. Determine the work for this process. The constant heat capacity of refrigerant-134a is $C_{v,av}$ = 1.7 kJ/kg °C.

4.39. A piston-and-cylinder device contains 0.5 kg nitrogen at 30°C. The nitrogen is compressed in an internally reversible, adiabatic process until the temperature is 42°C. Determine the work for this process. The ratio of constant heat capacities $\gamma = C_p/C_v = 1.4$ for the nitrogen.

4.40. Ten kmoles of hydrogen are heated from 25 to 275°C. Estimate the change in enthalpy in kJ.

4.41. Fifty kg of hydrogen is heated from −10 to 100°C. Estimate the change in enthalpy in kJ.

4.42. Twenty five kg of hydrogen are cooled from 20 to −50°C. Estimate the change in enthalpy ΔH in Btu.

4.43. Ten kg of carbon dioxide is heated from 30 to 300°C in a steady state flow process at a pressure sufficiently low that the carbon dioxide may be considered as an ideal gas. (a) Estimate the value of the heat required, (b) Estimate the average heat capacity in J/gmol K for the process.

4.44. The molar heat capacity of propane gas in ideal-gas state is given as a function of temperature in Kelvin: $C_p^{ig}/R = 1.213 + 28.785 \times 10^{-3}\,T - 8.824\,T \times 10^{-6}$ (Table B1)

Convert this equation to an equation for C_p for temperature in °C.

4.45. The molar heat capacity of methane gas in ideal-gas state is given as s function of temperature in Kelvin: $C_p^{ig}/R = 1.702 + 9.082 \times 10^{-3}\,T - 2.164\,T \times 10^{-6}$ (from Table B1)

Convert this equation to an equation for C_p in J/g °C.

4.46. The molar heat capacity of methane gas in ideal-gas state is given as s function of temperature in Kelvin: $C_p^{ig}/R = 1.702 + 9.082 \times 10^{-3}\,T - 2.164\,T \times 10^{-6}$ (from Table B1)

Convert this equation to an equation for C_p in J/g °C.

4.47. Ten kg of water at 25°C in a closed vessel of 0.5 m^3 in volume is heated to 120°C and 1,000 kPa. Estimate the change of enthalpy and the final quality of the steam in the vessel.

4.48. Twenty two kg of water at 25°C in a closed vessel of 2.6 m^3 in volume is heated to 120°C and 1,000 kPa. Estimate the change of enthalpy and the quality of the steam in the vessel.

4.49. Estimate the enthalpy of a 10 lb steam at 120 psia with a quality of 27%.

4.50. Calculate the change in enthalpy when 150 lb of nitrogen at 25 psia is heated from 50 to 700°F in a constant pressure process. The heat capacity in Btu/lbmol °F is

$$C_p^{ig} = 6.895 + 0.7624 \times 10^{-3} T - 0.7009 \times 10^{-7} T^2$$

4.51. Calculate the change in enthalpy when 200 lb of nitrogen at 20 psia is cooled from 500 to 100°F in a constant pressure process.The heat capacity in Btu/lbmol °F is

$$C_p^{ig} = 6.895 + 0.7624 \times 10^{-3} T - 0.7009 \times 10^{-7} T^2$$

4.52. Calculate the change in enthalpy when 500 lb of oxygen at 20 psia is heated from 60 to 450°F in a constant pressure process. The heat capacity in Btu/lbmol °F is

$$C_p^{ig} = 6.895 + 0.7624 \times 10^{-3} T - 0.7009 \times 10^{-7} T^2.$$

4.53. Calculate the change in enthalpy when 265 ft^3 of carbon dioxide at 20 psia is heated from 80 to 360°F in a constant pressure process. The heat capacity in Btu/lbmol °F is

$$C_p^{ig} = 8.448 + 5.757 \times 10^{-3} T - 21.59 \times 10^{-7} T^2$$

4.54. Calculate the change in enthalpy when 1150 ft^3 of carbon monoxide at 20 psia is cooled from 250 to 75°F in a constant pressure process. The heat capacity in Btu/lbmol °F is

$$C_p^{ig} = 6.865 + 0.8024 \times 10^{-3} T - 0.7367 \times 10^{-7} T^2$$

4.55. Calculate the change in enthalpy when 500 lb of carbon monoxide at 20 psia is heated from 50 to 290°F in a constant pressure process. The heat capacity in Btu/lbmol °F is

$$C_p^{ig} = 6.865 + 0.8024 \times 10^{-3} T - 0.7367 \times 10^{-7} T^2$$

4.56. Ten kg of carbon dioxide at 50°C and 1 atm is heated to 200°C at constant pressure. Carbon dioxide is assumed to be an ideal gas. Estimate the changes in internal energy and enthalpy.

4.57. A 50 ft^3 rigid tank is filled with saturated vapor at 150 psia. The steam is cooled as the heat is transferred from the tank and the final pressure of the steam drops to 20 psia. Estimate: (a) the mass of the steam that has condensed, (b) the final temperature of the steam, and (c) the amount of heat transferred from the steam.

4.58. A piston-and-cylinder device contains R-134a which is initially at −10°C and 200 kPa. The R-134a undergoes a isochoric heating to 80°C. Estimate the work in kJ/kg.

4.59. The primary energy source for cells is the aerobic oxidation of sugar called glucose ($C_6H_{12}O_6$). Estimate standard heat of reaction for the oxidation of glucose:

$C_6H_{12}O_6(s) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(g)$

4.60. Synthesis gas is a mixture of H_2 and CO. One of the uses of synthesis gas is to produce methanol from the following reaction: $CO(g) + 2H_2(g) \rightarrow CH_3OH(g)$

Estimate the standard heat of reaction.

4.61. Determine the standard heats of a reaction at 298.15 K for the reactions below:

(a) $N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$

(b) $CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$

4.62. Estimate the heat of reaction for the combustion of propane:

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(g)$$

4.63. Estimate the heat of reaction for the combustion of ethane:

$$C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2(g) + 3H_2O(g)$$

4.64. Estimate the heat of reaction for the combustion of methane:

$$CH_4 + 2O_2 \rightarrow CO_2(g) + 2H_2O(g)$$

4.65. Nitric acid (HNO_3) is produced by the oxidation of ammonia. Estimate the standard heat of reaction: $NH_3 + 2O_2 \rightarrow HNO_3 + H_2O$

4.66. Estimate the maximum temperature that can be reached by the combustion of methane with air at constant pressure. Both the methane and air enter the combustion chamber at 25°C and 1 atm. The combustion reaction is: $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$

4.67. Find the heat of reaction and determine whether the process is exothermic or endothermic for the following chemical reaction: $16H_2S(g) + 8SO_2(g) \rightarrow 16H_2O(l) + 3S_8(s)$.

4.68. Heating value of a fuel vary if the water produced is in the vapor state or liquid state. The higher heating value (HHV) of a fuel is its standard heat of combustion when the water product is liquid; the lower heating value when the water product is vapor. Estimate the HHV and the LHV for natural gas represented by pure methanol: $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$.

4.69. Estimate the HHV and the LHV for heating oil represented by pure n-decane. As liquid n-decane heat of formation is −249.7 kJ/mol: $C_{10}H_{22}(l) + 15.5O_2(g) \rightarrow 10CO_2(g) + 11H_2O(g)$.

4.70. What is the standard heat of combustion at 25°C of C_6H_{12} (g) when the reaction products are $CO_2(g)$ and $H_2O(g)$?

$C_6H_{12}(g) + 9O_2 \rightarrow 6CO_2(g) + 6H_2O(g)$

4.71. What is the standard heat of combustion at 25°C of $6CH_3OH$ when the reaction products are $CO_2(g)$ and $H_2O(g)$? The reaction is: $6CH_3OH(g) + 9O_2 \rightarrow 6CO_2(g) + 12H_2O(g)$.

4.72. Estimate the standard heat of combustion of n-pentane gas at 25°C when the combustion products are $CO_2(g)$ and $H_2O(l)$: $C_5H_{12}(g) + 8O_2(g) \rightarrow 5CO_2(g) + 6H_2O(l)$.

4.73. Estimate the standard heat of reaction of following reactions at 25°C.
(a) $4NH_3(g) + 5O_2(g) = 4NO(g) + 6H_2O(g)$
(b) $C_2H_4(g) + 1/2O_2(g) = 2(CH_2)O(g)$
(c) $CH_3OH(g) + 1/2O_2(g) = HCHO(g) + H2O(g)$
(d) $C_2H_5OH(l) + O_2(g) = CH3COOH(l) + H2(g)$

4.74. A heating oil with an average chemical composition of $C_{10}H_{18}$ is burned with oxygen completely in a bomb calorimeter. The heat released is measured as 43,900 J/g at 25°C. The combustion on the calorimeter takes place at constant volume and produces liquid water. Estimate the standard heat of reaction of the oil at 25°C when the products are (g) H_2O and CO_2 (g).

4.75. Derive the following isentropic relation for ideal gases with constant specific heats.

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$$

4.76. A piston and cylinder device with a free-floating piston has an initial volume of 0.1 m^3 and contains 0.6 kg of steam at 400 kPa. Heat is transferred into the steam until the temperature reaches 300°C while the pressure remains constant. Determine the heat and work transfer.

4.77. 1 kg Superheated steam in a piston-cylinder system is initially at 200°C and 1300 kPa. The steam is cooled at constant pressure until the half of the mass condenses. Estimate the final temperature and the volume change.

4.78. 1.21 lb Superheated refrigerant-134a is initially at 150°F and 140 psia. The refrigerant is cooled to 5°F at constant pressure until it exists as compressed liquid. Estimate the changes in internal energy and total volume.

4.79. Refrigerant-134a with a flow rate of 0.12 kg/s is cooled to 40°C at constant pressure in a condenser by using cooling water. Initially, the refrigerant is at 1,200 kPa and 50°C. Estimate the heat removed by the cooling water.

4.80. Air with a flow rate of 500 ft^3/s is heated from 100 to 910°F at approximately atmospheric pressure for a combustion process. What is the rate of heat transfer required?

4.81. An oven wall is made of 6 inch thick forebrick. If the interior of the wall is at 1550°F and the exterior of the wall is at 350°F, estimate the heat loss per hour. The thermal conductivity of the forebrick is 0.81 Btu/hr °F ft and assumed remain constant.

4.82. Estimate the thickness (Δx) needed for a cork insulation with $k = 0.04$ J/m s K when the heat transfer is 13.8 W/m^2 between the walls with temperatures T_1 = 100°C and T_2 = 20°C.

4.83. A resistance heater within a well-insulated tank is used to heat 0.8 kg of water. The heater passes a current of 0.2 Ampere (A) for 30 min from a 120-V source. The water in the tank is originally at 25°C. Estimate the temperature of the water after 30 min of heating.

4.84. A resistance heater within a well-insulated tank is used to heat 4 kg of water. The heater passes a current of 0.2 Ampere (A) from a 120-V source. The water in the tank is originally at 20°C. Estimate the time necessary for the temperature of the water to reach 45°C.

4.85. A resistance heater within a tank is used to heat water. The heater passes a current of 0.4 Ampere (A) for 2 h from a 120-V source. A heat loss of 8.7 kW occurs from the tank to surroundings. Estimate the amount of heat transfer to the water after 2 h of heating.

4.86. A resistance heater within a tank is used to heat 150 kg water. The heater passes a current of 0.6 Ampere (A) for 8 h from a 120-V source. A heat loss of 38.2 kW occurs from the tank to surroundings. The water in the tank is originally at 5°C. Estimate the amount of heat transfer to the water after 8 h of heating.

4.87. A resistance heater within a well-insulated room is used to heat the inside air. The heater passes a current of 2 Ampere (A) from a 120-V source. Estimate the amount of heat transfer to the air after 1 h of heating.

4.88. A resistance heater within a well-insulated room is used to heat the inside air. The heater passes a current of 2 Ampere (A) for 3 h from a 120-V source. Estimate the amount of heat transfer to the air after 3 h of heating.

4.89. A resistance heater within a well-insulated room is used to heat the inside air. The heater passes a current of 0.8 Ampere (A) for 2 h from a 120-V source. The heat loss from the room is 29.0 kJ. Estimate the amount of heat transfer to the air after 2 h of heating.

4.90. A wall of an oven is made of 10 in thick brick. If the interior wall of the oven is at 2,000°F and the exterior of the wall is at 70°F estimate the heat loss per hour. The average value of the thermal conductivity of the brick is 0.81 Btu/hr ft °F.

4.91. A vertical plate receives solar radiation of 1000 W/m^2. The plate is insulated at the back and loses heat by convection heat transfer through the air flow. The heat transfer coefficient is 35 W/m^2 K and the air temperature is 22°C. The absorptivity of the surface α is 0.6. Estimate the surface temperature of the plate.

4.92. An insulated frame wall of a house has an average thermal conductivity of 0.0318 Btu/f ft R. The wall is 6 in thick and it has an area of 160 ft^2. The inside air temperature is 70°F and the heat transfer coefficient for convection between the inside air and the wall is 1.5 Btu/h ft^2 R. On the outside of the wall, the convection heat transfer coefficient is 6 Btu/h ft^2 R and the air temperature is -10°F. Ignoring radiation, determine the rate of heat transfer through the wall at steady-state in Btu/h.

4.93. A small rigid cylindrical vessel contains 1 kg of humid air at 80°C under a total pressure of 1 bar. The humid air inside the vessel contains 0.150 kg of water vapor. Determine the relative humidity of the air in the container.

4.94. A small rigid cylindrical vessel contains 1 kg of humid air at 75°C under a total pressure of 1 bar. The humid air inside the vessel contains 0.10 kg of water vapor. Determine the relative humidity of the air in the container.

4.95. A water heating systems delivers 230 kW with a temperature difference of 20°C into circulating water. Estimate the volumetric flow rate mass flow rate of the water.

4.96. Heat is added at a rate of 100 J/sec to a material whose initial temperature is 20°C. At this temperature, the material is a solid with a specific heat of 2.4 J/g °C. The melting point of this material is 36°C, latent heat of fusion is 340 J/g, and the specific heat at liquid phase is 4.1 J/g C°. If the mass of material is 0.5 kg, how long will it take to reach a final temperature of 40°C?

4.97. A vessel contains ethanol and water in equilibrium. If the composition of the liquid is 35% ethanol, what is the water concentration in the vapor phase and what percent of liquid is present at these conditions?

4.98. A vessel contains ethanol and water in equilibrium. What is the change in mixing enthalpy if the system starts at 90% ethanol vapor and ends at 1% ethanol liquid?

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Chapter 5
Energy Balances

5.1 Balance Equations

According to energy conservation law, the total inflow of energy into a system must be equal to the total outflow of energy from the system. The flow of energy can be in various forms, such as work, heat, electricity, and light. The total energy of a system can be subdivided and classified in various ways. For example, it is sometimes convenient to distinguish potential energy (which is a function of coordinates) from kinetic energy (which is a function of coordinate time derivatives). It may also be convenient to distinguish gravitational energy, electric energy, and thermal energy from each other.

Figure 5.1 shows an open system with mass and energy interactions with its surroundings. Especially for open systems involving fluid-flow processes, energy balance alone may not fully describe the processes. Therefore, other balance equations of mass, entropy, and exergy may also be required. These balance equations are the main tools of analyses of energy interactions of various processes in closed and open systems. Mass and energy are always conserved in a process. However entropy and exergy are not conserved and the balance equations of them account a *source term* (see Fig. 5.1b) [1, 6]. The source term mainly refers to internal production or consumption of a property such as mass, energy, entropy, and exergy in a system. For example, in an internal chemical reaction in a system, a substance may be consumed and heat of reaction may be released. So the chemical reaction acts as a source for internal change apart from the boundary interactions of the system with its surroundings. The conservation equations do not have the source terms and hence are different from the balance equations. In energy balance calculations, we mainly use all or the combinations of mass, energy, entropy, and exergy balance equations. Next sections present the formulations of these balance equations for steady-state and unsteady-state processes, and present examples of using these equations to describe the energy interactions in closed and open systems.

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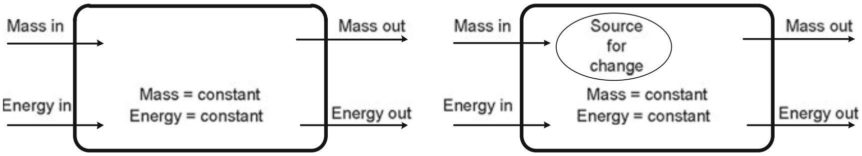


(a) **(b)**

Fig. 5.1 **a** An open steady-state flow process with no internal source of changing mass and energy, **b** an open steady-state flow process with an internal source for change in mass and energy, entropy, and exergy. For example, in an internal chemical reaction in a system, a substance may be consumed and heat of reaction may be released. So the chemical reaction acts as source for internal change apart from the boundary interactions of the system with its surroundings

5.2 Mass Balance

In a closed system, mass is constant as the boundary does not permit the transfer of matter between the system and its surroundings. However, mass and energy interactions take place in an open system as seen in Fig. 5.1. The amount of mass flowing through a cross section per unit time is the mass flow rate $\dot{m}$. Here the dot over the symbol indicates the amount of mass per unit time. The mass flow rate of a fluid flowing in a pipe is proportional to cross-sectional area A of the pipe, the density ρ, and the average velocity v of the fluid, and is given by

$$\dot{m} = vA\rho \tag{5.1}$$

In Eq. 5.1, the fluid flow is assumed to be in a one-dimensional flow and the velocity is assumed to be constant across the cross section. When there is no chemical reaction within a system, *mass balance* for an unsteady-state flow process is given by

$$\frac{dm}{dt} + \sum_i (\dot{m}_i)_{\text{out}} - \sum_i (\dot{m}_i)_{\text{in}} = 0 \tag{5.2}$$

As Eq. 5.2 shows that the total amount of incoming masses is equal to the total amount of outgoing masses in the same units. This is known as the *conservation of mass*. This form of mass conservation equation is also called the *continuity equation* [2]. The conservation of mass principle is a fundamental principle in nature. At steady state flow processes, the accumulation term (*dm*/*dt*) becomes zero, and we have

$$\sum_i (\dot{m}_i)_{\text{out}} - \sum_i (\dot{m}_i)_{\text{in}} = 0 \tag{5.3}$$

For example, in a pump, the amount of water entering the pump is equal to the amount of water leaving it at a steady-state pumping process.

Many engineering devices, such as pumps, nozzles, compressors, and turbines involve a single fluid flow. Usually, we denote the flow at the inlet state by the

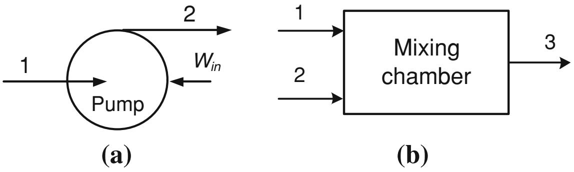


Fig. 5.2 Input and output flows in a **a** pump and **b** mixing chamber

subscript 1 and the flow at the exit state by the subscript 2, as seen in for a pump in Fig. 5.2a. Then, for a single fluid-flow system mass balance is expressed by

$$\dot{m}_1 = \dot{m}_2 \text{ or } \rho_1 v_1 A_1 = \rho_2 v_2 A_2 \tag{5.4}$$

For a mixer chamber shown in Fig. 5.2b, with two inlet flow and one outlet flow, mass balance becomes

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \tag{5.5}$$

The quantity of material may be mass, number of moles, or volumetric flow rate associated with a fluid flow. Using the mole flow rate $\dot{n}$, the steady-state balance equation is expressed by

$$\sum_i (\dot{n}_i)_{\text{out}} - \sum_i (\dot{n}_i)_{\text{in}} = 0 \tag{5.6}$$

The volume of the fluid flowing in a pipe or a duct per unit time is known as the *volumetric flow rate* $\dot{Q}$ in m^3/s or ft^3/h, and is given by

$$\dot{Q} = vA \tag{5.7}$$

where v is the average velocity of the flow and A is the cross-sectional area of a pipe or duct. The mass and volume flow rates are related by

$$\dot{m} = \rho \dot{Q} \tag{5.8}$$

For *incompressible fluids* such as liquids, the density remains constant. The conservation of mass relations for incompressible fluid flows is given by

$$\sum_i (\dot{Q}_i)_{\text{out}} - \sum_i (\dot{Q}_i)_{\text{in}} = 0 \tag{5.9}$$

The conservation of mass relations can be simplified for a single incompressible fluid flow by

$$\dot{Q}_1 = \dot{Q}_2 \text{ or } v_1 A_1 = v_2 A_2 \tag{5.10}$$

Liquids are mostly incompressible fluids. Sometimes, gases may also be assumed as incompressible under suitable conditions. Table 5.1 shows several mass balance relationships for specific cases.

Table 5.1 Specific mass and volume balance equations

General mass balance equation	$\frac{dm}{dt}+\sum_i (\dot{m}_i)_{\text{out}}-\sum_i (\dot{m}_i)_{\text{in}}=0$
General mole balance equation	$\frac{dn}{dt}+\sum_i (\dot{n}_i)_{\text{out}}-\sum_i (\dot{n}_i)_{\text{in}}=0$
Closed system $\dot{m}=0$; $\dot{n}=0$; $\dot{Q}=0$	$\frac{dm}{dt}=0;\ \frac{dn}{dt}=0;\ \frac{dQ}{dt}=0$
Open steady-state single fluid flow	$\dot{m}_1=\dot{m}_2;\ \rho_1 v_1 A_1=\rho_2 v_2 A_2$
Single, steady incompressible fluid flow $\rho=$ constant	$\dot{Q}_1=\dot{Q}_2;\ v_1 A_1=v_2 \mathrm{A}_2$

5.3 Energy Balance

In open and closed systems, energy can cross the boundary in the form of heat q and work W. If the energy exchange is because of temperature difference between a system and its surroundings, this energy exchange appears as heat otherwise it appears as work. When a force acts on a system through a distance, then energy is transferred as work. The heat and work interactions change the internal energy of a closed system ΔU, which is estimated by

$$\Delta U=q+W \tag{5.11}$$

According to the modern energy sign convention recommended by the International Union of Pure and Applied Chemistry, the signs of heat and work are considered positive for their transfers into the system from their surroundings. Heat and work are negative when they are transferred out of the system to the surroundings. Total internal energy is an extensive property as its value depends on the quantity of material in a system.

Finite exchanges of energy between a system and its surroundings obey the energy balance

$$\Delta(\text{Energy of the system})+\Delta(\text{Energy of the surroundings})=0 \tag{5.12}$$

Figure 5.1 shows the mass and energy interactions between a system and its surroundings. As the energy is conserved, the net rate of change of energy within the system is equal to the net rate of energy exchanged between the system and its surroundings at steady state. Streams in various numbers may flow into and out of the system. These streams may have energy associated with them in the forms of internal, kinetic, and potential energies. All these forms of energy contribute to the energy change of the system [4].

5.3.1 Unsteady-State Flow Systems

When there is no chemical reaction taking place in a system, the general energy balance for an unsteady-state open system is given by

$$\frac{d(mU)}{dt} + \Delta\left(H + \frac{1}{2}v^2 + zg\right)\dot{m} = \dot{q} + \dot{W}_s \tag{5.13}$$

where U is the internal energy, H is the enthalpy, v is the average velocity, z is the elevation above a datum level, and g is the acceleration of gravity. The work $\dot{W}_s$ denotes the work other than the pressure work (PV) and called the shaft work. Each unit of mass flow transports energy at a rate $[H + (1/2)v^2 + zg]\dot{m}$.

5.3.2 Steady-State Flow Systems

The accumulation term d(mU)/dt is zero for *steady-state flow processes*, and the general energy balance at steady-state fluid-flow process becomes

$$\dot{m}\left(\Delta H + \frac{\Delta v^2}{2} + g\Delta z\right) = \dot{q} + \dot{W}_s \tag{5.14}$$

For the English engineering systems of units, we have

$$\dot{m}\left(\Delta H + \frac{\Delta v^2}{2g_c} + \frac{g}{g_c}\Delta z\right) = \dot{q} + \dot{W}_s \tag{5.15}$$

If the kinetic and potential energy changes are small enough, then Eq. 5.15 reduces to

$$\sum_i (\dot{m}_i H_i)_{\text{out}} - \sum_i (\dot{m}_i H_i)_{\text{in}} = \dot{q} + \dot{W}_s \tag{5.16}$$

Equation 5.15 is widely applicable to many thermal engineering systems. For a single fluid flow process, energy balance becomes

$$\dot{m}\Delta H = \dot{q} + \dot{W}_s \tag{5.17}$$

When the energy is expressed per number of moles, such as kJ/kmol or Btu/lbmol, the energy balance given in Eq. 5.16 becomes

$$\sum_i (\dot{n}_i H_i)_{\text{out}} - \sum_i (\dot{n}_i H_i)_{\text{in}} = \dot{q} + \dot{W}_s \tag{5.18}$$

Consider an adiabatic, steady-state, and one-dimensional flow of a compressible fluid in a duct or in a pipe. If there is no shaft work and the changes in potential and kinetic energies are negligible, then Eq. 5.17 reduces to

$$\Delta H = 0 \tag{5.19}$$

All energy types in Eqs. 5.11–5.19 require the same energy units. In the SI system the unit for energy is the joule. Other units are the Btu, ft lb_f, and calorie. Table 5.2 shows several energy balances for specific cases.

Table 5.2 Specific energy balance equations

General balance equation	$\frac{d(mU)}{dt}+\Delta\left(H+\frac{1}{2}v^2+zg\right)\dot{m}=\dot{q}+\dot{W}_s$
Steady-state flow processes	$\Delta\left(H+\frac{1}{2}v^2+zg\right)\dot{m}=\dot{q}+\dot{W}_s$
Open steady-state flow with negligible kinetic and potential energies	$\sum_i(\dot{m}_iH_i)_{\text{out}}-\sum_i(\dot{m}_iH_i)_{\text{in}}=\dot{q}+\dot{W}_s$
Open steady-state flow with negligible kinetic and potential energies	$\sum_i(\dot{n}_iH_i)_{\text{out}}-\sum_i(\dot{n}_iH_i)_{\text{in}}=\dot{q}+\dot{W}_s$
Steady-state single flow processes with negligible kinetic and potential energies	$\dot{m}\Delta H=\dot{q}+\dot{W}_s$
Isenthalpic process	$\dot{m}\Delta H=0$
Adiabatic process $\dot{q}=0$	$\dot{m}\Delta H=\dot{W}_s$
Processes with no work interactions	$\dot{m}\Delta H=\dot{q}_s$
Closed system $\dot{m}=0$	$\Delta U=q+W$

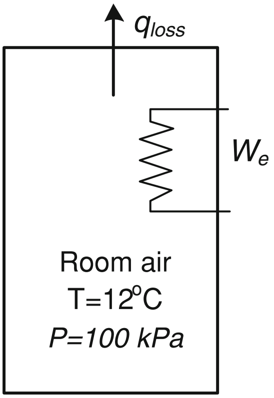
Mass and energy are the conserved properties, and they cannot be created or destroyed. However, mass and energy can be converted to each other according to the well-known equation proposed by Einstein

$$E=mc^2 \tag{5.20}$$

where c is the speed of light. Equation 5.20 suggests that the mass of a system is related to its energy. However, for all energy interactions taking place in practice, except the nuclear reactions, the change of mass is extremely small hence negligible.

Example 5.1 Closed system energy balance calculations

A 60 m^3 room is heated by an electrical heater. The room air originally is at 12°C and 100 kPa. The room loses heat at a rate of 0.2 kJ/s. The air has a constant heat capacity of $C_{v,av}=0.72$ kJ/kg°C. If the electrical heater supplies energy at a rate of 3 kW estimate the time necessary for the room temperature to reach 22°C.



Solution:
Assumptions: The air is ideal gas. This is a closed system of air in the room.
$C_{v,av} = 0.72$ kJ/kg°C, $R = 8.314$ Pa m^3/mol K
$P_1 = 100$ kPa, $T_1 = 12°\text{C}$ (285 K), $V_{\text{room}} = 60\ \text{m}^3$, $T_2 = 22°\text{C}$ (295 K), $MW_{\text{air}} = 29$ kg/kmol

Electrical energy supplied: $W_e = 3$ kW, $q_{\text{loss}} = 0.2$ kW
$q_{\text{net}} = (3 - 0.2)$ kW $= 2.8$ kW

The amount of mass of air in the room:
$m_{\text{air}} = MW(\text{moles of air}) = MW\dfrac{P_1 V_{\text{room}}}{RT_1} = 73.4$ kg

Energy balance: $q_{\text{net}}\Delta t = (m\Delta U)_{\text{air}} = m_{\text{air}}C_{v,av}(T_2 - T_1)$
(2.8 kW) (Δt) = (73.4 kg) (0.72 kJ/kg °C) (22 − 12)°C
$\Delta t = 189$ s = **3.1 min**

5.4 Entropy Balance

In every process, an entropy effect exists either within the system or through the boundary of the system. Entropy is an extensive property, and if a system consists of several parts, the total entropy is equal to the sum of the entropies of each part. Entropy is not conserved and hence entropy is produced in irreversible processes. Heat and mass flows can transfer entropy. No entropy is transferred by work. The balance equation for entropy in a fluid-flow system is

$$\frac{d(mS)}{dt} = \Delta(\dot{m}S) + \sum_i \frac{\dot{q}_i}{T_i} + \dot{S}_{\text{prod}} \tag{5.21}$$

where $\Delta(\dot{m}S)$ is the net entropy change by the mass of the flowing streams, $\dot{q}_i$ is the heat flow rate for flow i through the boundary, T_i is the temperature at which the heat flow $\dot{q}_i$ transfers across the boundary, and $\dot{S}_{\text{prod}}$ is the rate of entropy production and represents the source term [1, 5]. In a closed system, Eq. 5.21 becomes

$$\frac{dS}{dt} = \sum_i \frac{\dot{q}_i}{T_i} + \dot{S}_{\text{prod}} \tag{5.22}$$

At steady-state condition, Eqs. 5.21 and 5.22 reduce to their following steady-state forms

$$0 = \Delta(\dot{m}S) + \sum_i \frac{\dot{q}_i}{T_i} + \dot{S}_{\text{prod}} \quad \text{(open system)} \tag{5.23}$$

$$0 = \sum_i \frac{\dot{q}_i}{T_i} + \dot{S}_{\text{prod}} \quad \text{(closed system)} \tag{5.24}$$

Table 5.3 Specific entropy balance equations

General balance equation with single flow	$\frac{d(mS)}{dt} = \dot{m}(S_1 - S_2) + \frac{\dot{q}}{T} + \dot{S}_{\text{prod}}$
Open steady-state system with single flow	$0 = \dot{m}(S_1 - S_2) + \frac{\dot{q}}{T} + \dot{S}_{\text{prod}}$
Closed system $\dot{m} = 0$	$\frac{dS}{dt} = \frac{\dot{q}}{T} + \dot{S}_{\text{prod}}$
Adiabatic process $\dot{q} = 0$	$\frac{dS}{dt} = \dot{S}_{\text{prod}}$
Reversible process	$\dot{S}_{\text{prod}} = 0$
Irreversible process	$\dot{S}_{\text{prod}} > 0$

In a closed system entropy increases when an irreversible process takes place, and becomes unchanged when a reversible process takes place in the system. Energy exchange accompanied by entropy transfer appears as the *heat transfer*, and energy exchange that is not accompanied by entropy transfer appears as the *work interaction*. The concept of entropy production is discussed further in the next section. Table 5.3 shows the several specific cases of entropy balance equation.

5.5 Exergy Balance

The exergy change ΔEx of a closed system is estimated by Çengel and Boles [1] and Demirel [3]

$$\Delta Ex = \Delta H - T_o \Delta S \tag{5.25}$$

Here the Δ denotes the difference between the initial and final state (reference state), and T_o is the reference temperature. Exergy change of a fluid flow with a unit mass flow rate in an open system is given by

$$\Delta Ex = \Delta H - T_o \Delta S + \frac{\Delta v^2}{2} + g\Delta z \tag{5.26}$$

Exergy is an extensive property and a thermodynamic potential. Exergy is not conserved and always lost during a process. The exergy balance states that the exergy change during a process in a system is equal to the difference between the net exergy transfer and the exergy lost during a process within the system as a result of irreversibilities. The exergy balance is expressed by

$$\Delta \dot{E}x = \dot{E}x_{\text{in}} - \dot{E}x_{\text{out}} - \dot{E}x_{\text{loss}} \tag{5.27}$$

$$\text{Change in exergy} = \text{exergy in} - \text{exergy out} - \text{exergy loss} \tag{5.28}$$

Exergy loss is positive in an irreversible process and vanishes in a reversible process. The rate of loss exergy $\dot{E}x_{\text{loss}}$ represents the overall imperfections, and is directly proportional to the rate of entropy production due to irreversibilities in a process. The rate of exergy loss is expressed by

$$\dot{E}x_{\text{loss}} = T_o \dot{S}_{\text{prod}} \tag{5.29}$$

This equation shows that the rate of exergy transferred into the control volume must exceed the rate of exergy transferred out, and the difference is the exergy lost due to irreversibilities.

Example 5.2 Exergy loss calculations

In a mixer, we mix a saturated steam (stream 1) at 110°C with a superheated steam (stream 2) at 1,000 kPa and 300°C. The saturated steam enters the mixer at a flow rate 1.5 kg/s. The product mixture (stream 3) from the mixer is at 350 kPa and 240°C. The mixer operates at adiabatic conditions. Determine the rate of energy dissipation if the surroundings are at 290 K.

Solution:
Assume that the kinetic and potential energy effects are negligible, this is a steady adaibatic process, and there are no work interactions.

The properties of steam from the steam tables:
Stream 1: saturated steam (Table F3)
$T_1 = 110°\text{C}$, $H_1 = 2{,}691.3$ kJ/kg, $S_1 = 7.2388$ kJ/kg K

Stream 2: superheated steam (Table F4)
$P_2 = 1{,}000$ kPa, $T_2 = 300°\text{C}$, $H_2 = 3{,}052.1$ kJ/kg, $S_2 = 7.1251$ kJ/kg K

Stream 3: superheated steam (Table F4)
$P_3 = 350$ kPa, $T_3 = 240°\text{C}$, $H_3 = 2{,}945.7$ kJ/kg, $S_3 = 7.4045$ kJ/kg K

The mass, energy, and entropy balances for the mixer at steady state are:

Mass balance: $\dot{m}_{\text{out}} = \dot{m}_{\text{in}} \quad \rightarrow \quad \dot{m}_1 + \dot{m}_2 = \dot{m}_3$
Energy balance: $\dot{E}_{\text{out}} = \dot{E}_{\text{in}} \quad \rightarrow \quad \dot{m}_1 H_1 + \dot{m}_2 H_2 = \dot{m}_3 H_3$
Entropy balance: $\dot{S}_{\text{in}} - \dot{S}_{\text{out}} + \dot{S}_{\text{prod}} = 0 \rightarrow \dot{m}_1 S_1 + \dot{m}_2 S_2 - \dot{m}_3 S_3 + \dot{S}_{\text{prod}} = 0$

Combining the mass and energy balances we estimate the flow rate of the superheated steam $\dot{m}_2$:

$$\dot{m}_1 H_1 + \dot{m}_2 H_2 = (\dot{m}_1 + \dot{m}_2) H_3$$

$$\dot{m}_2 = \frac{\dot{m}_1 (H_1 - H_3)}{H_3 - H_2} = \frac{1.5\,\text{kg/s}(2{,}691.3 - 2{,}945.7)\,\text{kJ/kg}}{(2{,}945.7 - 3{,}052.1)\,\text{kJ/kg}} = 3.58\,\text{kg/s}$$

The mass flow rate of the warm water $\dot{m}_3$: $\dot{m}_3 = \dot{m}_1 + \dot{m}_2 = 1.5 + 3.58 = 5.08\,\text{kg/s}$.

The rate of entropy production for this adiabatic mixing process:

$$\dot{S}_{\text{prod}} = \dot{m}_3 S_3 - \dot{m}_1 S_1 - \dot{m}_2 S_2$$

$$\dot{S}_{\text{prod}} = 5.08\,\text{kg/s}\,(7.4045) - 1.5\,\text{kg/s}\,(7.2388) - 3.58\,\text{kg/s}(7.1251) = 1.25\,\text{kJ/s K}$$

The energy dissipated because of mixing:

$$\dot{E}_{\text{loss}} = T_o \dot{S}_{\text{prod}} = 290\text{ K}(1.25\text{ kJ/s K}) = \mathbf{362.5\,kW}$$

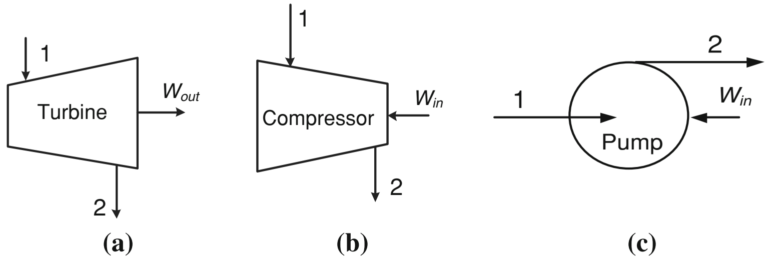


Fig. 5.3 Schematics of **a** turbine, **b** compressor, and **c** pump

5.6 Fluid-Flow Processes

Many thermal engineering devices and processes operate under the steady-state conditions for a long period of time. For example, in a steam power plant the processes using pumps, boilers, turbines, and compressors operate until the system is shut down for maintenance; therefore, they are analyzed as steady-state flow processes.

5.6.1 Turbines Compressors and Pumps

Figure 5.3 shows a single steady fluid-flow turbine, compressor, and pump. In a steam power plant, the hot and pressurized fluid passes through a turbine and the work is done against the blades, which are attached to the shaft. As a result the turbine drives the electric generator and produces work. The work is transferred to the surroundings and its sign is negative. Heat transfer effects in a turbine are usually negligible [1, 6].

Compressors, pumps, and fans increase the pressure of fluids; therefore, a work from the surroundings must be supplied. Pumps use incompressible fluids that are liquids, while compressors and fans use compressible fluids of gases. Fans only slightly increase the pressure of gases. Potential energy changes are usually negligible in all these devices. Kinetic energy and heat effects are usually negligible in turbines.

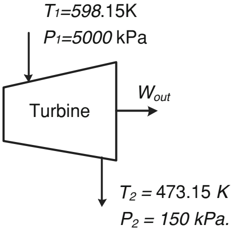
For a pump, we may neglect the kinetic and potential energies and assume that there is no considerable heat exchange with the surroundings. For turbines, compressors, and pumps we have the following similar relations for energy balance equation

$$\dot{m}\Delta H = \dot{m}(H_2 - H_1) = \dot{q} + \dot{W} \tag{5.30}$$

For a turbine, the work is transferred to the surroundings and will have a negative sign. However, the work is transferred from the surroundings for compressors and pumps, and the sign of work for them is positive.

Example 5.3 Turbine calculations

A superheated steam (stream 1) expands in a turbine from 5,000 kPa and 325°C to 150 kPa and 200°C. The steam flow rate is 10.5 kg/s. If the turbine generates 1.1 MW of power, determine the heat loss to the surroundings.



Solution:

Assume that the kinetic and potential energy effects are negligible; this is a steady process.

The properties of steam from the steam tables from Appendix F, Table F4:
Stream 1: Superheated steam:
$P_1 = 5000$ kPa, $T_1 = 325$°C (598.15 K), $H_1 = 3001.8$ kJ/kg

Stream 2: Superheated steam:
$P_2 = 150$ kPa, $T_2 = 200$°C (473.15 K), $H_2 = 2872.9$ kJ/kg
$\dot{W}_{\text{out}} = -1100\,\text{kW} = -1100\,\text{kJ/s}$

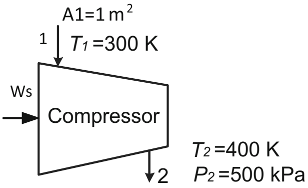
The mass and energy balances for the turbine are:
Mass balance: $\dot{m}_{\text{out}} = \dot{m}_{\text{in}}$
Energy balance: $\dot{E}_{\text{out}} = \dot{E}_{\text{in}} \longrightarrow \dot{m}_1(H_2 - H_1) = \dot{q}_{\text{out}} + W_{\text{out}}$
Heat loss from the energy balance

$$\begin{aligned}\dot{q}_{\text{out}} &= -\dot{W}_{\text{out}} + \dot{m}_1(H_2 - H_1) = 1100\,\text{kJ/s} + (10.5\,\text{kg/s})(2872.9 - 3001.8)\text{kJ/kg}\\ &= \mathbf{-253.45\,kJ/s}\end{aligned}$$

The sign is negative as the heat is lost from the system.

Example 5.4 Compressor calculations

Air enters a compressor at 100 kPa, 300 K, and a velocity of 2 m/s through a feed line with a cross-sectional area of 1.0 m^2. The effluent is at 500 kPa and 400 K. Heat is lost from the compressor at a rate of 5.2 kW. If the air behaves as an ideal gas, what is the power requirement of the compressor in kW.



Solution:

Assume: The compressor is at steady state, air is ideal gas, and the change in the potential and kinetic energy of the fluid from the inlet to the outlet is negligible.

$R = 8.314$ Pa m^3/mol K, $MW = 29$ kg/kmol; $v_1 = 2$ m/s, $A_1 = 1.0$ m^2
$P_1 = 100$ kPa, $T_1 = 300$ K, $P_2 = 500$ kPa, $T_2 = 400$ K, $\dot{q}_{\text{loss}} = -5.2$ kW

For ideal gas: $V_1 = \dfrac{RT_1}{P_1} = 0.025\,\text{m}^3/\text{mol}$.

The specific volume: $(1/\rho)_{air} = \dfrac{V_1}{MW_{\text{air}}} = 0.86$ m^3/kg

The mass flow rate of air: $\dot{m} = \dfrac{v_1 A_1}{(1/\rho)} = 2.32$ kg/s

From Table D1 for ideal gas of air: $H_2 = 400.9$ kJ/kg, $H_1 = 300.2$ kJ/kg
Energy balance: $\dot{m}(H_2 - H_1) - \dot{q} = \dot{W}$
$(2.32\,\text{kg/s})((400.9 - 300.2)\text{kJ/kg}) + 5.2\,\text{kW} = \dot{W} = \mathbf{238.8\,kW}$

This is the work needed by the compressor and the sign is positive.

Example 5.5 Pump power calculation
A pump increases the pressure in liquid water from 100 kPa at 25°C to 4,000 kPa. What is the minimum horsepower motor required to drive the pump for a flow rate of 0.01 m^3/s?

Solution:
Assume that the pump operates adiabatically and nearly isothermally, changes in potential and kinetic energy are negligible, and water is incompressible.

$P_1 = 100$ kPa, $T_1 = 298.15$ K, $P_2 = 4{,}000$ kPa, $Q = 0.01$ m^3/s

Energy balance: $\dot{q} + \dot{W}_{\text{pump}} = \dot{m}\Delta H$

For an adiabatic operation $(\dot{q} = 0)$: $\dot{W}_{\text{pump}} = \dot{m}\Delta H$

Since the water is incompressible the internal energy is only the function of temperature. $\Delta U = 0$ as the system is isothermal.

$\Delta H = \Delta U + \Delta(PV) = V\Delta P$

The specific volume of saturated liquid water at 25°C: $V_1 = 0.001003$ m^3/kg (Table F3)

The mass flow rate: $\dot{m} = \dfrac{Q}{V_1} = 9.97\,\text{kg/s}$

$$\dot{W}_{\text{pump}} = \dot{m}V_1(P_2 - P_1) = (9.97\,\text{kg/s})(0.001003\ \text{m}^3/\text{kg})(4000 - 100)\,\text{kPa}\left(\text{kJ/kPa m}^3\right)$$
$$= \mathbf{39\,kJ/s} = \mathbf{39\,kW} = \mathbf{52.3\,hp} \qquad (1\,\text{hp} = 745.7\,\text{W}).$$

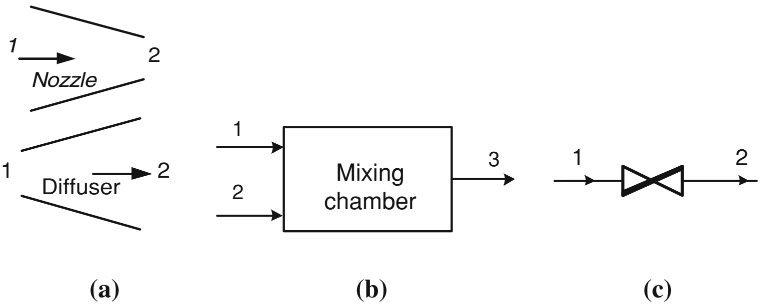


Fig. 5.4 Single steady-flow processes: **a** nozzle and diffuser, **b** mixing chamber, **c** throttle valve

5.6.2 Nozzles and Diffusers

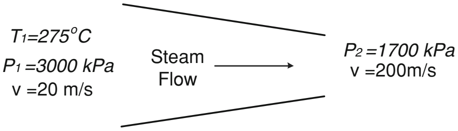
Nozzles and diffusers are widely used in jet engines. A converging nozzle increases the velocity of a fluid while the pressure of the fluid is reduced. A diffuser (diverging nozzle) increases the pressure of a fluid, while the velocity of the fluid is reduced. In nozzle and diffusers, the rate of heat interactions between the system and its surroundings are usually very small, and process may be analyzed as adiabatic ($q = 0$). Nozzle and diffusers generally involve no work, and changes in potential energy are negligible, therefore, the analyses of such processes may require kinetic energy changes [6]. Figure 5.4a shows schematics of nozzles and diffusers.

For a converging nozzle the velocity increases, then we take into account the kinetic energy, and usually neglect the potential energy. There is no work effect and energy balance becomes:

$$\Delta\left(H + \frac{1}{2}v^2\right)\dot{m} = \dot{q} \tag{5.31}$$

Example 5.6 Nozzle calculations

In a converging nozzle steam flow is accelerated from 20 to 200 m/s. The steam enters the nozzle at 3,000 kPa and 275°C and exits at 1,700 kPa. The nozzle inlet's cross-sectional area is 0.005 m^2. The nozzle loses heat at a rate of 76 kJ/s. Estimate the steam mass flow rate and exit temperature.



Solution:
Assumptions: This is a steady-state flow.

Inlet: P_1 = 3,000 kPa, T_1 = 275°C, v_1 = 20 m/s, A_1 = 0.005 m^2, $\dot{q}_{\text{loss}}$= − 76 kJ/s
H_1 = 2,928.2 kJ/kg, V_1 = 76.078 cm^3/g = 0.0761 m^3/kg (Table F4)

Outlet: P_2 = 1,700 kPa, v_2 = 200 m/s
The steam mass flow rate: $\dot{m}_s = \frac{1}{V_1} A_1 v_1 = \mathbf{1.314\,kg/s}$
Energy balance: $\dot{m}_s\left[(H_2 - H_1) + \left(\frac{v_2^2}{2} - \frac{v_1^2}{2}\right)\left(\frac{1\,\text{kJ/kg}}{1000\,m^2/\text{s}^2}\right)\right] = \dot{q}_{\text{loss}}$
Estimate the enthalpy at the exit H_2:

$$(1.314\,\text{kg/s})\left[(H_2 - 2{,}928.2) + \left(\frac{200^2}{2} - \frac{20^2}{2}\right)\left(\frac{1\,\text{kJ/kg}}{1{,}000\,\text{m}^2/\text{s}^2}\right)\right] = -76\,\text{kJ/s}$$

H_2 = 2,850.56 kJ/kg, T_2 (at H_2 and P_2) **= 225°C** (approximate) (From Table F4)

5.6.3 Mixing Chambers

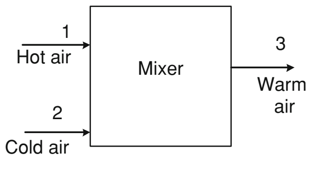
In thermal engineering applications, mixing two flow streams in a chamber is very common. For example, mixing of a hot stream with a cold stream produces a warm stream. Conservation of mass and energy principles require that the sum of incoming mass flow rates and enthalpy rates are equal to the mass flow rates and enthalpy rates of the sum of outgoing streams. For example, for the mixing chamber in Fig. 5.4b, mass and energy balances become

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \tag{5.32}$$

$$\dot{m}_1 H_1 + \dot{m}_2 H_2 = \dot{m}_3 H_3 \tag{5.33}$$

Mixing chambers are usually well insulated hence they are generally adiabatic. The kinetic and potential energy effects are negligible. Mixing chambers do not involve any kind of work production [2, 6].

Example 5.7 Mixing chamber calculations
A hot air at 900 K is mixed with cold air at 300 K in a mixing chamber operating under adiabatic conditions. Flow rate of the cold air is 2.4 kg/s. The outlet stream is warm air at 700 K. Estimate the flow rate of hot air.



Solution:
Assumptions: This is a steady-state flow process. Kinetic and potential energy changes are negligible. The heat loss from the mixer is negligible. The air streams are ideal gases.
For an ideal gas, enthalpy depends only on the temperature.

Hot air in: $\dot{m}_1 = \text{unknown}, T_1 = 900\,\text{K}; H_1 = 933.0\,\text{kJ/kg}$ (Table D1)

Cold air in: $\dot{m}_2 = 2.4$ kg/s; $T_1 = 300\,\text{K}; H_2 = 300.2\,\text{kJ/kg}$ (Table D1)

Outlet stream: warm air at 700 K and $H_3 = 713.3$ kJ/kg (Table D1)

Energy and mass balances are:
$\dot{m}_1 H_1 + \dot{m}_2 H_2 = \dot{m}_3 H_3$
$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Combining and organizing these equations yield the hot air mass flow rate:
$\dot{m}_1 = \dot{m}_2 \dfrac{H_3 - H_2}{H_1 - H_3} = (2.4\ \text{kg/s})\left(\dfrac{713.3 - 300.2}{933.0 - 713.3}\right) = \mathbf{4.51\,kg/s}$

5.6.4 *Throttling Valve*

In a throttling valve (see Fig. 5.4c), a fluid flows through a restriction, such as an orifice, a partly closed valve, capillary tube, or a porous structure with negligible kinetic energy and potential energy changes. Throttling valve causes a considerable pressure drop without involving any work. Throttling valves usually operate under adiabatic conditions [1]. When there is no or negligible heat transfer then the energy balance equation for the single steady flow throttling becomes

$$H_1 = H_2 \tag{5.34}$$

Since the values of enthalpy at the inlet and at the outlet are the same, throttling valve is called as an *isenthalpic process*. This equation can also be expressed as:

$$\text{internal energy} + \text{pressure energy} = \text{constant} \tag{5.35}$$

$$(U + PV)_1 = (U + PV)_2 = \text{constant} \tag{5.36}$$

A throttling process does not change the temperature of an ideal gas since the enthalpy of an ideal gas depends only on temperature. For most real gases, however, pressure drop at constant enthalpy results in temperature decrease. If a wet steam is throttled to a considerably low pressure, the liquid evaporates and the steam may become superheated. Throttling of a saturated liquid may cause vaporization (or flashing) of some of the liquid, which produces saturated vapor and liquid mixture. For throttling valves with large exposed surface areas such as capillary tubes, heat transfer may be significant.

Energy may remain the same in the throttling valve, while exergy is lost because of the expansion of the fluid.

Example 5.8 Throttling process calculations

(a) A steam at 600 kPa and 200°C is throttled to 101.32 kPa. Estimate the temperature of the steam after throttling.

(b) A wet steam at 1,200 kPa and with a quality of 0.96 is throttled to 101.32 kPa. Estimate the enthalpy and the temperature of the throttled steam.

Solution:

Assume: no heat transfer occurs, and kinetic and potential energy changes are negligible in the throttling process

Data from Table F4:

(a) Inlet: P_1 = 600 kPa, and T_1 = 200°C, H_1 (600 kPa, 200°C) = 2,849.7 kJ/kg
Outlet: P_2 = 101.32 kPa
For adiabatic throttling: $H_1 = H_2$
From Table F4: T_2 (101.32 kPa, 2,849.7 kJ/kg) = **187.1°C** (after an interpolation)
The temperature drop (ΔT = 2.9°C) is small.

(b) Throttling a wet steam to a lower pressure may cause the liquid to evaporate and the vapor to become superheated.
Inlet: the wet steam is saturated at: P_1 = 1,200 kPa, T_{sat} = 187.9°C, x = 0.96 (Table F3)

$H_{1\text{sat vap}}$ = 2,782.7 kJ/kg; $H_{1\text{sat liq}}$ = 798.4 kJ/kg from Table F3
$H_1 = (1-x)H_{1\text{sat liq}} + xH_{1\text{sat vap}} = \mathbf{2,683.5\,kJ/kg}$

Outlet: P_2 = 101.32 kPa
T_2 (101.32 kPa, 2,683.5 kJ/kg) = **103.6°C**.
Since $T_2 > T_{2\text{sat}}$ at 101.32 kPa, the throttled steam is superheated.

The temperature drop (ΔT = 84.3°C) is considerable and results because of evaporation of liquid within the wet steam.

Example 5.9 Throttling of a refrigerant

Refrigerant-134a in a refrigerator enters a throttling valve as saturated liquid at 85.8 psia and is throttled to a pressure of 18.8 psia. Estimate the quality of the refrigerant and temperature drop at the exit.

Solution:
Inlet conditions: saturated liquid: $P_1 = 85.8$ psia and $T_1 = 70°\mathrm{F}$, $H_1 = 33.9$ Btu/lb (Table E1)

Exit conditions: saturated mixture of liquid and vapor at $P_{2,\ \mathrm{sat}} = 18.8$ psia and $T_{2\mathrm{sat}} = -5°\mathrm{F}$, $H_{2\mathrm{sat\ liq}} = 10.1$ Btu/lb, $H_{2\mathrm{sat\ vap}} = 101.0$ Btu/lb (Table E1)

Throttling process: $H_1 = H_2 = 33.9 = (1-x)\ H_{2\mathrm{sat\ liq}} + x\ H_{2\mathrm{sat\ vap}}$

Quality of the saturated mixture: $x = \dfrac{m_{\mathrm{vap}}}{m_{\mathrm{total}}} = \dfrac{33.9 - 10.1}{101 - 10.1} = \mathbf{0.25}$

After the throttling process 25.0% of the saturated liquid is evaporated.
Temperature drop: $\Delta T = T_2 - T_1 = (-5 - 70)\ °\mathrm{F} = \mathbf{-75°F}$.

5.6.5 Heat Exchangers

In the mixing chambers hot and cold fluid streams mix and exchange heat from hot to cold streams. In heat exchangers, such as condensers, hot and cold fluid streams exchange heat without mixing. Figure 5.5 shows a typical shell and tube heat exchanger. For example, in the tube side, cold flow stream 3 enters and leaves the tube as hot flow stream 4. On the other hand, a hot flow stream 1 enters the shell side and leaves as flow stream 2. Heat exchangers may have various designs, such as double-pipe and shell and tube, and are widely used in thermal engineering systems [2]. Conservation of mass and energy principles requires that the sum of incoming mass flow rates and enthalpy rates equals to the mass flow rates and enthalpy rates of outgoing flows. For example, for the heat exchanger shown in Fig. 5.5 mass and energy balances become

$$\dot{m}_1 = \dot{m}_2 \text{ and } \dot{m}_3 = \dot{m}_4 \tag{5.37}$$

$$\dot{m}_1(H_2 - H_1) = \dot{m}_3(H_4 - H_3) \tag{5.38}$$

Heat exchangers involve no work interactions and usually operate with negligible kinetic and potential energy changes for hot and cold fluid flows.

Example 5.10 Heat exchanger calculations
A steam is cooled in a condenser using cooling water. The steam enters the condenser at 20 kPa and a quality of 0.9, and exits at 20 kPa as saturated liquid. The steam flow rate 3 kg/s. The cooling water enters the condenser at 18°C and exits at 40°C. Average heat capacity of the cooling water is $C_{p,av} = 4.2$ kJ/kg°C. Estimate the mass flow rate of the cooling water.

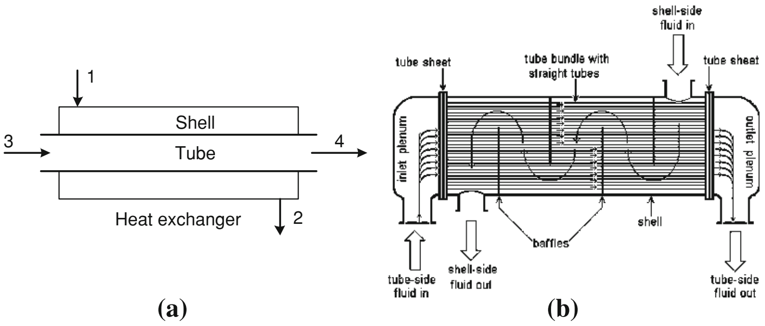
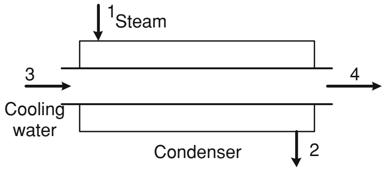


Fig. 5.5 **a** Schematic of a typical heat exchanger where hot and cold fluid flows do not mix with each other, **b** schematic of a shell and tube heat exchanger. Baffles help distribute the shell side fluid around the tube bundle



Solution:

Assumptions: This is a steady-state system. Changes in kinetic energy and potential energies are negligible.

Cooling water: $T_3 = 18°\text{C}$, $T_4 = 40°\text{C}$, $C_{p,av} = 4.2$ kJ/kg°C
Steam flow rate: $\dot{m}_s = 3$ kg/s
Steam is saturated liquid and vapor mixture: $P_1 = 20$ kPa, $x_1 = 0.90$

$H_{1\text{sat liq}} = 251.4$ kJ/kg, $H_{1\text{sat vap}} = 2{,}609.7$ kJ/kg (Table F3)
$H_1 = (1 - x_1)H_{1\text{sat liq}} + xH_{1\text{sat vap}} = 2373.9\,\text{kJ/kg}$

Exit: saturated liquid at $P_2 = 20$ kPa, $H_2 = 251.4$ kJ/kg (Table F3)
Energy balance: heat removed by the cooling water = heat lost by the steam
$\dot{m}_w C_{p,av}(T_4 - T_3) = -\dot{m}_s(H_2 - H_1)$

$$\dot{m}_w = \dot{m}_s \frac{(H_1 - H_2)}{C_{p,av}(T_4 - T_3)} = (3\,\text{kg/s})\left(\frac{2373.9 - 251.4}{(4.2\,\text{kJ/kg°C})(40 - 18)°\text{C}}\right) = \mathbf{69.24\,kg/s}$$

5.6.6 *Pipe and Duct Flows*

The transport of fluids in pipes and ducts has wide applications in many fluid-flow processes. Fluids mainly flow through pipes and ducts at steady-state flow conditions. Under normal operating conditions, heat interactions of pipe and duct flows may be considerable, especially for long pipes and ducts. For example, a pipe with a hot fluid flowing inside must be insulated to reduce the heat loss to the surroundings during the transportation of the fluid.

The velocities of fluid flows in pipes and ducts are usually low and the kinetic energy changes may be negligible. This is especially true when the cross-sectional area remains constant and the heat effects are small. Kinetic energy changes, however, may be considerable when the cross-sectional area changes for gases flowing in a duct. The potential energy changes may also be considerable when a fluid undergoes a large elevation change as it flows in a pipe or duct.

5.7 Energy Balance in a Cyclic Process

Most of the processes described above are part of some important thermal cyclic process, using the Carnot cycle, heat pump, or refrigeration cycle. These thermal cyclic processes are used for power production as well as for heating ventilation and air conditioning (HVAC) purposes [1, 6]. The next section presents the practical energy balance equations for the Carnot cycle.

For a fuel-fired power plant using the Carnot cycle for converting heat into work, a common heat sources is the combustion of coal, natural gas, or oil. Figure 5.6 describes the main processes within the Carnot cycle. The main processes are:

- Process 4–1: the water is pumped from low to high pressure; the pump requires little input energy.
- Process 1–2: the high pressure liquid enters a boiler where it is heated at a constant pressure by an external heat source to become a dry saturated vapor. The input energy required can be easily calculated using on an enthalpy–entropy chart.
- Process 2–3: the dry saturated vapor expands through a turbine, generating power. This decreases the temperature and pressure of the vapor, and some condensation may occur.
- Process 3–4: The wet vapor then enters a condenser where it is condensed at a constant pressure to become a saturated liquid to start a new cycle.

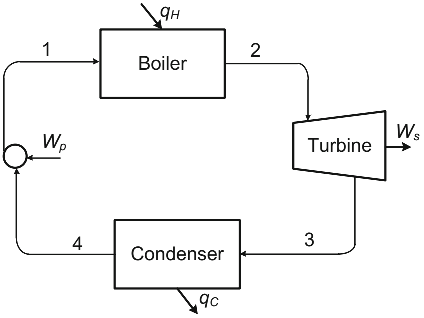
In a Carnot cycle, the pump, turbine, heat addition (in the boiler), and rejection (in the condenser) would be *isentropic* and hence maximize the network output. The process analyses yield the following energy balance equations: pump power needed $W_{p,\text{in}}$ for a unit mass flow rate of a fluid becomes

$$W_{p,\,\text{in}} = V_4(P_1 - P_4) \tag{5.39}$$

where V_4 is the specific volume at state 4 that is the saturated liquid water P_i is the pressures at state i. Enthalpy rate at state 1, H_1, is

$$H_1 = H_4 + W_{p,\text{in}} \tag{5.40}$$

Fig. 5.6 Typical processes in a Carnot cycle to produce work



The heat input q_{in} to the pressurized water in the boiler is

$$q_{\text{in}} = (H_2 - H_1) \tag{5.41}$$

The discharged heat rate q_{out} at the condenser is

$$q_{\text{out}} = (H_4 - H_3) \tag{5.42}$$

The net value of the work, W_{net} produced is

$$W_{\text{net}} = (q_{\text{in}} - q_{\text{out}}) \tag{5.43}$$

Here, the absolute values of heat input and heat output are used. The sign of the work produced would be minus. Some examples of using these equations in power production are presented in Chap. 6 in Sect. 6.4.

Problems

5.1. Develop a simple energy balance formulation for a steady- state flow operations: (a) Pump; (b) Gas turbine; (c) Gas compressor; (d) Nozzle; (e) Throttle valve.

5.2. A copper ingot of 1 kg is heat treated at 400°C and then quenched in a 50 l oil bath initially at 15°C. Assuming no heat exchange with the surroundings, determine the temperature of the ingot and the oil when they reach thermal equilibrium. Data: $C_{v,\text{ copper}} = 0.386$ kJ/kg K, $C_{v,\text{ oil}} = 1.8$ kJ/kg K, $\rho_{\text{copper}} = 8{,}900$ kg/m^3, $\rho_{\text{oil}} = 910$ kg/m^3

5.3. A well-insulated 30 m^3 tank is used to store exhaust steam. The tank contains 0.01 m^3 of liquid water at 30°C in equilibrium with the water vapor. Estimate the internal energy of the tank.

5.4. A superheated steam at a rate of 0.6 lb/s flows through a heater. The steam is at 100 psia and 380°F. If an electrical heater supplies 37.7 Btu into the steam at constant pressure estimate the final temperature of the steam.

5.5. A tank of 4 ft^3 contains superheated steam of 1 lb and 120 psia. The tank is heated at constant pressure. The amount of heat added is 200 Btu. Estimate the temperature of the steam after the heating process.

5.6. A 60 m^3 room is heated by an electrical heater. The room air originally is at 12°C and 100 kPa. The room loses heat at a rate of 0.2 kJ/s. If the electrical heater supplies 3 kW estimate the time necessary for the room temperature to reach 22°C.

5.7. A 1-kW heater is used to heat a room with dimensions (3 m) (4.5 m) (4 m). Heat loss from the room is 0.15 kW and the pressure is always atmospheric. The air in the room may be assumed to be an ideal gas. The air has a constant heat capacity of $C_{v,av} = 0.72$ kJ/kg °C. Initially the room temperature is 290 K. Determine the temperature in the room after 10 min.

5.8. A tank filled with 10 lb of air is heated. The air originally is at 40 psia and 100°F. After heating, the air pressure becomes 60 psia. Estimate the amount of heat transferred. Heat capacity for the air is 0.171 Btu/lb °F and remains constant during the heating process.

5.9. A 2.0 m^3 tank filled with hydrogen (H_2) at 200 kPa and 500 K. The hydrogen is cooled until its temperature drops to 300 K. Estimate the amount of heat removed from the tank. Heat capacity for the hydrogen is $C_{v,av} = 10.4$ kJ/kg °C and remains constant during the heating process.

5.10. An electrical resistance heater is used to heat a room from 17°C to 22°C within 30 min. The room has the dimensions of $4 \times 4 \times 5$ m^3. The air in the room is at atmospheric pressure. The heat loss from the room is negligible. Estimate the power needed for this temperature change.

5.11. A room with dimensions of (5 m) (5 m) (6 m) is heated with a radiator supplying 8,000 kJ/h. HeatHeat loss from the room is 800 kJ/h. The air is originally at 15°C. Estimate the time necessary to heat the room to 24°C.

5.12. A 2 kW heater is used to heat a room with dimensions (3 m) (4.5 m) (4 m). Heat loss from the room is negligible and the pressure is always atmospheric. The air in the room may be assumed to be an ideal gas, and the heat capacity is 29 J/mol K. Initially the room temperature is 290 K. Determine the rate of temperature increase in the room.

5.13. A resistance heater within a well-insulated tank is used to heat 20 kg of water. The heater passes a current of 0.4 Ampere (A) from a 120-V source. The water in the tank is originally at 10°C. Estimate the time necessary for the temperature of the water to reach 60°C.

5.14. A resistance heater within a tank is used to heat 5 kg of water. The heater passes a current of 0.8 Ampere (A) for 2 h from a 120-V source. A heat loss of 15.6 kW occurs from the tank to surroundings. The water in the tank is originally at 30°C. Estimate the temperature of the water after 2 h of heating.

5.15. A resistance heater within a tank is used to heat 150 kg of water. The heater passes a current of 0.6 Ampere (A) for 8 h from a 120-V source. A heat loss of 38.2 kW occurs from the tank to surroundings. The water in the tank is originally at 5°C. Estimate the temperature of the water after 8 h of heating.

5.16. A resistance heater within a well-insulated 120 m^3 room is used to heat the inside air. The heater passes a current of 2 Ampere (A) from a 120 V source. The air originally is at 15°C and 100 kPa. Estimate the time necessary for the inside air temperature to reach 21°C.

5.17. A resistance heater within a well-insulated 85 m^3 room is used to heat the inside air. The heater passes a current of 2 Ampere (A) for 3 h from a 120-V source. The air originally is at 20°C and 100 kPa. Estimate the temperature of the air after 3 h of heating.

5.18. A resistance heater within a well-insulated 105 m^3 room is used to heat the inside air. The heater passes a current of 0.8 Ampere (A) for 2 h from a 120-V source. The air originally is at 17°C and 100 kPa. The heat loss from the room is 29.0 kJ. Estimate the temperature of the air after 2 h of heating.

5.19. A condenser in a power plant is used to condense the discharged steam from the turbine by using cooling water. The temperature rise of the cooling water is 12°C. The discharged steam enters the condenser at 10 kPa with a quality of 0.95 and exits as saturated liquid water at constant pressure. If the steam flow rate is 5 kg/s estimate the flow rate of cooling water.

5.20. A condenser in a power plant is used to condense the discharged steam from the turbine by using cooling water at a flow rate of 160 kg/s. Inlet temperature of the cooling water is 15°C. The discharged steam enters the condenser at 10 kPa with a quality of 0.95 and exits as saturated liquid water at constant pressure. If the discharged steam flow rate is 6.5 kg/s estimate the exit temperature of the cooling water.

5.21. A 20 lb refrigerant 134a is flowing in a coil and is cooled by an air flow. The refrigerant enters the coil at 140°F and 140 psia, and leaves as saturated vapor at 140 psia. The air enters the heat exchanger at 14.7 psia and 480 R. Volumetric flow rate of the air is 150 ft^3/s. Estimate the exit temperature of the air.

5.22. A 5 lb refrigerant 134a flowing in a coil is cooled by an air flow. The refrigerant enters the coil at 200°F and 100 psia and leaves as saturated vapor at 100 psia. The air enters the heat exchanger at 14.7 psia and 480 R. Volumetric flow rate of the air is 250 ft^3/s. Estimate the exit temperature of the air.

5.23. Refrigerant 134a is cooled in a condenser using cooling water. The refrigerant enters the condenser at 1,000 kPa and 90°C, and exits at 1,000 kPa and 30°C. The cooling water at a flow rate of 2.0 kg/s enters the condenser at 20°C and exits at 27°C. Estimate the mass flow rate of the refrigerant.

5.24. A steam is cooled in a condenser using cooling water. The steam enters the condenser at 20 kPa and a quality of 0.9, and exits at 20 kPa as saturated liquid. The steam flow rate 3 kg/s. The cooling water enters the condenser at 18°C and exits at 26°C. Estimate the mass flow rate of the cooling water.

5.25. A compressed liquid water at 20°C and a superheated steam at 150°C and 400 kPa are fed into a mixing chamber operating under adiabatic conditions. Flow rate of the compressed liquid water is 12 kg/s. The outlet stream is saturated liquid water at 400 kPa. Estimate the flow rate of superheated steam.

5.26. A superheated steam at a flow rate of 50 kg/s and at 150°C, 200 kPa is mixed with another superheated steam at 350°C and 200 kPa in a mixing chamber operating under adiabatic conditions. The outlet stream is a superheated steam at 225°C and 200 kPa. Estimate the flow rate of superheated steam at 350°C and 200 kPa.

5.27. A hot water at 80°C is mixed with cold water at 20°C in a mixing chamber operating under adiabatic conditions. Flow rate of the cold water is 15.0 kg/s. The outlet stream is warm water at 45°C and 100 kPa. Estimate the flow rate of hot water.

5.28. A hot air at 900 R is mixed with cold air at 520 R in a mixing chamber operating under adiabatic conditions. Flow rate of the cold air is 24 lb mol/s. The outlet stream is warm air at 700 R. Estimate the flow rate of hot air.

5.29. A superheated steam at 300°C and 300 kPa is mixed with liquid water with a flow rate of 4 kg/s and at 20°C in a mixing chamber operating under adiabatic conditions. The outlet stream is at 60°C and 300 kPa. Estimate the flow rate of superheated steam.

5.30. An open feed water heater in a steam power plant operates at steady-state with liquid entering at $T_1 = 40°\text{C}$ and $P_1 = 7$ bar. Water vapor at $T_2 = 200°\text{C}$ and $P_2 = 7$ bar enters in a second feed stream. The effluent is saturated liquid water at $P_3 = 7$ bar. Estimate the ratio of the mass flow rates of the two feed streams.

5.31. Initially the mixing tank shown below has 100 kg of water at 25°C. Later two other water inlet streams 1 and 2 add water and outlet stream 3 discharges water. The water in the tank is well mixed and the temperature remains uniform and equal to the temperature of outlet stream 3. Stream 1 has a flow rate of 20 kg/h and is at 60°C, while stream 2 has a flow rate of 15 kg/h and is at 40°C. The outlet stream has a flow rate of 35 kg/h. Determine the time-dependent temperature of the water in the mixing tank.

5.32. In a mixer, we mix a saturated steam (stream 1) at 110°C with a superheated steam (stream 2) at 1,000 kPa and 300°C. The saturated steam enters the mixer at a flow rate 1.5 kg/s. The product mixture (stream 3) from the mixer is at 350 kPa and 240°C. The mixer loses heat at a rate 2 kW. Determine the rate of energy dissipation if the surroundings are at 300 K.

5.33. In a mixer, we mix liquid water (1) at 1 atm and 25°C with a superheated steam (2) at 325 kPa and 200°C. The liquid water enters the mixer at a flow rate of 70 kg/h. The product mixture (3) from the mixer is at 1 atm and 55°C. The mixer loses heat at a rate of 3,000 kJ/h. Estimate the flow rate of superheated steam and the rate of entropy production.

5.34. In a steady-state mixing process, 50.25 kg/s of saturated steam (stream 1) at 501.15 K is mixed with 7.363 kg/s of saturated steam (stream 2) at 401.15 K. The mixer is well insulated and adiabatic. Determine the energy dissipation (work loss) if the surroundings are at 298.15 K.

5.35. In a steady-state mixing process, 50.0 kg/s of saturated steam (stream 1) at 501.15 K is mixed with 17.0 kg/s of saturated steam (stream 2) at 423.15 K. The product steam (stream 3) is at 473.15 K. Determine the rate of heat loss.

5.36. In a steady-state mixing process, 15 kmol/s of air (stream 1) at 550 K and 2 atm is mixed with 40 kmol/s of air (stream 2) at 350 K and 1 atm. The product (stream 3) is at 300 K and 1 atm. Determine the heat loss.

5.37. A steam turbine produces a power output of 3.80 MW. The steam at the inlet is at 1,000 psia and 900°F. The steam at the exits is saturated at 12 psia. Estimate the heat loss if the steam flow rate is 12.8 lb/s.

5.38. A steam turbine produces 3.80 MW. The steam at the inlet is at 900 psia and 900°F. The steam at the exits is saturated at 5 psia. Estimate the heat loss if the steam flow rate is 16.2 lb/s.

5.39. A steam turbine consumes 4,000 lb/h steam at 540 psia and 800°F. The exhausted steam is at 165 psia. The turbine operation is adiabatic.

   (a) Determine the exit temperature of the steam and the work produced by the turbine.
   (b) Determine the entropy production if the turbine efficiency is 80%.

5.40. A superheated steam (stream 1) expands in a turbine from 5,000 kPa and 325°C to 150 kPa and 200°C. The steam flow rate is 10.5 kg/s. If the turbine generates 1.1 MW of power, determine the heat loss to the surroundings.

5.41. A superheated steam (stream 1) expands in a turbine from 5,000 kPa and 325°C to 150 kPa and 200°C. The steam flow rate is 10.5 kg/s. If the turbine generates 1.1 MW of power, determine the heat loss to the surroundings.

5.42. Steam expands in a turbine from 6,600 kPa and 300°C to a saturated vapor at 1 atm. The steam flow rate is 9.55 kg/s. If the turbines power output is 1 MW, estimate the rate of heat loss.

5.43. Steam expands adiabatically in a turbine from 850 psia and 600°F to a wet vapor at 12 psia with a quality of 0.9. Estimate the steam flow rate if the turbines' power output is 2 MW.

5.44. Steam expands adiabatically in a turbine from 800 psia and 650°F to a wet vapor at 10 psia with a quality of 0.95. Estimate the steam flow rate if the turbine' power output is 2 MW.

5.45. Air enters an insulated compressor operating at steady state at 1.0 bar, 300 K with a mass flow rate of 3.6 kg/s and exits at 2.76 bar. Kinetic and potential energy effects are negligible. (a) Determine the minimum theoretical power input required, in kW, and the corresponding exit temperature, in K. (b) If the actual exit temperature is 420 K, determine the power input, in kW, and the isentropic compressor efficiency.

5.46. A compressor increases the pressure of carbon dioxide from 100 to 600 kPa. The inlet temperature is 300 K and the outlet temperature is 400 K. The mass flow rate of carbon dioxide is 0.01 kmole/s. The power required by the compressor is 55 kW. The temperature of the surroundings is 290 K. Determine the minimum amount of work required.

5.47. Hydrogen gas is compressed from an initial state at 100 kPa, 300 K and 5 m^3 to 300 kPa and 370 K. The compression process is polytropic ($PV^{\gamma} = \text{constant}$). The average heat capacity of hydrogen is $C_{p,\,av} = 29.1$ J/mol K. Estimate the total entropy change of the system.

5.48. A compressor receives air at 15 psia and 80°F with a flow rate of 1.2 lb/s. The air exits at 40 psia and 300°F. At the inlet the air velocity is low, but increases to 250 ft/s at the outlet of the compressor. Estimate the power input of the compressor if it is cooled at a rate of 200 Btu/s.

5.49. In an adiabatic compression operation, air is compressed from 20°C and 101.32 kPa to 520 kPa. The air flow rate is 22 mol/s. Estimate the work required under isentropic operation.

5.50. Refrigerant-134a with a flow rate of 0.1 lb/s enters a compressor as saturated vapor at $T_1 = 5$°F ($P_{sat} = 23.8$ psia) and exits a superheated vapor at 60°F and 40 psia. Estimate the energy transferred during the compression process.

5.50. Refrigerant-134a with a flow rate of 0.1 lb/s enters a compressor as saturated vapor at $T_1 = 5$°F ($P_{sat} = 23.8$ psia) and exits a superheated vapor at 60°F and 40 psia. Estimate the energy transferred during the compression process.

5.51. Air enters a compressor at 100 kPa, 300 K, and a velocity of 6 m/s through a feed line with a cross-sectional area of 3 m^2. The effluent is at 500 kPa and 400 K and has a velocity of 2 m/s. Heat is lost from the compressor at a rate of 160 kW. If the air behaves as an ideal gas, what is the power requirement of the compressor in kW.

5.52. Carbon dioxide at a flow rate of 1.5 kg/s enters a compressor at 300 K and 100 kPa and exits at 480 K. Estimate the volumetric flow rate of CO_2 and the power for compression.

5.53. Propane with a flow rate of 5 lb/s enters a compressor as a saturated vapor at 30°F and 66.5 psia. The propane leaves the compressor as superheated vapor at 140 psia and 100°F. Estimate the heat transfer to the propane in the steady-state flow process.

5.54. In a two-stage continuous compression process, methane (stream 1) enters the first compressor at 300 K and 1 bar. The methane (stream 2) leaves the second compressor at 300 K and 60 bar. The flow rate of methane is 0.5 kg/s. The total power input is 400 kW. The intercooler between the compressors uses cooling water. The surroundings are at 295 K. Estimate the minimum work required and the heat removed in the intercooler.

5.55. In a two-stage continuous compression process, methane (stream 1) enters the first compressor at 300 K and 1 bar. The methane (stream 2) leaves the second compressor at 350 K and 80 bar. The flow rate of methane is 0.6 kg/s. The total power input is 450 kW. The intercooler between the compressors uses cooling water. The cooling water enters the cooler of 295 K and leaves at 305. The surroundings are at 295 K. Estimate the cooling water rate.

5.56. In an adiabatic compression operation, air is compressed from 20°C and 101.32 kPa to 520 kPa with an efficiency of 0.7. The air flow rate is 20 mol/s. The air is assumed to be an ideal gas. Estimate the ideal work required.

5.57. Refrigerant 134a enters a compressor operating at steady state as saturated vapor at 2 bar with a volumetric flow rate of 0.019 m^3/s**.** The refrigerant is compressed to a pressure of 8 bar in an internally reversible process according to $PV^{1.03}$ = constant. Estimate (a) the power required, in kW, and (b) the rate of heat transfer, in kW.

5.58. Air is compressed from 1 bar and 310 K to 8 bar. Estimate the specific work and heat transfer if the air follows a polytropic process path with $\gamma = 1.32$.

5.59. A pump increases the pressure in liquid water from 100 at 25°C to 2,500 kPa. What is the minimum horsepower motor required to drive the pump for a flow rate of 0.005 m^3/s?

5.60. A pump increases the pressure in liquid water from 100 at 25°C to 3,000 kPa. What is the minimum horsepower motor required to drive the pump for a flow rate of 0.25 m^3/s?

5.61. In a converging nozzle air flow is accelerated from 20 to 60 m/s. The air at the inlet is at 400 kPa, 127°C. The inlet cross sectional area of the nozzle is 90 cm^2. At the outlet the air flow pressure drops to 100 kPa. Estimate the air mass flow rate and exit temperature.

5.62. In a converging nozzle steam flow is accelerated from 20 to 200 m/s. The steam enters the nozzle at 3,000 kPa and 275°C and exits at 900 kPa. The nozzle inlet's cross-sectional area is 0.005 m^2. The nozzle loses heat at a rate of 76 kJ/s. Estimate the steam mass flow rate and exit temperature.

5.63. In a converging nozzle carbon dioxide (CO_2) flow is accelerated to 400 m/s. The CO_2 enters the nozzle at 1,000 kPa and 500 K and exits at 900 kPa. Flow rate of the CO_2 is 5,000 kg/h. The nozzle inlet's cross-sectional area is 0.005 m^2. Estimate the inlet velocity and exit temperature of the CO_2.

5.64. Steam expands in a nozzle from inlet conditions of 500°F, 250 psia, and a velocity of 260 ft/s to discharge conditions of 95 psia and a velocity 1,500 ft/s. If the flow is at 10 lb/s and the process is at steady state and adiabatic, determine the outlet temperature.

5.65. Air with a flow rate of 1 kg/s enters a nozzle at 400 K and 60 m/s and leaves the nozzle at a velocity 346 m/s. The air inlet pressure is 300 kPa, while the pressure at the outlet is 100 kPa. The rate of heat lost in the nozzle is 2.5 kJ/kg. Determine the enthalpy at the outlet.

5.66. Steam enters a nozzle at 30 psia and 300°F, and exits as a saturated vapor at 300°F. The steam enters at a velocity of 1,467 ft/s, and leaves at 75 ft/s. The nozzle has an exit area of 0.5 ft^2. Determine the rate of energy dissipation when the ambient temperature $T_o = 500$ R.

5.67. A steam enters a nozzle at 500 kPa and 220°C, and exits at 400 kPa and 175°C. The steam enters at a velocity of 200 m/s, and leaves at 50 m/s. The nozzle has an exit area of 0.2 m^2. Determine the rate of heat loss to the surroundings.

5.68. A steam enters a nozzle at 4,000 kPa and 425°C with a velocity of 50 m/s. It exits at 286.18 m/s. The nozzle is adiabatic and has an inlet area of 0.005 m^2. Estimate the enthalpy of the outlet stream.

5.69. A steam enters a nozzle at 3,200 kPa and 300°C with a velocity of 20 m/s. It exits at 274.95 m/s. The nozzle is adiabatic and has an inlet area of 0.01 m^2. Estimate the enthalpy at the outlet and the amount of loss of work if the surroundings are at 300 K.

5.70. Steam at 8,200 kPa and 500°C passes through a throttling process so that the pressure is suddenly reduced to 7,400 kPa. What is the expected temperature after the throttle?

5.71. 5 kg/s of superheated steam at 400°C and 1,100 kPa is throttled to 125 kPa adiabatically through a valve. Determine the outlet temperature and the work loss if the surroundings are at 298.15 K.

5.72. Refrigerant 134a expands adiabatically in an expansion valve. The refrigerant enters at $P_1 = 140$ psia and $T_1 = 140$°F, and exits at 50 psia. The reference conditions are $P_o = 21.2$ psia and $T_o = 0$°F. Determine the loss of exergy and second law efficiency.

5.73. Superheated steam with a flow rate of 2.0 kg/s is throttled to 1,700 kPa. The steam is initially at 4,100 kPa and 300°C. Estimate the lost work potential of the steam during this throttling process.

5.74. Refrigerant-134a is throttled by a valve. The refrigerant enters the valve as a saturated liquid at 30 psia and exits at 15 psia. Estimate the exit temperature and quality of the refrigerant.

5.75. Steam is throttled by a valve adiabatically. The steam enters the valve at 1,000 psia and 600°F. At the exit the steam is at 850 psia. Estimate the drop in temperature.

5.76. A steam at 900 psia and 700°F is throttled in a valve to 55 psia at a rate of 20 lb/min at steady state. Determine the entropy production due to expansion of the steam.

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Chapter 6
Energy Production

6.1 Energy Production

Energy production mainly involves converting one form of energy into another form that is needed the most. For example, the sources of chemical energy from fossil fuels and nuclear resources are used to produce approximately 90% of the world's electricity. Petroleum (also known as crude oil) as a fossil fuel is another main source of energy. After refining the petroleum into its fraction, various fuels such as gasoline, kerosene, diesel, and fuel oil are produced. Therefore, energy production mainly involves the conversion of existing fossil fuels and nuclear resources as well as the renewable energy sources into those forms of energy needed the most in a certain application. There are various forms of energy production in the world, each with its own risks and benefits. The world's power demand is expected to rise by 60% by 2030. *Cogeneration* is the production of more than one useful form of energy (such as process heat and electric power) from the same energy source [31, 33].

6.2 Electric Power Production

A fossil fuel power plant produces electricity by converting fossil fuel energy into mechanical work. The two major power plant systems are based on the steam turbine cycle and the gas turbine cycle mostly using fossil fuels. The steam cycle relies on the Rankine cycle in which high pressure and high temperature steam produced in a boiler is expanded through a turbine that drives an electric generator. The discharged steam from the turbine gives up its heat of condensation in a condenser to a heat sink such as water from a river or a lake. The condensate is pumped back into the boiler to restart a new cycle. The heat taken up by the cooling water in the condenser is dissipated mostly through cooling towers into the atmosphere (see Fig. 6.1).

Y. Demirel, *Energy*, Green Energy and Technology,
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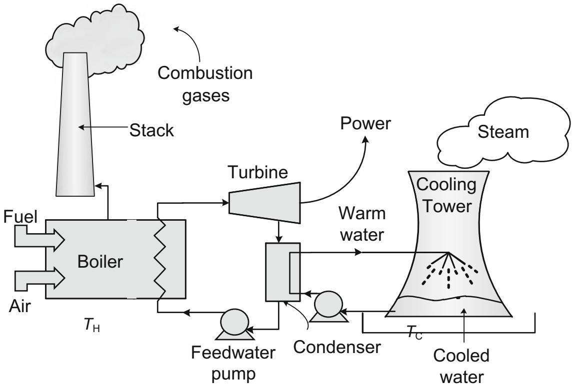
Fig. 6.1 Schematic of a steam power plant



The fundamental principles of electricity generation were discovered during the 1820s and the early 1830s by the British scientist Michael Faraday. Based on Faraday's work, electricity is produced by the movement of a loop of wire, or disc of copper between the poles of a magnet. Most of the electricity produced results from steam turbines. The combustion of fossil fuels supplies most of the heat to these turbines, with a significant fraction from nuclear fission and some from renewable resources. Today, steam turbines produce about 80% of the electric power in the world by using a variety of heat sources.

Assuming that nitrogen remains inert, the complete combustion of a fossil fuel using air as the oxygen source may be represented approximately by the following reaction:

$$C_xH_y + \left(x+\frac{y}{4}\right)O_2 + 3.76\left(x+\frac{y}{4}\right)N_2 \rightarrow xCO_2 + \left(\frac{y}{2}\right)H_2O - 3.76\left(x+\frac{y}{4}\right)N_2 + \text{Heat} \tag{6.1}$$

where C_xH_y represents a fossil fuel consisting of carbon (C) and hydrogen (H) only, with stoichiometric coefficients of x and y, respectively, depending on the fuel type. A fossil fuel, such as coal or natural gas, may have other elements such as sulfur and compounds such as minerals beside the carbon and hydrogen. A simple example is the combustion of coal (taken here as consisting of pure carbon): $C + O_2 \rightarrow CO_2$. Coal is prepared by grinding it to powder and mixing it with air which preheats the coal to drive off excess moisture content and transports it to the furnace.

Most of the electricity in the United States is produced using steam turbines. In steam turbines, coal or natural gas is burned in a furnace to heat water in a boiler to produce steam. In 2009, 45% of the Country's nearly 4 trillion kWh of electricity used coal as its source of energy. Example 6.1 illustrates the analysis of an adiabatic steam turbine. Figure 6.2 shows the various energy sources used to produce electricity in the U.S. Centralized power production became possible when it was recognized that alternating current power lines can transport electricity at very low

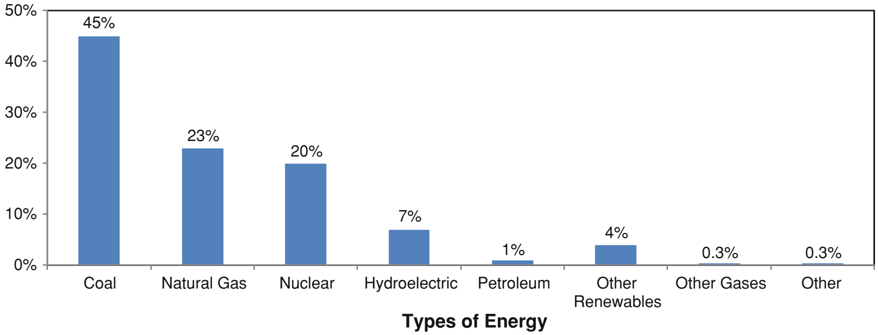


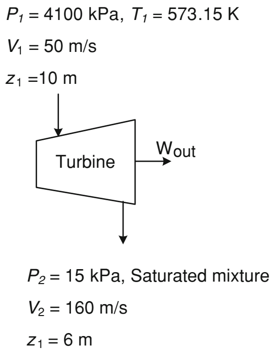
Fig. 6.2 Energy sources used in electricity production in the U.S. [12]

costs across great distances and power transformers can adjust the power by raising and lowering the voltage.

Renewable energy sources such as photovoltaics, wind, biomass, hydro, and geothermal can also provide clean and sustainable electricity. However, renewable energy sources are naturally variable, requiring energy storage or a hybrid system to accommodate daily and seasonal changes. One solution is to produce hydrogen through electrolysis by splitting of water and to use that hydrogen in a fuel cell to produce electricity during times of low power production or peak demand, or to use the hydrogen in fuel cell vehicles.

Example 6.1 Power production by an adiabatic steam turbine

A superheated steam at 4100 kPa and 300°C expands adiabatically in a steam turbine and exits at 15 kPa with a quality of $x = 0.9$. Velocity of the steam at the inlet is 50 m/s and at the exit 160 m/s. Elevation at the inlet is 10 m and at the exit 6 m. Estimate the power produced for the steam flow rate of 1kg/s.



Solution:
Assume: Steady-state adiabatic ($q_{\text{loss}} = 0$) process.

Steam flow rate: $\dot{m}_s = 1\,\text{kg/s}$
From Table F4:
Inlet conditions: $P_1 = 4100$ kPa and $T_1 = 300°\text{C}$, $v_1 = 50$ m/s, $z_1 = 10$ m,
$H_1 = 2958.5$ kJ/kg,

Exit conditions: Saturated mixture of liquid and vapor water: (Table F3)
$P_{2,\text{sat}} = 15$ kPa, $T_{2,\text{sat}} = 54.0°\text{C}$, $H_{2\text{sat liq}} = 226.0$ kJ/kg,
$H_{2\text{sat vap}} = 2599.2$ kJ/kg, $x = 0.9$, $v_2 = 160$ m/s, $z_2 = 6$ m

$$H_{2\text{mix}} = (1 - x)H_{\text{sat liq}} + xH_{\text{sat vap}} = (1 - 0.9)226\,\text{kJ/kg} + (0.9)2599.2\,\text{kJ/kg} = 2361.9\,\text{kJ/kg}$$

Energy balance: $W_{\text{out}} = \dot{m}\left(\Delta H + \frac{\Delta v^2}{2} + g\Delta z\right)$

$$\Delta H = H_2 - H_1 = (2361.9 - 2958.5)\text{kJ/kg} = -596.6\,\text{kJ/kg}$$

$$\Delta KE = \frac{v_2^2 - v_1^2}{2} = \left(\frac{160^2 - 50^2}{2}\right)\text{m}^2/\text{s}^2\left(\frac{\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = 11.55\,\text{kJ/kg}$$

$$\Delta PE = g(z_2 - z_1)\left(\frac{\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = 9.81(6 - 10)\text{m}^2/\text{s}^2\left(\frac{\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = -0.04\,\text{kJ/kg}$$

$$W_{\text{out}} = \dot{m}\left(\Delta H + \frac{\Delta v^2}{2} + g\Delta z\right) = (1\text{kg/s})(-596.6 + 11.5 - 0.04)\text{kJ/kg} = \mathbf{-585.1\ kW}$$

Contribution of kinetic energy is less than 2%, and the contribution of potential energy is negligible. In practice, changes in kinetic and potential energies are assumed to be negligible.

6.3 Transmission of Energy

Electricity grids transmit and distribute power from production source to end user (see Fig. 6.3). Sources include coal or natural gas burning power plants as well as nuclear and solar power plants. A combination of substations, transformers, towers, and cables are used to maintain a constant flow of electricity at the required levels of voltage such as 110 or 220 V. Grids also have a predefined carrying capacity or load. New small-scale energy sources may be placed closer to the consumers so that less energy is lost during electricity distribution. New technology like superconductivity or improved power factor correction may also decrease the energy lost [1].

Crude oil is carried and distributed through long pipelines between the sources and refineries where it is fractioned to many different types of fuels, such as gasoline, kerosene, and fuel oil. Pipelines can also distribute the refined fractions of the crude oil to end users. Slurry pipelines are sometimes used to transport coal. Oil pipelines are made of steel or plastic tubes with inner diameter typically from

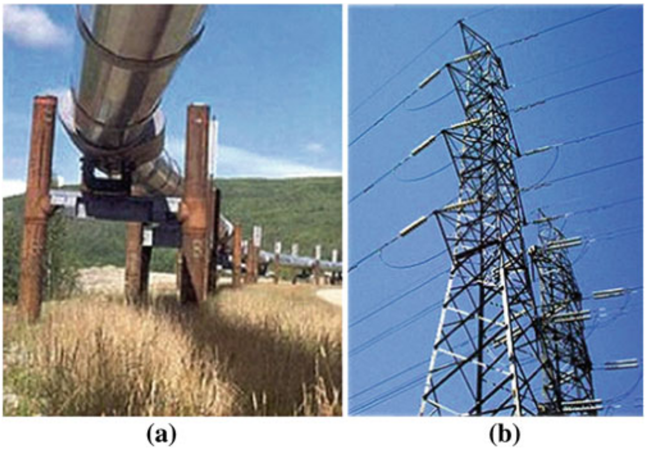


Fig. 6.3 Transmission of energy: **a** an elevated section of the Alaska pipeline, **b** electric grid: pilons and cables distribute power

0.3 to 4 ft (0.1–1.2 m). For natural gas, pipelines are constructed of carbon steel and vary in size from 0.2 to 5 ft (0.06–1.5 m) in diameter, depending on the type of pipeline. The gas is pressurized by compressor stations. Most pipelines are buried at a typical depth of about 3–6 ft (0.9–1.8 m).

6.3.1 Distributed Energy Resources

Distributed energy resources are small power production or storage systems located close to the point of use. Distributed energy resources usually have higher efficiencies through cogeneration and may reduce emissions of carbon dioxide, because of their use of onsite renewable resources and low greenhouse gas fuels such as natural gas as seen in Fig. 6.4. Some distributed generation technologies, like photovoltaic and fuel cells, can generate electricity with no emissions or less emissions than that of central station fossil fuel-fired power plants. For distributed generation to enhance system level efficiency, improvements will be required in the performance of power-producing equipment, including advanced sensors and controls, energy storage, and heat exchangers to improve waste heat recovery and cycle efficiencies. Other advantages include fuel source flexibility, reduced transmission and distribution line losses, enhanced power quality and reliability, and more user control. Distributed generation permits consumers who are producing electricity for their own needs, to send their surplus electrical power back into the power grid [1].

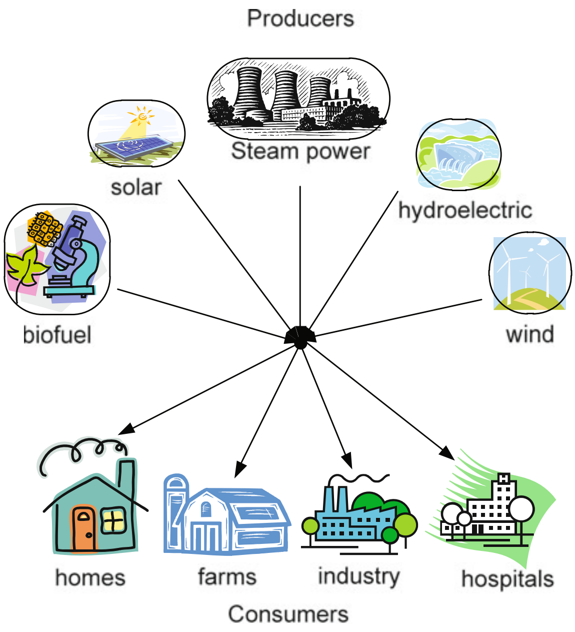


Fig. 6.4 Transition to distributed energy resources and use

6.4 Power Producing Engine Cycles

The systems used to produce a net power output are called *engines*. Most power producing engines operate with cyclic processes using a working fluid. Steam power plants use water as the working fluid. Actual engine cycles are complex to analyze. Therefore it is common to analyze the cycles by assuming that they operate without friction, heat losses, and other complexities [6, 32]. Such a cycle is known as the ideal engine. The analysis of ideal engines yields the major operating parameters controlling the cycle performance [4].

A *heat engine*, for example, converts heat to mechanical energy by bringing a working fluid from a high temperature state T_H to a lower temperature state T_C. Figure 6.5 shows typical pressure–volume PV and temperature-entropy TS diagrams of ideal engine cycles. On both the PV and TS diagrams, the area enclosing the process curves of a cycle represents the net work produced during the cycle, which is equivalent to the net heat transfer for the cycle. As seen in Fig. 6.5, The characteristics of cycles on a TS diagram are:

- Heat addition increases entropy,
- Heat rejection process decreases entropy,
- Isentropic (internally reversible and adiabatic) process takes place at constant entropy.

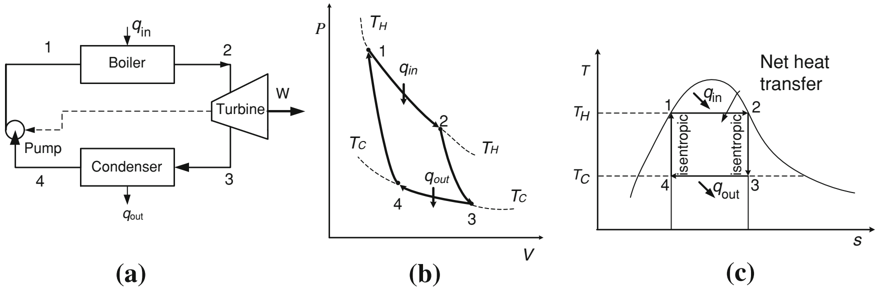


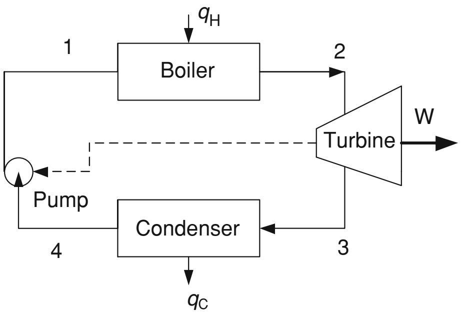
Fig. 6.5 Typical ideal engine cycles: **a** cyclic processes, **b** on a pressure–volume (*PV*) diagram, **c** on a temperature-entropy (*TS*) diagram

The area under the heat addition process on a *TS* diagram measures the total heat input, and the area under the heat rejection process measures the total heat output. The difference between these two areas represents the net heat transfer and also the net work output. Therefore, any modifications that improve the net heat transfer rate will also improve the net work output. Example 6.2 illustrates the analysis power output from a steam power plant [4, 6, 32].

A heat "source" heats the working fluid in the high temperature state. The working fluid generates work in the engine while transferring the remaining heat to the colder "sink" until it reaches a low temperature state. The working fluid usually is a liquid or gas. During the operation of an engine some of the thermal energy is converted into work and the remaining energy is lost to a heat sink mainly the general surroundings. Example 6.3 estimates the water mass flow rate for a given power output.

Example 6.2 Steam power production

A steam power production plant uses steams at 8200 kPa and 823.15 K. The turbine discharges the steam at 30 kPa. The turbine and pump operate reversibly and adiabatically. Determine the work produced for every kg steam produced in the boiler.



Solution:
Assume that the turbine and the pump operate reversibly and adiabatically; no pressure drop across condenser and boiler; only heat transfer occurs at condenser and boiler.

Steam flow rate: $\dot{m}_s = 1\,\mathrm{kg/s}$
Steam data from Table F4:
Turbine inlet: $P_2 = 8200$ kPa; $T_2 = 823.15$ K; $H_2 = 3517.8$ kJ/kg;
$S_2 = 6.8646$ kJ/kg K

Turbine outlet: $P_3 = 30$ kPa; $T_3 = 342.27$ K, $V_4 = 0.001022$ m^3/kg (Table F3)
$H_{3\text{sat liq}} = 289.30$ kJ/kg, $H_{3\text{sat vap}} = 2625.4$ kJ/kg
$S_{3\text{sat liq}} = 0.9441$ kJ/kg K, $S_{3\text{sat vap}} = 7.7695$ kJ/kg K

For an ideal operation $S_2 = S_3 = 6.8646$. Since $S_3 < S_{3\text{sat vap}}$ the discharged steam is a mixture of liquid and vapor. Solve for fraction of vapor, x, using entropy balance for the exhaust of the turbine:

$$x_3 = \frac{S_2 - S_{3\text{sat liq}}}{S_{3\text{sat vap}} - S_{3\text{sat liq}}} = \frac{6.8646 - 0.9441}{7.7695 - 0.9441} = 0.867$$

$H_3 = 0.867(2625.4) + (1 - 0.867)(289.3) = 2315.8\,\mathrm{kJ/kg},\ T_2 = 342.27\,\mathrm{K(Saturated)}$
$H_1 = H_4 + (P_1 - P_4)\,V_4 = 289.3 + (8200 - 30)\,(0.001022) = 297.65$ kJ/kg
$q_{\text{out}} = (H_3 - H_4) = (2315.8 - 289.3)\,\mathrm{kJ/kg} = 2026.5\,\mathrm{kJ/kg}$ (absolute value)
$q_{\text{in}} = (H_2 - H_1) = (3517.8 - 297.65)$ kJ/kg $= 3220.2$ kJ/kg

Net work output for 1 kg/s steam: $W_{\text{out}} = \dot{m}_s(q_{\text{in}} - q_{\text{out}}) = \mathbf{1193.7\,kW}$ (Absolute value)

Example 6.3 Steam flow rate calculation in a power plant
A steam power plant output is 50 MW. It uses steam (stream 1) at 8200 kPa and 550°C. The discharged steam (stream 2) is saturated at 75 kPa. If the expansion in the turbine is adiabatic determine the steam flow rate.

Solution:
Assume that kinetic and potential energy are negligible, and the system is at steady state.
(a) Basis: 1 kg/s steam with the properties from the steam tables
Turbine inlet:
$H_1 = 3517.8$ kJ/kg, $S_1 = 6.8648$ kJ/kg K at $T_1 = 550°\mathrm{C}$, $P_1 = 8200$ kPa (Table F4)
Turbine outlet:
$S_{2\text{sat vap}} = 7.3554$ kJ/kg K, $S_{2\text{sat liq}} = 1.2131$ kJ/kg K at $P_2 = 75$ kPa (saturated steam)
$H_{2\text{sat vap}} = 2663.0$ kJ/kg, $H_{2\text{sat liq}} = 384.45$ kJ/kg at (Table F3)

At isentropic conditions, we have $S_2 = S_1 < 7.3554$ kJ/kg K
Therefore, the discharged steam is wet steam:
x_s (the quality at isentropic operation): $x_s = \dfrac{6.8646 - 1.2131}{7.4570 - 1.2131} = 0.905$
The discharged steam enthalpy at isentropic conditions H_{2s} is
$H_{2s} = H_{2\text{sat liq}}(1 - x_s) + H_{2\text{sat vap}} x_s = 384.45(1 - 0.905) + 2663(0.905) = 2446.8\,\text{kJ/kg}$

The steam flow rate: $\dot{m} = \dfrac{-50000\,\text{kW}}{(H_{2s} - H_1)\text{kJ/kg}} = \mathbf{46.7\,kg/s}$

6.4.1 Carnot Cycle

A Carnot *heat engine* performs the conversion of heat to mechanical energy by bringing a working fluid from a high temperature state T_{H} to a lower temperature state T_{C}. Figure 6.5 shows a typical pressure–volume *PV* and temperature-entropy *TS* diagrams of ideal engine cycles. On both the *PV* and *TS* diagrams, the area enclosed by the process curves of a cycle represents the net heat transfer to be converted to mechanical energy by the engine.

Carnot cycle consists of four totally reversible processes shown in Fig. 6.5c:

- Process 1–2: Isothermal heat addition at constant temperature T_{H}.
- Process 2–3: Isentropic expansion at constant entropy $S_2 = S_3$.
- Process 3–4: isothermal heat rejection at constant temperature T_{C}.
- Process 4–1: isentropic compression at constant entropy $S_4 = S_1$.

From Fig. 6.5c, we can estimate the amounts of added and rejected heats per unit mass flow rate of a working fluid

$$q_{\text{in}} = T_H(S_2 - S_1) \tag{6.2}$$

$$q_{\text{out}} = T_C(S_4 - S_3) \tag{6.3}$$

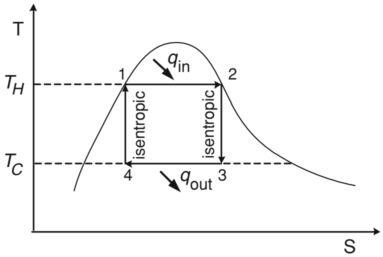
The net power output becomes

$$W_{\text{out}} = q_{\text{in}} - q_{\text{out}} \tag{6.4}$$

Example 6.4 illustrates the analysis of power output from a Carnot cycle.

Example 6.4 Power output from a Carnot cycle
A Carnot cycle uses water as the working fluid at a steady flow process. Heat is transferred from a source at 250°C and water changes from saturated liquid to saturated vapor. The saturated steam expands in a turbine at 10 kPa, and a heat of 1045 kJ/kg is transferred in a condenser at 10 kPa. Estimate the net power output of the cycle for a flow rate of 10 kg/s of the working fluid.

Solution:
Assumptions: Kinetic and potential energy changes are negligible.

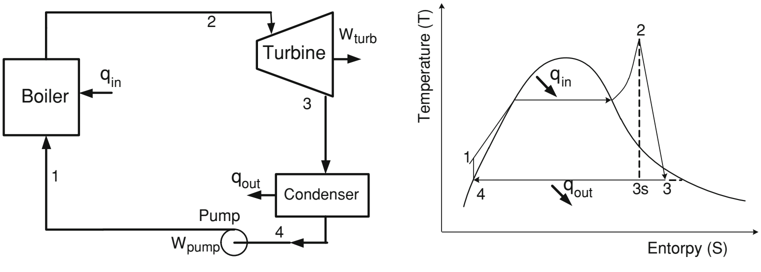


Data from Table F3:
$\dot{m} = 10\,\mathrm{kg/s}$
Turbine inlet:
$P_{sat} = 3977.6$ kPa, $T_{\mathrm{H}} = 250°\mathrm{C} = 523.15$ K,
Turbine outlet:
$T_{\mathrm{C}} = T_{\mathrm{sat}}$ (at 10 kPa) $= 45.8°\mathrm{C} = 318.8$ K
Heat supplied is equivalent to the heat of vaporization at $T_{\mathrm{H}} = 250°\mathrm{C}$.
$H_{1\mathrm{sat\ liq}} = 1085.8$ kJ/kg K, $H_{2\mathrm{sat\ vap}} = 2800.4$ kJ/kg K, at $P_1 = P_2 = 3977.6$ kPa
$q_{\mathrm{in}} = H_{2\mathrm{sat\ vap}} - H_{2\mathrm{sat\ liq}} = 1714.6$ kJ/kg, $q_{\mathrm{out}} = 1045$ kJ/kg
Total Net power output of the cycle: $\dot{W}_{\mathrm{net}} = \dot{m}(q_{\mathrm{in}} - q_{\mathrm{out}}) = \mathbf{6696.0\,kW}$

6.4.2 Rankine Cycle

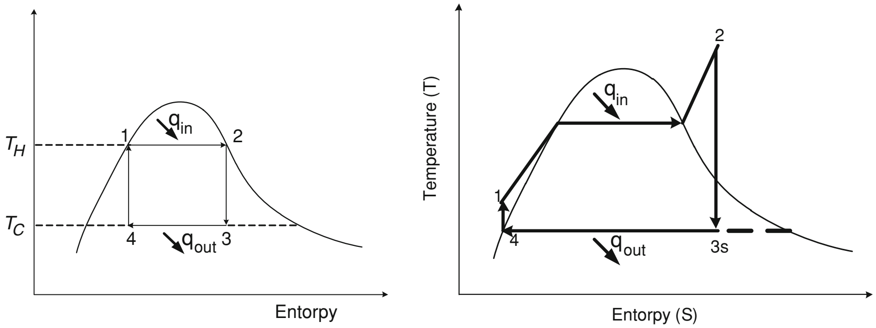
The *Rankine cycle* converts heat into work and generates about 80% of all electric power used throughout the world. Figure 6.6 describes the main processes within the cycle. Common heat sources are the combustion of coal, natural gas, oil, and the fission of nuclear material. The Rankine cycle processes are:

- Process 1–2: The high pressure liquid enters a boiler where it is heated at constant pressure by an external heat source to become a dry saturated vapor.
- Process 2–3: The dry saturated vapor expands through a turbine, generating power. This decreases the temperature and pressure of the vapor, and some condensation may occur.
- Process 3–4: The wet vapor discharged from the turbine enters a condenser where it is condensed at a constant pressure to become a saturated liquid.
- Process 4–1: The water is pumped from low to high pressure to start a new cycle.



(a) **(b)**

Fig. 6.6 **a** Schematic of Rankine cycle. **b** Rankine cycle processes on a *T* versus *S* diagram



(a) **(b)**

Fig. 6.7 **a** Carnot cycle. **b** Ideal Rankine cycle on a *T S* diagram, where on both the cycles pumps and turbines operate at constant entropy (isentropic operation)

The Rankine cycle is sometimes referred to as a practical Carnot cycle because in an ideal Rankine cycle the pump and turbine would be *isentropic* and produce no entropy and hence maximize the work output shown in Fig. 6.7 as the line 2–3s where the entropy remains constant. The main difference is that the heat addition (in the boiler) and heat rejection (in the condenser) are isobaric in the Rankine cycle and isentropic in the Carnot cycle.

6.4.2.1 Analysis of Ideal Rankine Cycle

The analyses of processes yield the following equations for a Rankine cycle: Pump power needed

$$\dot{W}_{p,\mathrm{in}} = \dot{m}V_4(P_1 - P_4) \tag{6.5}$$

where $\dot{m}$ is the steam mass flow rate, V_4 is the specific volume at state 4 that is the saturated liquid water, and P_i is the pressures at state i. Enthalpy rate at state 1, H_1, is

$$\dot{m}H_1 = \dot{m}H_4 + \dot{W}_{p,\mathrm{in}} \tag{6.6}$$

For isentropic process $S_1 = S_4$ and $S_2 = S_3$. The quality of the discharged wet steam, x_{3s}, shows the molar or mass fraction of vapor ($S_3 < S_{3\mathrm{sat\ vap}}$):

$$x_{3s} = \frac{(S_3 - S_{3\mathrm{sat\,liq}})}{(S_{3\mathrm{sat\,vap}} - S_{3\mathrm{sat\,liq}})} \tag{6.7}$$

where S_3 is the entropy at state 3, $S_{3\mathrm{sat\ vap}}$, and $S_{3\mathrm{sat\ liq}}$ are the entropy of saturated vapor and saturated liquid at state 3, respectively. Enthalpy rate of the wet steam at state 3 is

$$\dot{m}H_3 = \dot{m}[(1 - x_{3s})H_{3\mathrm{sat\,liq}} + x_{3s}H_{3\mathrm{sat\,vap}}] \tag{6.8}$$

where $H_{3\mathrm{sat\ vap}}$ and $H_{3\mathrm{sat\ liq}}$ are the saturated vapor and saturated liquid enthalpies at state 3. The rate of heat input, q_{in}, to the pressurized water in the boiler is

$$\dot{q}_{\mathrm{in}} = \dot{m}(H_2 - H_1) \tag{6.9}$$

The discharged heat rate $\dot{q}_{\mathrm{out}}$ at the condenser is

$$\dot{q}_{\mathrm{out}} = \dot{m}(H_4 - H_3) \tag{6.10}$$

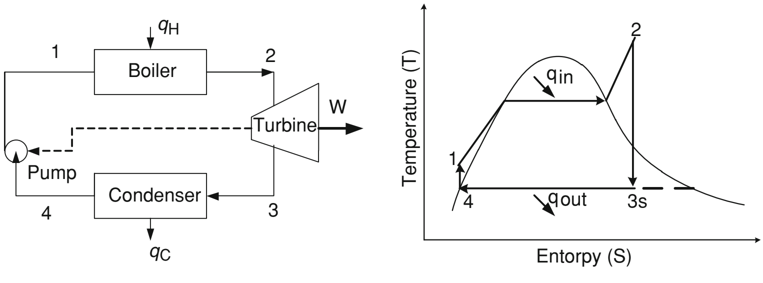
Net value of the work $\dot{W}_{\mathrm{net}}$ produced is

$$\dot{W}_{\mathrm{net}} = (\dot{q}_{\mathrm{in}} - \dot{q}_{\mathrm{out}}) \tag{6.11}$$

Performance of a steam turbine will be limited by the quality discharged steam. Discharged steam with a low quality may decrease the life of turbine blades and efficiency of the turbine. The easiest way to overcome this problem is by superheating the steam. Example 6.5 illustrates the analysis of an ideal Rankine cycle.

Example 6.5 Analysis of a simple ideal Rankine cycle

A steam power plant operates on a simple ideal Rankine cycle shown below. The turbine receives steam at 698.15 K and 4100 kPa, while the discharged steam is at 40 kPa. The mass flow rate of steam is 8.5 kg/s. Determine the net work output.



Solution:
Assume that the kinetic and potential energy changes are negligible.
$\dot{m}_s = 8.5\ \text{kg/s}$

$P_2 = P_1 = 4100$ kPa; $H_2 = 3272.3$ kJ/kg: $S_2 = 6.8450$ kJ/kg (Table F4)
Saturated steam properties at $P_3 = P_4 = 40$ kPa, $V_4 = 0.001022\ \text{m}^3/\text{kg}$ (Table F3)

$H_{3\text{sat vap}} = 2636.9$ kJ/kg; $H_4 = H_{3\text{sat liq}} = 317.65$ kJ/kg;
$S_{3\text{sat vap}} = 7.6709$ kJ/kg K; $S_{3\text{sat liq}} = 1.0261$ kJ/kg K
Basis: mass flow rate of 1 kg/s:

$$W_{p,\text{in}} = V_1(P_1 - P_4) = (0.001022)(4100 - 40)\left(\frac{1\text{kJ}}{1\ \text{kPa m}^3}\right) = 4.14\,\text{kJ/kg}$$

$$H_1 = H_4 + W_{p,\text{in}} = 321.79\ \text{kJ/kg}$$

Isentropic process $S_1 = S_4$ and $S_3 = S_2$. The quality of the discharged wet steam ($S_3 < S_{3\text{sat vap}}$):
$x_{3s} = (6.845 - 1.0262)/(7.6709 - 1.0261) = 0.875$
$H_3 = 317.65(1 - 0.875) + 2636.9 \times 0.875 = 2356.6\ \text{kJ/kg}$
$q_{\text{in}} = H_2 - H_1 = 2950.5\ \text{kJ/kg}$
$q_{\text{out}} = H_3 - H_4 = 2038.9\ \text{kJ/kg}$
With a steam flow rate of 8.5 kg/s, we have
$\dot{W}_{\text{net}} = \dot{m}(q_{\text{in}} - q_{\text{out}}) = 7748.6\ \text{kW} = \mathbf{7.75\,MW}$

6.4.3 Brayton Cycle

A gas turbine cycle relies on the *Brayton cycle* using air as the working fluid as shown in Fig. 6.8. An ideal Brayton cycle consists of the following processes:

- *Isentropic process*—Ambient air is drawn into the compressor.
- *isobaric process*—The compressed air then runs through a combustion chamber where fuel is burned, heating the air at a constant-pressure process.
- *isentropic process*—The heated, pressurized air then gives up its energy by expanding through a turbine (or series of turbines).
- *isobaric process*—Heat rejection to the surroundings.

Some of the electricity produced from the turbine is used to drive the compressor through a crankshaft arrangement. The gas turbine requires clean fuels such as natural gas or light fuel oil.

Actual Brayton cycle has the processes:

- Compression (adiabatic),
- Heat addition (isobaric),

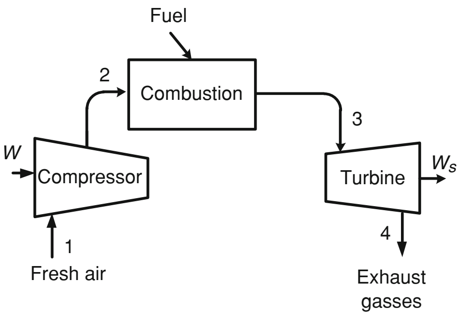


Fig. 6.8 Schematic of ideal Brayton cycle with processes of adiabatic compression, isobaric heat addition, adiabatic expansion, and isobaric heat rejection

- Expansion (adiabatic),
- Heat rejection (isobaric).

Since neither the compression nor the expansion can be truly isentropic, losses through the compressor and the expander may be considerable. Increasing the compression ratio increases the overall power output of a Brayton system. Intercooling the working fluid decreases the amount of work needed for the compression stage overall and increases the fuel consumption of the combustion chamber. To increase the power output for a given compression ratio, air expands through a series of turbines and then is passed through a second combustion chamber before expanding to ambient pressure [4, 7].

6.4.4 Stirling Engine

A Stirling engine is a heat engine operating by cyclic compression and expansion of the working fluid at different temperature levels such that there is a net conversion of heat energy to mechanical work. The working fluid is mainly air although other gases can also be used. The Stirling engine is highly efficient compared to steam engines and can use almost any heat source [17, 28]. The Stirling engine is classified as an external combustion engine, as all heat transfers to and from the working fluid take place through the engine wall. The engine cycle consists of compressing gas, heating the gas, expanding the hot gas, and finally cooling the gas before repeating the cycle. Its practical use is largely confined to low power domestic applications.

6.4.5 *Combined Cycles*

A combined cycle power plant uses the Brayton cycle of the gas turbine with the Rankine cycle of a heat recovery steam generator. The combined cycle plants are designed in a variety of configurations composed of a number of gas turbines followed by a steam turbine. They generate power by burning natural gas in a gas turbine and use residual heat to generate additional electricity from steam [4, 21].

Coal gasification produces a fuel gas that is capable of being used in the gas turbine. By integrating coal gasification with gas turbine and steam cycles, a low pollutant emission can be achieved while using coal. A potential additional advantage of the integrated gasification combined cycle is the capability of capturing carbon dioxide from the fuel gas and making it ready for high-pressure pipeline transportation to a carbon sequestration site.

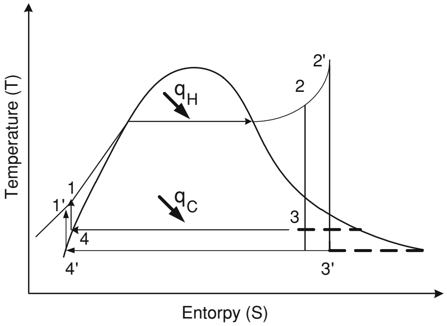
6.5 Improving the Power Production in Steam Power Plants

Improvements on power plant operations may increase efficiency and power output while reducing the fuel consumption. The modifications for improvements aim at increasing the average temperature at which heat is transferred to the steam in the boiler and decrease the average temperature at which heat is removed in the condenser [6, 9, 20, 27]. Some common modifications in steam power production are summarized in the following sections.

6.5.1 *Modification of Operating Conditions of the Condenser and Boiler*

Superheating the steam to high temperature increases the temperature at which the heat flows into the boiler and increases the power output and quality of the discharged steam. Figure 6.9 shows the effects of superheating the steam to higher temperatures and reducing the condenser pressure on the ideal Rankine cycle on a *TS* diagram. The area enclosed by the process curve "1′–2′–3′–4′" is larger than that of the area for "1–2–3–4" and represents the net work output increase of the cycle under higher boiler temperature and lower condenser pressure. The operating pressures may be as high as 30 MPa (4500 psia) in modern steam power plants operating at supercritical pressures ($P > 22.09$ MPa). By metallurgical constraints, the temperature of steam is limited. The temperature at the turbine inlet may be as high as 620°C [7].

Fig. 6.9 Effects of superheating the steam to higher temperatures and reducing the condenser pressure on an ideal Rankine cycle



6.5.2 Reheating the Steam

Superheating the steam to high temperatures enables the expansion of the steam in various stages instead of a single expansion process. Mainly, reheating increases the power output and the steam quality to protect the material. Figure 6.10 shows a typical reheat Rankine cycle. In an ideal reheat Rankine cycle with two-stage expansion, for example, the steam is expanded to an intermediate pressure isentropically in the high-pressure turbine section, and sent to the boiler to be reheated. In the low-pressure turbine section, the reheated steam is expanded to the condenser operating pressure. Example 6.6 illustrates a simple analysis of ideal reheat Rankine cycle.

Example 6.6 Simple reheat Rankine cycle in a steam power plant
A simple ideal reheat Rankine cycle is used in a steam power plant shown in Fig. 6.10. Steam enters the turbine at 9000 kPa and 823.15 K and leaves at 4350 kPa and 698.15 K. The steam is reheated at constant pressure to 823.15 K. The discharged steam from the low-pressure turbine is at 10 kPa. The net power output of the turbine is 40 MW. Determine the mass flow rate of steam.

Solution:
Assume that the kinetic and potential energy changes are negligible, and this is a steady process.

Consider Fig. 6.10.
Data: Steam data from Table F3 and Table F4
$V_1 = 0.00101$ m^3/kg, $P_3 = 9000$ kPa, $H_3 = 3509.8$ kJ/kg, $S_3 = 6.8143$ kJ/kg
$P_6 = 10$ kPa
$T_4 = 698.15$ K, $P_4 = 4350$ kPa, $H_4 = 3268.5$ kJ/kg, $S_3 = S_4 = 6.8143$ kJ/kg
$T_5 = 823.15$ K, $P_5 = 4350$ kPa, $H_5 = 3555.2$ kJ/kg, $S_5 = S_6 = 7.1915$ kJ/kg

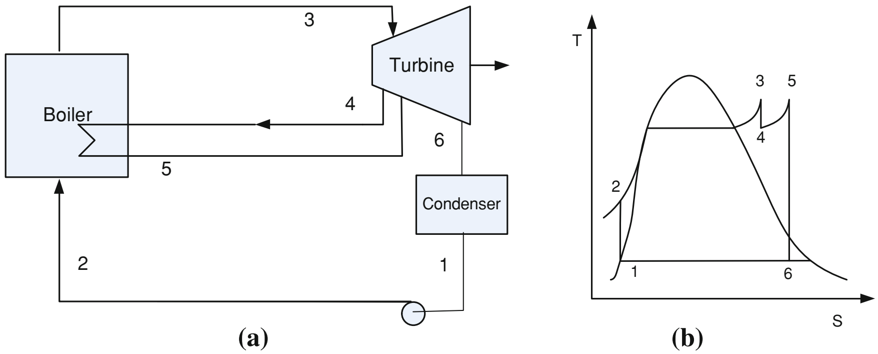


Fig. 6.10 **a** Ideal reheat Rankine cycle. **b** T versus S diagram for the reheat Rankine cycle

Saturated vapor and liquid data:
$H_{6\text{sat vap}} = H_{1\text{sat vap}} = 2584.8$ kJ/kg, $H_{1\text{sat liq}} = H_{6\text{sat liq}} = 191.81$ kJ/kg (Table F3)
$S_{6\text{sat vap}} = 8.1511$ kJ/kg K, $S_{6\text{sat liq}} = 0.6493$ kJ/kg K
Based on $\dot{m} = 1\,\text{kg/s}$ steam flow rate:

$$W_{p,\text{in}} = V_1(P_2 - P_1) = 0.00101(9000 - 10)\left(\frac{1\text{kJ}}{1\text{ kPa m}^3}\right) = 9.08\text{ kJ/kg}$$

$$H_2 = H_1 + W_{p,\text{in}} = 200.9\text{ kJ/kg}$$

Because this is an isentropic process $S_5 = S_6$ and $S_1 = S_2$. We estimate the quality of the discharged wet steam ($S_6 < S_{6\text{sat vap}}$) after passing through the turbine:
$x_{6s} = (7.1915 - 0.6493)/(8.1511 - 0.6493) = 0.872$
$H_6 = 191.81(1 - 0.872) + 2584.8(0.872) = 2278.7\text{ kJ/kg}$

Heat interactions:
$q_{23,\text{in}} = H_3 - H_2 = 3308.9\text{ kJ/kg}$
$q_{45,\text{in}} = H_5 - H_4 = 286.7\text{ kJ/kg}$
$q_{\text{out}} = H_1 - H_6 = 2086.9\,\text{kJ/kg}$
$q_{\text{in}} = q_{23,\text{in}} + q_{45,\text{in}} = 3595.6\,\text{kJ/kg}$
$\dot{W}_{\text{out}} = \dot{m}(q_{\text{in}} - q_{\text{out}}) - \dot{m}(3595.5 - 2086.9)\text{kJ/kg} = 40000\,\text{kW}$
$\dot{m} = \mathbf{26.5\ kg/s}$

In this ideal reheat Rankine cycle, the expanded steam from the first part of the high-pressure section is reheated in the boiler until it reaches the boiler exit temperature. The reheated steam is expanded through the turbine to the condenser conditions. The reheating decreases the moisture within the discharged steam.

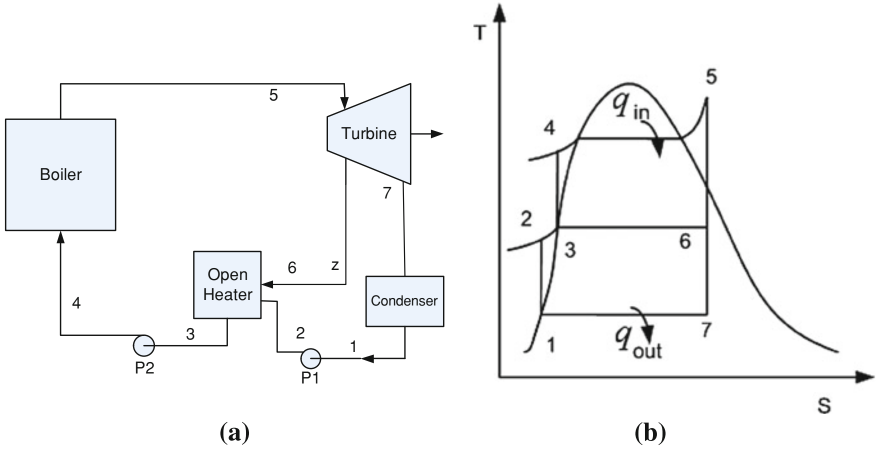


Fig. 6.11 **a** Ideal regenerative Rankine cycle. **b** Temperature *T* versus entropy *S* diagram for ideal regenerative Rankine cycle. Here P1 and P2 show the circulation pumps

6.5.3 Regeneration

Increasing the boiler water feed temperature by using the expanding steam is possible in a regenerative cycle. Figure 6.11 shows a typical regenerative Rankine cycle. Steam extracted at intermediate pressures from the turbine is used to heat the boiler water feed. The steam at stage 3 leaves the condenser as a saturated liquid at the condenser operating pressure by adjusting the fraction of steam extracted from the turbine. Regeneration helps deairate the water and control the discharged steam flow rate. Example 6.7 illustrates a simple analysis of ideal regenerative Rankine cycle.

Example 6.7 Power output of ideal regenerative Rankine cycle

A steam power plant is using an ideal regenerative Rankine cycle shown in Fig. 6.11. Steam enters the high-pressure turbine at 8200 kPa and 773.15 K, and the condenser operates at 20 kPa. The steam is extracted from the turbine at 350 kPa to heat the feed water in an open heater. The water is a saturated liquid after passing through the feed water heater. Determine the net power output of the cycle.

Solution**:**

Assume that the kinetic and potential energy changes are negligible, and this is a steady-state process.

Consider Fig. 6.11.
Basis: steam flow rate is 1 kg/s
The steam data are from Table F_3 and Table F_4:

$V_1 = 0.001017$ m^3/kg, $V_3 = 0.001079$ m^3/kg,
$T_5 = 773.15$ K, $P_5 = 8200$ kPa, $H_5 = 3396.4$ kJ/kg, $S_5 = 6.7124$ kJ/kg

$P_1 = P_7 = 20$ kPa,
$H_{7\text{sat vap}} = H_{1\text{sat vap}} = 2609.9$ kJ/kg, $H_{7\text{sat liq}} = H_{1\text{sat liq}} = 251.45$ kJ/kg,
$S_{7\text{sat vap}} = 7.9094$ kJ/kg K, $S_{7\text{sat liq}} = 0.8321$ kJ/kg K

$P_2 = P_3 = 350$ kPa,
$H_{6\text{sat liq}} = H_{3\text{sat liq}} = 584.27$ kJ/kg, $H_{6\text{sat vap}} = H_{3\text{sat vap}} = 2731.50$ kJ/kg
$S_{3\text{sat liq}} = 1.7273$ kJ/kg K, $S_{3\text{sat vap}} = 6.9392$ kJ/kg K

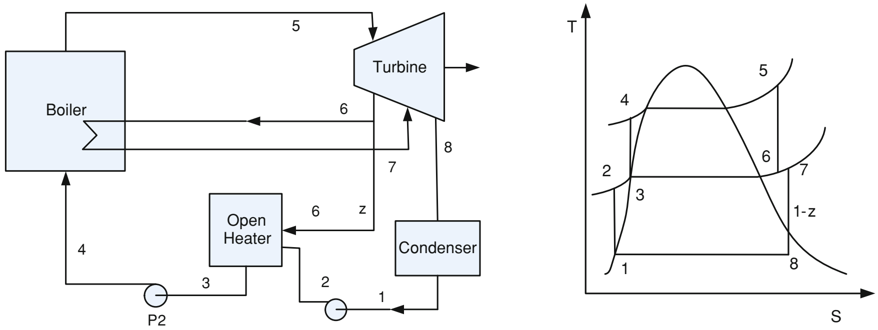
In this ideal regenerative Rankine cycle, the steam extracted from the turbine heats the water from the condenser, and the water is pumped to the boiler. Sometimes, this occurs in several stages. The condensate from the feed water heaters is throttled to the next heater at lower pressure. The condensate of the final heater is flashed into the condenser.

$$\begin{aligned}
W_{p1} &= V_1(P_2 - P_1) = 0.001017(350 - 20)\left(\frac{1\,\text{kJ}}{1\,\text{kPa}\,\text{m}^3}\right) = 0.335\,\text{kJ/kg} \\
H_2 &= H_1 + W_{p1} = 252.78\,\text{kJ/kg} \\
W_{p2} &= V_3(P_4 - P_3) = 0.001079(8200 - 350)\left(\frac{1\,\text{kJ}}{1\,\text{kPa}\,\text{m}^3}\right) = 8.47\,\text{kJ/kg} \\
H_4 &= H_3 + W_{p2} = 592.74\,\text{kJ/kg}
\end{aligned}$$

Because this is an isentropic process, $S_5 = S_6 = S_7$. We estimate the quality of the discharged wet steam at states 6 ($S_5 < S_{6\text{sat vap}}$) and 7 ($S_5 < S_{7\text{sat vap}}$):

$$\begin{aligned}
x_6 &= \frac{6.7124 - 1.7273}{6.9392 - 1.7273} = 0.956 \\
H_6 &= 584.27(1 - 0.956) + 2731.50(0.956) = 2638.0\,\text{kJ/kg} \\
x_7 &= \frac{6.7124 - 0.8321}{7.9094 - 0.8321} = 0.83 \\
H_7 &= 252.45(1 - 0.83) + 2609.9(0.83) = 2211.18\,\text{kJ/kg K}
\end{aligned}$$

The fraction of steam extracted is estimated from the energy balance:
$\dot{m}_6 H_6 + \dot{m}_2 H_2 = \dot{m}_3 H_3$
In terms of the mass fraction $z = \dot{m}_6/\dot{m}_3$, the energy balance becomes
$zH_6 + (1 - z)H_2 = H_3$
The mass fraction: $z = \dfrac{H_3 - H_2}{H_6 - H_2} = 0.139$
$q_{\text{in}} = (H_5 - H_4) = 2803.66\,\text{kJ/kg}$
$q_{\text{out}} = (1 - z)(H_7 - H_1) = 1686.52\,\text{kJ/kg}$
$W_{\text{net}} = (q_{\text{in}} - q_{\text{out}}) = \mathbf{1117.13\,kJ/kg}$



(a) (b)

Fig. 6.12 **a** Schematic of ideal reheat regenerative Rankine cycle. **b** *T-S* diagram of the cycle

6.5.4 Reheat–Regenerative Rankine Cycle

In *reheat–regenerative Rankine cycle*, shown in Fig. 6.8, the part of steam extracted from the turbine heats the water from the condenser, and the remaining part is reheated in the boiler. Example 6.8 illustrates a simple analysis of reheat–regenerative Rankine cycle.

Example 6.8 Ideal reheat–regenerative cycle

A steam power plant is using an ideal reheat regenerative Rankine cycle. Steam enters the high pressure turbine at 9000 kPa and 773.15 K and leaves at 850 kPa. The condenser operates at 10 kPa. Part of the steam is extracted from the turbine at 850 kPa to heat the water in an open heater, where the steam and liquid water from the condenser mix and direct contact heat transfer takes place. The rest of the steam is reheated to 723.15 K, and expanded in the low pressure turbine section to the condenser pressure. The water is a saturated liquid after passing through the water heater and is at the heater pressure. The flow rate of steam is 32.5 kg/s. Determine the power produced.

Solution:
Assume negligible kinetic and potential energy changes, and that this is a steady-state process.

Consider Fig. 6.12.
The steam data from Table F3 and Table F4:
$P_5 = 9000$ kPa, $H_5 = 3386.8$ kJ/kg, $S_5 = 6.6600$ kJ/kg K, $T_5 = 773.15$ K
$P_1 = P_8 = 10$ kPa, $H_{8\text{sat vap}} = 2584.8$ kJ/kg, $H_{8\text{sat liq}} = 191.83$ kJ/kg,
$V_1 = 0.00101$ m^3/kg
$S_{8\text{sat vap}} = 8.1511$ kJ/kg K, $S_{8\text{sat liq}} = 0.6493$ kJ/kg K

$P_3 = 850$ kPa, $H_{3\text{sat liq}} = 732.03$ kJ/kg, $H_{3\text{sat vap}} = 2769.90$ kJ/kg,
$V_3 = 001079$ m^3/kg
$P_7 = 850$ kPa, $H_7 = 3372.7$ kJ/kg, $S_7 = 7.696$ kJ/kg K, $T_7 = 723.15$ kPa
S_5 and $P_6 = 850$ kPa → $T_6 = 450.0$ K, $H_6 = 2779.58$ kJ/kg

Work and enthalpy estimations for a unit mass flow rate of steam yield:

$$W_{p1} = V_1(P_2 - P_1) = 0.00101(850 - 10)\left(\frac{1\,\text{kJ}}{1\,\text{kPa}\,\text{m}^3}\right) = 0.848\,\text{kJ/kg}$$
$$H_2 = H_1 + W_{p1} = 192.68\,\text{kJ/kg}$$
$$W_{p2} = V_3(P_4 - P_3) = 0.001079(9000 - 850)\left(\frac{1\,\text{kJ}}{1\,\text{kPa}\,\text{m}^3}\right) = 90.046\,\text{kJ/kg}$$
$$H_4 = H_3 + W_{p2} = 7410.07\,\text{kJ/kg}$$

Because this is an isentropic process, $S_5 = S_6$ and $= S_7 = S_8$, we estimate the quality of the discharged wet steam at state 8 ($S_7 < S_{8\text{sat vap}}$):

$$x_8 = \frac{7.696 - 0.6493}{8.1511 - 0.6493} = 0.94$$
$$H_8 = 191.83(1 - 0.94) + 2584.8(0.94) = 2439.63\,\text{kJ/kg}$$

The fraction of steam extracted is estimated from the energy balance $\dot{m}_6 H_6 + \dot{m}_2 H_2 = \dot{m}_3 H_3$.
In terms of the mass fraction $z = \dot{m}_6/\dot{m}_3$, the energy balance becomes: $zH_6 + (1 - z)H_2 = H_3$.
The mass fraction is

$$z = \frac{H_3 - H_2}{H_6 - H_2} = \frac{732.03 - 192.68}{2779.58 - 192.68} = 0.208$$

The turbine work output with $\dot{m} = 1\,\text{kg/s}$ working fluid is:
$q_{\text{in}} = [(H_5 - H_4) + (1 - z)(H_7 - H_6)] = 3115.18\,\text{kW}$
$q_{\text{reheat}} = z(H_7 - H_6) = 593.12\,\text{kW}$
$q_{\text{out}} = (1 - z)(H_8 - H_1) = 1779.14\,\text{kW}$
For steam flow rate of 36.5 kg/s:
$\dot{W}_{\text{net}} = \dot{m}_s(q_{\text{in}} - q_{\text{out}}) = \mathbf{48,764\,kW} = \mathbf{48.8\,MW}$

6.6 Geothermal Power Plants

Figure 6.13 shows a schematic of a geothermal power plant. Geothermal power comes from heat energy buried beneath the surface of the earth. There are three types of geothermal power plants:

- *Dry Steam Power Plants*: The geothermal steam goes directly to a turbine, where it expands and produces power. The expanded steam is injected into the geothermal well.

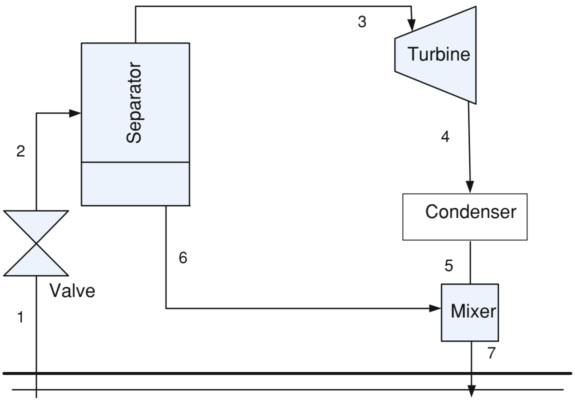


Fig. 6.13 Schematic of a geothermal plant

- *Flash Steam Power Plants*: Geothermal fluids above 360°F (182°C) can be flashed in a tank at low pressure causing some of the fluid to rapidly vaporize. The vapor then expands in a turbine.
- *Binary-Cycle Power Plants*: Moderate-temperature geothermal fluids between 85 and 170°C are common. The term "binary" refers to dual-fluid systems, wherein hot geothermal brine is pumped through a heat exchange network to transfer its energy to a working fluid driving a power train. A hot geothermal fluid and a suitable working fluid with a much lower boiling point then the geothermal fluid pass through a heat exchanger. The vaporized working fluid drives the turbines; no working fluid is emitted into the atmosphere. The working fluids may be isobutene, isopentane, n-pentane, or ammonia.

At temperatures below about 200°C, binary power systems are favored for relative cost effectiveness. In general, above about 200°C, flashing geothermal fluids to produce steam and directly driving turbine/generator is preferred. Example 6.9 illustrates a simple analysis of a steam power plant using a geothermal source [4, 10].

Example 6.9 A steam power plant using a geothermal energy source

A steam power plant is using a geothermal energy source. The geothermal source is available at 220°C and 2319.8 kPa with a flow rate of 200 kg/s. The hot water goes through a valve and a flash drum. Steam from the flash drum enters the turbine at 550 kPa and 428.62 K. The discharged steam from the turbine has a quality of $x_4 = 0.96$. The condenser operates at 10 kPa. The water is a saturated liquid after passing through the condenser. Determine the work output of turbine.

Solution:

Assume: The kinetic and potential energy changes are negligible, and this is a steady-state process.

The steam data from Table F3 and Table F4:
$T_1 = 493.15$ K, $P_1 = 2319.8$ kPa, $H_1 = H_2 = 943.7$ kJ/kg, $S_1 = 2.517$ kJ/kg K,
$T_3 = 428.62$ K, $P_3 = 550$ kPa, $H_3 = 2751.7$ kJ/kg, $S_3 = 6.787$ kJ/kg K (saturated),
$H_{3\text{sat vap}} = 2551.7$ kJ/kg, $H_{3\text{sat liq}} = 655.80$ kJ/kg, $S_{3\text{sat vap}} = 6.787$ kJ/kg K,
$S_{3\text{sat liq}} = 1.897$ kJ/kg K
$P_4 = 10$ kPa, $H_{4\text{sat vap}} = 2584.8$ kJ/kg, $H_{4\text{sat liq}} = 191.8$ kJ/kg

In this geothermal power plant, the hot water is flashed and steam is produced. This steam is used in the turbine.

The rate of vapor is estimated from the quality at state 2. The fraction of steam after flashing is:

$$x_2 = \frac{943.7 - 655.8}{2751.7 - 655.8} = 0.159$$

$$S_2 = (1 - 0.159)1.897 + 0.159(6.787) = 2.6756$$

The steam flow rate is: $\dot{m}_3 = x_2(\dot{m}_1) = 0.159(200) = 31.84\,\text{kg/s}$
From the mass balance around the flash drum, we have $\dot{m}_6 = \dot{m}_1 - \dot{m}_3 = 168.15\,\text{kg/s}$

The discharged steam has the quality of: $x_4 = 0.96$
$H_4 = (1-0.96)H_{4\text{sat liq}} + (0.96)H_{4\text{sat vap}} = 2489.08$ kJ/kg

From the flash drum at state 6, we have
$\dot{W}_{\text{net}} = \dot{m}_3(H_4 - H_3) = \mathbf{-8363.71\,kW}$

6.7 Cogeneration

Figure 6.14 shows a typical cogeneration plant. Cogeneration plant produces electric power and process heat from the same heat source. This may lead to the utilization of more available energy and the reduction of waste heat. A cogeneration plant, for example, may use the waste heat from Brayton engines, typically for hot water production or for space heating. The process heat in industrial plants usually needs steam at 500–700 kPa, and 150–200°C. The steam expanded in the turbine to the process pressure is used as process heat. Cycles making use of cogeneration may be an integral part of large processes where the energy of the expanded steam from the turbine at intermediate pressure may be fully utilized in producing electricity and process heat simultaneously. The *utilization factor* for a cogeneration plant is the ratio of the energy used in producing power and process heat to the total energy input. Examples 6.10 and 6.11 illustrate simple analyses of energy output in cogeneration plants [4, 7].

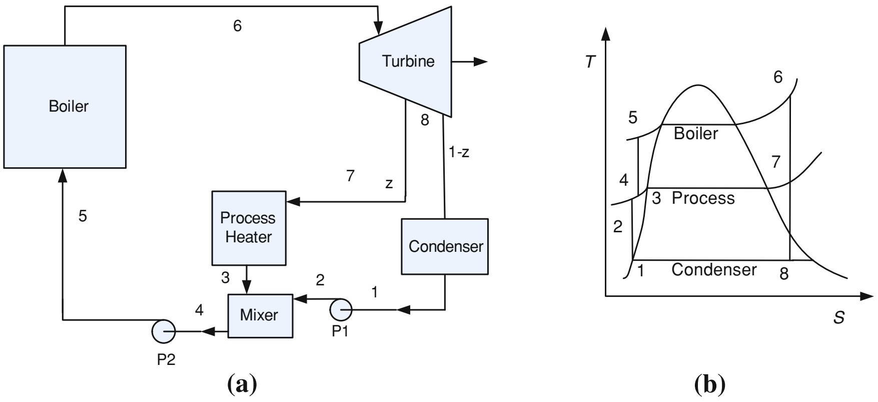


Fig. 6.14 **a** Schematic of ideal cogeneration plant. **b** *TS* diagram

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Example 6.10 Energy output in a cogeneration plant

A cogeneration plant is using steam at 8200 kPa and 773.15 K (see Fig. 6.14). One-fourth of the steam is extracted at 700 kPa from the turbine for cogeneration. After it is used for process heat, the extracted steam is condensed and mixed with the water output of the condenser. The rest of the steam expands from 8200 kPa to the condenser pressure of 10 kPa. The steam flow rate produced in the boiler is 60 kg/s. Determine the work output and process heat produced.

Solution:
Assume that the kinetic and potential energy changes are negligible, and this is a steady-state process.
Consider Fig. 6.14.
The steam data from Table F3 and Table F4:
$\dot{m} = 60\,\mathrm{kg/s}, z = 0.25$
$P_1 = P_8 = 10$ kPa, $H_{1\text{sat vap}} = 2584.8$ kJ/kg, $H_{1\text{sat liq}} = 191.83$ kJ/kg,
$V_1 = 0.00101$ m^3/kg, $S_{1\text{sat vap}} = 8.1511$ kJ/kg K, $S_{1\text{sat liq}} = 0.6493$ kJ/kg K

$P_3 = P_7 = P_2 = P_4 = 700$ kPa, $H_3 = 697.06$ kJ/kg, $S_3 = 1.9918$ kJ/kg K
Table F_4:
$P_6 = 8200$ kPa, $T_6 = 773.15$ K, $H_6 = 3396.4$ kJ/kg, $S_6 = 6.7124$ kJ/kg K

In this cogeneration cycle, the steam extracted from the turbine is used as process heat. The liquid condensate from the process heat is combined with the output of the condenser.
Basis: mass flow rate = 1 kg/s

$$W_{p1} = V_1(P_2 - P_1) = 0.00101(700 - 10)\left(\frac{1\,\mathrm{kJ}}{1\,\mathrm{kPa\,m^3}}\right) = 0.697\,\mathrm{kJ/kg}$$

$$H_2 = H_1 + W_{p1} = 191.83 + 0.697 = 192.53\,\mathrm{kJ/kg}$$

From the energy balance around the mixer, we have $\dot{m}_3/\dot{m}_6 = 0.25$

$\dot{m}_6 = \dot{m}_4 = 60\,\text{kg/s}$, $\dot{m}_3 = \dot{m}_7 = 15\,\text{kg/s}$, $\dot{m}_8 = \dot{m}_1 = 0.75(60) = 45.0\,\text{kg/s}$
$\dot{m}_4 H_4 = \dot{m}_2 H_2 + \dot{m}_3 H_3$
$H_4 = [45(192.53) + 15(697.06)]/60 = 318.66$ kJ/kg
$T_4 = 349.15$ K, $V_4 = 0.001027$ kg/m^3

$$W_{p2} = V_4(P_5 - P_4) = 0.001027(8200 - 700)\left(\frac{1\,\text{kJ}}{1\,\text{kPa}\,\text{m}^3}\right) = 7.70\,\text{kJ/kg}$$

$H_5 = H_4 + W_{p2} = 326.36\,\text{kJ/kg}$
Isentropic processes: $S_6 = S_7 = S_8 = 6.7124$ and $P_7 = 700$ kPa,
$H_7 = 2765.68$ kJ/kg.

We estimate the quality of the discharged wet steam at state 8:

$$x_8 = \frac{6.7124 - 0.6493}{8.1511 - 0.6493} = 0.808$$

$H_8 = 191.83(1 - 0.808) + 2584.80(0.808) = 2125.87\,\text{kJ/kg}$

The energy balance yields the fraction of steam extracted
$\dot{W}_{\text{total}} = \dot{m}_6(H_7 - H_6) + \dot{m}_8(H_8 - H_7) = -66634.44\,\text{kW}$
$\sum \dot{W}_{pi} = \dot{m}_1 W_{p1} + \dot{m}_4 W_{p2} = 493.51\,\text{kW}$

The net work output:
$\dot{W}_{\text{net}} = \dot{W}_{\text{total}} - \sum \dot{W}_{pi} = \mathbf{-66140.93\,kW}$
$\dot{q}_{\text{process}} = \dot{m}_7(H_7 - H_3) = \mathbf{31029.3\,kW}$

Example 6.11 Estimation of process heat in a cogeneration plant

A cogeneration plant uses steam at 900 psia and 1000°F to produce power and process heat. The steam flow rate from the boiler is 16 lb/s. The process requires steam at 70 psia at a rate of 3.2 lb/s supplied by the expanding steam in the turbine with a value of $z = 0.2$. The extracted steam is condensed and mixed with the water output of the condenser. The remaining steam expands from 70 psia to the condenser pressure of 3.2 psia. Determine the rate of process heat.

Solution:
Assume that the kinetic and potential energy changes are negligible, and this is a steady-state process.

Consider Fig. 6.14. The steam data from Table F1 and Table F2:
$\dot{m}_6 = 16\,\text{lb/s}$, $z = \dot{m}_3/\dot{m}_6 = 0.2$, $\dot{m}_3 = 3.2\,\text{lb/s}$
$P_1 = P_8 = 3.2$ psia, $H_{1\text{sat vap}} = 1123.6$ Btu/lb, $H_{1\text{sat liq}} = 111.95$ Btu/lb
$V_1 = 0.01631$ ft^3/lb
$S_{1\text{sat vap}} = 0.2051$ Btu/lb R, $S_{1\text{sat liq}} = 1.8810$ Btu/lb R
$P_3 = 70$ psia, $H_3 = 272.74$ Btu/lb, (Saturated)
$P_6 = 900$ psia, $H_6 = 1508.5$ Btu/lb, $S_6 = 1.6662$ Btu/lb R, $T_6 = 1000$°F

In this cogeneration cycle, the steam extracted from the turbine is used in process heat. The liquid condensate from the process heat is combined with the output of the condenser.

Basis: mass flow rate = 1 lb/s

$W_{p1} = V_1(P_2 - P_1) = 0.01631(70 - 3.2)\left(\frac{1\,\text{Btu}}{5.4039\,\text{psia}\,\text{ft}^3}\right) = 0.20\,\text{Btu/lb}$

$H_2 = H_1 + W_{p1} = 111.95 + 0.20 = 112.15\,\text{Btu/lb}$

From the energy balance around the mixer, we have z = 0.2:

$$\dot{m}_4 H_4 = \dot{m}_2 H_2 + \dot{m}_3 H_3 \quad H_4 = (\dot{m}_2 H_2 + \dot{m}_3 H_3)/\dot{m}_4$$

Basis: 1 lb/s then $\dot{m}_2 = \dot{m}_1 = 0.8\,\text{lb/s}$, $\dot{m}_3 = 0.2$ lb/s, $\dot{m}_4 = 1$ lb/s

$H_4 = [0.8(112.18) + 0.2(272.74]/1 = 144.29$ Btu/lb → $S_4 = 0.2573$ Btu/lb R

$T_4 = 635.87$ R

$W_{p2} = V_4(P_5 - P_4) = 0.0175(900 - 70)\left(\frac{1\,\text{Btu}}{5.4039\,\text{psia}\,\text{ft}^3}\right) = 2.7$ Btu/lb

$H_5 = H_4 + W_{p2} = 147.0$ Btu/lb

Because these are isentropic processes, $S_6 = S_{7\text{s}} = S_{8\text{s}} = 1.6662$ Btu/lb R $P_7 = 70$ psia, $H_{7\text{s}} = 1211.75$ Btu/lb.

Quality of the discharged wet steam at state 8s is:

$x_{8s} = \frac{1.6662 - 0.2051}{1.8810 - 0.2051} = 0.871$

$H_{8s} = 111.95(1 - 0.871) + 1123.6(0.871) = 993.93$ Btu/lb

The steam quality at state 8: $x_8 = \frac{993.9 - 111.95}{1123.60 - 111.95} = 0.87$

Process heat: $\dot{q}_{\text{process}} = \dot{m}_3(H_7 - H_3) = \mathbf{3004.8\,Btu/s}$

6.8 Nuclear Power Plants

Nuclear power is a method in which steam is produced by heating water through a process called *nuclear fission*. Nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller parts, often producing free neutrons and photons in the form of *gamma rays* (γ). *Gamma rays* are electromagnetic radiation of frequencies above 10^{19} Hz, and therefore have energies above 100 keV and wavelength less than 10 pm. In a nuclear power plant, a reactor contains a core of nuclear fuel, primarily uranium. When atoms of uranium fuel are hit by neutrons, they fission (split) releasing heat and more neutrons. Under controlled conditions, these neutrons can strike and split more uranium atoms.

Typical fission releases about two hundred million eV of energy (1 eV is 96.485 kJ/mol). By contrast, most chemical oxidation reactions, such as burning coal, release at most a few eV. In a nuclear reactor, the energy is converted to heat as the particles and gamma rays collide with the atoms that make up the reactor and its working fluid, usually water or occasionally heavy water.

Fusion power, on the other hand, is generated by nuclear fusion reactions where two light atomic nuclei fuse together to form a heavier nucleus and in doing so, release a large amount of energy. If two light nuclei fuse, they will generally form a single nucleus with a slightly smaller mass than the sum of their original masses. The difference in mass is released as energy according to Albert Einstein's mass-energy equivalence formula $E = mc^2$. The dividing line between "light" and "heavy" is iron-56. Above this atomic mass, energy will generally be released by nuclear fission reactions. Most fusion reactions combine isotopes of hydrogen that are protium, deuterium, or tritium to form isotopes of helium ^{3}He or ^{4}He. Most fusion power plants involve using the fusion reactions to create heat, which is then used to operate a steam turbine, which drives generators to produce electricity. This is similar to most coal, oil, and gas-fired power production plants [3].

Nuclear fusion requires precisely controlled temperature, pressure, and magnetic field parameters to generate net energy. If the reactor were damaged, these parameters would be disrupted and the heat generation in the reactor would rapidly cease. In contrast, the fission products in a fission reactor continue to generate heat for several hours or even days after reactor shutdown, meaning that melting of fuel rods is possible even after the reactor has been stopped due to continued accumulation of heat.

6.9 Hydropower Plants

Hydropower is a process in which the force of flowing water is used to spin a turbine connected to a generator to produce electricity. Most hydroelectric power comes from the potential energy of dammed water driving a turbine and generator. The power extracted from the water depends on the volume and the amount of potential energy in water is proportional to the head, which is difference in height between the source and the water's outflow. A simple formula for approximating electric power production at a hydroelectric plant is:

$$\dot{W} = \dot{Q}\rho g\Delta z = \dot{m}g\Delta z \tag{6.13}$$

where $\dot{W}$ is the power, ρ is the density of water (~ 1000 kg/m^3), Δz is the height, Q is the volumetric flow rate, and g is the acceleration due to gravity. Annual electric energy production depends on the available water supply. In some installations the water flow rate can vary by a factor of 10:1 over the course of a year. Example 6.12 illustrates the analysis of hydroelectric power output.

Hydropower eliminates the use of fossil fuels and hence carbon dioxide emission. Hydroelectric plants also tend to have longer economic lives (50 years or longer) than fuel-fired power production. The sale of hydroelectricity may cover the construction costs after 5–8 years of full operation [15]. Operating labor cost is also usually low, as plants are automated. The hydroelectric capacity is either the actual annual energy production or by installed capacity. A hydroelectric plant rarely operates at its full capacity over a full year. The ratio of annual average power output to installed capacity is the *capacity factor* for a hydroelectric power plant. There are large, small, and micro hydropower plant operations, which are summarized below.

- *Large hydroelectric power stations* have outputs from over a few hundred megawatts to more than 10 GW. Many large hydroelectric projects supply public electricity networks. The construction of these large hydroelectric facilities and the changes it makes to the environment are monitored by specialized organizations, such as the International Hydropower Association (http://hydropower.org/).
- *Small hydroelectric power plants* have a capacity of up to 10 MW. Some are created to serve specific industrial plants, such as for aluminum electrolytic plants, for which substantial amount of electricity is needed.
- Micro hydroelectric power installations typically produce up to 100 KW of power. These installations can provide power to an isolated home or small community. Sometimes, micro hydro systems may complement photovoltaic solar energy systems, because water flow and available hydro power may be highest in the winter when solar energy is at a minimum.

Example 6.12 Hydroelectric power output

A hydroelectric plant operates by water falling from a 200 ft height. The turbine in the plant converts potential energy into electrical energy, which is lost by about 5% through the power transmission so that the available power is 95%. If the mass flow rate of the water is 396 lb/s, estimate the power output of the hydro plant.

Solution:

Equation: $\dot{W} = \dfrac{\dot{m} g \Delta z}{g_c}$

Data: Δz = 200 ft, water flow rate 396 lb/s; transmission loss = 5%

$$\dot{W} = \frac{(396\,\text{lb/s})(32.2\,\text{ft}^2/\text{s})(200\,\text{ft})}{32.2\,\text{ft lb/lb}_\text{f}\text{s}^2}\left(\frac{1.055\,\text{kW}}{778\,\text{lb}_\text{f}\text{ft/s}}\right) = 107.4\,\text{kW}$$

With the transmission loss the available power: 107.4 kW (1−0.05) = **102.0 kW**.

6.10 Wind Power Plants

The Earth is unevenly heated by the sun and the differential heating drives a global atmospheric convection system leading to the wind. *Wind power* is the conversion of wind energy into electricity by using wind turbines. A wind turbine is a device for converting the kinetic energy in wind into the mechanical energy of a rotating shaft. The generator is usually connected to the turbine shaft through gears which turn the generator at a different speed than the turbine shaft. Power electronic controls and converts the electricity into the correct frequency and voltage to feed into the power grid at 60 or 50 Hertz.

The power produced by a wind turbine is proportional to the kinetic energy of the wind captured by the wind turbine. The kinetic energy of the wind is equal to the product of the kinetic energy of air per unit mass and the mass flow rate of air through the blade span area:

Wind power = (efficiency) (kinetic energy) (mass flow rate of air)

$$\dot{W}_{\text{wind}} = \eta_{\text{wind}} \frac{v^2}{2} (\rho A v) = \eta_{\text{wind}} \frac{v^2}{2} \rho \frac{\pi D^2}{4} v \tag{6.14}$$

After rearrangement, we have

$$\dot{W}_{\text{wind}} = \eta_{\text{wind}} \rho \frac{\pi v^3 D^2}{8} = (\text{constant}) v^3 D^2 \tag{6.15}$$

$$\text{constant} = \frac{\eta_{\text{wind}} \rho \pi}{8} \tag{6.16}$$

where ρ is the density of air, v is the velocity of air, D is the diameter of the blades of the wind turbine, and η_{wind} is the efficiency of the wind turbine. Therefore, the power produced by the wind turbine is proportional to the cube of the wind velocity and the square of the blade span diameter. The strength of wind varies, and an average value for a given location does not alone indicate the amount of energy a wind turbine could produce there. To assess the frequency of wind speeds at a particular location, a probability distribution function is often fit to the observed data.

At the end of 2009, the worldwide capacity of wind-powered generators was 159.2 GW. Large-scale wind farms are connected to the electric power transmission network, while the smaller facilities are used to provide electricity to isolated locations. Wind energy, as an alternative to fossil fuels, is plentiful, renewable, widely distributed, clean, and produces no greenhouse gas emissions during operation. Wind power is non-dispatchable, and for economic operation, all of the available output must be taken when it is available. Problems of variability are addressed by grid energy storage, batteries, pumped-storage hydroelectricity, and energy demand management. Wind power has negligible fuel costs, projected useful life of the equipment in excess of twenty years, but a high capital cost. The estimated average cost per unit includes the cost of construction of the turbine and transmission facilities [1, 24].

In a wind farm, individual turbines are interconnected with a medium voltage (often 34.5 kV), power collection system, and communications network. At a substation, this medium-voltage electric current is increased in voltage with a transformer for connection to the high voltage electric power transmission system. Wind turbine generators need extensive modeling of the dynamic electromechanical characteristics to ensure stable behavior. The ratio between annual average power and installed capacity rating of a wind-power production is the *capacity factor*. Typical capacity factors for wind power change between 20 and 40%. Example 6.13 illustrates the windmill calculations.

Wind energy penetration refers to the fraction of energy produced by wind compared with the total available production capacity. There is no generally accepted maximum level of wind penetration. An interconnected electricity grid usually includes reserve production and transmission capacity to allow for equipment failures; this reserve capacity can also serve to regulate for the varying power production by wind plants. At present, a few grid systems have penetration of wind energy above 5%: Despite the power forecasting methods used, predictability of wind plant output remains low for short-term operation. Pumped-storage hydroelectricity or other forms of grid energy storage can store energy developed by high-wind periods and release it when needed.

Apart from the availability of wind itself, other factors include the availability of transmission lines, value of energy, cost of land acquisition, land use considerations, and environmental impact of construction and operations. *Wind power density* is a calculation of the effective power of the wind at a particular location. A map showing the distribution of wind power density is a first step in identifying possible locations for wind turbines.

Small-scale wind power has the capacity to produce up to 50 kW of electrical power. Isolated communities may use small-scale wind turbines to displace fossil fuel consumption. Example 6.13 discusses the windmill power production.

Example 6.13 Windmill power estimations

A farm of windmills supplies a power output of 1 MW for a community. Each windmill has blades 10 m in diameter. At the location of the windmills, the average velocity of the wind is 11 m/s and the average temperature is 20°C. Estimate the minimum number of windmills to be installed.

Solution: Air is ideal gas and the pressure is atmospheric.
Inlet: $v = 11$ m/s, $R = 8.314$ kPa m^3/kmol K, $T = 293$ K, $D = 10$ m,
$MW_{\mathrm{air}} = 29$ kg/kmol
Power output $= 1$ MW

Density of air $\rho = (MW)\dfrac{P}{RT} = \dfrac{(29\,\mathrm{kg/kmol})101.3\,\mathrm{kPa}}{(8.314\,\mathrm{kPa\ m^3/kmol\,K})(293\,\mathrm{K})} = 1.2\,\mathrm{m^3/kg}$

Air mass flow rate: $\dot{m} = \rho A v = \rho\pi\frac{D^2}{4}v = 1036.2\,\mathrm{kg/s}$

Power from each windmill:

$$KE = \dot{m}\frac{v^2}{2} = 1036.2\,\mathrm{kg/s}\frac{(11\,\mathrm{m/s})^2}{2}\left(\frac{\mathrm{kJ/kg}}{1000\,\mathrm{m^2/s^2}}\right) = 62.7\,\mathrm{kW}$$

The minimum number of windmills to be installed:
1000 kW/62.7 kW = **16 windmills**

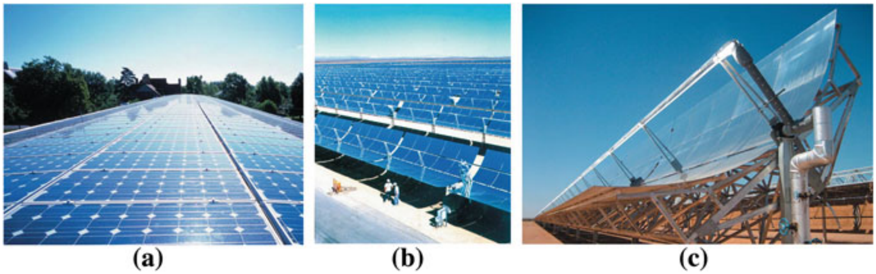
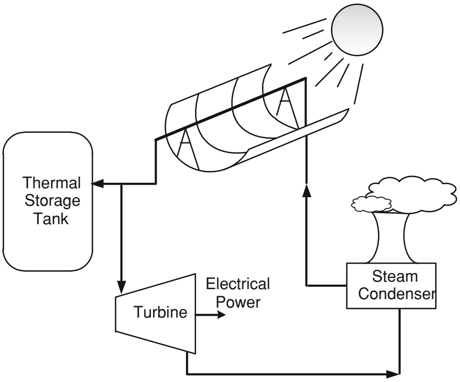


Fig. 6.15 **a** Photovoltaic system at Oberlin College's Adam Joseph Lewis Center for Environmental Studies **b** The 150-megawatt (MW) Kramer Junction plants shown here are part of a 354 MW series of SEGS (solar electric generating system) facilities, each using parabolic trough collectors to collect the sun's energy to generate steam to drive a conventional steam turbine. The plants have been operating in the California Mojave Desert for two decades. **c** Parabolic trough solar collectors at the recently dedicated 1-MW Saguaro power plant outside Tucson concentrate sunlight onto a receiver tube located along the trough's focal line. The solar energy heats the working fluid in the receiver tube, which vaporizes a secondary fluid to power a turbine [22]

Fig. 6.16 Concentrating solar power technologies offer utility-scale power production [12]



6.11 Solar Power Plants

Solar power is derived from the energy of sunlight. Average insolation changes from 150 to 300 W/m^2 or 3.5 to 7.0 kWh/m^2 day. There are two main types of technologies for converting solar energy to electricity: photovoltaic and solar–thermal electric (see Fig. 6.15 and Fig. 6.16).

- *Photovoltaic conversion* produces electricity directly from sunlight in a solar cell. There are many types of photovoltaic cells, such as thin film, monocrystalline silicon, polycrystalline silicon, and amorphous cells, as well as multiple types of concentrating solar power. Photovoltaic power initially is

Fig. 6.17 **a** Stirling solar dish power production. **b** World's first commercial solar power tower located in Seville, Andalusia, Spain

used in small- and medium-sized applications, from the calculator powered by a single solar cell to off-grid homes powered by photovoltaic modules (see Fig. 6.15a)

- *Solar–thermal electric production* based on concentrating solar power systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. The concentrated solar energy heat is used to produce steam to drive turbines and produce electricity. A parabolic trough consists of a linear parabolic reflector that concentrates light onto a receiver positioned along the reflector's focal line (see Figs. 6.15b, c, and 6.16). The receiver is a tube positioned right above the middle of the parabolic mirror and is filled with a working fluid. The reflector is made to follow the Sun during the daylight hours by tracking along a single axis [25].

A Stirling solar dish consists of a standalone parabolic reflector that concentrates light onto a receiver positioned at the reflector's focal point. The reflector tracks the sun along two axes and captures the sun's energy through a parabolic dish solar concentrator. The concentrated energy drives a Stirling engine, which spins a generator producing electricity [17]. Figure 6.17a shows a Stirling concentrating solar power system. The advantages of Stirling solar over photovoltaic cells are higher efficiency of converting sunlight into electricity and longer lifetime.

A solar power tower concentrates light on a central receiver atop a tower, which is mounted at the center of a large field (see Fig. 6.17b). Mirrors, called heliostats, track the sun throughout the day and reflect sunlight to the receiver. Early designs used water heated to steam by the sun's energy to drive turbines. New systems use liquid salt because of its thermal characteristics. The salt is usually a mixture of 60% sodium nitrate and 40% potassium nitrate. The mixture melts at 220°C/428°F. Cold salt is pumped from a holding tank through the receiver where the focused sunlight heats it to over 1000°F. The hot salt passes through a heat exchanger that makes steam to drive turbines. Power towers are more cost effective, offer higher

Table 6.1 Global hydrogen production

Source	(%)
Natural gas	48
Petroleum	30
Coal	18
Water	4

efficiency, and better energy storage capability among concentrated solar power technologies.

Solar installations in recent years have also begun to expand into residential areas, with governments offering incentive programs to make renewable (green) energy sources a more economically viable option [5].

6.12 Hydrogen Production

Hydrogen does not occur naturally and thus it must be generated from some other energy sources. Steam reforming of natural gas is the most common method of producing commercial bulk hydrogen. It is also the least expensive method. At high temperatures and in the presence of a metal-based catalyst (nickel), steam reacts with methane to yield carbon monoxide and hydrogen. These two reactions are reversible in nature.

$$CH_4 + H_2O \rightarrow CO + 3\ H_2 \quad (750\text{–}800^\circ\text{C, endothermic}) \tag{6.17}$$

Additional hydrogen can be recovered by a lower temperature gas-shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2\ (\text{Low temperature shift at 190-210}^\circ\text{C, exothermic}) \tag{6.18}$$

Table 6.1 shows the global hydrogen production sources. Most hydrogen on earth is bonded to oxygen in water. Hydrogen is therefore an energy carrier like electricity, and not a primary energy source like natural gas. Hydrogen burns cleanly, producing little or no harmful emissions or CO_2. It has the highest energy content per unit of weight of any known fuel. When hydrogen is used in a fuel cell, its only waste is water.

To make hydrogen a renewable fuel, the production of it should use renewable energy, such as wind power or solar power. About half of the hydrogen produced is used for ammonia (NH_3) synthesis by the Haber process. The ammonia is used directly or indirectly as fertilizer. The other half of hydrogen is used to convert heavy petroleum sources into lighter fractions to use as fuels.

Hydrogen can also be produced by electrolysis of water, in which the water is split into hydrogen and oxygen

$$2H_2O \rightarrow 2H_2 + O_2 \tag{6.19}$$

The current best water-electrolysis processes have an efficiency of 50–80%, so that 1 kg of hydrogen requires 50–80 kWh of electricity. Using electricity produced by photovoltaic systems may offer the cleanest way to produce hydrogen. Photo electrochemical light harvesting systems may generate sufficient voltage to split water.

Hydrogen can also be produced via pyrolysis or gasification of biomass resources such as agricultural residues like peanut shells, consumer wastes including plastics and waste grease, or biomass specifically grown for energy uses. Biomass pyrolysis produces bio oil that contains a wide spectrum of valuable chemicals and fuels, including hydrogen. Highly concentrated sunlight can be used to generate the high temperatures needed to split methane into hydrogen and carbon in a solar-driven thermochemical process

$$CH_4 + \text{heat} \rightarrow C + 2H_2 \tag{6.20}$$

The produced hydrogen can be recycled to the Sabatier process.

6.13 Fuel Cells

A *fuel cell* oxidizes a fuel, such as hydrogen or methane, electrochemically to produce electric power. It consists of two electrodes separated by an electrolyte. The fuel and oxygen are continuously fed into the cell and the products of reaction are withdrawn continuously. The fuel makes intimate contact with the anode, fuel electrode. Oxygen, usually in air, makes intimate contact with the cathode, oxygen electrode. Half-cell reactions take place at each electrode. The sum of the half-cell reactions is the overall reaction. The type of electrolyte characterizes the type of fuel cell. Schematic fuel cell using hydrogen as fuel is illustrated in Fig. 6.18. When the electrolyte is acidic, the half-cell reactions occurring at the hydrogen electrode (anode) and at the oxygen electrode (cathode) are

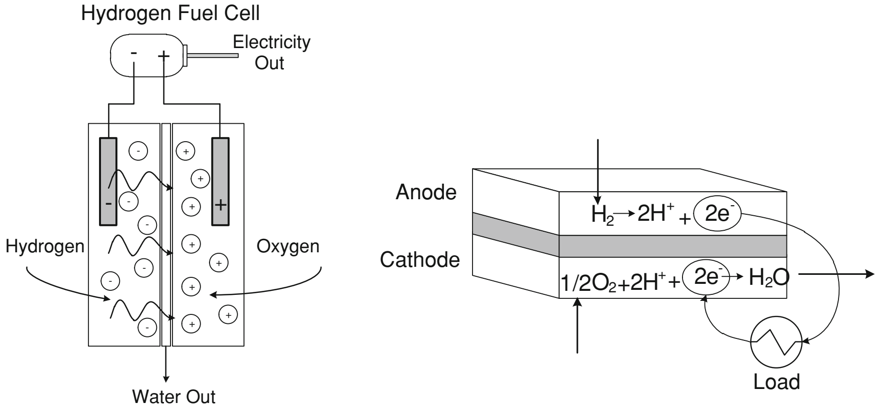
$$H_2 \rightarrow 2H^+ + 2e^- \quad \text{(anode)} \tag{6.21}$$

$$\frac{1}{2}O_2 + 2e^- + 2H^+ \rightarrow H_2O(g) \quad \text{(cathode)} \tag{6.22}$$

The electrons with negative charge (e^-) are released at the anode. These electrons produce an electric current which is used by the reaction occurring at the cathode. The electric current is carried out by an external circuit. The cation H^+ migrates from anode to cathode through the electrolyte. The sum of the half-cell reactions is the overall reaction taking place at the fuel cell

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O(g) \tag{6.23}$$

A thin solid polymer known as *proton exchange membrane* serves as an acid electrolyte in the hydrogen/oxygen fuel cell. Each side of the membrane is bonded



(a) **(b)**

Fig. 6.18 **a** Schematic of a hydrogen fuel cell. The waste product is water. Source, **b** half-cell reactions for a hydrogen/oxygen fuel cell with acidic electrolyte

to a porous carbon electrode impregnated with platinum which serves as a catalyst. The porous electrode provides a very large interface area for the reaction and facilitates the diffusion of hydrogen and oxygen into the cell and the water vapor out of the cell. Cells can be connected in series to make a compact unit with a required level of energy output and operate at a temperature near 60°C.

For each mole of hydrogen consumed, 2 mol of electrons pass to the external circuit. Therefore, the electrical energy (work) is the product of the charge transferred and the voltage V of the cell

$$W_e = -2FV = \Delta G \tag{6.24}$$

where F is the Faraday's constant ($F = 96485$ coulomb/mol) and ΔG is the Gibbs energy. The electric work of reversible and isothermal fuel cell is

$$W_e = \Delta H - q = \Delta G \tag{6.25}$$

Consider a hydrogen/oxygen fuel cell operating at 20°C and 1 bar with pure hydrogen and oxygen as reactants and water vapor as product. The overall reaction is the standard formation reaction for water and the from Appendix C Table C1, we have

$$\Delta H = \Delta H^o_{f,\mathrm{H_2O}} = -241,818\,\mathrm{J/mol} \text{ and } \quad \Delta G = \Delta G^o_{f,\mathrm{H_2O}} = -228,572\,\mathrm{J/mol}$$

Therefore, for the hydrogen/oxygen fuel cell the electric work and the voltage are

$$\mathrm{W_e} = -228,572\,\mathrm{J/mol} \text{ and } \quad V = \frac{-\Delta G}{2F} = 1.184\,\mathrm{V}$$

Using the air instead of pure oxygen in a reversible and isothermal fuel cell, we have

$$\mathrm{W_e} = -226{,}638\,\mathrm{J/mol} \text{ and } \quad V = 1.174\,\mathrm{volts}(\text{hydrogen/air fuel cell})$$

In practice, operating voltage of hydrogen/oxygen fuel cell is around 0.6–0.7 volts, because of internal irreversibilities which reduce the electric work produced and increase the heat transfer to the surroundings.

Fuel cells are very efficient, but expensive to build. Small fuel cells can power electric cars. Large fuel cells can provide electricity in remote places with no power lines. Because of the high cost to build fuel cells, large hydrogen power plants may not be built in the near future. However, fuel cells are being used in some places as a source of emergency power, from hospitals to wilderness locations. Portable fuel cells are being manufactured to provide longer power for laptop computers, cell phones, and military applications [23, 34].

6.13.1 Direct Methanol Fuel Cells

Direct methanol fuel cells are a subcategory of proton exchange fuel cells in which methanol is used as the fuel. Methanol is toxic, flammable, and a liquid from −97.0 to 64.7°C at atmospheric pressure. Methanol is fed as a weak solution (usually around 1 M, i.e. about 3% in mass). At the anode, methanol and water are adsorbed on a catalyst usually made of platinum and ruthenium particles, and lose protons until carbon dioxide is formed. Direct methanol fuel cells use a methanol solution to carry the reactant into the cell; common operating temperatures are in the range 50–120°C. Water is consumed at the anode and is produced at the cathode. Protons (H^+) are transported across the proton exchange membrane often made from Nafion to the cathode where they react with oxygen to produce water. Electrons are transported through an external circuit from anode to cathode, providing power to connected devices. The half-reactions taking place at the anode and cathode, and the overall reactions of the cell are

$$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \quad (\text{Anode}) \tag{6.26}$$

$$3/2\ O_2 + 6H^+ + 6e^- \rightarrow 3H_2O \quad (\text{Cathode}) \tag{6.27}$$

$$CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2H_2O + \text{electrical energy (Overall Reaction)} \tag{6.28}$$

The only waste products with these types of fuel cells are carbon dioxide and water. Currently, platinum is used as the catalyst for both half-reactions. Efficiency is presently quite low for these cells, so they are targeted especially to portable application, where energy and power density are more important than efficiency. These cells need improvements for the loss of methanol and the management of carbon dioxide created at the anode.

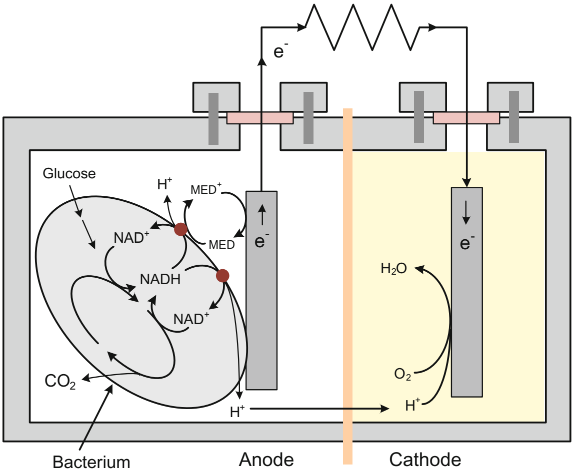


Fig. 6.19 A general layout of a microbial fuel cell in which in the anodic compartment the bacteria can bring about oxidative conversions while in the cathodic compartment chemical and microbial reductive processes can occur [30]

6.13.2 *Microbial Fuel Cell*

A *microbial fuel cell* converts chemical energy, available in a bio substrate, directly into electricity. To achieve this, bacteria are used as a catalyst to convert a variety of organic compounds into CO_2, water, and energy. The microorganisms use the produced energy to grow and to maintain their metabolism. A microbial fuel cell can harvest a part of this microbial energy in the form of electricity. A microbial fuel cell consists of an anode, a cathode, a proton exchange membrane, and an electrical circuit as seen in Fig. 6.19. The bacteria live in the anode and convert a bio substrate such as glucose, acetate but also waste water into CO_2, protons, and electrons

$$C_{12}H_{22}O_{11} + 13H_2O \rightarrow 12CO_2 + 48H^+ + 48e^- \tag{6.29}$$

Due to the ability of bacteria to transfer electrons to an insoluble electron acceptor, microbial fuel cell collects the electrons originating from the microbial metabolism. The electrons then flow through an electrical circuit to the cathode. The potential difference (Volt) between the anode and the cathode, together with the flow of electrons (Ampere) results in the generation of electrical power. The protons flow through the proton exchange membrane to the cathode. At the cathode the electrons, oxygen, and protons combine to form only water. The two electrodes are at different potentials (about 0.5 V). Microbial fuel cells use inorganic mediators to tap into the electron transport chain of cells and channel electrons produced. Some possible mediators include natural red, methylene blue, or thionine. The mediator exits the cell laden with electrons that it shuttles to an electrode where it deposits them. This electrode becomes the anode negatively charged electrode. After releasing the electrons, the mediator returns to its original oxidized state ready to repeat the process. Therefore, the microbial activity is strongly dependent on the redox potential of the anode [30].

6.14 Biomass and Bioenergy Production

Biomass is material derived from recently living organisms, which includes plants, animals, and their by-products. It is a renewable energy source based on the carbon cycle. Some agricultural products grown for biofuel production include corn, soybeans, willow switchgrass, rapeseed, wheat, sugar beet, palm oil, miscanthus, sorghum, cassava, and jatropha [2]. Biodegradable outputs from the industry, agriculture, forestry, and households can be used for biofuel production, using for example: (i) anaerobic digestion to produce biogas, (ii) gasification to produce syngas (H_2 + CO), or (iii) by direct combustion. These materials can be burned directly in steam-electric power plants, or converted to gas that can be burned in steam generators, gas turbines, or internal combustion engine generators. Biomass accounts for about 1% of the electricity generated in the United States. The use of biomass can therefore contribute to waste management as well as fuel.

Bioenergy is renewable energy derived from biological sources, to be used for heat, electricity, or vehicle fuel. Biofuel derived from plant materials is among the most rapidly growing renewable energy technologies. In the United States, corn-based ethanol is currently the largest source of biofuel as a gasoline substitute or additive. As bioenergy is the energy extracted from the biomass, the biomass is the fuel and the bioenergy is the energy contained in the fuel [18].

Biomass can be fermented directly to produce hydrogen, ethanol, and high-value chemicals. Certain photosynthetic microbes produce hydrogen from water in their metabolic activities using light energy. Photo biological technology holds great promise, but because oxygen is produced along with the hydrogen, the technology must overcome the limitation of oxygen sensitivity of the hydrogen-evolving enzyme systems. A new system is also being developed that uses a metabolic switch (sulfur deprivation) to cycle algal cells between a photosynthetic growth phase and a hydrogen production phase.

The production processes of sugar and ethanol in Brazil takes full advantage of the energy stored in sugarcane. Part of the bagasse is currently burned at the mill to provide heat for distillation and electricity to run the machinery. This allows ethanol plants to be energetically self-sufficient and even sell surplus electricity to utilities. Estimates of potential power generation from bagasse range from 1,000 to 9,000 MW, depending on technology.

6.14.1 Bioethanol Production

Ethanol is a clear, colorless alcohol fuel made from the sugars found in grains, such as corn, sorghum, and barley, sugar cane, and sugar beets. Therefore, ethanol is a renewable fuel. The most common processes to produce ethanol today use yeast to ferment the sugars (glucose) and starch. Sugar cane and sugar beets are also common sources used to produce ethanol. Fermentation is a natural microbiological process where sugars are converted to alcohol and carbon dioxide by yeast (*Saccharomyces cerevisiae*—a type of fungi) in about 24–36 h. The overall reaction within the yeast may be represented by

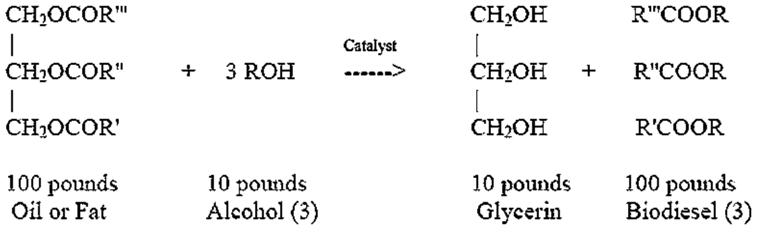
$$\begin{gathered} C_6H_{12}O_6 \rightarrow 2(CH_3CH_2OH) + 2CO_2 \\ \text{Sugar} \rightarrow \text{Alcohol} + \text{Carbon dioxide gas} \end{gathered} \tag{6.30}$$

The resulting solution is distilled to get pure ethanol. For each pound of simple sugars, yeast can produce approximately 1/2 pound (0.15 gal) of ethanol and an equivalent amount of carbon dioxide. Corn consists of 72% starch, which is broken down into simple sugar by adding an enzyme (glucoamylase) so it can be fermented with yeast. By-products include high fructose corn syrup, food additives such as citric acid, corn oil (cooking oil), and livestock feed.

With advanced technology, cellulosic biomass, such as trees and grasses, can also be used as feedstock for ethanol production by using acids or enzymes to create sugars that can be fermented. Cellulosic ethanol involves a more complicated production process than conventional ethanol made from fermentation of starches or sugars. However, this process can reduce concerns that increasing ethanol production will reduce food supply. Cellulosic biomass requires less energy, fertilizers, and water than grains. Cellulosic biomass can also be grown on lands that are not suitable for growing food. Many grasses can produce two harvests a year for many years without a need for annual replanting [14, 35].

6.14.2 Biodiesel and Green Diesel Production

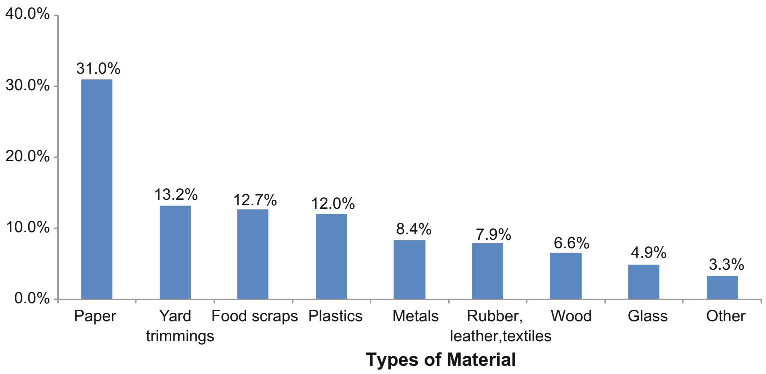
Biodiesel production involves transesterification of feedstock of vegetable oils or animal fats catalytically with a short-chain aliphatic alcohol typically methanol. One hundred pounds of fat or oil such as soybean oil are reacted with 10 pounds of a short-chain alcohol in the presence of a catalyst to produce 10 pounds of glycerin and 100 pounds of biodiesel. R', R'', and R''' indicate the fatty acid chains associated with the oil or fat which are largely palmitic, stearic, oleic, and linoleic acids for naturally occurring oils and fats.



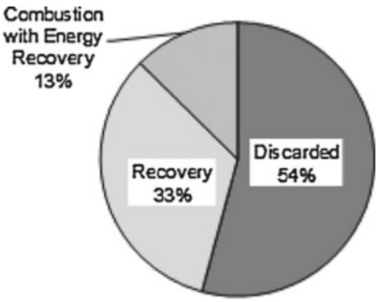
$$\begin{array}{lcccccc} CH_2OCOR''' & & & & CH_2OH & & R'''COOR \\ | & & & \text{Catalyst} & [& & \\ CH_2OCOR'' & + & 3\ ROH & \text{------>} & CH_2OH & + & R''COOR \\ | & & & & [& & \\ CH_2OCOR' & & & & CH_2OH & & R'COOR \\ & & & & & & \\ \text{100 pounds} & & \text{10 pounds} & & \text{10 pounds} & & \text{100 pounds} \\ \text{Oil or Fat} & & \text{Alcohol (3)} & & \text{Glycerin} & & \text{Biodiesel (3)} \end{array} \tag{6.31}$$

The base-catalyzed reaction occurs at low temperature and pressure, yields high conversion (98%) with minimal side reactions and reaction time. Animal and plant fats and oils are typically made of triglycerides which are esters containing three free fatty acids and the glycerol. Water and other non-oil materials should be removed from the feedstock. Water causes the triglycerides to hydrolyze, giving salts of fatty acids (soaps). Sufficient alcohol is added to make up an excess of usually six parts alcohol to one part triglyceride for the reaction to complete. A titration estimates how much alkaline is needed to completely neutralize any free fatty acids present, thus ensuring a complete transesterification. The reaction take place around 55°C (131°F). Reaction time varies from 1 to 8 h. Products of the reaction include not only biodiesel, but also, glycerin, excess alcohol, and some water. All of these by-products must be removed. Residual methanol is typically removed through distillation and recycled to the reactor [8].

Green diesel is produced by removing the oxygen by catalytic reaction with hydrogen from renewable feedstock containing triglycerides and fatty acids, producing a paraffin-rich product, water, and carbon oxides [19]. Triglycerides and fatty free acids both contain long, linear aliphatic hydrocarbon chains, which are partially unsaturated and have a carbon number range similar to the molecules found in petroleum diesel fuels. Therefore, green diesel has a heating value equal to conventional diesel and is fully compatible for blending with the standard mix of petroleum-derived diesel fuels. Biodiesel has around 11% oxygen, whereas petroleum-based diesel and green diesel have no oxygen. Petroleum diesel has around 10 ppm sulfur and biodiesel and green diesel have less than 1 ppm sulfur. Fossil fuel consumption over the life cycle is expected to be reduced by 84–90% for green diesel produced from soybean oil or palm oil, respectively, when hydrogen is produced from renewable resources. Feedstocks rich in saturated fats, such as palm and tallow oil, require less hydrogen than feedstocks higher in olefin content, such as soybean or rapeseed oil [19]. The yield of green diesel depends on both feedstock type and the level of hydroisomerization required to achieve product cloud point specification.



(a)



(b)

Fig. 6.20 **a** Generation of municipal solid waste. **b** Management of municipal solid waste [13]

6.14.3 Energy from Solid Waste

Garbage, often called municipal solid waste, is the source of about 12% of the total biomass energy consumed in the United States. Municipal solid waste contains biomass like paper, cardboard, food scraps, grass clippings, leaves, wood, and leather products, and other non-biomass combustible materials, mainly plastics and other synthetic materials made from petroleum (see Fig. 6.20).

Recycling and composting programs may reduce the share of biomass in municipal solid waste that is land filled or burned. Solid waste can be burned in special waste-to-energy plants, which produce heat to make steam to heat buildings or to produce electricity. Such plants help reduce the amount of solid waste to be buried in landfills. There are also solid waste incinerators that simply burn the solid waste without electricity production.

6.15 Other Energy Production Opportunities

There are other energy production systems and processes either under development or operation with limited scale [29]. Some of these energy production opportunities are:

- *Solid-state generation* (without moving parts) is of particular interest in portable applications. This area is largely dominated by thermoelectric devices, though thermionic and thermophotovoltaic systems have been developed as well.
- *Piezoelectric devices* are used for power generation from mechanical strain, particularly in power harvesting.
- *Betavoltaics* are another type of solid-state power generator which produces electricity from radioactive decay.
- *Fluid-based magnetohydrodynamic* power generation has been studied as a method for extracting electrical power from nuclear reactors and also from more conventional fuel combustion systems.
- *Osmotic power* finally is another possibility at places where salt and sweet water merges in rivers and seas.
- Electromagnetic Energy Harvesting.
- Harvesting Circuits.
- Thermoelectrics.
- Microbatteries.

6.16 Levelized Energy Cost

Levelized energy cost is the price at which electricity must be produced from a specific source to break even. It is an economic assessment tool in calculating the costs of generation from different sources. The costs include initial investment, operations and maintenance, cost of fuel, and cost of capital. It can be defined in a single formula as [12]

$$LEC = \frac{\sum_i^n \frac{I_i + M_i + F_i}{(1+r)^i}}{\sum_i^n \frac{E_i}{(1+r)^i}} \tag{6.32}$$

- LEC = Average lifetime levelised electricity generation cost
- I = Investment expenditures
- M = Operations and maintenance expenditures
- F = Fuel expenditures
- E = Electricity production

Table 6.2 Estimated levelized cost of new generation resources plants entering service in 2016

Plant type	Capacity factor (%)	U.S. average Levelized costs[a] (2009) ($/MW h)			
		Capital cost	Operating and maintenance	Transmission investment	Average total cost
Conventional coal	85	65.3	28.1	1.2	94.8
Advanced coal	85	74.6	33.6	1.2	109.4
Natural gas-fired combined cycle	87	17.5	47.5	1.2	66.1
Advanced combined cycle	87	17.9	44.0	1.2	63.1
Conventional combustion turbine	30	45.8	75.1	3.5	124.5
Advanced combustion turbine	30	31.6	68.4	3.5	103.5
Advanced nuclear	90	90.1	22.8	1.0	113.9
Wind	34	83.9	9.6	3.5	97.0
Wind—Offshore	34	209.3	28.1	5.9	243.2
Solar PV[1]	25	194.6	12.1	4.0	210.7
Solar thermal	18	259.4	46.6	5.8	311.8
Geothermal	92	79.3	21.4	1.0	101.7
Biomass	83	55.3	56.0	1.3	112.5
Hydro	52	74.5	10.1	1.9	86.4

[a] Costs are expressed in terms of net AC power available to the grid for the installed capacity
Source Energy Information Administration [12]

- r = Interest rate
- n = Useful life of operation

Typically levelized energy costs are calculated over 20- to 40-year lifetimes, and are given in the units of currency per kilowatt-hour, for example $/kWh or $/MW h. When comparing levelized energy costs for alternative systems typically only the costs of connecting the generating source into the transmission system is included. Table 6.2 lists the estimated cost of electricity by source for plants entering service in 2016 from a December 16, 2010 report of the U.S. Department of Energy (DOE). Total system levelized cost gives the dollar cost per MW h that must be charged over time in order to pay for the total cost. These calculations take into account the level of carbon dioxide produced by coal plants. Levelized cost represents the present value of the total cost of building and operating a generating plant over an assumed useful life of operation by taking into account capital cost, fuel cost, operation and maintenance costs, financing costs, and an assumed utilization rate for each plant type.

- Capital costs tend to be low for fossil fuel power stations; high for wind turbines, solar photovoltaic, and nuclear. The capital costs are usually high for waste to energy, wave and tidal, and solar thermal plants.

- Operating and maintenance costs tend to be high for nuclear, coal, and waste-to-energy (ash disposal, emissions clean up, operating steam generators) and low for wind turbines, solar photovoltaic, renewables, and oil and gas-fired units.
- Fuel costs are high for fossil fuel and biomass sources, very low for nuclear and renewables.
- Revenue from the sales of heat can balance operating costs, and reduce the net costs in the case of cogeneration that is combined heat and power generation and district heating schemes.
- The costs of waste, waste treatment, and insurance costs are not included.

To evaluate the total cost of production of electricity, the costs are converted to a net present value using the time value of money. These costs are all brought together using cumulative discounted cash flows over the useful life of operation. Table 6.2 shows the levelized cost of new generation resources in the annual energy outlook 2011 [12].

6.17 Thermodynamic Cost

Thermodynamic cost takes into account irreversibilities that reduces the available energy in a process. Thermoeconomics assigns costs to exergy-related variables by using the *exergy cost theory* and *exergy cost balances* by using: (a) cost accounting methods and optimization methods, such as exergy cost theory for a rational price assessment, and (b) optimization by minimizing the overall cost under a proper set of financial, environmental, and technical constraints, to identify the optimum design and operating conditions. Cost accounting methods use average costs as a basis for a rational price assessment, while optimization methods employ marginal costs in order to minimize the costs of the products of a system or a component. *Extended exergy* accounts for the environmental impact in a more systematic way by estimating the resource-based value of a commodity. Consider a separation process with outputs containing hot streams with various chemicals having conditions considerably different from environmental temperatures and concentrations. To achieve zero environmental impact, these streams must be brought to both thermal and chemical equilibrium with the surroundings [9, 20, 26]. Example 6.14 illustrates the cost calculations in power production.

6.18 Ecological Cost

Ecological cost analysis may minimize the depletion of nonrenewable natural resources. Determining the extraction of raw materials and fossil fuels from natural resources is not sufficient in fully understanding the ecological impact of production processes. The production, conversion, and utilization of energy may lead to environmental problems, such as air and water pollution, impact on the use of land and rivers, thermal pollution due to mismanagement of waste heat, and global climate change. The influence of waste products discharged into the environment should also be considered. The waste products may be harmful to agriculture, plant life, human health, and industrial activity.

6.18.1 Ecological Planning

Ecological planning for sustainable development should take into account the uncontrollable waste exergy emission in the environment. There are environmental impacts associated with the production and transmission of electricity. Emissions that result from the combustion of the fossil fuels include carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter, and heavy metals such as mercury. Nearly all combustion byproducts may have negative impacts on the environment and human health [11, 16, 22]:

- CO_2 is a greenhouse gas and a source of global warming. Power plants that burn fossil fuels and materials made from fossil fuels and some geothermal power plants are the sources of about 40% of the total U.S. carbon dioxide emissions.
- SO_2 causes acid rain, which is harmful to plants and animals that live in water, and it worsens or causes respiratory illnesses and heart diseases, particularly in children and the elderly. SO_2 emissions are controlled by wet and dry scrubbers, which involve mixing lime in the fuel (coal) or spraying a lime solution into the combustion gases. Fluidized bed combustion can also be used to control SO_2.
- NO_x contributes to ground level ozone, which irritates and damages the lungs. NO_x emissions can be controlled by several different techniques and technologies, such as low NO_x burners during the combustion phase or selective catalytic and non-catalytic converters during the post combustion phase.
- Particulate matter results in hazy conditions in cites and scenic areas, and, along with ozone, contributes to asthma and chronic bronchitis, especially in children and the elderly. Very small or “fine particulate matter” is also thought to cause emphysema and lung cancer. Heavy metals such as mercury can be hazardous to human and animal health. Particulate matter emissions are controlled with devices that clean the combustion gases that exit the power plant, such as “Baghouses” use large filters, electrostatic precipitators use charged plates, and wet scrubbers use a liquid solution.

6.18.2 Coal-Fired Power Plants

Coal-fired power plants are required to meet standards that limit the amounts of some of the substances that they release into the air:

- Coal-fired plants can use coal that is low in sulfur content. Coal can also be pretreated and processed to reduce the types and amounts of undesirable compounds in combustion gases.
- The coarse solid residue that results from burning solid fuels is called ash. The largest particles collect at the bottom of the boiler and are removed and quenched with water. Smaller and lighter particulates are called fly ash and are collected in air emission control devices, and are usually mixed with the bottom ash.
- Power transmission and distribution lines, using towers, carry electricity from power plants to customers. The towers and lines impact the visual landscape and disturb trees near the wires, native plant populations, and wildlife. Power lines under the ground are more expensive and may result in a greater disturbance of the landscape than overhead lines.

6.18.3 Nuclear Power Plants

Nuclear power plants are not a source of greenhouse gases or other emissions, but they do produce two kinds of radioactive wastes [3]:

- *Low-level radioactive waste*—This includes items that have become contaminated with radioactive material, such as clothing, wiping rags, mops, filters, reactor water treatment residues, and equipment and tools. Low-level waste is stored at nuclear power plants until the radioactivity in the waste decays to a level where it is allowed to be disposed of as ordinary trash or it is sent to a low-level waste disposal site.
- *Spent* (*used*) *nuclear fuel*—The spent fuel assemblies are highly radioactive and must initially be stored in specially designed pools resembling large swimming pools (water cools the fuel and acts as a radiation shield) or in specially designed dry storage containers. An increasing number of reactor operators now store their older spent fuel in dry storage facilities using special outdoor concrete or steel containers with air cooling.

Problems

6.1. In a steam-power plant, steam at 200 psia and 600°F enters a turbine and exits at 5 psia and 200°F. The steam enters the turbine through a 2.5-inch-diamateter pipe with a velocity of 11 ft/s and exits through a 9-inch-diamater pipe. Estimate the power produced by the turbine.

6.2. A turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 1100 kPa enters the turbine. The steam flow rate is 3 kg/s. The inlet tube diameter is 10 cm. After expanding in the turbine, the steam exits through a pipe of diameter 25 cm. At the exit the steam is at 300°C and 110 kPa. Estimate the work produced by the turbine.

6.3. A turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 550°C and 1500 kPa enters the turbine. The steam flow rate is 4 kg/s. The inlet tube diameter is 12 cm. After expanding in the turbine, the steam exits through a pipe of diameter 28 cm. At the exit the steam is saturated at 110 kPa (at 102.3°C). Estimate the work produced by the turbine.

6.4. A turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 4000 kPa enters the turbine. The steam flow rate is 10 kg/s. The inlet tube diameter is 10 cm. After expanding in the turbine, the steam exits through a pipe of diameter 30 cm. At the exit the steam is at 150 kPa and 120°C. Estimate the work produced by the turbine.

6.5. A turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 8000 kPa enters the turbine. The steam flow rate is 15 kg/s. The inlet tube diameter is 9 cm. After expanding in the turbine, the steam exits through a pipe of diameter 35 cm. At the exit the steam is saturated at 100 kPa (99.63°C). Estimate the work produced by the turbine.

6.6. A superheated steam at 4100 kPa and 300°C expands adiabatically in a steam turbine and exits at 15 kPa with a quality of $x = 0.87$. Velocity of the steam at the inlet is 50 m/s and at the exit 160 m/s. Elevation at the inlet is 10 m and at the exit 6 m. Estimate the power produced for the steam flow rate of 1 kg/s.

6.7. A turbine serves as an energy source for a small electrical generator. The turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 1100 kPa enters the turbine. The steam flow rate is 3 kg/s. At the exit the steam is at 300°C and 110 kPa. Estimate the work produced by the turbine.

6.8. A steam at 8000 kPa and 400°C expands in a turbine. At the exit the steam is at 20 kpa with a quality of 0.9. Estimate the power output if the steam flow rate is 11.5 kg/s.

6.9. A steam at 8400 kPa and 400°C expands in a turbine. At the exit the steam is at 15 kpa with a quality of 0.92. Estimate the power output if the steam flow rate is 11.5 kg/s.

6.10. A steam expands in a turbine. The steam enters the turbine at 9000 kPa and 450°C and exits at 10 kPa with a quality of 0.95. If the turbine produces a power of 6.5 MW estimate the steam flow rate.

6.11. A hot exhaust gas is heating a boiler to produce superheated steam at 100 psia and 400°F. In the meantime, the exhaust gas is cooled from 2500 to 350°F. Saturated liquid water (stream 1) at 14.7 psia enters the boiler with a flow rate of 200 lb/h. Superheated steam (stream 2) is used in a turbine, and discharged as saturated steam (stream 3) at 14.7 psia. Determine the molar flow rate of the exhaust gas needed and the maximum work produced. Assume that the surroundings are at 70°F, and the heat capacity of the flue gas is $C_p = 7.606 + 0.0006077T$, where T is in Rankine and C_p is in Btu/(lbmol R).

6.12. A steam expands in a turbine. The steam enters the turbine at 1000 psia and 800°F and exits as a saturated vapor at 5 psia. The turbine produces a power of 5 MW. If the steam flow rate is 20 lb/s, estimate the heat loss from the turbine.

6.13. A turbine serves as an energy source for a small electrical generator. The turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 550°C and 1500 kPa enters the turbine. The steam flow rate is 4 kg/s. At the exit the steam is saturated at 110 kPa (at 102.3°C). Estimate the work produced by the turbine.

6.14. A turbine serves as an energy source for a small electrical generator. The turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 4000 kPa enters the turbine. The steam flow rate is 10 kg/s. At the exit the steam is at 150 kPa and 120°C. Estimate the work produced by the turbine.

6.15. A turbine serves as an energy source for a small electrical generator. The turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 8000 kPa enters the turbine. The steam flow rate is 15 kg/s. At the exit the steam is saturated at 100 kPa (99.63°C). Estimate the work produced by the turbine.

6.16. Steam at 8200 kPa and 823.15 K (state 1) is being expanded to 30 kPa in a continuous operation. Determine the final temperature (state 2), entropy produced, and work produced per kg of steam for an isothermal expansion through a turbine.

6.17. Steam enters an adiabatic turbine at 5000 kPa and 450°C and leaves as a saturated vapor at 140 kPa. Determine the work output per kg of steam flowing through the turbine if the process is reversible and changes in kinetic and potential energies are negligible.

6.18. Steam at 8200 kPa and 823.15 K (state 1) is being expanded to 30 kPa in a continuous operation. Determine the final temperature (state 2), entropy produced, and work produced per kg of steam for an adiabatic expansion through a turbine.

6.19. A steady flow adiabatic turbine receives steam at 650 K and 8200 kPa, and discharges it at 373.15 K and 101.32 kPa. If the flow rate of the steam is 12 kg/s determine (a) The maximum work and (b) The work loss if the surroundings are at 298.15 K.

6.20. A turbine discharges steam from 6 MPa and 400°C to saturated vapor at 360.15 K while producing 480 kJ/kg of shaft work. The temperature of surroundings is 300 K. Determine the maximum possible production of power in kW.

6.21. A Carnot cycle uses water as the working fluid in a steady-flow process. Heat is transferred from a source at 400°C and water changes from saturated liquid to saturated vapor. The saturated steam expands in a turbine at 10 kPa, and a heat of 1150 kJ/kg is transferred in a condenser at 10 kPa. Estimate the net power output of the cycle for a flow rate of 10 kg/s of the working fluid.

6.22. A Carnot cycle uses water as the working fluid in a steady-flow process. Heat is transferred from a source at 400°C and water changes from saturated liquid to saturated vapor. The saturated steam expands in a turbine at 30 kPa, and a heat of 1150 kJ/kg is transferred in a condenser at 30 kPa. Estimate the net power output of the cycle for a flow rate of 14.5 kg/s of the working fluid.

6.23. A steam power production plant uses steams at 8200 kPa and 823.15 K. The turbine discharges the steam at 30 kPa. The turbine and pump operate reversibly and adiabatically. Determine the work produced for every kg steam produced in the boiler.

6.24. A steam power plant operates on a simple ideal Rankine cycle shown below. The turbine receives steam at 698.15 K and 4400 kPa, while the discharged steam is at 15 kPa. The mass flow rate of steam is 12.0 kg/s. Determine the net work output.

6.25. A reheat Rankine cycle is used in a steam power plant. Steam enters the high-pressure turbine at 9000 kPa and 823.15 K and leaves at 4350 kPa. The steam is reheated at constant pressure to 823.15 K. The steam enters the low-pressure turbine at 4350 kPa and 823.15 K. The discharged steam from the low-pressure turbine is at 10 kPa. The steam flow rate is 24.6 kg/s. Determine the net power output.

6.26. A reheat Rankine cycle is used in a steam power plant. Steam enters the high-pressure turbine at 10000 kPa and 823.15 K and leaves at 4350 kPa. The steam is reheated at constant pressure to 823.15 K. The steam enters the low-pressure turbine at 4350 kPa and 823.15 K. The discharged steam from the low-pressure turbine is at 15 kPa. The steam flow rate is 38.2 kg/s. Determine the net power output.

6.27. A simple ideal reheat Rankine cycle is used in a steam power plant shown below. Steam enters the turbine at 9200 kPa and 823.15 K and leaves at 4350 kPa and 698.15 K. The steam is reheated at constant pressure to 823.15 K. The discharged steam from the low-pressure turbine is at 15 kPa. The net power output of the turbine is 75 MW. Determine the mass flow rate of steam.

6.28. A steam power plant is using an actual regenerative Rankine cycle. Steam enters the high-pressure turbine at 11000 kPa and 773.15 K, and the condenser operates at 10 kPa. The steam is extracted from the turbine at

475 kPa to heat the water in an open heater. The water is a saturated liquid after passing through the water heater. The steam flow rate is 65 kg/s. Determine the work output.

6.29. A steam power plant is using an actual regenerative Rankine cycle. Steam enters the high-pressure turbine at 10000 kPa and 773.15 K, and the condenser operates at 30 kPa. The steam is extracted from the turbine at 475 kPa to heat the water in an open heater. The water is a saturated liquid after passing through the water heater. The steam flow rate is 45.6 kg/s. Determine the work output.

6.30. A steam power plant is using an ideal regenerative Rankine cycle shown below. Steam enters the high-pressure turbine at 8400 kPa and 773.15 K, and the condenser operates at 10 kPa. The steam is extracted from the turbine at 400 kPa to heat the feed water in an open heater. The water is a saturated liquid after passing through the feed water heater. Determine the net power output of the cycle.

6.31. A steam power plant is using an actual reheat regenerative Rankine cycle. Steam enters the high-pressure turbine at 11000 kPa and 773.15 K, and the condenser operates at 10 kPa. The steam is extracted from the turbine at 2000 kPa to heat the water in an open heater. The steam is extracted at 475 kPa for process heat. The water is a saturated liquid after passing through the water heater. Determine the work output for a flow rate of steam of 66.0 kg/s.

6.32. A steam power plant is using an ideal reheat regenerative Rankine cycle. Steam enters the high-pressure turbine at 9400 kPa and 773.15 K and leaves at 850 kPa. The condenser operates at 15 kPa. Part of the steam is extracted from the turbine at 850 kPa to heat the water in an open heater, where the steam and liquid water from the condenser mix and direct contact heat transfer takes place. The rest of the steam is reheated to 723.15 K, and expanded in the low-pressure turbine section to the condenser pressure. The water is a saturated liquid after passing through the water heater and is at the heater pressure. The flow rate of steam is 20 kg/s. Determine the power produced.

6.33. A steam power plant is using an actual reheat regenerative Rankine cycle. Steam enters the high-pressure turbine at 10800 kPa and 773.15 K, and the condenser operates at 15 kPa. The steam is extracted from the turbine at 2000 kPa to heat the water in an open heater. The steam is extracted at 475 kPa for process heat. The water is a saturated liquid after leaving the water heater. The steam flow rate is 30.8 kg/s. Determine the power produced.

6.34. A steam power plant is using a geothermal energy source. The geothermal source is available at 220°C and 2320 kPa with a flow rate of 180 kg/s. The hot water goes through a valve and a flash drum. Steam from the flash drum enters the turbine at 550 kPa and 428.62 K. The discharged steam from the turbine has a quality of $x_4 = 0.95$. The condenser operates at 40 kPa. The water is a saturated liquid after passing through the condenser. Determine the net work output.

6.35. A steam power plant is using a geothermal energy source. The geothermal source is available at 220°C and 2320 kPa with a flow rate of 50 kg/s. The hot water goes through a valve and a flash drum. Steam from the flash drum enters the turbine at 550 kPa and 428.62 K. The discharged steam from the turbine has a quality of $x_4 = 0.90$. The condenser operates at 15 kPa. The water is a saturated liquid after passing through the condenser. Determine the net work output.

6.36. A cogeneration plant is using steam at 5500 kPa and 748.15 K to produce power and process heat. The amount of process heat required is 10000 kW. Twenty percent of the steam produced in the boiler is extracted at 475 kPa from the turbine for cogeneration. The extracted steam is condensed and mixed with the water output of the condenser. The remaining steam expands from 5500 kPa to the condenser conditions. The condenser operates at 10 kPa. Determine the network output.

6.37. A cogeneration plant is using steam at 8400 kPa and 773.15 K (see Fig. 6.14). One-fourth of the steam is extracted at 600 kPa from the turbine for cogeneration. After it is used for process heat, the extracted steam is condensed and mixed with the water output of the condenser. The rest of the steam expands from 600 kPa to the condenser pressure of 10 kPa. The steam flow rate produced in the boiler is 60 kg/s. Determine the work output.

6.38. A cogeneration plant uses steam at 900 psia and 1000°F to produce power and process heat. The steam flow rate from the boiler is 40 lb/s. The process requires steam at 70 psia at a rate of 5.5 lb/s supplied by the expanding steam in the turbine. The extracted steam is condensed and mixed with the water output of the condenser. The remaining steam expands from 70 psia to the condenser pressure of 3.2 psia. Determine the work output.

6.39. One kmole of air is initially at 1 atm, -13°C, performs a power cycle consisting of three internally reversible processes in series. Step 1-2: Adiabatic compression to 5 atm. Step 2-3: Isothermal expansion to 1 atm. Step 3-1: Constant-pressure compression. Determine the net work output.

6.40. A steam power plant output is 62 MW. It uses steam (stream 1) at 8200 kPa and 550°C. The discharged stream (stream 2) is saturated at 15 kPa. If the expansion in the turbine is adiabatic, and the surroundings are at 298.15 K, determine the steam flow rate.

6.41. A steam power plant output is 55 MW. It uses steam (stream 1) at 8400 kPa and 500°C. The discharged stream (stream 2) is saturated at 30 kPa. If the expansion in the turbine is adiabatic, and the surroundings are at 298.15 K, determine the steam flow rate.

6.42. In a hydropower plant, a hydroturbine operates with a head of 33 m of water. Inlet and outlet conduits are 1.70 m in diameter. If the outlet velocity of the water is 4.6 m/s estimate the power produced by the turbine.

6.43. In a hydropower plant, a hydroturbine operates with a head of 46 m of water. Inlet and outlet conduits are 1.80 m in diameter. If the outlet velocity of the water is 5.5 m/s estimate the power produced by the turbine.

6.44. Consider a hydropower plant reservoir with an energy storage capacity of 1.5 10^6 kWh. This energy is to be stored at an average elevation of 40 m relative to the ground level. Estimate the minimum amount of water to be pumped back to the reservoir.

6.45. Consider a hydropower plant reservoir with an energy storage capacity of 2.0 10^6 kWh. This energy is to be stored at an average elevation of 460 m relative to the ground level. Estimate the minimum amount of water to be pumped back to the reservoir.

6.46. A farm of windmills supplies a power output of 2 MW for a community. Each windmill has blades 10 m in diameter. At the location of the windmills, the average velocity of the wind is 11 m/s and the average temperature is 20°C. Estimate the minimum number of windmills to be installed.

6.47. A farm of windmills supplies a power output of 3 MW for a community. Each windmill has blades 11 m in diameter. At the location of the windmills, the average velocity of the wind is 14 m/s and the average temperature is 20°C. Estimate the minimum number of windmills to be installed.

6.48. A farm of windmills supplies a power output of 4.2 MW for a community. Each windmill has blades 10 m in diameter. At the location of the windmills, the average velocity of the wind is 15 m/s and the average temperature is 20°C. Estimate the minimum number of windmills to be installed.

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Chapter 7
Energy Conversion

7.1 Energy Conversion

In most processes, energy is constantly changing from one form to another. This is called *energy conversion*. Examples include the living systems converting the solar energy to chemical energy by synthesizing food from water and carbon dioxide through the photosynthesis. The mechanical energy of a waterfall can also be converted to electromagnetic energy in a generator. An internal combustion engine converts the potential chemical energy in gasoline into heat, which is then transformed into the kinetic energy that moves a vehicle. A solar cell converts solar radiation into electrical energy that can then be used to light a bulb or power a computer. The energy that enters a conversion device or a process is turned into other forms of energy, so an equal quantity of energy before and after is maintained. That means the energy is conserved during any form of energy conversion in a system.

Energy is most usable where it is most concentrated as in highly structured chemical bonds in gasoline and sugar. All other forms of energy may be completely converted to heat, but the conversion of heat to other forms of energy cannot be complete. Due to inefficiencies such as friction, heat loss, and other factors, thermal efficiencies of energy conversion are typically much less than 100%. For example, only 35–40% of the heat can be converted to electricity in a steam power plant and a typical gasoline automobile engine operates at around 25% efficiency. With each energy conversion, a part of the energy is lost usually in less useful and dispersed form of thermal energy, as illustrated in Fig. 7.1. For example, a light bulb converts only around 10% of electrical energy to light and the remaining is converted to heat, which is difficult to use to do work. This shows that there are limitations to the efficiency for energy conversion. Only a part of energy may be converted to useful work and the remainder of the energy must be reserved to be transferred to a thermal reservoir at a lower temperature [2, 4, 5, 13].

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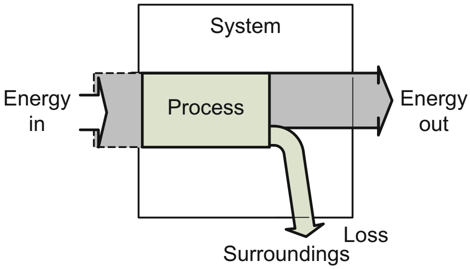


Fig. 7.1 Schematic of the energy usage and conversion in a process. Output energy at a new form is always lower than input energy. The total energy input is recovered in various other forms and hence the energy is conserved

There are many different processes and devices that convert energy from one form to another. Table 7.1 shows a short list of such processes and devices. When electric current flows in a circuit, it can transfer energy to do work. Devices convert electrical energy into many useful forms, such as heat (electric heaters), light (light bulbs), motion (electric motors), sound (loudspeaker), and information technological processes (computers). Electric energy is one of the most useful forms of output energy, which can be produced by various mechanical and/or chemical devices. There are seven fundamental methods of directly transforming other forms of energy into electrical energy [5, 31]:

- *Static electricity* is produced from the physical separation and transport of charge. Electrons are mechanically separated and transported to increase their electric potential and imbalance of positive and negative charges leads to static electricity. For example, lightning is a natural example of static discharge. Also low conductivity fluids in pipes can build up static electricity.
- *Electromagnetic induction*, where an electrical generator, dynamo, or alternator transforms kinetic energy into electricity. Almost all commercial electrical generation is done using electromagnetic induction, in which mechanical energy forces an electrical generator to rotate. There are many different methods of developing the mechanical energy, including heat engines, hydro, wind, and tidal power.
- *Electrochemistry* is the direct transformation of chemical energy into electricity, as in a battery, fuel cell, or nerve impulse.
- *Photoelectric effect* is the transformation of light into electrical energy, as in solar cells.
- *Thermoelectric effect* is the direct conversion of temperature differences to electricity, as in thermocouples, thermopiles, and thermionic converters.
- *Piezoelectric effect* is the electricity from the mechanical strain of electrically anisotropic molecules or crystals.
- *Nuclear transformation* is the creation and acceleration of charged particles. The direct conversion of nuclear energy to electricity by beta decay is used only on a small scale.

Table 7.1 Some of the processes and devices converting energy from one form to another

Process and device	Energy in	Useful energy output
Steam engine	Heat	Mechanical energy
Photosynthesis	Solar energy	Chemical energy
Hydroelectric dams	Gravitational potential energy	Electric energy
Windmills	Mechanical energy	Electric energy
Electric generator	Mechanical energy	Electric energy
Diesel or petrol engine	Chemical energy	Mechanical energy
Electric motor	Electric energy	Mechanical energy
Fuel cells	Chemical energy	Electric energy
Battery	Chemical energy	Electric energy
Electric bulb	Electric energy	Heat & light
Resistance heater	Electric energy	Heat
Ocean thermal power	Heat	Electric energy
Bioluminescence	Chemical energy	Light energy
Nerve impulse	Chemical energy	Electrical energy
Muscular activity	Chemical energy	Mechanical energy
Geothermal power	Heat	Electric energy
Wave power	Mechanical energy	Electric energy
Friction	Kinetic energy	Heat
Thermoelectric	Heat	Electric energy
Piezoelectrics	Strain	Electric energy

Granet and Bluestein [13], Chih [4]

7.2 Series of Energy Conversions

It takes a whole series of energy conversions in various processes before a useful form of energy becomes available. For example, when you use your computer, there are several following energy conversion processes involved:

- Chemical energy stored in coal is released as heat when the coal is burned.
- The heat is used to produce steam which is converted into mechanical energy in a turbine.
- The generator converts mechanical energy into electric energy that travels through the power lines into your home.
- From the power outlet at home, the computer receives that electric energy.

In a conventional internal combustion engine, these energy transformations are involved:

- Potential energy in the fuel is converted to kinetic energy of expanding gas after combustion.
- Kinetic energy of expanding gas is converted to piston movement and hence to rotary crankshaft movement.
- Rotary crankshaft movement is passed into the transmission assembly to drive the wheels of a car.

7.3 Conversion of Chemical Energy of Fuel to Heat

Chemical energy of a fuel is converted to heat during a combustion or oxidation reaction. Combustion reactions are exothermic and release heat. Heat of combustion is the same as heat of reaction for a combustion reaction, which is discussed in Sect. 4.3.4. For example, standard heat of combustion of propane (C_3H_8) can be estimated by using the standard heats of formation tabulated in Table C1. The combustion reaction of 1 mol propane is:

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(g) + \text{Heat} \tag{7.1}$$

When the products and reactants are at their standard states (ideal-gas state at 1 bar and 25°C) the standard heat of reaction is expressed by

$$\Delta H_r^o = \sum_i v_i \Delta H_{fi}^{\text{o}} = v_{CO_2} \Delta H_{fCO_2}^{\text{o}} + v_{H_2O} \Delta H_{fH_2O}^{\text{o}} + v_{C_3H_8} \Delta H_{fC_3H_8}^{\text{o}} \tag{7.2}$$

where v_i is the stoichiometric coefficient of substance i, which is positive for a product and negative for a reactant. For example, for the reaction above $v_{CO_2} = 3$, $v_{H_2O} = 4, v_{C_3H_8} = -1$.

7.3.1 Heating Value of a Fuel

The *heating value* of a fuel is the amount of heat released during combustion [35]. It is measured in units of energy per unit of the substance, usually mass, such as: kJ/kg, Btu/m^3, or kcal/kg. The heating values for fuels are expressed as the higher heating value (HHV), lower heating value (LHV), or gross heating value (GHV). HHV is determined by bringing all the products of combustion back to the original precombustion temperature, and in particular condensing any water vapor produced. The combustion process of a fuel consisting of carbon and hydrogen can be approximately represented by

$$[C + H](\text{Fuel}) + [O_2 + N_2](\text{Air}) \rightarrow CO_2 + H_2O(\text{liquid}) + N_2 + \text{Heat (HHV)} \tag{7.3}$$

$$[C + H](\text{Fuel}) + [O_2 + N_2](\text{Air}) \rightarrow CO_2 + H_2O(\text{vapor}) + N_2 + \text{Heat (LHV)} \tag{7.4}$$

where C = Carbon, H = Hydrogen, O = Oxygen, and N = Nitrogen. Gross heating value takes into account the heat used to vaporize the water during the combustion reaction as well as the water existing within the fuel before it has been burned. This value is especially important for fuels such as wood or coal, which contains some amount of water prior to burning. Heating value is also discussed in Sect. 2.4. Higher and lower heating values of some common fuels, and energy density of some fuels are tabulated in Tables 2.7, 2.8, and 2.9.

Lower heating value (or *net calorific value*) is determined by subtracting the heat of vaporization of the water vapor from the higher heating value. A common method of relating higher heating value to lower heating value is:

$$\begin{aligned}&\mathrm{LHV} = \mathrm{HHV} - \left(\Delta H_{\mathrm{vap}}\right)\left(n_{\mathrm{H_2O,\,out}}/n_{\mathrm{fuel,\,in}}\right)\left(MW_{\mathrm{H_2O,\,out}}/MW_{\mathrm{fuel,\,in}}\right)\\ &\text{or}\\ &\mathrm{LHV} = \mathrm{HHV} - \left(\Delta H_{\mathrm{vap}}\right)\left(m_{\mathrm{H_2O,\,out}}/m_{\mathrm{fuel,\,in}}\right)\end{aligned} \tag{7.5}$$

where ΔH_{vap} is the heat of vaporization of water (in kJ/kg or Btu/lb), $n_{\mathrm{H_2O,\,out}}$ is the moles of water vaporized and $n_{\mathrm{fuel,in}}$ is the number of moles of fuel combusted, $MW_{\mathrm{H_2O}}$ is the molecular weight of water, and MW_{fuel} is the molecular weight of fuel. Example 7.1 illustrates the estimation of lower heating value from higher heating value, while Example 7.2 shows the estimation of heating values from the standard heat of combustion.

Example 7.1 Estimation of lower heating value from higher heating value
Higher heating value of natural gas is measured as 23,875 Btu/lb around room temperature (70°F). Convert this higher heating value to lower heating value. Heat of vaporization of water: ΔH_{vap} = 1,055 Btu/lb (70 °F).

Solution:
Assume that the natural gas is represented by methane CH_4.

The combustion of methane: $CH_4 + 3/2O_2 \rightarrow CO_2 + 2H_2O$
Higher heating value: HHV(methane) = 23875 Btu/lb,
From Table A1:
$MW_{\mathrm{H_2O}} = (H_2) + 1/2(O_2) = 2 + 16 = 18$ lb/lbmol
$MW_{\mathrm{CH_4}} = (C) + 4(H) = 12 + 4 = 16$ lb/lbmol

$n_{\mathrm{CH_4}} = 1$ lbmol and $n_{\mathrm{H_2O}} = 2$ lbmol and $n_{\mathrm{H_2O}}/n_{\mathrm{CH_4}} = 2/1$

Heat of vaporization: ΔH_{vap} = 1055 Btu/lb (70°F)

Lower heating value:
$\mathrm{LHV} = \mathrm{HHV} - (\Delta H_{\mathrm{vap}})\,(n_{\mathrm{H_2O,\,out}}/n_{\mathrm{fuel,in}})(MW_{\mathrm{H_2O,\,out}}/MW_{\mathrm{fuel,in}})$ (Eq. 7.5)
LHV = 23875 Btu/lb – (1055 Btu/lb)(2/1)(18/16) = **21500 Btu/lb**

Example 7.2 Estimating the heating values from the standard heat of combustion
The combustion reaction of 1 mol propane is:

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(g)$$

Estimate the higher and lower heating values of 1 kg of propane at room temperature. Heat of vaporization is assumed as ΔH_{vap} = 2,442 kJ/kg (25°C).

Solution:
When the products and reactants are at their standard states (ideal-gas state at 1 bar and 25°C) the standard heat of reaction is expressed by

$$\Delta H_r^o = \sum_i v_i \Delta H_{fi}^o = v_{CO_2}\Delta H_{fCO_2}^o + v_{H_2O}\Delta H_{fH_2O}^o + v_{C_3H_8}\Delta H_{fC_3H_8}^o$$

Stoichiometric coefficients: $v_{CO_2} = 3$, $v_{H_2O} = 4$, and $v_{C_3H_8} = -1$.
Using the standard heats of formation form Table C1, the heat of combustion of one mole of propane (C_3H_8) is estimated by

$$\begin{aligned}\Delta H_{r298}^{o} &= 3(-393.51)\,\mathrm{kJ/gmol} + 4(-241.818)\,\mathrm{kJ/gmol} - (-104.7)\,\mathrm{kJ/gmol} \\ &= -2043.1\,\mathrm{kJ/gmol}\end{aligned}$$

Here the standard heat of reaction for oxygen is zero, as it is a naturally existing molecule in the environment.

Molecular weight of propane: MW = 44 g/gmol = 0.044 kg/mol. (Table A1)
Heat released after the combustion of 1 kg of propane is the lower heating value since the water product is at vapor state:

$$\Delta H_{r298}^{o} = \mathrm{LHV} = (2043.1\ \mathrm{kJ/gmol})(\mathrm{gmol}/0.044\ \mathrm{kg}) = 46{,}430\ \mathrm{kJ/kg}$$

The higher heating value:
$MW_{H_2O} = (H_2) + 1/2(O_2) = 2 + 16 = 18$ kg/kmol
$MW_{C_3H_8} = 3(C) + 8(H) = 36 + 8 = 44$ kg/kmol
$n_{C_3H_8} = 1$ gmol and $n_{H2O} = 4$ gmol
$\Delta H_{vap} = 2{,}442$ kJ/kg (25°C)

After rearranging Eq. 7.5 higher heating value becomes:
$\mathrm{HHV} = \mathrm{LHV} + (\Delta H_{vap})\,(n_{H_2O,out}/n_{C_3H_8,in})(MW_{H_2O,out}/MW_{C_3H_8,in})$
HHV = 46,430 kJ/kg + (2,442 kJ/kg)(4/1)(18/44) = **50,426 kJ/kg**

7.4 Thermal Efficiency of Energy Conversions

Thermal efficiency is a measure of the amount of thermal energy that can be converted to another useful form. For an energy conversion device such as a boiler or furnace, the thermal efficiency η_{th} is the ratio of the amount of useful energy to the energy that went into the conversion

$$\eta_{th} = \frac{q_{useful}}{q_{in}} \tag{7.6}$$

No energy conversion device is 100% efficient. Most conversion devices and processes we use every day, such as light bulbs and steam power production operate with a low thermal efficiency. For example, most incandescent light bulbs are only 5–10% efficient because most of the electric energy is lost as heat to the surroundings. An electric resistance heater has a thermal efficiency close to 100%. When comparing heating units, such as a highly efficient electric resistance heater with an 80% efficient natural gas-fueled furnace, an economic analysis is needed to determine the most cost-effective choice [10, 23, 33, 36].

Thermal efficiency usually involves a comparison of the total chemical energy in the fuels, and the useful energy extracted from the fuels in the form of kinetic energy. Which definition of heating value is being used as input energy affects the value of efficiency when the efficiency is determined by dividing the energy output by the input energy released by a fuel.

If a liquid water flow is used in a boiler to produce saturated vapor, the heat gained by the water can be expressed as the summation of sensible heat increase plus latent heat of vaporization

$$\dot{q} = \dot{m}(C_{p,av}\Delta T + \Delta H_{\text{vap}}) \tag{7.7}$$

where $\dot{q}$ is the heat gained, $\dot{m}$ is the mass flow rate, C_p is the specific heat capacity, ΔT is the temperature difference between inlet and outlet of the water in the boiler, and ΔH_{vap} is the heat of vaporization. Vaporization process needs heat and the condensation process releases heat as shown below

$$H_2O(\text{liquid}) + \Delta H_{\text{vap}} \rightarrow H_2O(\text{vapor}) \qquad \text{Vaporization} \tag{7.8}$$

$$H_2O(\text{vapor}) \rightarrow H_2O(\text{liquid}) + \Delta H_{\text{cond}} \qquad \text{Condensation} \tag{7.9}$$

The heat of vaporization is equal to the heat of condensation at the same temperature and pressure

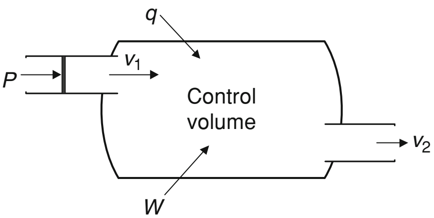
$$\Delta H_{\text{vap}} = -\Delta H_{\text{cond}} \text{ (At the same temperature and pressure)} \tag{7.10}$$

The flue gases from boilers are in general not condensed. Therefore, actual amount of heat available to the boiler is the lower heating value since part of the heat of combustion of the fuel is used for the evaporation of the water. An accurate control of the air supply is essential to the boilers efficiency. Too much air cools the furnace and carries away useful heat, while the combustion will be incomplete with little air and unburned fuel will be carried over and smoke produced. *Net calorific value* of a fuel excludes the energy in the water vapor discharged to the stack in the combustion process. For heating systems their peak steady-state thermal efficiency is often stated as, for example, this furnace is 90% efficient, but a more detailed measure of seasonal energy effectiveness is the annual fuel utilization efficiency (AFUE), which is discussed in Sect. 9.4.

7.5 Ideal Fluid-Flow Energy Conversions

For fluid-flow systems, enthalpy rather than the internal energy is used in engineering since the fluid-flow work (PV) is taken into account within the enthalpy. Figure 7.2 shows an open steady-state flow system.

Fig. 7.2 Fluid-flow with heat and work interactions between the control volume and surroundings: $\dot{m}(\Delta H+\Delta v^2/2+g\Delta z)=\dot{q}+\dot{W}_s$ at constant pressure



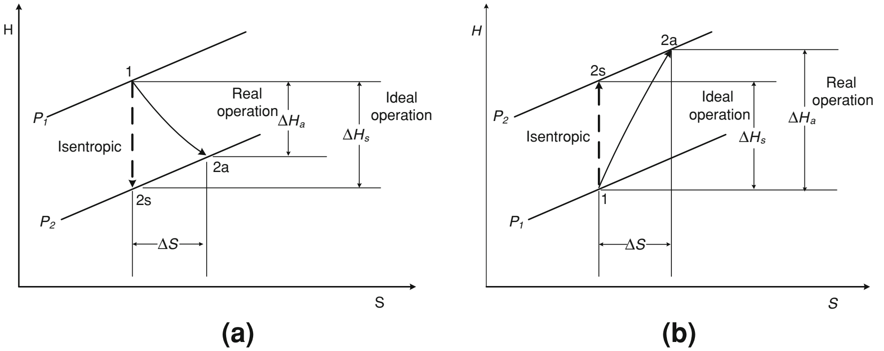


Fig. 7.3 Fluid flow work **a** in a turbine ($P_1 > P_2$), **b** in a compressor ($P_1 < P_2$); ideal operation is isentropic in a turbine and produces maximum work; ideal operation is isentropic in a compressor and requires minimum work

The general relation between the heat and work for a fluid-flow is expressed by:

$$\dot{m}\left(\Delta H+\frac{\Delta v^2}{2}+g\Delta z\right)=\dot{q}+\dot{W}_s \tag{7.11}$$

Heat transfer and work transfer should be distinguished based on the entropy transfer:

- Energy interaction that is accompanied by entropy transfer is heat transfer.
- Energy interaction that is not accompanied by entropy transfer is work.

For a process producing work, such a turbine as shown in Fig. 7.3a, the *ideal work* is the maximum possible work (isentropic) produced. However, for a process requiring work, such as a compressor shown in Fig. 7.3b, the ideal work is the minimum amount of required work (isentropic). These limiting values of work occur when the change of state in the process is accomplished reversibly [5, 27, 37]. For such processes friction, heat loss, and other losses are negligible. When the changes in kinetic and potential energies are negligible Eq. 7.11 becomes

$$\dot{m}\Delta H=\dot{q}+\dot{W}_s \tag{7.12}$$

For a uniform surrounding temperature T_o and using the definition of heat flow as

$$\dot{q} = T_o \Delta(\dot{m}S) \tag{7.13}$$

ideal work becomes

$$\dot{W}_{\text{ideal}} = \dot{W}_{\text{rev}} = \Delta(\dot{m}H) - T_o \Delta(\dot{m}S) \tag{7.14}$$

A reversible process, however, is hypothetical and used mainly for determination of the ideal work limit and comparing it with the actual work for the same property change. When the ideal work is produced (Fig. 7.3a), for example in a turbine, we have the *adiabatic or isentropic efficiency* defined by

$$\eta_{Ts} = \frac{W_{\text{prod}}}{W_{\text{ideal}}} = \frac{H_1 - H_{2a}}{H_1 - H_{2s}} = \frac{\Delta H_a}{\Delta H_s} \text{ (work produced)} \tag{7.15}$$

With the ideal work required (Fig. 7.3b), such as in a compressor, the *isentropic efficiency* η_s is obtained by

$$\eta_{Cs} = \frac{W_{\text{ideal}}}{W_{\text{req}}} = \frac{H_{2s} - H_1}{H_{2a} - H_1} = \frac{\Delta H_s}{\Delta H_a} \text{ (work required)} \tag{7.16}$$

Reversible work $\dot{W}_{\text{rev}}$ in terms of the values of exergy [20] for a process between the specified initial and final states is defined by

$$\dot{W}_{\text{rev}} = \dot{m}(Ex_1 - Ex_2) + \left(1 + \frac{T_o}{T}\right)\dot{q} \tag{7.17}$$

where T_o is the reference temperature. Example 7.3 illustrates the maximum expansion work calculations, while Example 7.4 calculates the isentropic efficiency.

Example 7.3 Maximum work (ideal work) calculations

One mole of air expands from an initial state of 500 K and 10 atm to the ambient conditions of the surroundings at 300 K and 1 atm. An average heat capacity of the air is $C_{p,av}$ = 29.5 J/mol K. Estimate the maximum work.

Solution:

Assume: air is ideal-gas system and the change of state is completely reversible.

T_1 = 500 K, P_1 = 10 atm, T_2 = 300 K, P_2 = 1 atm, $C_{p,av}$ = 29.5 J/mol K,
R = 8.314 J/mol K

For an ideal-gas, enthalpy is independent of pressure and its change is

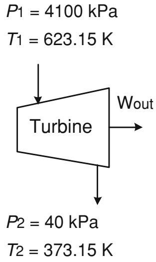
$$\Delta H = \int_1^2 C_{p,av} \mathrm{d}T = C_{p,av}(T_2 - T_1) = -5{,}900\,\text{J/mol}$$

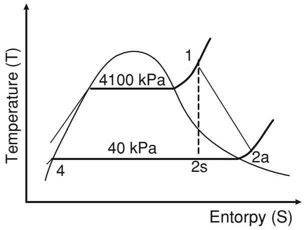
Change in entropy: $\Delta S = C_{p,av} \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right) = 34.21\ \text{J/mol K}$, Eq. (4.50)

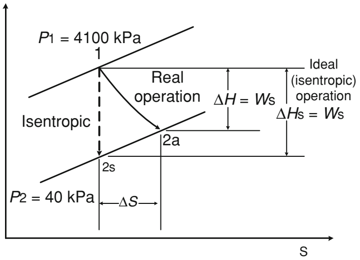
Ideal work: $W_{\text{ideal}} = W_{\text{rev}} = \Delta H - T_o \Delta S = \mathbf{-16163\ J/mol}$
The negative sign indicates that the expansion work is transferred to the surroundings.

Example 7.4 Isentropic turbine efficiency

An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The steam leaves the turbine at 40 kPa and 100°C. The steam mass flow rate is 8 kg/s. Determine the isentropic efficiency of the turbine.







Solution:
Assume: steady-state adiabatic operation. The changes in kinetic and potential energies are negligible.

Inlet conditions: superheated steam (Table F4)
P_1 = 4,100 kPa, T_1 = 623.15 K, H_1 = 3,092.8 kJ/kg, S_1 = 6.5727 kJ/kg K
Exit conditions: saturated steam (Table F3)
P_2 = 40 kPa, T_2 = 373.15 K, H_{2a} = 2,683.8 kJ/kg,
$S_{2\text{sat vap}}$ = 7.6709 kJ/kg K, $S_{2\text{sat liq}}$ = 1.2026 kJ/kg K at 40 kPa
$H_{2\text{sat vap}}$ = 2,636.9 kJ/kg, $H_{2\text{sat liq}}$ = 317.6 kJ/kg at 40 kPa (Table F4)
For the isentropic operation $S_1 = S_2$ = 6.5727 kJ/kg K
Since $S_{2\text{sat liq}} < S_2 = S_{2\text{sat vap}}$ the steam at the exit is saturated liquid–vapor mixture, and the quality of that mixture x_{2s} is

$$x_{2s} = \frac{S_2 - S_{2\text{sat liq}}}{S_{2\text{sat vap}} - S_{2\text{sat liq}}} = \frac{6.5727 - 1.2026}{7.6709 - 1.2026} = 0.83$$

$$H_{2s} = (1 - x_{2s})H_{2\text{sat liq}} + x_{2s}H_{2\text{sat vap}} = 2{,}243.1\ \text{kJ/kg (Isentropic)}$$

H_{2a} = 2,683.8 kJ/kg (Real operation)
H_1 = 3,092.8 kJ/kg

Isentropic efficiency becomes: $\eta_{Ts} = \frac{H_1 - H_{2a}}{H_1 - H_{2s}} = \mathbf{0.48}$ **(or 48%)**

7.6 Lost Work

The difference between the ideal work and the actual work is due to irreversibilities within the selected path between the initial and final states for a process. The extent of irreversibility is equivalent to exergy lost and is a measure of lost work potential [7]. Lost work is defined as a difference between the actual and ideal work and related to the rate of entropy production. Actual work is

$$\dot{W}_{\text{act}} = \Delta\left[\dot{m}\left(H + \frac{v^2}{2} + gz\right)\right] - \dot{q} \tag{7.18}$$

For surrounding temperature T_o, ideal work is

$$\dot{W}_{\text{ideal}} = \Delta\left[\dot{m}\left(H + \frac{v^2}{2} + gz\right)\right] - T_o\Delta(\dot{m}S) \tag{7.19}$$

Then the lost work

$$\dot{W}_{\text{lost}} = \dot{W}_{\text{act}} - \dot{W}_{\text{ideal}} = \dot{q} - T_o\Delta(\dot{m}S) \tag{7.20}$$

The lost work occurs because of the rate entropy production $\dot{S}_{\text{prod}}$, which is defined from the entropy balance in Sect. 5.4 by Eq. 5.20

$$\dot{S}_{\text{prod}} = \Delta(\dot{m}S) - \frac{\dot{q}}{T_o} \tag{7.21}$$

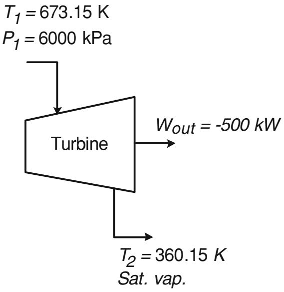
Therefore Eq. (7.20) becomes

$$\dot{W}_{\text{lost}} = T_o\dot{S}_{\text{prod}} \tag{7.22}$$

Since the rate of entropy production is always positive $(\dot{S}_{\text{prod}} > 0)$ for irreversible processes, then $\dot{W}_{\text{lost}} > 0$. Only when a process is completely reversible then $\dot{W}_{\text{lost}} = 0$ since $\dot{S}_{\text{prod}} = 0$. The rate of entropy production and hence the amount of lost work will increase as the irreversibility increases for a process. This leads to increase in the amount of energy that is unavailable and hence wasted. Example 7.5 illustrates the lost work calculations, while 7.6 estimates the minimum power required in a compressor.

Example 7.5 Estimation of lost work

A turbine discharges steam from 6 MPa and 400°C to saturated vapor at 360.15 K while producing 500 kW of shaft work. The temperature of surroundings is 290 K. Determine maximum possible production of power in kW and the amount of work lost.



Solution:
Assume: the turbine operates at steady-state. Kinetic and potential energy changes are negligible.

Basis: 1 kg/s steam flow rate
Inlet: superheated steam: H_1 = 3,180.1 kJ/kg, S_1 = 6.5462 kJ/kg K (Table F4)
Outlet: saturated steam: H_2 = 2,655.3 kJ/kg, S_2 = 7.5189 kJ/kg (Table F3)
$W_{\text{out}} = -$ 500 kW, T_{o} = 290 K
$\Delta H = H_2 - H_1$ = (2,655.3 − 3,180.1) kJ/kg = − 524.8 kJ/kg
The amount of heat transfer: $q = -W + H_2 - H_1 = -24.8$ kJ/kg
We can determine the entropy production from an entropy balance on the turbine operating at steady-state that exchanges heat only with the surroundings:

$$S_{\text{prod}} = S_2 - S_1 - \frac{q}{T_o} = 7.5189 - 6.5462 + 24.8\ \text{kJ/kg}/(290)\text{K} = 1.06\ \text{kJ/kg K}$$

Lost work: $W_{\text{lost}} = T_o S_{\text{prod}} = 307.4$ kJ/kg
Maximum work output:

$$W_{\text{ideal}} = W_{\max} = W_{\text{s}} - T_o S_{\text{prod}} = -500 - 307.4 = \mathbf{-807.4\,kJ/kg}$$

Example 7.6 Estimation of a minimum power required in a compressor
A compressor receives air at 15 psia and 80°F with a flow rate of 1.0 lb/s. The air exits at 40 psia and 300°F. Estimate the minimum power input to the compressor. The surroundings are at 520 R.

Solution:
Assume that potential energy effects are negligible, and steady process. Adiabatic compression with q_{loss} = 0.

Basis: air flow rate = $\dot{m}$ = 1 lb/s. The surroundings are at 520 R
The properties of air from Table D1 after conversions from SI units:

State 1: P_1 = 15 psia, T_1 = 540 R, H_1 = 129.0 Btu/lb, S_1 = 0.6008 Btu/lb R

State 2: $P_2 = 40$ psia, $T_2 = 760$ R, $H_2 = 182.0$ Btu/lb, $S_2 = 0.6831$ Btu/lb R
Compressor work:
$\dot{W}_s = \dot{m}(H_2 - H_1) = (1\ \text{lb/s})(182.08 - 129.06)\,\text{Btu/lb} = 53.0\ \text{Btu/s}$

The entropy production: $\dot{S}_{\text{prod}} = \dot{m}(S_2 - S_1) = 0.0823\ \text{Btu/s R}$ (Eq. 7.21)
Lost work: $\dot{W}_{\text{lost}} = \dot{m}T_o S_{\text{prod}} = 42.8\ \text{Btu/s}$
Minimum work required:
$\dot{W}_{\text{ideal}} = \dot{W}_{\text{min}} = \dot{m}\left(\Delta H - T_o S_{\text{prod}}\right) = (53.0 - 42.8)\ \ \text{Btu/s} = \mathbf{10.2\,Btu/s}$

7.7 Efficiency of Mechanical Conversions

Transfer of mechanical energy is usually accomplished through a rotating shaft. When there is no loss (for example, in the form of friction) mechanical energy can be converted completely from one mechanical form to another. The mechanical energy conversion efficiency is estimated by

$$\eta_{mech} = \frac{\text{energy out}}{\text{energy in}} \tag{7.23}$$

For example, a mechanical energy conversion efficiency of 95% shows that 5% of the mechanical energy is converted to heat as a result of friction and other losses [6, 10].

In fluid-flow systems, a pump receives shaft work usually from an electric motor, and transfers this shaft work partly to the fluid as mechanical energy and partly to the frictional losses as heat. As a result, the fluid pressure or velocity, or elevation is increased. A turbine, however, converts the mechanical energy of a fluid to shaft work. The energy efficiency for a pump is defined by

$$\eta_{pump} = \frac{\text{mechanical energy out}}{\text{mechanical energy in}} = \frac{\dot{E}_{\text{mech out}}}{\dot{W}_{\text{shaft in}}} \tag{7.24}$$

Mechanical energy efficiency of a fan is the ratio of kinetic energy of air at the exit to the mechanical power input. If a fan, for example, is using a 50 W motor and producing an air flow velocity of 15 m/s and the air mass flow rate of 0.3 kg/s, then the mechanical energy efficiency of the fan becomes

$$\eta_{fan} = \frac{\dot{E}_{\text{mech out}}}{\dot{W}_{\text{shaft in}}} = \frac{(0.3\,\text{kg/s})(15\,\text{m/s})^2/2}{50\ \ \text{W}} = 0.675$$

Here, the velocity at the inlet is zero, $v_1 = 0$, and the pressure energy and potential energy are zero ($\Delta P = 0$, and $\Delta z = 0$). The energy efficiency for a turbine is defined by

$$\eta_{turb} = \frac{\text{mechanical energy output}}{\text{mechanical energy (extracted from fluid) in}} = \frac{\dot{W}_{\text{shaft out}}}{\dot{E}_{\text{mech in}}} \tag{7.25}$$

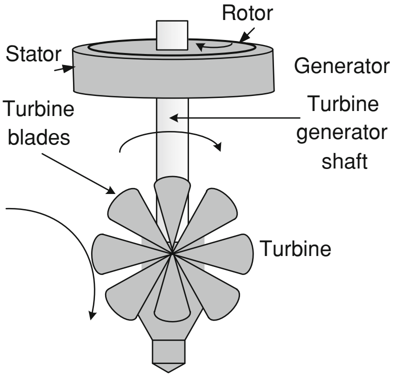


Fig. 7.4 A typical turbine and generator. The overall efficiency of a hydraulic turbine-generator is the ratio of the thermal energy of the water converted to the electrical energy; for a turbine efficiency of 0.8 and a generator efficiency of 0.9, we have: $\eta_{\text{turb}-\text{gen}} = \eta_{\text{turb}}\eta_{\text{gen}} = (0.8)(0.95) = 0.76$

The motor efficiency and the generator efficiency, on the other hand, are defined by

$$\eta_{motor} = \frac{\text{mechanical power output}}{\text{electrical energy input}} = \frac{\dot{W}_{\text{shaft out}}}{\dot{W}_{\text{elect in}}} \quad \text{(motor)} \tag{7.26}$$

$$\eta_{gen} = \frac{\text{electrical power output}}{\text{mechanical power input}} = \frac{\dot{W}_{\text{elect out}}}{\dot{W}_{\text{shaft in}}} \quad \text{(generator)} \tag{7.27}$$

A hydraulic turbine is combined with its generator in power production cycles, as shown in Fig. 7.4. A pump is also combined with its motor. Therefore, a combined or overall efficiency for turbine-generator and pump-motor systems is defined as follows

$$\eta_{\text{turb}-\text{gen}} = \eta_{\text{turb}}\eta_{\text{gen}} = \frac{\dot{W}_{\text{electout}}}{\Delta\dot{E}_{\text{mechin}}} \quad \text{(turbine}-\text{generator systems)} \tag{7.28}$$

The overall efficiency of a hydraulic turbine-generator shows the fraction of the mechanical energy of the water converted to electrical energy.

$$\eta_{\text{pump}-\text{motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\Delta\dot{E}_{\text{mech}}}{\dot{W}_{\text{electin}}} \quad \text{(pump}-\text{motor systems)} \tag{7.29}$$

The overall efficiency of a pump-motor system shows the fraction of the electrical energy converted to mechanical energy of the fluid [5, 37]. Example 7.7 illustrates the estimation of heat loss in an electric motor, while Example 7.8 illustrates the estimation of mechanical efficiency of a pump.

Example 7.7 Heat loss in an electric motor

An electric motor attached to a pump draws 10.0 A at 110 V. At steady load the motor delivers 1.32 hp of mechanical energy. Estimate the heat loss from the motor.

Solution:

Assume that the load to motor is steady.

I = 10.0 A, V = 110 V, $\dot{W}_s$ = 1.32 hp = 983 W
The electric power received by the motor is used to create a pump work and heat:

Power received: $\dot{W}_e = IV = 1{,}100\,\mathrm{W}$
Heat loss: $\dot{q}_{\mathrm{loss}} = \dot{W}_e - \dot{W}_s = 1{,}100 - 983 = \mathbf{117\,W}$.
Only 983 kW of the 1,100 kW is converted to the pump work.

Example 7.8 Mechanical efficiency of a pump
The pump of a water storage tank is powered with a 16-kW electric motor operating with an efficiency of 90%. The water flow rate is 55 l/s. The diameters of the inlet and exit pipes are the same, and the elevation difference between the inlet and outlet is negligible. The absolute pressures at the inlet and outlet are 100 and 300 kPa, respectively. Determine the mechanical efficiency of the pump.

Solution:
Assume: steady-state one-dimensional and adiabatic flow. Kinetic and potential energy changes are negligible.
ρ_{water} = 1,000 kg/m^3 = 1 kg/l
Mass flow rate of water: $\dot{m}_{\mathrm{water}} = \rho\dot{Q} = (1\ \mathrm{kg/l})(55\ \mathrm{l/s}) = 55\ \mathrm{kg/s}$
Electric motor delivers the mechanical shaft work:
$W_{\mathrm{pump}} = \eta_{\mathrm{motor}}\dot{W}_{\mathrm{electric}} = (0.9)(16\ \mathrm{kW}) = 14.4\ \mathrm{kW}$
Increase in the mechanical energy of the water:

$$\Delta\dot{E}_{\mathrm{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1)\right)$$

After neglecting kinetic and potential energies:

$$\Delta\dot{E}_{\mathrm{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho}\right) = (55\,\mathrm{kg/s})\left(\frac{(300-100)\mathrm{kPa}}{1000\ \mathrm{kg/m^3}}\right)\left(\frac{\mathrm{kJ}}{\mathrm{kPa\ m^3}}\right) = 11.0\,\mathrm{kW}$$

The mechanical efficiency of the pump is

$$\eta_{\mathrm{pump}} = \frac{\Delta\dot{E}_{\mathrm{mech}}}{\dot{W}_{\mathrm{pump}}} = \frac{11\,\mathrm{kW}}{14.4\ \mathrm{kW}} = \mathbf{0.763\ or\ 76.3\%}$$

Only 11 kW of the 14.4 kW received by the pump is converted to the pump work. Remaining 3.4 kW is lost as heat because of friction.

7.8 Conversion of Thermal Energy by Heat Engines

Heat engines transform thermal energy q_{in} into mechanical energy or work W_{out}. Some examples of heat engines include the steam engine, heat pump, gasoline (petrol) engine in an automobile, the diesel engine, and gas power cycles. All of

Table 7.2 Comparison of the processes for some of the heat engines

Cycle	Compression	Heat addition	Expansion	Heat rejection
Rankine	Adiabatic	Isobaric	Adiabatic	Isobaric
Carnot	Isentropic	Isothermal	Isentropic	Isothermal
Ericsson	Isothermal	Isobaric	Isothermal	Isobaric
Stirling	Isothermal	Isochoric	Isothermal	Isochoric
Diesel	Adiabatic	Isobaric	Adiabatic	Isochoric
Otto	Adiabatic	Isochoric	Adiabatic	Isochoric
Brayton	Adiabatic	Isobaric	Adiabatic	Isobaric

Table 7.3 Various types of cycles for heat engines

External combustion cycles	Without phase change: Brayton, Carnot, Ericsson, Stirling With phase change: Rankine, Two-phased Stirling
Internal combustion cycles	Without phase change: Diesel, Otto
Refrigeration cycles	Vapor-compression
Heat pump cycles	Vapor-compression

these heat engines drive the mechanical motion of the engine by the expansion of heated gases. Some heat engines operate with phase-change cycles, such as steam power production by Rankine cycle where liquid water changes to vapor after adding heat. After expansion in the cycle, the vapor condenses into liquid water. Other type of heat engines operate without phase-change cycles, such as Brayton cycle where a hot gas is cooled after the expansion in the heat engine. Typical gas power cycles consists of compressing cool gas, heating the gas, expanding the hot gas, and finally cooling the gas before repeating the cycle. Table 7.2 lists some important engines and their cycle processes. Typical thermal efficiency for power plants in the industry is around 33% for coal- and oil-fired plants, and up to 50% for combined-cycle gas-fired plants. Combined-cycle gas-turbine plants are driven by both steam and natural gas [13, 15, 28].
Each process in a cycle is at one of the following states:

- Isothermal (at constant temperature)
- Isobaric (at constant pressure)
- Isochoric (at constant-volume)
- Adiabatic (no heat is added or removed)

Engine types vary as shown in Table 7.3. In the combustion cycles, once the mixture of air and fuel is ignited and burnt, the available energy can be transformed into the work by the engine. In a reciprocating engine, the high-pressure gases inside the cylinders drive the engine's pistons. Once the available energy has been converted to mechanical work, the remaining hot gases are vented out and this allows the pistons to return to their previous positions [15].

Some of the available heat input is not converted into work, but is dissipated as waste heat q_{out} into the environment. The thermal efficiency of a heat engine is the percentage of heat energy that is converted into work, and is estimated by

$$\eta_{\mathrm{th}} = \frac{W_{\mathrm{out}}}{q_{\mathrm{in}}} = 1 - \frac{q_{\mathrm{out}}}{q_{\mathrm{in}}} \tag{7.30}$$

The efficiency of even the best heat engines is low; usually below 50% and often far below. So the energy lost to the environment by heat engines is a major waste of energy resources, although modern cogeneration, combined cycle, and energy recycling schemes are beginning to use this waste heat for other purposes. This inefficiency can be attributed mainly to three causes:

- Thermal efficiency of any heat engine is limited by the Carnot efficiency.
- Specific types of engines may have lower limits on their efficiency due to the inherent irreversibility of the engine cycle they use.
- The non-ideal behavior of real engines, such as mechanical friction and losses in the combustion process, may cause further efficiency losses.

Thermal efficiency of heat engine cycles cannot exceed the limit defined by the Carnot cycle which states that the overall efficiency is dictated by the difference between the lower and upper operating temperatures of the engine. This limit assumes that the engine is operating in ideal conditions that are frictionless processes, ideal-gases, perfect insulators, and operation at infinite time. A car engine's real-world fuel economy is usually measured in the units of miles per gallon (or fuel consumption in liters per 100 km). Even when aided with turbochargers and design aids, most engines retain an *average* efficiency of about 18–20%. Rocket engine efficiencies are still better, up to 70%, because they combust at very high temperatures and pressures, and are able to have very high expansion ratios. For stationary and shaft engines, fuel consumption is measured by calculating the *brake specific fuel consumption* which measures the mass flow rate of fuel consumed divided by the power produced. Example 7.8 illustrates the estimation of fuel consumption of a car.

The engine efficiency alone is only one factor. For a more meaningful comparison, the overall efficiency of the entire energy supply chain from the fuel source to the consumer should be considered. Although the heat wasted by heat engines is usually the largest source of inefficiency, factors such as the energy cost of fuel refining and transportation, and energy loss in electrical transmission lines may offset the advantage of a more efficient heat engine. Engines must be optimized for other goals besides efficiency such as low pollution. Vehicle engines must also be designed for low emissions, adequate acceleration, fast starting, light weight, and low noise. These requirements may lead to compromises in design that may reduce efficiency. Large stationary electric generating plants have fewer of these competing requirements so the Rankine cycles are significantly more efficient than vehicle engines. Therefore, replacing internal combustion vehicles with electric vehicles, which run on a battery recharged with electricity generated by burning fuel in a power plant, has the theoretical potential to increase the thermal efficiency of energy use in transportation, thus decreasing the demand for fossil fuels [6, 29].

Real engines have many departures from ideal behavior that waste energy, reducing actual efficiencies far below the theoretical values given above. Examples of non-ideal behavior are:

- Friction of moving parts.
- Inefficient combustion.
- Heat loss from the combustion chamber.
- Non-ideal behavior of the working fluid.
- Inefficient compressors and turbines.
- Imperfect valve timing.

Example 7.9 Thermal efficiency of a heat engine

Heat is transferred to a heat engine from a furnace at a rate of 90 MW. The waste heat is discharged to the surroundings at a rate of 55 MW. Estimate the net power output and thermal efficiency of the engine if all the other power losses are neglected.

Solution:
Assume: steady-state process with negligible heat losses.

$\dot{q}_{in} = 90\ \text{MW},\ \dot{q}_{out} = 55\ \text{MW}$

Net power output: $\dot{W}_{\text{net out}} = \dot{q}_{\text{in}} - \dot{q}_{\text{out}} = \mathbf{35\,MW}$

Thermal efficiency: $\eta_{th} = \dfrac{\dot{W}_{\text{net}}}{q_{\text{in}}} = \dfrac{35}{90} = \mathbf{0.388\ (or\ 38.8\%)}$

The heat engine can convert 38.8% of the heat transferred from the furnace.

Example 7.10 Fuel consumption of a car

The overall efficiencies are about 25–28% for gasoline car engines, 34–38% for diesel engines, and 40–60% for large power plants [6]. A car engine with a power output of 120 hp has a thermal efficiency of 24%. Determine the fuel consumption of the car if the fuel has a higher heating value of 20,400 Btu/lb.

Solution:
Assume: the car has a constant power output.
Net heating value ≅ higher heating value (0.9) = 18,360 Btu/lb (Approximate)
Car engine power output and efficiency: $\dot{W}_{\text{net}} = 120\,\text{hp}, \eta_{\text{th}} = 0.24$

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{q}_{\text{in}}} \rightarrow \dot{q}_{\text{in}} = \frac{\dot{W}_{\text{net}}}{\eta_{\text{th}}} = \frac{120\ \text{hp}}{0.24}\left(\frac{2{,}545\text{Btu/h}}{\text{hp}}\right)$$

$\dot{q}_{in} = 1{,}272{,}500\,\text{Btu/hr}$

Net heating value ≅ higher heating value (0.9) = 18,360 Btu/lb

$$\text{Fuel consumption} = \dot{q}_{in}/\text{net heating value} = 1{,}272{,}500\,\text{Btu/h}/18{,}360\,\text{Btu/lb} = \mathbf{69.3\,lb/h}$$

Assuming an average density of 0.75 kg/l:
ρ_{gas} = (0.75 kg/l)(2.2 lb/kg)(l/0.264 gal) = 6.25 lb/gal
Fuel consumption in terms of gallon: (69.3 lb/h)/(6.25 lb/gal) = **11.1 gal/h**

7.8.1 Air-Standard Assumptions

Internal combustion cycles of Otto and Diesel engines as well as the gas turbines are some well-known examples of engines that operate on gas cycles. In the gas power cycles, the working fluid remains gas for the entire cycle. In the analysis of gas power cycles, the following assumptions known as *air-standard assumptions* are used:

- Working fluid is air and always behaves as an ideal gas.
- All processes in the cycle are internally reversible (isentropic).
- Heat-addition process uses an external heat source.
- Heat-rejection process restores the working fluid to its original state.

It is also assumed that the air has a constant value for the ratio of specific heats determined at room temperature (25°C or 77°F). With this air-standard assumptions are called the *cold-air-standard assumptions*. These assumptions simplify the analysis of gas power cycles without significantly deviating from the actual cycle [6].

7.8.2 Isentropic Processes of Ideal Gases

Entropy change of ideal gas is expressed by

$$\Delta S = S_2 - S_1 = \int_1^2 C_p(T)\frac{dT}{T} - R\ln\left(\frac{P_2}{P_1}\right) \tag{7.31}$$

Under isentropic conditions ($\Delta S = 0$) and constant heat capacity $C_{p,av}$, Eq. 7.31 becomes

$$0 = C_{p,av}\ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right) \tag{7.32}$$

For ideal-gas, the heat capacities are related by

$$C_p - C_v = R \tag{7.33}$$

From Eqs. 7.32 and 7.33 the following relations may be derived

$$\left(\frac{T_2}{T_1}\right)=\left(\frac{V_1}{V_2}\right)^{(\gamma-1)} \text{ and } \left(\frac{T_2}{T_1}\right)=\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma} \tag{7.34}$$

where $\gamma = C_p/C_v$.

Under isentropic conditions ($\Delta S = 0$) and variable heat capacities, Eq. 7.31 becomes

$$0 = S_{T2} - S_{T1} - R\ln\left(\frac{P_2}{P_1}\right) \tag{7.35}$$

where $S_{\mathrm{T}1}$ and $S_{\mathrm{T}2}$ are the values of entropy at temperatures T_1 and T_2, respectively. After rearranging, Eq. (7.35) yields,

$$\frac{P_2}{P_1} = \exp\left(\frac{S_{T2}-S_{T1}}{R}\right) = \frac{\exp(S_{T2}/R)}{\exp(S_{T1}/R)} = \frac{P_{r2}}{P_{r1}} \tag{7.36}$$

where P_{r1} is called the *relative pressure* given by $\exp(S_{T1}/R)$, which is dimensionless quantity. Using the ideal-gas relation

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \tag{7.37}$$

the relative specific volume V_r ($V_r = T/P_r$) is derived by

$$\frac{V_2}{V_1} = \frac{T_2/P_{r2}}{T_1/P_{r1}} = \frac{V_{r2}}{V_{r1}} \tag{7.38}$$

The values of P_r and V_r are tabulated for the air against temperature in Appendix D, Table D1. Equations 7.35–7.38 account the variation of specific heats with temperature and are valid only for isentropic processes of ideal-gases. Equations 7.36 and 7.38 are useful in the analysis of gas power cycles operating with isentropic processes [5].

7.8.3 Conversion of Mechanical Energy by Electric Generator

In electricity generation, an *electric generator* converts mechanical energy to electrical energy generally using *electromagnetic induction*. Electromagnetic induction is the production of electric potential (voltage) across a conductor moving through a magnetic field. A generator forces electrons in the windings to flow through the external electrical circuit. The source of mechanical energy may be water falling through a turbine, waterwheel, an internal combustion engine, and a wind turbine. The reverse is the conversion of electrical energy into mechanical energy, which is done by an electric motor. Figure 7.4 shows a schematic view of a generator.

The efficiency of a generator is determined by the power of the load circuit and the total power produced by the generator. For most commercial electrical generators, this ratio can be as high as of 95%. The losses typically arise from the transformer, the copper windings, magnetizing losses in the core, and the rotational friction of the generator. The overall efficiency of a hydraulic turbine-generator is the ratio of the thermal energy of the water converted to the electrical energy and obtained by

$$\eta_{\text{turb}-\text{gen}} = \eta_{\text{turb}}\eta_{\text{gen}} \tag{7.39}$$

Michael Faraday discovered the operating principle of electromagnetic generators. The principle, later called Faraday's law, is that an electromotive force is generated in an electrical conductor that encircles a varying magnetic flux. The two main parts of a generator are rotor and stator. Rotor is the rotating part, while stator is the stationary part. The armature of generator windings generates the electric current. The armature can be on either the rotor or the stator. Because power transferred into the field circuit is much less than in the armature circuit, alternating current generators mostly have the field winding on the rotor and the stator as the armature winding.

An electric generator or electric motor uses magnetic field coils. If the field coils are not powered, the rotor in a generator can spin without producing any usable electrical energy. When the generator first starts to turn, the small amount of magnetism present in the iron core provides a magnetic field to get it started, generating a small current in the armature. This flows through the field coils, creating a larger magnetic field which generates a larger armature current. This "bootstrap" process continues until the magnetic field in the core levels off due to saturation and the generator reaches a steady-state power output. Very large power station generators often utilize a separate smaller generator to excite the field coils of the larger generator [6].

The *dynamo* was the first electrical generator capable of delivering power for industry. The dynamo uses electromagnetic principles to convert mechanical rotation into the direct current. A dynamo consists of a stationary structure, which provides a constant magnetic field, and a set of rotating windings which turn within that field. A *commutator* is a rotary electrical switch in certain types of electric motors or electrical generators that periodically reverses the current direction between the rotor and the external circuit.

7.8.4 Carnot Engine Efficiency

A Carnot *heat engine* converts heat to mechanical energy by bringing a working fluid from a high temperature state T_H to a lower temperature state T_C. Figure 7.5 shows a typical pressure–volume *PV* and temperature-entropy *TS* diagrams of ideal engine cycles. On both the *PV* and *TS* diagrams, the area enclosed by the process curves of a cycle represents the net heat transfer to be converted to mechanical energy by the engine. Therefore, any modifications that improve the net heat transfer rate will also improve the thermal efficiency [37].

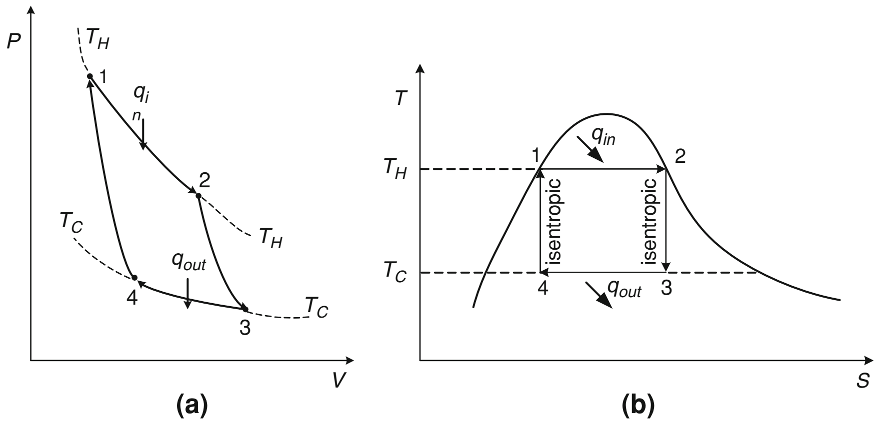


Fig. 7.5 Typical ideal engine cycles **a** on a pressure–volume *PV* diagram, **b** on a temperature-entropy *TS* diagram

A heat source heats the working fluid in the high temperature state. The working fluid generates work in the engine while transferring remaining heat to the colder sink until it reaches a low temperature state. The working fluid usually is a gas or liquid. During the operation of an engine some of the thermal energy is converted into work and the remaining energy is lost to a heat sink, mainly the general surroundings.

Carnot cycle is composed of four totally reversible processes shown in Fig. 7.5:

- Process 1–2: isothermal heat-addition at constant temperature T_H
- Process 2–3: isentropic expansion at constant entropy $S_2 = S_3$
- Process 3–4: isothermal heat rejection at constant temperature T_C
- Process 4–1: isentropic compression at constant entropy $S_4 = S_1$

Thermal efficiency of the Carnot engine is calculated by

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} \tag{7.40}$$

From Fig. 7.5b, we can estimate the amounts of added q_{in} and rejected heat q_{out} values as

$$q_{\text{in}} = T_H(S_2 - S_1) \tag{7.41}$$

$$q_{\text{out}} = T_C(S_4 - S_3) \tag{7.42}$$

Using Eqs. 7.41 and 7.42 in Eq. 7.40, we have

$$\eta_{\text{th}} = 1 - \frac{T_C(S_4 - S_3)}{T_H(S_2 - S_1)} = 1 - \frac{T_C}{T_H} \tag{7.43}$$

since the power cycles are isentropic and we have $S_2 = S_3$ and $S_4 = S_1$. Equation 7.43 shows that heat engines efficiency is limited by Carnot's efficiency which is equal to the temperature difference between the hot (T_H) and cold (T_C) divided by the temperature at the hot end, all expressed in absolute temperatures. The Carnot cycle is a standard against which the actual or ideal cycle can be compared. The Carnot cycle has the highest thermal efficiency of all heat engines operating between the same heat source temperature T_H and the same sink temperature T_C.

The cold side of any heat engine is close to the ambient temperature of the environment of around 300 K, such as a lake, a river, or the surrounding air. Therefore, most efforts to improve the thermodynamic efficiencies of various heat engines focus on increasing the temperature of the hot source within material limits. The highest value of T_H is limited by the maximum temperature that the components of the heat engine, such as pistons or turbine blades, can withstand.

The thermal efficiency of Carnot engine is independent of the type of the working fluid, or whether the cycle operates in a closed or steady-flow system. For example, if an automobile engine burns gasoline at a temperature of $T_H = 1{,}200$ K and the air at exhaust temperature is $T_C = 800$ K, then its maximum possible efficiency is:

$$\eta_{\text{Carnot}} = 1 - \frac{800\text{K}}{1{,}200\ \text{K}} = 0.33 \text{ or } 33\%$$

Totally reversible engine cycle is very difficult to achieve in reality as it requires very large heat exchangers and needs very long time. Practical engines have efficiencies far below the Carnot limit. For example, the average automobile engine is less than 35% efficient. As Carnot's theorem only applies to heat engines, devices that convert the fuel's energy directly into work without burning it, such as fuel cells, can exceed the Carnot efficiency. Actual cycles involve friction, pressure drops as well as the heat losses in various processes in the cycle; hence they operate at lower thermal efficiencies [2, 4, 13, 21].

7.8.5 Endoreversible Heat Engine Efficiency

A Carnot engine must operate at an infinitesimal temperature gradient, and therefore the Carnot efficiency assumes the infinitesimal limit. Endoreversible engine gives an upper bound on the energy that can be derived from a real process that is lower than that predicted by the Carnot cycle, and accommodates the heat loss occurring as heat is transferred. This model predicts how well real-world heat engines can perform [3, 16] by using the following relationship

$$\eta_{\max} = 1 - \sqrt{\frac{T_C}{T_H}} \tag{7.44}$$

Table 7.4 compares the efficiencies of engines operating on the Carnot cycle, endoreversible cycle, and actual cycle. As can be seen, the values of observed efficiencies of actual operations are close to those obtained from the endoreversible cycles.

Table 7.4 Efficiencies of engines operating on the Carnot cycle, endoreversible cycle, and actual cycle

Power plant	T_C (°C)	T_H (°C)	η (Carnot)	η (Endoreversible)	η (Observed)
Coal-fired power plant	25	565	0.64	0.40	0.36
Nuclear power plant	25	300	0.48	0.28	0.30
Geothermal power plant	80	250	0.33	0.18	0.16

Callen [3]

7.8.6 Rankine Engine Efficiency

The Rankine cycle is used in steam turbine power plants. A turbine converts the kinetic energy of a moving fluid to mechanical energy. The steam is forced against a series of blades mounted on a shaft connected to the generator. The generator, in turn, converts its mechanical energy to electrical energy based on the relationship between magnetism and electricity. Most of the world's electric power is produced with Rankine cycle. Since the cycle's working fluid changes from liquid to vapor and back to liquid water during the cycle, their efficiencies depend on the properties of water. The thermal efficiency of modern steam turbine plants with reheat cycles can reach 47%, and in combined-cycle plants it can approach 60%.

Figure 7.6 describes the main processes within the Rankine cycle. The main processes of the Rankine cycle are:

Process 4–1: the water is pumped from low to high pressure.

Process 1–2: the high-pressure liquid enters a boiler where it is heated at constant pressure by an external heat source to become a vapor.

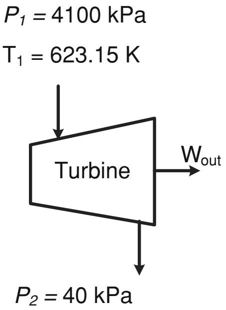
Process 2–3: the vapor expands through a turbine, generating power. This decreases the temperature and pressure of the vapor, and some condensation may occur.

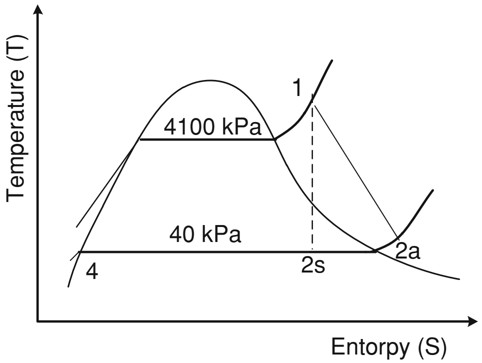
Process 3–4: the wet vapor then enters a condenser where it is condensed at a constant pressure to become a saturated liquid.

The Rankine cycle is sometimes referred to as a practical Carnot cycle (see Fig. 7.5) because in an ideal Rankine cycle the pump and turbine would be *isentropic* and produce no entropy and hence maximize the work output. The main difference is that heat addition (in the boiler) and rejection (in the condenser) are isobaric in the Rankine cycle and isentropic in the theoretical Carnot cycle [13, 37]. Example 7.1 illustrates the estimation of thermal efficiency of an ideal Rankine cycle, and Example 7.12 analyzes the power output of steam power plant.

Example 7.11 Steam turbine efficiency and power output

An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The steam leaves the turbine at 40 kPa. The steam mass flow rate is 8 kg/s. If the isentropic efficiency is 0.75, determine the actual power output of the turbine.



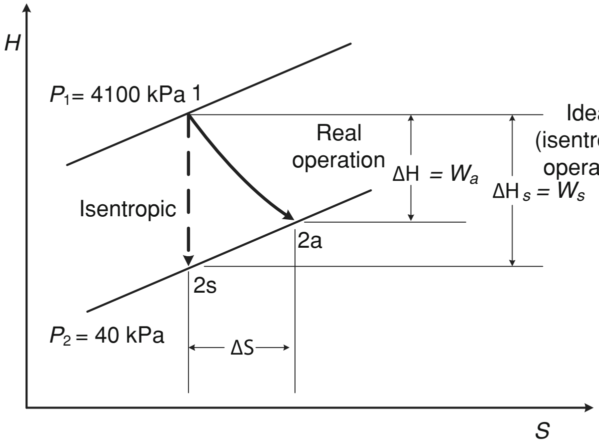


Solution:
Assume: steady-state adiabatic operation. The changes in kinetic and potential energies are negligible.

Data from Table F4:
Inlet conditions:
P_1 = 4,100 kPa, T_1 = 623.15 K, H_1 = 3,092.8 kJ/kg, S_1 = 6.5727 kJ/kg K

Exit conditions:
P_2 = 40 kPa, $S_{2\text{sat vap}}$ = 7.6709 kJ/kg K, $S_{2\text{sat liq}}$ = 1.0261 kJ/kg K
$H_{2\text{sat vap}}$ = 2,636.9 kJ/kg, $H_{2\text{sat liq}}$ = 317.6 kJ/kg at 40 kPa (Table F3)

For the isentropic operation $S_1 = S_2$ = 6.5727 kJ/kg K
Since $S_1 < S_{2\text{sat vap}}$ the steam at the exit is saturated liquid–vapor mixture
Quality of the saturated mixture: $x_{2s} = \dfrac{S_2 - S_{2\text{sat liq}}}{S_{2\text{sat vap}} - S_{2\text{sat liq}}} = \dfrac{6.5727 - 1.0261}{7.6709 - 1.0261} = 0.83$
$H_{2s} = (1 - x_{2s})H_{2\text{sat liq}} + x_{2s}H_{2\text{sat vap}} = 2243.1\,\text{kJ/kg}$



Using isentropic efficiency of 0.75, we can estimate the actual enthalpy H_{2a},

$$\eta_t = \frac{H_1 - H_{2a}}{H_1 - H_{2s}} = 0.75 \rightarrow H_{2a} = 2{,}455.5 \text{ kJ/kg}$$

Actual power output which is not isentropic $\dot{W}_a$ (see figure above)

$$\begin{aligned}\dot{m}\Delta H &= \dot{W}_a = \dot{m}(H_{2a} - H_1) = (8 \text{ kg/s})(2{,}455.5 - 3{,}092.8) = -5{,}098.4 \text{ kW}\\ &= \mathbf{-5.098\,MW}\end{aligned}$$

Maximum power output: $\dot{W}_s$ (see figure above) is only achievable by isentropic expansion.

$$\begin{aligned}\dot{m}\Delta H &= \dot{W}_a = \dot{m}(H_{2s} - H_1) = (8 \text{ kg/s})(2{,}243.1 - 3{,}092.8) = -6{,}797.6 \text{ kW}\\ &= \mathbf{-6.797\,MW}\end{aligned}$$

The Enthalpy-entropy *HS* diagram above explains the difference between real and ideal turbine operation. The signs are negative for work output.

Example 7.12 Estimation of thermal efficiency of a Rankine cycle
A Rankine cycle shown in Fig. 7.6 uses natural gas to produce 0.12 MW power. The combustion heat supplied to a boiler produces steam at 10,000 kPa and 798.15 K, which is sent to a turbine. The turbine efficiency is 0.7. The discharged steam from the turbine is at 30 kPa. The pump efficiency is 0.75. Determine:

(a) The thermal efficiency of an ideal Rankine cycle.
(b) The thermal efficiency of an actual Rankine cycle.

Solution:
Assume that kinetic and potential energy changes are negligible, and the system is at steady-state.
Consider Fig. 7.6.

(a) The basis is 1 kg/s steam.

Turbine in:

H_2 = 3,437.7 kJ/kg, S_2 = 6.6797 kJ/kg K, at T_2 = 798.15 K; P_2 = 10,000 kPa (Table F4)

Turbine out:

$H_{4\text{sat liq}} = H_{3\text{sat liq}}$ = 289.3 kJ/kg K; $H_{4\text{sat vap}} = H_{3\text{sat vap}}$ = 2,625.4 kJ/kg K;

at $P_3 = P_4$ = 30 kPa, $S_{3\text{sat liq}}$ = 0.9441 kJ/kg K; $S_{3\text{sat vap}}$ = 7.7695 kJ/kg K; at P_3 = 30 kPa (Table F3)

η_{turb} = 0.70; η_{pump} = 0.75; V = 1,020 cm^3/kg at T = 342.15 K

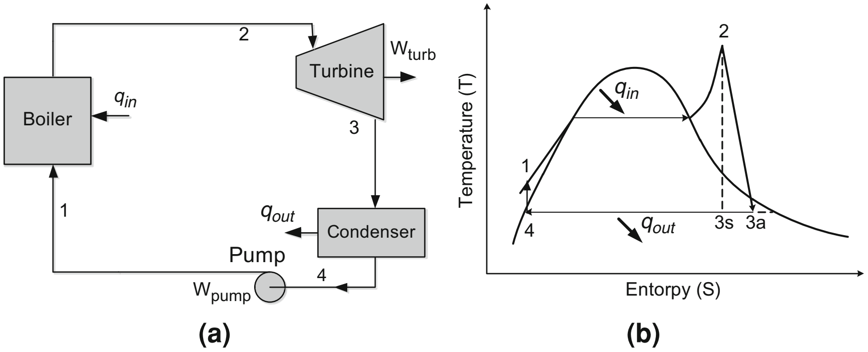
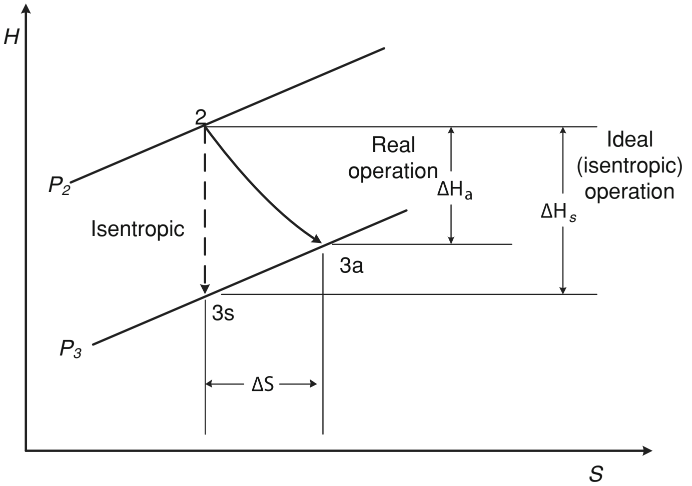


Fig. 7.6 **a** Schematic of Rankine cycle, **b** Rankine cycle processes on a *T* versus *S* diagram; Process 2–3s shows isentropic expansion, while process 2–3a shows a real expansion process where entropy is not constant and the amount of waste heat increases

For the ideal Rankine cycle, the operation is isentropic, and $S_2 = S_3$. However, $S_2 < S_{3\text{sat vap}}$, and the discharged steam from the turbine is wet steam.

The quality of the wet steam x_{3s}: $x_{3s} = \dfrac{S_2 - S_{3\text{sat liq}}}{S_{3\text{sat vap}} - S_{3\text{sat liq}}} = 0.84$

The enthalpy of the wet steam H_{3s}:
$H_{3s} = (1 - x_{3s})H_{3\text{ sat liq}} + x_{3s}H_{3\text{ sat liq}} = 2{,}252.4\,\text{kJ/kg}$
Ideal operation: $W_s = \Delta H_s = H_{3s} - H_2 = -1{,}185.3$ kJ/kg (isentropic expansion)



$P_3 = P_4$, $P_1 = P_2$
From the isentropic pump operation, we have: $W_{ps} = V(P_2 - P_3) = 10.2\,\text{kJ/kg}$
So the enthalpy at point 1: $H_{1s} = \Delta W_{ps} + H_4 = 10.2 + 289.3 = 299.5$ kJ/kg
The heat required in the boiler becomes: $q_{\text{in}} = H_2 - H_{1s} = 3138.2\,\text{kJ/kg}$
The net work for the ideal Rankine cycle:

$W_{\text{net},s} = W_p + \Delta H_s = (10.2 - 1185.3)\ \text{kJ/kg} = -1175.1\ \text{kJ/kg}$

The efficiency of the ideal Rankine cycle: $\eta_{\text{ideal cycle}} = \dfrac{W_{\text{net},s}}{q_{in}} = \mathbf{0.374\ or\ 37.4\%}$

(b) Actual cycle efficiency: $\dfrac{\Delta H_a}{\Delta H_s} = \eta_{t,\text{actual}}$

With the turbine efficiency of $\eta_t = 0.7$, we have: $\Delta H_a = \eta_t \Delta H_s = -829.7\ \text{kJ/kg}$

Pump efficiency: $\dfrac{\Delta W_{ps}}{\Delta W_{pa}} = \eta_{\text{pump}}$: we have: $W_{pa} = \dfrac{W_{\text{ps}}}{\eta_{\text{pump}}} = 13.6\ \text{kJ/kg}$

The net work for the actual cycle: $W_{\text{net,act}} = W_{pa} + \Delta H_a = -816.1\ \text{kJ/kg}$

$H_{1a} = \Delta W_{pa} + H_4 = (13.6 + 289.3)\ \text{kJ/kg} = 302.9\ \text{kJ/kg}$

$q_{\text{in,act}} = H_2 - H_{1a} = (3{,}437.7 - 302.9)\ \text{kJ/kg} = 3{,}134.81\ \text{kJ/kg}$

Therefore, the efficiency of the actual cycle: $\eta_{\text{actual}} = \dfrac{W_{\text{net,act}}}{q_{\text{in,act}}} = \mathbf{0.260\ or\ 26\%}$

Comparison of the two efficiencies shows that both operations have relatively low efficiencies, although the actual cycle is considerably less efficient than the ideal Rankine cycle (37.4%). The actual cycles involves friction and pressure drops as well as the heat losses in various processes; therefore have lower thermal efficiency than those of ideal cycles.

7.8.7 Brayton Engine Efficiency

The Brayton cycle was first proposed by George Brayton in around 1870. The Brayton cycle is used for gas turbines operating on an open cycle as shown in Fig. 7.7. The Brayton engine consists of three main components: a compressor, a combustion chamber, and a turbine. The air after being compressed in the compressor is heated by burning fuel in it. The heated air expands in a turbine and produces the power. The two main applications of gas-turbine engines are jet engines and electric power production. Jet engines take a large volume of hot gas from a combustion process and feed it through a nozzle which accelerates the plane to high speed (see Fig. 7.8). Gas-turbine cycle engines employ a continuous combustion system where compression, combustion, and expansion occur simultaneously at different places in the engine [32]. The combustion takes place at constant pressure. The fuel must be transportable to the combustion chamber, and that the fuel releases sufficient heat of combustion to produce necessary power.

Some of the power produced in the turbine of a gas-turbine power plant is used to drive the compressor. The ratio of the compressor work to the turbine work is called the *back work ratio*. Sometimes, more than one-half of the turbine work may be used by the compressor [21].

The Brayton cycle is analyzed as open system. By neglecting the changes in kinetic and potential energies, the energy balance on a unit-mass basis is

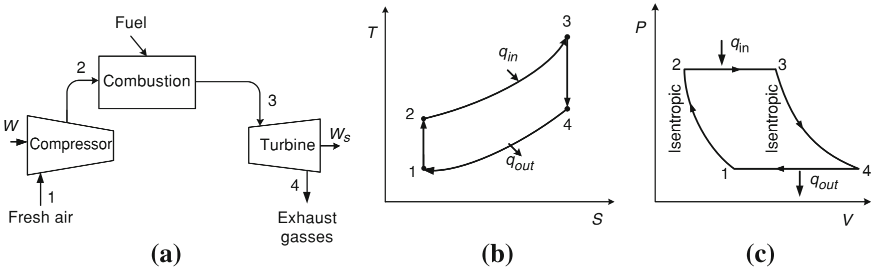


Fig. 7.7 **a** Schematic of open Brayton cycle, **b** ideal Brayton cycle on a *TS* diagram with processes of isentropic adiabatic compression, isobaric heat addition, isentropic adiabatic expansion, and isobaric heat rejection, **c** ideal Brayton cycle on a *PV* diagram

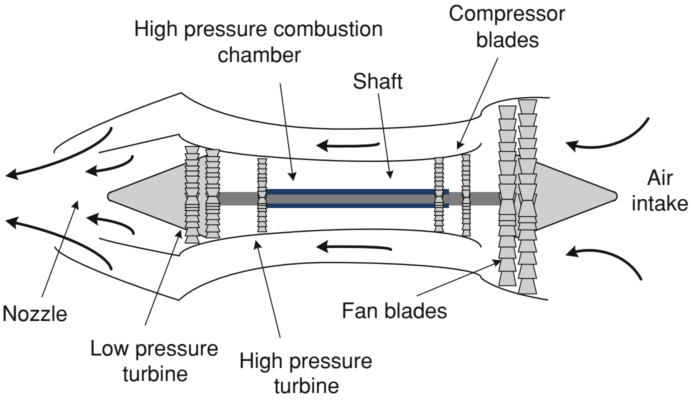


Fig. 7.8 Schematic of a jet engine using gas power cycle

$$\Delta H = (q_{\text{in}} - q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) \tag{7.45}$$

Assuming constant heat capacity, thermal efficiency can be derived using the heat added q_{in} and heat rejected q_{out}

$$\eta_{\text{Brayton}} = 1 - \left(\frac{q_{\text{out}}}{q_{\text{in}}}\right) = 1 - \left(\frac{C_{p,av}(T_4 - T_1)}{C_{p,av}(T_3 - T_2)}\right) \tag{7.46}$$

Upon rearrangement, Eq. 7.46 reduces to

$$\eta_{\text{Brayton}} = 1 - \left(\frac{T_1}{T_2}\right)\left(\frac{T_4/T_1 - 1}{T_3/T_2 - 1}\right) \tag{7.47}$$

Figure 7.7 shows that processes 1–2 and 3–4 are isentropic, and $P_2 = P_3$ and $P_4 = P_1$, thus the previously derived equations for isentropic process are expressed by

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma} \text{and} \left(\frac{T_3}{T_4}\right) = \left(\frac{P_3}{P_4}\right)^{(\gamma-1)/\gamma}$$

Therefore, the thermal efficiency is estimated by

$$\eta_{\text{Brayton}} = 1 - \left(\frac{1}{r_p^{(\gamma-1)/\gamma}}\right) \quad \text{(for constant heat capacity)} \tag{7.48}$$

where r_p is the compression ratio (P_2/P_1) and $\gamma = C_p/C_v$. Equation 7.48 shows that the Brayton cycle depends on the pressure ratio of the gas-turbine and the ratio of specific heats of the working fluid. The typical values of pressure ratio change between 5 and 20 [5]. As seen from Fig. 7.7, part of the electricity produced is used to drive the compressor. The back work ratio r_{bw} shows the part of the produced energy is diverted to the compressor

$$r_{\text{bw}} = \frac{W_{\text{comp.in}}}{W_{\text{turb.out}}} \tag{7.49}$$

Example 7.13 illustrates the analysis of an ideal Brayton cycle when the heat capacity is temperature dependent, while Example 7.14 illustrates the analysis of a real Brayton cycle. Example 7.15 illustrates the analysis of an ideal Brayton cycle with constant specific heats.

Example 7.13 Simple ideal Brayton cycle calculations with variable specific heats
A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The fresh air temperature is 295 K at the compressor inlet and 1,300 K at the end of the compressor (inlet of the turbine). Using the standard-air assumptions, determine the thermal efficiency of the cycle.

Solution:
Assume that the cycle is at steady-state flow and the changes in kinetic and potential energy are negligible. Heat capacity of air is temperature dependent, and the air is an ideal-gas.
Consider Fig. 7.7.
Basis: 1 kg air. Using the data from the Appendix: Table D1
Process 1–2 isentropic compression
At $T_1 = 295$ K, $H_1 = 295.17$ kJ/kg; (P_r is the relative pressure defined in Eq. 7.36).

$$\frac{P_{r2}}{P_{r1}} = \frac{P_2}{P_1} = P_r \rightarrow P_{r2} = (9)(1.3068) = 11.76$$

Approximate values from Table D1 for the compressor exit at $P_{r2} = 11.76$
$T_2 = 550$ K and $H_2 = 555.74$ kJ/kg
Process 3–4 isentropic expansion in the turbine as seen on the *TS* diagram in Fig. 7.7.
$T_3 = 1{,}300$ K, $H_3 = 1{,}395.97$ kJ/kg; $P_{r3} = 330.9$ (From Table D1)

$$\frac{P_{r4}}{P_{r3}} = \frac{P_4}{P_3} \rightarrow P_{r4} = \left(\frac{1}{9}\right)(330.9) = 36.76$$

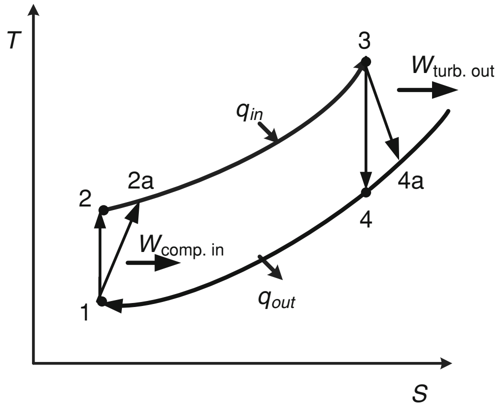
Approximate values from Table D1 at the exit of turbine $P_{r4} = 36.76$:
$T_4 = 745$ K and $H_4 = 761.87$ kJ/kg
The work input to the compressor:
$W_{\text{comp.in}} = H_2 - H_1 = (555.74 - 295.17)\ \text{kJ/kg} = 260.6\ \text{kJ/kg}$
The work output of the turbine:
$W_{\text{turb.out}} = H_4 - H_3 = (761.87 - 1{,}395.97)\ \text{kJ/kg} = -634.1\ \text{kJ/kg}$
The net work out: $W_{\text{net}} = W_{\text{out}} - W_{\text{in}} = -(634.1 - 260.6) = -373.53\ \text{kJ/kg}$
The back work ratio r_{bw} becomes: $r_{\text{bw}} = \dfrac{W_{\text{comp.in}}}{W_{\text{turb.out}}} = \dfrac{260.6}{634.1} = 0.41$ or 41%
This shows that 41% of the turbine output has been used in the compressor.
The amount of heat added: $q_{\text{in}} = H_3 - H_2 = 1{,}395.97 - 555.74 = 840.23\ \text{kJ/kg}$
The amount of heat rejected: $q_{\text{out}} = H_1 - H_4 = 295.17 - 761.87 = -466.7\ \text{kJ/kg}$
The thermal efficiency: $\eta_{\text{th}} = \dfrac{W_{\text{net}}}{q_{\text{in}}} = 1 - \dfrac{q_{\text{out}}}{q_{\text{in}}} = \mathbf{0.444\ or\ (44.4\%)}$

Example 7.14 Thermal efficiency of an actual Brayton cycle with variable specific heats

A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The fresh air temperature is 295 K at the compressor inlet and 1,300 K at the end of the compressor and at the inlet of the turbine. Assume the gas-turbine cycle operates with a compressor efficiency of 85% and a turbine efficiency of 85%. Determine the thermal efficiency of the cycle.

Solution:

Assume that the cycle is at steady-state flow and the changes in kinetic and potential energy are negligible. Heat capacity of air is temperature dependent, and the air is an ideal-gas. The standard-air assumptions are applicable
Basis: 1 kg air.



At $T_1 = 295$ K, $H_1 = 295.17$ kJ/kg; $P_{r1} = 1.3068$; (Table D1) P_r is the relative pressure (Eq. 7.36).

$$\frac{P_{r2}}{P_{r1}} = \frac{P_2}{P_1} = P_r \rightarrow P_{r2} = (9)(1.3068) = 11.76$$

Approximate values from Table D1 for the compressor exit at P_{r2} = 11.76:
T_2 = 550 K and H_2 = 555.74 kJ/kg
Process 3–4 isentropic expansion in the turbine as seen on the *TS* diagram above
T_3 = 1,300 K, H_3 = 1,395.97 kJ/kg; P_{r3} = 330.9 (From Table D1)

$$\frac{P_{r4}}{P_{r3}} = \frac{P_4}{P_3} \rightarrow P_{r4} = \left(\frac{1}{9}\right)(330.9) = 36.76$$

Approximate values from Table D1 at the exit of turbine at 36.76:
T_4 = 745 K and H_4 = 761.87 kJ/kg
The work input to the compressor:
$W_{\text{comp.in}} = H_2 - H_1 = (555.74 - 295.17)\,\text{kJ/kg} = 260.57\ \text{kJ/kg}$
The work output of the turbine:
$W_{\text{turb.out}} = H_4 - H_3 = (761.87 - 1,395.97)\,\text{kJ/kg} = -634.10\ \text{kJ/kg}$
From the efficiency definitions for compressor and turbine, we have

$$\eta_{\text{C}} = \frac{W_{Cs}}{W_{Ca}} \rightarrow W_{Ca} = \frac{W_{Cs}}{\eta_C} = \frac{260.6\ \text{kJ/kg}}{0.85}$$
$$= 306.6\ \text{kJ/kg (Actual compression work)}$$

(where $W_{\text{comp.in}} = W_{Cs} = 260.6$ kJ/kg in Example 7.13)
The work output of the turbine with a 85% efficiency

$$\eta_T = \frac{W_{Ta}}{W_{Ts}} \rightarrow W_{Ta} = \eta_T(W_{Ts}) = 0.85(634.1\ \text{kJ/kg}) = 539.0\text{kJ/kg}$$

(where$W_{\text{turb.out}} = W_s = 634.1$ kJ/kg in ideal operation in Example 7.13)
The net work out: $W_{\text{net}} = W_{\text{out}} - W_{\text{in}} = -(539.0 - 306.6) = -232.4$ kJ/kg
The back work ratio r_{bw} becomes: $r_{\text{bw}} = \frac{W_{\text{comp.in}}}{W_{\text{turb.out}}} = \frac{306.6}{539.0} = 0.568$
This shows that the compressor is now consuming 56.8% of the turbine output. The value of back work ratio increased from 41 to 56.8% because of friction, heat losses, and other non-ideal conditions in the cycle.
Enthalpy at the exit of compressor:

$$W_{Ca} = H_{2a} - H_1 \rightarrow H_{2\text{a}} = W_{Ca} + H_1 = (306.6 + 295.2)\text{kJ/kg} = 601.8\ \text{kJ/kg}$$

Heat added: $q_{\text{in}} = H_3 - H_{2a} = 1{,}395.97 - 601.8 = 794.2$ kJ/kg
The thermal efficiency: $\eta_{\text{th}} = \frac{W_{\text{net}}}{q_{\text{in}}} = \frac{232.4\text{kJ/kg}}{794.2\ \text{kJ/kg}} = \mathbf{0.292\ (or\ 29.2\%)}$
The actual Brayton-gas cycle thermal efficiency drops to 0.292 from 0.444. Efficiencies of the compressor and turbine affects the performance of the cycle. Therefore, for a better cycle thermal efficiency, significant improvements are necessary for the compressor and turbine operations.

	Ideal	Actual
W_{net}, kJ/kg	373.5	232.4
W_{C}, kJ/kg	260.6	306.6
W_{T}, kJ/kg	634.1	539.0
q_{in}, kJ/kg	840.2	794.2
q_{out}, kJ/kg	466.7	561.8
η_{th} %	44.4	29.2

Example 7.15 Ideal Brayton cycle with constant specific heats

A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The air temperature is 300 K at the compressor inlet and 1,200 K at the end of the compressor. Using the standard-air assumptions and $\gamma = 1.4$ determine the thermal efficiency of the cycle.

Solution:

Assume that the cycle is at steady-state flow and the changes in kinetic and potential energy are negligible. The specific heat capacities are constant, and the air is an ideal-gas.

Consider Fig. 7.7.
Basis: 1 kg air and $\gamma = 1.4$.
Using the data from the Appendix: Table D1
Process 1–2 isentropic compression
$T_1 = 300$ K, $H_1 = 300.2$ kJ/kg;

From Eq. 7.34: $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma} \rightarrow T_2 = 300(9)^{0.4/1.4} = 562 \text{ K}$

Process 3–4 isentropic expansion in the turbine as seen on the *TS* diagram above

$$T_3 = 1{,}200 \text{ K and } \frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{(\gamma-1)/\gamma} \rightarrow T_4 = 1{,}200\left(\frac{1}{9}\right)^{0.4/1.4} \rightarrow T_4 = 640.5 \text{ K}$$

From Eq. 7.46: $$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)_4}$$
$$= 1 - \frac{640.5 - 300}{1{,}200 - 562} = \mathbf{0.466 \text{ or } 46.6\%}$$

From Eq. 7.48: $$\eta_{\text{Brayton}} = 1 - \left(\frac{1}{r_p^{(\gamma-1)/\gamma}}\right) = \mathbf{0.463 \text{ or } 46.3\%}$$

The results of efficiency calculations are close to each other; for a constant heat capacity it is easy to use Eq. 7.48 directly to estimate the efficiency using the compression ratio r_p.

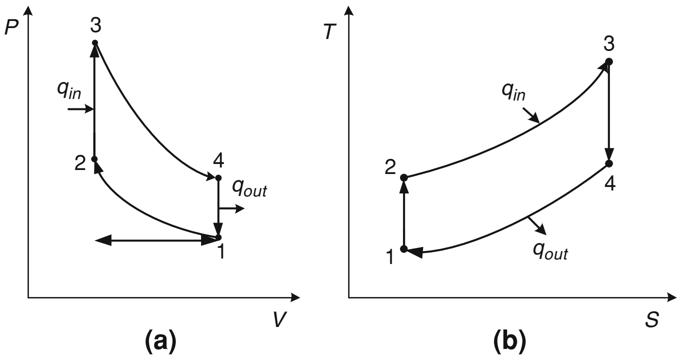


Fig. 7.9 Thermodynamic diagrams of Otto cycle; **a** Otto cycle on a *PV* diagram, **b** Otto cycle on a *TS* diagram

7.8.8 Otto Engine Efficiency

An *Otto cycle* is named after Nikolaus A. Otto who manufactured a four-stroke engine in 1876 in Germany. Otto cycle describes the functioning of a typical ideal cycle for spark-ignition reciprocating piston engine. This cycle is common in automobile internal combustion engines using a chemical fuel with oxygen from the air. The combustion process results heat, steam, carbon dioxide, and other chemicals at very high temperature. Petroleum fractions, such as diesel fuel, gasoline and petroleum gases are the most common fuels. Bioethanol, biodiesel, and hydrogen can also be used as fuels with modified engines.

Internal combustion engines require either spark ignition or compression ignition of the compressed air–fuel mixture [5, 15]. Gasoline engines take in a mixture of air and gasoline and compress it to around 12.8 bar (1.28 MPa), then use a high-voltage electric spark to ignite the mixture. The compression level in diesel engines is usually twice or more than a gasoline engine. Diesel engines will take in air only, and shortly before peak compression, a small quantity of diesel fuel is sprayed into the cylinder via a fuel injector that allows the fuel to instantly ignite. Most diesels also have a battery and charging system. Diesel engines are generally heavier, noisier, and more powerful than gasoline engines. They are also more fuel-efficient in most circumstances and are used in heavy road vehicles, some automobiles, ships, railway locomotives, and light aircraft.

Figure 7.9 shows the Otto engine cycles on *PV* and *TS* diagrams. The ideal cycle processes are:

- Process 1–2 is an isentropic compression of the air as the piston moves from bottom dead center to top dead center (*Intake stroke*).
- Process 2–3 is a constant-volume heat transfer to the air from an external source while the piston is at top dead center. This process leads to the ignition of the fuel–air mixture (*Compression stroke*).
- Process 3–4 is an isentropic expansion (*Power stroke*).

- Process 4–1 completes the cycle by a constant-volume process in which heat is rejected from the air while the piston is at bottom dead center (*Exhaust stroke*).

In the case of a four-stroke Otto cycle, technically there are two additional processes as shown in Fig. 7.9a: one for the exhaust of waste heat and combustion products (by isobaric compression), and one for the intake of cool oxygen-rich air (by isobaric expansion). However, these are often omitted in a simplified analysis. Processes 1–2 and 3–4 do work on the system but no heat transfer occurs during adiabatic expansion and compression. Processes 2–3 and 4–1 are isochoric (constant-volume) therefore heat transfer occurs but no work is done as the piston volume does not change.

Idealized *PV* diagram in Fig. 7.9b of the Otto cycle shows the combustion heat input q_{in} and the waste exhaust output q_{out}. The power stroke is the top curved line and the bottom is the compression stroke.

The Otto cycle is analyzed as a close system. The energy balance on a unit-mass basis is

$$\Delta U = (q_{\text{in}} - q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) \tag{7.50}$$

Assuming that the heat capacity is constant, thermal efficiency can be derived by the heat added q_{in} and heat rejected q_{out}

$$\eta_{\text{Otto}} = 1 - \left(\frac{q_{\text{out}}}{q_{\text{in}}}\right) = 1 - \left(\frac{C_{v,av}(T_4 - T_1)}{C_{v,av}(T_3 - T_2)}\right) \tag{7.51}$$

In an ideal Otto cycle, there is no heat transfer during the process 1–2 and 3–4 as they are reversible adiabatic processes. Heat is supplied only during the constant-volume processes 2–3 and heat is rejected only during the constant-volume processes 4–1.

Upon rearrangement:

$$\eta_{\text{Otto}} = 1 - \left(\frac{T_1}{T_2}\right)\left(\frac{T_4/T_1 - 1}{T_3/T_2 - 1}\right) \tag{7.52}$$

Since $T_4/T_1 = T_3/T_2$, (see Fig. 7.8), Eq. (7.52) reduces to:

$$\eta_{\text{Otto}} = 1 - \left(\frac{T_1}{T_2}\right) \tag{7.53}$$

From the isentropic equations of ideal gases, we have

$$C_v \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{V_2}{V_1}\right) = 0 \tag{7.54}$$

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{V_1}{V_2}\right)^{(\gamma-1)} = r^{(\gamma-1)} \tag{7.55}$$

where r is the compression ratio (V_1/V_2) and $\gamma = C_p/C_v$, and $R = C_p - C_v$ for an ideal-gas. Then the thermal efficiency can be expressed as

$$\eta_{\text{Otto}} = 1 - \left(\frac{1}{r^{(\gamma-1)}}\right) \quad \text{(constant specific heats)} \tag{7.56}$$

The specific heat ratio of the air–fuel mixture γ varies somewhat with the fuel, but is generally close to the air value of 1.4, and when this approximation is used the cycle is called an *air-standard cycle*. However, the real value of γ for the combustion products of the fuel/air mixture is approximately 1.3.

Equation 7.56 shows that the Otto cycle depends upon the compression ratio $r = V_1/V_2$. At the higher compression ratio, the efficiency is higher and the temperature in the cylinder is higher. However the maximum compression ratio is limited approximately to 10:1 for typical automobiles. Usually this does not increase much because of the possibility of auto ignition, which occurs when the temperature of the compressed fuel/air mixture becomes too high before it is ignited by the flame front leading to *engine knocking*. Example 7.16 illustrates the analysis of an ideal Otto engine with temperature-dependent heat capacities, while Example 7.17 illustrates with constant heat capacities.

Example 7.16 Efficiency calculations of ideal Otto engine with variable specific heats

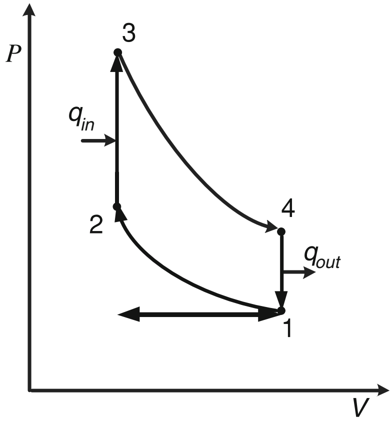
An ideal Otto cycle operates with a compression ratio ($r = V_{\text{max}}/V_{\text{min}}$) of 8.8. Air is at 101.3 kPa and 280 K at the start of compression (state 1). During the constant-volume heat-addition process, 1,000 kJ/kg of heat is transferred into the air from a source at 1,900 K. Heat is discharged to the surroundings at 280 K. Determine the thermal efficiency of energy conversion.

Solution:

Assume that the surroundings are at 280 K and the kinetic and potential energy changes are negligible. The specific heats are temperature dependent.

Heat capacity of air is temperature dependent, and the air is an ideal-gas. The *PV* diagram below shows the cycle and the four processes

Processes in the cycle:



1–2 Isentropic compression
2–3 Constant-volume heat transfer
3–4 Isentropic expansion
4–1 Constant-volume heat discharge

Basis: 1 kg air. Using the data from the Appendix:
q_{in} = 1,000 kJ/kg
U_1 = 199.75 kJ/kg; V_{r1} = 783.0 at T = 280 K From Table D1
(V_{r} is the relative specific volume defined in Eq. 7.38)

$$\frac{V_{r2}}{V_{r1}} = \frac{V_2}{V_1} = \frac{1}{8.8} \rightarrow V_{r2} = \frac{V_{r1}}{r} = \frac{783}{8.8} = 88.97$$

At the value of V_{r2} = 88.97, the air properties from Table D1: U_2 = 465.5 kJ/kg and T_2 = 640 K

From isentropic compression of air, we estimate

$$P_2 = P_1\left(\frac{T_2}{T_1}\right)\left(\frac{V_1}{V_2}\right) = 101.3\left(\frac{640}{280}\right)8.8 \ = 2{,}037 \text{ kPa(ideal-gas equation)}$$

The heat transferred in the path 2–3:

$$q_{\text{in}} = 1{,}000 \text{ kJ/kg} = U_3 - U_2 \rightarrow U_3 \ = 1465.5 \text{ kJ/kg}$$

At U_3 = 1,465.5 kJ kg, we estimate T_3 and V_{r3} by interpolation using the data below

T (K)	U (kJ/kg)	V_r
1,750	1,439.8	4.328
1,800	1,487.2	3.994
1,777	1,465.5	4.147

V_{r3} = 4.147 at T_3 = 1777 k

We estimate the pressure at state 3 as before

$$P_3 = P_2\left(\frac{T_3}{T_2}\right)\left(\frac{V_2}{V_3}\right) = 2{,}037\left(\frac{1{,}777}{640}\right)(1) \ = 5{,}656 \text{ kPa}$$

Internal energy of air at state 4.

$$\left(\frac{V_{r4}}{V_{r3}}\right) = \left(\frac{V_4}{V_3}\right) = 8.8 \rightarrow V_{r4} = (8.8)(4.147) \ = 36.5$$

At V_{r4} = 36.5, approximate values from Table D1 for: U_4 = 658 kJ/kg and T_4 = 880 K
The process 4–1 is a constant heat discharge. We estimate the discharged heat q_{out}

$$q_{\text{out}} = U_1 - U_4 \rightarrow q_{\text{out}} \ = -458.2 \text{ kJ/kg}$$

$$P_4 = P_3\left(\frac{T_4}{T_3}\right)\left(\frac{V_3}{V_4}\right) = 5{,}656\left(\frac{880}{1{,}777}\right)\left(\frac{1}{8.8}\right) = 318.3\ \text{kPa}$$

The net heat transfer is equal to the net work output:

$$W_{\text{net}} = q_{\text{in}} - q_{out} = (1{,}000 - 458.2)\,\text{kJ/kg} = 541.8\,\text{kJ/kg}$$

So the thermal efficiency: $\eta_{\text{th}} = \frac{W_{\text{net}}}{q_{\text{in}}} = \mathbf{0.542\ or\ 54.2}\%$

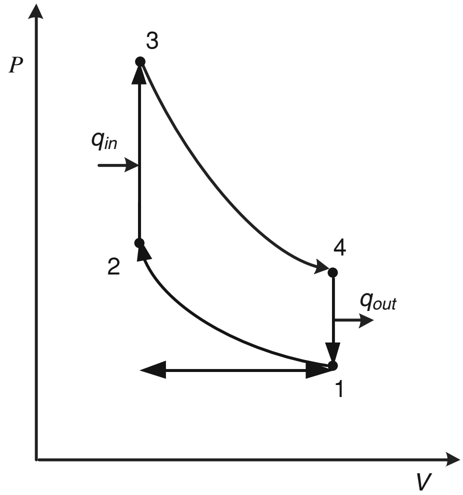
Although all the processes are internally reversible, the heat transfer and discharge take place at finite temperature difference, and are irreversible.

Example 7.17 Efficiency calculations of an ideal Otto cycle with constant specific heats

An ideal Otto cycle operates with a compression ratio ($V_{\text{max}}/V_{\text{min}}$) of 8. Air is at 101.3 kPa and 300 K at the start of compression (state 1). During the constant-volume heat-addition process, 730 kJ/kg of heat is transferred into the air from a source at 1,900 K. Heat is discharged to the surroundings at 300 K. Determine the thermal efficiency of energy conversion. The average specific heats: $C_{p,av}$ = 1.00 kJ/kg K and $C_{v,av}$ = 0.717 kJ/kg K.

Solution:
Assume: the air-standard assumptions are applicable. The changes in kinetic and potential energy s are negligible. The specific heats are constant.

The *PV* diagram below shows the cycle and the four states



Processes in the cycle:
1–2 Isentropic compression
2–3 Constant-volume heat transfer
3–4 Isentropic expansion

4–1 Constant-volume heat discharge

Basis: 1 kg air.
q_{in} = 730 kJ/kg

Using the data from Table D1 at T_o = 300 K: U_1 = 214.1 kJ/kg.
The average specific heats:
$C_{p,av}$ = 1.0 kJ/kg K and $C_{p,av}$ = 0.717 kJ/kg K and γ = 1/0.717 = 1.4.
From Eq. 7.34:

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \rightarrow T_2 = \frac{V_1}{V_2}T_1 = 8(300\ \text{K})^{0.4} = 689\ \text{K}$$

Estimate T_3 from the heat transferred at constant-volume in process 2–3:

$$q_{\text{in}} = U_3 - U_2 = C_{v,av}(T_3 - T_2) \rightarrow T_3\ = 1{,}703\ \text{K}$$

Process 3–4 isentropic expansion: $T_4 = T_3\left(\frac{V_3}{V_4}\right)^{\gamma-1} = 1{,}703.0\left(\frac{1}{8}\right)^{0.4} = 741.3\ \text{K}$

Process 4–1: $q_{\text{out}} = U_4 - U_1 = C_{v,av}(T_4 - T_1)\ = 316.4\ \text{kJ/kg}$, q_{in} = 730 kJ/kg
Net heat transfer is equal to the net work output:
$W_{\text{net}} = q_{\text{in}} - q_{\text{out}}\ = 730.0 - 316.4 = 413.6\,\text{kJ/kg}$
From Eq. 7.56: So the thermal efficiency is
$\eta_{\text{Otto}} = 1 - \left(\frac{1}{r^{(\gamma-1)}}\right) = 0.564$ (or 56.4%)

7.8.9 Diesel Engine Efficiency

Figure 7.10 shows an ideal Diesel cycle on the *PV* and *TS* diagrams. The compression-ignited engine is first proposed by Rudolph Diesel in 1890. Most truck and automotive diesel engines use a similar cycle to spark-ignited gasoline engine, but with a compression heating ignition system, rather than needing a separate ignition system. In combustion-ignited engine, the air is compressed to a temperature that is above the autoignition temperature of the fuel. Therefore the combustion starts as the fuel is injected into the hot air at constant pressure. This variation is called the diesel cycle.

The Diesel cycle is analyzed as a piston-cylinder of a close system. The amount of heat transferred to the working fluid air at constant pressure on a unit-mass basis is

$$q_{\text{in}} = P_2(V_3 - V_2) + (U_3 - U_2) = H_3 - H_2 = C_{p,av}(T_3 - T_2) \tag{7.57}$$

The amount of heat rejected at constant-volume is

$$q_{\text{out}} = U_1 - U_4 = C_{v,av}(T_1 - T_4) \tag{7.58}$$

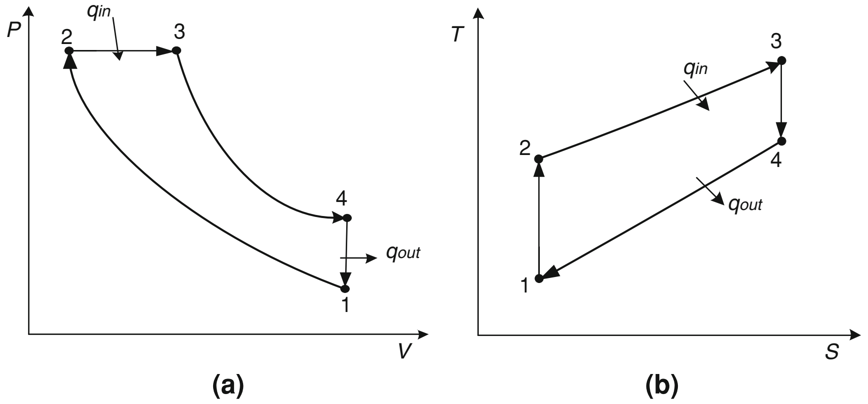


Fig. 7.10 Ideal Diesel cycle **a** on *PV* diagram, **b** on *TS* diagram; the cycle follows the numbers 1–4 in clockwise direction

Alternatively, thermal efficiency can be derived by the heat added q_{in} and heat rejected q_{out}

$$\eta_{\mathrm{Diesel}} = 1 - \left(\frac{q_{\mathrm{out}}}{q_{\mathrm{in}}}\right) = 1 - \left(\frac{(T_4 - T_1)}{\gamma(T_3 - T_2)}\right) = 1 - \left(\frac{T_1(T_4/T_1 - 1)}{\gamma T_2(T_3/T_2 - 1)}\right) \quad (7.59)$$

where $\gamma = C_p/C_v$. In an ideal Diesel cycle, the cutoff ratio r_c is defined as the ratio of the volume after and before the combustion

$$r_c = \frac{V_3}{V_2} \quad (7.60)$$

After using the cutoff ratio r_c and compression ratio $r = V_1/V_2$ with the isentropic ideal-gas relations, given in Eq. 7.33, the thermal efficiency of energy conversion becomes

$$\eta_{\mathrm{Diesel}} = 1 - \frac{1}{r^{(\gamma-1)}}\left(\frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}\right) \text{ (With constant specific heats)} \quad (7.61)$$

Equation 7.61 shows that as the cutoff ratio r_c decreases, the efficiency of the Diesel cycle increases. For the limiting ratio of $r_c = 1$, the value of the bracket in Eq. 7.61 becomes unity, and the efficiencies of the Otto and Diesel cycles become identical. Thermal efficiencies of large diesel engines vary from 35 to 40% [5, 15]. Example 7.18 illustrates the analysis of diesel engine with constant heat capacity, while Example 7.19 with temperature dependent heat capacity.

Example 7.18 Thermal efficiency of an ideal Diesel engine with the constant specific heats

An ideal Diesel cycle has an air-compression ratio of 20 and a cutoff ratio of 2. At the beginning of the compression, the fluid pressure, temperature, and volume are 14.7 psia, 70°F, and 120 in^3, respectively. The average specific heats of air at room temperature are $C_{p,av} = 0.24$ Btu/lb R and, $C_{v,av} = 0.171$ Btu/lb R. Estimate the thermal efficiency with the cold-air-standard assumptions.

Solution:
Assume: the cold-air-standard assumptions are applicable. Air is ideal-gas. The changes in kinetic and potential energies are negligible.

Consider Fig. 7.10.

$P_1 = 14.7$ psia, $T_1 = 70°\text{F}$, and $V_1 = 120$ in^3, $C_{p,av} = 0.24$ Btu/lb R and, $C_{v,av} = 0.171$ Btu/lb R, $R = 10.73$ psia ft^3/lbmol R, $MW = 29$ lb/lbmol

$\gamma = C_{p,av}/C_{v,av} = 1.4$, $r = 20$ and $r_c = 2$.

The air mass: $m_{\text{air}} = MW\dfrac{PV}{RT} = 0.0052\,\text{lb}$

The volumes for each process: $V_1 = V_4 = 120$ in^3

$V_2 = V_1/r = 6$ in^3

$V_3 = V_2\, r_c = 12$ in^3

Process 1–2: isentropic compression: $\left(\dfrac{T_2}{T_1}\right) = \left(\dfrac{V_1}{V_2}\right)^{(\gamma-1)} \rightarrow T_2 = 1{,}756.6\ \text{R}$

(Eq. 7.34)

Process 2–3: Heat addition at constant pressure for ideal gas:

$\left(\dfrac{T_3}{T_2}\right) = \left(\dfrac{V_3}{V_2}\right) \rightarrow T_3 = 3{,}513\ \text{R}$

$q_{\text{in}} = m(H_3 - H_2) = mC_{p,av}(T_3 - T_2) = 2.19\,\text{Btu}$

Process 3–4: isentropic expansion: $\left(\frac{T_4}{T_3}\right) = \left(\frac{V_3}{V_4}\right)^{(\gamma-1)} \rightarrow T_4 = 1{,}398\ \text{R}$

Process 4–1: heat rejection at constant-volume for ideal-gas

$q_{\text{out}} = m(H_1 - H_4) = mC_{v,av}(T_4 - T_1) = 0.772\,\text{Btu}$

The net work output is equal to the difference between heat input (q_{in}) and waste heat (q_{out})

$W_{\text{out}} = q_{\text{in}} - q_{\text{out}} = (2.19 - 0.772) = 1.418$ Btu

Thermal efficiency: $\eta_{\text{th}} = \dfrac{W_{\text{net}}}{q_{\text{in}}} = \mathbf{0.647\ (or\ 64.7\%)}$

Thermal efficiency can also be estimated from Eq. (7.61):

$$\eta_{\text{Diesel}} = 1 - \frac{1}{r^{(\gamma-1)}}\left(\frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}\right) = \mathbf{0.647 (or\ 64.7\%)}$$

Example 7.19 Thermal efficiency of an ideal Diesel engine with variable specific heats

An ideal Diesel cycle has an air-compression ratio of 18 and a cutoff ratio of 2. At the beginning of the compression, the fluid pressure and temperature are 100 kPa, 300 K, respectively. Utilizing the cold-air-standard assumptions, determine the thermal efficiency.

Solution:
Assume: the cold-air-standard assumptions are applicable. Air is ideal-gas. The changes in kinetic and potential energies are negligible. The specific heats depend on temperature.
Consider Fig 7.10.
$P_1 = 100$ kPa, $T_1 = 300$ K, $r = V_1/V_2 = 18$ and $r_c = V_3/V_2 = 2$.
At 300 K, $U_1 = 214.1$ kJ/kg, $V_{r1} = 621.2$
(V_r is the relative specific volume) (Table D1)

From Eq. 7.38:

$$\frac{V_{r2}}{V_{r1}} = \frac{V_2}{V_1} = \frac{1}{18} \rightarrow V_{r2} = \frac{V_{r1}}{r} = \frac{621.2}{18} = 34.5$$

At this value of V_{r2}= 34.5, approximate values for:
$H_2 = 932.9$ kJ/(kg K), $T_2 = 900$ K (Table D1)

The heat transferred at constant pressure in process 2–3:

$$\frac{V_3}{T_3} = \frac{V_2}{T_2} = \longrightarrow T_3 = \frac{V_3}{V_2} T_2 = 2T_2 = 1800 \text{ K}$$

$$H_3 = 2003.3 \text{ kJ/kg}, \ V_{r3} = 4.0 \text{ (Table D1)}$$

$$q_{\text{in}} = H_3 - H_2 = 1{,}070.4 \text{ kJ/kg}$$

Processes 3–4: Next, we need to estimate the internal energy of air at state 4:

$$\left(\frac{V_{r4}}{V_{r3}}\right) = \left(\frac{V_4}{V_3}\right) = \left(\frac{V_4}{2V_2}\right) = \left(\frac{18}{2}\right) \rightarrow V_{r4} = (9)(4.0) = 36$$

At $V_{r4} = 36$, $U_4 = 659.7$ kJ/kg (Table D1)

The process 4–1 is heat discharge at constant-volume. We estimate the discharged heat q_{out}

$$q_{\text{out}} = U_4 - U_1 = 659.7 - 214.1 = 445.6 \text{ kJ/kg}$$

The net heat transfer is equal to the net work output:

$$W_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 1{,}070.4 - 445.6 = 624.8 \text{ kJ/kg}$$

So the thermal efficiency is $\eta_{\text{th}} = \dfrac{W_{\text{net}}}{q_{\text{in}}} = \mathbf{0.583 \text{ or } 58.3}\%$

7.8.10 Ericsson and Stirling Engine Efficiency

The Ericsson engine is an "*external combustion engine*" because it is externally heated. The four processes that occur in an ideal Ericsson cycle are:

- Process 1–2: isothermal compression. The compressed air flows into a storage tank at constant pressure.
- Process 2–3: isobaric heat addition. The compressed air flows through the regenerator and picks up heat.
- Process 3–4: isothermal expansion. The cylinder expansion-space is heated externally, and the gas undergoes isothermal expansion.
- Process 4–1: isobaric heat removal. Before the air is released as exhaust, it is passed back through the regenerator, thus cooling the gas at a low constant pressure, and heating the regenerator for the next cycle.

A *Stirling engine* operates by cyclic compression and expansion of air or other gas at different temperature levels and converts the heat of hot gas into mechanical work. The Stirling engine has high efficiency compared to steam engines and can use almost any heat source [14, 15, 29]. Stirling cycle has four totally reversible processes:

- Process 1–2: isothermal heat addition from external source
- Process 2–3: internal heat transfer from working fluid to regenerator at constant-volume
- Process 3–4: isothermal heat rejection
- Process 4–1: internal heat transfer from regenerator back to working fluid at constant-volume.

Heat addition during process 1–2 at T_H and heat rejection process 3–4 at T_C are both isothermal. For a reversible isothermal process heat transfer is estimated by

$$q = T\Delta S \tag{7.62}$$

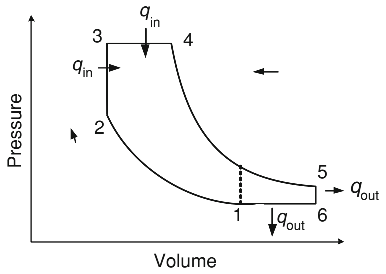
The change in entropy of an ideal-gas at isothermal conditions is

$$\Delta S_{1-2} = -R\ln\frac{P_2}{P_1} \tag{7.63}$$

Using Eqs. 7.62 and 7.63, the heat input and output are estimated by

$$q_{\mathrm{in}} = T_H(S_2 - S_1) = T_H\left(-R\ln\frac{P_2}{P_1}\right) = RT_H\ln\frac{P_1}{P_2} \tag{7.64}$$

$$q_{out} = T_C(S_4 - S_3) = T_C\left(-R\ln\frac{P_4}{P_3}\right) = RT_C\ln\frac{P_3}{P_4} \tag{7.65}$$



The ideal Atkinson cycle consists of following operations:
1–2 Isentropic or reversible adiabatic compression
2–3 Isochoric heating
3–4 Isobaric heating
4–5 Isentropic expansion
5–6 Isochoric cooling
6–1 Isobaric cooling

Fig. 7.11 Ideal Atkinson gas cycle

The thermal efficiency of the Ericsson cycle becomes

$$\eta_{\text{Ericsson}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{RT_C \ln(P_4/P_3)}{RT_H \ln(P_1/P_2)} = 1 - \frac{T_C}{T_H} \tag{7.66}$$

Since $P_1 = P_4$ and $P_3 = P_2$.

Both the ideal Ericsson and Stirling cycles are external combustion engines. Both the cycles are totally reversible as is the Carnot cycle and have the same thermal efficiency between the same temperature limits when using an ideal-gas as the working fluid

$$\eta_{\text{Ericsson}} = \eta_{\text{Stirling}} = \eta_{\text{Carnot}} = 1 - \frac{T_C}{T_H} \tag{7.67}$$

Both the cycles utilize regeneration to improve efficiency. Between the compressor and the expander heat is transferred to a thermal energy storage device called the regenerator during one part of the cycle and is transferred back to the working fluid during another part of the cycle. Equation 7.67 is valid for both the closed and steady-state flow cycles of the engines.

7.8.11 Atkinson Engine Efficiency

The *Atkinson engine* is an internal combustion engine and is used in some modern hybrid electric applications. Figure 7.11 shows the cyclic processes in the Atkinson engine. In the engine, the expansion ratio can differ from the compression ratio and the engine can achieve greater thermal efficiency than a traditional piston engine [15]. Expansion ratios are obtained from the ratio of the combustion chamber volumes when the piston is at bottom dead center and top dead center

In Atkinson cycle, the intake valve allows a reverse flow of intake air. The goal of the modern Atkinson cycle is to allow the pressure in the combustion chamber at the end of the power stroke to be equal to atmospheric pressure; when this occurs, all the available energy has been utilized from the combustion process. For any given portion of air, the greater expansion ratio allows more energy to be converted from heat to useful mechanical energy, hence the engine is more efficient. The disadvantage of the four-stroke Atkinson cycle is the reduced power output as a smaller portion of the compression stroke is used to compress the intake air. Atkinson cycles with a supercharger to make up for the loss of power density are known as *Miller engines* [15, 29]. The power of the Atkinson engine can be supplemented by an electric motor. This forms the basis of an Atkinson cycle-based hybrid electric drivetrain.

7.9 Improving Efficiency of Heat Engines

The followings may be some options toward increasing the efficiency of heat engines [4, 10, 13, 21]:

- Increased hot side temperature is the approach used in modern combined-cycle gas turbines. The melting point of the construction of materials and environmental concerns regarding NO_x production limit the maximum temperature on the heat engines.
- Lowering the output temperature by using mixed chemical working fluids, such as using a 70/30 mix of ammonia and water as its working fluid may also increase the efficiency. This mixture allows the cycle to generate useful power at considerably lower temperatures.
- Use of supercritical fluids, such as CO_2 as working fluids may increase the efficiency.
- Exploit the chemical properties of the working fluid, such as nitrogen dioxide (NO_2), which has a natural dimer as di-nitrogen tetra oxide (N_2O_4). At low temperature, the N_2O_4 is compressed and then heated. The increasing temperature causes each N_2O_4 to break apart into two NO_2 molecules. This lowers the molecular weight of the working fluid, which drastically increases the efficiency of the cycle. Once the NO_2 has expanded through the turbine, it is cooled and recombined into N_2O_4. This is then fed back to the compressor for another cycle.
- New fuels, such as hydrogen, may have positive impact on the performance of the engines since the energy density of hydrogen is considerably higher than that of electric batteries.

7.10 Hydroelectricity

Hydroelectricity is the production of electrical power through the use of the gravitational force of falling or flowing water. Figure 7.12 shows a schematic of a conventional hydroelectric dam, in which hydroelectric power comes from the

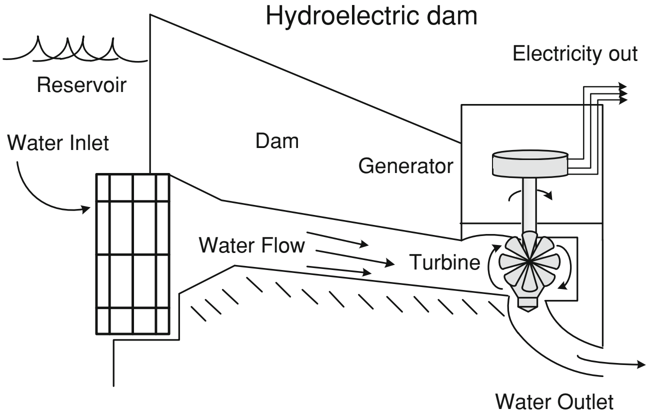


Fig. 7.12 Cross-section of a conventional hydroelectric dam

potential energy of dammed water driving a water turbine and generator. The power extracted from the water depends on the volume and on the difference in height between the source and the water's outflow. This height difference is called the head. The amount of potential energy in water is proportional to the head. A large pipe called the penstock delivers water to the turbine. Example 7.20 illustrates the efficiency calculations for a hydraulic turbine.

Pumped-storage method produces electricity to supply high peak demands by moving water between reservoirs at different elevations. At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine. Compared to wind farms, hydroelectricity power plants have a more predictable load factor. If the project has a storage reservoir, it can generate power when needed. Hydroelectric plants can be easily regulated to follow variations in power demand [12]. One method of meeting the additional electric power demand at peak usage is to pump some water from a source such as a lake back to the reservoir of a hydropower plant at a higher elevation when the demand or the cost of electricity is low. Example 7.21 illustrates the pumped energy in a hydropower plant.

Example 7.20 Efficiency of a hydraulic turbine

Electricity is produced by a hydraulic turbine installed near a large lake. Average depth of the water in the lake is 45 m. The water mass flow rate is 600 kg/s. The produced electric power is 220 kW. The generator efficiency is 95%. Determine the overall mechanical efficiency of the turbine-generator and the shaft work transferred from the turbine to the generator.

Solution:

Assume: the mechanical energy of water at the turbine exit is small and negligible. The density of the water is 1,000 kg/m^3.

$\dot{m} = 600\text{kg/s}, \eta_{\text{gen}} = 0.95$

$\dot{W}_{\text{out}} = 220\,\text{kW}$

$\dot{W}_{\text{fluid}} = \dot{m}gz = (600\,\text{kg/s})(9.81\,\text{m/s}^2)(45\,\text{m})(\text{kJ/kg} = 1000\,\text{m}^2/\text{s}^2) = 264.9\ \text{kW}$

The overall mechanical efficiency of the turbine-generator:

$$\eta_{\text{overall}} = \eta_{\text{turb}}\eta_{\text{gen}} = \frac{\text{energy out}}{\text{energy in}} = \frac{220\,\text{kW}}{264.9\ \text{kW}} = \mathbf{0.83}$$

$\eta_{\text{gen}} = 0.95$

$$\eta_{\text{overall}} = \eta_{\text{turb}}\eta_{\text{gen}} = 0.83 \rightarrow \ \eta_{\text{turb}} = \frac{\eta_{\text{overall}}}{\eta_{\text{gen}}} = 0.87$$

The shaft power transferred from the turbine:

$$\dot{W}_{\text{turb}} = \eta_{\text{turb}}\dot{W}_{\text{fluid}} = 0.87\ (264.9\,\text{kW}) = 230.5\,\text{kW}$$

The lake supplies 264.9 kW of mechanical energy to the turbine. Only 87% of the supplied energy is converted to shaft work. This shaft work drives the generator and 220 kW is produced.

Example 7.21 Pumped energy in a hydropower plant

Consider a hydropower plant reservoir with an energy storage capacity of 1×10^6 kWh. This energy is to be stored at an average elevation of 60 m relative to the ground level. Estimate the minimum amount of water has to be pumped back to the reservoir.

Solution:

Assume that the evaporation of the water is negligible.

$PE = 1\times10^6$ kWh, $\Delta z = 60$ m, g = 9.8 m/s^2

Energy of the work potential of the water: $PE = mg\Delta z$
Amount of water:

$$m = \frac{PE}{g\Delta z} = \frac{1\times10^6\,\text{kWh}}{9.8\,\text{m/s}^2(60\,\text{m})}\left(\frac{3600\,\text{s}}{\text{h}}\right)\left(\frac{1000\,\text{m}^2/\text{s}^2}{1\,\text{kJ/kg}}\right) = \mathbf{6.122 \times 10^9\,kg}$$

7.11 Wind Electricity

The power produced by a wind turbine is proportional to the kinetic energy of the wind captured by the wind turbine, and estimated by

$$\dot{W}_{\text{wind}} = \eta_{\text{wind}} \rho \frac{\pi v^3 D^2}{8} \tag{7.68}$$

where ρ is the density of air, v is the velocity of air, D is the diameter of the blades of the wind turbine, and η_{wind} is the efficiency of the wind turbine. Therefore, the power produced by the wind turbine is proportional to the cube of the wind velocity and the square of the blade span diameter. The strength of wind varies, and an average value for a given location does not alone indicate the amount of energy a wind turbine could produce there [24]. Example 7.22 illustrates the efficiency calculations for a wind turbine.

Example 7.22 Efficiency of a wind turbine

A wind turbine-generator with a 25-foot-diameter blade produces 0.5 kW of electric power. In the location of the wind turbine, the wind speed is 11 mile per hour. Determine the efficiency of the wind turbine-generator.

Solution:

Assume: the wind flow is steady. The wind flow is one-dimensional and incompressible. The frictional effects are negligible.
$\rho_{\text{air}} = 0.076$ lb/ft^3, $D = 25$ ft
Actual power production = 0.5 kW

Kinetic energy can be converted to work completely.
The power potential of the wind is its kinetic energy.

Average speed of the wind: $v_1 = (11\,\text{mph})\left(\frac{1.4667\,\text{ft/s}}{1\,\text{mph}}\right) = 16.13\,\text{ft/s}$

The mass flow rate of air: $\dot{m} = \rho v_1 A = \rho v_1 \frac{\pi D^2}{4} = 601.4\,\text{lb/s}$

$$\dot{W}_{\text{max}} = \dot{m}\frac{v_1^2}{2g_c} = (601.4\,\text{lb/s})\frac{(16.13\,\text{ft/s})^2}{2}\left(\frac{1\,\text{lb}_\text{f}}{32.2\,\text{lb}_\text{m}\,\text{fts}^2}\right)\left(\frac{1\,\text{kW}}{737.56\,\text{lb}_\text{f}\,\text{ft/s}}\right) = 3.29\,\text{kW}$$

This is the available energy to the wind turbine. The turbine-generator efficiency is

$$\eta_{\text{wind turb}} = \frac{\dot{W}_{\text{act}}}{\dot{W}_{\text{max}}} = \frac{0.5\,\text{kW}}{3.29\,\text{kW}} = \mathbf{0.152\ or\ 15.2\%}$$

Only 15.2% of the incoming kinetic energy is converted to electric power. The remaining part leaves the wind turbine as outgoing kinetic energy.

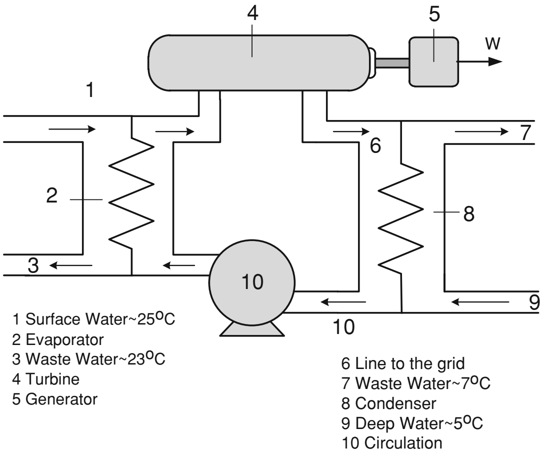


Fig. 7.13 Diagram of a closed-cycle ocean thermal energy conversion (OTEC) plant

7.12 Geothermal Electricity

Geothermal electricity refers to the energy conversion of geothermal energy to electric energy. Technologies in use include dry steam power plants, flash steam power plants, and binary cycle power plants. Geothermal power is considered to be sustainable because the heat extraction is small compared with the earth's heat content. Estimates of the geothermal electricity generating potential vary from 35 to 2,000 GW. Current worldwide installed capacity is around 11 GW.

Geothermal electric plants have until recently been built exclusively where high temperature geothermal resources are available near the surface. The development of binary cycle power plants and improvements in drilling and extraction technology may enable enhanced geothermal systems over a much greater geographical range [8].

The thermal efficiency of geothermal electric plants is low, around 10–23%, because geothermal fluids are at a low temperature compared with steam temperature from boilers. This low temperature limits the efficiency of heat engines in extracting useful energy during the generation of electricity. Exhaust heat is wasted, unless it can be used directly, for example, in greenhouses, timber mills, and district heating. In order to produce more energy than the pumps may consume, electricity generation requires high temperature geothermal fields and specialized heat cycles.

7.13 Ocean Thermal Energy Conversion

Ocean thermal energy conversion uses the difference between cooler deep and warmer shallow or surface ocean waters to run a heat engine and produce useful work, usually in the form of electricity (see Fig. 7.13). Warm surface seawater is pumped through a heat exchanger to vaporize the fluid. The expanding vapor turns the turbo-generator. Cold water, pumped through a second heat exchanger, condenses the vapor into a liquid, which is then recycled through the system. In the tropics, the temperature difference between surface and deep water is a modest 20–25°C. Ocean thermal energy conversion systems is still considered an emerging technology with a thermal efficiency of 1–3%, which is well below the theoretical maximum for this temperature difference of between 6 and 7% [1, 17]. The most commonly used heat cycle for ocean thermal energy conversion systems is the Rankine cycle using a low-pressure turbine system. Closed-cycle engines use working fluids such as ammonia or R-134a. Open-cycle engines use vapor from the seawater itself as the working fluid.

7.14 Thermoelectric Effect

Thermoelectric effect involves energy conversions between heat and electricity as a temperature difference creates an electric potential or electric potential creates a heat flow leading to a temperature difference [31]. There are two thermoelectric effects:

- The *Seebeck effect* refers to conversion of heat to electricity.
- The *Peltier effect* refers to conversion of electricity to heat.

Measuring temperature by *thermocouples* operating between a hot and a cold junction is based on the Seebeck effect. A commonly used thermoelectric material in such applications is Bismuth telluride (Bi_2Te_3). The thermoelectric efficiency approaches to the Carnot limit.

Thermoelectric materials can be used as refrigerators, called “thermoelectric coolers”, or “Peltier coolers”, although it is far less common than vapor-compression refrigeration. Compared to a vapor-compression refrigerator, the main advantages of a Peltier cooler are its lack of moving parts or circulating liquid, and its small size and flexible shape. Another advantage is that Peltier coolers do not require refrigerant liquids, which can have harmful environmental effects. The main *disadvantage* of Peltier coolers is that they cannot simultaneously have low cost and high power efficiency. Advances in thermoelectric materials may lead to the creation of Peltier coolers that are both cheap and efficient.

7.15 Efficiency of Heat Pumps and Refrigerators

Heat pumps, refrigerators, and air conditioners use an outside work to move heat from a colder to a warmer region, so their function is the opposite of a heat engine. Since they are heat engines, these devices are also limited by the Carnot efficiency.

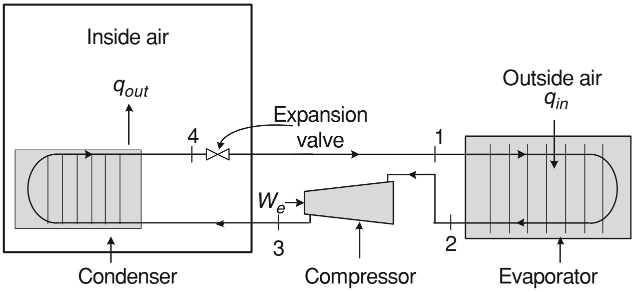


Fig. 7.14 A typical heat pump for heating a room; compressor pumps a gas from a low temperature region to a high temperature region. Within the evaporator, heat of vaporization is absorbed from the outside surroundings. Compressor increases the pressure and temperature of the vapor, and pumps it through the cycle. In the condenser, the vapor condenses and releases heat of condensation to the inside surroundings. The expansion valve causes a flash of the liquid to boil because of sudden drop in pressure; complete vaporization of the liquid takes place in the evaporator

A heat pump can be used for heating or cooling as part of *heating, ventilation, and air conditioning* [18] applications. The heat pump can heat and when necessary it uses the basic refrigeration cycle to cool. To do that a heat pump can change which coil is the condenser and which the evaporator by controlling the flow direction of the refrigerant by a reversing valve. So the heat can be pumped in either direction. In cooler climates it is common to have heat pumps that are designed only to heat. In heating mode, the outside heat exchanger is the evaporator and the indoor exchanger is the condenser to discharge heat to the inside air. In cooling mode, however, the outside heat exchanger becomes the condenser and the indoor exchanger is the evaporator to absorb heat from the inside air. The next sections discuss the heat pumps and refrigerators [5, 37]

7.15.1 Heat Pumps

A heat pump uses a fluid which absorbs heat as it vaporizes and releases the heat when it condenses. Figure 7.14 shows a typical heat pump drawing heat from the ambient air. A heat pump requires external work to extract heat q_C (q_{in}) from the outside air (cold region) and deliver heat q_H (q_{out}) to the inside air (hot region). The most common heat pump is a phase-change heat pump. During the cycle of such a heat pump, the compressor pumps a gas through the condenser where it gets cooled down and finally condenses into liquid phase after releasing heat of condensation q_{out}. Then the liquid flows through an expansion valve where its pressure and temperature both drop considerably. Further it flows through the evaporator where it warms up and evaporates to gaseous phase again by extracting heat of vaporization q_{in} from the surroundings.

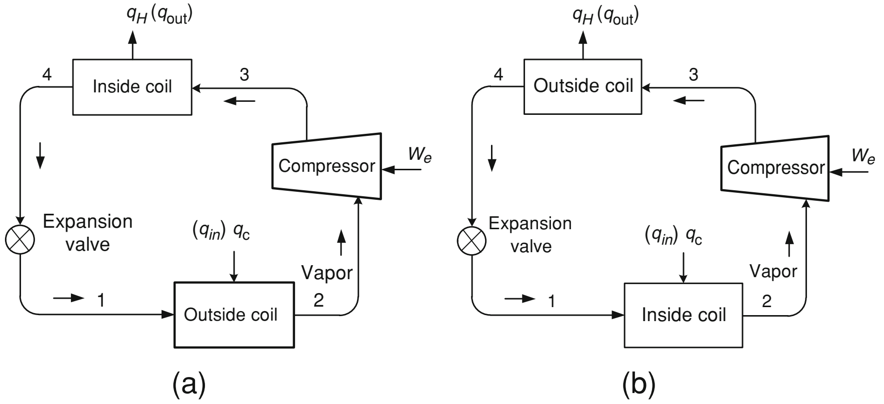


Fig. 7.15 A heat pump can be used: **a** to heat a house in the winter, and **b** to cool in the summer. A reversing valve reverses the direction of the fluid-flow so the inside coil in the summer is used as outside coil in the winter

In heat pumps, the work energy W_{in} provided mainly in the form of electricity is converted into heat, and the sum of this energy and the heat energy that is moved from the cold reservoir (q_C) is equal to the total heat energy added to the hot reservoir q_H

$$\dot{q}_H = \dot{q}_C + \dot{W}_{\text{in}} \tag{7.69}$$

Thermal efficiency of heat pumps are measured by the coefficient of performance COP_{HP} defined by

$$\text{COP}_{\text{HP}} = \frac{\dot{q}_H}{\dot{W}_{\text{in}}} \tag{7.70}$$

The amount of heat they move can be greater than the input work. Therefore, heat pumps can be a more efficient way of heating than simply converting the input work into heat, as in an electric heater or furnace. The limiting value of the Carnot efficiency for the heat pump is

$$\text{COP}_{\text{HP}} \leq \frac{T_H}{T_H - T_C} \quad \text{(heating)} \tag{7.71}$$

Equation 7.71 shows that the COP decreases with increasing temperature difference between the hot and cold regions.

Figure 7.15 compares the flow directions of the working fluid when the heat pump is used for heating and for cooling. A reversing valve reverses the direction of the fluid-flow so the inside coil in the summer is used as the outside coil in the winter. This means that the working fluid is evaporated in the inside coil extracting heat from the warm air inside and is condensed outside discharging heat to warm outside surroundings in the summer [6]. Example 7.23 illustrates the analysis of a heat pump.

Example 7.23 Heat pump calculations
A heat pump provides 60 MJ/h to a house. If the compressor requires an electrical energy input of 5 kW, calculate the COP. If electricity costs \$0.08 per kWh and the heat pump operates 100 h per month, how much money does the homeowner save by using the heat pump instead of an electrical resistance heater?

Solution:
The heat pump operates at steady-state.
COP for a heat pump with a heat supply of 60 MJ/h = 16.66 kW: and $W_{\mathrm{HP}} = 5$ kW

$$\mathrm{COP_{HP}} = \frac{q_{\mathrm{out}}}{W_{\mathrm{HP}}} = \mathbf{3.33}$$

An electrical resistance heater converts all of the electrical work supplied W_e into heat q_H. Therefore, in order to get 16.66 kW into your home, you must buy 16.66 kW of electrical power.
Cost of resistance heater:
Power = 16.66 kW

$$\begin{aligned}&\mathrm{Cost(\$/month) = Electricity(\$0.08/kWh)Power(16.66\,kW)Time(100\,h/month)}\\&\quad = 133.3\,\mathrm{\$/month}\end{aligned}$$

Cost of heat pump with a power of 5 kW:

$$\begin{aligned}&\mathrm{Cost(\$/month) = Electricity(\$0.08/kWh)Power(5.0\,kW)Time(100\,h/month)}\\&\quad = 40.0\,\mathrm{\$/month}\end{aligned}$$

Therefore, monthly saving is (133.3 − 40.0) \$/month = **93.3 \$/month**.
Electrical resistance heaters are not very popular, especially in cold climates. The thermal efficiency of a heat pump drops significantly as the outside temperature falls. When the outside temperature drops far enough that the $\mathrm{COP_{HP}} \sim 1$, it becomes more practical to use the resistance heater.

7.15.2 *Refrigerators*

Figure 7.16 shows a typical refrigeration cycle. A refrigerator is a heat engine in which work is required to extract energy from the freezing compartment and discharge that heat to the room through a condenser at the back of the refrigerator. This leads to further cooling of the cold region. One of the common refrigerant is 1,1,1,2-tetrafluoroethane (CF_3CH_2F) known as R-134a. R-134a has a boiling point temperature of –26.2°C (–15.0 °F) and a latent heat of 216.8 kJ/kg at 1.013 bar. It is compatible with most existing refrigeration equipment. R-134a has no harmful influence on the ozone layer of the earth's atmosphere. It is noncorrosive and nonflammable. R-134a is used for medium-temperature applications, such as air

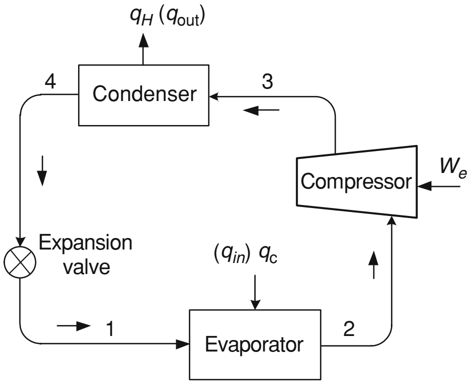


Fig. 7.16 A typical refrigeration cycle; the evaporator is the freezing compartment of the fridge, where the refrigerant absorb heat to be vaporized. The condenser is usually at the back of the fridge, where the heat of condensation is discharged to outside hot surroundings

conditioning and commercial refrigeration. Another refrigerant is pentafluoroethane (C_2HF_5) known as R-125, which is used in low- and medium-temperature applications. With a boiling point of −55.3°F at atmospheric pressure, R-125 is nontoxic, nonflammable, and noncorrosive.

Thermal efficiency of refrigerators and air conditioners is called the coefficient of performance COP_R:

$$COP_R = \frac{\dot{q}_C}{\dot{W}_{in}} \tag{7.72}$$

The limiting value of the Carnot efficiency for the refrigeration processes is

$$COP_R \leq \frac{T_C}{T_H - T_C} \quad \text{(cooling)} \tag{7.73}$$

Equation 7.73 shows that the COP_R decreases with increasing temperature difference between the hot and cold regions. Example 7.24 illustrates the analysis of a refrigerator. When the desired effect is cooling the heat resulting from the input work is just an unwanted byproduct. In everyday usage the efficiency of air conditioners is often rated by the *Seasonal Energy Efficiency Ratio* (SEER), which is discussed in detail in Sect. 9.4. Example 7.25 illustrates the estimation of the heat rejected in refrigeration cycle, while Example 7.26 illustrates the coefficient of performance estimation.

Example 7.24 Analysis of a refrigeration cycle

In a refrigeration cycle, the superheated R-134a (state 2) enters a compressor at 263.15 K and 0.18 MPa. The R-134a (state 3) leaves the compressor at 313.15 K and 0.6 MPa, and enters a condenser, where it is cooled by cooling water. The R-134a (state 4) leaves the condenser at 293.15 K and 0.57 MPa as saturated liquid, and enters a throttling valve. The partially vaporized R-134a (state 1) leaves the valve at 0.293 MPa. The cycle of R-134a is completed when it passes through an evaporator to absorb heat from the matter to be refrigerated. The flow rate of R-134a is 0.2 kg/s. The total power input is 60 kW. The surroundings are at 290 K. Determine the coefficient of performance and the exergy loss of the cycle.

Solution:
Assume that kinetic and potential energy changes are negligible, and the system is at steady-state.

Consider Fig. 7.16.
From Tables E1 to E2 the data for R-134a:
H_2 = 242.06 kJ/kg; at T_2 = 263.15 K; P_2 = 0.18 MPa (superheated vapor)

H_3 = 278.09 kJ/kg, at T_3 = 313.15 K, P_3 = 0.6 MPa (superheated vapor)

H_4 = 77.26 kJ/kg, at T_4 = 293.15 K, P_4 = 0.571 MPa (saturated liquid)
P_1 = 0.293 MPa, T_1 = 273.15 K

$W_{\mathrm{in}} = 60\,\mathrm{kW}$, $\dot{m}_{\mathrm{r}} = 0.2\,\mathrm{kg/s}$

T_{o} = 290 K, $T_{\mathrm{evaporator}}$ = 273 K, $T_{\mathrm{condenser}}$ = 290 K

The throttling process where H_4 = H_1 = 77.26 kJ/kg (Stage 1) causes partial vaporization of the saturated liquid coming from the condenser.

The vapor part of the mixture, known as 'quality,' can be obtained using the enthalpy values at 0.293 MPa

$H_{1,\mathrm{sat\ liq}}$ = 50.02 kJ/kg, $H_{1,\mathrm{sat\ vap}}$ = 247.23 kJ/kg

$$x_1 = \frac{77.26 - 50.02}{247.23 - 50.02} = 0.138$$

For the cycle, the total enthalpy change is zero.

At the compressor, outside energy W_{in} is needed
At the evaporator, heat transfer, q_{in}, from the matter to be cooled is used to evaporate the refrigerant R-134a.

The heat absorbed within the evaporator from the contents of the refrigerator is

$$\dot{q}_{\mathrm{in}} = \dot{m}_r(H_2 - H_1) = 32.96\,\mathrm{kW}$$

The energy balance indicates the total energy (W_{in} + q_{in}) removed:

$$\dot{W}_{\mathrm{in}} + \dot{q}_{\mathrm{in}} = \dot{q}_{\mathrm{out}} = 92.96\,\mathrm{kW}$$

$$\dot{W}_{\mathrm{ideal,in}} = \dot{m}_{\mathrm{r}}(H_3 - H_2) = 7.20\,\mathrm{kW}$$

Coefficient of performance (COP) of the refrigerator:

$$\mathrm{COP} = \frac{\dot{q}_{\mathrm{in}}}{\dot{W}_{\mathrm{ideal,in}}} = \frac{H_2 - H_1}{H_3 - H_2} = \mathbf{4.57}$$

The total work (exergy) loss:

$$\dot{Ex}_{\mathrm{total}} = \dot{W}_{\mathrm{in}} + \left(1 - \frac{T_0}{T_{\mathrm{evaporater}}}\right)\dot{q}_{\mathrm{in}} - \left(1 - \frac{T_0}{T_{\mathrm{condenser}}}\right)(-\dot{q}_{\mathrm{out}}) = \mathbf{58.94\,kW}$$

Exergy analysis identifies the performance of individual processes. Finding ways to improve the thermodynamic performance of individual steps is equally important.

Example 7.25 Heat rejection by a refrigerator

Food compartment of a refrigerator is maintained at 4°C by removing heat from it at a rate of 350 kJ/min. If the required power input of the refrigerator is 1.8 kW, determine (a) the coefficient of performance (COP) of the refrigerator, (b) the rate of heat discharged to the surroundings.

Solution:
Assume: steady-state operation.

$$\dot{q}_c = 350\,\mathrm{kJ/min}, \quad \dot{W}_{\mathrm{net,in}} = 1.8\,\mathrm{kW},$$

$$\mathrm{COP_R} = \frac{\dot{q}_C}{\dot{W}_{\mathrm{net,in}}} = \frac{350\,\mathrm{kJ/min}}{1.8\,\mathrm{kW}}\left(\frac{\mathrm{kW}}{60\,\mathrm{kJ/min}}\right) = \mathbf{3.2}$$

This means that 3.2 kJ of heat is removed from the refrigerator for each kJ of energy supplied.

(b) Energy balance

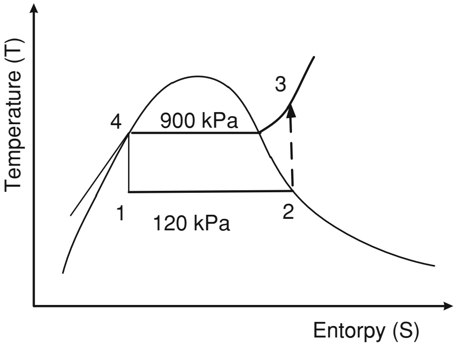
$$\dot{q}_H = \dot{q}_C + \dot{W}_{\mathrm{net,in}} = 350\,\mathrm{kJ/min} + 1.8\,\mathrm{kW}\left(\frac{60\,\mathrm{kJ/min}}{kW}\right) = \mathbf{458\,kJ/min}$$

Both the heat removed from the refrigerator space and the energy supplied to the refrigerator as electrical work are discharged to surrounding air.

Example 7.26 Coefficient of performance of a vapor-compression refrigeration cycle

An ideal vapor-compression refrigeration cycle uses R-134a. The compressor inlet and outlet pressures are 120 and 900 kPa. The mass flow rate of refrigerant is 0.04 kg/s. Determine the coefficient of performance.

Solution;
Assume: steady-state operation. The changes in kinetic and potential energies are negligible.



Solution:
Assume: steady-state adiabatic operation. The changes in kinetic and potential energies are negligible.

The refrigerant mass flow rate = 0.04 kg/s
P_2 = 120 kPa, H_2 = 233.86 kJ/kg, S_2 = 0.9354 kJ/kg K
P_3 = 900 kPa, For the isentropic compression:
$S_3 = S_2$ = 0.9354 kJ/kg K → H_3 = 276.7 kJ/kg,
P_4 = 900 kPa, $H_{4\text{sat liq}}$ = 99.56 kJ/kg; $H_{1\text{sat liq}} = H_{4\text{sat liq}}$ (throttling)

Power input to the compressor:
$\dot{W}_{\text{in}} = \dot{m}(H_3 - H_2) = (0.04\,\text{kg/s})(276.7 - 233.86)\,\text{kJ/kg} = 1.71\,\text{kW}$
Heat removed from the refrigerator space:

$$\dot{q}_C = \dot{m}(H_2 - H_1) = (0.04\,\text{kg/s})(233.86 - 99.56)\,\text{kJ/kg} = 5.37\,\text{kW}$$

The heat discharged from the refrigerator to the surrounding:

$$\dot{q}_H = \dot{m}(H_3 - H_4) = (0.04\,\text{kg/s})(276.7 - 99.56)\,\text{kJ/kg} = 7.08\,\text{kW}$$

$$\text{COP}_R = \frac{\dot{q}_C}{\dot{W}_{\text{in}}} = \frac{5.37\,\text{kW}}{1.71\,\text{kW}} = \mathbf{3.14}$$

This refrigerator is capable of removing 3.14 units of energy from the refrigerated space for each unit of electric energy it consumes.

7.16 Efficiency of Fuel Cells

A *fuel cell* is an electrochemical cell that converts chemical energy of a fuel into electric energy. Electricity is generated from the reaction between a fuel supply and an oxidizing agent. A hydrogen fuel cell uses hydrogen as fuel and oxygen (usually from air) as oxidant. Other fuels include hydrocarbons and alcohols (see Sect. 6.15). A typical fuel cell produces a voltage from 0.6 to 0.7 V at full rated load. To deliver the desired amount of energy, the fuel cells can be combined in series and parallel circuits, where series circuits yield higher voltage, and parallel circuits allow a higher current to be supplied. Such a design is called a *fuel cell stack*. The cell surface area can be increased to allow stronger current from each cell [22].

The efficiency of a fuel cell depends on the amount of power drawn from it. Drawing more power means drawing more current and hence increasing the losses in the fuel cell. Most losses appear as a voltage drop in the cell, so the efficiency of a cell is almost proportional to its voltage. For this reason, it is common to show graphs of voltage versus current (polarization curves) for fuel cells. A typical cell running at 0.7 V has an efficiency of about 50%, meaning that 50% of the energy content of the hydrogen is converted into electrical

Table 7.5 Types of fuel cell using polymer membrane as electrolyte

Fuel cell	Power output	T (°C)	Cell efficiency (%)
Proton exchange membrane fuel cell	100 W–500 kW	150–120 (Nafion)	50–70
Direct methanol fuel cell	100 mW–1 kW	90–120	20–30
Microbial fuel cell	Low	< 40	Low

Mench [26]; Vielstich et al. [39]

energy and the remaining 50% will be converted into heat. Fuel cells are not heat engines and so their efficiency is not limited by the Carnot cycle efficiency. Consequently, they can have very high efficiencies in converting chemical energy to electrical energy, especially when they are operated at low power density, and using pure hydrogen and oxygen as reactants. Fuel cell vehicles running on compressed hydrogen may have a power-plant-to-wheel efficiency of 22% if the hydrogen is stored as high-pressure gas [19, 39]. Table 7.5 compares the efficiency of several fuel cells.

The overall efficiency (electricity to hydrogen and back to electricity) of such plants (known as *round-trip efficiency*) is between 30 and 50%, depending on conditions. While a much cheaper lead-acid battery might return about 90%, the electrolyzer/fuel cell system can store indefinite quantities of hydrogen, and is therefore better suited for long-term storage.

7.17 Energy Conversions in Biological Systems

All living systems have to convert energy to the chemical energy in the form of energy rich chemical compounds. The two biochemical cyclic processes for such conversions are the oxidative phosphorylation in animals and the photosynthesis in plants. These cycles are discussed briefly in the next sections.

7.17.1 Energy Conversion by Oxidative Phosphorylation

In oxidative phosphorylation, the electrons are removed from food molecules in electron transport chain. A series of proteins in the membranes of mitochondria use the energy released from passing electrons from reduced molecules like NADH onto oxygen to pump protons across the membrane in mitochondria. The flow of protons causes the rotation of stalk subunit of a large protein called the ATPase. The rotation of ATPase changes the shape of the active site and synthesize adenosine triphosphate (ATP) from adenosine diphosphate (ADP) and inorganic phosphorus (Pi)

$$\mathrm{ADP} + \mathrm{Pi} = \mathrm{ATP} \tag{7.74}$$

ATP is an energy-rich compound having three phosphate group attached to a nucleoside of adenine called adenosine. Of the three phosphate groups, the terminal one has a weak linkage. This phosphate group can break spontaneously whenever ATP forms a complex with an enzyme. The breaking up of this bond releases chemical energy causing an immediate shift in the bond energy giving rise to ADP. The energy of ATP is used for all the activity of living cells, such as transport of ions and molecules, synthesis of new proteins and other substances, and the growth and development. ATP therefore acts as 'energy currency of the cell' and is used to transfer chemical energy between different biochemical reaction cycles [7, 25].

7.17.2 Energy from Photosynthesis

Photosynthesis is the synthesis of carbohydrates from sunlight and carbon dioxide (CO_2). The capture of solar energy is similar in principle to oxidative phosphorylation, as the proton motive force then drives ATP synthesis. The electrons needed to drive this electron transport chain come from light-gathering proteins called photosynthetic reaction centers. In plants, cyanobacteria and algae, oxygenic photosynthesis splits water, with oxygen produced as a waste product. This process uses the ATP and NADPH produced by the photosynthetic reaction centers. This carbon-fixation reaction is carried out by the enzyme RUBisCO.

7.17.3 Metabolism

Metabolism is the set of biochemical reactions that occur in living organisms to maintain life. Metabolism is usually divided into two categories catabolism and anabolism. Catabolism breaks down organic matter, for example to harvest energy in cellular respiration. Anabolism uses energy to construct components of cells such as proteins and nucleic acids. Adenosine triphosphate (ATP) is used to transfer chemical energy between different biochemical reaction cycles. ATP in cells is continuously regenerated and acts as a bridge between catabolism and anabolism, with catabolic reactions generating ATP and anabolic reactions consuming it.

7.17.4 Biological Fuels

Biological fuels can be categorized in three groups: carbohydrates (CH), representing a mixture of mono-, di-, and poly-saccarides, fats (F), and proteins (Pr) [25]. Carbohydrates are straight-chain aldehydes or ketones with many hydroxyl groups that can exist as straight chains or rings. Carbohydrates are the most abundant biological molecules, and play numerous roles, such as the storage and transport of energy (starch, glycogen) and structural components such as cellulose in plants.

The fuel value is equal to the heat of reaction of combustion (oxidation). Carbohydrates and fats can be completely oxidized while proteins can only be partially oxidized and hence a lower fuel value. The energy expenditure may be calculated from the energy balance. Assume that (i) carbohydrate (CH), fat (F), and protein (Pr) are the only compounds involved in the oxidation process, (ii) the other compounds are stationary, and (iii) the uptake and elimination of oxygen, carbon dioxide, and nitrogen is instantaneous. Energy balance is

$$\dot{E} = \sum_i (\dot{n}\Delta H_r)_i = (\dot{n}\Delta H_r)_{\mathrm{CH}} + (\dot{n}\Delta H_r)_{\mathrm{F}} + (\dot{n}\Delta H_r)_{\mathrm{Pr}} = \dot{q} + \dot{W} \tag{7.75}$$

7.17.5 Converting Biomass to Biofuels

Technologies for converting biomass to biofuels are often classified in two main categories: *thermochemical conversion* and *biological conversion.*

- *Thermochemical conversion* involves applying heat to break down biomass into chemical intermediates that can be used to make fuel substitutes. Many of these thermal technologies are known for well over a century and are used primarily in transforming coal into fuels. Gasification combined with catalytic conversion of syngas (carbon monoxide and hydrogen) to fuels, for example, hydrogen, liquid fuels, mixed alcohols, or dimethyl ether. Pyrolysis of biomass produces bio-oils that could serve as intermediates in a petroleum refinery.
- *Biological conversion* focuses on fermentation of carbohydrates in biomass to ethanol and other chemicals. Fermentation technology, of course, is among the earliest conversion processes [38]. Optimal combinations of both biological and thermochemical fuel production may lead to greater energy efficiency in the transformation of the energy of biomass into useable fuels.

In 2005, 3.9 billion gallons of ethanol fuel primarily from the fermentation of starch in corn grain were produced and sold in the United States. Estimations show that an upper limit on ethanol production from corn at around 10 billion gallons per year, which represents a very small fraction of U.S. demand for gasoline [23, 34]. Because a gallon of ethanol contains only 67% as much energy as a gallon of gasoline, 10 billion gallons of ethanol would represent only 7 billion gallons per year corresponding to 5% of gasoline demand in U.S.

Accessing energy in lignocellulosic biomass greatly increases the potential supply of biofuels. Figure 7.17 provides a schematic representation of the conversion process of cellulosic feedstock to biofuels. Cellulosic biomass needs

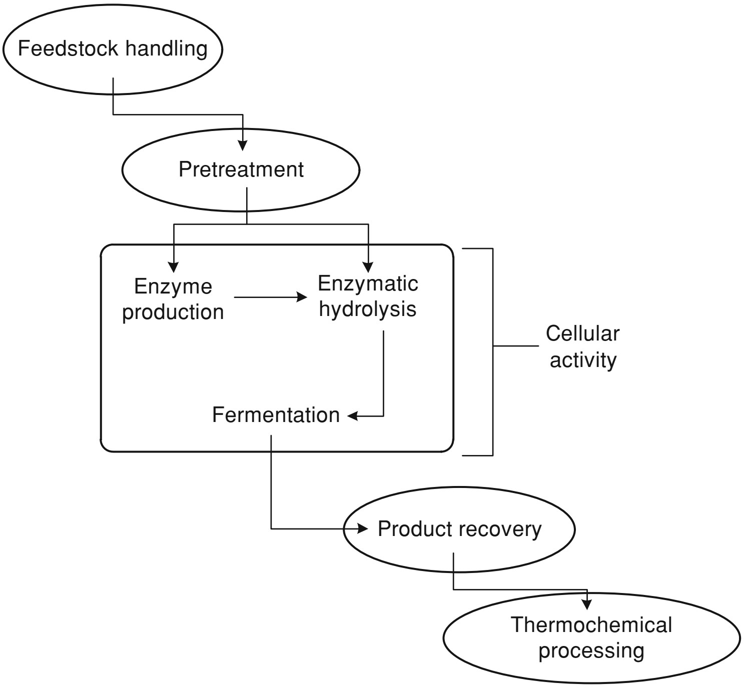


Fig. 7.17 Process schematic of biological conversion of lignocellulosic biomass to ethanol

pretreatment and enzymatic processes before it can be converted to biofuel by fermentation. The critical technology advancements need of biological catalysts that can cost-effectively break down the carbohydrate polymers in biomass to sugars and microbes that can ferment all of the sugars in biomass to ethanol [9, 11, 30].

Government incentives for biodiesel have spurred significant growth in the vegetable oil-based biodiesel fuel substitute. Converting vegetable oil to biodiesel is a relatively simple thermochemical process in which the natural oil is synthesized with methanol to form fatty acid methyl ester [23].

Problems

7.1 A pump delivers water from the bottom of a storage tank open to the atmosphere containing water at 75°F. The water in the storage tank is 10 ft deep and bottom of the tank is 50 ft above the ground. The pump delivers the water at 80°F and 100 psia to another tank, which is 10 ft above the ground. If the water flow rate is 5,000 lb/h and pump efficiency is 80%, estimate the power in hp required.

7.2 The pump of a water storage tank is powered with a 18-kW electric motor operating with an efficiency of 90%. The water flow rate is 40 l/s. The diameters of the inlet and exit pipes are the same, and the elevation difference between the inlet and outlet is negligible. The absolute pressures at the inlet and outlet are 100 and 400 kPa, respectively. Determine the mechanical efficiency of the pump.

7.3 The pump of a water storage tank is powered with a 18-kW electric motor operating with an efficiency of 85%. The water flow rate is 30 l/s. The diameters of the inlet and exit pipes are the same, and the elevation difference between the inlet and outlet is negligible. The absolute pressures at the inlet and outlet are 100 and 500 kPa, respectively. Determine the mechanical efficiency of the pump.

7.4 A wind turbine-generator with a 24-foot-diameter blade produces 0.35 kW of electric power. In the location of the wind turbine, the wind speed is 11 mile per hour. Determine the efficiency of the wind turbine-generator.

7.5 A wind turbine-generator with a 27-foot-diameter blade produces 0.4 kW of electric power. In the location of the wind turbine, the wind speed is 10 mile per hour. Determine the efficiency of the wind turbine-generator.

7.6 A hydroelectric plant operates by water falling from a 25 m height. The turbine in the plant converts potential energy into electrical energy with an assumed efficiency of 85%. The electricity is lost by about 8% through the power transmission. Estimate the mass flow rate of the water necessary to power a 500 W light bulb.

7.7 A hydroelectric plant is generating 125 kW of power. If their turbines only convert the potential energy form the water with a 75% efficiency, find the height change for the water flow rate of 480 kg/s must fall in order to continue to make 125 kW of power.

7.8 A hydroelectric plant operates by water falling from a 40 m height. The turbine in the plant converts potential energy into electrical energy with an assumed efficiency of 80%. The electricity is lost by about 8% through the power transmission. Estimate the mass flow rate of the water necessary to power a 1,500 W light bulb.

7.9 A hydroelectric plant operates by water falling from a 150 ft height. The turbine in the plant converts potential energy into electrical energy with an assumed efficiency of 82%. The electricity is lost by about 6% through the power transmission. Estimate the mass flow rate of the water necessary to power a 3,500 W light bulb.

7.10 A hydroelectric plant operates by water falling from a 200 ft height. The turbine in the plant converts potential energy into electrical energy with an assumed efficiency of 85%. The electricity is lost by about 5% through the power transmission so the available power is 95%. Estimate the mass flow rate of the water necessary to power a 3,500 W light bulb.

7.11 A hydroelectric plant operates by water falling from a 200 ft height. The turbine in the plant converts potential energy into electrical energy with an assumed efficiency of 85%. The power is lost by about 5% through the power transmission so the available power is 95%. If the mass flow rate of the water 396 lb/s, estimate the power output of the hydro plant.

7.12 An electric motor attached to a pump draws 10.2 A at 110 V. At steady load the motor delivers 1.32 hp of mechanical energy. Estimate the rate of heat transfer from the motor.

7.13 An electric motor attached to a pump draws 12 A at 110 V. At steady load the motor delivers 1.5 hp of mechanical energy. Estimate the rate of heat transfer from the motor.

7.14 Air enters an insulated compressor operating at steady-state at 1.0 bar, 300 K with a mass flow rate of 3.6 kg/s and exits at 2.76 bar. Kinetic and potential energy effects are negligible. (a) Determine the minimum theoretical power input required, in kW, and the corresponding exit temperature, in K. (b) If the actual exit temperature is 420 K, determine the power input, in kW, and the isentropic compressor efficiency.

7.15 Air enters an insulated compressor operating at steady-state at 1.0 bar, 300 K with a mass flow rate of 2.5 kg/s and exits at 2.6 bar. Kinetic and potential energy effects are negligible. (a) Determine the minimum theoretical power input required, in kW, and the corresponding exit temperature, in K. (b) If the actual exit temperature is 420 K, determine the power input, in kW, and the isentropic compressor efficiency.

7.16 A compressor increases the pressure of carbon dioxide from 100 to 600 kPa. The inlet temperature is 300 K and the outlet temperature is 400 K. The mass flow rate of carbon dioxide is 0.01 kmol/s. The power required by the compressor is 55 kW. The temperature of the surroundings is 290 K. Determine the minimum amount of work required and the coefficient of performance.

7.17 A compressor increases the pressure of carbon dioxide from 100 to 500 kPa. The inlet temperature is 300 K and the outlet temperature is 400 K. The mass flow rate of carbon dioxide is 0.015 kmol/s. The power required by the compressor is 60 kW. The temperature of the surroundings is 290 K. Determine the minimum amount of work required and the coefficient of performance.

7.18 A compressor receives air at 15 psia and 80°F with a flow rate of 1.2 lb/s. The air exits at 40 psia and 300°F. At the inlet the air velocity is low, but increases to 250 ft/s at the outlet of the compressor. Estimate the power input to the compressor if it is cooled at a rate of 200 Btu/s.

7.19 A compressor receives air at 15 psia and 80°F with a flow rate of 1.5 lb/s. The air exits at 50 psia and 300°F. At the inlet the air velocity is low, but increases to 250 ft/s at the outlet of the compressor. Estimate the power input to the compressor if it is cooled at a rate of 150 Btu/s.

7.20 In an adiabatic compression operation, air is compressed from 20°C and 101.32 to 520 kPa with an efficiency of 0.7. The air flow rate is 22 mol/s. Assume that the air remains ideal-gas during the compression. The surroundings are at 298.15 K. Determine the thermodynamic efficiency η_{th} and the rate of energy dissipated $\dot{E}_{\mathrm{loss}}$.

7.21 In an adiabatic compression operation, air is compressed from 25°C and 101.32 to 560 kPa with an efficiency of 0.7. The air flow rate is 20 mol/s. Assume that the air remains ideal-gas during the compression. The surroundings are at 298.15 K. Determine the thermodynamic efficiency η_{th} and the rate of energy dissipated $\dot{E}_{\mathrm{loss}}$.

7.22 The power required to compress 0.05 kg/s of steam from a saturated vapor state at 50°C to a pressure of 800 kPa at 200°C is 15 kW. Find the conversion rate of power input to heat loss from the compressor.

7.23 The power required to compress 0.1 kg/s of steam from a saturated vapor state at 80°C to a pressure of 1,000 kPa at 200°C is 28 kW. Find the conversion rate of power input to heat loss from the compressor.

7.24 A steam turbine consumes 4,000 lb/h steam at 540 psia and 800°F. The exhausted steam is at 165 psia. The turbine operation is adiabatic.

(a) Determine the exit temperature of the steam and the work produced by the turbine.

(b) Determine the thermal efficiency.

7.25 A steam turbine consumes 3,800 lb/h steam at 540 psia and 800°F. The exhausted steam is at 180 psia. The turbine operation is adiabatic.

(a) Determine the exit temperature of the steam and the work produced by the turbine.

(b) Determine the thermal efficiency.

7.26 A superheated steam (stream 1) expands in a turbine from 5,000 kPa and 325°C to 150 kPa and 200°C. The steam flow rate is 15.5 kg/s. If the turbine generates 1.1 MW of power, determine the heat loss to the surroundings and thermal efficiency.

7.27 A superheated steam (stream 1) expands in a turbine from 6,000 kPa and 325°C to 150 kPa and 200°C. The steam flow rate is 16.2 kg/s. If the turbine generates 1.2 MW of power, determine the heat loss to the surroundings and thermal efficiency.

7.28 Steam expands in a turbine from 6,600 kPa and 300°C to a saturated vapor at 1 atm. The steam flow rate is 9.55 kg/s. If the turbine generates a power of 1 MW, determine the thermal efficiency.

7.29 Steam expands in a turbine from 7,000 kPa and 300°C to a saturated vapor at 1 atm. The steam flow rate is 14.55 kg/s. If the turbine generates a power of 1.5 MW, determine the thermal efficiency.

7.30 Steam expands adiabatically in a turbine from 850 psia and 600°F to a wet vapor at 12 psia with a quality of 0.9. The turbine produces a power output of 1,500 Btu/s. Estimate the thermal efficiency for a steam flow rate of 12.8 lb/s.

7.31 Steam expands adiabatically in a turbine from 900 psia and 600°F to a wet vapor at 10 psia with a quality of 0.9. The turbine produces a power output of 1,550 Btu/s. Estimate the thermal efficiency for a steam flow rate of 14.2 lb/s.

7.32 A turbine produces 65,000 kW electricity with an efficiency of 70%. It uses a superheated steam at 8,200 kPa and 550°C. The discharged stream is a saturated mixture at 75 kPa. If the expansion in the turbine is adiabatic, and the surroundings are at 298.15 K, determine the thermodynamic efficiency and the work loss.

7.33 A turbine produces 70 MW electricity with an efficiency of 70%. It uses a superheated steam at 8,800 kPa and 550°C. The discharged stream is a saturated mixture at 15 kPa. If the expansion in the turbine is adiabatic, and the surroundings are at 298.15 K, determine the thermodynamic efficiency and the work loss.

7.34 A Carnot cycle use water as the working fluid at a steady-flow process. Heat is transferred from a source at 250°C and water changes from saturated liquid to saturated vapor. The saturated steam expands in a turbine at 10 kPa, and heat is transferred in a condenser at 10 kPa. Estimate the thermal efficiency and net power output of the cycle.

7.35 A Carnot cycle use water as the working fluid at a steady-flow process. Heat is transferred from a source at 200°C and water changes from saturated liquid to saturated vapor. The saturated steam expands in a turbine at 20 kPa, and heat is transferred in a condenser at 20 kPa. Estimate the thermal efficiency of the cycle and the amount of heat transferred in the condenser for a flow rate of 5.5 kg/s of the working fluid.

7.36 A Carnot cycle use water as the working fluid at a steady-flow process. Heat is transferred from a source at 200°C and water changes from saturated liquid to saturated vapor. The saturated steam expands in a turbine at 10 kPa, and heat is transferred in a condenser at 10 kPa. Estimate the thermal efficiency of the cycle and the amount of heat transferred in the condenser for a flow rate of 7.5 kg/s of the working fluid.

7.37 A Carnot cycle use water as the working fluid at a steady-flow process. Heat is transferred from a source at 400°F and water changes from saturated liquid to saturated vapor. The saturated steam expands in a turbine at 5 psia, and heat is transferred in a condenser at 5 psia. Estimate the thermal efficiency of the cycle and the amount of heat transferred in the condenser for a flow rate of 10 lb/s of the working fluid.

7.38 Consider a simple ideal Rankine cycle. If the turbine inlet temperature and the condenser pressure are kept the same, discuss the effects of increasing the boiler pressure on:

- Turbine power output
- Heat Supplied
- Thermal efficiency
- Heat rejected

7.39 Consider a simple ideal Rankine cycle. If the boiler and the condenser pressures are kept the same, discuss the effects of increasing the temperature of the superheated steam on:

- Turbine power output
- Heat Supplied

- Thermal efficiency
- Heat rejected

7.40 A steam power production plant burns fuel at 1,273.15 K (T_H), and cooling water is available at 290 K (T_C). The steam produced by the boiler is at 8,200 kPa and 823.15 K. The condenser produces a saturated liquid at 30 kPa. The turbine and pump operate reversibly and adiabatically. Determine the thermal efficiency of the cycle for the steam flow rate of 1 k/s.

7.41 A steam power plant operates on a simple ideal Rankine cycle. The boiler operates at 3,000 kPa and 350°C. The condenser operates at 30 kPa. The mass flow rate of steam is 22 kg/s. Estimate the thermal efficiency of the cycle and the net power output.

7.42 A steam power plant operates on a simple ideal Rankine cycle shown below. The turbine receives steam at 698.15 K and 4,100 kPa, while the discharged steam is at 40 kPa. The mass flow rate of steam is 3.0 kg/s. In the boiler, heat is transferred into the steam from a source at 1,500 K (T_H). In the condenser, heat is discharged to the surroundings at 298 K (T_C) The condenser operates at 298 K. Determine the thermal efficiency of the cycle.

7.43 A steam power plant operates on a simple ideal Rankine cycle. The boiler operates at 5,000 kPa and 300°C. The condenser operates at 20 kPa. The mass flow rate of steam is 25 kg/s. Estimate the thermal efficiency of the cycle and the net power output.

7.44 A steam power plant operates on a simple ideal Rankine cycle. The boiler operates at 10,000 kPa and 400°C. The condenser operates at 30 kPa. The power output of the cycle is 140 MW. Estimate the thermal efficiency of the cycle and the mass flow rate of the steam.

7.45 A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,500 kPa and 400°C. Discharge pressure of the steam from the turbine is 15 kPa. Determine the thermal efficiency of the cycle.

7.46 A simple ideal Rankine cycle is used in a steam power plant. Steam enters the turbine at 6,600 kPa and 798.15 K. The net power output of the turbine is 35 kW. The discharged steam is at 10 kPa. Determine the thermal efficiency.

7.47 A steam power plant operates on a simple ideal Rankine cycle. The boiler operates at 10,000 kPa and 500°C. The condenser operates at 10 kPa. The power output of the cycle is 175 MW. Turbine operates with an isentropic efficiency of 0.80, while the pump operates with an isentropic efficiency of 0.90. Estimate the thermal efficiency of the cycle and the heat transferred in the condenser.

7.48 A steam power plant operates on a simple ideal Rankine cycle. The boiler operates at 10,000 kPa and 400°C. The condenser operates at 10 kPa. The power output of the cycle is 145 MW. Turbine operates with an isentropic efficiency of 0.85, while the pump operates with an isentropic efficiency of

0.95. Estimate the thermal efficiency of the cycle and the heat transferred in the condenser.

7.49 A steam power plant operates on a simple ideal Rankine cycle. The boiler operates at 10,000 kPa and 400°C. The condenser operates at 10 kPa. The mass flow rate of steam is 110 kg/s. Turbine operates with an isentropic efficiency of 0.85, while the pump operates with an isentropic efficiency of 0.95. Estimate the thermal efficiency and the power output of the cycle.

7.50 A steam power plant operates on a simple ideal Rankine cycle. The boiler operates at 8,000 kPa and 400°C. The condenser operates at 20 kPa. The mass flow rate of steam is 80 kg/s. Turbine operates with an isentropic efficiency of 0.85, while the pump operates with an isentropic efficiency of 0.90. Estimate the thermal efficiency and the power output of the cycle.

7.51 A steam power plant shown below uses natural gas to produce 0.1 MW power. The combustion heat supplied to a boiler produces steam at 10,000 kPa and 798.15 K. The turbine efficiency is 0.7. The discharged steam from the turbine is at 30 kPa, and is sent to a condenser. The condensed water is pumped to the boiler. The pump efficiency is 0.90. Determine the thermal efficiency of the cycle.

7.52 A steam power plant shown below uses natural gas to produce 0.12 MW power. The combustion heat supplied to a boiler produces steam at 10,000 kPa and 798.15 K. The turbine efficiency is 0.75. The discharged steam from the turbine is at 30 kPa, and is sent to a condenser. The condensed water is pumped to the boiler. The pump efficiency is 0.85. Determine:
(a) The thermal efficiency of an ideal Rankine cycle.
(b) The thermal efficiency of an actual Rankine cycle.

7.53 A steam power plant shown below uses natural gas to produce 0.12 MW power. The combustion heat supplied to a boiler produces steam at 9,000 kPa and 798.15 K. The turbine efficiency is 0.8. The discharged steam from the turbine is at 10 kPa, and is sent to a condenser. The condensed water is pumped to the boiler. The pump efficiency is 0.9. Determine:
(a) The thermal efficiency of an ideal Rankine cycle.
(b) The thermal efficiency of an actual Rankine cycle.

7.54 A simple ideal reheat Rankine cycle is used in a steam power plant shown below. Steam enters the turbine at 9,000 kPa and 823.15 K and leaves at 4,350 kPa and 698.15 K. The steam is reheated at constant pressure to 823.15 K. The discharged steam from the low-pressure turbine is at 10 kPa. The net power output of the turbine is 40 MW. In the boiler, heat is transferred into the steam from a source at 1,600 K (T_H). In the condenser, heat is discharged to the surroundings at 298 K (T_C). The condenser operates at 298 K. The turbine efficiency is 0.8 and the pump efficiency is 0.9. Determine the mass flow rate of steam and the thermal efficiency of the cycle.

7.55 A steam power plant is using an ideal regenerative Rankine cycle shown below. Steam enters the high-pressure turbine at 8,200 kPa and 773.15 K, and the condenser operates at 20 kPa. The steam is extracted from the turbine at 350 kPa to heat the feed water in an open heater. The water is a saturated liquid after passing through the feed water heater. The work output of the turbine is 50 MW. In the boiler, heat is transferred into the steam from a source at 1,600 K (T_H). In the condenser, heat is discharged to the surroundings at 285 K (T_C). Determine the thermal efficiency of the cycle.

7.56 A steam power plant is using an ideal reheat regenerative Rankine cycle shown below. Steam enters the high-pressure turbine at 9,000 kPa and 773.15 K and leaves at 850 kPa. The condenser operates at 10 kPa. Part of the steam is extracted from the turbine at 850 kPa to heat the water in an open heater, where the steam and liquid water from the condenser mix and direct contact heat transfer takes place. The rest of the steam is reheated to 723.15 K, and expanded in the low-pressure turbine section to the condenser pressure. The water is a saturated liquid after passing through the water heater and is at the heater pressure. The work output of the turbine is 75 MW. In the boiler, heat is transferred into the steam from a source at 1,600 K (T_H). In the condenser, heat is discharged to the surroundings at 285 K (T_C). Determine the thermal efficiency of the cycle.

7.57 A steam power plant is using a geothermal energy source. The geothermal source is available at 220°C and 2,320 kPa with a flow rate of 200 kg/s. The hot water goes through a valve and a flash drum. Steam from the flash drum enters the turbine at 550 kPa and 428.62 K. The discharged steam from the turbine has a quality of $x_4 = 0.96$. The condenser operates at 10 kPa. The water is a saturated liquid after passing through the condenser. Determine the thermal efficiency of the cycle.

7.58 A geothermal power production plant produces 7 MW power. Inlet temperature of the hot geothermal liquid source is 150°C. The flow rate of the hot liquid water is 220 kg/s. The reference state is at 25°C. Estimate the second law efficiency of the plant.

7.59 A reheat Rankine cycle is used in a steam power plant. Steam enters the high-pressure turbine at 9,000 kPa and 823.15 K and leaves at 4,350 kPa. The steam is reheated at constant pressure to 823.15 K. The steam enters the low-pressure turbine at 4,350 kPa and 823.15 K. The discharged steam from the low-pressure turbine is at 10 kPa. The net power output of the turbine is 65 MW. The isentropic turbine efficiency is 80%. The pump efficiency is 95%. In the boiler, heat is transferred into the steam from a source at 1,600 K. In the condenser, heat is discharged to the surroundings at 298 K. The condenser operates at 298 K. Determine the thermal efficiency.

7.60 A reheat Rankine cycle is used in a steam power plant. Steam enters the high-pressure turbine at 10,000 kPa and 823.15 K and leaves at 4,350 kPa. The steam is reheated at constant pressure to 823.15 K. The steam enters the low-pressure turbine at 4,350 kPa and 823.15 K. The discharged steam from the low-pressure turbine is at 15 kPa. The net power output of the turbine is 65 MW. The isentropic turbine efficiency is 80%. The pump efficiency is

95%. In the boiler, heat is transferred into the steam from a source at 1,600 K. The condenser operates at 298 K. Determine the thermal efficiency.

7.61 A steam power plant is using an actual regenerative Rankine cycle. Steam enters the high-pressure turbine at 11,000 kPa and 773.15 K, and the condenser operates at 10 kPa. The steam is extracted from the turbine at 475 kPa to heat the water in an open heater. The water is a saturated liquid after passing through the water heater. The work output of the turbine is 90 MW**.** The pump efficiency is 95% and the turbine efficiency is 75%. In the boiler, heat is transferred into the steam from a source at 1,700 K. In the condenser, heat is discharged to the surroundings at 285 K. Determine the thermal efficiency.

7.62 A steam power plant is using an actual regenerative Rankine cycle. Steam enters the high-pressure turbine at 10,000 kPa and 773.15 K, and the condenser operates at 15 kPa. The steam is extracted from the turbine at 475 kPa to heat the water in an open heater. The water is a saturated liquid after passing through the water heater. The work output of the turbine is 90 MW**.** The pump efficiency is 90% and the turbine efficiency is 80%. In the boiler, heat is transferred into the steam from a source at 1,700 K. In the condenser, heat is discharged to the surroundings at 285 K. Determine the thermal efficiency.

7.63 A steam power plant is using an actual reheat regenerative Rankine cycle. Steam enters the high-pressure turbine at 11,000 kPa and 773.15 K, and the condenser operates at 10 kPa. The steam is extracted from the turbine at 2,000 kPa to heat the water in an open heater. The steam is extracted at 475 kPa for process heat. The water is a saturated liquid after passing through the water heater. The work output of the turbine is 90 MW. The turbine efficiency is 80%. The pumps operate isentropically. In the boiler, heat is transferred into the steam from a source at 1,700 K. In the condenser, heat is discharged to the surroundings at 290 K. Determine the thermal efficiency of the plant.

7.64 A steam power plant is using an actual reheat regenerative Rankine cycle. Steam enters the high-pressure turbine at 10,000 kPa and 773.15 K, and the condenser operates at 15 kPa. The steam is extracted from the turbine at 2,000 kPa to heat the water in an open heater. The steam is extracted at 475 kPa for process heat. The water is a saturated liquid after passing through the water heater. The work output of the turbine is 85 MW. The turbine efficiency is 80%. The pumps operate isentropically. In the boiler, heat is transferred into the steam from a source at 1,700 K. In the condenser, heat is discharged to the surroundings at 290 K. Determine the thermal efficiency of the plant.

7.65 A steam power plant operates on a regenerative cycle. Steam enters the turbine at 700 psia and 800°F and expands to 1 psia in the condenser. Part of the steam is extracted at 60 psia. The efficiencies of the turbine and pump are 0.80 and 0.95, respectively. If the mass flow rate of steam is 9.75 lb/s estimate the thermal efficiency of the turbine.

7.66 A steam power plant operates on a regenerative cycle. Steam enters the turbine at 750 psia and 800°F and expands to 5 psia in the condenser. Part of the steam is extracted at 60 psia. The efficiencies of the turbine and pump are 0.80 and 0.90, respectively. If the mass flow rate of steam is 10.5 lb/s estimate the thermal efficiency of the turbine.

7.67 A cogeneration plant shown below uses steam at 900 psia and 1,000°F to produce power and process heat. The steam flow rate from the boiler is 16 lb/s. The process requires steam at 70 psia at a rate of 3.2 lb/s supplied by the expanding steam in the turbine. The extracted steam is condensed and mixed with the water output of the condenser. The remaining steam expands from 70 psia to the condenser pressure of 3.2 psia. In the boiler, heat is transferred into the steam from a source at 3,000 R. In the condenser, heat is discharged to the surroundings at 540 R. If the turbine operates with an efficiency of 80% and the pumps with an efficiency of 85%, determine the thermal efficiency of the cycle.

7.68 A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The fresh air temperature is 300 K at the compressor inlet and 1,200 K at the end of the compressor and at the inlet of the turbine. Using the standard-air assumptions, determine the thermal efficiency of the cycle.

7.69 A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The fresh air temperature is 300 K at the compressor inlet and 1,200 K at the end of the compressor and at the inlet of the turbine. Assume the gas-turbine cycle operates with a compressor efficiency of 80% and a turbine efficiency of 80%. Determine the thermal efficiency of the cycle.

7.70 The net work of a power cycle is 8×10^6 Btu/s and the heat transfer to the cold reservoir, q_C, is 12×10^6 Btu/s. The hot source operates at 1,400 R and the cold source temperature is 560 R. What is the ratio of the achieved thermal efficiency to the maximum thermal efficiency of the cycle?

7.71 The net work of a power cycle is 25 MW and the heat transfer to the cold reservoir, q_C, is 67 MW. The hot source operates at 573 K and the cold source temperature is 285. What is the ratio of the achieved thermal efficiency to the maximum thermal efficiency of the cycle?

7.72 The net work of a power cycle is 52,000 Btu/s and the heat transfer to the cold reservoir, q_C, is 69,000 Btu/s. The hot source operates at 1,450 R and the cold source temperature is 550 R. What is the ratio of the achieved thermal efficiency to the maximum thermal efficiency of the cycle?

7.73 The net work of a power cycle is 75,000 Btu/s and the heat transfer to the cold reservoir, q_C, is 85,000 Btu/s. The hot source operates at 1,500 R and the cold source temperature is 530 R. What is the ratio of the achieved thermal efficiency to the maximum thermal efficiency of the cycle?

7.74 An ideal Otto cycle operates with a compression ratio (V_{max}/V_{min}) of 8.9. Air is at 101.3 kPa and 300 K at the start of compression (state 1). The maximum and minimum temperatures in the cycle are 1,360 and 300 K. Specific heats depend on the temperature. Determine the thermal efficiency of the cycle and the thermal efficiency of a Carnot cycle working between the same temperature limits.

7.75 An ideal Otto cycle operates with a compression ratio ($V_{\max}/V_{\min}$) of 9.2. Air is at 101.3 kPa and 300 K at the start of compression (state 1). During the constant-volume heat-addition process, 730 kJ/kg of heat is transferred into the air from a source at 1,900 K. Heat is discharged to the surroundings at 280 K. Determine the thermal efficiency of energy conversion.

7.76 An ideal Otto cycle operates with a compression ratio ($V_{\max}/V_{\min}$) of 9. Air is at 101.3 kPa and 295 K at the start of compression (state 1). During the constant-volume heat-addition process, 900 kJ/kg of heat is transferred into the air from a source at 1,800 K. Heat is discharged to the surroundings at 295 K. Determine the thermal efficiency of the energy conversion.

7.77 An ideal Otto cycle operates with a compression ratio (= $V_{\max}/V_{\min}$) of 8.5. Air is at 101.3 kPa and 285 K at the start of compression (state 1). During the constant-volume heat-addition process, 1,000 kJ/kg of heat is transferred into the air from a source at 1,800 K. Heat is discharged to the surroundings at 280 K. Determine the thermal efficiency of energy conversion.

7.78 An ideal Otto cycle operates with a compression ratio (=$V_{\max}/V_{\min}$) of 10. Air is at 101.3 kPa and 295 K at the start of compression (state 1). During the constant-volume heat-addition process, 1,000 kJ/kg of heat is transferred into the air from a source at 1,800 K. Heat is discharged to the surroundings at 295 K. Determine the thermal efficiency of the energy conversion.

7.79 An ideal Otto cycle operates with a compression ratio (r = $V_{\max}/V_{\min}$) of 8. Air is at 101.3 kPa and 300 K at the start of compression (state 1). The maximum and minimum temperatures in the cycle are 1,300 and 300 K, respectively. Determine the thermal efficiency of energy conversion and the thermal efficiency of the Carnot engine. The average specific heats are $C_{p,av}$ = 1.00 kJ/kg K and $C_{v,av}$ = 0.717 kJ/kg K

7.80 An ideal Otto cycle operates with a compression ratio (r = $V_{\max}/V_{\min}$) of 8.8. Air is at 101.3 kPa and 300 K at the start of compression (state 1). The maximum and minimum temperatures in the cycle are 1,400 and 300 K, respectively.. Determine the thermal efficiency of energy conversion and the thermal efficiency of the Carnot engine. The average specific heats are $C_{p,av}$ = 1.00 kJ/kg K and $C_{v,av}$ = 0.717 kJ/kg K

7.81 One kmol of carbon dioxide is initially at 1 atm and −13°C performs a power cycle consisting of three internally reversible processes in series. Step 1–2: adiabatic compression to 5 atm. Step 2–3: isothermal expansion to 1 atm. Step 3–1: constant-pressure compression. Determine the net work, in Btu/lb_m and the thermal efficiency.

7.82 An ideal Diesel cycle has an air-compression ratio of 18 and operating with maximum temperature of 2,660 R. At the beginning of the compression, the fluid pressure and temperature are 14.7 psia, 540, respectively. The average specific heats of air at room temperature are $C_{p,av}$ = 0.24 Btu/lb R and, $C_{v,av}$

= 0.171 Btu/lb R. Utilizing the cold-air-standard assumptions, determine the thermal efficiency.

7.83 An ideal Diesel cycle has an air-compression ratio of 18 and operating with maximum temperature of 2,200 K. At the beginning of the compression, the fluid pressure and temperature are 100 kPa, and 290 K, respectively. The average specific heats of air at room temperature are $C_{p,av}$ = 1.0 kJ/kg K and, $C_{v,av}$ = 0. 718 kJ/kg K. Utilizing the cold-air-standard assumptions, determine the thermal efficiency of the cycle.

7.84 An ideal Diesel cycle has an air-compression ratio of 16 and a cutoff ratio of 2. At the beginning of the compression, the fluid pressure, temperature, and volume are 100 kPa, 300 K, respectively. The average specific heats of air at room temperature are $C_{p,av}$ = 1.005 kJ/kg K, $C_{v,av}$ = 0.7181 kJ/kg K. Utilizing the cold-air-standard assumptions, determine the thermal efficiency of the cycle.

7.85 An ideal Diesel cycle has an air-compression ratio of 16 and a cutoff ratio of 2. At the beginning of the compression, the fluid pressure, temperature, and volume are 100 kPa, 290 K, respectively. The average specific heats of air at room temperature are $C_{p,av}$ = 1.005 kJ/kg K, $C_{v,av}$ = 0.7181 kJ/kg K. Utilizing the cold-air-standard assumptions, determine the thermal efficiency of the cycle.

7.86 A refrigerator using tetrafluoroethane (R-134a) as refrigerant operates with a capacity of 10,000 Btu/h. The refrigerated space is at 15°F. The evaporator and condenser operate with a 10°F temperature difference in their heat transfer. Cooling water enters the condenser at 70°F. Therefore, the evaporator is at 5°F, and the condenser is at 80°F. Determine the ideal and actual power necessary if the compressor efficiency is 85%.

7.87 In a refrigeration cycle, the superheated R-134a (state 2) enters a compressor at 200°F and 90.0 psia. The R-134a (state 3) leaves the compressor at 360°F and 140 psia, and enters a condenser, where it is cooled by cooling water. The R-134a (state 4) leaves the condenser at 90.5°F and 120 psia as saturated liquid, and enters a throttling valve. The partially vaporized R-134a (state 1) leaves the valve at 100 psia. The cycle of R-134a is completed when it passes through an evaporator to absorb heat from the matter to be refrigerated. The flow rate of R-134a is 0.2 lb/s. The total power input is 85 Btu/s. The cooling water enters the condenser at 80°F and leaves at 115°F. The surroundings are at 210°F. Determine the overall exergy loss.

7.88 In a tetrafluoroethane (R-134a) refrigeration cycle, the superheated R-134a (state 1) enters a compressor at 253.15 K and 0.14 MPa. The R-134a (state 2) leaves the compressor at 303.15 K and 0.5 MPa, and enters a condenser, where it is cooled by cooling water. The R-134a (state 3) leaves the condenser at 299.87 K and 0.75 MPa and enters a throttling valve. The partially vaporized R-134a (state 4) leaves the valve at 0.205 MPa. The cycle is completed by passing the R-134 through an evaporator to absorb heat from the matter to be refrigerated. The R-134a (state 1) leaves the evaporator as superheated vapor. The flow rate of R-134a is 0.16 kg/s. The total power input is 750 kW. Estimate the coefficient of performance.

7.89 A refrigerator using tetrafluoroethane (R-134a) as refrigerant operates with a capacity of 250 Btu/s. Cooling water enters the condenser at 70°F. The evaporator is at 10°F, and the condenser is at 80°F. The refrigerated space is at 20°F. Determine the ideal and actual power necessary if the compressor efficiency is 75%. Assume that the kinetic and potential energy changes are negligible.

7.90 A refrigerator using tetrafluoroethane (R-134a) as refrigerant (tetrafluoroethane) operates with a capacity of 2,500 kW. Cooling water enters the condenser at 280 K. Evaporator is at 271.92 K, and the condenser is at 299.87 K. The refrigerated space is at 280 K. Determine the ideal and actual power necessary if the compressor efficiency is 80%. Assume that the kinetic and potential energy changes are negligible.

7.91 A refrigeration cycle has a COP = 3.0. For the cycle, q_H = 2,000 kJ. Determine q_C and W_{net}, each in kJ.

7.92 A refrigeration cycle has a COP = 2.5. For the cycle, q_H = 1,500 kJ. Determine q_C and W_{net}, each in kJ.

7.93 In a pentafluoroethane (R-125) refrigeration cycle, the saturated R-125 (state 1) enters a compressor at 250 K and 3 bar. The R-125 (state 2) leaves the compressor at 320 K and 23.63 bar, and enters a condenser, where it is cooled by cooling water. The R-125 (state 3) leaves the condenser as saturated liquid at 310 K and 18.62 bar and enters a throttling valve. The partially vaporized R-125 (state 4) leaves the valve at 255 K and 3.668 bar. The cycle is completed by passing the R-125 through an evaporator to absorb heat from the matter to be refrigerated. The R-125 leaves the evaporator as saturated vapor. The evaporator temperature is 275.15 K. The flow rate of R-125 is 0.75 kg/s. The total power input is 60 kW. The cooling water enters the condenser at 293.15 K and leaves at 295.15 K. The surroundings are at 298.15 K. Determine the coefficient of performance.

7.94 A refrigerator using tetrafluoroethane (R-134a) as refrigerant operates with a capacity of 10,000 Btu/h. The refrigerated space is at 15°F. The evaporator and condenser operate with a 10°F temperature difference in their heat transfer. Cooling water enters the condenser at 70°F. Therefore, the evaporator is at 5°F, and the condenser is at 80°F. Determine the coefficient of performance if the compressor efficiency is 85%.

7.95 In a refrigeration cycle, the superheated R-134a (state 2) enters a compressor at 200°F and 90.0 psia. The R-134a (state 3) leaves the compressor at 360°F and 140 psia, and enters a condenser, where it is cooled by cooling water. The R-134a (state 4) leaves the condenser at 90.5°F and 120 psia as saturated liquid, and enters a throttling valve. The partially vaporized R-134a (state 1) leaves the valve at 100 psia. The cycle of R-134a is completed when it passes through an evaporator to absorb heat from the matter to be refrigerated. The flow rate of R-134a is 0.2 lb/s. The total power input is 85 Btu/s. The cooling water enters the condenser at 80°F and leaves at 115°F. The surroundings are at 210°F. Determine the coefficient of performance.

7.96 In a tetrafluoroethane (R-134a) refrigeration cycle, the superheated R-134a (state 1) enters a compressor at 253.15 K and 0.14 MPa. The R-134a (state 2) leaves the compressor at 303.15 K and 0.5 MPa, and enters a condenser, where it is cooled by cooling water. The R-134a (state 3) leaves the condenser at 299.87 K and 0.75 MPa and enters a throttling valve. The partially vaporized R-134a (state 4) leaves the valve at 0.205 MPa. The cycle is completed by passing the R-134 through an evaporator to absorb heat from the matter to be refrigerated. The R-134a (state 1) leaves the evaporator as superheated vapor. The flow rate of R-134a is 0.16 kg/s. The total power input is 750 kW. Estimate the coefficient of performance.

7.97 A refrigerator using tetrafluoroethane (R-134a) as refrigerant operates with a capacity of 250 Btu/s. Cooling water enters the condenser at 70°F. The evaporator is at 10°F, and the condenser is at 80°F. The refrigerated space is at 20°F. Determine the coefficient of performance if the compressor efficiency is 75%. Assume that the kinetic and potential energy changes are negligible.

7.98 A refrigerator using tetrafluoroethane (R-134a) as refrigerant (tetrafluoroethane) operates with a capacity of 2,500 kW. Cooling water enters the condenser at 280 K. Evaporator is at 271.92 K, and the condenser is at 299.87 K. The refrigerated space is at 280 K. Determine the ideal and actual power necessary if the compressor efficiency is 80%. Assume that the kinetic and potential energy changes are negligible.

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Chapter 8
Energy Storage

8.1 Energy Storage and Regulation

Devices or physical media can store some form of energy to perform a useful operation at a later time. A battery stores readily convertible chemical energy to operate a mobile phone, a hydroelectric dam stores energy in a reservoir as gravitational potential energy, and ice storage tanks store thermal energy to meet peak demand for cooling. Battery and fossil fuels such as coal and gasoline store chemical energy. Synthesis of some energy rich biomolecules such as adenosine triphosphate (ATP) stores and transforms chemical energy in living systems. Sunlight is also captured by plants as *chemical potential energy*, when carbon dioxide and water are converted into carbohydrates.

Two important physical media for storage and regulation of thermal energy are water and hydrogen. Table 8.1 lists some thermo physical properties of water and hydrogen, including the heats of formation of water in liquid and vapor states. Their material and thermo physical properties make them unique in not only storing and transforming energy but also regulation of the temperature of the earth. Hydrogen represents a store of potential energy which can be released by nuclear fusion in the sun in the form of light. Solar energy may be stored as chemical energy by photosynthesis after it strikes the earth. Also, when water evaporates from oceans and is deposited high above sea level, it drives turbine/generators to produce electricity, hence sunlight may again be stored as gravitational potential energy.

8.1.1 Water

Approximately 80% of the earth's surface is water. Water has a high specific heat capacity of 4.185 kJ/kg °C, which is much higher than that of soil and rock (see Table 8.1). Water can retain and store a large amount of heat per volume

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Table 8.1 Physical properties of water and hydrogen

Compound	*MW*	ρ kg/m^3	$C_{p,av}$ kJ/kg K	T_m °C	T_b °C	ΔH_v kJ/kg	ΔH_m kJ/kg
Water (H_2O)	18.02	1,000	4.18	0.0	100.0	2,257	333.7
Hydrogen (H_2)	2.02	70.7	10.0	−259.2	−252.8	445.7	59.5

Cengel and Turner [2]; Rigden [18]
MW: molecular weight, T_m: temperature of melting, $C_{p,av}$: average heat capacity, ρ: density, ΔH_m: Heat of fussion, ΔH_{vap}: Heat of vaporization

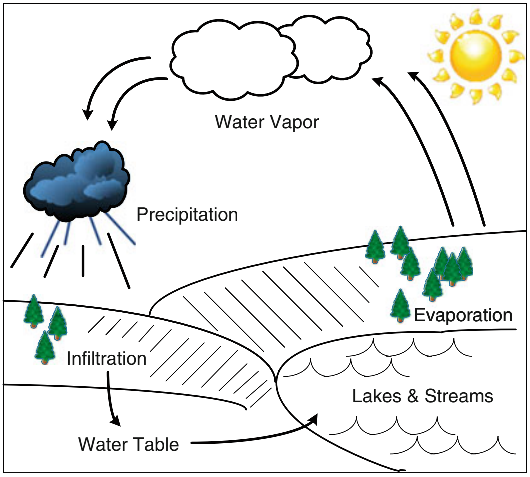


Fig. 8.1 Water circulation on the earth

making the oceans the world's massive temperature regulator. Therefore, the temperature of water changes more slowly than that of the earth's surface. In addition, water has large heat of vaporization of around 2,257 kJ/kg at 20°C. This means that a large amount of latent heat can be transferred over long distances in vapor form and released after condensing as rain (see Fig. 8.1). Accumulation of rain at high elevation reservoirs stores of large amounts of potential energy, which drives turbines to produce electricity. The oceans control the earths' energy balance as they absorb nearly four times more insolation than the earth.

Liquid water also helps to control the amount of carbon dioxide in the atmosphere by dissolving it into the form of "carbonic acid" (soda water). Some of the dissolved carbon dioxide combines with minerals in the water and settles to the ocean floor to form limestone. Water is also essential for all life-forms as most animals and plants contain more than 60% of water by volume, which helps organisms to regulate their body temperature. Therefore, water regulates the temperature of the earth as well as the temperature of living systems.

8.1.2 Hydrogen

Hydrogen is a versatile storage medium due to its conversion to useful work in a fuel cell to produce electricity as well as its usage in an internal combustion engine. Hydrogen is also being developed as an electrical power storage medium. It must first be manufactured by other energy sources and may become a significant energy storage medium in using renewable energies. Hydrogen can be manufactured by steam reforming of natural gas. When manufactured by this method it is a derivative fuel like gasoline. When produced by electrolysis of water, it is a form of chemical energy storage. About 50 kWh (180 MJ) of solar energy is required to produce 1 kg of hydrogen. At an electricity cost of \$0.09/kWh, hydrogen costs around \$4.50/kg. Large quantities of gaseous hydrogen can be stored in underground caverns and in depleted oil or gas fields for many years, and can function as multipurpose energy storage.

8.2 Types of Energy Storage

The method of energy storage may be chosen on the basis of stability, ease of transport, energy capture, and release. The main energy storage technologies involve the storage of energy in thermal, electrical, chemical, and mechanical forms:

- *Thermal.* Thermal energy can be stored by sensible and latent heats at temperatures above or below the ambient temperatures. Heat is also stored for short- or long-term applications. Thermal energy from the sun, for example, can be captured by solar collectors and stored in a reservoir for daily or seasonal use. Thermal energy for cooling can be stored in ice.
- *Electrical.* Dams can be used to store hydroelectricity by accumulating large amounts of water at high altitudes. The water then turns a turbine and generates electricity. Also by using pumped-storage hydroelectricity stores energy by pumping water back into the reservoir. A capacitor can store electric charge as a part of electrical energy production system. Batteries can also store electric energy to be used in portable electrical devices.
- *Chemical.* Stable chemical compounds such as fossil fuels store chemical energy. Biological systems can store energy in chemical bonds of energy-rich molecules, such as glucose and ATP. Other forms of chemical energy storage include hydrogen, synthetic hydrocarbon fuel, and batteries.
- *Mechanical.* Energy can be stored in pressurized gases such as in compressed air, and used to operate vehicles and power tools. Hydraulic accumulator, flywheel, and springs can also store mechanical energy.

The following sections discuss these energy storage technologies.

8.3 Thermal Energy Storage

Thermal energy storage technologies balance the energy demand and energy production. For example, the solar energy would be available during the night time or in the winter season if it is stored previously. Also a stored and transformed energy can be used somewhere else different from the location where it is captured or produced. The thermal storage medium may be maintained at a temperature above (hotter) or below (colder) that of the ambient temperature of 25°C. In hot climates, the primary applications of thermal energy storage are cold storage because of large electricity demand for air conditioning. Thermal energy storage may be planned for short term or seasonal. Some advantages of utilizing thermal energy storage are [7]:

- Reduced energy consumptions and carbon footprint.
- Reduced initial equipment and maintenance costs.
- Reduced pollutant emissions such as $CO_{2.}$
- Increased flexibility of operation, efficiency, and effectiveness of equipment utilization.
- Process application in portable and rechargeable way at the required temperature.
- Isothermal and higher storage capacity per unit weight.
- Energy from any source (thermal or electrical) when needed.

Thermal energy is generally stored in the form of sensible heat and latent heat. Figure 8.2 compares the characteristics of heat storage by sensible and latent heats. Temperature keeps increasing as a material absorbs and store sensible heat until it reaches a temperature where a phase changing occurs. Under their melting points, the solid—liquid phase changing materials store sensible heat and their temperature rises as they absorb the heat (see Fig. 8.2a). When phase changing materials reach their melting temperature they absorb large amounts of latent heat at an almost constant temperature until melting is completed. If the outside heat supply continues, then the melted material starts to store sensible heat. A material may freeze at a temperature lower than its actual freezing temperature. This is called *subcooling*. Also, a material may melt at a temperature higher than its actual melting temperature. This is called *superheating*. Subcooling and superheating of a phase changing material create an interval for temperature control (see Fig. 8.2b). This temperature interval between the subcooling and superheating may be reduced by adding nucleating agents to phase changing material.

Stored heat is usually transferred to a *heat transfer fluid* such as water or air in a heat exchanger system as seen in Fig. 8.3. When air is used as heat transfer fluid, the cold inside room air extracts the heat as it flows through a heat storage system and the warm air out of the storage is fed directly into the room [4, 5].

Night time low-cost electricity may be used to store energy as sensible heat or/and latent heat. The stored energy is then used for the cooling/heating needs during the peak demand hours. Thermal energy storage systems can be designed using

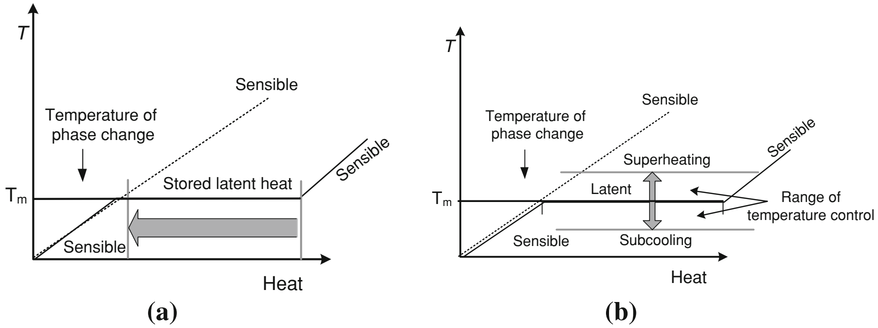


Fig. 8.2 **a** Comparison of sensible heat with latent heat storage, **b** temperature control during phase change energy storage; subcooling and super heating of a phase changing material creates a range for temperature control; this range may be reduced by adding nucleating agents to phase changing material

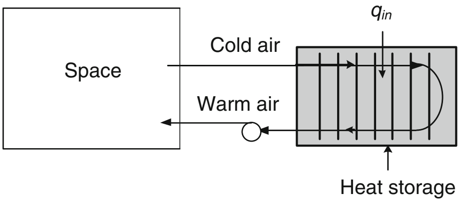


Fig. 8.3 Direct space heating using air as the heat transfer fluid. Cold inside room air flows through a heat storage system and the warm air is fed directly into the room for heating

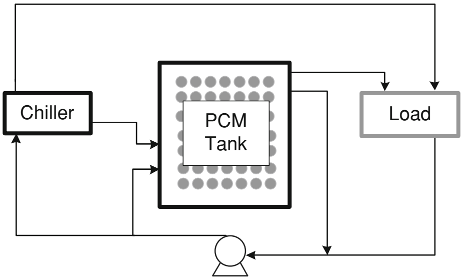


Fig. 8.4 Configuration of a thermal energy storage system with phase change material (PCM)

chilled water, ice, and encapsulated phase change material. Phase change material modules installed in a chilled water tank have proven to increase the energy density and improve the performance of water- and ice-based thermal energy storage systems. Figure 8.4 shows a typical arrangement of cooling using phase change material. A phase change material in the supplementary tank is charged by the chiller during off-peak hours. During peak demand hours the cooling is achieved by the stored energy in the phase change material energy storage tank as the heat exchange fluid passes through phase change material tank. This stabilizes the load during peak demand hours and shifts the load to the off-peak period.

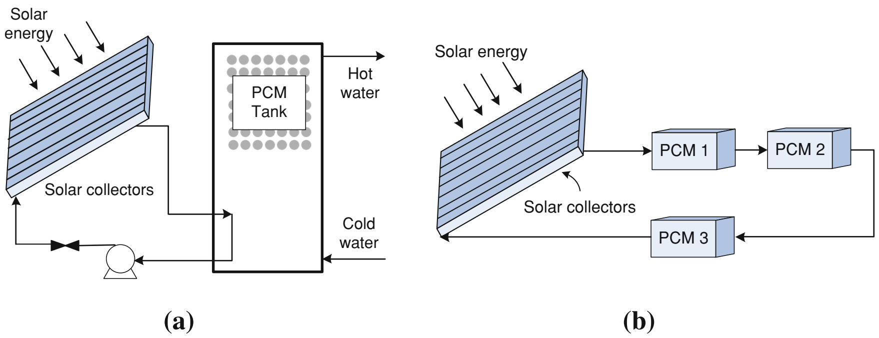


Fig. 8.5 Configuration of solar energy storage in the forms of sensible and latent heats: **a** solar water heater with heat storage with phase changing material (PCM), **b** Hot and cold energy storage of solar energy using various phase changing materials working at high and low temperatures; PCM 1–PCM 3 refer to phase changing materials with different heat storage characteristics (see Tables 8.3 and 8.4)

8.3.1 Solar Energy Storage

Due to time-dependence of sun exposure, the efficiency of solar thermal systems relies on the well-integrated thermal energy storage technology. For example, in utilizing solar water collectors with thermal energy storage, higher efficiency is achieved by bridging the gap between solar heat availability and hot water demand. Solar thermal energy is usually captured by active solar collectors and transferred to insulated storage systems for various applications, such as space heating, domestic or process water heating, as seen in Fig. 8.5. Most practical active solar heating systems have storage for a few hours to a day's worth of energy collected. There are also a growing number of seasonal thermal storage systems being used to store summer energy for space heating during winter. Water-based technology for thermal energy storage is practical because of the large heat of fusion of water (see Table 8.1). The original definition of a "ton" of cooling capacity was the heat to melt one ton of ice every 24 h. This definition has since been replaced by one ton Heating Ventilation and Air Conditioning (HVAC) capacity of 12,000 Btu/h.

Many of the early applications utilized solar water collectors with water storage because of the advantages of increased efficiency and reduced size. For home heating, water has to go through a heat exchanger to release its heat to a room. However, solar heating systems that use air as the transfer medium are being recommended for home usage because of direct heating, less potential for damage from a leak, or frozen water. In *direct heating*, the warm air coming from the solar air collector can be fed to a room for heating. Also air collectors and ducting are usually cheaper and require less maintenance [4, 5].

Table 8.2 Some materials used for heat storage in the form of sensible heating, volumetric heat capacity or energy density is defined by ρC_p = J/m^3·K

Material	Temp. Range T °C	Density ρ kg/m^3	Heat capacity $C_{p,av}$ J/kg°C	Energy density $\rho C_{p,av}$ kJ/m^3 °C
[a]50% Ethylene Glycol 50% water	0–100	1,075	3,480	3,741
Dowtherm A	12–260	867	2,200	1,907
Therminol 66	−9–343	750	2,100	1,575
Water	0–100	1,000	4,190	4,190
Grainte	–	2,400	790	1,896
Draw salt: 50% $NaNO_3$–50%KNO_3	220–540	1,733	1,550	2,686
[a]Molten salt: 50% KNO_3−40% $NaNO_2$−7% $NaNO_3$	142–540	1,680	1,560	2,620

[a] Weight percentages

8.3.2 Sensible Heat Storage

Sensible heat is stored by raising its temperature of a material and is estimated by

$$q = mC_{p,av}\Delta T = \rho V C_{p,av}\Delta T \tag{8.1}$$

where q is the sensible heat stored (J, Btu), V is the volume (m^3, ft^3), ρ is the density (kg/m^3, lb/ft^3), m is the mass (kg, lb), $C_{p,av}$ is the average specific heat capacity of material (kJ/kg°C, Btu/lb°F), and ΔT is the temperature change (°C, °F). Energy density or volumetric heat capacity is defined by the product of density and heat capacity: $\rho C_{p,av}$. Table 8.2 shows some materials used for heat storage in the form of sensible heating. Stored heat is usually transferred by a heat transfer fluid such as water or air to the location where it is to be used as seen in Fig. 8.5. Example 8.1 illustrates the sensible heat storage calculations.

Example 8.1 Sensible heat storage calculations

(a) Estimate sensible heat stored in 2 m^3 water and 2 m^3 granite heated from 20 to 40°C.

(b) Estimate the heat stored in 1,000 lb of water heated from 20 to 30°F. Assume that average heat capacity is: $C_{p,av}$ = 1.0 Btu/lb°F.

Solution:
Assume that the values of heat capacity remain constant.

(a) Sensible heat storage by water and granite:
Use Eq. (8.1) with the data for heat capacity $C_{p,av}$ and density ρ from Table 8.2:
Water: $q = \rho V C_{p,av}\Delta T = (1000\,\mathrm{kg/m^3})(2\,\mathrm{m^3})(4190\,\mathrm{J/kg°C})(40-20)°\mathrm{C} = 167,600\,\mathrm{kJ}$

$$= 167,600\,\mathrm{kJ}/(3600\,\mathrm{s/h}) = \mathbf{46.55\,kWh}$$

Granite: $q = \rho V C_{p,av} \Delta T = (2400\,\mathrm{kg/m^3})(2\,\mathrm{m^3})(790\,\mathrm{J/kg^\circ C})(40-20)^\circ\mathrm{C} = 75840\,\mathrm{kJ}$ = (75840 kJ)/(3600 s/h) = **21.06 kWh**

(b) Heat stored in 1,000 lb of water heated when the average specific heat of water is 1.0 Btu/lb°F:

$$q = mC_{p,av}\Delta T = (1000\,\mathrm{lb})(1.0\,\mathrm{Btu/lb^\circ F})(30-20)^\circ\mathrm{F} = 10000\,\mathrm{Btu} = 10550\,\mathrm{kJ}$$

= 10550 kJ/(3600 s/h) = **2.93 kWh**

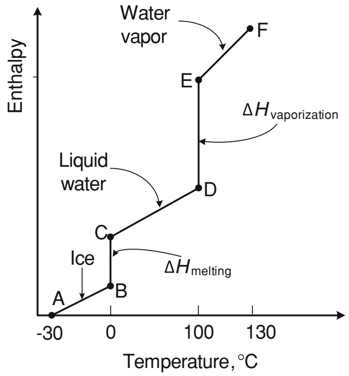
8.3.3 Latent Heat Storage by Phase Changing Material

Latent heat storage can be achieved through solid–solid, solid–liquid, solid–gas, and liquid–gas phase changes. Liquid–gas transitions have a higher heat of transformation than solid–liquid transitions. However, liquid–gas phase changes are not practical because of the large volumes or high pressures required to store the materials when they are in their gas phase states. Solid–solid phase changes are typically very slow and have a rather low heat of transformation. Therefore, the main phase change used for heat storage is the solid–liquid change. Figure 8.6 shows the change of enthalpy of water from solid to vapor state on enthalpy-temperature diagram. Between −30 and 0°C the sensible heat of water increases. At 0°C the water starts to melt by absorbing heat of melting. After the melting is completed, the liquid water is heated until 100°C [11, 20, 24].

Phase changing materials used for storing heat are chemical substances that undergo a solid–liquid transition at temperatures within the desired range for heating and cooling purposes. During the transition process, the material absorbs energy as it goes from a solid to a liquid state and releases energy as it goes back to a solid from liquid state. A phase changing material should possess:

- Melting temperature in the desired operating temperature range.
- High latent heat of fusion per unit volume.
- High specific heat, density, and thermal conductivity.
- Small changes of volume and vapor pressure on phase change at operating temperatures.
- Congruent melting (solid compositions is the same as the composition of the liquid melt).
- Chemical stability and complete reversible freeze/melt cycles.
- Noncorrosive, nontoxic, nonflammable, and nonexplosive.
- Low cost and availability.

Latent heat storage technology reduces temperature fluctuations and offers a higher heat storage capacity per volume/mass. The temperature and the amount of energy stored can be adjusted by selecting a specific phase changing material. Total heat stored by a solid-to-liquid phase changing material between initial and final temperatures would be estimated by



Enthalpy of water between – 30°C and 130°C:

- Process A-B: Increase in sensible heat of ice between – 30°C and 0°C
- Process B-C: Phase change from solid to liquid: melting of ice at 0°C; heat of melting ($\Delta H_{\text{melting}}$) is required.
- Process C-D: Increase in sensible heat of liquid water between 0°C –100°C.
- Process D-E: Phase change from liquid to vapor at 100°C; heat of vaporization ($\Delta H_{\text{vaporization}}$) is required.
- Process E-F: Increase in sensible heat of water vapor between 100°C and 130°C.

Fig. 8.6 Change of enthalpy values of water from solid state (ice) to vapor state between −30°C and 130°C. Between −30°C and 0°C the sensible heat of water increases. At 0°C the water starts to melt by absorbing heat of melting. After the melting process is completed, the liquid water is heated until 100°C at which the transformation from liquid to vapor starts. After absorbing the heat of vaporization all the liquid water becomes vapor. Between 100°C and 130°C, the water in vapor state increases its sensible heat

$$\begin{aligned} q_{\text{stored}} &= \text{Solid sensible heat} + \text{Latent heat} + \text{Liquid sensible heat} \\ q_{\text{stored}} &= mC_{ps,av}(T_m - T_i) + m\Delta H_m + mC_{pl,av}(T_f - T_m)\left(T_f > T_{\text{m}} > T_i\right) \end{aligned} \tag{8.2}$$

where m is the mass of phase changing material, $C_{ps,av}$ and $C_{pl,av}$ are the average heat capacities for solid and liquid phases, respectively, T_m is the temperature of melting, T_i and T_f are the initial and final temperatures, respectively, and ΔH_m is the heat of melting. Stored heat is transferred by a heat transfer fluid such as water or air in a heat exchanger. Consider a phase changing material, which is melted; when the heat transfer fluid temperature T_f is lower than the melting temperature ($T_f < T_m$), the phase changing material solidifies and releases its heat of melting to the heat transfer fluid. Consider a phase changing material at solid state; when the temperature of heat transfer fluid is higher than the melting temperature ($T_f > T_m$), phase changing material starts melting and stores heat.

Various phase changing materials are available in any required temperature range from −5°C up to 190°C storing 5–14 times more heat per unit volume than conventional storage materials such as water [16]. Tables 8.3 and 8.4 present short lists of some common materials for heat storage. The most commonly used phase change materials are salt hydrates, fatty acids, esters, and various paraffins (such as octadecane). The chemical composition of salts is varied in the mixture to achieve the required phase change temperature and stability in phase transformations. Special nucleating agents may be added to the mixture to minimize phase change salt separation and eliminating super cooling. Salt hydrates have high volumetric latent heat storage capacity, sharp melting point, high heat of fusion, and thermal conductivity. Salt hydrates are nontoxic, nonflammable, and economical. They

Table 8.3 Comparison of typical storage densities of various materials for energy storage in the forms of sensible and latent heats

Method/Material	kJ/l	kJ/kg	Temperature (°C)
Sensible heat			
Granite	50	17	$\Delta T = 20$
Water	84	84	$\Delta T = 20$
Latent heat of melting			
Water	330	330	0
Lauric acid		178	42–44
Capric acid		153	32
Butyl stearate		140	19
Paraffin	180	200	5–130
Paraffin C18	196	244	28
Salthydrate	300	200	5–130
Salt	600–1,500	300–700	300–800
Latent heat of evaporation			
Water	2,452	2,450	1 atm and 25°C

Mehling and Cabeza [16]

Table 8.4 Properties of some phase change materials (PCMs)

PCM	T_m (°C)	ΔH_m (kJ/kg)	$C_{pl,av}$ (kJ/kg K)	$C_{ps,av}$ (kJ/kg K)	k_l (W/m K)	k_s (W/m K)	ρ_l (kg/m^3)	ρ_s (kg/m^3)
Water	0	333	4.19	2.0	0.595	2.2	1,000	920
n-Hexadecane	18	235	2.1	1.95	0.156	0.43	765	835
Octadecane $CH_3(CH_2)_{16}CH_3$	28	243	2.2	1.8	0.15	0.42	775	~900
n-Eicosane	36.4	248	2.4	1.92	0.146	0.426	769	910
n-Docosane $CH_3(CH_2)_{20}CH_3$	44.5	196–252	~2.5	~1.9	0.15	0.4	778	920
Paraffins	10–70	125–240	1.7	1.7	0.15	0.25	~700	~900

Mehling and Cabeza [16]

T_m Temperature of melting; H_m Heat of fussion; $C_{pl,av}$ Average heat capacity at liquid state
$C_{ps,av}$ Average heat capacity at solid state; ρ_l Density at liquid state; ρ_s Density at solid state

however can be corrosive and have a finite life of around 10,000 cycles. All salt-based phase changing material solutions must be encapsulated to prevent water evaporation or uptake. The packaging material should conduct heat well. It should be durable enough to withstand frequent changes in the storage material's volume as phase changes occur. Packaging must also resist leakage and corrosion. Materials of encapsulation include stainless steel, polypropylene, and polyolefin [21, 25].

Organic phase changing materials, such as paraffin (C_nH_{2n+2}) and fatty acids ($CH_3(CH_2)_{2n}COOH$) freeze without much subcooling with self-nucleating properties [19]. They are chemically stable with relatively high heat of fusion, safe, nonreactive, and recyclable. On the other hand, they have low volumetric latent heat storage capacity and low thermal conductivity in their solid state, thus requiring high heat transfer rates during the freezing cycle. They can be expensive and flammable at high temperatures. Sometimes mixtures of phase change materials may be more beneficial. *Thermal-composite* is a term given to combinations of phase change materials and other (usually solid) structures. A simple example is a copper mesh immersed in paraffin. Table 8.4 shows a short list of some phase change materials and their thermo-physical properties. Example 8.2 illustrates the heat storage estimations for home heating.

Example 8.2 Heat storage calculations

A typical two-story home with a roof surface area of 1,260 ft^2 and a wall surface area of 2,400 ft^2 is to be heated with solar energy storage using a salt hydrate as phase change material. It presently has as an insulation of 6 inches in the roof and 1 inch in the walls. Inside temperature will be held at 70°F and expected outside low temperature is 10°F. Average solar radiation is 650 Btu/ft^2 and the cost of solar air collector is \$1.1/ft^2. The salt hydrate costs around \$0.15/lb. Estimate the costs of salt hydrate and solar air collectors.

Solution:

Assume that the approximate thermal conductivity of the walls and roof is: $k = 025$ Btu/h °F ft^2.

Average solar radiation is 650 Btu/ft^2 and the cost of solar air collector is \$1.1/ft^2. The salt hydrate costs around \$0.15/lb and its heat of melting is 145 Btu/lb.

Heating requirement of building with present insulation:

Heat loss from roof (Δx = 6/12 = 0.5 ft); ΔT = (10−70)°F = −60°F

$$q_{\text{loss, roof}} = -kA\frac{\Delta T}{\Delta x} = -\left(0.025\,\text{Btu/h°F ft}^2\right)\left(1260\,\text{ft}^2\right)\left(-60°\text{F}/0.5\,\text{ft}\right) = 3780\,\text{Btu/h}$$

Heat loss from walls (Δx =1 in = 0.083 ft)

$$q_{\text{loss,wall}} = -kA\frac{\Delta T}{\Delta x} = -\left(0.025\text{Btu/h°Fft}^2\right)\left(2400\text{ft}^2\right)\left(-60°\text{F}/0.083\text{ft}\right) = 43373\text{Btu/h}$$

Total heat loss = Total heating requirement

q_{loss} = 3780 Btu/h + 43373 Btu/h = 47153 Btu/h

Total heat storage material needed:

m_s = (47153 Btu/h) (24 h)/145 Btu/lb = 7804.0 lb

Cost of salt hydrate = (7804.0 lb) (\$0.15/lb) = **\$1170.6**

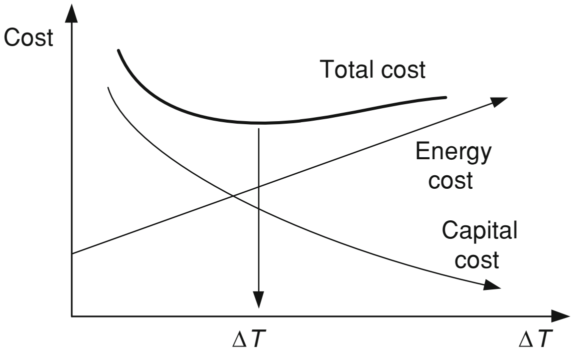
Size and cost of collector to meet present heating requirements:

Area of collectors = (47153 Btu/h) (24 h)/(650 Btu/ft^2) = 1740 ft^2

Cost of collectors: (1740 ft^2)(\$1.1/ft^2) = **\$1914.0**

Total cost of solar energy capture and its storage:
Cost total = \$1170.6 + \$1914.0 = **\$3084.6**

Annual cost of heating may be optimized by compromising between the two opposing effects of capital costs of thermal energy storage system and fuel as shown below.



As the temperature difference between hot and cold space increases, the capital cost may decrease while the energy (fuel) cost increases. The total cost should be optimized for a required value for ΔT.

8.3.4 Ice Storage

Ice storage is the thermal energy storage using ice. It is practical because of the large heat of fusion of water. One metric ton of water (one cubic meter) can store 334 MJ or 317,000 Btu, 93 Wh, or 26.4 ton-hours. The original definition of a "ton" of cooling capacity was the heat to melt one ton of ice every 24 h. One ton HVAC capacity is known as 12,000 Btu/h. A small storage unit can hold enough ice to cool a large building for a day or a week, by using, for example, off-peak power and other such intermittent energy sources.

8.3.5 Molten Salt Technology

Molten salt can be employed as a heat store to retain heat collected by a solar tower so that it can be used to generate electricity. The molten salt is a mixture of 60% sodium nitrate and 40% potassium nitrate, by mass, called *saltpeter*. It is nonflammable, nontoxic, and is used in the chemical and metals industries as a heat transfer fluid. The salt is kept as liquid at 288°C (550°F) in an insulated storage tank and is pumped through panels in a solar collector where the focused sun heats it to 566°C (1,051°F). It is then sent to a well-insulated storage tank.

When electricity is needed, the hot salt is pumped to a conventional steam generator to produce superheated steam for the turbine/generator of a power plant.

8.3.6 Seasonal Thermal Energy Storage

A *seasonal thermal storage* retains heat deposited during the hot summer months for use during colder winter weather for heating. For cooling, the winter is used to store cold heat to be used in the summer. The heat is typically captured using solar collectors, although other energy sources are sometimes used separately or in parallel. Seasonal (or "annualized") thermal storage can be divided into three broad categories:

- Low-temperature systems use the soil adjoining the building as a heat store medium. At depths of about 20 ft (6 m) temperature is naturally "annualized" at a stable year-round temperature. Two basic techniques can be employed:
  - In the *passive seasonal heat storage*, solar heat is directly captured by the structure's spaces through windows and other surfaces in summer and then passively transferred by conduction through its floors, walls, and sometimes roof into adjoining thermally buffered soil. It is then passively returned by conduction and radiation as those spaces cool in winter.
  - The *active seasonal heat storage* concept involves the capture of heat by solar collectors or geothermal sources and deposited in the earth or other storage masses or mediums. A heat transfer fluid in a coil embedded in the storage medium is used to deposit and recover heat.
- Warm-temperature systems also use soil or other heat storage mediums to store heat, but employ active mechanisms of solar energy collection in summer to store heat and extract in winter. Water circulating in solar collectors transfer heat to the storage units beneath the insulated foundation of buildings. A ground source heat pump may be used in winter to extract the heat from the storage system. As the heat pump starts with a relatively warm temperature the coefficient of performance may be high.
- High-temperature systems are essentially an extension of the building's HVAC and water heating systems. Water or a phase change material is normally the storage medium.

Advantages of seasonal storage systems:

- Seasonal storage is a renewable energy utilization system.
- Stored thermal energy would be available in the desired amount, time, and location.
- Nontoxic, noncorrosive, and inexpensive storage mediums can be selected for a required application.
- Seasonal heat storage needs relatively moderate initial and maintenance costs.

- Size and capacity of heat storage system can be adjusted based on the size of the space to be conditioned.
- It can be used as preheater and precooler of existing heating and cooling systems.
- It is possible to use water as heat transfer fluid during charging the storage with water solar heaters, and airflow for discharging mode.

8.3.7 Seasonal Solar Thermal Energy Storage for Greenhouse Heating

The three common processes in a seasonal thermal energy storage for greenhouse heating are:

- Charging: the charging is for capturing solar energy by solar air heaters and feeding the warm air to the storage unit through the coils embedded in the heat storage tank.
- Storing: the storage process is for storing the captured solar energy by sensible and latent heat using a phase change material in a well-insulated heat storage tank.
- Discharging: the discharge process, on the other hand, is for recovering the stored heat by the cold air flowing through the heat storage tank and delivering the warm air to the greenhouse directly when necessary.

Figure 8.7 shows the schematics of the seasonal solar energy storage systems by paraffin for greenhouse heating with a data acquisition and control system to activate the required process, such as discharging process [3].

Figure 8.8 shows the charging and discharging operations within the three units of

- Unit 1: solar air heaters
- Unit 2: heat storage
- Unit 3: greenhouse.

Ambient air is heated to around 60–75°C by the solar radiation using solar air collectors. The warm air from the solar collectors flows in spiral coils embedded inside the storage tank and heats the paraffin. When the temperature of the greenhouse drops below a set point of around 14°C, the discharge process is activated so that cold air from the greenhouse flows through the hot and melted paraffin, recovers a part of the latent heat, and delivers it to the greenhouse until raising the temperature to a required level. The data acquisition system controls the activation and deactivation of the discharge process. Energy losses occur in various levels in all the three units.

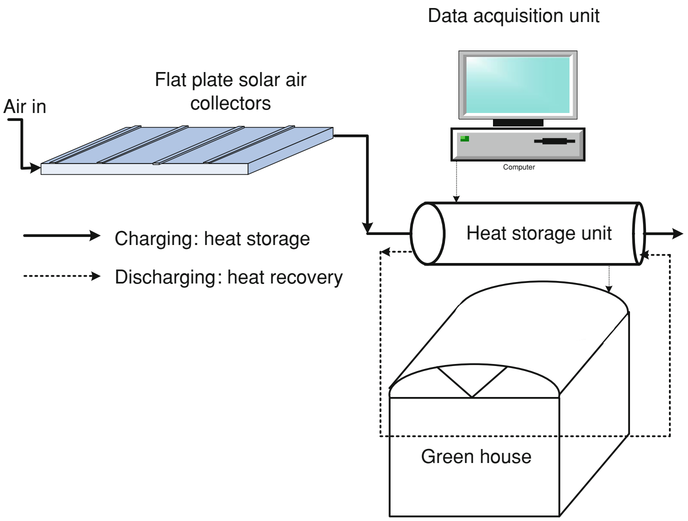


Fig. 8.7 Seasonal heat storage system using paraffin as a phase change material for heating a greenhouse [5]

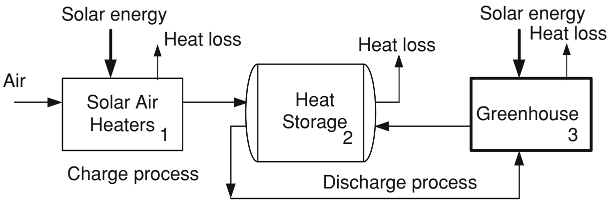


Fig. 8.8 Schematic structure with three components of the seasonal heat storage system: Unit 1 is for capturing solar energy to heat the air and send it to the heat storage, Unit 2 is for heat storage by sensible and latent heats of paraffin, and Unit 3 is the greenhouse. The discharge process takes place between the greenhouse and heat storage when the temperature in the greenhouse drops below a set value

Figure 8.9 shows typical temperature profiles of paraffin and airflow in charging and discharging modes. Here, the paraffin starts with the cold-solid temperature of T_{sc} and ends with the storage-hot temperature of T_{sh}, representing the cold and hot level of temperatures within the storage unit. An average temperature of T_s may be assumed for thermal energy storage calculations. The m_c is the airflow rate for charging and m_d is the airflow rate for discharging, while T_{ci} and T_{co} are the inlet and outlet temperatures for charging (loading) and T_{di} and T_{do} are inlet and outlet temperatures for discharging (recovery) process, respectively.

The latent heat storage system undergoes a temperature difference of (T_{sh}–T_{sc}). The solar heat captured through the series of solar collectors would be estimated by

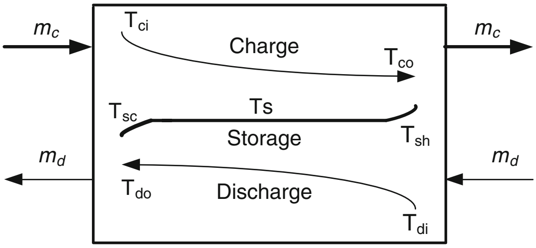


Fig. 8.9 Approximate temperature profiles of airflow and heat storage material; m_c is the airflow rate for charging and m_d is the airflow rate for discharging, T_{ci} and T_{co}: inlet and outlet temperatures for charging (loading); T_{di} and T_{do}: inlet and outlet temperatures for discharging (recovery); T_{sc} and T_{sh}: cold and hot temperatures of paraffin temperatures, respectively

$$\dot{q}_{\mathrm{c}} = \dot{m}_{\mathrm{c}} C_{p,av}(T_{\mathrm{ci}} - T_{\mathrm{co}}) \tag{8.3}$$

where $\dot{m}_{\mathrm{c}}$ is the charging fluid flow rate, T_{ci} and T_{co} are the inlet and outlet temperatures of the air, and $C_{p,av}$ is the average heat capacity of air. The heat captured will be delivered to the heat storage unit by the charging process. The heat stored by the paraffin q_{s} will be (i) sensible heat until the temperature of the solid paraffin reaches its lower temperature of melting, (ii) latent heat, and (iii) sensible heat until the temperature of the melted paraffin reaches the temperature T_{sh}. The amount of stored heat q_{s} is estimated by

$$q_{\mathrm{s}} = m_s\left[C_{ps,av}(T_{\mathrm{s}} - T_{\mathrm{sc}}) + \Delta H_{\mathrm{m}} + C_{pl,av}(T_{\mathrm{sh}} - T_{\mathrm{s}})\right] \tag{8.4}$$

where ΔH_m is the heat of melting, T_{sc} and T_{sh} are the lowest and highest melting points of the paraffin, and $C_{ps,av}$ and $C_{pl,av}$ denote the average heat capacities of solid and liquid states of the paraffin, respectively. T_{s} is an average temperature of the paraffin, which may be approximated as $T_{\mathrm{s}} = (T_{\mathrm{sc}} + T_{\mathrm{sh}})/2$.

The thermal efficiency is the ratio of amount of heat stored to the amount of heat captured at a certain time interval

$$\eta_s = \frac{\text{actual heat stored}}{\text{maximum energy gain}} = \frac{\dot{q}_s}{\dot{q}_{\mathrm{c}}} \tag{8.5}$$

The recovered heat through the discharge process is estimated by

$$\dot{q}_{\mathrm{d}} = \dot{m}_{\mathrm{d}} C_{p,av}(T_{\mathrm{di}} - T_{\mathrm{do}}) \tag{8.6}$$

where T_{di} is the temperature of air from the greenhouse, T_{do} is the temperature of the air leaving the heat storage system, and $C_{p,av}$ is the average heat capacity of air in the discharge process. The approximate thermal efficiency of the discharged process is estimated by

$$\eta_d = \frac{\dot{q}_d}{\dot{q}_s} \tag{8.7}$$

All the temperatures are time dependent, and the charging and discharging cycles need to be monitored over the time of operation. Example 8.3 illustrates the latent heat storage calculations.

Example 8.3 Latent heat storage calculations

A phase change material of 60 kg octadecane is heated from 20 to 30°C by a solar energy system, which supplies heat at a rate of 2 kW. Assume that the octadecane is fully melted. Estimate the minimum size of the storage unit and the time necessary for the charging process.

Solution:

Assume that there is no heat loss from the thermal energy storage system.

$T_{\mathrm{sc}} = 20°\mathrm{C}, T_{\mathrm{sh}} = 30°\mathrm{C}, T_{\mathrm{s}} = 28°\mathrm{C}, m_s = 60.0\,\mathrm{kg}, \dot{q}_{\mathrm{net}} = 2\,\mathrm{kW}, \dot{q}_{\mathrm{loss}} = 0\,\mathrm{kW}$

Use data from Table 8.4

PCM	T_m (°C)	ΔH_m (kJ/kg)	$C_{pl,av}$ (kJ/kg K)	$C_{ps,av}$ (kJ/kg K)	k_l (W/m K)	k_s (W/m K)	ρ_l (kg/m^3)	ρ_s (kg/m^3)
Octadecane $CH_3(CH_2)_{16}CH_3$	28	243	2.2	1.8	0.15	0.42	775	~900

Total heat stored:

$q_s = m_s[C_{ps,av}(T_{\mathrm{s}} - T_{\mathrm{sc}}) + \Delta H_{\mathrm{m}} + C_{pl,av}(T_{\mathrm{sh}} - T_{\mathrm{s}})]$

q_s = 60 kg[(1.8 kJ/kg K)(28–20)°C + 243 kJ/kg + (2.2 kJ/kg K)(30−28)°C] = 15,708 kJ

$V_{\mathrm{tank}} = m/\rho_s$ = 60 kg/(775 kg/m^3) = **0.08 m^3**

Energy balance: energy supplied = energy stored + energy lost

Energy lost = 0; $\dot{q}_{\mathrm{net}}$ = 2 kW

Energy supplied = ($\dot{q}_{\mathrm{net}}$)(Δt) = q_s = 15,708 kJ

Δt = **7854 s = 2.2 h**

Contributions of sensible heats:

q_s = 60 kg[(1.8 kJ/kg K)(28−20)°C + (2.2 kJ/kg K)(30−28)°C]/15,708 kJ

q_s = (864 + 264) kJ/15708 kJ = 0.055 + 0.017

Contributions of sensible heats are 5.5% for solid state and 1.7% for liquid state; therefore the main contribution toward heat storage comes from latent heat of octadecane. The charging process needs 2.2 h to supply the heat of 15,708 kJ required.

8.3.8 Underground Thermal Energy Storage Systems

Underground thermal energy storage (UTES) can store large amounts of low-temperature heat for space heating and cooling as well as for preheating and precooling. Common energy sources include winter ambient air, heat-pump reject water, solar energy, and process heat. UTES may supply all or part of heating and/or cooling requirements of buildings or processes. A heat pump may be used to decrease or increase the storage temperature for cooling or heating. Underground thermal energy may store energy, which is actively gathered, or store waste, or by-product energy, which is called the double effect storage and more likely to be more economical [1]. UTES encompasses both aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES) systems. These systems are discusses briefly in the following sections.

8.3.9 Aquifer Thermal Energy Storage

Aquifers are underground, geological formations and can have gravel, sand, or rocks. ATES may be used on a short-term or long-term basis for:

- The sole source of energy for partial storage.
- A temperature useful for direct application.
- Combination with a dehumidification system, such as desiccant cooling.

Cold storage water is usually supplied at 2–5°C, with a cooling power typically ranging from 200 kW to 20 MW, and with the stored cooling energy of 29 GWh. Cold storage underground is now a standard design option in several countries such as Sweden. The duration of storage depends on the local climate and the type of building and/or process.

ATES is used extensively for various applications such as heating of greenhouses. In summer, the greenhouse is cooled with groundwater, pumped from an aquifer, which is the cold source. This heats the water, which is then stored by the aquifer system. In winter, the warm water is pumped up to supply heat to the greenhouse. The now cooled water is returned to the cold source. The combination of cold and heat storage with heat pumps has an additional benefit for greenhouses, as it may be combined with humidification. In the closed circuit system, the hot water is stored in one aquifer, while the cold water is stored in another. The water is used to heat or cool the air, which is moved by fans. Such a system can be completely automated.

Chemical changes in groundwater due to temperature and pressure variations with ATES may cause operational and maintenance problems. These problems are avoidable and manageable. Flushing is a recommended practice to maintain the efficiency well. Potential environmental concerns over the use of earth energy heat pump and UTES are:

- The possible leakage of the heat exchanger fluid into the natural environment.
- Thermally induce biochemical effects on groundwater quality.
- Ecological distress due to chemical and thermal pollution.
- External contaminants entering the ground water.

All these and other possible problems are addressed within the guidelines and standards for planning, construction, and operation of UTES [17].

Ground source heat pump systems can significantly lower the heating and cooling operating costs and can qualify for renewable energy credits under sustainable building rating programs. One study [1] shows that 65% less energy

Table 8.5 Four types of applications of UTES and their typical performances

Application	Energy source %	[a]Payback period, year	[b]COP
Direct heating and cooling	90–95	0–2	20–40
Heating and cooling with heat pump	80–87	1–3	5–7
Heat pump supported heating only	60–75	4–8	3–4
Direct cooling only	90–97	0–2	20–60

Andersson [1]

[a] Payback period is the time in years to recover the cost of investment fully

[b] COP is the coefficient of performance

consumption is attainable with existing technologies at reasonable costs, and a heat pump supported UTES can play a useful role in achieving these reductions. Table 8.5 displays the performances of various types of UTES applications.

8.3.10 Borehole Thermal Energy Systems

Borehole Thermal Energy Systems (BTES) applications involve the use of boreholes, typically 5–200 m deep, and operate in closed loop, in which there is no contact between the natural groundwater and heat exchanger fluid. Typically a BTES includes one or more bareholes containing barehole heat exchangers, such as U-tubes, through which waste energy (hot or cold) is circulated and transferred to the ground for storage. BTES is typically applied for combined heating and cooling often supported with heat pumps for a better usage of the low-temperature heat from the storage. For example, there are more than 300,000 boreholes in Sweden, delivering around 27% of all space heating requirements [1, 7].

In a solar energy integrated application, solar heated water is pumped into a BTES system consisting of 144 boreholes, each 37 m (121 ft) deep and operates with the ground temperature of around 90°C (194°F). During winter, the hot water flows from the BTES system to the houses through a distribution network. Once inside the house, it flows through a heat exchanger with coil units, over which air is blown. The hot air then heats the house. Each house also has an independent solar thermal system installed on its sloped roof to provide domestic hot water. This system has a 90% solar fraction, meaning 90% of the energy required to heat the air and water within the community is provided by the sun. This results in an emission reduction of over five tons of CO_2 per house per year.

8.4 Electric Energy Storage

A *capacitor* is a device for storing electric charge and used as parts of electrical systems. Figure 8.10 shows a flat plate model for a capacitor. The forms of practical capacitors vary widely, but all contain at least two conductors separated

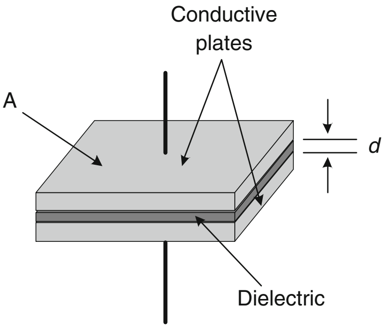


Fig. 8.10 Parallel plate model for a capacitor. The capacitance increases with area and decreases with separation; A is the surface area of the capacitor, and d is the thickness of dielectric

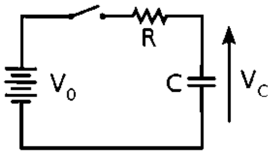


Fig. 8.11 A simple resistor–capacitor circuit demonstrates charging of a capacitor

by a nonconductor. For example, a capacitor consists of metal foils separated by a layer of insulating film. When there is a potential difference (voltage) across the conductors, a static electric field develops across the dielectric, causing positive charge to collect on one plate and negative charge on the other plate. Energy is stored in the electrostatic field. An ideal capacitor is characterized by a single constant value called the capacitance, measured in Farads. Capacitance is the ratio of the electric charge on each conductor to the potential difference between them. Capacitors may be used to produce high intensity releases of energy, such as a camera's flash.

The dielectric is just a die electrical insulator. Examples of dielectric mediums are glass, air, paper, vacuum, and even a semiconductor depletion region chemically identical to the conductors. A capacitor is assumed to be self-contained and isolated, with no net electric charge and no influence from any external electric field. The conductors thus hold equal and opposite charges on their facing surfaces, and the dielectric develops an electric field. In SI units, a capacitance of one farad means that one coulomb of charge on each conductor causes a voltage of one volt across the device. In practice the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit, resulting in a breakdown voltage.

The capacitor is a reasonably general model for electric fields within electric circuits as shown in Fig. 8.11. An ideal capacitor is fully characterized by a constant capacitance C, defined as the ratio of charge $\pm Q$ on each conductor to the voltage V between them:

$$C = \frac{Q}{V} \tag{8.8}$$

Work must be done by an external influence to transport charge between the conductors. When the external influence is removed the charge separation persists in the electric field and energy is stored. The energy is released when the charge is allowed to return to its equilibrium position. The work done in establishing the electric field, and hence the amount of energy stored, is given by:

$$W = \int_0^Q V dQ = \int_0^Q \frac{Q}{C} dQ = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2} VQ \tag{8.9}$$

As the capacitor reaches equilibrium with the source voltage, the voltage across the resistor and the current through the entire circuit decay exponentially. *Discharging* of a charged capacitor demonstrates exponential decay.

The capacitance increases with area and decreases with separation. The capacitance is therefore greatest in devices made from materials with a high permittivity, large plate area, and small distance between plates. The maximum energy is a function of dielectric volume, permittivity, and dielectric strength per distance. Thus increasing the plate area and decreasing the separation between the plates while maintaining the same volume does not change the amount of energy the capacitor can store [14].

The dual of the capacitor is the inductor, which stores energy in the magnetic field rather than the electric field. Inductors consist of coils of wire for concentrating the magnetic field and collecting the induced voltage. Generated voltage is proportional to the rate of change in current in a circuit and the proportionality coefficient is the inductance L in henry in SI units

$$V = L\frac{dI}{dt} \tag{8.10}$$

8.4.1 Hydroelectric Energy Storage

Pumped-storage hydroelectricity is a type of hydroelectric power generation used by some power plants for *load balancing*. 1 kg mass elevated to 1,000 m can store 9.8 kJ of energy. The pumped-storage hydroelectricity stores energy in the form of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost off-peak electric power is used to run the pumps. The stored water is released through turbines to produce electric power. Although the losses of the pumping process makes the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of *peak demand*, when electricity prices are highest. Example 8.4 illustrates the electric energy storage by the pumped energy in a hydropower plant.

Example 8.4 Pumped energy in a hydropower plant

One method of meeting the additional electric power demand at peak usage is to pump some water from a source such as a lake back to the reservoir of a hydropower plant at a higher elevation when the demand or the cost of electricity is low. Consider a hydropower plant reservoir with an energy storage capacity of 0.5×10^6 kWh. This energy is to be stored at an average elevation of 40 m relative to the ground level. Estimate the minimum amount of water has to be pumped back to the reservoir.

Solution:

Assume that the evaporation of water is negligible.

$PE = 0.5 \times 10^6$ kWh, $\Delta z = 40$ m, $g = 9.8$ m/s^2

Energy of the work potential of the water: $PE = mg\Delta z$

$$\text{Amount of water: } m = \frac{PE}{g\Delta z} = \frac{0.5 \times 10^6\,\text{kWh}}{9.8\,\text{m/s}^2(40\,\text{m})}\left(\frac{3600\,\text{s}}{\text{h}}\right)\left(\frac{1000\,\text{m}^2/\text{s}^2}{1\,\text{kJ/kg}}\right)$$
$$= \mathbf{4.59 \times 10^9\,kg}$$

8.4.2 Electric Energy Storage in Battery

An electrical *battery* is one or more electrochemical cells that can store electric energy in the form of chemical energy as well as convert stored chemical energy into electrical energy. Alessandro Volta invented the first battery in 1800. Batteries come in various sizes, such as miniature cells and car batteries as shown in Fig. 8.12. Figure 8.12 shows the symbol used for the battery in electric circuit diagrams and various types of batteries. There are two types of batteries: *primary batteries*, which are disposable and designed to be used once and discarded, and *secondary batteries*, which are rechargeable and designed to be recharged and used multiple times. Rechargeable batteries can have their chemical reactions reversed by supplying electrical energy to the cell (Fig. 8.12f).

Zinc–carbon batteries and alkaline batteries are the common types of disposable batteries. Generally, these batteries have higher energy densities than rechargeable batteries. Rechargeable batteries, therefore, can store electric energy in the form of chemical energy. For example, they can be used to store electrical energy in batteries to be used in electric vehicles. The battery of electric vehicles can be charged from the grid. Because the stored energy is derived from electricity, it is possible to use other forms of alternative energy such as wind, solar, geothermal, nuclear, or hydroelectric in electric vehicles [13].

The oldest form of rechargeable battery is the lead-acid battery used in cars. Low manufacturing cost and its high surge current levels (450 A) make lead-acid battery use common where a large capacity (over approximately 10 A h) is required. The anode of the battery is lead metal while the cathode is made of lead

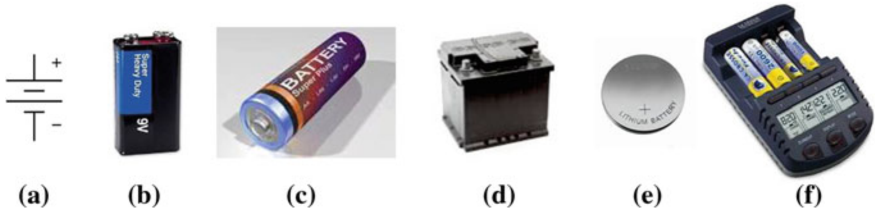


Fig. 8.12 Various types of batteries: **a** the symbol for a battery in a circuit diagram, **b** 9 volt battery, **c** 1.5 volt battery, **d** rechargeable car battery, **e** lithium battery, and **f** battery charger

(IV) oxide. During the discharge, the chemical reaction that takes place at the anode, negative electrode, is

$$\mathrm{Pb(s)} + \mathrm{SO_4}^{-2}\mathrm{(aq)} \rightarrow \mathrm{PbSO_4(s)} + 2\mathrm{e}^- \tag{8.11}$$

The chemical reaction that takes place at the cathode, positive electrode, is

$$\mathrm{PbO_2(s)} + \mathrm{SO_4}^{-2}\mathrm{(aq)} + 4\mathrm{H}^+\mathrm{(aq)} + 2\mathrm{e}^- \rightarrow \mathrm{PbSO_4(s)} + 2\mathrm{H_2O(l)} \tag{8.12}$$

During discharge, sulfuric acid is used up and lead sulfate is deposited on both electrodes. The battery becomes “dead” when the electrodes are fully covered with lead sulfate. During recharging the chemical reaction that takes place at the anode is

$$\mathrm{PbSO_4(s)} + 2\mathrm{H_2O(l)} \rightarrow \mathrm{PbO_2(s)} + \mathrm{SO_4}^{-2}\mathrm{(aq)} + 4\mathrm{H}^+\mathrm{(aq)} + 2\mathrm{e}^- \tag{8.13}$$

the chemical reaction that takes place at the cathode is

$$\mathrm{PbSO_4(s)} + 2\mathrm{e}^- \rightarrow \mathrm{Pb(s)} + \mathrm{SO_4}^{-2}\mathrm{(aq)} \tag{8.14}$$

By passing a current the battery can be recharged. Recharging reverses both reactions and leads to sulfuric acid regeneration and the removal of the lead sulfate from the electrodes. Lead-acid batteries should not be discharged to below 20% of their full capacity, because internal resistance will cause heat and damage when they are recharged.

8.4.3 Rechargeable Battery for Electric Car

The electric car uses a bank of onboard batteries, generally lithium ion batteries, to generate power for the motor. The choice of material used for the anode, cathode, and electrolyte determines the performance, safety, and life span of lithium ion batteries. Lithium ion batteries (see Fig. 8.13) are also lighter. Many electric cars utilize lithium ion batteries, which contain layers of lithium isolated between plates which are made from a combination of cobalt and oxygen atoms [15, 26].

Fig. 8.13 Lithium ion battery for electric cars [15, 26]

The batteries in electric cars must be charged from an external power source. The charging time depends on the type and capacity of the batteries and the type of outlet they are charging from. A standard 120 V outlet can provide about 1.5 kW per hour of charge. If you plug it into a 240 V circuit then about 6.6 kW per hour can be charged, drastically cutting the charge time. When calculating efficiency this must be taken into account [10, 22].

Battery life in cars is measured in cycles rather than the time or distance traveled. A battery cycle is one charge and one discharge and the number of cycles is usually expressed as a range because how the battery is used and charged can affect its life. There are various kinds of batteries commonly considered and used in electric vehicles as well as for general purposes [10, 15, 26]:

- Nickel–Cadmium (NiCd) batteries are rechargeable batteries used by power tools, portable electronics, and electric toys. They all use NiCd batteries because of their long life and low cost. With a 40–60 Wh/kg (watt-hour per kilogram) energy to weight ratio and a life cycle of around 1,000–2,000 cycles they are an inexpensive source of power.
- Nickel-Metal Hydride (NiMH) batteries have better energy to weight ratio than NiCd at 30–80 Wh/kg and are free of the toxic element of cadmium. Nickel-metal hydride batteries have a life of about 800–1,000 cycles. Low-capacity nickel metal hydride batteries (1,700–2,000 mA h) can be charged for about 1,000 cycles, whereas high capacity NiMH batteries (above 2,500 mA h) can be charged for about 500 cycles.
- Lithium–ion batteries power laptops or other battery-powered consumer electronics. An efficient 100–160 Wh/kg energy to weight ratio makes these the battery of choice in most high power/low weight applications. Lithium–ion batteries have a life of approximately 1,200 cycles.

The standard hybrid vehicle increases fuel efficiency by adding additional battery capacity and charging capability. Plug-in vehicles thereby operate on energy derived from the electrical grid rather than from gasoline. Electric motors are more efficient than internal combustion engines, however, much of the electricity is produced from coal, which has a low thermal efficiency and higher carbon-to-energy ratio than petroleum. A computer inside the vehicle determines when it is most efficient for the vehicle to be fueled by electricity or by liquid fuel (either petroleum or biofuels) [26].

Hybrid vehicles have improved efficiency in three ways. First, the gasoline engine can be sized slightly smaller and therefore operate in a more efficient range because the electric motor can supplement the engine when needed. Second, the gasoline engine can be shut down during periods when it would be operating inefficiently, particularly idling at stops, but also at slow speeds. Finally, it enables regenerative braking whereby some of the vehicle's kinetic energy is converted into electricity by the electric motor acting as a generator and charging the battery [23].

In plug-in hybrid vehicles, the small battery is replaced with a larger battery pack. Plug-in hybrid vehicles use both electric and gasoline drive and can be plugged into a standard home voltage. The vehicles have onboard controls to use the appropriate power source for maximum efficiency. Plug-in hybrid vehicles with modest battery packs could run primarily on the electric motor with stored energy for around 20 miles/day, thereby reducing the gasoline use [22].

8.5 Chemical Energy Storage

The free energy available from the electron-transport cycle is used in producing the proton flow through the inner membrane in mitochondria to synthesize adenosine triphosphate (ATP) in living cells. ATP is an energy rich compound having three phosphate groups attached to a nucleoside of adenine, called adenosine (adenine + pentose sugar). The terminal one of the three phosphate groups has a weak bond linkage and can break spontaneously whenever ATP forms a complex with an enzyme. The breaking up of this bond releases chemical energy causing an immediate shift in the bond energy giving rise to adenosine diphosphate. ATP formation therefore acts as the chemical energy storage of the living cell [6, 16].

In plants, ATP is used in biochemical cycles to synthesize carbohydrates such as glucose from carbon dioxide and water. The glucose is stored mainly in the form of starch granules consisting of a large number of glucose units. This polysaccharide is produced by all green plants as chemical energy store. Starch is processed to produce many of the sugars in processed foods.

A *biological battery* generates electricity from sugar in a way that is similar to the processes observed in living organisms. The battery generates electricity through the use of enzymes that break down carbohydrates, which are essentially sugar. A similarly designed sugar drink can power a phone using enzymes to generate electricity from carbohydrates that covers the phone's electrical needs [12].

8.5.1 Bioenergy Sources

Carbohydrates, fats, and proteins are the major metabolic fuels (sources of energy) of living systems. Chemical energy released by oxidation of these fuels is stored as energy rich molecules such as ATP in living cells. Energy contents of the major metabolic fuels are:

- Carbohydrates release about 4 kcal/g (17 kJ/g).
- Fats release about 9 kcal/g (37 kJ/g).
- Proteins release about 4 kcal/g (17 kJ/g).

In a human body excess energy is stored mainly by:

- Fat-triacylglycerol (triglyceride): triacylglycerol is the major energy store of the body.
- Glycogen: energy stored by glycogen is relatively small but it is critical. For example muscle glycogen is oxidized for muscle contraction.

Metabolism is the set of biochemical reactions that occur in living organisms to maintain life and consists of two major pathways of catabolism and anabolism. In catabolism, organic matter is broken down, for example, to harvest energy. In anabolism, the energy is used to construct components of cells such as proteins and nucleic acids. Daily energy expenditure includes the energy required for the basal metabolic rate and for the physical activity everyday. Basal metabolic rate for a person is approximately 24 kcal/kg (101 kJ/kg) body weight per day [9].

8.5.2 Energy Storage in Biofuels

Various biofuels, or biomass can be helpful in reducing the use of hydrocarbon fuels. Some chemical processes, such as Fischer–Tropsch synthesis can convert the carbon and hydrogen in coal, natural gas, biomass, and organic waste into short hydrocarbons suitable as replacements for existing hydrocarbon fuels. Many hydrocarbon fuels have the advantage of being immediately usable in existing engine technology and existing fuel distribution infrastructures. A long-term high oil price may make such synthetic liquid fuels economical on a large-scale production despite some of the energy in the original source being lost in the conversion processes [8].

Carbon dioxide and hydrogen can be converted into methane and other hydrocarbon fuels with the help of energy from another source preferably a renewable energy source. As hydrogen and oxygen are produced in the electrolysis of water,

$$2H_2O \rightarrow 2H_2 + O_2 \tag{8.15}$$

hydrogen would then be reacted with carbon dioxide in producing methane and water in the Sabatier reaction

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{8.16}$$

Produced water would be recycled back to the electrolysis stage, reducing the need for new pure water. In the electrolysis stage oxygen would also be stored for methane combustion in a pure oxygen environment (eliminating nitrogen oxides). In the combustion of methane, carbon dioxide and water are produced.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{8.17}$$

Produced carbon dioxide would be recycled back to the Sabatier process. Methane production, storage, and adjacent combustion would recycle all the reaction products, creating a cycle.

Methane is the simplest hydrocarbon with the molecular formula CH_4. Methane can be stored more easily than hydrogen and the technologies for transportation, storage, and combustion infrastructure are highly developed. Methane would be stored and used to produce electricity later. Besides that, methanol can also be synthesized from carbon dioxide and hydrogen. If the hydrogen is produced by electrolysis using electricity from wind power, then the electricity is stored by the production of methane or methanol.

8.5.3 Energy Storage in Voltaic Cell

Each voltaic cell consists of two half cells connected in series by a conductive electrolyte containing anions and cations. One half-cell includes electrolyte and the positive electrode is called the cathode. Negatively charged ions called anions migrate to the cathode. The other half-cell includes electrolyte and the negative electrode is called the anode. The positively charged ions called cations migrate to the anode. In the redox reaction that powers the battery, cations are reduced (electrons are added) at the cathode, while anions are oxidized (electrons are removed) at the anode. The electrodes do not touch each other but are electrically connected by the electrolyte. Figure 8.14 shows the half cells of a copper-zinc battery.

In a copper-zinc battery, the tendency for Zn to lose electron is stronger than that for copper. When the two cells are connected by a *salt bridge* and an *electric conductor* as shown in Fig. 8.15 to form a closed circuit for electrons and ions to flow, copper ions (Cu^{2+}) actually gain electrons to become copper metal. Electrons flow through the electric conductors connecting the electrodes and ions flow through the salt bridge. The overall reaction of the cell is

$$Zn + Cu^{2+} = Zn^{2+} + Cu \tag{8.18}$$

Fig. 8.14 Half cells of a copper-zinc battery- copper-zinc voltaic cells; Zn electrode to lose electron according to the reaction so it is cathode: $Zn = Zn^{2+} + 2e^-$

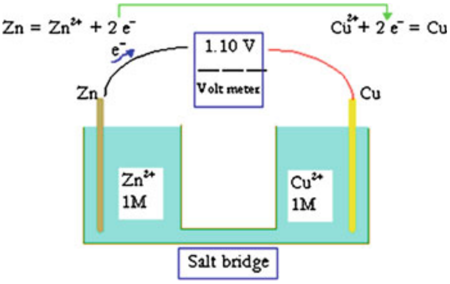
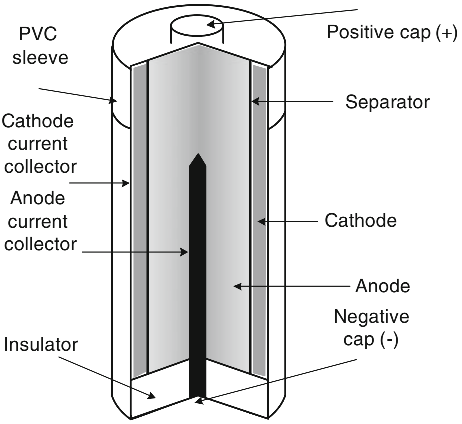


Fig. 8.15 Schematic of a dry cell [13]



The net electromotive force of the cell is the difference between the reduction potentials of the half-reactions. The electrical driving force of a cell is known as the *terminal voltage* (ΔV) and is measured in volts. An ideal cell has negligible internal resistance, so it would maintain a constant terminal voltage until exhausted. If such a cell maintained 1.5 V and stored a charge of one coulomb then on complete discharge it would perform 1.5 J of work. A battery is a collection of multiple electrochemical cells, for example, a 1.5 V AAA battery is a single 1.5 V cell, and a 9 V battery has six 1.5 V cells in series (see Fig. 8.12).

Other portable rechargeable batteries include several “dry cell” types using paste in place of liquid electrolyte and are therefore useful in appliances such as mobile phones and laptop computers. Cells of this type include nickel–cadmium (NiCd), nickel metal hydride (NiMH) and lithium–ion (Li-ion) cells. Lithium–ion has the highest share of the dry cell rechargeable market. Meanwhile, NiMH has replaced NiCd in most applications due to its higher capacity, but NiCd remains in use in power tools, two-way radios, and medical equipment. Figure 8.15 shows the main layers of a dry cell [13].

The battery capacity printed on a battery is usually the product of 20 h multiplied by the maximum constant current that a new battery can supply for 20 h at

68°F (20°C), down to a predetermined terminal voltage per cell. A battery rated at 100 A h will deliver 5 A over a 20 h period at room temperature. The relationship among current, discharge time, and capacity for a lead-acid battery is approximated by Peukert's law:

$$t = \frac{Q_B}{I^k} \tag{8.19}$$

where Q_B is the capacity when discharged at a rate of 1 A, I is the current drawn from battery, t is the amount of time (in hours) that a battery can sustain, and k is a constant around 1.3. When discharging at low rate, the battery's energy is delivered more efficiently than at higher discharge rates, but if the rate is too low, it will self-discharge during the long time of operation, again lowering its efficiency. Sodium–sulfur batteries are being used to store wind power [13].

8.6 Mechanical Energy Storage

Energy may also be stored in pressurized gases or alternatively in a vacuum. Compressed air, for example, may be used to operate vehicles and power tools. Large-scale compressed air energy storage (CAES) facilities may be used to supplement demands on electricity generation by providing energy during peak hours and storing energy during off-peak hours. Such systems save on expensive generating capacity since it only needs to meet average consumption [2].

8.6.1 Compressed Air Energy Storage

CAES technology stores low cost off-peak energy, in the form of compressed air in an underground reservoir. The air is then released during peak load hours and heated with the exhaust heat of a standard combustion turbine. This heated air is converted into energy through expansion turbines to produce electricity. Energy storage systems often use large underground caverns due to their very large volume, and thus the large quantity of energy that can be stored with only a small pressure change. The cavern space can be compressed adiabatically with little temperature change and heat loss. CAES can also be employed on a smaller scale such as exploited by air cars and air-driven locomotives. CAES application using sequestered carbon dioxide is also possible for energy storage.

Compression of air generates heat and the air gets warmer. If no extra heat is added, the air will be much colder after decompression, which requires heat. If the heat generated during compression can be stored and used again during decompression, the efficiency of the storage improves considerably. CAES can be achieved in adiabatic, diabatic, or isothermic processes:

- *Adiabatic storage* retains the heat produced by compression and returns it to the air when the air is expanded to generate power. Heat can be stored in a fluid such as hot oil (up to 300°C) or molten salt solutions (600°C).
- *Diabatic storage* dissipates the extra heat with intercoolers (thus approaching isothermal compression) into the atmosphere as waste. Upon removal from storage, the air must be reheated prior to expansion in the turbine to power a generator which can be accomplished with a natural gas-fired burner.
- *Isothermal compression* and expansion approaches attempt to maintain operating temperature by constant heat exchange to the environment. They are only practical for low power levels and some heat losses are unavoidable. Compression process is not exactly isothermal and some heat losses will occur.

The ideal gas law for an isothermal process is

$$PV = nRT = \text{constant} \tag{8.20}$$

$$W_{AB} = nRTln(V_B/V_A) = nRTln(P_A/P_B) \tag{8.21}$$

where A and B are the initial and final states of the system and W represents the maximum energy that can be stored or released. In practice, no process is perfectly isothermal and the compressors and motors will have heat losses. Compressed air can transfer power at very high flux rates, which meets the principal acceleration and deceleration objectives of transportation systems, particularly for hybrid vehicles. Examples 8.5 and 8.6 illustrate the simple analysis of mechanical energy storage by compressed air.

Example 8.5 Maximum air compressed energy storage

Determine the maximum available energy if we compress 1,450 kg air from 100 kPa to 1,200 kPa at 300 K at isothermal conditions with a heat loss of 24,000 kJ.

Solution:
Assume that air is ideal gas.

$MW = 29$ kg/kmol, $R = 8.314$ kJ/kmol K,
$P_1 = 100$ kPa, $P_2 = 1200$ kPa, $m = 1450$ kg
Number of moles of air = 1450/29 = 50 kmol
Mechanical energy stored:

$$W_{\max} = -nRT\ln\left(\frac{P_1}{P_2}\right) = -(50\,\text{kmol})(8.314\,\text{kJ/kmol K})$$

$$(300\,\text{K})\ \ln(100/1200) = 309{,}892.7\,\text{kJ}$$

$q_{\text{loss}} = 24000$ kJ

Net energy to be stored:
$W_{\max} - q_{\text{loss}} = (309892.7 - 24000)$ kJ = **285,892.7 kJ = 285.9 MJ**

Example 8.6 Maximum air compressed energy storage in a large cavern
An underground cavern will be used to store the energy of compressed air. If the cavern has a volume of 29,000 m^3 determine the value of stored energy by the compression of air from 100 to 1,500 kPa at 300 K at isothermal conditions with a heat loss of 55,000 kJ.

Solution:
Assume that air is ideal gas. Cavern space is under ideal gas conditions and at standard temperature and pressure (25°C and 1 atm).
$MW = 29$ kg/kgmol, R = 8.314 kJ/kmol K, $P_1 = 100$ kPa, $P_2 = 1500$ kPa
Under ideal gas conditions and at standard temperature and pressure (25°C and 1 atm)
1 mol of air occupies 22.4 l and 1 kmol occupies 2.24×10^4 l
Volume = 29,000 m^3 = 2.9×10^7 l
Approximate number of moles of air = 2.9 10^7 l/2.24×10^4 l = 1,294.6 kmol
Energy stored:

$$W = -nRT\ln\left(\frac{P_1}{P_2}\right)$$
$$= -(1294.6\,\text{kmol})(8.314\,\text{kJ/kmol K})(300\,\text{K})\ln(100/1500) = 8,744,270.6\,\text{kJ}$$

$q_{\text{loss}} = 55000$ kJ
Net energy to be stored = $W_{\max} - q_{\text{loss}}$ = **8,689,270.6 kJ or 8,689.3 MJ**

8.6.2 Flywheel Energy Storage

Flywheel energy storage works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy. Most flywheel energy storage systems use electricity to accelerate and decelerate the flywheel, but devices that directly use mechanical energy are also being developed. Advanced flywheel energy storage systems have rotors made of high strength carbon filaments, suspended by magnetic bearings, and spinning at speeds from 20,000 to over 50,000 rpm in a vacuum enclosure.

8.6.3 Hydraulic Accumulator

A *hydraulic accumulator* is an energy storage device in which a non-compressible hydraulic fluid is held under pressure by an external source. That external source can be a spring, a raised weight, or a compressed gas. An accumulator is used in a hydraulic system so that the pump does not need to be so large to cope with extremes of demand. Also, the supply circuit can respond more quickly to any temporary demand and to smooth pulsations. Compressed gas accumulators are the most common type. These are also called hydro-pneumatic accumulators.

8.6.4 Springs

A *spring* is an elastic material used to store mechanical energy. When a spring is compressed or stretched, the force it exerts is proportional to its change in length. The *spring constant* of a spring is the change in the force it exerts divided by the change in deflection of the spring. An extension or compression spring has units of force divided by distance, for example lb_f/in or N/m. The stiffness (or rate) of springs in parallel is additive, as is the compliance of springs in series.

Depending on the design and required operation, any material can be used to construct a spring, as long as the material has the required combination of rigidity and elasticity.

Problems

8.1. (a) Estimate sensible heat stored in 6 m^3 water and 6 m^3 granite heated from 20 to 40°C.

(b) Estimate the heat stored in 500 lb of water heated from 20 to 30°F.

8.2. (a) Estimate sensible heat stored in 1.1 m^3 Dowtherm A and 1.1 m^3 therminol 66 heated from 20 to 240°C.

(b) Estimate the heat stored in 500 lb of molten salt heated from 150 to 300°C.

8.3. (a) Estimate sensible heat stored in 2.5 m^3 mixture of 50% ethylene glycol and 50% water and 2.5 m^3 water heated from 20 to 65°C.

(b) Estimate the heat stored in 1,500 lb of draw salt heated from 250 to 400°C.

8.4. A typical square two-story home with a roof surface area of 1,260 ft^2 and a wall surface area of 2,400 ft^2 is to be heated with solar energy storage using a salt hydrate as phase change material. It presently has an insulation of 6 inches in the roof and 1 inch in the walls. Inside temperature will be held at 70°F and expected outside low temperature is 10°F. Average solar radiation is 300 Btu/ft^2 and the cost of solar air collector is \$1.5/ft^2. The salt hydrate costs around \$0.2/lb. Estimate the costs of salt hydrate and solar air collectors.

8.5. A typical square two-story home with a roof surface area of 1,200 ft^2 and a wall surface area of 2,200 ft^2 is to be heated with solar energy storage using a salt hydrate as phase change material. It presently has as an insulation of 6 inches in the roof and 1 inch in the walls. Inside temperature will be held at 70°F and expected outside low temperature is 10°F. Average solar radiation is 350 Btu/ft^2 and the cost of solar air collector is \$1.4/ft^2. The salt hydrate costs around \$0.22/lb. Estimate the costs of salt hydrate and solar air collectors.

8.6. Energy from a thermal energy storage system is used to heat a room from 15 to 25°C. The room has dimensions of $(4 \times 4 \times 5)$ m^3. The air in the room is at atmospheric pressure. The heat loss from the room is negligible. Estimate the amount of n-hexadecane needed if the heat of melting is the stored energy for this temperature change.

8.7. Energy from a thermal energy storage system is used to heat a room from 12 to 27°C. The room has dimensions of $(4 \times 5 \times 5)$ m^3. The air in the room is at atmospheric pressure. The heat loss from the room is negligible. Estimate the amount of *n-octadecane* needed if the heat of melting is the stored energy for this temperature change.

8.8. Energy from a thermal energy storage system is used to heat a room from 14 to 24°C. The room has dimensions of $(5 \times 5 \times 5)$ m^3. The air in the room is at atmospheric pressure. The heat loss from the room is negligible. Estimate the amount of paraffin needed if the heat of melting is the stored energy for this temperature change.

8.9. A room with dimensions of $(5 \times 5 \times 6)$ m^3 is heated with a thermal energy storage supplying a heating rate of 80 kJ/h. Heat loss from the room is 2 kJ/h. The air is originally at 15°C. Estimate the time necessary to heat the room to 24°C.

8.10. A 0.50-kW solar thermal energy storage system is used to heat a room with dimensions 3.0 m × 4.5 m × 4.0 m. Heat loss from the room is 0.15 kW and the pressure is always atmospheric. The air in the room may be assumed to be an ideal gas. The air has a constant heat capacity of $C_{v,av} = 0.72$ kJ/kg °C. Initially the room temperature is 15°C. Determine the temperature in the room after 30 min.

8.11. A 60 m^3 room is heated by a thermal energy storage system. The room air originally is at 12°C and 100 kPa. The room loses heat at a rate of 0.2 kJ/s. If the thermal energy storage system supplies 0.8 kW estimate the time necessary for the room temperature to reach 22°C.

8.12. A superheated steam at a rate of 0.6 lb/s flows through a heater. The steam is at 100 psia and 380°F. If a heat storage system supplies 37.7 Btu/s into the steam at constant pressure estimate the final temperature of the steam.

8.13. A superheated steam at a rate of 0.9 lb/s flows through a heater. The steam is at 100 psia and 380°F. If a heat storage system supplies 25.4 Btu/s into the steam at constant pressure estimate the final temperature of the steam.

8.14. A thermal energy storage system is used to heat 20 kg of water in a well-insulated tank. The storage system supplies a heat at a rate of 1.5 kW. The water in the tank is originally at 10°C. Estimate the time necessary for the temperature of the water to reach 50°C and the amount of salt hydrate with a heat of melting of 200 kJ/kg.

8.15. A thermal energy storage system is used to heat 120 kg of water in a well-insulated tank. The storage system supplies heat at a rate of 1.5 kW. The water in the tank is originally at 15°C. Estimate the time necessary for the temperature of the water to reach 50°C and the amount of n-hexadecane with a heat of melting of 235 kJ/kg (Table 8.4).

8.16. A thermal energy storage system is used to heat 150 kg of water. The heat is stored by latent heat of paraffin. The storage supplies heat at a rate of 2.3 kW. A heat loss of 0.35 kW occurs from the tank to surroundings. The water in the tank is originally at 20°C. Estimate the temperature of the water after 2 h of heating and amount of paraffin required.

8.17. A thermal energy storage system is used to heat 50 kg of water. The heat is stored by latent heat of paraffin. The storage supplies heat at a rate of 2.0 kW. A heat loss of 0.4 kW occurs from the tank to surroundings. The water in the tank is originally at 5°C. Estimate the temperature of the water after 3 h of heating and amount of paraffin required.

8.18. A phase change material of 20 kg octadecane is heated from 20 to 30°C by a solar energy system, which supplies heat at a rate of 2 kW. Assume that the octadecane is fully melted. Estimate the time necessary for the process and the minimum size of the storage unit.

8.19. A phase change material of 50 kg n-hexadecane is heated from 12 to 26°C by a solar energy system, which supplies heat at a rate of 1.5 kW. Assume that the *n-hexadecane* is fully melted. Estimate the time necessary for the process and the minimum size of the storage unit.

PCM	T_m (°C)	ΔH_m (kJ/kg)	$C_{pl,\ av}$ (kJ/kg K)	$C_{ps,av}$ (kJ/kg K)	k_l (W/m K)	k_s (W/m K)	ρ_l (kg/m^3)	ρ_s (kg/m^3)
Water	0	333	4.19	2.0	0.595	2.2	1,000	920
n-Hexadecane	18	235	2.1	1.95	0.156	0.43	765	835

8.20. A phase change material of 120 kg octadecane is heated from 20 to 30°C by a solar energy system, which supplies heat at a rate of 2 kW. Assume that the octadecane is fully melted. Estimate the time necessary for the process and the minimum size of the storage unit.

8.21. A phase change material of 60 kg n-eicosane is heated from 20 to 42°C by a solar energy system, which supplies heat at a rate of 1.8 kW. Assume that the n-eicosane is fully melted. Estimate the time necessary for the process and the minimum size of the storage unit.

8.22. A phase change material of 100 kg docosane is heated from 20 to 55°C by a solar energy system, which supplies heat at a rate of 1.2 kW. Assume that the docosane is fully melted. Estimate the time necessary for the process and the minimum size of the storage unit.

8.23. A phase change material of 30 kg docosane is heated from 20 to 55°C by a solar energy system, which supplies heat at a rate of 1.1 kW. Assume that the docosane is fully melted. Estimate the time necessary for the process and the minimum size of the storage unit.

8.24. One method of meeting the additional electric power demand at peak usage is to pump some water from a source such as a lake back to the reservoir of a hydropower plant at a higher elevation when the demand or the cost of electricity is low. Consider a hydropower plant reservoir with an energy storage capacity of 2×10^6 kWh. This energy is to be stored at an average elevation of 60 m relative to the ground level. Estimate the minimum amount of water to be pumped back to the reservoir.

8.25. One method of meeting the additional electric power demand at peak usage is to pump some water from a source such as a lake back to the reservoir of a hydropower plant at a higher elevation when the demand or the cost of electricity is low. Consider a hydropower plant reservoir with an energy storage capacity of 1.2×10^6 kWh. This energy is to be stored at an average elevation of 52 m relative to the ground level. Estimate the minimum amount of water to be pumped back to the reservoir.

8.26. One method of meeting the additional electric power demand at peak usage is to pump some water from a source such as a lake back to the reservoir of a hydropower plant at a higher elevation when the demand or the cost of electricity is low. Consider a hydropower plant reservoir with an energy storage capacity of 3.45×10^6 kWh. This energy is to be stored at an average elevation of 44 m relative to the ground level. Estimate the minimum amount of water to be pumped back to the reservoir.

8.27. Determine the maximum available energy from compression of 725 kg air from 100 to 1,200 kPa at 300 K at isothermal conditions with a loss of 24,000 kJ.

8.28. Determine the maximum available energy if we compress 1,100 kg air from 100 to 1,100 kPa at 290 K at isothermal conditions with a loss of 21,200 kJ.

8.29. Determine the maximum available energy if we compress 540 kg air from 100 to 1,100 kPa at 290 K at isothermal conditions with a loss of 12,000 kJ.

8.30. Determine the maximum available energy if we compress 1,450 kg air compression from 100 to 1,200 kPa at 300 K at isothermal conditions with a loss of 24,000 kJ.

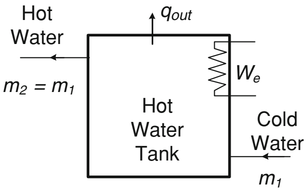
8.31. An underground cavern will be used to store energy of compressed air. If the cavern has a volume of 58,000 m^3 determine the maximum available energy from compression of air from 100 to 1,500 kPa at 300 K at isothermal conditions with a loss of 55,000 kJ.

8.32. An underground cavern will be used to store energy of compressed air. If the cavern has a volume of 90,000 m^3 determine the maximum available energy from compression of air from 100 to 1,400 kPa at 300 K at isothermal conditions with a loss of 50,000 kJ.

8.33. An underground cavern will be used to store energy of compressed air. If the cavern has a volume of 58,000 ft^3 determine the maximum available energy from compression of air from 15 to 600 psia at 540 R at isothermal conditions with a loss of 50,000 Btu.

8.34. An underground cavern will be used to store energy of compressed air. If the cavern has a volume of 150,000 ft^3 determine the maximum available energy from compression of air from 15 to 500 psia at 540 R at isothermal conditions with a loss of 100,000 Btu.

8.35. A well-insulated 30-m^3 tank is used to store exhaust steam. The tank contains 0.01 m^3 of liquid water at 30°C in equilibrium with the water vapor. Determine the amount of wet-exhaust steam, in kg, from a turbine at 1 atm at the end of an adiabatic filling process. The wet steam has the quality of 90%, and the final pressure within the tank is 1 atm. Assume that heat transfer between the liquid water and the steam is negligible.



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Chapter 9
Energy Conservation

9.1 Energy Conservation and Recovery

Energy conservation mainly refers to reducing energy consumption and increasing efficiency in energy usage. Energy conservation may lead to increased security, financial gain, and environmental protection. For example, electric motors consume a considerable amount of electrical energy and operate at efficiencies between 70 and 90%. Therefore, using an electric motor operating with higher efficiency will conserve energy throughout its useful life. Energy recovery leads to reducing the energy input by reducing the overall waste energy from a system. For example, a waste energy, mainly in the form of sensible or latent heat, from a subsystem may be usable in another part of the same system. Therefore, energy recovery may be a part of energy conservation. There is a large potential for energy recovery in industries and utilities leading to reduced use of fossil fuels and emission of CO_2 and NO_x. Some examples of energy recovery are:

- Hot water from processes such as power plants and steel mills may be used for heating of homes and offices in the nearby area. Energy conservation through insulation or improved buildings may also help. Low temperature heat recovery would be more effective for a short distance from producer to consumer.
- Regenerative brake is used in electric cars and trains, where the part of kinetic energy is recovered and stored as chemical energy in a battery.
- Active pressure reduction systems where the differential pressure in a pressurized fluid flow is recovered rather than converted to heat in a pressure reduction valve.
- Energy recycling.
- Water heat recycling.
- Heat recovery steam generator.
- Heat regenerative cyclone engine.

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- Thermal diode.
- Thermoelectric modules.

9.2 Conservation of Energy in Industrial Processes

Most of the industrial processes depend on stable and affordable energy supply to be competitive. Some of these industrial processes produce energy, while others use energy. For example, a Rankine engine produces electricity and compressors use it. Energy conservation in both types of processes will increase thermal efficiency and reduce wasted energy. The following sections discuss some possible process improvements that may lead to energy conservation in power production and compressor work.

9.2.1 Energy Conservation in Power Production

Section 6.7 discusses some possible modifications in improving the efficiency of power plants. Here, some examples underline the importance of energy conservation in Rankine cycle and Brayton cycle. In a Brayton cycle operating as gas-turbine engine, the temperature of the exhaust gas leaving the turbine T_4 is often higher than the temperature of the gas leaving the compressor T_2 as seen in Fig. 9.1. Therefore, the gas leaving the compressor can be heated in a regenerator by the hot exhaust gases as shown in Fig. 9.1b. Regenerator is a counter-flow heat exchanger, which is also known as *recuperator*, and recovers waste heat. The thermal efficiency of the Brayton cycle increases as a result of regeneration because the portion of energy of the exhaust gases is used to preheat the gas entering to the combustion chamber. Thus, in turn, regeneration can reduce the fuel input required for the same net work output from the cycle. The addition of a regenerator (operating without thermal losses) does not affect the net work output of the cycle. A regenerator with higher effectiveness will conserve more fuel. The effectiveness ε of the regenerator operating under adiabatic conditions is defined by

$$\varepsilon = \left(\frac{H_5 - H_2}{H_4 - H_2}\right) \tag{9.1}$$

The enthalpies H_i are shown in Fig. 9.1b. Under the cold-air standard temperature assumptions (Chap. 7.8.1), the effectiveness ε of the regenerator is defined approximately by

$$\varepsilon \simeq \left(\frac{T_5 - T_2}{T_4 - T_2}\right) \tag{9.2}$$

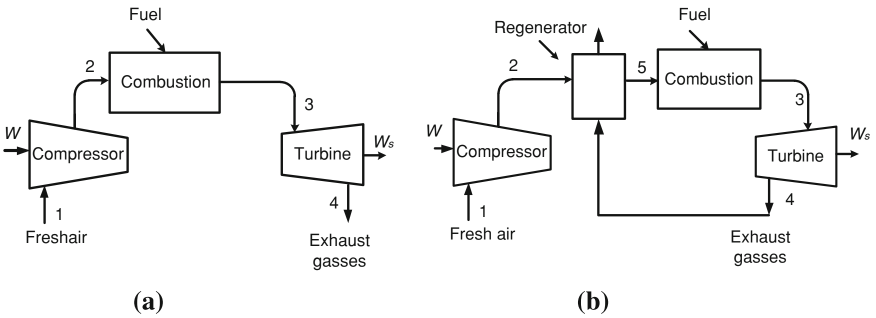


Fig. 9.1 **a** Simple Brayton cycle. **b** Brayton cycle with regeneration; the condition for regeneration is $T_4 > T_2$

The regeneration is possible only when $T_4 \gg T_2$. The effectiveness of most regenerators used in practical engine operations is below 0.85 [7].

Under the cold-air standard temperature assumptions, thermal efficiency of an ideal Brayton cycle with regeneration depends on the ratio of minimum to maximum temperatures and the pressure ratio, and estimated by

$$\eta_{\text{th.regen.}} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(\gamma-1)/\gamma} \tag{9.3}$$

where r_p is the compression ratio (P_2/P_1) and $\gamma = C_p/C_v$.

Example 9.1 Energy conservation by regeneration in a Brayton cycle

A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The fresh air temperature at the compressor inlet is 295 K. The air temperature at the inlet of the turbine is 1,300 K. The cycle operates with a compressor efficiency of 80% and a turbine efficiency of 80%. The unit cost of fuel is \$0.14/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.78, determine the thermal efficiency of the cycle and annual conservation of fuel.

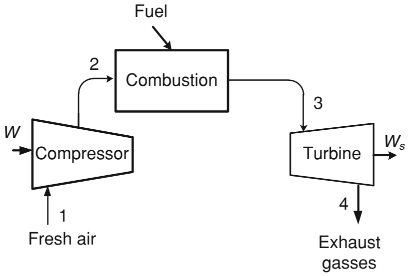
Solution:

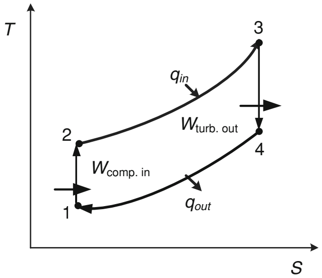
Assume that the cycle is at steady-state flow and the changes in kinetic and potential energies are negligible. Heat capacity of the air is temperature dependent, and the air is an ideal gas.

(a) Basis: 1 kg/s air.

$\eta_{\text{turb}} = 0.8$, $\eta_{\text{comp}} = 0.8$, $r_p = P_2/P_1 = 9$

Process 1-2: isentropic compression





Data from (Table D1):
$T_1 = 295$ K, $H_1 = 295.17$ kJ/kg, $P_{r1} = 1.3068$

P_r shows the relative pressure defined in Eq. (7.36).

$$\frac{P_{r2}}{P_{r1}} = \frac{P_2}{P_1} = r_p \rightarrow P_{r2} = (9)(1.3068) = 11.76$$

Approximate values from Table D1 for the compressor exit:
at $P_{r2} = 11.76$: $T_2 = 550$ K and $H_2 = 555.74$ kJ/kg

Process 3–4: isentropic expansion in the turbine as seen on the *TS* diagram above
$T_3 = 1{,}300$ K, $H_3 = 1{,}395.97$ kJ/kg, $P_4/P_3 = 1/r_p = 1/9$, $P_{r3} = 330.9$

$$\frac{P_{r4}}{P_{r3}} = \frac{P_4}{P_3} \rightarrow P_{r4} = \left(\frac{1}{9}\right)(330.9) = 36.76$$

Approximate values from Table D1 at the exit of turbine:
at $P_{r4} = 36.76$: $T_4 = 745$ K and $H_4 = 761.87$ kJ/kg

The work input to the compressor:

$$W_{\text{comp.in}} = \frac{H_2 - H_1}{\eta_{\text{comp}}} = \frac{(335.74 - 295.17)\,\text{kJ/kg}}{0.8} = 325.7\,\text{kJ/kg}$$

The work output of the turbine:

$$W_{\text{turb.out}} = \eta_{\text{turb}}(H_3 - H_4) = 0.8(1{,}395.97 - 761.87) = 507.3\ \text{kJ/kg}$$

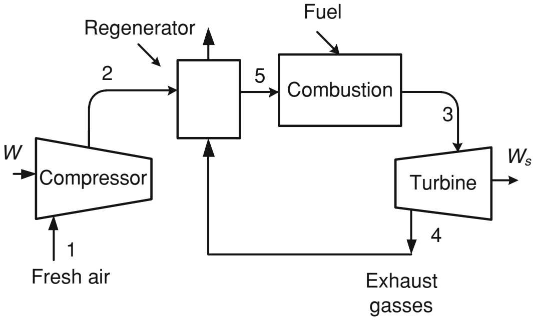
The back work ratio r_{bw}: $r_{\text{bw}} = \frac{W_{\text{comp.in}}}{W_{\text{turb.out}}} = \frac{325.7}{507.3} = 0.64$

This shows that 64% of the turbine output has been used in the compressor.
Net work output: $W_{\text{net}} = W_{\text{out}} - W_{\text{in}} = (507.3 - 325.7)\,\text{kJ/kg} = 181.6\ \text{kJ/kg}$

The actual air enthalpy at the compressor outlet:
$H_{2\text{a}} = H_1 + W_{\text{comp.in}} = (295.17 + 325.70)\,\text{kJ/kg} = 620.87\ \text{kJ/kg}$
The amount of heat added: $q_{\text{in}} = H_3 - H_{2a} = 1{,}395.97 - 620.87 = 775.1\ \text{kJ/kg}$
The thermal efficiency: $\eta_{\text{th}} = \frac{W_{\text{net}}}{q_{\text{in}}} = \frac{181.6}{775.1} = \mathbf{0.234\ or\ 23.4\%}$

The temperature of the exhaust air, T_4, and the actual enthalpy are estimated from the energy balance: $W_{\text{turb out}} = H_{4a} - H_3$
$H_{4a} = 1{,}395.97 - 507.3 = 888.67$ kJ/kg → $T_4 = 860$ K (From Table D1)
Advances in the compressor and turbine designs with minimal losses increase the efficiency of these components. In turn, a significant increase in the thermal efficiency of the cycle is possible.

(b) $T_4 = 860$ K and $T_2 = 550$ K, since $T_4 > T_2$ regeneration is possible. Regeneration with effectiveness of $\varepsilon = 0.78$:



$$\varepsilon = \left(\frac{H_5 - H_2}{H_4 - H_2}\right) = \frac{H_5 - 620.9}{888.67 - 620.9} = 0.78 \rightarrow H_5 = 829.80 \text{ kJ/kg}$$

$q_{\text{in}} = H_3 - H_5 = 1{,}395.97 - 829.8 = 566.2\ \text{kJ/kg}$
This represents a conservation of 840.2 – 566.2 = 274.0 kJ/kg from the fuel required.

The thermal efficiency: $\eta_{\text{th}} = \dfrac{W_{\text{net}}}{q_{\text{in}}} = \dfrac{181.6}{566.2} = \mathbf{0.32\ or\ 32\%}$

Unit cost of fuel = \$0.14/kWh
Days of operation 360, hours of operation per year = 360(24) =8,640 h/year
Conserved fuel: (274 kJ/kg)(1 kg/s) (8,640 h/year) = 2,367,360 kWh/year
Saved money: (2,367,360 kWh/year) (\$0.14/kWh) = **\$331,430/year**

After the regeneration, the thermal efficiency has increased from 23 to 32% in the actual Brayton cycle operation. The addition of a regenerator (operating without thermal losses) does not affect the net work output of the cycle. Savings of fuel and costs are considerable.

9.2.1.1 Conservation of Energy by the Process Improvements

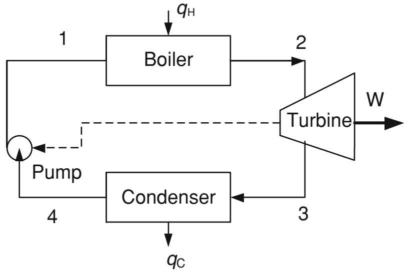
Some of the possible modifications in operation of steam power plants to increase the efficiency are [6, 5]:

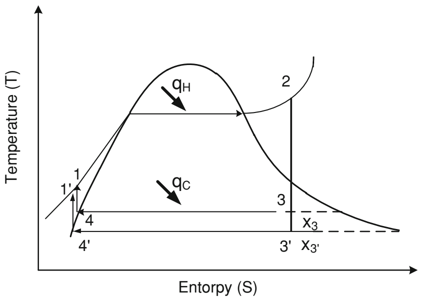
- Increasing the efficiency of a Rankine cycle by reducing the condenser pressure. Example 9.2 illustrates the estimation of efficiency of a Rankine cycle operating at two different discharge pressures. The thermal efficiency increased from 27.6 to 33.4% by reducing the condenser pressure from 78.5 to 15.0 kPa. However the quality of the discharged steam decreased from 0.9 to 0.84, which is not desirable for the blades of the turbine. Savings are considerable since the power output increased. Example 9.3 compares the actual thermal efficiency with the maximum thermal efficiency obtained from fully reversible Carnot cycle.
- Increasing the efficiency of a Rankine cycle by increasing the boiler pressure. Example 9.4 illustrates the estimation of thermal efficiency of a Rankine cycle operating at a higher pressure. The thermal efficiency increased from 0.276 to 0.326 by increasing the boiler pressure from 3,500 to 9,800 kPa. However the quality of the discharged steam decreased from 0.9 to 0.80, which is not desirable for the blades of the turbine.
- Increasing the efficiency of a Rankine cycle by increasing the boiler temperature. Example 9.5 illustrates the estimation of thermal efficiency of a Rankine cycle operating at a higher temperature. The thermal efficiency increased from 0.276 to 0.298 by increasing the boiler temperature from 400 to 525°C. The quality of the discharged steam increased from 0.9 to 0.96, which is desirable for the protection of the turbine blades. Example 9.6 compares the estimated thermal efficiency with the maximum thermal efficiency obtained from the fully reversible Carnot cyle.

Example 9.2 Increasing the efficiency of a Rankine cycle by reducing the condenser pressure

A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,500 kPa and 400°C. Discharge pressure of the steam from the turbine is 78.5 kPa.

(a) Determine the thermal efficiency of the cycle.
(b) If the pressure of the discharge steam is reduced to 15 kPa determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is $0.10/kWh.





Solution:
Assume that the cycle is at steady-state flow and the changes in kinetic and potential energy are negligible. Efficiency of pump and turbine is 100%.

(a) $\dot{m}_s = 20.0\ \mathrm{kg/s}$
Using the data from the Appendix: Tables F3 and F4
Superheated steam (Table F4):
$P_2 = P_1 = 3{,}500$ kPa, $H_2 = 3{,}224.2$ kJ/kg, $S_2 = 6.8443$ kJ/kg, $T_2 = 400$°C
Saturated steam (Table F3):
$P_3 = P_4 = 78.5$ kPa ($T_{\mathrm{sat}} = 366.15$ K), $V_4 = 0.001038\ \mathrm{m^3/kg}$
$H_{3\mathrm{sat\ vap}} = 2{,}665.0$ kJ/kg, $\mathrm{H}_4 = H_{3\mathrm{sat\ liq}} = 389.6$ kJ/kg
$S_{3\mathrm{sat\ vap}} = 7.4416$ kJ/kg K, $S_{3\mathrm{sat\ liq}} = 1.2271$ kJ/kg K
Basis: 1 kg/s steam.
With a pump efficiency of $\eta_{\mathrm{pump}} = 100\%$

$$W_{p,\mathrm{in}} = V_1(P_1 - P_4) = (0.001038)(3{,}500 - 78.5)\left(\frac{1\,\mathrm{kJ}}{1\ \mathrm{kPa\ m^3}}\right) = 3.55\,\mathrm{kJ/kg}$$

$$H_1 = H_4 + W_{p,\mathrm{in}} = 393.1\,\mathrm{kJ/kg}$$

Isentropic process $S_1 = S_4$ and $S_3 = S_2$.

The quality of the discharged wet steam ($S_2 < S_{3\mathrm{sat\ vap}}$): $6.8443 < 7.4416$
$x_3 = (6.8463 - 1.2271)/(7.4416 - 1.2271) = 0.90$
$H_3 = 389.6(1 - 0.90) + 2{,}665.0 \times 0.90 = 2{,}437.5\,\mathrm{kJ/kg}$

Heat interactions:
$q_{\mathrm{in}} = H_2 - H_1 = 3{,}224.2 - 393.1 = 2{,}831.1\ \mathrm{kJ/kg}$
$q_{\mathrm{out}} = H_3 - H_4 = 2{,}437.5 - 389.6 = 2{,}048.0\,\mathrm{kJ/kg}$
The thermodynamic efficiency of the cycle: $\eta_{\mathrm{th}} = 1 - \dfrac{q_{\mathrm{out}}}{q_{\mathrm{in}}} = \mathbf{0.276\ or\ 27.6}\%$
Therefore, the plant uses only 27.6% of the heat it received in the boiler.
Turbine work output:
$W_{\mathrm{out}} = H_2 - H_3 = 3{,}224.2 - 2{,}437.5 = 786.7\ \mathrm{kJ/kg}$
Net work output:
$W_{\mathrm{net}} = (q_{\mathrm{in}} - q_{\mathrm{out}}) = (2{,}831.1 - 2{,}048.0) = 783.1\ \mathrm{kJ/kg}$

(b) Steam properties (Table F3):
$P_3 = P_4 = 15$ kPa, $T_{\mathrm{sat}} = 327.15$ K, $V_4 = 0.001014\ \mathrm{m^3/kg}$
$H_{3\mathrm{sat\ vap}} = 2{,}599.2$ kJ/kg, $\mathrm{H}_4 = H_{3\mathrm{sat\ liq}} = 226.0$ kJ/kg,
$S_{3\mathrm{sat\ vap}} = 8.0093$ kJ/kg K, $S_{3\mathrm{sat\ liq}} = 0.7550$ kJ/kg K

With a pump efficiency of: $\eta_{\mathrm{pump}} = 100\%$

$$W_{p,\mathrm{in}} = V_1(P_1 - P_4) = (0.001014)(3{,}500 - 15)\left(\frac{1\,\mathrm{kJ}}{1\ \mathrm{kPa\ m^3}}\right) = 3.53\,\mathrm{kJ/kg}$$

$$H_1 = H_4 + W_{p,\mathrm{in}} = 226.0 + 3.53 = 229.5\ \mathrm{kJ/kg}$$

Isentropic process $S_1 = S_4$ and $S_3 = S_2$.
The quality of the discharged wet steam ($S_3 < S_{3\mathrm{sat\ vap}}$): $6.8443 < 8.0093$
$x_{3'} = (6.8443 - 0.7550)/(8.0093 - 0.7550) = 0.84$
$H_{3'} = 226.0(1 - 0.84) + 2{,}599.2 \times 0.84 = 2{,}219.5\ \mathrm{kJ/kg}$

Heat interactions:

$q_{\text{in}} = H_2 - H_1 = 3,224.2 - 229.5 = 2,994.7 \ \text{kJ/kg}$

$q_{\text{out}} = H_{3'} - H_4 = 2,219.5 - 226.0 = 1,993.5 \ \text{kJ/kg}$

The thermal efficiency of the cycle: $\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = \mathbf{0.334 \ or \ 33.4}\%$

Therefore, the plant uses only 33.4% of the heat it received in the boiler.

Turbine work output

$W_{\text{out}} = H_2 - H_{3'} = 3,224.2 - 2,219.5 = 1,004.7 \ \text{kJ/kg}$

Cycle work out:

$W_{\text{net}} = (q_{\text{in}} - q_{\text{out}}) = (2,994.7 - 1,993.5) = 1,001.2 \ \text{kJ/kg}$

For a 360 days of operation = (360)(24) = 8,640 h/year

The annual increase in the net power output:

(20 kg/s)(1,001.2 – 783.1) kJ/kg (8,640) h/year = 37,687,680 kWh/year

For a unit selling price of electricity of $0.1/kWh

Annual saving = **$3,768,768/year**

The thermal efficiency increased from 0.276 to 0.334 by reducing the condenser pressure from 78.5 to 15.0 kPa. However the quality of the discharged steam decreased from 0.9 to 0.84, which is not desirable for the blades of the turbine. Savings are considerable.

Example 9.3 Maximum possible efficiency calculation in Example 9.2

Estimate the maximum possible efficiency for parts (a) and (b) in Example 9.2 and compare them with those obtained in parts (a) and (b) in Example 9.2.

Solution:

(a) The thermal efficiency of a Carnot cycle operating between the same temperature limits: $T_{\text{min}} = T_3 = 366.15$ K and $T_{\text{max}} = T_2 = 673.15$ K

$$\eta_{\text{th, Carnot}} = 1 - \frac{T_{\text{min}}}{T_{\text{max}}} = 1 - \frac{366.15\,\text{K}}{673.15 \ \text{K}} = \mathbf{0.456 \ or \ 45.6}\%$$

The difference between the two efficiencies occurs because of the large temperature differences. The ratio of the efficiencies, $\eta_{\text{th}}/\eta_{\text{th, Carnot}} = 0.276/0.456 = 0.60$ shows that only 60% of the possible efficiency is achieved in the cycle.

(b) The thermal efficiency of a Carnot cycle operating between the same temperature limits: $T_{\text{min}} = T_{3'} = 327.15$ K and $T_{\text{max}} = T_2 = 673.15$ K

$$\eta_{\text{th, Carnot}} = 1 - \frac{T_{\text{min}}}{T_{\text{max}}} = 1 - \frac{327.15}{673.15} = \mathbf{0.514 \ of \ 51.4}\%$$

The ratio of the efficiencies, $\eta_{\text{th}}/\eta_{\text{th, Carnot}} = 0.334/0.51 = 0.65$ shows that only 65% of the possible efficiency is achieved in the cycle.

Example 9.4 Increasing the efficiency of a Rankine cycle by increasing the boiler pressure

A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,500 kPa and 400°C. Discharge pressure of the steam from the turbine is 78.5 kPa.

(a) If the pressure of the boiler is increased to 9,800 kPa while maintaining the turbine inlet temperature at 400°C, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.10/kWh.

Solution:

Assume that the cycle is at steady-state flow and the changes in kinetic and potential energies are negligible. Pump efficiency of $\eta_{\text{pump}} = 1$

Basis: 1 kg/s steam. Using the data from the Appendix: Tables F3 and F4
From Example 9.2 part a: $\eta_{\text{th}} = 0.276$ and $W_{\text{net}} = 783.1$ kJ/kg at 3500 kPa

(a) Superheated steam:
$P_2 = P_1 = 9{,}800$ kPa; $H_2 = 3{,}104.2$ kJ/kg: $S_2 = 6.2325$ kJ/kg K, $T_2 = 400$°C

Saturated steam:
$P_3 = P_4 = 78.5$ kPa, $T_{\text{sat}} = 366.15$ K, $V_4 = 0.001038$ m^3/kg (Table F3)
$H_{3\text{sat vap}} = 2{,}665.0$ kJ/kg; $H_4 = H_{3\text{sat liq}} = 389.6$ kJ/kg;
$S_{3\text{sat vap}} = 7.4416$ kJ/kg K; $S_{3\text{sat liq}} = 1.2271$ kJ/kg K

$$W_{p,\text{in}} = V_1(P_1 - P_4) = (0.001038)(9{,}800 - 78.5)\left(\frac{1\,\text{kJ}}{1\ \text{kPa m}^3}\right) = 10.1\,\text{kJ/kg}$$

$$H_1 = H_4 + W_{p,\text{in}} = 389.6 + 10.1 = 399.7\ \text{kJ/kg}$$

Isentropic process $S_1 = S_4$ and $S_3 = S_2$.
The quality of the discharged wet steam x_3: ($S_3 < S_{3\text{sat vap}}$): $6.2325 < 7.4416$
$x_3 = (6.2325 - 1.2271)/(7.4416 - 1.2271) = 0.80$
$H_3 = 389.6(1 - 0.8) + 2{,}665.0 \times 0.8 = 2{,}210.0\,\text{kJ/kg}$

Heat interactions:
$q_{\text{in}} = H_2 - H_1 = 3{,}104.2 - 399.7 = 2{,}704.5\ \text{kJ/kg}$
$q_{\text{out}} = H_3 - H_4 = 2{,}210.0 - 389.6 = 1{,}820.4\ \text{kJ/kg}$
The thermodynamic efficiency of the cycle: $\eta_{\text{th}} = 1 - \dfrac{q_{\text{out}}}{q_{\text{in}}} = \mathbf{0.326\ or\ 32.6}\%$

Therefore, the plant uses only 32.6% of the heat it received in the boiler.
The thermal efficiency increased from 0.276 to 0.326 by increasing the boiler pressure from 3,500 to 9,800 kPa. However, the quality of the discharged steam decreased from 0.9 to 0.80, which is not desirable for the blades of the turbine.

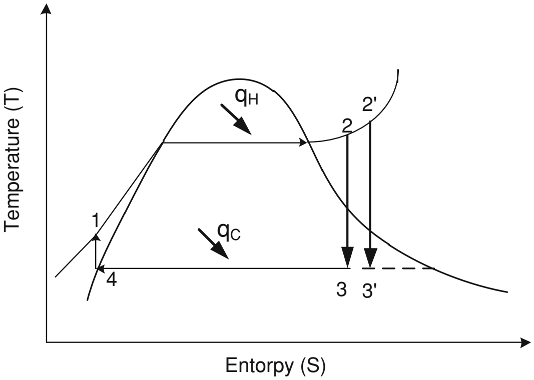
Turbine work output: $W_{\text{out}} = H_3 - H_2 = (3{,}104.2 - 2{,}210.0)\,\text{kJ/kg} = 894.2\ \text{kJ/kg}$
Cycle work out: $W_{\text{net}} = (q_{\text{in}} - q_{\text{out}}) = (2{,}704.5 - 1{,}820.4)\,\text{kJ/kg} = 884.1\ \text{kJ/kg}$

(b) $\dot{m}_s = 20.0$ kg/s,
For a 360 days of operation = (360)(24) = 8,640 h/year
The annual increase in the net power output:
(20 kg/s)(884.1 – 783.1) kJ/kg (8,640) h/year = 17,452,800 kWh/year
For a unit selling price of electricity of $0.1/kWh: annual saving = **$1,745,280**

Example 9.5 Increasing the efficiency of a Rankine cycle by increasing the boiler temperature

A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,500 kPa and 400°C. Discharge pressure of the steam from the turbine is 78.5 kPa.

(a) If the temperature of the boiler is increased to 525°C while maintaining the pressure at 3,500 kPa, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is \$0.10/kWh.



Solution:
Assume that the cycle is at steady-state flow and the changes in kinetic and potential energy are negligible.

(a) Basis: 1 kg/s steam. Using the data from the Appendix: Tables F3 and F4:

From Example 9.2 part a: $\eta_{\mathrm{th}} = 0.276$ and $W_{\mathrm{net}} = 783.1$ kJ/kg at 400°C
Superheated steam:
$P_2 = P_1 = 3{,}500$ kPa; $H_2 = 3{,}506.9$ kJ/kg: $S_2 = 7.2297$ kJ/kg, $T_2 = 525°\mathrm{C}$
Saturated steam:
$P_3 = P_4 = 78.5$ kPa, $T_{\mathrm{sat}} = 366.15$ K, $V_4 = 0.001038$ m^3/kg (Table F3)
$H_{3\mathrm{sat\ vap}} = 2{,}665.0$ kJ/kg, $H_{3\mathrm{sat\ liq}} = 389.6$ kJ/kg, $S_{3\mathrm{sat\ vap}} = 7.4416$ kJ/kg K, $S_{3\mathrm{sat\ liq}} = 1.2271$ kJ/kg K

$$W_{p,\mathrm{in}} = V_1(P_1 - P_4) = (0.001038)(3{,}500 - 78.5)\left(\frac{1\,\mathrm{kJ}}{1\ \mathrm{kPa\ m^3}}\right) = 3.55\,\mathrm{kJ/kg}$$

$$H_1 = H_4 + W_{p,\mathrm{in}} = 389.6 + 3.55 = 393.15\ \mathrm{kJ/kg}$$

Isentropic process $S_1 = S_4$ and $S_3 = S_2$.
The quality of the discharged wet steam ($S_2 < S_{3\mathrm{sat\ vap}}$): $7.2297 < 7.4416$

$$x_{3'} = (7.2297 - 1.2271)/(7.4416 - 1.2271) = 0.96$$

$$H_{3'} = 389.6(1 - 0.96) + 2{,}665.0 \times 0.96 = 2{,}574.0\,\mathrm{kJ/kg}$$

Heat interactions:
$q_{\text{in}} = H_2 - H_1 = 3{,}506.9 - 393.1 = 3{,}113.8\ \text{kJ/kg}$
$q_{\text{out}} = H_{3'} - H_4 = 2{,}574.0 - 389.6 = 2{,}184.4\ \text{kJ/kg}$

The thermodynamic efficiency of the cycle is

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = \mathbf{0.298\ or\ 29.8}\%$$

Therefore, the plant uses only 29.8% of the heat it received in the boiler.
The thermal efficiency increased from 0.276 to 0.298 by increasing the boiler temperature from 400 to 525°C. The quality of the discharged steam increased from 0.9 to 0.96, which is desirable for the protection of the turbine blades.

Turbine work out: $W_{\text{out}} = H_2 - H_{3'} = (3{,}506.9 - 2{,}574.0) = 932.9\ \text{kJ/kg}$
Cycle work out: $W_{\text{net}} = (q_{\text{in}} - q_{\text{out}}) = (3{,}113.8 - 2{,}184.4) = 929.4\ \text{kJ/kg}$

(b) $\dot{m}_s = 20.0\ \text{kg/s}$
For a 360 days of operation = (360)(24) = 8,640 h/year
The annual increase in the net power output
(20 kg/s)(929.4 – 783.1) kJ/kg (8,640) h/year = 25,280,640 kWh/year
With a unit selling price of electricity of \$0.1/kWh: Annual saving = **\$2,528,064**

Example 9.6 Estimation of maximum possible efficiencies in Example 9.5
Estimate the maximum possible efficiency for parts (a) and (b) in Example 9.5 and compare them with those obtained in parts (a) and (b) in Example 9.5.

Solution:

(a) The thermal efficiency of a Carnot cycle operating between the temperature limits of $T_{\text{min}} = 366.15$ K and $T_{\text{max}} = 673.15$ K:

$$\eta_{\text{th, Carnot}} = 1 - \frac{T_{\text{min}}}{T_{\text{max}}} = 1 - \frac{366.15\,\text{K}}{673.15\,\text{K}} = \mathbf{0.45\ or\ 45}\%$$

The ratio of the efficiencies, $\eta_{\text{th}}/\eta_{\text{th,Carnot}} = 0.276/0.45 = 0.61$ shows that only 61% of the possible efficiency is achieved in the cycle with the boiler temperature of 400°C.

(b) The thermal efficiency of a Carnot cycle operating between the temperature limits of $T_{\text{min}} = 366.15$ K and $T_{\text{max}} = 798.15$ K:

$$\eta_{\text{th,Carnot}} = 1 - \frac{T_{\text{min}}}{T_{\text{max}}} = 1 - \frac{366.15\,\text{K}}{798.15\ \text{K}} = \mathbf{0.54\ or\ 54}\%$$

The ratio of the efficiencies, $\eta_{\text{th}}/\eta_{\text{th,Carnot}} = 0.298/0.54 = 0.55$ shows that only 55% of the possible efficiency is achieved in the cycle with the boiler temperature of 525°C.

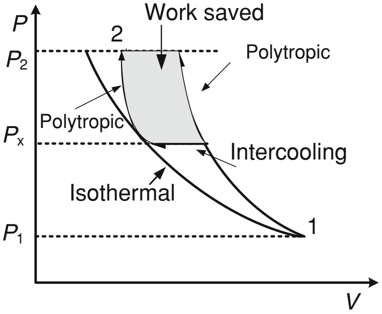


Fig. 9.2 Energy conservation in the compression work by intercooling; the work saved appears between two polytropic compressions starting at the second stage with the pressure P_x

9.2.2 Energy Conservation in the Compression and Expansion Work

It is possible to save energy in the compression work by minimizing the friction, turbulence, heat transfer, and other losses. A practical way of energy conservation is to keep the specific volume of the gas small during the compression work. This is possible by maintaining the temperature of the gas low as the specific volume is proportional to temperature. Therefore, cooling the gas as it is compressed may reduce the cost of compression work in a multistage compression with intercooling as seen in Fig. 9.2. The gas is cooled to the initial temperature between the compression stages by passing the gas through a heat exchanger called the intercooler. Energy recovery by intercooling may be significant especially when a gas is to be compressed to very high pressure [7]. Example 9.7 illustrates the energy conservation in a two-stage compression work by intercooling.

As the Fig. 9.2 shows the work saved varies with the value of intermediate pressure P_x, which needs to be optimized. The total work input for a two-stage compression process is the sum of the work inputs for each stage, and estimated by

$$W_{\text{comp}} = W_{\text{comp1}} + W_{\text{comp2}} \tag{9.4}$$

$$W_{\text{comp}} = \frac{\gamma R T_1}{MW(\gamma - 1)}\left[\left(\frac{P_x}{P_1}\right)^{(\gamma-1)/\gamma}\right] + \frac{\gamma R T_1}{MW(\gamma - 1)}\left[\left(\frac{P_2}{P_x}\right)^{(\gamma-1)/\gamma}\right]$$

In Eq. 9.4, P_x is the only variable. The optimum value of P_x is obtained by differentiation of Eq. 9.4 with respect to P_x and setting the resulting expression equal to zero. Then, the optimum value of P_x becomes

$$P_{\text{x}} = (P_1 P_2)^{1/2} \text{ or } \frac{P_x}{P_1} = \frac{P_2}{P_x} \tag{9.5}$$

Therefore, energy conservation will be maximum, when the pressure ratio across each stage of the compressor is the same and compression work at each stage becomes identical

$$W_{\text{comp1}} = W_{\text{comp2}} \tag{9.6}$$

$$W_{\text{comp}} = \frac{2\gamma R T_1}{MW(\gamma - 1)}\left[\left(\frac{P_x}{P_1}\right)^{(\gamma-1)/\gamma}\right] \tag{9.7}$$

Example 9.8 illustrates the estimation of minimum and actual power required by a compressor. Example 9.9 illustrates how to produce power out of a cryogenic expansion process. Reduction of pressure by using throttling valve wastes the energy. Replacing the throttling valve with a turbine produces power and hence conserves electricity [7].

Example 9.7 Energy conservation in a two-stage compression work by intercooling

Air with a flow rate of 2 kg/s is compressed in a steady-state and reversible process from an inlet state of 100 kPa and 300 K to an exit pressure of 1,000 kPa. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.15/kWh and the compressor is operated 360 days per year.

Solution:

Assumptions: steady-state operation; air is ideal gas; kinetic and potential energies are negligible.

$P_2 = 1{,}000$ kPa, $P_1 = 100$ kPa, $T_1 = 300$ K, $\gamma = 1.3$, $MW_{\text{air}} = 29$ kg/kmol

Basis 1 kg/s air flow rate

(a) Work needed for polytropic compression with $\gamma = 1.3$

$$W_{\text{comp}} = \frac{\gamma R T_1}{MW(\gamma - 1)}\left[\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}\right]$$

$$= \frac{1.3(8.314\,\text{kJ/kmolK})(300\,\text{K})}{29\ \text{kg/kmol}\ (1.3-1)}\left[\left(\frac{1{,}000}{300}\right)^{(1.3-1)/1.3} - 1\right] = \mathbf{261.3\,kJ/kg}$$

(b) Ideal two-stage polytropic compression with intercooling ($\gamma = 1.3$)

$$P_x = (P_1P_2)^{1/2} = (100 \times 1{,}000)^{1/2} = 316.2\,\text{kPa}$$

$$W_{\text{comp}} = \frac{2\gamma R T_1}{MW(\gamma - 1)}\left[\left(\frac{P_x}{P_1}\right)^{(\gamma-1)/\gamma}\right]$$

$$= \frac{2(1.3)(8.314\,\text{kJ/kmolK})(300\,\text{K})}{29\ \text{kg/kmol}\ (1.3-1)}\left[\left(\frac{316.2}{100}\right)^{(1.3-1)/1.3} - 1\right] = \mathbf{226.8\,kJ/kg}$$

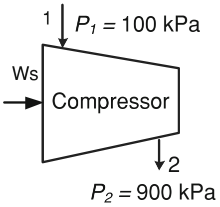
Recovered energy = (261.3 – 226.8) kJ/kg = 34.5 kJ/kg

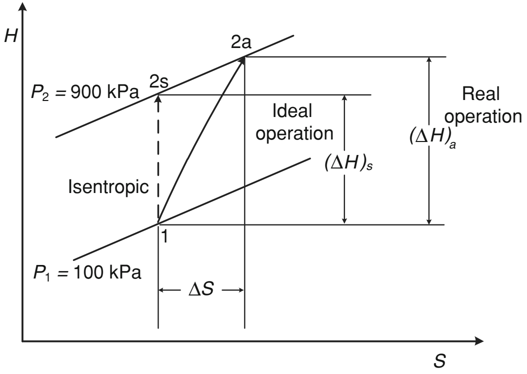
Reduction in energy use: $\dfrac{261.3 - 226.8}{261.3} = 0.13$ or 13%

(c) Conservation of compression work = (2 kg/s) (261.3 – 226.8) kJ/kg = 69 kW
Yearly conserved work: (69 kW) (8,640 h/year) = 596,160 kWh/year
Saving in electricity (2,385,745 kWh/year) ($0.15/kWh) = **$89,424/year**

The compression work has been reduced by 13% when two stages of polytropic compression are used instead of single polytropic compression and conserved 596,160 kWh/year.

Example 9.8 Compressor efficiency and power input
An adiabatic compressor is used to compress air from 100 kPa and 290 K to a pressure of 900 kPa at a steady-state operation. The isentropic efficiency of the compressor is 80%. The air flow rate is 0.4 kg/s. Determine the minimum and actual power needed by the compressor.





Solution:
Assume: steady-state adiabatic operation. Air is ideal gas. The changes in kinetic and potential energies are negligible.

Enthalpies of ideal gas depend on temperature only.
The air mass flow rate = 0.4 kg/s, $\eta_C = 0.8$
Inlet conditions (Table D1):

$P_1 = 100$ kPa, $T_1 = 290$ K, $H_1 = 290.16$ kJ/kg, $Pr_1 = 1.2311$

Exit conditions (Table D1): $P_2 = 900$ kPa
Enthalpy of air at the exit is from Eq. 7.36 and Table D1.

$$Pr_2 = Pr_1 \frac{P_2}{P_1} = 1.2311 \left(\frac{900\,\text{kPa}}{100\ \text{kPa}} \right) = 11.1$$

From Table D1: for $Pr_2 = 11.1$, we find $T_2 = 540$ K and $H_{2\text{s}} = 544.35$ kJ/kg

$$\eta_C = \frac{H_{2s} - H_1}{H_{2a} - H_1} = 0.8 \rightarrow H_{2\text{a}}$$

$H_{2\text{a}} = 607.9$ kJ/kg and $T_2 = 600$ K (Table D1) (Approximate)
As seen from the *TS* diagram above $H_{2\text{a}}$ is the actual enthalpy at the exit.

Actual power required:

$\dot{m}\Delta H_a = \dot{W}_{\text{net, in}} = \dot{m}(H_{2a} - H_1) = 0.4\ \text{kg/s}\ (607.9 - 290.16)\ \text{kJ/kg} = \mathbf{127.1\,kW}$

Minimum power required:

$\dot{m}\Delta H_s = \dot{W}_{\text{net, in}} = \dot{m}(H_{2s} - H_1) = 0.4\ \text{kg/s}\ (544.3 - 290.1)\ \text{kJ/kg} = \mathbf{101.7\,kW}$

If the operation was ideal the rate of conserved energy would be 25.4 kW or 20% savings.

Example 9.9 Energy conservation in expansion by replacing a throttle valve with a turbine

A cryogenic manufacturing plant handles liquid methane at 115 K and 5,000 kPa at a rate of 0.3 m^3/s. In the plant a throttling valve reduces the pressure of liquid methane to 1,000 kPa. A new process considered replaces the throttling valve with a turbine in order to produce power while reducing the pressure to 1,000 kPa at 110 K. Using the data for the properties of liquid methane below estimate:

(a) the power that can be produced by the turbine.

(b) the savings in electricity usage per year if the turbine operates 360 days per year with a unit cost of electricity at $0.09/kWh.

T (K)	P (kPa)	H (kJ/kg)	S (kJ/kg K)	C_p (kJ/kg K)	ρ (kg/m^3)
110	1,000	209.0	4.875	3.471	425.8
110	2,000	210.5	4.867	3.460	426.6
110	5,000	215.0	4.844	3.432	429.1
120	1,000	244.1	5.180	3.543	411.0
120	2,000	245.4	5.171	3.528	412.0
120	5,000	249.6	5.145	3.486	415.2

Source Çengel and Turner [7]

Solution:

Assumptions: steady-state and reversible operation; adiabatic turbine, methane is ideal gas; kinetic and potential energies are negligible.

(a) P_1 = 5,000 kPa, T_1 = 115 K, Q_1 = 0.30 m^3/s

H_1 = 232.3 kJ/kg = (215.0 + 249.6)/2, ρ_1 = 422.15 kg/m^3 = (429.1 + 415.2)/2

P_2 = 1,000 kPa, H_2 = 209.0 kJ/kg

Unit cost of electricity = $0.09/kWh

Mass flow rate: $\dot{m} = \rho Q_1 = 422.15\ \text{kg/m}^3(0.3\ \text{m}^3/\text{s}) = 126.6\,\text{kg/s}$

Power produced:

$\dot{W}_{\text{out}} = \dot{m}(H_1 - H_2) = 126.6\ \text{kg/s}\ (232.5 - 209.0)\text{kJ/kg} = \mathbf{2{,}949.8\,kW}$

Annual power production:

$\dot{W}_{\text{out}}\Delta t = (2{,}949.8\,\text{kW})(360)(24)\text{h/year} = 25{,}486{,}099\ \text{kW}\,\text{h/year}$

Saving in electricity usage:
(25,486,099 kWh/year)($0.09/kWh) = **$2,293,748/year**

Reduction of pressure by using throttling valve wastes the potential of power production. Replacing the valve with a turbine will produce power and hence conserve electricity.

9.2.3 Conservation of Energy by High-Efficiency Electric Motors

Practically all compressors are powered by electric motor. Electric motors cannot convert the electrical energy they consume into mechanical energy completely. Electric motor efficiency is defined by

$$\eta_{\text{Motor}} = \frac{\text{mechanical power}}{\text{electrical power}} = \frac{\dot{W}_{\text{comp}}}{\dot{W}_{\text{elect}}} \tag{9.8}$$

Motor efficiency range: $0.7 < \eta_{\text{motor}} < 96$. The portion of electric energy that is not converted to mechanical power is converted to heat, which is mostly unusable.

For example, assuming that no transmission losses occur:

- A motor with an efficiency of 80% will draw an electrical power of 1/0.8 = 1.25 kW for each kW of shaft power it delivers.
- If the motor is 95% efficient, then it will draw 1/0.95 = 1.05 kW only to deliver 1 kW of shaft work.
- Therefore between these two motors, electric power conservation is 1.25 (η_{motor} = 95%) kW – 1.05 (η_{motor} = 95%) = 0.20 kW.

High-efficiency motors are more expensive but its operation saves energy. Saved energy is estimated by

$$\dot{W}_{\text{elect.saved}} = \dot{W}_{\text{elect.std}} - \dot{W}_{\text{elect.efficient}} = \dot{W}_{\text{comp}}\left(\frac{1}{\eta_{\text{std}}} - \frac{1}{\eta_{\text{efficient}}}\right) \tag{9.9}$$

$$\dot{W}_{\text{elect.saved}} = (\text{Rated power})(\text{Load factor})\left(\frac{1}{\eta_{\text{std}}} - \frac{1}{\eta_{\text{efficient}}}\right) \tag{9.10}$$

where the *rated power* is the nominal power delivered at full load of the motor and listed on its label. *Load factor* is the fraction of the rated power at which the motor normally operates. Annual saving is estimated by

$$\text{Annual energy saving} = (\dot{W}_{\text{elect.saved}})(\text{Annual operation hours}) \tag{9.11}$$

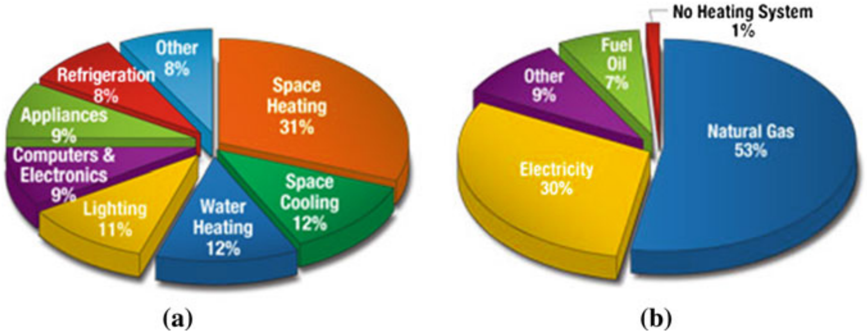


Fig. 9.3 **a** Home usage of energy: Heating is the largest part of the energy cost. Heating and cooling consume more energy than any other system at home. Typically, 50% of the utility bill goes for heating and cooling, **b** Household heating by various sources; use of natural gas has the largest source of fuel for heating houses

- A compressor that operates at partial load causes the motor to operate less efficiently. The efficiency of motor will increase with the load.
- Using the cold outside air for compressor intake lowers the compressor work and conserves energy.

9.3 Energy Conservation in Home Heating and Cooling

Space heating and cooling as well as water heating at home accounts around 55% of the utility bill as seen in Fig. 9.3a. To conserve energy, one should identify from where the home is losing energy, assign priorities, and form an efficiency plan that improves efficiency and reduces costs. For example, the potential energy savings from reducing drafts in a home may range from 5 to 30% per year. Heat loss through the ceiling and walls in your home could be very large if the insulation levels are less than the recommended minimum. Inspect heating and cooling equipment annually, or as recommended by the manufacturer. If the unit is more than 15 years old, the newer and energy-efficient units may reduce the cost [1, 2, 20]. Sources for heating vary as seen in Fig. 9.3b. Use of natural gas has the largest source of fuel for heating houses in the United States. In colder climates, windows that are gas filled with low emissivity coatings on the glass reduces heat loss. In warmer climates, windows with selective coatings may reduce heat gain (see Fig. 9.4). Setting the thermostat low in the winter and high in the summer as comfortable as possible may reduce the cost of heating and cooling. Also the followings can reduce the cost:

- Clean or replace filters on furnaces once a month or as needed.
- Clean baseboard heaters and radiators and make sure they are not blocked.

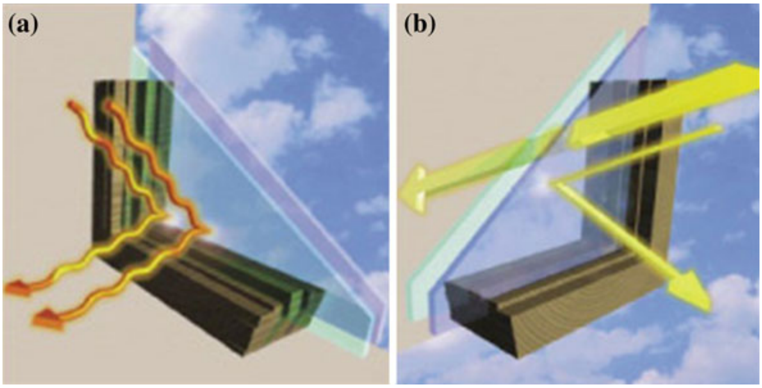


Fig. 9.4 **a** Double-pane windows with low-emittance coating on the glass reflect heat back into the room during the winter months, **b** Windows with low-emittance coatings on the glass reflect some of the sunlight, keeping your rooms cooler [26]

- During summer, keep the window coverings closed during the day to lower solar gain.
- Select energy-efficient products when you buy new heating and cooling equipment.

Water heating typically accounts for about 12% of your utility bill. Insulate the electric, natural gas, or oil hot-water storage tank as shown in Fig. 9.5. Most water heaters can last around 15 years. However replacing the units older than 7 years may reduce the cost of energy.

9.3.1 Home Heating by Fossil Fuels

Residential furnaces have a heat input rate of less than 225,000 Btu/h (66,000 W) and residential boilers have a heat input rate of less than 300,000 Btu/h (88,000 W). The residential furnace is an appliance that provides heated air with a blower to circulate air through the duct distribution system. The residential boiler is a cast-iron, steel, aluminum, or copper pressure vessel heat exchanger designed to burn fossil fuels to heat a suitable medium such as water. Hot water can be distributed via baseboard radiators or radiant floor systems, while steam is distributed through pipes to steam radiators. Furnaces heat air and distribute the heated air through the house using ducts, while boilers heat water, providing either hot water or steam for heating. Most furnaces and boilers operate on natural gas, oil, or propane. Steam boilers operate at a higher temperature than hot-water boilers. Oil-fired furnaces and boilers can use heating oil blended with biodiesel, which produce less pollution than pure heating oil [20, 23].

A condensing furnace or boiler condenses the water vapor produced in the combustion process and uses the heat from this condensation. Although

Fig. 9.5 Water heater

condensing units cost more than non-condensing units, the condensing unit can reduce the consumption of fuel and the cost over the 15-to 20-year life of the unit. Old furnaces and boilers can be retrofitted to increase their efficiency. Some retrofitting options include installing programmable thermostats, upgrading ductwork in forced-air systems, and adding zone control for hot-water systems. Still the costs of retrofits should be compared with the cost of a new boiler or furnace.

9.3.2 Home Heating by Electric Resistance

An all-electric furnace or boiler has no flue loss through a chimney. Electric resistance heating converts nearly 100% of the energy in the electricity to heat. However, most electricity is produced from oil, natural gas, or coal by converting only about 30% of the fuel's energy into electricity. Because of production and transmission losses, electric heat is often more expensive than heat produced using combustion appliances, such as natural gas, propane, and oil furnaces. Heat pumps are preferable in most climates, as they easily cut electricity use by 50% when compared with electric resistance heating. It is also possible to use heat storage systems to avoid heating during times of peak power demand [3].

Blowers (large fans) in electric furnaces move air over a group of three to seven electric resistance coils, called elements, each of which is typically rated at 5 kW. A built-in thermostat prevents overheating and may shut the furnace off if the blower fails or if a dirty filter blocks the airflow.

When operated in heating mode, a heat pump is more efficient than operating resistance heaters. Because an electric heater can convert only the input electrical energy directly to output heat energy with none of the efficiency or conversion advantages of a heat pump. Likewise, when a heat pump operates near its most inefficient outside temperature, typically 0°F, the heat pump will perform close to the same as a resistance heater. Example 9.10 illustrates a simple analysis of heating a house by heat pump. Example 9.11 discusses the energy conservation in house heating by Carnot heat pump.

Fig. 9.6 A home using a liquid-based solar system for space and water heating. The solar units are environmentally friendly and can be installed on roof to blend with the architecture of a house [18, 26]

9.3.3 Home Heating by Solar Systems

Active or passive solar systems can be used for residential heating. There are two basic types of active solar heating systems using either liquid or air heated in the solar collectors. The solar units are environmentally friendly and can now be installed on an a roof to blend with the architecture of a house. *Liquid-based systems*, as shown in Fig. 9.6, heat water or an antifreeze solution, whereas *air-based systems* heat air in an air collector [10]. A circulating pump transports the fluid through the collector so its temperature increases 10–20°F (5.6–11°C). The flow rate through a solar-water collector should be between 0.02 and 0.03 gallons per minute per square foot of collector. Both of these systems absorb solar radiation and transfer it directly to the interior space or to a storage system. Liquid systems are more often used when storage is included, and are well suited for boilers with hot-water radiators and heat pumps. These collectors easily last decades.

Active solar heating systems may reduce the cost more when they are used for most of the year. The economics of an active space heating system improve if it also heats domestic water. Heating homes with active solar energy systems can significantly reduce the fossil fuel consumptions, air pollution, and emission of greenhouse gases [19].

Passive solar heaters do not have fans or blowers. In passive solar building design, windows, walls, and floors are made to collect, store, and distribute solar energy in the form of heat in the winter and reject solar heat in the summer. A passive solar building takes advantage of the local climate. Elements to be considered include window placement, thermal insulation, thermal mass, and shading.

Example 9.10 Heating a house by heat pump

A heat pump is used to heat a house and maintain it at 18°C. On a day where the outside temperature is −2°C, the house is losing heat at a rate of 75,000 kJ/h. The heat pump operates with a coefficient of performance (COP) of 2.8. Determine (a) power needed by the heat pump, (b) the rate of heat absorbed from the surrounding cold air.

Solution:
Assume: steady-state operation.

(a) House is maintained at 18°C.
Heat pump must supply the same amount of lost heat from the cold source:
q_H = 75,000 kJ/h = 20.83 kW
Power required by the heat pump:

$$\mathrm{COP_{HP}} = \frac{\dot{q}_H}{\dot{W}_{\mathrm{net,\,in}}} \rightarrow \dot{W}_{\mathrm{net,\,in}} = \frac{\dot{q}_H}{\mathrm{COP_{HP}}} = \frac{20.83\,\mathrm{kW}}{2.8} = \mathbf{7.44\,kW}$$

(b) Energy balance: $\dot{q}_H - \dot{q}_C = \dot{W}_{\mathrm{net,\,in}} = 7.44\ \mathrm{kW}$
$\dot{q}_C = \dot{q}_H - \dot{W}_{\mathrm{net,\,in}} = (20.83 - 7.44)\mathrm{kW} = \mathbf{13.39\,kW}$
13.39 kW is extracted from the outside. The house is paying only for the energy of 7.44 kW that is supplied as electrical work to the heat pump.
If we have to use electricity in a resistance heater we have to supply 20.83 kW, so the energy conserved by using heat pump instead of electric heater is 13.39/20.83 = 0.64 (or 64%).

Example 9.11 Energy conservation in house heating by Carnot heat pump

A Carnot heat pump is used to heat a house during the winter. The house is maintained at 20°C. The house is estimated to be losing heat at a rate of 120,000 kJ/h when the outside temperature is −4°C. Determine the minimum power needed by the heat pump and the rate of heat absorbed from the surrounding cold air.

Solution:
Assume: Steady-state operation.

The temperatures of hot and cold sources:
$T_H = 273.15 + 20°\mathrm{C} = 293.15$ K and $T_C = 273.15 - 4°\mathrm{C} = 269.15$ K
The amount of heat to be supplied to warm inside room:
$q_H = 120{,}000$ kJ/h $= 33.33$ kW
Minimum amount of power is possible only for a fully reversible heat pump. This heat pump is Carnot heat pump.
Coefficient of performance for a Carnot heat pump:

$$\mathrm{COP_{HP}} = \frac{\dot{q}_H}{\dot{W}_{\mathrm{net,\,in}}} = \frac{1}{1 - (T_C/T_H)} = \frac{1}{1 - (269.15\,\mathrm{K}/293.15\,\mathrm{K})} = 12.2$$

Since the house is losing heat at a rate of 120,000 kJ/h to maintain the house 20°C, the heat pump must supply the same amount of heat from the cold source:

Energy balance: $\mathrm{COP_{HP}} = \frac{\dot{q}_H}{\dot{W}_{\mathrm{net,\,in}}} \rightarrow \dot{W}_{\mathrm{net,\,in}} = \frac{\dot{q}_H}{\mathrm{COP_{HP}}} = \mathbf{2.73\,kW}$

Table 9.1 Some typical values of annual fuel utilization efficiency (AFUE) for furnace and boilers

Fuel	Furnace/boiler	AFUE (%)
Heating oil	Cast-iron (pre-1970)	60
	Retention head burner	70–78
	Mid-efficiency	83–89
Electric heating	Central or baseboard	100
Natural gas	Conventional	55–65
	Mid-efficiency	78–84
	Condensing	90–97
Propane	Conventional	55–65
	Mid-efficiency	79–85
	Condensing	88–95
Firewood	Conventional	45–55
	Advanced	55–65
	State-of-the-Art	75–90

Lekov et al. [21]

$$\dot{q}_C = \dot{q}_H - \dot{W}_{\mathrm{net,\,in}} = (33.3 - 2.73)\mathrm{kW} = \mathbf{30.57\,kW}$$

The house pays for only 2.73 kW. If we use electricity for heating by an electric resistance heater, the rate of heat necessary is 33.3 kW. A necessary heat of 30.6 kW is supplied from the surrounding cold air. Therefore, the energy conserved is 30.6/33.3 = 0.92 (or 92%).

9.4 Energy Efficiency Standards

Thermal efficiency of residential furnaces and boilers is measured by annual fuel utilization efficiency (AFUE). Annual fuel utilization efficiency is the ratio of heat output of the furnace or boiler compared to the total energy consumed by them over a typical year. Annual fuel utilization efficiency does not account for the circulating air and combustion fan power consumptions and the heat losses of the distributing systems of duct or piping. An AFUE of 90% means that 90% of the energy in the fuel becomes heat for the home and the other 10% escapes up the chimney and elsewhere. Heat losses of the duct system or piping can be as much as 35% of the energy output of the furnace. Table 9.1 shows some typical values of AFUE for furnace and boiler using various fossil fuels and electricity [21]. Some of the minimum allowed AFUE ratings in the United States are:

- Non-condensing fossil-fueled, warm-air furnace is 78%.
- Fossil-fueled boiler is 80%.
- Gas-fueled steam boiler is 75%.

The annual savings from replacement of heating system with more efficient one may be estimated by using Table 9.2 assuming that both systems have the same

Table 9.2 Assuming the same heat output, estimated savings for every $100 of fuel costs by increasing an existing heating equipment efficiency

Existing System AFUE (%)	New and upgraded system AFUE (%)							
	60	65	70	75	80	85	90	95
55	$8.3	$15.4	$21.4	$26.7	$31.2	$35.3	$38.9	$42.1
60	–	$7.7	$14.3	$20.0	$25.0	$29.4	$33.3	$37.8
65	–	–	$7.1	$13.3	$18.8	$23.5	$27.8	$31.6
70	–	–	–	$6.7	$12.5	$17.6	$22.2	$26.3
75	–	–	–	–	$6.5	$11.8	$16.7	$21.1
80	–	–	–	–	–	$5.9	$11.1	$15.8
85	–	–	–	–	–	–	$5.6	$10.5

Lekov et al. [21]

heat output. For older units, actual savings in upgrading to a new system could be much higher than that indicated in the table.

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) is an international technical society for heating, ventilation, air-conditioning, and refrigeration. AFUE is calculated using ASHRAE Standard 103 (ASHRAE 2007). A furnace with a thermal efficiency of 78% may yield an AFUE of only 64% or so, for example, under the standards' test conditions.

9.4.1 Efficiency of Air Conditioner

The Energy Efficiency Ratio (EER) of a particular cooling device is the ratio of *output* cooling (in Btu/h) to *input* electrical power (in Watts) at a given operating point. The efficiency of air conditioners is often rated by the *Seasonal Energy Efficiency Ratio* (SEER). The SEER rating of a unit is the cooling output in Btu during a typical cooling season divided by the total electric energy input in watt-hours during the same period. The coefficient of performance (COP) is an instantaneous measure (i.e. a measure of power divided by power), whereas both EER and SEER are averaged over a duration of time. The time duration considered is several hours of constant conditions for EER, and a full year of typical meteorological and indoor conditions for SEER. Typical EER for residential central cooling units $= 0.875 \times$ SEER. A SEER of 13 is approximately equivalent to a COP of 3.43, which means that 3.43 units of heat energy are removed from indoors per unit of work energy used to run the heat pump. SEER rating more accurately reflects overall system efficiency on a seasonal basis and EER reflects the system's energy efficiency at peak day operations.

Air conditioner sizes are often given as "tons" of cooling where 1 ton of cooling is being equivalent to 12,000 Btu/h (3,500 W). This is approximately the power required to melt one ton of ice in 24 h. Example 9.12 illustrates the estimation of electric cost of an air conditioner.

Example 9.12 Electricity cost of air conditioner

Estimate the cost of electricity for a 5,000 Btu/h (1,500 W) air-conditioning unit operating, with a SEER of 10 Btu/W h. The unit is used for a total of 1,500 h during an annual cooling season and the unit cost of electricity is \$0.14/kWh.

Solution:

Air conditioner sizes are often given as "tons" of cooling where 1 ton of cooling is being equivalent to 12,000 Btu/h (3,500 W).

The unit considered is a small unit and the annual total cooling output would be:

(5,000 Btu/h) × (1,500 h/year) = 7,500,000 Btu/year

With a seasonal energy efficiency ratio (SEER) of 10, the annual electrical energy usage:

(7,500,000 Btu/year)/(10 Btu/Wh) = 750,000 Wh/year = 750 kW h/year

With a unit cost of electricity of \$0.14/kWh, the annual cost:

(750 kWh/year)(\$0.14/kWh) = **\$105/year**

The average power usage may also be calculated more simply by:

Average power = (Btu/hr)/(SEER, Btu/Wh) = 5,000/10 = 500 W = 0.5 kW

With the electricity cost of \$0.14/kWh, the cost per hour:

(0.5 kW) (\$0.14)/kWh = \$0.07/h

For 1,500 h/year, the total cost: (\$0.07/h) (1,500 h/year) **= \$105**

9.4.2 Maximum Possible Efficiency for Cooling

The refrigeration process with the maximum possible efficiency is the Carnot cycle. The coefficient of performance (COP) of an air conditioner using the Carnot cycle is:

$$\mathrm{COP}_{\mathrm{Carnot}} = \frac{T_C}{T_H - T_C} \tag{9.12}$$

where T_C is the indoor temperature and T_H is the outdoor temperature in K or R. The EER is calculated by multiplying the COP by 3.413 which is the conversion factor from Btu/h to Watts:

$$\mathrm{EER}_{\mathrm{Carnot}} = 3.413(\mathrm{COP}_{\mathrm{Carnot}}) \tag{9.13}$$

For an outdoor temperature of 100°F (311 K) and an indoor temperature of 95°F (308 K), the above equation gives a COP of 103, or an EER of 350. This is about 10 times as efficient as a typical home air conditioner available today. The maximum EER decreases as the difference between the inside and outside air temperature increases. For example:

T_H = 120 F (49°C) = 322.15 K, and T_C = 80°F (27°C) = 300.15 K

$\mathrm{COP}_{\mathrm{Carnot}}$ = 300.15 K/(322.15 – 300.15) K = 13.6 or
EER = (3.413) (13.6) = 46.4

The maximum SEER can be calculated by averaging the maximum values of EER over the range of expected temperatures for the season.

Central air conditioners should have a SEER of at least 14. Substantial energy savings can be obtained from more efficient systems. For example:

By upgrading from SEER 9 to SEER 13.
Reduction in power consumption = (1 − 9/13) = 0.30.

This means that the power consumption is reduced by 30%. Residential air condition units may be available with SEER ratings up to 26. Example 9.13 illustrates the calculation of the annual cost of power used by an air conditioner. Example 9.14 discusses possible saving in cooling by using a unit operating at a higher SEER rating.

Example 9.13 Calculating the annual cost of power for an air conditioner
Estimate the annual cost of electric power consumed by a 6 ton air conditioning unit operating for 2,000 h per year with a SEER rating of 10 and a power cost of $0.16/kWh.

Solution:
Air conditioner sizes are often given as "tons" of cooling:
1 ton of cooling = 12,000 Btu/h (3,500 W).
This is approximately the power required to melt one ton of ice in 24 h.
The annual cost of electric power consumption: (6)(12,000 Btu/h) = 72,000 Btu/h

$$\text{Cost} = \frac{(\text{Size, Btu/h})(\text{time, h/year})(\text{Cost of energy, \$/kWh})}{(\text{SEER, Btu/Wh})(1{,}000\,\text{W/kW})}$$

(72,000 Btu/h)(2,000 h/year)($0.16/kWh)/[(10 Btu/W h)(1,000 W/kW)]
= **$2,304/ year**

For the temperatures of hot and cold sources:

$T_H = 273.15 + 20°\text{C} = 293.15\ \text{K}$

$T_C = 273.15 - 4°\text{C} = 269.15\ \text{K}$

$T_H - T_C = 24\ \text{K}$

$$\text{EER}_{\text{Carnot}} = 3.41\left(\frac{T_C}{T_H - T_C}\right) = 3.41(269.13/24) = \mathbf{38.24}$$

The maximum EER decreases as the difference between the inside and outside air temperature increases.

Example 9.14 Reducing the cost of cooling with a unit operating at a higher SEER rating
A 4 ton current residential air conditioner operates with a seasonal energy efficiency ratio (SEER) rating of 10. This unit will be replaced with a newer unit operating with a SEER rating of 22. The unit operates 130 days with an average 10 h per day. Average inside and outside temperatures are 21 and 3°C, respectively. The unit cost of energy is $0.16/kWh. Estimate the savings in the cost of electricity and the maximum energy efficiency ratio.

Solution:
Cooling load of 4 tons: (4)(12,000 Btu/h) = 48,000 Btu/h (14,000 W).
(130 days/year)(10 h/day) = 1,300 h/year
The estimated cost of electrical power:
SEER = 10, and an energy cost of \$0.16/kWh, using 130 days of 10 h/day operation:
Cost = (48,000 Btu/h)(1,300 h/year)(\$0.16/kWh)/[(10 Btu/W h)(1,000 W/kW)]
= \$998.4/year
SEER = 22, and an energy cost of \$0.16/kWh, using 130 days of 10 h/day operation:
Cost = (48,000 Btu/h)(1,300 h/year)(\$0.16/kWh)/[(22 Btu/W h)(1,000 W/kW)]
= \$453.8/year
Annual saving = \$998.4/year − \$453.8/year = **\$44.6/year**
The ratio of typical EER to maximum $\text{EER}/\text{EER}_{\text{max}} = 19.25/52.31 = 0.368$

Typical EER for the current cooling unit:
EER = 0.875 (SEER) = 0.875 (10) = 8.75

Typical EER for the new cooling unit:
EER = 0.875 (SEER) = 0.875 (22) = 19.25

Maximum value of EER:
The temperatures of hot and cold sources:
$T_H = 273.15 + 21°\text{C} = 294.15\ \text{K}$
$T_C = 273.15 + 3°\text{C} = 276.15\ \text{K}$
$T_H - T_C = 18\ \text{K}$

$$\text{EER}_{\text{Carnot}} = 3.41\left(\frac{T_C}{T_H - T_C}\right) = 3.41(276.13/18) = \mathbf{52.31}$$

The maximum EER decreases as the difference between the inside and outside air temperature increases. The annual saving is significant after using a more efficient unit. The value of EER for the new unit is only 36.6% of the maximum value of EER.

9.4.3 Fuel Efficiency

Fuel efficiency means the efficiency of a process that converts chemical energy contained in a fuel into kinetic energy or work. The increased fuel efficiency is especially beneficial for fossil fuel power plants or industries dealing with combustion of fuels. In the transportation field, fuel efficiency is expressed in miles per gallon (mpg) or kilometers per liter (km/l). Fuel efficiency is dependent on many parameters of a vehicle, including its engine parameters, aerodynamic drag, and weight. Hybrid vehicles offer higher fuel efficiency using two or more power sources for propulsion, such as a small combustion engine combined with and electric motors [21, 16, 11]. Example 9.15 compares the heating by electricity and by natural gas. Examples 9.16 and 9.17 discuss the amounts of coal necessary in a coal-fired steam power plant in two different efficiency values for the combustion and generator efficiency. The examples show that with the increased combustion efficiency and generator efficiency, the required amount of coal is reduced to 23.9 from 36.6 ton/h. This leads to around 35% savings of coal.

Example 9.15 Comparison of energy sources of electricity with natural gas for heating

The efficiency of electric heater is around 73%, while it is 38% for natural gas heaters. A house heating requires 4 kW. The unit cost of electricity is \$0.1/kWh, while the natural gas costs \$0.60/therm. Estimate the rate of energy consumptions for both the electric and gas heating systems.

Solution:

Energy supplied by the electric heater:

$q_{\text{used}} = q_{\text{in}}\, \eta_{\text{th}} = (4\text{ kW})\,(0.73) = 2.92\text{ kW}$

The unit cost of energy is inversely proportional to the efficiency:

Unit cost of electric energy = (unit cost of energy)/(efficiency)

= \$0.1/0.73 = **\$0.137/kWh**

Therm = 29.3 kWh (Table 1.10)

Energy input to the gas heater (at the same rate of used energy that is 2.92 kW):

$q_{\text{in, gas}} = q_{\text{used}}/\eta_{\text{th}} = 2.92/0.38 = 3.84\text{ kW}$ (=13100 Btu/h)

Therefore, a gas burner should have a rating of at least 13,100 Btu/h to have the same performance as the electric unit.

Unit cost of energy from the gas = cost of energy/efficiency

= [(\$0.60/therm)/(29.3 kWh/therm)]/0.38

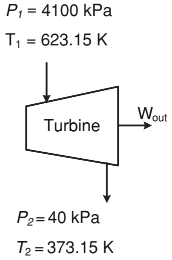
= **\$0.054/kWh**

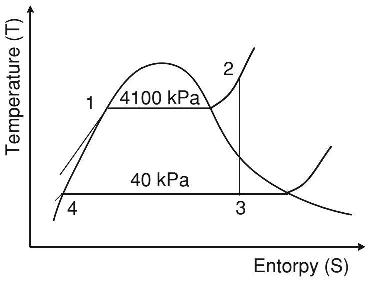
Ratio of unit cost of gas to electric energy; \$0.054/\$0.137 = 0.39

The cost of utilized natural gas is around 39% of the electricity cost; therefore heating with an electric heater will cost more for heating.

Example 9.16 Overall plant efficiency and required amount of coal in a coal-fired steam power plant

An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The power output is 50 MW. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.75 and the generator efficiency is 0.9, determine the overall plant efficiency and the amount of coal supplied per hour.





Solution:
Assume: steady-state adiabatic operation. The changes in kinetic and potential energies are negligible.

Basis: steam flow rate = 1 kg/s
Combustion efficiency $\eta_{comb} = 0.75$
Generator efficiency $\eta_{gen} = 0.9$
Power output = 50 MW = 50,000 kW
From Table F4:
Turbine inlet conditions:
$P_2 = 4{,}100$ kPa, $T_2 = 623.15$ K, $H_2 = 3{,}092.8$ kJ/kg, $S_2 = 6.5727$ kJ/kg K
Turbine outlet conditions:
$P_4 = P_3 = 40$ kPa, $T_3 = 373.15$ K, $V_4 = 1.027$ cm^3/g = 0.001027 m^3/kg
$S_{4\text{sat vap}} = 7.6709$ kJ/kg K, $S_{4\text{sat liq}} = 1.2026$ kJ/kg K at 40 kPa
$H_{4\text{sat vap}} = 2{,}636.9$ kJ/kg, $H_{4\text{sat liq}} = 317.6$ kJ/kg at 40 kPa (Table F3)

$$W_{p,\text{in}} = V_4(P_1 - P_4) = (0.001027\ \text{m}^3/\text{kg})\,(4{,}100 - 40)\text{kPa}\left(1\ \text{kJ}/1\,\text{kPa m}^3\right) = 4.2\ \text{kJ/kg}$$
$$H_1 = H_4 + W_{p,\text{in}} = 317.6 + 4.2 = 321.8\ \text{kJ/kg}$$

For the isentropic operation $S_3 = S_2 = 6.5727$ kJ/kg K
Since $S_2 < S_{3\text{sat vap}}$: $6.5727 < 7.6709$ the steam at the exit is saturated liquid–vapor mixture.

Quality of that mixture: $x_3 = \dfrac{S_2 - S_{2\text{sat liq}}}{S_{2\text{sat vap}} - S_{2\text{sat liq}}} = \dfrac{6.5727 - 1.2026}{7.6709 - 1.2026} = 0.83$
$$H_3 = (1 - x_3)H_{3\text{sat liq}} + x_3 H_{3\text{sat vap}} = 2243.1\,\text{kJ/kg}$$

Heat interactions:
$$q_{in} = \dot{m}(H_2 - H_1) = (3{,}092.8 - 321.8)\,\text{kJ/kg} = 2771.0\,\text{kJ/s}$$
$$q_{out} = \dot{m}(H_3 - H_4) = (2{,}243.1 - 317.6)\,\text{kJ/kg} = 1{,}925.5\,\text{kJ/s}$$

Thermal efficiency: $\eta_{th} = 1 - \dfrac{q_{out}}{q_{in}} = 0.305$ or 30.5%
Overall plant efficiency: $\eta_{overall} = \eta_{th}\eta_{comb}\eta_{gen}$ = (0.305)(0.75)(0.9) = **0.205 or 20.5%**

The rate of coal energy required: $\dot{E}_{coal} = \dfrac{\dot{W}_{net}}{\eta_{overall}} = \dfrac{50{,}000\,\text{kW}}{0.205}$ = 243,900 kJ/s
Energy of coal (bituminous) = 24,000 kJ/kg (Table 2.6)
$\dot{m}_{coal} = \dfrac{\dot{E}_{coal}}{\eta_{overall}} = \dfrac{243{,}900}{24{,}000}\left(\dfrac{1\ \text{ton}}{1{,}000\ \text{kg}}\right)$ = 0.0101 ton/s = **36.6 ton/h**

Example 9.17 Required amount of coal in a coal-fired steam power plant
An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The steam flow rate is 42 kg/s. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.77 and the generator efficiency is 0.95, determine the overall plant efficiency and the amount of coal supplied per hour.

Solution:
Assume: steady-state adiabatic operation. The changes in kinetic and potential energies are negligible.

Basis: steam flow rate = 1 kg/s
Combustion efficiency $\eta_{\mathrm{comb}} = 0.77$
Generator efficiency $\eta_{\mathrm{gen}} = 0.95$

Turbine inlet:
$P_2 = 4{,}100$ kPa, $T_2 = 623.15$ K, $H_2 = 3{,}092.8$ kJ/kg, $S_2 = 6.5727$ kJ/kg K (Table F4)

Turbine exit:
$P_4 = P_3 = 40$ kPa $T_3 = 373.15$ K, $V_4 = 1.027$ cm^3/g $= 0.001027$ m^3/kg (Table F3)
$S_{4\mathrm{sat\ vap}} = 7.6709$ kJ/kg K, $S_{4\mathrm{sat\ liq}} = 1.2026$ kJ/kg K at 40 kPa
$H_{4\mathrm{sat\ vap}} = 2{,}636.9$ kJ/kg, $H_{4\mathrm{sat\ liq}} = 317.6$ kJ/kg at 40 kPa (Table F4)

$$W_{p,\mathrm{in}} = V_4(P_1 - P_4) = (0.001027\ \mathrm{m3/kg})(4{,}100 - 40)\ \mathrm{kPa}\ (1\ \mathrm{kJ}/1\ \mathrm{kPa\ m}^3)$$
$$= 4.2\ \mathrm{kJ/kg}$$

$H_1 = H_4 + W_{p,\mathrm{in}} = 317.6 + 4.2 = 321.8$ kJ/kg
For the isentropic operation $S_3 = S_2 = 6.5727$ kJ/kg K
Since $S_2 < S_{3\mathrm{sat\ vap}}$: $6.5727 < 7.6709$ the steam at the exit is saturated liquid–vapor mixture.

Quality of the mixture: $x_3 = \dfrac{S_2 - S_{2\mathrm{sat\,liq}}}{S_{2\mathrm{sat\,vap}} - S_{2\mathrm{sat\,liq}}} = \dfrac{6.5727 - 1.2026}{7.6709 - 1.2026} = 0.83$

$H_3 = (1 - x_3)H_{3\mathrm{sat\,liq}} + x_3 H_{3\mathrm{sat\,vap}} = 2{,}243.1\ \mathrm{kJ/kg}$

Heat interactions:
$q_{\mathrm{in}} = (H_2 - H_1) = (3{,}092.8 - 321.8)\ \mathrm{kJ/kg} = 2{,}771.0\ \mathrm{kJ/kg}$
$q_{\mathrm{out}} = (H_3 - H_4) = (2{,}243.1 - 317.6)\ \mathrm{kJ/kg} = 1{,}925.5\ \ \mathrm{kJ/kg}$
$\dot{W}_{\mathrm{net\,out}} = \dot{m}(q_{\mathrm{in}} - q_{\mathrm{out}}) = (42\ \mathrm{kg/s})(2{,}771.0 - 19{,}25.5)\ \mathrm{kJ/kg} = 35{,}511\ \mathrm{kW}$

The thermal efficiency
$\eta_{\mathrm{th}} = 1 - \dfrac{q_{\mathrm{out}}}{q_{\mathrm{in}}} = 0.305$ or 30.5%

The overall plant efficiency: $\eta_{\mathrm{overall}} = \eta_{\mathrm{th}}\eta_{\mathrm{comb}}\eta_{\mathrm{gen}} = (0.305)(0.77)(0.95) = 0.223$

The rate of coal energy supply: $\dot{E}_{\mathrm{coal}} = \dfrac{\dot{W}_{\mathrm{net}}}{\eta_{\mathrm{overall}}} = \dfrac{35{,}511}{0.223} = 159{,}165\ \mathrm{kJ/s}$

Energy of coal (bituminous) = 24,000 kJ/kg (Table 2.8 and Table 2.9)

$$\dot{m}_{\mathrm{coal}} = \frac{\dot{E}_{\mathrm{coal}}}{\eta_{\mathrm{overall}}} = \frac{159{,}165}{24{,}000}\left(\frac{1\ \mathrm{ton}}{1{,}000\ \mathrm{kg}}\right) = 0.0066\ \mathrm{ton/s} = 23.9\ \mathrm{ton/h}$$

With the increased combustion efficiency and generator efficiency, the required amount of coal is reduced to 23.9 from 36.6 ton/h. This leads to around 35% savings of coal.

9.4.4 Fuel Efficiency of Vehicles

The fuel efficiency of vehicles can be expressed in miles per gallon (mpg) or liters (l) per km. Comparison reveals:

- An average north American mid-size car travels 21 mpg (US) (11 l/100 km) city, 27 mpg (US) (9 l/100 km) highway.
- A modern European mid-size car travels 36 mpg (6.5 l/100 km) city, 47 mpg (5 l/100 km) motorway

Diesel engines generally achieve greater fuel efficiency than gasoline engines. Passenger car diesel engines have energy efficiency of up to 41% but more typically 30%, and petrol engines of up to 37.3%, but more typically 20%. The higher compression ratio is helpful in raising the energy efficiency, but diesel fuel also contains approximately 10% more energy per unit volume than gasoline which contributes to the reduced fuel consumption for a given power output.

Fuel efficiency directly affects emissions causing pollution. Cars can run on a variety of fuel sources, such as gasoline, natural gas, liquefied petroleum gases, biofuel, or electricity. All these create various quantities of atmospheric pollution. A kilogram of carbon produces approximately 3.63 kg of CO_2 emissions. Typical average emissions from combustion of gasoline and diesel are:

- Gasoline combustion emits 19.4 lb CO_2/US gal or (2.32 kg CO_2/l)
- Diesel combustion emits 22.2 lb CO_2/US gal or (2.66 kg CO_2/l)

These values are only the CO_2 emissions of the final forms of fuel products and do not include additional CO_2 emissions created during the drilling, pumping, transportation, and refining steps of the fuel production [11]. Examples 9.18 and 9.19 illustrate the estimation of fuel consumption of a car and show that the conservation in fuel and reduction in emission of CO_2 are significant when the fuel efficiency of car increases.

Example 9.18 Fuel consumption of a car

The overall efficiencies are about 25–28% for gasoline car engines, 34–38% for diesel engines, and 40–60% for large power plants [7]. A car engine with a power output of 120 hp has a thermal efficiency of 24%. Determine the fuel consumption of the car if the fuel has a higher heating value of 20,400 Btu/lb.

Solution:
Assume: the car has a constant power output.
Gasoline car engine:

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{q}_{\text{in}}} \rightarrow \dot{q}_{\text{in}} = \frac{\dot{W}_{\text{net}}}{\eta_{\text{th}}} = \frac{120\,\text{hp}}{0.24}\left(\frac{2{,}545\,\text{Btu/h}}{\text{hp}}\right)$$

$$\dot{q}_{\text{in}} = 1{,}272{,}500\,\text{Btu/hr}$$

Net heating value = higher heating value (1 – 0.1) = 18,360 Btu/lb (approximately)

Fuel consumption = $\dot{q}_{\text{in}}$/net heating value = 1,272,500 Btu/h/18,360 Btu/lb = 69.3 lb/h

Assuming an average gasoline density of 0.75 kg/l:

ρ_{gas} = (0.75 kg/l)(2.2 lb/kg)(l/0.264 gal) = 6.25 lb/gal

Fuel consumption in terms of gallon: (69.3 lb/h)/(6.25 lb/gal) = **11.1 gal/h**
Diesel engine with an efficiency of 36%:

$$\eta_{\mathrm{th}} = \frac{\dot{W}_{\mathrm{net}}}{\dot{q}_{\mathrm{in}}} \rightarrow \dot{q}_{\mathrm{in}} = \frac{\dot{W}_{\mathrm{net}}}{\eta_{\mathrm{th}}} = \frac{120\,\mathrm{hp}}{0.36}\left(\frac{2{,}545\,\mathrm{Btu/h}}{\mathrm{hp}}\right) = 848{,}333\,\mathrm{Btu/h}$$

$\dot{q}_{\mathrm{in}} = \mathbf{848{,}333\,Btu/h}$

9.4.5 Energy Conservation While Driving

Some possible energy conservation steps are:

- Speeding, rapid acceleration, and braking waste gas. It can lower your gas mileage by 33% at highway speeds and by 5% around town. Gas mileage usually decreases rapidly at speeds above 60 mph and observing the speed limit may lead to fuel saving of 7–23%.
- An extra 100 pounds in your vehicle could reduce the fuel efficiency by up to 2%.
- Using cruise control helps save gas.
- Fixing a serious maintenance problem, such as a faulty oxygen sensor, can improve your mileage by as much as 40%.
- Gas mileage may be improved by up to 3.3% by keeping your tires inflated to the proper pressure.

The most efficient machines for converting energy to rotary motion are electric motors, as used in electric vehicles. However, electricity is not a primary energy source so the efficiency of the electricity production has also to be taken into account. In the future, hydrogen cars powered either through chemical reactions in a fuel cell that create electricity to drive electrical motors or by directly burning hydrogen in a combustion engine may be commercially available. These vehicles have near zero pollution from the exhaust pipe. Potentially the atmospheric pollution could be minimal, provided the hydrogen is made by electrolysis using electricity from non-polluting sources such as solar, wind, or hydroelectricity. In addi-tion to the energy cost of the electricity or hydrogen production, transmission and/or storage losses to support large-scale use of such vehicles should also be accounted.

Example 9.19 Fuel conservation with a more fuel-efficient car
Assume two cars one with 11 l/100 km city and 9 l/100 km highway, and the other 6.5 l/100 km in city traffic and at 5 l/100 km motorway are used. Estimate the annual fuel saving and emission reduction achieved with the more fuel-efficient car traveling an average 15,000 km per year.

Solution:
Fuel saving for every 100 km city driving in liters = (11 – 6.5) l = 4.5 l
Fuel saving for every 100 km highway driving in liters = (9 – 5) l = 4.0 l

Average saving for 100 km is (4.0 + 4.5) l/2 = 4.2 l
A fuel-efficient car can conserve an average of about 4.2 l gasoline for every 100 km.
For a car driving 15,000 km per year, the amount of fuel conserved would be:
(15,000 km/year) (4.2 l/100 km) = **630 l/year (167 gallon/year)**

Gasoline combustion emits 19.4 lb CO_2/US gal or (2.32 kg CO_2/l)
Annual emission reduction = (2.32 kg CO_2/l) (630 l/year)
= **1,462 kg/year (or 3,294 lb/year)**
Both the conservation in fuel and reduction in emission of CO_2 are significant with increased fuel efficiency of cars globally.

9.4.6 Regenerative Braking

In conventional braking systems, the excess kinetic energy is converted to heat by friction in the brake pads and therefore wasted. Regenerative braking is the conversion of the vehicle's kinetic energy into chemical energy, which is stored in the battery and used in driving again in battery-powered and hybrid gas/electric vehicles. The recovery is around 60% [25]. The advanced algorithms in the motor control the motor torque for both driving and regenerative braking. A torque command is derived from the position of the throttle pedal. The motor controller converts this torque command into the appropriate 3-phase voltage and current waveforms to produce the commanded torque in the motor in the most efficient way. When the torque serves to slow the vehicle then energy is returned to the battery.

Negative torque applied to the rear wheels can cause a car to become unstable since regenerative braking is a source of negative torque. The traction control system limits regenerative braking if the rear wheels start to slip. The control system provides the driver instant positive and negative torque command. Regenerative braking is limited when the batteries are fully charged, and motor controller will limit regenerative torque in this case. It is possible that with the increased use of battery-powered vehicles, a safe regenerative braking will be an efficient way of converting and recovering the kinetic energy.

9.5 Energy Conservation in Electricity Distribution and Smart Grid

A *smart grid* is a form of electricity network using digital technology. Smart grid delivers electricity to consumers to control appliances at homes, optimize power flows, reduce waste, and maximize the use of lowest-cost production resources. The smart grid is envisioned to overlay the ordinary electrical grid with an information and net metering system that includes smart meters. The increased data transmission capacity has made it possible to apply sensing, measurement and control devices with two-way communications to electricity production, transmission, distribution, and consumption parts of the power grid. These devices could communicate information about grid condition to system users, operators, and automated devices. Therefore, the average consumer can respond dynamically to changes in grid conditions [22].

A smart grid includes an intelligent monitoring system that keeps track of all electricity flowing in the system. It also has the capability of integrating renewable electricity such as solar and wind. When power is least expensive the user can allow the smart grid to turn on selected home appliances such as washing machines or some processes in a factory. At peak times, it could turn off selected appliances to reduce demand [12]. Some smart grid functions are:

1. Motivate consumers to actively participate in operations of the grid.
2. Provide higher quality power that will save money wasted from outages.
3. Accommodate all generation and storage options.
4. Enable electricity markets to flourish by running more efficiently.
5. Enable higher penetration of intermittent power generation sources.

9.5.1 Standby Power

Standby power refers to the electricity consumed by many appliances when they are switched off or in standby mode. The typical power loss per appliance is low (from 1 to 25 W) but when multiplied by the billions of appliances in houses and in commercial buildings, standby losses represent a significant fraction of total world electricity use. Standby power may account for consumption between 7 and 13% of household power consumption. Technical solutions to the problem of standby power exist in the form of a new generation of power transformers that use only 100 mW in standby mode and thus can reduce standby consumption by up to 90%. Another solution is the 'smart' electronic switch that cuts power when there is no load and restores it immediately when required.

9.5.2 Energy Conservation in Lighting

Energy for lighting accounts for about 10% of the household electric bill (see Fig. 9.3). Compact fluorescent bulbs (see Fig. 9.7) use about 75% less energy than standard lighting, produces 75% less heat, and lasts up to 10 times longer. Compact fluorescent bulbs contain a very small amount of mercury sealed within the glass tubing. Although linear fluorescent and compact fluorescent bulbs cost a bit more than incandescent bulbs initially, over their lifetime they are cheaper because of the less electricity they use [26]. Example 9.20 illustrates the energy conservation by using the compact fluorescent bulbs.

Fig. 9.7 Compact fluorescent bulbs use about 75% less energy than standard lighting

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Example 9.20 Conservation of energy with compact fluorescent bulbs

Assume that an average residential rate of electricity is \$0.14/kWh and a household consumes about 10,000 kWh per year. If the lighting is provided by compact fluorescent bulbs only, estimate the conservation of energy and saving per year.

Solution:

Assume that 11% of the energy budget of household is for lighting, and compact fluorescent bulbs consume about 75% less energy than standard lighting.

Annual energy use and cost with standard lighting:
(10,000 kWh/year) (0.11) = 1,100 kW/year
(1,100 kW/year)(\$0.14/kWh) = \$154/year

Annual energy use and cost with compact fluorescent bulbs:
(1,100 kW/year) (1 – 0.75) = 275 kWh/year
(275 kWh/year) (\$0.14/kWh) = \$38.5/year

Annual energy and cost savings:
(1,100 – 275) kWh = **825 kWh**
(154 – 38.5)\$/year = **\$115.5/year**

Conservation of energy and cost with compact fluorescent bulbs are.

9.5.3 Energy Harvesting

Despite the high initial costs, energy harvesting is often more effective in cost and resource utilization when done on a group of houses, co-housing, local district, or village rather than an individual basis. This leads to the reduction of electrical transmission and electricity distribution losses, which may be about 7% of the energy transferred. The net zero fossil energy consumption requires locations of geothermal, microhydro, solar, and wind resources to sustain the concept. One of the key areas of debate in zero energy building design is over the balance between energy conservation and the distributed point-of-use harvesting of renewable energy such as solar and wind energy. Wide acceptance of zero or close to zero energy building technology may require more government incentives, building code regulations, or significant increases in the cost of conventional energy [26, 13, 4]. Some benefits of energy harvesting are:

- Isolation for building owners from future energy price increases.
- Increased comfort due to more-uniform interior temperatures.
- Reduced total cost of ownership due to improved energy efficiency.

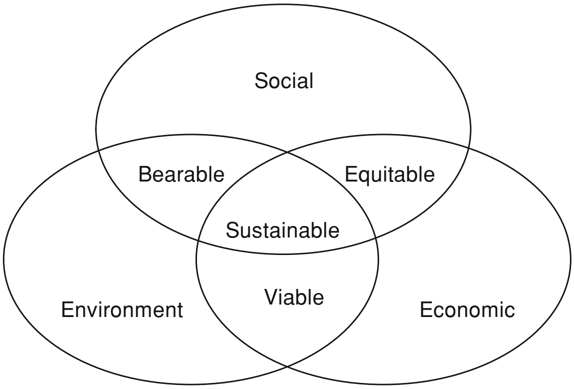


Fig. 9.8 Three elements of sustainability [23, 24]

9.6 Conservation of Energy and Sustainability

Sustainability is improving the quality of human life while living within the carrying capacity of supporting ecosystems. The overall driver of human impact on earth systems is the destruction of biophysical resources, and especially, the earth's ecosystems. Sustainability formulation attempts to explain the environmental impact of human consumption I in terms of three components: population P, levels of consumption that is affluence A, and impact per unit of resource use, which is termed as technology T, and presented by Daly and Farley [8], Hak et al. [15] and Soederbaum [24]

$$I = P \times A \times T \tag{9.14}$$

Sustainability measurement is used as the quantitative basis for the sustainability of environmental, social, and economic domains (see Fig. 9.8). A challenge to sustainability is the combination of population increase in the developing world and unsustainable consumption levels in the developed world. Some sustainability principles are:

- Reduce dependence on natural deposits such as fossil fuels, ores, and minerals.
- Reduce dependence on synthetic chemicals and other unnatural substances.
- Meet human needs fairly.

Zero energy building and green building are two efforts toward sustainability. The goal of green building and sustainable architecture is to use resources more efficiently and reduce a building's negative impact on the environment. Zero energy buildings achieve the goal by completely or very significantly reducing energy use and greenhouse gas emissions for the life of the building. Zero energy buildings may or may not be considered “green” in all areas, such as reducing waste, and using recycled building materials. However, zero energy buildings may have a much lower ecological impact compared with other ‘green’ buildings that require imported energy and/or fossil fuel. Green building certification programs require reducing the use of energy considerably [14].

9.7 Exergy Conservation and Exergy

Energy conservation through exergy concepts for some steady-state flow processes are [6, 9]:

- Exergy is lost by irreversibilities associated with pressure drops, fluid friction, and stream-to-stream heat transfer due to temperature differences.
- In a steam power plant, exergy transfers are due to work and heat, and exergy is lost within the control volume.
- In a waste-heat recovery system, we might reduce the heat transfer irreversibility by designing a heat recovery steam generator with a smaller stream-to-stream temperature difference, and/or reduce friction by designing a turbine with a higher efficiency.
- A cost-effective design may result from a consideration of the trade-offs between possible reduction of exergy loss and potential increase in operating cost.

9.8 Energy Recovery on Utilities Using Pinch Analysis

A process may have available hot and cold streams. When the hot and cold streams exchange heat between them, heat is recovered and the hot and cold utility requirements may be minimized. Pinch analysis yields optimum energy integration of process heat and utilities by matching the hot and cold streams with a network of heat exchangers. In the pinch analysis, hot and cold streams can only exchange energy up to a minimum allowable temperature difference $\Delta T_{\min}$, which is called the pinch point leading to the minimum driving force for heat transfer [9, 17].

An increase in $\Delta T_{\min}$ causes higher energy and lower capital costs (a smaller heat exchanger area as seen in Fig. 9.9). For example, an increase of 5°C from a value of $\Delta T_{\min} = 10°\mathrm{C}$ decreases the heat exchanger area by 11%, and increases the required minimum energy by about 9%. To find the optimum value of $\Delta T_{\min}$, the total annual cost is plotted against it. An optimum $\Delta T_{\min}$ appears at the

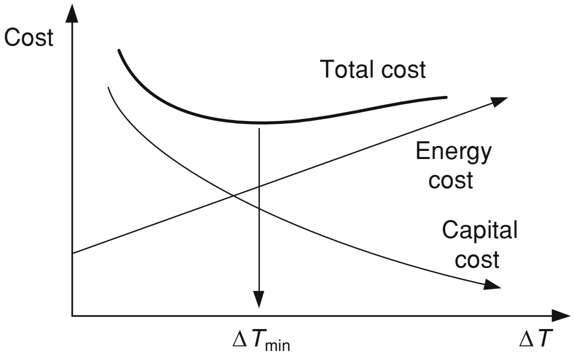


Fig. 9.9 Optimum ΔT_{min} from energy cost and capital cost changes

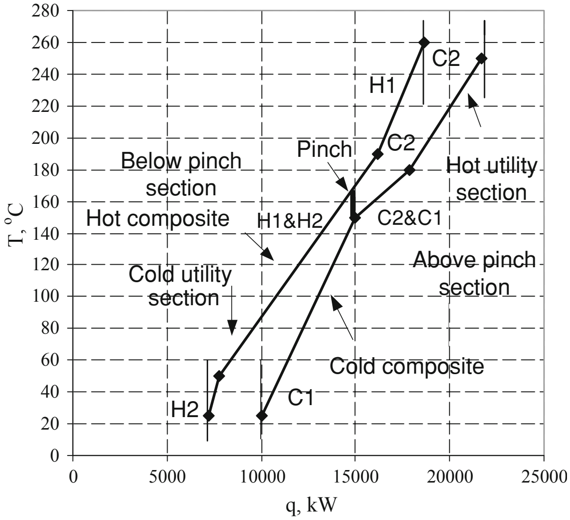


Fig. 9.10 Hot and cold composite curves for a ΔT_{min} of 20°C using two hot (H) streams and two cold (C) streams

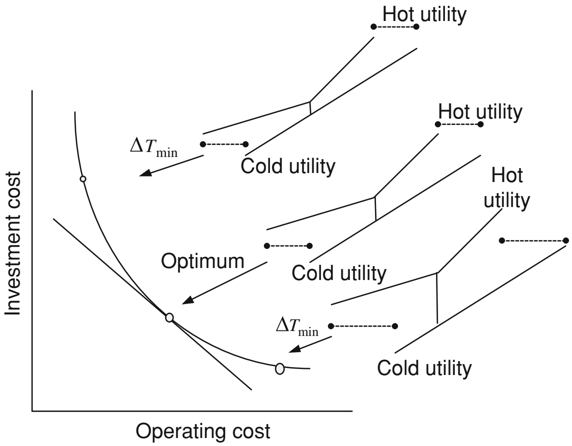
minimum total annual cost of energy and capital. The optimum value for ΔT_{min} is generally in the range of 3–40°C and needs to be established for a process.

9.8.1 Composite Curves

Temperature-enthalpy diagrams called *composite curves* represent the thermal characteristics of hot and cold streams and the amount of heat transferred between them (see Fig. 9.10). The enthalpy change rate for each stream is

$$\dot{q} = \dot{m}\Delta H = \dot{m}C_p\Delta T = MC\Delta T \tag{9.15}$$

Fig. 9.11 Principle of pinch technology



where ΔH is the enthalpy change rate, $\dot{m}$ is the mass flow rate, C_p is the heat capacity, ΔT is the temperature change in a stream, and MC is the heat capacity rate $\dot{m}C_p$. The enthalpy change rates are added over each temperature interval that includes one or more of the streams. This leads to hot and cold composite curves of the streams shown in Fig. 9.10. If $\dot{m}C_p$ is constant, q versus T would be a straight line

$$\Delta T = \frac{1}{\dot{m}C_p}\dot{q} \tag{9.16}$$

Enthalpy changes rather than absolute enthalpies are estimated, and the horizontal location of a composite line on the diagram is arbitrarily fixed. One of the two curves is moved horizontally until the distance of the closest vertical approach matches the selected value of $\Delta T_{\min}$. The pinch point is the location of $\Delta T_{\min}$ on the adjusted composite diagram where the hot and cold curves most closely approach each other in temperature in a vertical direction. The overshoot of the hot composite curve represents the minimum cold utility ($q_{c,\ \min}$) required, and the overshoot of the cold composite curve represents the minimum hot utility ($q_{h,\ \min}$) required (see Figs. 9.10 and 9.11). Example 9.21 illustrates the use of pinch analysis in processing heat integration and minimizing the hot and cold utilities.

Above the pinch, only the hot utility is required, while only the cold utility is required below the pinch. These diagrams enable engineers to minimize the expensive utilities. Pinch analysis may also lead to optimum integration of evaporators, condensers, furnaces, and heat pumps by reducing the utility requirements. Pinch analysis is utilized widely in industry leading to considerable energy savings. Figure 9.11 displays the importance of minimum temperature approach between available hot and cold utilities. As the values of $\Delta T_{\min}$ increase the amount of hot and cold utilities increase together with the operating cost. On the other hand, as the values of $\Delta T_{\min}$ decreases, the investment cost increases. So these two opposing costs should be optimized as seen in Fig. 9.9.

Example 9.21 Energy conservation by the pinch analysis

In a process, available hot and cold process streams and their heat capacities are shown below.

Hot and Cold Process Stream Conditions

Streams		T_{in} (°C)	T_{out} (°C)	$C = \dot{m}C_p$(kW/°C)	$q = \dot{m}C_p\Delta T$(kW)
C1	Cold 1	25	180	40	6,200
C2	Cold 2	150	250	55	5,500
H1	Hot 1	260	50	35	−7,350
H2	Hot 2	190	25	25	−4,125

Construct the balanced composite curves for the process with $\Delta T_{\min} = 20$ and 10°C, and compare the amounts of hot and cold utilities needed

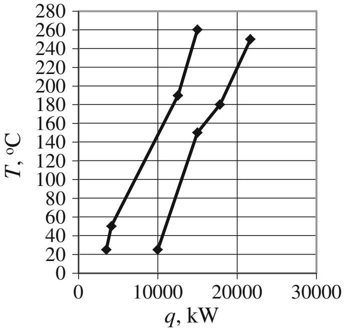
Solution:

Assume that heat capacities of hot and cold streams are constant.

A starting enthalpy change rate is chosen as 10,000 kW at 25°C for the streams to be heated, while for the streams to be cooled, the base value chosen is 15,000 kW at 260°C. Initial temperature interval with overlaps is shown below:

Initial temperature interval					Initial enthalpy selection	
Streams	Temperature interval (°C)		C (kW/°C)	q (kW)	T (°C)	q (kW)
					25	10,000(arbitrary)
C1	25	150	40	5,000	150	15,000
C1&C2	150	180	95	2,850	180	17,850
C2	180	250	55	3,850	250	21,700
				11,700		
					260	15,000(arbitrary)
H1	260	190	35	−2,450	190	12,550
H2&H1	190	50	60	−8,400	50	4,150
H2	50	25	25	−625	25	3,525
				−11,475		

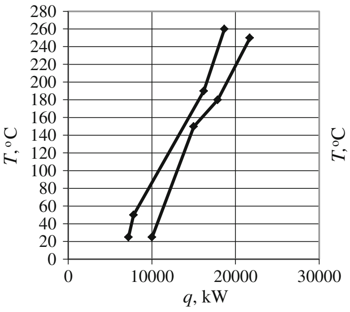
This table may be converted to the hot and cold composite curves below



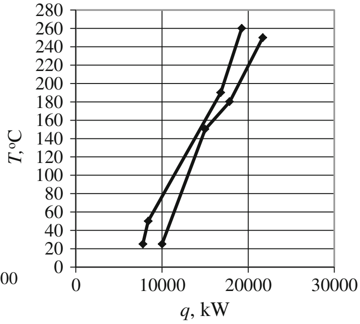
Here the composite curves move to each other so that at the pinch point minimum temperature difference would $\Delta T_{\min} = 20°C$, the diagram is called a *balanced composite diagram.*

Revised temperature interval					Revised enthalpy selection	
Stream	Required temperature interval (°C)		C (kW/°C)	q (kW)	q (kW)	T (°C)
					10,000	25
C1	25	150	40	5,000	15,000	150
C1&C2	150	180	95	2,850	17,850	180
C2	180	250	55	3,850	21,700	250
				11,700		
					18,650	260
H1	260	190	35	−2,450	16,200	190
H2&1	190	50	60	−8,400	7,800	50
H2	50	25	25	−625	7,175	25
				−11,475		

Composite diagram with $\Delta T_{\min} = 20$ and 10°C approach temperatures are shown below



$\Delta T_{\min} = 20°C$



$\Delta T_{\min} = 10°C$

For approach temperatures of $\Delta T_{\min} = 10$ and 20°C estimated minimum hot and cold utilities are:

Cold utility (i.e. cooling water): $q_{\text{cold, min}}$ (kW)	2,225	2,825
Hot utility (i.e. steam): $q_{\text{hot, min}}$ (kW)	2,450	3,050
Approach temperatures: $\Delta T_{\min}$ (°C)	10	20

Energy savings = (3,050 – 2,450) kW = 600 kW
Energy savings = (2,825 – 2,225) kW = 600 kW

This simple analysis shows that the smaller approach temperature reduces the utilities needed considerably.

Problems

9.1. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The fresh air temperature at the compressor inlet is 295 K. The air temperature at the inlet of the turbine is 1,300 K. The cycle operates with a compressor efficiency of 80% and a turbine efficiency of 80%. The flow rate gas is 3 kg/s and unit cost of fuel is $0.15/kWh. The cycle operates 360 days per year.
   (a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.
   (b) If the power plant operates with a regenerator with an effectiveness of 0.80, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.2. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The fresh air temperature at the compressor inlet is 300 K. The air temperature at the inlet of the turbine is 1,300 K. The cycle operates with a compressor efficiency of 85% and a turbine efficiency of 85%. The flow rate gas is 5 kg/s and unit cost of fuel is $0.15/kWhr. The cycle operates 360 days per year.
   (a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.
   (b) If the power plant operates with a regenerator with an effectiveness of 0.80, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.3. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 8$. The fresh air temperature at the compressor inlet is 300 K. The air temperature at the inlet of the turbine is 1,350 K. The cycle operates with a compressor efficiency of 85% and a turbine efficiency of 80%. The flow rate gas is 5 kg/s and unit cost of fuel is $0.11/kWh. The cycle operates 360 days per year.
   (a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.
   (b) If the power plant operates with a regenerator with an effectiveness of 0.7, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.4. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 15$. The fresh air temperature at the compressor inlet is 290 K. The air temperature at the inlet of the turbine is 1,400 K. The cycle operates with a compressor efficiency of 90% and a turbine efficiency of 80%. The flow rate gas is 4.5 kg/s and unit cost of fuel is \$0.16/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.75, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.5. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 14$. The fresh air temperature at the compressor inlet is 290 K. The air temperature at the inlet of the turbine is 1,400 K. The cycle operates with a compressor efficiency of 90% and a turbine efficiency of 80%. The flow rate gas is 4.5 kg/s and unit cost of fuel is \$0.16/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.75, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.6. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 7.5$. The fresh air temperature at the compressor inlet is 290 K. The air temperature at the inlet of the turbine is 1,250 K. The cycle operates with a compressor efficiency of 90% and a turbine efficiency of 85%. The flow rate gas is 6.5 kg/s and unit cost of fuel is \$0.10/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.75, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.7. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 11.0$. The fresh air temperature at the compressor inlet is 290 K. The air temperature at the inlet of the turbine is 1,350 K. The cycle operates with a compressor efficiency of 85% and a turbine efficiency of 80%. The flow rate gas is 6.0 kg/s and unit cost of fuel is \$0.10/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.76, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.8. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 10.0$. The fresh air temperature at the compressor inlet is 290 K. The air temperature at the inlet of the turbine is 1,350 K. The cycle operates with a compressor efficiency of 85% and a turbine efficiency of 80%. The flow rate gas is 6.0 kg/s and unit cost of fuel is \$0.10/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.76, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.9. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,500 kPa and 400°C. Discharge pressure of the steam from the turbine is 78.5 kPa.

(a) Determine the thermal efficiency of the cycle.

(b) If the pressure of the discharge steam is reduced to 15 kPa determine the thermal efficiency.

(c) Determine the annual saving if the unit cost of electricity is \$0.15/kWh.

9.10. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 35 kg/s. The steam enters the turbine at 4,000 kPa and 350°C. Discharge pressure of the steam from the turbine is 101.3 kPa.

(a) Determine the thermal efficiency of the cycle.

(b) If the pressure of the discharge steam is reduced to 15 kPa determine the thermal efficiency.

(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.11. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 30 kg/s. The steam enters the turbine at 3,000 kPa and 400°C. Discharge pressure of the steam from the turbine is 67.5 kPa.

(a) Determine the thermal efficiency of the cycle.

(b) If the pressure of the discharge steam is reduced to 15 kPa determine the thermal efficiency.

(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.12. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 30 kg/s. The steam enters the turbine at 2,500 kPa and 300°C. Discharge pressure of the steam from the turbine is 62.5 kPa.

(a) Determine the thermal efficiency of the cycle.

(b) If the pressure of the discharge steam is reduced to 15 kPa determine the thermal efficiency.

(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.13. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 35 kg/s. The steam enters the turbine at 3,000 kPa and 350°C. Discharge pressure of the steam from the turbine is 78.5 kPa.

(a) Determine the thermal efficiency of the cycle.

(b) If the pressure of the boiler is increased to 10,000 kPa while maintaining the turbine inlet temperature at 350°C, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.14. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 42 kg/s. The steam enters the turbine at 2,500 kPa and 300°C. Discharge pressure of the steam from the turbine is 15.0 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the pressure of the boiler is increased to 9,000 kPa while maintaining the turbine inlet temperature at 300°C, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.15. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 50 kg/s. The steam enters the turbine at 4,000 kPa and 400°C. Discharge pressure of the steam from the turbine is 15.0 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the pressure of the boiler is increased to 11,000 kPa while maintaining the turbine inlet temperature at 400°C, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.16. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 35 kg/s. The steam enters the turbine at 3,500 kPa and 300°C. Discharge pressure of the steam from the turbine is 78.5 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the temperature of the boiler is increased to 500°C while maintaining the pressure at 3,500 kPa, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.15/kWh.

9.17. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 40 kg/s. The steam enters the turbine at 3,000 kPa and 300°C. Discharge pressure of the steam from the turbine is 15 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the temperature of the boiler is increased to 500°C while maintaining the pressure at 3,000 kPa, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.15/kWh.

9.18. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 40 kg/s. The steam enters the turbine at 6,000 kPa and 350°C. Discharge pressure of the steam from the turbine is 15 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the temperature of the boiler is increased to 500°C while maintaining the pressure at 6,000 kPa, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.15/kWh.

9.19. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 40 kg/s. The steam enters the turbine at 9,000 kPa and 400°C. Discharge pressure of the steam from the turbine is 15 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the temperature of the boiler is increased to 550°C while maintaining the pressure at 9,000 kPa, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is $0.15/kWh.

9.20. Estimate the maximum possible efficiency for parts (a) and (b) in Problem 9.18 and compare them with those obtained in parts (a) and (b) in Problem 9.18.

9.21. Estimate the maximum possible efficiency for parts (a) and (b) in Problem 9.19 and compare them with those obtained in parts (a) and (b) in Problem 9.19.

9.22. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,000 kPa and 400°C. Discharge pressure of the steam from the turbine is 78.5 kPa.
(a) If the pressure of the boiler is increased to 9,000 kPa while maintaining the turbine inlet temperature at 400°C, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.15/kWh.

9.23. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 4,000 kPa and 400°C. Discharge pressure of the steam from the turbine is 15 kPa.
(a) If the pressure of the boiler is increased to 9,500 kPa while maintaining the turbine inlet temperature at 400°C, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.15/kWh.

9.24. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 5,000 kPa and 350°C. Discharge pressure of the steam from the turbine is 15 kPa.
(a) If the pressure of the boiler is increased to 10,000 kPa while maintaining the turbine inlet temperature at 350°C, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.15/kWh.

9.25. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 9,800 kPa and 350°C. Discharge pressure of the steam from the turbine is 78.5 kPa.
(a) If the temperature of the boiler is increased to 600°C while maintaining the pressure at 9,800 kPa, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.16/kWh.

9.26. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 8,000 kPa and 325°C. Discharge pressure of the steam from the turbine is 78.5 kPa.
(a) If the temperature of the boiler is increased to 550°C while maintaining the pressure at 8,000 kPa, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.16/kWh.

9.27. Estimate the maximum possible efficiency for parts (a) and (b) in Problem 9.25 and compare them with those obtained in parts (a) and (b) in Problem 9.25.

9.28. Estimate the maximum possible efficiency for parts (a) and (b) in Problem 9.26 and compare them with those obtained in parts (a) and (b) in Problem 9.26.

9.29. Air with a flow rate of 4 kg/s is compressed in a steady-state and reversible process from an inlet state of 100 kPa and 300 K to an exit pressure of 1,000 kPa. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.20/kWh and the compressor is operated 360 days per year.

9.30. Air is compressed in a steady-state and reversible process from an inlet state of 100 kPa and 285 K to an exit pressure of 800 kPa. The mass flow rate of air is 8 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.35$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.35$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.08/kWh and the compressor is operated 360 days per year.

9.31. Air is compressed in a steady-state and reversible process from an inlet state of 110 kPa and 290 K to an exit pressure of 900 kPa. The mass flow rate of air is 10 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.1/kWh and the compressor is operated 360 days per year.

9.32. Air is compressed in a steady-state and reversible process from an inlet state of 110 kPa and 290 K to an exit pressure of 900 kPa. The mass flow rate of air is 10 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.2$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.2$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.12/kWh and the compressor is operated 360 days per year.

9.33. Air is compressed in a steady-state and reversible process from an inlet state of 100 kPa and 290 K to an exit pressure of 900 kPa. The mass flow rate of air is 5 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.25$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.25$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.11/kWh and the compressor is operated 360 days per year.

9.34. Air is compressed in a steady-state and reversible process from an inlet state of 100 kPa and 290 K to an exit pressure of 900 kPa. The mass flow rate of air is 3.5 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.09/kWh and the compressor is operated 360 days per year.

9.35. Natural gas contains mostly the methane gas. In a steady-state and reversible process, natural gas is compressed from an inlet state of 100 kPa and 290 K to an exit pressure of 1,000 kPa. The mass flow rate of natural gas is 8 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.08/kWh and the compressor is operated 360 days per year.

9.36. Natural gas contains mostly the methane gas. In a steady-state and reversible process, natural gas is compressed from an inlet state of 100 kPa and 290 K to an exit pressure of 900 kPa. The mass flow rate of natural gas is 5 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.2$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.2$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.08/kWh and the compressor is operated 360 days per year.

9.37. In a steady-state and reversible process, propane gas is compressed from an inlet state of 100 kPa and 300 K to an exit pressure of 900 kPa. The mass flow rate of propane is 3 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved work by intercooling and electricity per year if the unit cost of electricity is \$0.08/kWh and the compressor is operated 360 days per year.

9.38. In a steady-state and reversible process, hydrogen gas is compressed from an inlet state of 100 kPa and 300 K to an exit pressure of 1,100 kPa. The mass flow rate of hydrogen is 3 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved work by intercooling and electricity per year if the unit cost of electricity is \$0.12/kWh and the compressor is operated 360 days per year.

9.39. In a steady-state and reversible process, carbon dioxide gas is compressed from an inlet state of 100 kPa and 290 K to an exit pressure of 1,000 kPa. The mass flow rate of carbon dioxide is 4 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.16/kWh and the compressor is operated 360 days per year.

9.40. An adiabatic compressor is used to compress air from 100 kPa and 290 K to 900 kPa at a steady-state operation. The isentropic efficiency of the compressor is 80%. The air flow rate is 0.55 kg/s. Determine the minimum and actual power needed by the compressor.

9.41. An adiabatic compressor is used to compress air from 100 kPa and 290 K to 1,100 kPa at a steady-state operation. The isentropic efficiency of the compressor is 80%. The air flow rate is 0.35 kg/s. Determine the minimum and actual power needed by the compressor.

9.42. An adiabatic compressor is used to compress air from 100 kPa and 290 K to 1,400 kPa at a steady-state operation. The isentropic efficiency of the compressor is 85%. The air flow rate is 0.5 kg/s. Determine the minimum and actual power needed by the compressor.

9.43. An adiabatic compressor is used to compress air from 100 kPa and 290 K to 1,600 kPa at a steady-state operation. The isentropic efficiency of the compressor is 83%. The air flow rate is 0.4 kg/s. Determine the minimum and actual power needed by the compressor.

9.44. Estimate the power conservation when an electric motor with an efficiency of 78% is replaced with another motor operating at 88% efficiency. Both the motors drive compressor and must deliver a power of 24 kW for an average 2,500 h/year and the unit cost of electricity is $0.18/kWh.

9.45. Estimate the power conservation when an electric motor with an efficiency of 74% is replaced with another motor operating at 89% efficiency. Both the motors drive compressor and must deliver a power of 36 kW for an average 8,000 h/year and the unit cost of electricity is $0.14/kWh.

9.46. Estimate the power conservation when an electric motor with an efficiency of 74% is replaced with another motor operating at 89% efficiency. Both the motors drive compressor and must deliver a power of 18 kW for an average 80 h per day and the unit cost of electricity is $0.15/kWh.

9.47. A cryogenic manufacturing plant handles liquid methane at 115 K and 5,000 kPa at a rate of 0.15 m^3/s. In the plant a throttling valve reduces the pressure of liquid methane to 2,000 kPa. A new process considered replaces the throttling valve with a turbine in order to produce power while reducing the pressure. Using the data for the properties of liquid methane below estimate (a) the power that can be produced by the turbine, and (b) the savings in electricity usage per year if the turbine operates 360 days per year with a unit cost of electricity at $0.18/kWh.

T (K)	P (kPa)	H (kJ/kg)	S (kJ/kg K)	C_p (kJ/kg K)	ρ (kg/m^3)
110	1,000	209.0	4.875	3.471	425.8
110	2,000	210.5	4.867	3.460	426.6
110	5,000	215.0	4.844	3.432	429.1
120	1,000	244.1	5.180	3.543	411.0
120	2,000	245.4	5.171	3.528	412.0
120	5,000	249.6	5.145	3.486	415.2

Source Cengel and Turner [7]

9.48. A cryogenic manufacturing plant handles liquid methane at 115 K and 5,000 kPa at a rate of 0.2 m^3/s. In the plant a throttling valve reduces the pressure of liquid methane to 2,000 kPa. A new process considered replaces the throttling valve with a turbine in order to produce power while reducing the pressure. Using the data for the properties of liquid methane given in Problem 9.47, estimate (a) the power that can be produced by the turbine, (b) the savings in electricity usage per year if the turbine operates 300 days per year with a unit cost of electricity at $0.15/kWh.

9.49. A heat pump is used to heat a house and maintain it at 18°C. On a day where the outside temperature is −2°C, the house is losing heat at a rate of 79,200 kJ/h. The heat pump operates with a coefficient of performance (COP) of 3.5. Determine (a) power needed by the heat pump, (b) the rate of heat absorbed from the surrounding cold air.

9.50. A heat pump is used to heat a house and maintain it at 20°C. On a day where the outside temperature is 0°C, the house is losing heat at a rate of 34,500 kJ/h. The heat pump operates with a coefficient of performance (COP) of 3.0. Determine (a) power needed by the heat pump, (b) the rate of heat absorbed from the surrounding cold air.

9.51. A heat pump is used to heat a house and maintain it at 20°C. On a day where the outside temperature is 4°C, the house is losing heat at a rate of 65,500 kJ/h. The heat pump operates with a coefficient of performance (COP) of 3.9. Determine (a) power needed by the heat pump, (b) the rate of heat absorbed from the surrounding cold air.

9.52. A Carnot heat pump is used to heat a house during the winter. The house is maintained at 20°C. The house is estimated to be losing heat at a rate of 108,000 kJ/h when the outside temperature is −4°C. Determine the minimum power needed by the heat pump and the rate of heat absorbed from the surrounding cold air.

9.53. A Carnot heat pump is used to heat a house during the winter. The house is maintained at 20°C. The house is estimated to be losing heat at a rate of 78,000 kJ/h when the outside temperature is 2°C. Determine the minimum power needed by the heat pump and the rate of heat absorbed from the surrounding cold air.

9.54. Estimate the cost of electricity for a 10,000 Btu/h (3,000 W) air-conditioning unit operating, with a SEER of 10 Btu/Wh. The unit is used for a total of 1,500 h during an annual cooling season and the unit cost of electricity is $0.16/kWh.

9.55. Estimate the cost of electricity for a 12,000 Btu/h air-conditioning unit operating with a SEER of 14 Btu/Wh. The unit is used for a total of 2,500 h during an annual cooling season and the unit cost of electricity is $0.15/kWh.

9.56. Estimate the cost of electricity for a 9,000 Btu/h air-conditioning unit operating, with a SEER of 12 Btu/Wh. The unit is used for a total of 2,000 h during an annual cooling season and the unit cost of electricity is $0.18/kWh.

9.57. (a) Estimate the annual cost of electric power consumed by a 6 ton air conditioning unit operating for 1,000 h/year with a SEER rating of 10 and a power cost of $0.14/kWh.
(b) Estimate the value of EER for hot and cold temperatures of 20 and −4°C, respectively.

9.58. (a) Estimate the annual cost of electric power consumed by a 4 ton air-conditioning unit operating for 2,500 h/year with a SEER rating of 12 and a power cost of $0.18/kWh.
(b) Estimate the value of EER for hot and cold temperatures of 21 and −10°C, respectively.

9.59. (a) Estimate the annual cost of electric power consumed by a 9 ton air-conditioning unit operating for 3,000 h/year with a SEER rating of 14 and a power cost of $0.18/kWh.
(b) Estimate the value of EER for hot and cold temperatures of 21 and −5°C, respectively.

9.60. A 4 ton current residential air conditioner operates with a SEER rating of 10. This unit will be replaced with a newer unit operating with a SEER rating of 22. The unit operates 130 days with an average 10 h per day. Average inside and outside temperatures are 20 and −4°C, respectively. The unit cost of energy is $0.15/kWh. Estimate the savings in the cost of electricity and the maximum energy efficiency ratio.

9.61. A 4 ton current residential air conditioner operates with a SEER rating of 10. This unit will be replaced with a newer unit operating with a SEER rating of 22. The unit operates 120 days with an average 9 h per day. Average inside and outside temperatures are 20 and −0°C, respectively. The unit cost of energy is $0.17/kWh. Estimate the savings in the cost of electricity and the maximum energy efficiency ratio.

9.62. A 4 ton current residential air conditioner operates with a SEER rating of 10. This unit will be replaced with a newer unit operating with a SEER rating of 20. The unit operates 120 days with an average 7 h per day. Average inside and outside temperatures are 22 and −10°C, respectively. The unit cost of energy is $0.19/kWh. Estimate the savings in the cost of electricity and the maximum energy efficiency ratio.

9.63. The efficiency of an open burner is around 70% for electric heater units and 40% for natural gas units. We operate a 4-kW electric burner at a location where the unit costs of electricity and natural gas are $0.1/kWh and $0.60/therm, respectively. Estimate the rate of energy consumption by the burner and unit costs of the utilized energy for both electric and gas burners.

9.64. The efficiency of an open burner is around 72% for electric heater units and 39% for natural gas units. We operate a 6-kW electric burner at a location where the unit costs of electricity and natural gas are $0.1/kWh and $0.60/therm, respectively. Estimate the rate of energy consumption by the burner and unit costs of the utilized energy for both electric and gas burners.

9.65. The efficiency of an open burner is around 69% for electric heater units and 42% for natural gas units. We operate a 10-kW electric burner at a location where the unit costs of electricity and natural gas are \$0.1/kWh and \$0.60/therm, respectively. Estimate the rate of energy consumption by the burner and unit costs of the utilized energy for both electric and gas burners.

9.66. An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The power output is 60 MW. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.70 and the generator efficiency is 0.9, determine the overall plant efficiency and the amount of coal supplied per hour.

9.67. An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The power output is 60 MW. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.70 and the generator efficiency is 0.9, determine the overall plant efficiency and the amount of coal supplied per hour.

9.68. An adiabatic turbine is used to produce electricity by expanding a superheated steam at 5,800 kPa and 400°C. The power output is 55 MW. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.72 and the generator efficiency is 0.9, determine the overall plant efficiency and the amount of coal supplied per hour.

9.69. An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The steam flow rate is 42 kg/s. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.75 and the generator efficiency is 0.90, determine the overall plant efficiency and the amount of coal supplied per hour.

9.70. An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The steam flow rate is 42 kg/s. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.75 and the generator efficiency is 0.90, determine the overall plant efficiency and the amount of coal supplied per hour.

9.71. The overall efficiencies are about 25–28% for gasoline car engines, 34–38% for diesel engines, and 40–60% for large power plants (Çengel and Turner 2004). Compare the energy necessary for gasoline and diesel engines. The efficiency for the diesel is 36%. A car engine with a power output of 240 hp has a thermal efficiency of 24%. Determine the fuel consumption of the car if the fuel has a higher heating value of 20,400 Btu/lb.

9.72. The overall efficiencies are about 25–28% for gasoline car engines, 34–38% for diesel engines, and 40–60% for large power plants (Çengel and Turner 2004). Compare the energy necessary for gasoline and diesel engines. The efficiency for the diesel is 35%. A car engine with a power output of 180 hp has a thermal efficiency of 26%. Determine the fuel consumption of the car if the fuel has a higher heating value of 20,400 Btu/lb.

9.73. Fuel consumption of the two cars are one with 11 l/100 km city and 9 l/100 km highway, and the other 6.5 l/100 km in city traffic and at 5 l/100 km highway. Estimate the annual fuel saving and emission reduction achieved with the more fuel-efficient car traveling an average 7,500 km per year.

9.74. Fuel consumption of the two cars are one with 10 l/100 km city and 8 l/100 km highway, and the other 6.0 l/100 km in city traffic and at 5 l/100 km highway. Estimate the annual fuel saving and emission reduction achieved with the more fuel-efficient car traveling an average 10,000 km per year.

9.75. Fuel consumption of the two cars are one with 12 l/100 km city and 9 l/100 km highway, and the other 7.0 l/100 km in city traffic and at 6 l/100 km highway. Estimate the annual fuel saving and emission reduction achieved with the more fuel-efficient car traveling an average 12,000 km per year.

9.76. Assume that an average residential rate of electricity is \$0.14/kWh and a household consumes about 5,000 kWh per year. If the lighting is provided by compact fluorescent bulbs only, estimate the conservation of energy and saving per year

9.77. Assume that an average residential rate of electricity is \$0.16/kWh and a household consumes about 14,000 kWh per year. If the lighting is provided by compact fluorescent bulbs only, estimate the conservation of energy and saving per year

9.78. In a process, available hot and cold process streams and their heat capacities are shown below.

Hot and Cold Process Stream Conditions

Streams		T_{in} (°C)	T_{out} (°C)	$C = \dot{m}C_p$(kW/°C)
C1	Cold 1	20	180	40
C2	Cold 2	160	250	55
H1	Hot 1	280	60	35
H2	Hot 2	190	20	25

Construct the balanced composite curves for the process with $\Delta T_{\text{min}} = 20°\text{C}$ and $\Delta T_{\text{min}} = 10°\text{C}$, and compare the amounts of hot and cold utilities needed

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Chapter 10
Energy Coupling

10.1 Energy Coupling and Gibbs Free Energy

The Gibbs free energy of a system is defined as the enthalpy minus the product of temperature and entropy

$$G = H - TS \tag{10.1}$$

The Gibbs free energy of the system is a state function because it is defined in terms of thermodynamic properties that are state functions. The change in the Gibbs free energy of the system that occurs during a reaction is therefore equal to the change in the enthalpy of the system minus the change in the product of the temperature times the entropy of the system. If the reaction takes place at constant temperature, this equation can be written as follows

$$\Delta G = \Delta H - T\Delta S \tag{10.2}$$

Any reaction for which ΔG is negative should be favorable, or spontaneous, while any reaction for which ΔG is positive is unfavorable

$$\Delta G < 0. \quad \text{Favorable, or spontaneous reactions} \tag{10.3}$$

$$\Delta G > 0 \quad \text{Unfavorable, or non-spontaneous reactions} \tag{10.4}$$

Reactions are classified as either *exothermic* ($\Delta H < 0$) or *endothermic* ($\Delta H > 0$) on the basis of whether they give off or absorb heat. Reactions can be classified as *exergonic* ($\Delta G < 0$) or *endergonic* ($\Delta G > 0$) on the basis of whether the free energy of the system decreases or increases during the reaction.

Consider the following two reactions:

$$1.\ \mathrm{A} \rightarrow \mathrm{B} \quad \Delta G_{\mathrm{AB}} = (G_{\mathrm{B}} - G_{\mathrm{A}}) \ll 0,\ \text{exergonic} \tag{10.5}$$

$$2.\ \mathrm{C} \rightarrow \mathrm{D} \quad \Delta G_{\mathrm{AB}} = (G_{\mathrm{B}} - G_{\mathrm{A}}) > 0,\ \text{endergonic} \tag{10.6}$$

Y. Demirel, *Energy*, Green Energy and Technology,
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Then the first reaction can drive the second reaction if they are coupled and as long as their absolute values satisfy the following inequality

$$|\Delta G_{\mathrm{AB}}| > |\Delta G_{\mathrm{CD}}|. \tag{10.7}$$

Then the coupled reactions would have a total Gibbs energy with a negative value hence become exergonic and favorable reactions

$$(\Delta G_{\mathrm{AB}} + \Delta G_{\mathrm{CD}}) < 0 \tag{10.8}$$

Energy coupling may require some special mechanisms, such as enzyme kinetics and configurations in living systems, which are briefly discussed in the next section.

10.2 Energy Coupling in Living Systems

A coupled process can occur without its primary driving force, or opposite to the direction imposed by its primary driving force. For example, the living cells can pump ions from low to high concentration regions. Since the favorable transport of materials take place always from high to low concentration, this opposite transportation is possible only if it is coupled with an energy providing process. In living systems, this energy is provided by the adenosine triphosphate (ATP). Energy coupling in living systems means that the energy generated is harnessed by the cells to perform energy required processes. The metabolic pathways intersect in such a way that energy released from the favorable reactions of catabolism can be used to drive the unfavorable reactions of the anabolic pathways. This means that those biochemical cycles that give off a net amount of energy (exergonic) are used to drive those biochemical cycles that absorb a net amount of energy (endergonic). This transfer of energy from catabolism to anabolism is the result of energy coupling [25].

The chloroplasts in plants use the free energy of the sun to initiate electron transfer cycles and proton gradients to produce ATP in photosynthesis. In animals, respiration cycle initiate electron transfer cycle and proton gradient to produce ATP in oxidative phosphorylation. ATP is an energy rich biomolecule, which stores and provides energy necessary in living systems. Photosynthesis, oxidative phosphorylation, and molecular pumps represent some of the major energy coupling examples in living systems.

10.3 Bioenergetics

Bioenergetics is concerned with the energy production, conservation, and conversion processes in living systems [2, 9, 17]. The outside energy is used in the synthesis of an energy rich molecule called adenosine triphosphate (ATP) from adenosine diphosphate (ADP) and molecular phosphorous (Pi). The chemical formula of ATP

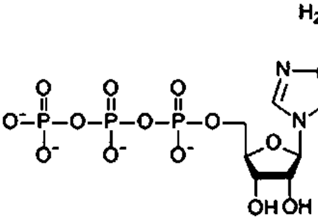


Fig. 10.1 Chemical formula of adenosine triphosphate (ATP). ATP is an energy rich compound having three phosphate groups attached to adenosine. Of the three phosphate groups, the terminal one has a weak linkage. This phosphate group can break spontaneously whenever ATP forms a complex with an enzyme. The breaking up of this bond releases chemical energy needed in all living systems

is shown in Fig. 10.1. ATP has three phosphate group attached to adenosine, in which the terminal phosphate has a weak linkage and can break spontaneously whenever ATP forms a complex with an enzyme and releases chemical energy. ATP therefore acts as energy storage and source of the living cell.

ATP synthesis is an endothermic reaction as it needs energy from outside. So the APT synthesis is coupled to electron transport chain. Therefore, the electron transport chain drives the ATP synthesis. Synthesizing of ATP is matched and synchronized to cellular ATP utilization through the hydrolysis (combining with water) of ATP

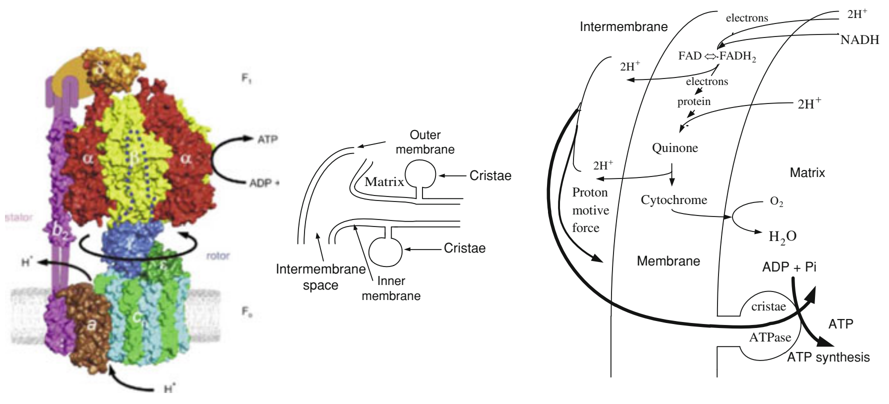
$$\mathrm{ADP} + \mathrm{P_i} + n\mathrm{H}^+_{\mathrm{in}} = \mathrm{ATP} + \mathrm{H_2O} + n\mathrm{H}^+_{\mathrm{out}}, \tag{10.9}$$

where ‘in’ and ‘out’ denote two phases separated by a membrane, and n is the ratio $\mathrm{H}^+/\mathrm{ATP}$, showing the level of transmembrane proton transport for each ATP to be synthesized. ATP utilization is coupled to synthesizing protein molecules, transporting ions and substrates, and producing mechanical work. ATP molecules, therefore, store and transfer energy in the living systems. For example, some of the internal mechanical work involves the pumping blood by the heart. Continuous biochemical cycles and transport processes maintain a stationary state by the regulated production and transfer of energy of the ATP.

Most biochemical reactions in bioenergetics occur in pathways, in which other reactions continuously add substrates and remove products. The rate of these reactions depends on the enzymes. Enzymes are proteins produced in cells and catalyze the reactions [26].

10.3.1 Mitochondria

Mitochondria are organelles typically ranging in size from 0.5 to 1 μm in length, found in the cytoplasm of eukaryotic cells. Mitochondria contain inner and outer membranes constructed with phospholipids into which specific proteins are



(a) **(b)** **(c)**

Fig. 10.2 **a** ATPases are a class of enzymes with F_o and F_1 subunits that catalyze the synthesis and hydrolysis of adenosine triphosphate (ATP). The cristae have the major coupling factors F_1 (a hydrophilic protein) and F_o (a hydrophobic lipoprotein complex). F_1 and F_o together comprise the ATPase (also called ATP synthase) [16]. **b** Inner membrane structure of the mitochondria. **c** Electron transport chain and oxidative phosphorylation of adenosine triphosphate [4]

embedded. Mitochondrial membranes produce two compartments called the intermembrane space and matrix space enclosed by the inner membrane (Fig. 10.2a). The inner membrane has numerous folds called *cristae* where the synthesis of ATP takes place.

10.3.2 Electron Transport Chain and Adenosine Triphosphate (ATP) Synthesis

The inner membrane houses the electron transport chain and adenosine triphosphate synthesis shown in Fig. 10.2c. The tricarboxylic acid cycle, also called the citric acid cycle, produces electron transport chain, which is the major energy-producing pathway. The electrons transport chain causes the proton flow across the inner membrane of the mitochondria and ATP is synthesized by the enzyme called the ATPases shown in Fig. 10.2a. ATPases are a class of enzymes with F_o and F_1 subunits that catalyze the synthesis and hydrolysis of ATP. The cristae have the major coupling factors F_1 (a hydrophilic protein) and F_o (a hydrophobic lipoprotein complex) [16].

In animals, the respiration chain generates energy by the oxidation of reducing equivalents of nutrients that are nicotinamide adenine nucleotides NADH and the flavin nucleotides $FADH_2$. When ADP levels are higher than ATP, the cell needs energy, and hence NADH is oxidized rapidly and the tricarboxylic acid cycle is accelerated. When the ATP level is higher than ADP, the electron transport chain slows down.

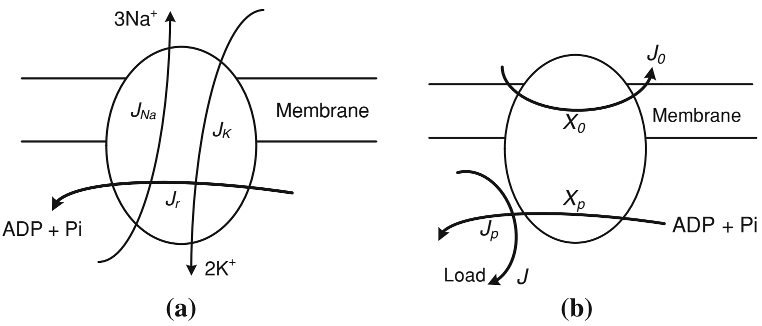


Fig. 10.3 **a** Active transport of Na^+ and K^+ ions coupled to hydrolysis of ATP [9, 14]. **b** Energy coupling between respiration cycle and oxidative phosphorylation taking place in the inner membrane of mitochondria. Here J_o and J_p are the oxygen flow rate and the ATP production rate, respectively, while X_o and X_p show the redox potential for oxidazible substances and the phosphate potential, respectively. The flow J represents a load (i.e. osmotic work) coupled to ATP production

Photosynthesis, driven by the light energy, leads to the production of ATP through electron transfer and photosynthetic phosphorylation. Photosynthetic energy conservation takes place in the thylakoid membrane of plant chloroplasts. These membranes facilitate the interactions between the redox system and the synthesis of ATP, and are referred to as coupling membranes.

10.3.3 Active Transport

Mitochondria are involved in the transport of ions and other molecules, such as Ca^{+2} and proteins. Active transport is the transport of a substance from low to high concentration and hence against its concentration gradient. This process is also known as uphill transport and needs energy. The hydrolysis of ATP provides energy for all cellular activity including active transport of ions and molecules. If the process uses chemical energy, such as the energy released from the hydrolysis of adenosine triphosphate, it is termed *primary active transport*. *Secondary active transport* involves the use of an electrochemical gradient produced within the cell.

Hydrolysis of one mole of ATP is an exergonic reaction releasing 31 kJ/mol at $pH = 7$. This energy drives various energy-dependent metabolic reactions and the transport of various ions such as K^+ and Na^+ as seen in Fig. 10.3a. These concentration gradients of K^+ and Na^+ are established by the active transport of both ions. The same enzyme, called the Na^+/K^+ ATPase uses the energy released from the hydrolysis of ATP to transport three Na^+ ions out of the cell for each two K^+ ions pumped into the cell against their concentration gradients (see Fig. 10.3a). Almost one-third of all the energy generated by the mitochondria in animal cells is used in active transport. In *indirect active transport* other transporter molecules use the energy already stored in the gradient of a directly-pumped ions [7, 8, 17].

10.4 Simple Analysis of Energy Coupling

Figure 10.3b illustrates electron transportation cycle driving the ATP production through the energy coupling. Stucki et al. [22] applied the following approximate representative linear phenomenological relations of the oxidative phosphorylation without a load such as active transport

$$J_o = L_o X_o + L_{op} X_p \tag{10.10}$$

$$J_p = L_{po} X_o + L_p X_p \tag{10.11}$$

Here J_o is the oxygen flow rate, J_p is the ATP production rate, X_o is the redox potential for oxidazible substances and X_p is the phosphate potential [6]. The J_o and J_p are called the flows, while X_o and X_p are called the forces. The L_{op} and L_{po} represent the cross coefficients, while L_o and L_p are called the primary coefficients. The cross coefficients, L_{op} and L_{po}, obey Onsager's reciprocal rules, which states that $L_{op} = L_{po}$.

The *degree of coupling* q is defined by

$$q = \frac{L_{op}}{(L_p L_o)^{1/2}} \quad 0 < |q| < 1, \tag{10.12}$$

and indicates the extent of overall coupling of the ATP production driven by the respiration cycle in the inner membrane of mitochondria. By defining the *phenomenological stoichiometry* Z by

$$Z = \left(\frac{L_o}{L_p}\right)^{1/2} \tag{10.13}$$

and by dividing Eq. (10.10) by Eq. (10.11), we obtain the flow ratio j and the force ratio x in terms of Z

$$j = \frac{J_o}{J_p Z} \tag{10.14}$$

$$x = \frac{X_o Z}{X_p} \tag{10.15}$$

The flow ratio j and force ratio x can be related to each other by the degree of coupling q as follows

$$j = \frac{x + q}{qZ + 1} \tag{10.16}$$

The energy dissipation Ψ is expressed by [6, 7]

$$\Psi = J_o X_o + J_p X_p = \text{input power} + \text{output power} > 0 \tag{10.17}$$

The efficiency of the linear energy coupling of oxidative phosphorylation may be defined as the ratio of output power to input power and in terms of the degree of coupling, and given by

$$\eta = -\frac{\text{output power}}{\text{input power}} = -\frac{J_p X_p}{J_o X_o} = -\frac{x+q}{q+(1/x)} \tag{10.18}$$

The value of optimum efficiency is a function of the degree of coupling only, and is expressed by

$$\eta_{\text{opt}} = \frac{q^2}{\left(1+\sqrt{1-q^2}\right)^2} = \tan^2(\alpha/2) \tag{10.19}$$

where $\alpha = \arcsin(q)$ [9, 21, 24]. The value of x at η_{opt} becomes

$$x_{opt} = -\frac{q}{1+\sqrt{1+q^2}} \tag{10.20}$$

Therefore, the optimum value of ratio of forces x depends only on the value of degree of coupling [6, 18]. Example 10.1 illustrates a simple representative analysis of energy coupling in photosynthesis.

Example 10.1 Efficiency of energy conversion of photosynthesis

Consider a model process with an energy exchange between a photon and a composite particle. In this over-simplified model, energy is exchanged through an excited state of the chloroplast by which energy rich electron/proton pairs from the water react with the carbon dioxide. This produces carbohydrate and oxygen molecules, and heat is dissipated away. The flows are related by an approximation [3]

$$\left(\frac{J_D}{J_q}\right)^2 = \frac{k_B n D}{k} \tag{10.21}$$

where $n \sim 3.3 \times 10^{28}$ molecules/m^3, which is a typical value for water and condensed matter in general, J_D mass flow of carbon dioxide (rate of diffusion), J_q is the heat flow, D is the diffusion coefficient, k is the thermal conductivity, and k_B is the Boltzmann constant.

Only a small part of the free energy of photons is available for photosynthesis, and the rest is dissipated. The efficiency of energy conversion in photosynthesis is low and varies in the range 2.4–7.5% [3]. The efficiency of energy conversion is defined by

$$\eta = \frac{J_D}{J_q}\frac{\Delta G}{h\upsilon} \tag{10.22}$$

where ΔG is the Gibbs energy per molecule and $h\upsilon$ is the energy per photon. Some approximate values for these driving forces are:

- $\Delta G \sim 7.95 \times 10^{-19}$ J/one unit carbohydrate
- $(h\upsilon) \sim 2.92 \times 10^{-19}$ J/a solar photon (pertaining to red light with a wave length of 680 nm, which is best absorbed by chlorophyll-α).
- Based on the thermal conductivity of water: $k = 0.607$ W/m K.
- Assuming that the intercellular diffusion of carbon dioxide could be the limiting process in photosynthesis, we have $D \sim 1.95 \times 10^{-9}$ m^2/s based on carbon dioxide in water or $D \sim 0.67 \times 10^{-9}$ m^2/s based on glucose in water.
- $k_B = 1.3806503 \times 10^{-23}$ m^2 kg/s^2 K

Using these approximate values in the following equation

$$\eta = \frac{J_D}{J_q}\left(\frac{7.95 \times 10^{-19}}{2.92 \times 10^{-19}}\right) = 2.72\left(\frac{k_B n D}{k}\right)^{1/2} \tag{10.23}$$

the approximate predicted values of efficiency of energy conversion become

η (predicted) (%)	η (measured) (%)	D (m^2/s)
2.4	4.9	0.10×10^{-9}
6.1	6.2	0.67×10^{-9}
7.5	~7	1.0×10^{-9}

Source Andriesse and Hollestelle [3]

Any plant growing under ideal conditions, the efficiency is expected to be close to 7%.

10.5 Variation of Energy Coupling

The value of degree of coupling q can be calculated from the measurements of oxygen flows at static head (sh) $(J_o)_{\mathrm{sh}}$ in which the net rate of ATP vanishes, and at uncoupled state (unc) $(J_o)_{\mathrm{unc}}$ where the proton gradient vanishes and the respiration cycles is uncoupled from the oxidative phosphorylation [5]

$$q = \sqrt{1 - (J_o)_{\mathrm{sh}}/(J_o)_{\mathrm{unc}}} \tag{10.24}$$

For example, the overall degree of energy coupling is higher for a rat liver mitochondrion (0.955 ± 0.021) than for brain (0.937 ± 0.026) or heart (0.917 ± 0.037) [5].

Required degrees of coupling of oxidative phosphorylation vary, when the ATP production is coupled to a load such as hydrolysis of the ATP (see Fig. 10.3b) [21]. The optimum production functions f for the ATP and output power production are given in terms of the degree of coupling

$$f = \tan^m(\alpha/2)\cos(\alpha) \tag{10.25}$$

The ATP production and power output occur at certain values of degrees of coupling:

- Maximum ATP production at optimal efficiency occurs at $q_f = 0.786$, $f = (J_p)_{\text{opt}}$.
- Maximum power output at optimal efficiency occurs at $q_p = 0.91, f = (J_p X_p)_{\text{opt}}$.
- Efficient ATP production at minimal energy cost occurs at $q_f^{ec} = 0.953$, $f = \eta(J_p)_{\text{opt}}$.
- Economic power output at minimal energy cost occurs at $q_p^{ec} = 0.972$, $f = \eta\ (J_p X_p)_{\text{opt}}$.

With the consideration of conductance matching, Stucki [18] determined four production functions, which are given in Table 10.1. Figure 10.4 shows the effect of degree of coupling on the optimum efficiency. The sensitivity of oxidative phosphorylation to a fluctuating ATP utilization is minimal at a degree of coupling $q = 0.95$. This means that the phosphate potential is highly buffered with respect to fluctuating energy demands at the degree of coupling, which is very close to the value of q_f^{ec}, at which net ATP production of oxidative phosphorylation occurs at the minimal energy cost [21, 22].

The degree of coupling depends on the nature of the output required from the energy coupling system in the mitochondria and on metabolic regulation and stability. In the heart and brain, the experimental value of q for the cellular respiration pathway is close to the value of $q_f^{ec} = 0.953$, which suggests that the pathway is optimized to economical ATP for cellular processes. In the brain, the value of $q_p = 0.91$ suggests a maximized cellular energy state. However, in the heart, the degree of coupling is 0.786, which is between q_p and q_f, and consistent with the maximum ATP production necessary for preserving the cellular energy state [5, 18].

The optimum output power $(J_1 X_1)_{\text{opt}}$ and the efficiency $(J_1 X_1\ \eta)_{\text{opt}}$ are calculated from the plots of $J_1 X_1$ versus x and $J_1 X_1 \eta$ versus x, respectively. A transition from q_p to q_f^{ec} causes a 12% drop in output power $(J_1 X_1)$ and a 51% increase in efficiency. For a favorable ATP production at optimal efficiency of oxidative phosphorylation, we should have $q < 1$.

10.5.1 Regulation of Energy Coupling

Regulation implies a physiological outcome as a result of manipulating a mitochondrial function. The physiological reasons for these regulations of mitochondria are mainly to match ATP supply efficiently to changes in workload in bioenergetics, as well as respond to external stimuli [12, 19]. The electrochemical proton gradient across the membrane is one of the important mechanisms for regulating the rate of respiration and ATP synthesis. Various substrates regulate

Table 10.1 Production functions with the consideration of conductance matching [5, 21]

Production function	Loci of the optimal efficiency states	q	Energy cost
Optimum rate of ATP production: $J_p = (q + x)ZL_oX_o$	From the plot of J_p vs. x: $(J_p)_{\text{opt}} = \tan(\alpha/2)\cos\alpha ZL_oX_o$	$q_f = 0.786$ $\alpha = 51.83^{\text{o}}$	No $\eta = \text{cons.}$
Optimum output power of OP: $J_pX_p = x(q + x)L_oX_o^2$	From the plot of J_pX_o vs. x: $(J_pX_p)_{\text{opt}} = \tan^2(\alpha/2)\cos\alpha L_oX_o^2$	$q_p = 0.910$ $\alpha = 65.53^{\text{o}}$	No $\eta = \text{cons.}$
Optimum rate of ATP production at minimal energy cost: $J_p\eta = -\dfrac{x(q+x)^2}{xq+1}ZL_oX_o$	From the plot of $J_I\ \eta$ versus x: $(J_p\eta)_{\text{opt}} = \tan^3(\alpha/2)\cos\alpha ZL_oX_o$	$q_f^{\text{ec}} = 0.953$ $\alpha = 72.38^{\text{o}}$	Yes
Optimum output power of OP at minimal energy cost: $J_pX_p\eta = -\dfrac{x^2(q+x)^2}{xq+1}L_oX_o^2$	From the plot of $J_I\ X_I\ \eta$ versus x: $(J_pX_p\eta)_{\text{opt}} = \tan^4(\alpha/2)\cos\alpha L_oX_o^2$	$q_p^{\text{ec}} = 0.972$ $\alpha = 76.34^{\text{o}}$	Yes

OP Oxidative phosphorylation; q_f, q_p are the degree of couplings at optimized ATP production and power output, respectively, and q_f^{ec}, q_p^{ec} are the degree of couplings at optimized ATP production and power output with minimal energy cost, respectively

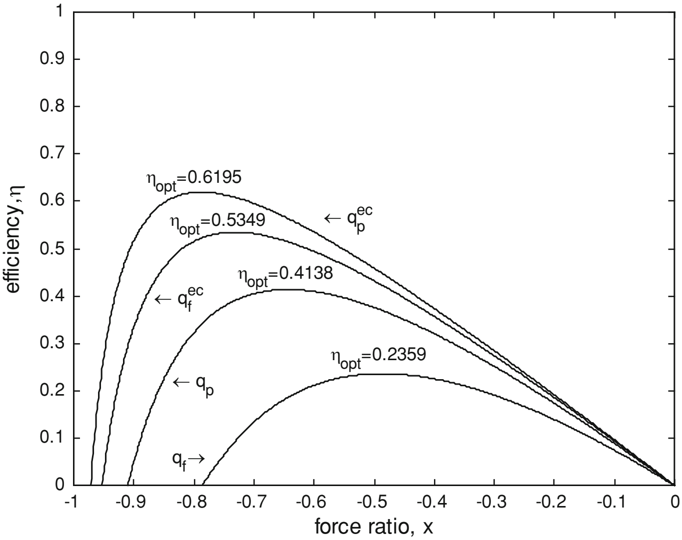


Fig. 10.4 Efficiency versus force ratio at various level of energy couplings. The change of efficiencies η, given in Eq. 10.18, in terms of flow ratio x (X_oZ/X_p) and for the degrees of couplings q_f, q_p, q_f^{ec}, andq_p^{ec} [21]

the metabolism of energy; fatty acids may regulate and tune the degree of coupling by inducing uncoupling, leading to optimum efficiency of oxidative phosphorylation. A fluctuating ATP/ADP ratio and deviations from the optimal efficiency of oxidative phosphorylation are largely overcome by some buffering enzymes. For example, the mitochondrial creatine kinase is a key enzyme of aerobic energy metabolism, and is involved in buffering, transporting, and reducing the transient nature of the system [11, 12, 23].

Stucki [19, 20] analyzed the sensitivity of the force (the phosphate potential) to the cellular ATP utilization, and found that the sensitivity is minimal at $q = 0.95$. This indicates that the phosphate potential is highly buffered with respect to the changing energy demand to maximize the kinetic stability and efficiency at the same degree of coupling. The standard reaction Gibbs energy of ATP production is obtained as 31.3 kJ/mol at $T = 20°\text{C}$, pH = 8.0, pMg = 2.5, and 0.08 M ionic strength, and the standard enthalpy of the reaction is 28.1 kJ/mol.

10.5.2 Uncoupling

ATP synthesis is matched to cellular ATP utilization for osmotic work of (downhill and uphill) transport, or mechanical work such as muscle contraction and rotation of bacterial flagellum. The uncoupling of the mitochondrial electron transport chain from the phosphorylation of ADP is physiological and optimizes the efficiency and fine tunes the degree of coupling of oxidative phosphorylation [12]. Fatty acids facilitate the net transfer of protons from intermembrane space into the mitochondrial matrix, hence lowering the proton electrochemical potential gradient and mediating weak uncoupling. Uncoupling proteins generally facilitate the dissipation of the transmembrane electrochemical potentials of H^+ or Na^+ produced by the respiratory chain, and result in an increase in the H^+ and Na^+ permeability of the coupling membranes. Some uncoupling is favorable for the energy-conserving function of cellular respiration [27].

10.5.3 Slippages and Leaks

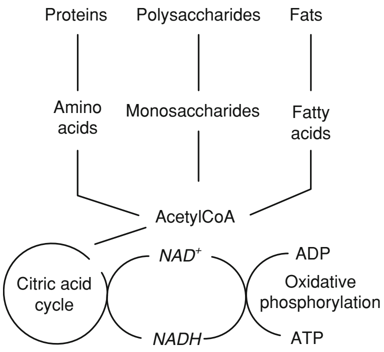
Mainly, slippage results when one of two coupled reactions in a cyclic process proceeds without its counterpart, which is also called intrinsic uncoupling. On the microscopic level, individual enzymes cause slippage by either passing a proton without contributing to ATP synthesis, or hydrolyzing ATP without contributing to proton pumping. On the macroscopic level, the measured degree of coupling may be different from the expected coupling.

In terms of the energy conversion, a slip may decrease efficiency; it may, however, allow dynamic control and regulation of the enzyme over the varying ranges of driving and driven forces. Mitochondrial energy metabolism may be regulated by the slippage of proton pumping. Slips and leaks occur in parallel. The rate of leakage of the coupling ions depends on the magnitude of the particular thermodynamic force operating within the system in the absence of the other force. In oxidative phosphorylation, leaks cause a certain uncoupling of two consecutive pumps, such as electron transport and ATP synthase, and may be described as the membrane potential-driven backflow of protons across the bilayer [24].

10.6 Metabolism

Metabolism is the set of biochemical reactions that occur in living organisms to maintain life. Metabolism consists of two pathways catabolism and anabolism. In catabolism organic matter is broken down, for example to harvest energy in cellular respiration. In anabolism, the energy is used to construct components of cells such as proteins and nucleic acids. In metabolic pathways, one chemical is transformed through a series of steps into another chemical by a sequence of enzymes. Enzymes allow some processes to drive desirable reactions that require energy by coupling them to spontaneous processes that release energy. One central coenzyme is adenosine triphosphate (ATP) is used to transfer chemical energy between different chemical reactions. ATP in cells is continuously regenerated and acts as a bridge between catabolism and anabolism, with catabolic reactions generating ATP and anabolic reactions consuming it through energy coupling [15].

Fig. 10.5 A simplified outline of the catabolism of biofuels proteins, carbohydrates, and fats leading to energy coupling systems [1]



10.6.1 Catabolism

Catabolism is the set of metabolic cyclic processes that break down and oxidize large molecules, including breaking down and oxidizing food molecules to simpler molecules, such as carbon dioxide and water. The catabolic reactions provide the energy and components needed by anabolic reactions.

The most common set of catabolic reactions in animals can be separated into three main stages (see Fig. 10.5). In the first, large organic molecules such as proteins, polysaccharides, or lipids are digested into their smaller components outside cells. Next, these smaller molecules are taken up by cells and converted to yet smaller molecules, usually acetyl coenzyme A (acetyl-CoA), which releases some energy. Finally, the acetyl group on the CoA is oxidized to water and carbon dioxide in the citric acid cycle and electron transport chain, releasing the energy that is stored by reducing the coenzyme nicotinamide adenine dinucleotide (NAD^+) into NADH.

These digestive enzymes include proteases that digest proteins into amino acids, as well as glycoside hydrolases that digest polysaccharides into monosaccharides as shown in Fig. 10.5.

The major route of breakdown is glycolysis, where sugars such as glucose and fructose are converted into pyruvate and some ATP is generated. This oxidation releases carbon dioxide as a waste product. Fatty acids release more energy upon oxidation than carbohydrates because carbohydrates contain more oxygen in their structures. Amino acids are either used to synthesize proteins and other biomolecules, or oxidized to urea and carbon dioxide as a source of energy.

10.6.2 Anabolism

Anabolism is the set of constructive metabolic processes where the energy released by catabolism is used to synthesize complex molecules in three basic stages. First, the production of precursors such as amino acids, monosaccarides, and nucleotides, second, their activation into reactive forms using energy from ATP, and third, the assembly of these precursors into complex molecules such as proteins, polysaccharides, lipids, and nucleic acids.

10.7 Bioenergy Sources

Carbohydrates, fats, and proteins are the major sources of chemical energy of the body and are obtained from the daily diet. Heat released by the oxidation of these fuels is used to maintain body's temperature:

- Carbohydrates release about 4 kcal/g (17 kJ/g).
- Fats release about and 9 kcal/g (39 kJ/g).
- Proteins release about 4 kcal/g (17 kJ/g).

Excess of the body's immediate energy needs is stored mainly by:

- Fat-triacylglycerol (triglyceride): adipose triacylglycerol is the major energy store of the body.
- Glycogen: energy stored by glycogen is relatively small but it is critical. For example muscle glycogen is oxidized for muscle contraction.

Daily energy expenditure is the amount of energy required daily and includes the energy required for the basal metabolic rate and for physical activity. Basal metabolic rate for a person is approximately 24 kcal/kg body weight per day and the basic physical activity requires approximately 30% of basal metabolic rate [13].

Carbohydrates are straight-chain aldehydes or ketones with many hydroxyl groups that can exist as straight chains or rings. Carbohydrates are the most abundant biological molecules, and play numerous roles, such as the storage and transport of energy (starch, glycogen), and structural components such as cellulose in plants, chitin in animals.

The fuel value is equal to the heat of reaction of combustion (oxidation). Carbohydrates and fats can be completely oxidized while proteins can only be partially oxidized and hence has lower fuel values. The energy expenditure may be calculated from the energy balance. Assume that (i) carbohydrate (CH), fat (F), and protein (Pr) are the only compounds involved in the oxidation process, (ii) the other compounds are stationary, and (iii) the uptake and elimination of oxygen, carbon dioxide, and nitrogen is instantaneous. From the energy balance, we have the energy expenditure $\dot{E}$

$$\dot{E} = \sum_i (\dot{n}\Delta H_r)_i = (\dot{n}\Delta H_r)_{\mathrm{CH}} + (\dot{n}\Delta H_r)_{\mathrm{F}} + (\dot{n}\Delta H_r)_{\mathrm{Pr}} = \dot{q} + \dot{W} \tag{10.26}$$

where the specific enthalpy values are: $\Delta H_{r,\mathrm{CH}} = -\ 17$ kJ/g, $\Delta H_{r,\mathrm{Fat}} = -\ 39$ kJ/g, $\Delta H_{r,\mathrm{CH}} = -\ 17$ kJ/g. Example 10.2 illustrates the oxidation of glucose, while Examples 10.3–10.5 discusses the energy expenditure estimations.

Example 10.2 Oxidation of glucose

(a) Estimate the reaction enthalpy for the isothermal and isobaric oxidation of glucose at 310 K and 1 atm.

(b) Estimate the energy expenditure for oxidation of 390 g/day glucose at steady conditions.

Solution:

Assume: the energy for transferring of gaseous components to aqueous solutions is small. The temperature correction for the heat of reaction is negligible.

$$C_6H_{12}O_6(aq) + \ 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$$

where the symbol (aq) denotes aqueous, (g) is the gas, and (l) is the liquid. If the control volume is a piece of tissue, the reaction above may take place in an aqueous solution (aq).

From Table C1, we obtain the enthalpy of formations for the components of the reaction above at the standard state (298 K and 1 atm)

$$\begin{aligned}\Delta H_r^o(298^\circ\text{K}) &= 6(-393) + 6(-286) - (-1264) - 6(0)\\ &= -2810\,\text{kJ/mol} \sim \Delta H_r(310^\circ\text{K})\end{aligned}$$

$$MW(\text{glucose}) = 180 \text{ g/gmol}$$

The energy expenditure $\dot{E}$ at a glucose consumption of 390 g/day is

$$n_G = \frac{(390\,\text{g/day})/(180\,\text{g/mol})}{(24\,\text{h/day})(3600\,\text{s/h})} = 0.025 \times 10^{-3}\,\text{mol/s}$$

$$\dot{E} = n_G(-\Delta H_r) = (0.025 \times 10^{-3}\,\text{mol/s})(2810\text{kJ/mol}) = \mathbf{70.2 \times 10^{-3}\,W = 70.2\,mW}$$

Example 10.3 Daily energy expenditure

A dietary history of an adult of 146 lb shows that he consumes approximately 150 g of carbohydrate, 50 g of protein, and 60 g of fat daily. The adult exercises regularly and consumes an average 480 kcal daily. Estimate the energy expenditure of this adult and comment if the energy intake is excessive.

Solution:

Daily energy expenditure is the amount of energy required daily and includes the energy required for the basal metabolic rate and for physical activity. Basal metabolic rate for a person is approximately 24 kcal/kg (101 kJ/kg) body weight per day [13].

Energy needed for physical exercise = 480 kcal/day

Energy expenditure = Basal metabolic rate + Physical exercise

Energy expenditure daily = (24 kcal/kg day)(146 lb)(kg/2.2 lb) + 480 kcal/day

= 1594 kcal/day + 480 kcal/day = **2074 kcal/day**

Energy intake:
Carbohydrates: 4 kcal/g → (150 g/day)(4 kcal/g) = 600 kcal/day.
Fats: 9 kcal/g → (60 g/day)(9 kcal/g) = 540 kcal/day.
Proteins: 4 kcal/g → (50 g/day)(4 kcal/g) = 200 kcal/day.

Total energy intake = (600 + 540 + 200) kcal/day = **1,340 kcal/day**

Total energy intake of 1,340 kcal/day is less than basal metabolic rate of 2,074 kcal.

Example 10.4 Energy expenditure in small organisms
Consider a small organism with a body weight of 10 μg consuming 4.0×10^{-9} mol oxygen every hour at steady state and eliminating 3.6×10^{-9} mol carbon dioxide, 0.4×10^{-9} mol N (as ammonia). The external work of the organism is 50×10^{-9} W. Estimate the energy expenditure and the heat loss using the heat of reactions given below.

Hydrocarbon (Glucose) (G): $C_6H_{12}O_6 + 6O_2(g) \rightarrow 6CO_2 + 6H_2O - 2870\,\text{kJ/mol}$

Fat(F): $C_{55}H_{104}O_6 + 78O_2 \rightarrow 55CO_2 + 52H_2O - 34300\,\text{kJ/mol}$

Protein(Pr): $C_{32}H_{48}O_{10}N_8 + 33O_2 \rightarrow 32CO_2 + 8NH_3 + 12H_2O - 14744\,\text{kJ/mol}$

Solution:
The energy expenditure may be calculated with the given reaction enthalpies:

$$\dot{E} = 2870(\dot{n})_{\mathrm{G}} + 34300(\dot{n})_{\mathrm{F}} + 14744(\dot{n})_{\mathrm{Pr}}\ (\text{kJ/h})$$

The number of mole flow rates is obtained from the reaction stoichiometric coefficients: For example for oxygen:

- one mole/h of glucose consumes 6 mol/h of O_2
- one mole/h of fat consumes 78 mol/h of O_2
- one mole/h of protein consumes 33 mol/h of O_2

With the similar procedure for carbon dioxide and nitrogen, we have

$$\dot{n}_{\mathrm{O}_2} = 6\dot{n}_G + 78\dot{n}_F + 33\dot{n}_{\mathrm{Pr}} = 4.0 \times 10^{-9}\text{mol/h}$$

$$\dot{n}_{\mathrm{CO}_2} = 6\dot{n}_G + 55\dot{n}_F + 32\dot{n}_{\mathrm{Pr}} = 3.6 \times 10^{-9}\text{mol/h}$$

$$\dot{n}_N = 8\dot{n}_{\mathrm{Pr}} = 0.4 \times 10^{-9}\text{mol/h}$$

After solving the equations above, we have the energy expenditure:

$$\begin{aligned}\dot{E} &= [2870(0.194)_{\mathrm{G}} + 34300(0.0152)_{\mathrm{F}} + 14744(0.05)_{\mathrm{Pr}}] \times 10^{-9} \\ &= 1820 \times 10^{-9}\,\text{kJ/h} = \mathbf{0.505\,\mu W}\end{aligned}$$

With $W = 50 \times 10^{-9}$ W = 0.05 μW
Heat loss: $\dot{q} = \dot{E} - \dot{W} = (0.506 - 0.050)\ \mu\text{W} = \mathbf{0.46\,\mu W}$

Example 10.5 Energy expenditure in an adult organism

An adult organism has an oxygen uptake of about 21.16 mol over 24 h, and the associated elimination of carbon dioxide and nitrogen is 16.95 mol and 5.76 g, respectively [10]. If the adult has performed 1.2 MJ of external work over the same period and his energy expenditure at rest is $\dot{E}_o = 65\,\mathrm{W}$, estimate his energy expenditure, heat loss, and net efficiency for the external work using the biological fuel parameters given below.

Fuel	Specific reaction enthalpy (kJ/g)	Specific turnover		
		O_2 (mmol/g)	CO_2 (mmol/g)	N (g/g)
CH	−17	33.3	33.3	–
Fat	−39	90.6	63.8	–
Pr	−17	43.3	34.43	0.16

CH: carbohydrate, Pr: Protein, *Source* Garby and Larsen [10]

Solution:

The energy expenditure may be calculated from the energy balance. Assume that (i) carbohydrate (CH), fat (F), and protein (Pr) are the only compounds involved in the oxidation process, (ii) the other compounds are stationary, and (iii) the uptake and elimination of oxygen, carbon dioxide, and nitrogen is instantaneous. From the first law of thermodynamics, we have

$$\dot{E} = \sum_i (\dot{m}\Delta H_r)_i = (\dot{m}\Delta H_r)_{\mathrm{CH}} + (\dot{m}\Delta H_r)_{\mathrm{F}} + (\dot{m}\Delta H_r)_{\mathrm{Pr}} = \dot{q} + \dot{W}\ (\mathrm{kJ/day})$$

Using the specific enthalpy values of the fuels:

$$17\dot{m}_{\mathrm{CH}} + 39\dot{m}_{\mathrm{F}} + 17\dot{m}_{\mathrm{Pr}} = \dot{q} + \dot{W} = \dot{E} \tag{a}$$

The conservation of mass with the parameters from above table:

$\dot{n}_{O_2} = 33.3\dot{m}_{\mathrm{CH}} + 90.6\dot{m}_{\mathrm{F}} = 21160\,\mathrm{mmol/day}$

$\dot{n}_{CO_2} = 33.3\dot{m}_{\mathrm{CH}} + 90.6\dot{m}_{\mathrm{F}} = 16950\,\mathrm{mmol/day}.$

From these equations, we obtain

$\dot{m}_{\mathrm{Pr}} = 5.76/0.16 = 36\,\mathrm{g/day}$

$\dot{m}_{\mathrm{CH}} = 208\,\mathrm{g/day}$

$\dot{m}_{\mathrm{F}} = 157\,\mathrm{g/day}$

From Eq. (a), we have:

Total energy expenditure = basal metabolic rate + physical exercise

$17(208) + 39(157) + 17(36) = -\dot{q} + (-\dot{W}) = \dot{E} = \mathbf{10271\,kJ/day}$

Since the work (part of physical exercise) is 1.2 MJ/day = 1200 kJ/day

Heat loss: $\dot{q} = (10271 - 1200)\ \mathrm{kJ/day} = \mathbf{9071\,kJ/day}$

Basal metabolic rate (energy expenditure at rest): $\dot{E}_o = 65\,\mathrm{W} = 5616\,\mathrm{kJ/day}$

A net available energy for physical exercise: (10271–5616) kJ/day
Then the bioenergetics efficiency is defined by

$$\eta_B = \frac{\dot{W}}{(\dot{E} - \dot{E}_o)} = \frac{1200}{(10271 - 5616)} = \mathbf{0.257\ or\ 25.7\%}$$

$\dot{E}_o$ is the energy expenditure during resting and $\dot{E}$ is the total energy.

Problems

10.1. Estimate the approximate daily energy expenditure of an adult of 55 kg.

10.2. Estimate the approximate daily energy expenditure of a child of 20 kg.

10.3. Estimate the approximate daily energy expenditure of an adult of 51 kg.

10.4. A dietary history of an adult of 65 kg shows that he eats approximately 250 g of carbohydrate, 120 g of protein, and 160 g of fat daily. The adult exercises regularly and consumes an average 600 kcal daily. Estimate the energy expenditure of this adult and comment if the energy intake is excessive.

10.5. A dietary history of a child of 25 kg shows that he eats approximately 150 g of carbohydrate, 80 g of protein, and 100 g of fat daily. The child exercises regularly and consumes an average 450 kcal daily. Estimate the energy expenditure of this adult and comment if the energy intake is excessive.

10.6. A dietary history of an adult of 75 kg shows that he eats approximately 275 g of carbohydrate, 160 g of protein, and 190 g of fat daily. The child exercises regularly and consumes an average 700 kcal daily. Estimate the energy expenditure of this adult and comment if the energy intake is excessive.

10.7. Discuss the consequences of hydrolyzing ATP rapidly.

10.8. Discuss the consequences of intake of uncouple to the human body.

10.9. Discuss the consequence of a lack of oxygen flow to the human body.

10.10. An organism lose heat at a rate of 1.64 W and performs an external work of 1.4 Nm/min. (a) Estimate the energy expenditure of the organism, (b) if the organism is able to pump 100 ml/min of fluid against a pressure drop of 25 mm Hg (3.34 kPa) with an efficiency of 10%, estimate the efficiency of pumping.

10.11. An organism lose heat at a rate of 2.1 W and performs an external work of 5 Nm/min. (a) Estimate the energy expenditure of the organism, (b) if the organism is able to pump 52 ml/min of fluid against a pressure drop of 2.5 mm Hg (0.334 kPa) with an efficiency of 10%, estimate the efficiency of pumping.

10.12. (a) Estimate the reaction enthalpy for the isothermal and isobaric oxidation of glucose at 310 K and 1 atm. (b) Estimate the energy expenditure for oxidation of 390 g/day glucose at steady conditions.

10.13. Consider a small organism with a body weight of 10 μg consuming 8.0×10^{-9} mol oxygen every hour at steady state and eliminating

7.1×10^{-9} mol carbon dioxide, 0.8×10^{-9} mol N (as ammonia). The external work of the organism is 80×10^{-9} W. Estimate the energy expenditure and heat loss using the heat of reactions given below.

$$\text{Hydrocarbon (Glucose) (G): } C_6H_{12}O_6 + 6O_2(g) \rightarrow 6CO_2 + 6H_2O - 2870\,\text{kJ/mol}$$

$$\text{Fat(F):} C_{55}H_{104}O_6 + 78O_2 \rightarrow 55CO_2 + 52H_2O - 34300\,\text{kJ/mol}$$

$$\text{Protein(Pr):} C_{32}H_{48}O_{10}N_8 + 33O_2 \rightarrow 32CO_2 + 8NH_3 + 12H_2O - 14744\,\text{kJ/mol}$$

10.14. An adult organism has an oxygen uptake of about 21.16 mol over 24 h, and the associated elimination of carbon dioxide and nitrogen is 16.95 mol and 5.76 g, respectively [10]. If the adult has performed 1.25 MJ of external work over the same period and his energy expenditure at rest is $\dot{E}_o = 72$ W, estimate his energy expenditure, heat loss, and net efficiency for the external work using the biological fuel parameters given below.

Fuel	Specific reaction enthalpy (kJ/g)	Specific turnover (mmol/g)		
		O_2 (mmol/g)	CO_2 (mmol/g)	N (g/g)
CH	−17	33.3	33.3	–
Fat	−39	90.6	63.8	–
Pr	−17	43.3	34.43	0.16

CH: Carbohydrate; Pr: Protein. *Source* Garby and Larsen [10]

10.15. An adult organism has an oxygen uptake of about 22.5 mol over 24 h, and the associated elimination of carbon dioxide and nitrogen is 17.4 mol and 6.6 g, respectively [10]. Estimate his energy expenditure, heat loss, and net efficiency for the external work using the biological fuel parameters given below.

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Appendix A
Physical and Critical Properties

Table A1 Physical properties of various organic and inorganic substances

Compound	Formula	*MW*	Sp Gr	T_m (K)	T_b (K)	ΔH_v (kJ/kg)	ΔH_m (kJ/kg)
Air		28.97					
Ammonia	NH_3	17.03	0.817	195.4	239.7	1374.0	322.4
Benzene	C_6H_6	78.11	0.879	278.7	353.3	394.3	126.0
Benzyl alcohol	C_7H_8O	108.13	1.045	257.8	478.4		
Butane	n-C_4H_{10}	58.12	0.579	134.8	272.7	383.6	80.3
Iso-Butane	i-C_4H_{10}	58.12	0.557	113.6	261.4	366.4	105.7
Carbon dioxide	CO_2	44.01	1.530	217.0			
Carbon disulfide	CS_2	76.14	1.261	161.1	319.4	351.9	
Carbon monoxide	CO	28.01	0.968	68.1	81.7	214.2	
Cyclohexane	C_6H_{12}	84.16	0.779	279.8	353.9	357.6	
Cyclopentane	C_3H_{10}	70.13	0.745	179.7	322.4	389.2	
Diethyl ether	$(C_2H_5)_2O$	74.12	0.708	156.9	307.8	352.1	
Ethane	C_2H_6	30.07	1.049	89.9	184.5	488.8	
Ethanol	C_2H_6O	46.07	0.789	158.6	351.7	837.8	109.0
Ethylene glycol	$C_2H_6O_2$	62.07	1.113	260.0	470.4	916.7	181.1
Gycerol	$C_3H_8O_3$	92.09	1.260	291.4	563.2		200.6
Heptane	C_7H_{16}	100.20	0.684	182.6	371.6	316.3	
Hexane	C_6H_{14}	86.17	0.659	177.8	341.9	335.3	
Hydrogen	H_2	2.02	0.069	14.0	20.4	445.5	59.5
Hydrogen chloride	HCl	36.47	1.268	158.9	188.1	444.2	
Hydrogen sulfide	H_2S	34.08	1.189	187.6	212.8	548.7	
Mercury	Hg	200.61	13.546				
Methane	CH_4	16.04	0.554	90.7	111.7	511.2	58.4
Methanol	CH_3OH	32.04	0.792	175.3	337.9	1101.7	99.2
Nitric acid	HNO_3	63.02	1.502	231.6	359.0	480.7	
Nitrogen	N_2	28.02	12.500	63.2	77.3	199.8	25.3
Nitrogen dioxide	NO_2	46.01	1.448	263.9	294.5	319.4	
Nitrogen oxide	NO	30.01	1.037	109.5	121.4	459.8	
Nitrogen pentoxide	N_2O_5	108.02	1.630	303.0	320.0		

(continued)

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Table A1 (continued)

Compound	Formula	*MW*	Sp Gr	T_m (K)	T_b (K)	ΔH_v (kJ/kg)	ΔH_m (kJ/kg)
Nitrous oxide	N_2O	44.02	1.226	182.1	184.4		
Oxygen	O_2	32.00	1.105	54.4		212.5	13.7
n-Pentane	C_5H_{12}	72.15	0.630	143.5	309.2	357.5	
Iso-pentane	i-C_5H_{12}	72.15	0.621	113.1	300.9		
Propane	C_3H_8	44.09	1.562	85.5	18.8		80.0
Propylene	C_3H_6	1500	7.792	1.637	22.706	−6.915	
n-Propyl alcohol	C_3H_8O	60.09	0.804	146.0			
Iso-Propyl alcohol	C_3H_8O	60.09	0.785	183.5			
n-Propyl benzene	C_9H_{12}	120.19	0.862	173.7	38.2		
Sodium hydroxide	NaOH	40.00	2.130	592.0	1663.0		
Sulfur dioxide	SO_2	64.07	2.264	197.7	263.1	388.6	
Sulfur trioxide	SO_3	80.07	2.750	290.0	316.5	522.0	
Sulfuric acid	H_2SO_4	98.08	1.834	283.5			
Toluene	$C_6H_5CH_3$	92.13	0.866	178.2	383.8	363.6	
Water	H_2O	18.02	1.000	273.2	373.2	2257.0	333.7

Source: Çengel and Boles [1], Himmelblau and Riggs [2]

Table A2 Critical properties

Species	*MW*	ω	T_c(K)	P_c (atm)	V_c (cm^3/gmol)
Air	28.97	0.035	132.5	37.2	88.3
H_2	2.02	−0.216	33.3	12.8	65.0
Air	28.97	0.035	132.0	36.4	86.6
N_2	28.01	0.038	126.2	33.5	90.1
O_2	32.00	0.022	154.4	49.7	74.4
CO	28.01	0.048	132.9	34.5	93.1
CO_2	44.01	0.224	304.2	72.8	94.1
NO	30.10	0.583	180.0	64.0	57.0
N_2O	44.01	0.141	309.7	71.7	96.3
SO_2	64.06	0.245	430.7	77.8	122.0
Cl_2	70.91	0.069	417.0	76.1	124.0
CH_4	16.04	0.012	191.1	45.8	98.7
C_2H_6	30.07	0.100	305.4	48.2	148.0
C_3H_6	42.08	0.140	365.0	45.5	181.0
C_3H_8	44.10	0.152	369.8	41.9	200.0
n-C_4H_{10}	58.12	0.200	425.2	37.5	255.0
i-C_4H_{10}	58.12	0.181	408.1	36.0	263.0
n-C_5H_{12}	72.15	0.252	469.5	33.2	311.0
n-C_6H_{14}	86.18	0.301	507.3	29.7	370.0
n-C_7H_{16}	100.20	0.350	540.1	27.0	432.0
n-C_8H_{18}	114.23	0.400	568.7	24.5	492.0
n-C_9H_{20}	128.26	0.444	594.6	22.6	548.0
Cyclohexane	84.16	0.210	553.0	40.0	308.0
Benzene	78.11	0.210	562.6	48.6	260.0

Source: Smith et al. [8]

Appendix B
Heat Capacities

Table B1 Heat capacities in the ideal-gas state: $C_p^{ig}/R = A + BT + CT^2$, T(K): $T = 298$ K to $T_{\max}$ K

Chemical species	Formula	$T_{\max}$ (K)	C_p^{ig}/R, 298 (K)	A	$10^3\ B$	$10^6\ C$
Methane	CH_4	1,500	4.217	1.702	9.081	−2.164
Ethane	C_2H_6	1,500	6.369	1.131	19.225	−5.561
Propane	C_3H_8	1,500	9.011	1.213	28.785	−8.824
Acetylene	C_2H_2	26.04	0.906	191.7	191.7	672.0
Ethylene	C_2H_4	28.05	0.975	104.0	169.5	481.2
n-Butane	C_4H_{10}	1,500	11.928	1.935	36.915	−11.402
n-Pentane	C_5H_{12}	1,500	14.731	2.464	45.351	−14.111
n-Hexane	C_6H_{14}	1,500	17.550	3.025	53.722	−16.791
n-Heptane	C_7H_{16}	1,500	20.361	3.570	62.127	−19.486
n-Octane	C_8H_{18}	1,500	23.174	4.108	70.567	−22.208
Benzene	C_6H_6	1,500	10.259	−0.206	39.064	−13.301
Cyclohexane	C_6H_{12}	1,500	13.121	−3.876	63.249	−20.928
Ethanol	C_2H_6O	1,500	8.948	3.518	20.001	−6.002
Methanol	CH_4O	1,500	5.547	2.211	12.216	−3.450
Toluene	C_7H_8	1,500	12.922	0.290	47.052	−15.716
Air		2,000	3.509	3.355	0.575	……
Ammonia	NH_3	1,800	4.269	3.578	3.020	……
Carbon monoxide	CO	2,500	3.507	3.376	0.557	……
Carbon dioxide	CO_2	2,000	4.467	5.457	1.045	……
Chlorine	Cl_2	3,000	4.082	4.442	0.089	……
Hydrogen	H_2	3,000	3.468	3.249	0.422	……
Nitrogen	N_2	2,000	3.502	3.280	0.593	……
Nitrogen dioxide	NO_2	2,000	4.447	4.982	1.195	……
Oxygen	O_2	2,000	3.535	3.639	0.506	……
Sulfur dioxide	SO_2	2,000	4.796	5.699	0.801	……
Sulfur trioxide	SO_3	2,000	6.094	8.060	1.056	……
Water	H_2O	2,000	4.038	3.470	1.450	……

Source: Smith et al. [8]

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Table B2 Heat capacities of liquids: $C_p/R = A + BT + CT^2$, T(K): T = 298 K to $T_{\max}$ K

Chemical species	C_p^{ig}/R, 298 (K)	A	$10^3\ B$	$10^6\ C$
Ammonia	9.718	22.626	−100.75	192.71
Aniline	23.070	15.819	29.03	−15.80
Benzene	16.157	−0.747	67.96	−37.78
Carbon tetrachloride	15.751	21.155	−48.28	101.14
Chlorobenzene	18.240	11.278	32.86	−31.90
Chloroform	13.806	19.215	−42.89	83.01
Cyclohexane	18.737	−9.048	141.38	−161.62
Ethanol	13.444	33.866	−172.60	349.17
Ethylene oxide	10.590	21.039	−86.41	172.28
Methanol	9.798	13.431	−51.28	131.13
n-Propanol	16.921	41.653	−210.32	427.20
Toluene	18.611	15.133	6.79	16.35
Water	9.069	8.712	1.25	−0.18

Source: Miller et al. [4]

Table B3 Heat capacities of solids: $C_p/R = A + BT + CT^{-2}$, T(K): T = 298 K to $T_{\max}$ K

Chemical species	$T_{\max}$ (K)	C_p^{ig}/R, 298 (K)	A	$10^3\ B$	$10^{-5}\ C$
CaO	2,000	5.058	6.104	0.443	−1.047
$CaCO_3$	1,200	9.848	12.572	2.637	−3.120
$CaCl_2$	1,055	8.762	8.646	1.530	−0.302
C(graphite)	2,000	1.026	1.771	0.771	−0.867
Cu	1,357	2.959	2.677	0.815	0.035
CuO	1,400	5.087	5.780	0.973	−0.874
Fe	1,043	3.005	−0.111	6.111	1.150
FeS	411	6.573	2.612	13.286	
NH_4Cl	458	10.741	5.939	16.105	
NaOH	566	7.177	0.121	16.316	1.948
SiO_2 (quartz)	847	5.345	4.871	5.365	−1.001

Source: Kelley and Bur [3], Pankratz and Bur [6]

Table B4 Ideal-gas specific heats of various common gases

T (K)	C_p (kJ/kg K)	C_v (kJ/kg K)	γ	C_p (kJ/kg K)	C_v (kJ/kg K)	γ	C_p (kJ/kg K)	C_v (kJ/kg K)	γ
	Air			Carbon dioxide (CO_2)			Carbon monoxide (CO)		
250	1.003	0.716	1.401	0.791	0.602	1.314	1.039	0.743	1.400
300	1.005	0.718	1.400	0.846	0.657	1.288	1.040	0.744	1.399
350	1.008	0.721	1.398	0.895	0.706	1.268	1.043	0.746	1.398
400	1.013	0.726	1.395	0.939	0.750	1.252	1.047	0.751	1.395
450	1.020	0.733	1.391	0.978	0.790	1.239	1.054	0.757	1.392
500	1.029	0.742	1.387	1.014	0.825	1.229	1.063	0.767	1.387
550	1.040	0.753	1.381	1.046	0.857	1.220	1.075	0.778	1.382
600	1.051	0.764	1.376	1.075	0.886	1.213	1.087	0.790	1.376
650	1.063	0.776	1.370	1.102	0.913	1.207	1.100	0.803	1.370
700	1.075	0.788	1.364	1.126	0.937	1.202	1.113	0.816	1.364
750	1.087	0.800	1.359	1.148	0.959	1.197	1.126	0.829	1.358
800	1.099	0.812	1.354	1.169	0.980	1.193	1.139	0.842	1.353
900	1.121	0.834	1.344	1.204	1.015	1.186	1.163	0.866	1.343
1000	1.142	0.855	1.336	1.234	1.045	1.181	1.185	0.888	1.335
Hydrogen (H_2)				Nitrogen (N_2)			Oxygen (O_2)		
250	14.051	9.927	1.416	1.039	0.742	1.400	0.913	0.653	1.398
300	14.307	10.183	1.405	1.039	0.743	1.400	0.918	0.658	1.395
350	14.427	10.302	1.400	1.041	0.744	1.399	0.928	0.668	1.389
400	14.476	10.352	1.398	1.044	0.747	1.397	0.941	0.681	1.382
450	14.501	10.377	1.398	1.049	0.752	1.395	0.956	0.696	1.373
500	14.513	10.389	1.397	1.056	0.759	1.391	0.972	0.712	1.365
550	14.530	10.405	1.396	1.065	0.768	1.387	0.988	0.728	1.358
600	14.546	10.422	1.396	1.075	0.778	1.382	1.003	0.743	1.350
650	14.571	10.447	1.395	1.086	0.789	1.376	1.017	0.758	1.343
700	14.604	10.480	1.394	1.098	0.801	1.371	1.031	0.771	1.337
750	14.645	10.521	1.392	1.110	0.813	1.365	1.043	0.783	1.332
800	14.695	10.570	1.390	1.121	0.825	1.360	1.054	0.794	1.327
900	14.822	10.698	1.385	1.145	0.849	1.349	1.074	0.814	1.319
1000	14.983	10.859	1.380	1.167	0.870	1.341	1.090	0.830	1.313

Source: Çengel and Boles [1], Wark [10]

Appendix C
Enthalpy and Gibbs Free Energy of Formations at 298.15 K

Table C1 Standard enthalpies and Gibbs energies of formation at 298.15 K

Chemical species	Formula	State	ΔH_{f298} (kJ/mol)	ΔG_{f298} (kJ/mol)
Methane	CH_4	(g)	−74.520	−50.460
Ethane	C_2H_6	(g)	−83.820	−31.855
Propane	C_3H_8	(g)	−104.680	−24.290
n-Butane	C_4H_{10}	(g)	−125.790	−16.570
n-Pentane	C_5H_{12}	(g)	−146.760	−8.650
Benzene	C_6H_6	(g)	82.930	129.665
Benzene	C_6H_6	(l)	49.080	124.520
Cyclohexane	C_6H_{12}	(g)	−123.140	31.920
Cyclohexane	C_6H_{12}	(l)	−156.230	26.850
Ethanol	C_2H_6O	(g)	−235.100	−168.490
Ethanol	C_2H_6O	(l)	−277.690	−174.780
Methanol	CH_4O	(g)	−200.660	−161.960
Methanol	CH_4O	(l)	−238.660	−166.270
Toluene	C_7H_8	(g)	50.170	122.050
Toluene	C_7H_8	(l)	12.180	113.630
Ammonia	NH_3	(g)	−46.110	−16.450
Calcium carbonate	$CaCO_3$	(s)	−1206.920	−1128.790
Calcium oxide	CaO	(s)	−635.090	−604.030
Carbon dioxide	CO_2	(g)	−393.509	−394.359
Carbon monoxide	CO	(g)	−110.525	−137.169
Hydrochloric acid	HCI	(g)	−92.307	−95.299
Hydrogen sulfide	H_2S	(g)	−20.630	−33.560
Iron oxide	FeO	(s)	−272.000	
Nitric acid	HNO_3	(l)	−174.100	−80.710
Nitrogen oxides	NO	(g)	90.250	86.550
	NO_2	(g)	33.180	51.310
Sodium carbonate	Na_2CO_3	(s)	−1130.680	−1044.440
Sodium chloride	$NaCl$	(s)	−411.153	−384.138

(continued)

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Table C1 (continued)

Chemical species	Formula	State	ΔH_{f298} (kJ/mol)	ΔG_{f298} (kJ/mol)
Sodium hydroxide	NaOH	(s)	−425.609	−379.494
Sulfur dioxide	SO_2	(g)	−296.830	−300.194
Sulfur trioxide	SO_3	(g)	−395.720	−371.060
Sulfur trioxide	SO_3	(l)	−441.040	
Water	H_2O	(g)	−241.818	−228.572
Water	H_2O	(I)	−285.830	−237.129

Source: Thermodynamic Research Center [9]

Appendix D
Ideal Gas Properties of Some Common Gases

Table D1 Ideal-gas properties of air

T (K)	H (kJ/kg)	P_r	U (kJ/kg)	V_r	S (kJ/kg K)
270	270.11	0.9590	192.60	808.0	1.596
280	280.13	1.0889	199.75	783.0	1.632
285	285.14	1.1584	203.33	706.1	1.650
290	290.16	1.2311	206.91	676.1	1.668
295	295.17	1.3068	210.49	647.9	1.685
300	300.19	1.3860	214.07	621.2	1.702
305	305.22	1.4686	217.67	596.0	1.718
310	310.24	1.5546	221.25	572.3	1.734
315	315.27	1.6442	224.85	549.8	1.751
320	320.29	1.7375	228.42	528.6	1.766
325	325.31	1.8345	232.02	508.4	1.782
330	330.34	1.9352	235.61	489.4	1.797
340	340.42	2.149	242.82	454.1	1.827
350	350.49	2.379	250.02	422.2	1.857
360	360.58	2.626	257.24	393.4	1.885
370	370.67	2.892	264.46	367.2	1.913
380	380.77	3.176	271.69	343.4	1.940
390	390.88	3.481	278.93	321.5	1.966
400	400.98	3.806	286.16	301.6	1.991
410	411.12	4.153	293.43	283.3	2.016
420	421.26	4.522	300.69	266.6	2.041
430	431.43	4.915	307.99	251.1	2.065
440	441.61	5.332	315.30	236.8	2.088
450	451.80	5.775	322.62	223.6	2.111
460	462.02	6.245	329.97	211.4	2.134
470	472.24	6.742	337.32	200.1	2.156
480	482.49	7.268	344.70	189.5	2.177
490	492.74	7.824	352.08	179.7	2.198
500	503.02	8.411	359.49	170.6	2.219

(continued)

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Table D1 (continued)

T (K)	H (kJ/kg)	P_r	U (kJ/kg)	V_r	S (kJ/kg K)
510	513.32	9.031	366.92	162.1	2.239
520	523.63	9.684	374.36	154.1	2.259
530	533.98	10.37	381.84	146.7	2.279
540	544.35	11.10	389.34	139.7	2.299
550	555.74	11.86	396.86	133.1	2.318
560	565.17	12.66	404.42	127.0	2.336
570	575.59	13.50	411.97	121.2	2.355
580	586.04	14.38	419.55	115.7	2.373
590	596.52	15.31	427.15	110.6	2.391
600	607.02	16.28	434.78	105.8	2.409
610	617.53	17.30	442.42	101.2	2.426
620	628.07	18.36	450.09	96.92	2.443
630	683.63	19.84	457.78	92.84	2.460
640	649.22	20.64	465.50	88.99	2.477
650	659.84	21.86	473.25	85.34	2.493
660	670.47	23.13	481.01	81.89	2.509
670	681.14	24.46	488.81	78.61	2.525
680	691.82	25.85	496.62	75.50	2.541
690	702.52	27.29	504.45	72.56	2.557
700	713.27	28.80	512.33	69.76	2.572
710	724.04	30.38	520.23	67.07	2.588
720	734.82	32.02	528.14	64.53	2.603
730	745.62	33.72	536.07	62.13	2.618
740	756.44	35.50	544.02	59.82	2.632
750	767.29	37.35	551.99	57.63	2.647
760	778.18	39.27	560.01	55.54	2.661
780	800.03	43.35	576.12	51.64	2.690
800	821.95	47.75	592.30	48.08	2.717
820	843.98	52.59	608.59	44.84	2.745
840	866.08	57.60	624.95	41.85	2.771
860	888.27	63.09	641.40	39.12	2.797
880	910.56	68.98	657.95	36.61	2.823
900	932.93	75.29	674.58	34.31	2.848
920	955.38	82.05	691.28	32.18	2.873
940	977.92	89.28	708.08	30.22	2.897
960	1000.55	97.00	725.02	28.40	2.921
980	1023.25	105.2	741.98	26.73	2.944
1000	1046.04	114.0	758.94	25.17	2.967
1020	1068.89	123.4	776.10	23.72	2.990
1040	1091.85	133.3	793.36	23.29	3.012
1060	1114.86	143.9	810.62	21.14	3.034
1080	1137.89	155.2	827.88	19.98	3.056
1100	1161.07	167.1	845.33	18.896	3.077
1120	1184.28	179.7	862.79	17.886	3.098
1140	1207.57	193.1	880.35	16.946	3.118

(continued)

Table D1 (continued)

T (K)	H (kJ/kg)	P_r	U (kJ/kg)	V_r	S (kJ/kg K)
1160	1230.92	207.2	897.91	16.064	3.139
1180	1254.34	222.2	915.57	15.241	3.159
1200	1277.79	238.0	933.33	14.470	3.178
1220	1301.31	254.7	951.09	13.747	3.198
1240	1324.93	272.3	968.95	13.069	3.217
1260	1348.55	290.8	986.90	12.435	3.236
1280	1372.24	310.4	1004.76	11.835	3.255
1300	1395.97	330.9	1022.82	11.275	3.273
1320	1419.76	352.5	1040.88	10.747	3.291
1340	1443.60	375.3	1058.94	10.247	3.309
1360	1467.49	399.1	1077.10	9.780	3.327
1400	1515.42	450.5	1113.52	8.919	3.362
1460	1587.63	537.1	1168.49	7.801	3.412
1500	1635.97	601.9	1205.41	7.152	3.445
1560	1708.82	710.5	1260.99	6.301	3.492
1600	1757.57	791.2	1298.30	5.804	3.523
1640	1806.46	878.9	1335.72	5.355	3.553
1700	1880.1	1025	1392.7	4.761	3.597
1750	1941.6	1161	1439.8	4.328	3.633
1800	2003.3	1310	1487.2	3.994	3.668
1850	2065.3	1475	1534.9	3.601	3.702
1900	2127.4	1655	1582.6	3.295	3.735
1950	2189.7	1852	1630.6	3.022	3.767
2000	2252.1	2068	1678.8	2.776	3.799
2100	2377.7	2559	1775.3	2.356	3.860

Source: Çengel and Boles [1], Wark [10]

Table D2 Ideal-gas properties of carbon dioxide, CO_2

T (K)	*H* (kJ/kmol)	*U* (kJ/kmol)	*S* (kJ/kmol K)	*T* (K)	*H* (kJ/kmol)	*U* (kJ/kmol)	*S* (kJ/kmol K)
0	0,000	0,000	0.000	600	22,280	17,291	243.199
220	6,601	4,772	202.966	610	22,754	17,683	243.983
230	6,938	5,026	204.464	620	23,231	18,076	244.758
240	7,280	5,285	205.920	630	23,709	18,471	245.524
250	7,627	5,548	207.337	640	24,190	18,869	246.282
260	7,979	5,817	208.717	650	24,674	19,270	247.032
270	8,335	6,091	210.062	660	25,160	19,672	247.773
280	8,697	6,369	211.376	670	25,648	20,078	248.507
290	9,063	6,651	212.660	680	26,138	20,484	249.233
298	9,364	6,885	213.685	690	26,631	20,894	249.952
300	9,431	6,939	213.915	700	27,125	21,305	250.663
310	9,807	7,230	215.146	710	27,622	21,719	251.368
320	10,186	7,526	216.351	720	28,121	22,134	252.065
330	10,570	7,826	217.534	730	28,622	22,522	252.755
340	10,959	8,131	218.694	740	29,124	22,972	253.439
350	11,351	8,439	219.831	750	29,629	23,393	254.117
360	11,748	8,752	220.948	760	20,135	23,817	254.787
370	12,148	9,068	222.044	770	30,644	24,242	255.452
380	12,552	9,392	223.122	780	31,154	24,669	256.110
390	12,960	9,718	224.182	790	31,665	25,097	256.762
400	13,372	10,046	225.225	800	32,179	25,527	257.408
410	13,787	10,378	226.250	810	32,694	25,959	258.048
420	14,206	10,714	227.258	820	33,212	26,394	258.682
430	14,628	11,053	228.252	830	33,730	26,829	259.311
440	15,054	11,393	229.230	840	34,251	27,267	259.934
450	15,483	11,742	230.194	850	34,773	27,706	260.551
460	15,916	12,091	231.144	860	35,296	28,125	261.164
470	16,351	12,444	232.080	870	35,821	28,588	261.770
480	16,791	12,800	233.004	880	36,347	29,031	262.371
490	17,232	13,158	233.916	890	36,876	29,476	262.968
500	17,678	13,521	234.814	900	37,405	29,922	263.559
510	18,126	13,885	235.700	910	37,935	30,369	264.146
520	18,576	14,253	236.575	920	38,467	30,818	264.728
530	19,029	14,622	237.439	930	39,000	31,268	265.304
540	19,485	14,996	238.292	940	39,535	31,719	265.877
550	19,945	15,372	239.135	950	40,070	32,171	266.444
560	20,407	15,751	239.962	960	40,607	32,625	267.007
570	20,870	16,131	240.789	970	41,145	33,081	267.566
580	21,337	16,515	241.602	980	41,685	33,537	268.119
590	21,807	16,902	242.405	990	42,226	33,995	268.670

Source: Çengel and Boles [1]

Table D3 Ideal-gas properties of hydrogen, H_2

T (K)	H (kJ/kmol)	U (kJ/kmol)	S (kJ/kmol K)	T (K)	H (kJ/kmol)	U (kJ/kmol)	S (kJ/kmol K)
0	0,000	0,000	0.000	1,440	42,808	30,835	177.410
260	7,370	5,209	126.636	1,480	44,091	31,786	178.291
270	7,657	5,412	127.719	1,520	45,384	32,746	179.153
280	7,945	5,617	128.765	1,560	46,683	33,713	179.995
290	8,233	5,822	129.775	1,600	47,990	34,687	180.820
298	8,468	5,989	130.574	1,640	49,303	35,668	181.632
300	8,522	6,027	130.754	1,680	50,622	36,654	182.428
320	9,100	6,440	132.621	1,720	51,947	37,646	183.208
340	9,680	6,853	134.378	1,760	53,279	38,645	183.973
360	10,262	7,268	136.039	1,800	54,618	39,652	184.724
380	10,843	7,684	137.612	1,840	55,962	40,663	185.463
400	11,426	8,100	139.106	1,880	57,311	41,680	186.190
420	12,010	8,518	140.529	1,920	58,668	42,705	186.904
440	12,594	8,936	141.888	1,960	60,031	43,735	187.607
460	13,179	9,355	143.187	2,000	61,400	44,771	188.297
480	13,764	9,773	144.432	2,050	63,119	46,074	189.148
500	14,350	10,193	145.628	2,100	64,847	47,386	189.979
520	14,935	10,611	146.775	2,150	66,584	48,708	190.796
560	16,107	11,451	148.945	2,200	68,328	50,037	191.598
600	17,280	12,291	150.968	2,250	70,080	51,373	192.385
640	18,453	13,133	152.863	2,300	71,839	52,716	193.159
680	19,630	13,976	154.645	2,350	73,608	54,069	193.921
720	20,807	14,821	156.328	2,400	75,383	55,429	194.669
760	21,988	15,669	157.923	2,450	77,168	56,798	195.403
800	23,171	16,520	159.440	2,500	78,960	58,175	196.125
840	24,359	17,375	160.891	2,550	80,755	59,554	196.837
880	25,551	18,235	162.277	2,600	82,558	60,941	197.539
920	26,747	19,098	163.607	2,650	84,368	62,335	198.229
960	27,948	19,966	164.884	2,700	86,186	63,737	198.907
1000	29,154	20,839	166.114	2,750	88,008	65,144	199.575
1040	30,364	21,717	167.300	2,800	89,838	66,558	200.234
1080	31,580	22,601	168.449	2,850	91,671	67,976	200.885
1120	32,802	23,490	169.560	2,900	93,512	69,401	201.527
1160	34,028	24,384	170.636	2,950	95,358	70,831	202.157
1200	35,262	25,284	171.682	3,000	97,211	72,268	202.778
1240	36,502	26,192	172.698	3,050	99,065	73,707	203.391
1280	37,749	27,106	173.687	3,100	100,926	75,152	203.995
1320	39,002	28,027	174.652	3,150	102,793	76,604	204.592
1360	40,263	28,955	175.593	3,200	104,667	78,061	205.181
1400	41,530	29,889	176.510	3,250	106,545	79,523	205.765

Source: Çengel and Boles [1]

Appendix E
Thermochemical Properties

Table E1 Saturated refrigerant-134a

T (°F)	P_{sat} (psia)	V (ft^3/lb)		U (Btu/lb)		H (Btu/lb)		S (Btu/lb R)	
		V_l	V_g	U_l	U_g	H_l	H_g	S_l	S_g
−40	7.490	0.01130	5.7173	-0.02	87.90	0.00	95.82	0.0000	0.2283
−30	9.920	0.01143	4.3911	2.81	89.26	2.83	97.32	0.0067	0.2266
−20	12.949	0.01156	3.4173	5.69	90.62	5.71	98.81	0.0133	0.2250
−15	14.718	0.01163	3.0286	7.14	91.30	7.17	99.55	0.0166	0.2243
−10	16.674	0.01170	2.6918	8.61	91.98	8.65	100.29	0.0199	0.2236
−5	18.831	0.01178	2.3992	10.09	92.66	10.13	101.02	0.0231	0.2230
0	21.203	0.01185	2.1440	11.58	93.33	11.63	101.75	0.0264	0.2224
5	23.805	0.01193	1.9208	13.09	94.01	13.14	102.47	0.0296	0.2219
10	26.651	0.01200	1.7251	14.60	94.68	14.66	103.19	0.0329	0.2214
15	29.756	0.01208	1.5529	16.13	95.35	16.20	103.90	0.0361	0.2209
20	33.137	0.01216	1.4009	17.67	96.02	17.74	104.61	0.0393	0.2205
25	36.809	0.01225	1.2666	19.22	96.69	19.30	105.32	0.0426	0.2200
30	40.788	0.01233	1.1474	20.78	97.35	20.87	106.01	0.0458	0.2196
40	49.738	0.01251	0.9470	23.94	98.67	24.05	107.39	0.0522	0.2189
50	60.125	0.01270	0.7871	27.14	99.98	27.28	108.74	0.0585	0.2183
60	72.092	0.01290	0.6584	30.39	101.27	30.56	110.05	0.0648	0.2178
70	85.788	0.01311	0.5538	33.68	102.54	33.89	111.33	0.0711	0.2173
80	101.370	0.01334	0.4682	37.02	103.78	37.27	112.56	0.0774	0.2169
85	109.920	0.01346	0.4312	38.72	104.39	38.99	113.16	0.0805	0.2167
90	118.990	0.01358	0.3975	40.42	105.00	40.72	113.75	0.0836	0.2165
95	128.620	0.01371	0.3668	42.14	105.60	42.47	114.33	0.0867	0.2163
100	138.830	0.01385	0.3388	43.87	106.18	44.23	114.89	0.0898	0.2161
105	149.630	0.01399	0.3131	45.62	106.76	46.01	115.43	0.0930	0.2159
110	161.040	0.01414	0.2896	47.39	107.33	47.81	115.96	0.0961	0.2157
115	173.100	0.01429	0.2680	49.17	107.88	49.63	116.47	0.0992	0.2155
120	185.820	0.01445	0.2481	50.97	108.42	51.47	116.95	0.1023	0.2153
140	243.860	0.01520	0.1827	58.39	110.41	59.08	118.65	0.1150	0.2143
160	314.630	0.01617	0.1341	66.26	111.97	67.20	119.78	0.1280	0.2128
180	400.220	0.01758	0.0964	74.83	112.77	76.13	119.91	0.1417	0.2101
200	503.520	0.02014	0.0647	84.90	111.66	86.77	117.69	0.1575	0.2044
210	563.510	0.02329	0.0476	91.84	108.48	94.27	113.45	0.1684	0.1971

Source: Çengel and Boles [1]

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Table E2 Superheated refrigerant R-134a

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
	P = 10 psia (T_{sat} = −29.7 °F)				P = 15 psia (T_{sat} = −14.3 °F)				P = 20 psia (T_{sat} = −29.7 °F)			
Sat	4.358	89.3	97.3	0.226	2.974	91.4	99.7	0.224	2.266	93.0	101.3	0.222
0	4.702	94.2	102.9	0.239	3.089	93.8	102.4	0.230	2.281	93.4	101.8	0.223
20	4.929	97.6	106.8	0.247	3.246	97.3	106.3	0.238	2.404	96.9	105.8	0.232
40	5.154	101.2	110.7	0.255	3.401	100.9	110.3	0.246	2.524	100.6	109.9	0.240
60	5.375	104.8	114.7	0.263	3.553	104.5	114.4	0.254	2.641	104.2	114.0	0.248
80	5.596	108.5	118.8	0.271	3.703	108.2	118.5	0.262	2.757	108.0	118.2	0.256
100	5.814	112.3	123.0	0.278	3.852	112.1	122.8	0.270	2.870	111.9	122.5	0.264
120	6.032	116.2	127.3	0.286	3.999	116.0	127.1	0.278	2.983	115.8	126.8	0.272
140	6.248	120.1	131.7	0.293	4.145	120.0	131.5	0.285	3.094	119.8	131.3	0.279
160	6.464	124.2	136.2	0.301	4.291	124.1	136.0	0.292	3.204	123.9	135.8	0.286
180	6.678	128.4	140.7	0.308	4.436	128.2	140.5	0.300	3.314	128.1	140.4	0.292
200	6.893	132.6	145.4	0.315	4.580	132.5	145.2	0.307	3.423	132.4	145.0	0.301
	P = 30 psia (T_{sat} = −29.7 °F)				P = 40 psia (T_{sat} = −29.7 °F)				P = 50 psia (T_{sat} = 40.3 °F)			
Sat	1.540	95.4	103.9	0.220	1.169	97.3	105.88	0.2197	0.942	98.71	107.4	0.218
40	1.646	99.9	109.1	0.231	1.206	99.3	108.26	0.2245				
60	1.729	103.7	113.3	0.239	1.272	103.2	112.62	0.2331	0.997	102.62	111.8	0.227
80	1.809	107.5	117.6	0.247	1.335	107.1	117.00	0.2414	1.050	106.62	116.3	0.236
100	1.888	111.4	121.9	0.255	1.397	111.0	121.42	0.2494	1.102	110.65	120.8	0.244
120	1.966	115.4	126.3	0.263	1.457	115.1	125.90	0.2573	1.152	114.74	125.3	0.252
140	2.042	119.5	130.8	0.271	1.516	119.2	130.43	0.2650	1.200	118.88	129.9	0.260
160	2.118	123.6	135.4	0.278	1.574	123.3	135.03	0.2725	1.284	123.08	134.6	0.267
180	2.192	127.8	140.0	0.285	1.631	127.6	139.70	0.2799	1.295	127.36	139.3	0.275
200	2.267	132.1	144.7	0.293	1.688	131.9	144.44	0.2872	1.341	131.71	144.1	0.282

(continued)

Table E2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
220	2.340	136.5	149.5	0.300	1.744	136.3	149.25	0.2944	1.387	136.12	148.9	0.289
240					1.800	140.8	154.14	0.3015	1.432	140.61	153.8	0.296
260					1.856	145.3	159.10	0.3085	1.477	145.18	158.8	0.303
280					1.911	149.9	164.13	0.3154	1.522	149.82	163.9	0.310
	P = 60 psia (T_{sat} = 49.9 °F)				P = 70 psia (T_{sat} = 58.4 °F)				P = 80 psia (T_{sat} = 65.9 °F)			
Sat	0.788	100.0	108.7	0.218	0.677	101.0	109.83	0.2179	0.593	102.02	110.8	0.217
60	0.813	102.0	111.0	0.222	0.681	101.4	110.23	0.2186				
80	0.860	106.1	115.6	0.231	0.723	105.5	114.96	0.2276	0.621	105.03	114.2	0.223
100	0.905	110.2	120.2	0.239	0.764	109.7	119.66	0.2361	0.657	109.30	119.0	0.232
120	0.948	114.3	124.8	0.248	0.802	113.9	124.36	0.2444	0.692	113.56	123.8	0.241
140	0.990	118.5	129.5	0.255	0.839	118.2	129.07	0.2524	0.726	117.85	128.6	0.249
160	1.030	122.7	134.2	0.263	0.875	122.4	133.82	0.2601	0.758	122.18	133.4	0.257
180	1.070	127.1	138.9	0.271	0.910	126.8	138.62	0.2678	0.789	126.55	138.2	0.264
200	1.110	131.4	143.7	0.278	0.944	131.2	143.46	0.2752	0.820	130.98	143.1	0.272
220	1.148	135.9	148.6	0.285	0.978	135.6	148.36	0.2825	0.850	135.47	148.0	0.279
240	1.187	140.4	153.6	0.293	1.011	140.2	153.33	0.2897	0.880	140.02	153.0	0.286
260	1.225	145.0	158.6	0.300	1.044	144.8	158.35	0.2968	0.909	144.63	158.1	0.294
280	1.262	149.6	163.6	0.307	1.077	149.4	163.44	0.3038	0.938	149.32	163.2	0.301
300	1.300	154.3	168.8	0.313	1.109	154.2	168.60	0.3107	0.967	154.06	168.3	0.307
	P = 90 psia (T_{sat} = 72.8 °F)				P = 100 psia (T_{sat} = 79.2 °F)				P = 120 psia (T_{sat} = 90.5 °F)			
Sat	0.527	102.8	111.6	0.217	0.474	103.6	112.46	0.2169	0.394	105.06	113.8	0.216
80	0.540	104.4	113.4	0.220	0.476	103.8	112.68	0.2173				
100	0.575	108.8	118.3	0.229	0.508	108.3	117.73	0.2265	0.408	107.26	116.3	0.221

(continued)

Table E2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
120	0.607	113.1	123.2	0.238	0.538	112.7	122.70	0.2352	0.435	111.84	121.5	0.230
140	0.638	117.5	128.1	0.246	0.567	117.1	127.63	0.2436	0.461	116.37	126.6	0.238
160	0.667	121.8	132.9	0.254	0.594	121.5	132.55	0.2517	0.482	120.89	131.6	0.247
180	0.696	126.2	137.8	0.262	0.621	125.9	137.49	0.2595	0.508	125.42	136.7	0.255
200	0.723	130.7	142.7	0.269	0.646	130.4	142.45	0.2671	0.530	129.97	141.7	0.262
220	0.751	135.2	147.7	0.277	0.671	135.0	147.45	0.2746	0.552	134.56	146.8	0.270
240	0.777	139.8	152.7	0.284	0.696	139.6	152.49	0.2819	0.573	139.20	151.9	0.277
260	0.804	144.4	157.8	0.291	0.720	144.2	157.59	0.2891	0.593	143.89	157.0	0.285
280	0.830	149.1	162.9	0.298	0.743	148.9	162.74	0.2962	0.614	148.63	162.2	0.292
300	0.856	153.9	168.1	0.305	0.767	153.7	167.95	0.3031	0.633	153.43	167.5	0.299
320	0.881	158.7	173.4	0.312	0.790	158.5	173.21	0.3099	0.653	158.29	172.8	0.306
	P = 140 psia (T_{sat} = 100.6 °F)				P = 160 psia (T_{sat} = 109.6 °F)				P = 180 psia (T_{sat} = 117.7 °F)			
Sat	0.335	106.2	114.9	0.216	0.291	107.2	115.91	0.2157	0.256	108.18	116.7	0.215
120	0.361	110.9	120.2	0.225	0.304	109.8	118.89	0.2209	0.259	108.77	117.4	0.216
140	0.384	115.5	125.2	0.234	0.326	114.7	124.41	0.2303	0.281	113.83	123.2	0.226
160	0.406	120.2	130.7	0.242	0.347	119.4	129.78	0.2391	0.301	118.74	128.7	0.235
180	0.427	124.8	135.8	0.251	0.366	124.2	135.06	0.2475	0.319	123.56	134.1	0.244
200	0.447	129.4	141.0	0.259	0.384	128.9	140.29	0.2555	0.336	128.34	139.5	0.252
220	0.466	134.0	146.1	0.266	0.402	133.6	145.52	0.2633	0.352	133.11	144.8	0.260
240	0.485	138.7	151.3	0.274	0.419	138.3	150.75	0.2709	0.367	137.90	150.1	0.268
260	0.503	143.5	156.5	0.281	0.435	143.1	156.00	0.2783	0.382	142.71	155.4	0.275
280	0.521	148.2	161.7	0.288	0.451	147.9	161.29	0.2856	0.397	147.55	160.7	0.282
300	0.538	153.1	167.0	0.295	0.467	152.7	166.61	0.2927	0.411	152.44	166.1	0.289
320	0.555	157.9	172.3	0.302	0.482	157.6	171.98	0.2996	0.425	157.38	171.5	0.296

(continued)

Table E2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
340	0.573	162.9	177.7	0.309	0.497	162.6	177.39	0.3065	0.439	162.36	177.0	0.303
360	0.589	167.9	183.2	0.316	0.512	167.6	182.85	0.3132	0.452	167.40	182.4	0.310
	P = 200 psia (T_{sat} = 125.3 °F)				P = 300 psia (T_{sat} = 156.2 °F)				P = 400 psia (T_{sat} = 179.9 °F)			
Sat	0.228	108.9	117.4	0.215	0.142	111.7	119.62	0.2132	0.096	112.77	119.9	0.210
160	0.263	117.9	127.7	0.232	0.146	112.9	121.07	0.2155				
180	0.280	122.8	133.2	0.241	0.163	118.9	128.00	0.2265	0.096	112.79	119.9	0.210
200	0.297	127.7	138.7	0.249	0.177	124.4	134.34	0.2363	0.114	120.14	128.6	0.223
220	0.312	132.6	144.1	0.257	0.190	129.7	140.36	0.2453	0.127	126.35	135.7	0.234
240	0.326	137.4	149.5	0.265	0.202	134.9	146.21	0.2537	0.138	132.12	142.3	0.243
260	0.340	142.3	154.9	0.272	0.213	140.1	151.95	0.2618	0.148	137.65	148.6	0.252
280	0.354	147.1	160.2	0.280	0.223	145.2	157.63	0.2696	0.157	143.06	154.7	0.261
300	0.367	152.1	165.6	0.287	0.233	150.3	163.28	0.2772	0.166	148.39	160.6	0.268
320	0.379	157.0	171.1	0.294	0.242	155.4	168.92	0.2845	0.174	153.69	166.5	0.276
340	0.392	162.0	176.6	0.301	0.252	160.5	174.56	0.2916	0.181	158.97	172.4	0.284
360	0.405	167.1	182.1	0.308	0.261	165.7	180.23	0.2986	0.189	164.26	178.2	0.291

Source: Çengel and Boles [1]

Table E3 Saturated propane

T ° (F)	P_{sat} (psia)	V (ft^3/lb)		U (Btu/lb)		H (Btu/lb)		S (Btu/lb R)	
		V_l	V_g	U_l	U_g	H_l	H_g	S_l	S_g
−140	0.6	0.02505	128.0000	−51.33	139.22	−51.33	153.6	−0.139	0.501
−120	1.4	0.02551	58.8800	−41.44	143.95	−41.43	159.1	−0.109	0.481
−100	2.9	0.02601	29.9300	−31.34	148.80	−31.33	164.8	−0.080	0.465
−80	5.5	0.02653	16.5200	−21.16	153.73	−21.13	170.5	−0.053	0.452
−60	9.7	0.02708	9.7500	−10.73	158.74	−10.68	176.2	−0.026	0.441
−40	16.1	0.02767	6.0800	−0.08	163.80	0.00	181.9	0.000	0.433
−20	25.4	0.02831	3.9800	10.81	168.88	10.94	187.6	0.025	0.427
0	38.4	0.02901	2.7000	21.98	174.01	22.19	193.2	0.050	0.422
10	46.5	0.02939	2.2500	27.69	176.61	27.94	196.0	0.063	0.420
20	55.8	0.02978	1.8900	33.47	179.15	33.78	198.7	0.074	0.418
30	66.5	0.03020	1.5980	39.34	181.71	39.71	201.4	0.087	0.417
40	78.6	0.03063	1.3590	45.30	184.30	45.75	204.1	0.099	0.415
50	92.3	0.03110	1.1610	51.36	186.74	51.89	206.6	0.111	0.414
60	107.7	0.03160	0.9969	57.53	189.30	58.16	209.2	0.123	0.413
70	124.9	0.03213	0.8593	63.81	191.71	64.55	211.6	0.135	0.412
80	144.0	0.03270	0.7433	70.20	194.16	71.07	214.0	0.147	0.411
90	165.2	0.03332	0.6447	76.72	196.46	77.74	216.2	0.159	0.410
100	188.6	0.03399	0.5605	83.38	198.71	84.56	218.3	0.171	0.410
110	214.3	0.03473	0.4881	90.19	200.91	91.56	220.3	0.183	0.409
120	242.5	0.03555	0.4254	97.16	202.98	98.76	222.1	0.195	0.408
130	273.3	0.03646	0.3707	104.33	204.92	106.17	223.7	0.207	0.406
140	306.9	0.03749	0.3228	111.70	206.64	113.83	225.0	0.220	0.405
150	343.5	0.03867	0.2804	119.33	208.05	121.79	225.9	0.233	0.403
160	383.3	0.04006	0.2426	127.27	209.16	130.11	226.4	0.246	0.401
170	426.5	0.04176	0.2085	135.60	209.81	138.90	226.3	0.259	0.398
180	473.4	0.04392	0.1771	144.50	209.76	148.35	225.3	0.273	0.394
190	524.3	0.04696	0.1470	154.38	208.51	158.94	222.8	0.289	0.387
200	579.7	0.05246	0.1148	166.65	204.16	172.28	216.5	0.309	0.376
206.1	616.1	0.07265	0.0726	186.99	186.99	195.27	195.3	0.343	0.343

Source: Moran and Shapiro [5]

Table E4 Superheated propane

T °(F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
	P = 0.75 psia (T_{sat} = −135.1 °F)				P = 1.5 psia (T_{sat} = −118.1 °F)			
Sat.	104.8	140.4	154.9	0.496	54.99	144.4	159.7	0.479
−110	113.1	146.6	162.3	0.518	56.33	146.5	162.1	0.486
−90	119.6	151.8	168.4	0.535	59.63	151.7	168.2	0.503
−70	126.1	157.2	174.7	0.551	62.92	157.1	174.5	0.520
−50	132.7	162.7	181.2	0.568	66.20	162.6	181.0	0.536
−30	139.2	168.6	187.9	0.584	69.47	168.4	187.7	0.552
−10	145.7	174.4	194.7	0.599	72.74	174.4	194.6	0.568
10	152.2	180.7	201.9	0.615	76.01	180.7	201.8	0.583
30	158.7	187.1	209.2	0.630	79.27	187.1	209.1	0.599
50	165.2	193.8	216.8	0.645	82.53	193.8	216.7	0.614
70	171.7	200.7	224.6	0.660	85.79	200.7	224.5	0.629
90	178.2	207.8	232.6	0.675	89.04	207.8	232.5	0.644
	P = 5.0 psia (T_{sat} = −83.0 °F)				P = 10.0 psia (T_{sat} = −58.8 °F)			
Sat.	18.00	153.0	169.6	0.454	9.47	159.0	176.6	0.441
−40	20.17	165.1	183.8	0.489	9.96	80.9	99.3	1.388
−20	21.17	171.1	190.7	0.505	10.47	86.9	106.3	1.405
0	22.17	172.2	197.7	0.521	10.98	93.1	113.4	1.421
20	23.16	183.5	205.0	0.536	11.49	99.5	120.8	1.436
40	24.15	190.1	212.5	0.552	11.99	106.1	128.3	1.452
60	25.14	196.9	220.2	0.567	12.49	113.0	136.1	1.467
80	26.13	204.0	228.2	0.582	12.99	120.0	144.1	1.482
100	27.11	211.3	236.4	0.597	13.49	127.3	152.3	1.497
120	28.09	218.8	244.8	0.611	13.99	134.9	160.7	1.512
140	29.07	226.5	253.4	0.626	14.48	142.6	169.4	1.526

(continued)

Table E4 (continued)

T °(F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
	P = 20.0 psia (T_{sat} = −30.7 °F)				P = 40.0 psia (T_{sat} = 2.1 °F)			
Sat.	4.971	166.2	184.6	0.430	2.594	174.6	193.8	0.422
20	5.648	182.4	203.3	0.471	2.723	180.6	200.8	0.436
40	5.909	189.1	211.0	0.487	2.864	187.6	208.8	0.453
60	6.167	195.9	218.8	0.502	3.002	194.6	216.9	0.469
80	6.424	203.1	226.9	0.518	3.137	201.8	225.1	0.484
100	6.678	210.5	235.2	0.533	3.271	209.4	233.6	0.500
120	6.932	218.0	243.7	0.548	3.403	217.0	242.2	0.515
140	7.184	225.8	252.4	0.562	3.534	224.9	251.1	0.530
160	7.435	233.9	261.4	0.577	3.664	232.9	260.1	0.545
180	7.685	242.1	270.6	0.592	3.793	241.3	269.4	0.559
200	7.935	250.6	280.0	0.606	3.921	249.8	278.9	0.574
	P = 60.0 psia (T_{sat} = 24.1 °F)				P = 80.0 psia (T_{sat} = 41.1 °F)			
Sat.	1.764	180.2	199.8	0.418	1.336	184.6	204.3	0.415
50	1.894	189.5	210.6	0.400	1.372	187.9	208.2	0.423
70	1.992	196.9	219.0	0.417	1.450	195.4	216.9	0.440
90	2.087	204.4	227.6	0.432	1.526	203.1	225.7	0.456
110	2.179	212.1	236.3	0.448	1.599	210.9	234.6	0.472
130	2.271	220.0	245.2	0.463	1.671	218.8	243.6	0.487
150	2.361	228.0	254.2	0.478	1.741	227.0	252.8	0.503
170	2.450	236.3	263.5	0.493	1.810	235.4	262.2	0.518
190	2.539	244.8	273.0	0.508	1.879	244.0	271.8	0.533
210	2.626	253.5	282.7	0.523	1.946	252.7	281.5	0.548
230	2.713	262.3	292.5	0.537	2.013	261.7	291.5	0.562
250	2.800	271.6	302.7	0.552	2.079	270.9	301.7	0.577

(continued)

Table E4 (continued)

T °(F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
	P = 100 psia (T_{sat} = 55.1 °F)				P = 120 psia (T_{sat} = 67.2 °F)			
Sat.	1.073	188.1	207.9	0.414	0.895	191.1	210.9	0.412
80	1.156	197.8	219.2	0.435	0.932	196.2	216.9	0.424
100	1.219	205.7	228.3	0.452	0.989	204.3	226.3	0.441
120	1.280	213.7	237.4	0.468	1.043	212.5	235.7	0.457
140	1.340	221.9	246.7	0.483	1.094	220.8	245.1	0.473
160	1.398	230.2	256.1	0.499	1.145	229.2	254.7	0.489
180	1.454	238.8	265.7	0.514	1.194	237.9	264.4	0.504
200	1.510	247.5	275.5	0.529	1.242	246.7	274.3	0.520
220	1.566	256.4	285.4	0.544	1.289	255.6	284.3	0.534
240	1.620	265.6	295.6	0.559	1.336	264.8	294.5	0.549
260	1.674	274.9	305.9	0.573	1.382	274.2	304.9	0.564
280	1.728	284.4	316.4	0.588	1.427	283.8	315.5	0.579
	P = 140 psia (T_{sat} = 78.0 °F)				P = 160 psia (T_{sat} = 87.6 °F)			
Sat.	0.765	193.7	213.5	0.412	0.667	196.0	215.7	0.411
100	0.823	222.9	224.2	0.431	0.697	201.2	221.9	0.422
120	0.872	232.4	233.8	0.448	0.743	209.9	231.9	0.439
140	0.919	242.1	243.5	0.464	0.786	218.4	241.7	0.456
160	0.964	251.7	253.2	0.480	0.827	227.2	251.7	0.472
180	1.007	261.4	263.0	0.496	0.867	235.9	261.6	0.488
200	1.050	271.4	273.0	0.511	0.905	244.9	271.7	0.504
220	1.091	281.5	283.2	0.526	0.943	254.0	282.0	0.519
240	1.132	291.7	293.5	0.541	0.980	263.4	292.4	0.534
260	1.173	302.1	303.9	0.556	1.016	272.8	302.9	0.549
280	1.213	312.7	314.6	0.571	1.051	282.6	313.7	0.564
300	1.252	323.6	325.5	0.585	1.087	292.4	324.6	0.578

Source: Moran and Shapiro [5]

Appendix F
Steam Tables

Table F1 Saturated steam tables in English units

T (°F)	P^{sat} (psia)	Spec. vol. V (ft^3/lb)		U (Btu/lb)		Enthalpy H (Btu/lb)		Entropy S (Btu/lb R)	
		V_l	V_g	U_l	U_g	H_l	H_g	S_l	S_g
32	0.0886	0.01602	3304.6	−0.02	1021.3	−0.02	1075.5	0.0000	2.1873
34	0.0960	0.01602	3061.9	2.00	1022.0	2.00	1076.4	0.0041	2.1802
36	0.1040	0.01602	2839.0	4.01	1022.6	4.01	1077.2	0.0081	2.1732
38	0.1125	0.01602	2634.2	6.02	1023.3	6.02	1078.1	0.0122	2.1663
40	0.1216	0.01602	2445.8	8.03	1023.9	8.03	1079.0	0.0162	2.1594
42	0.1314	0.01602	2272.4	10.03	1024.6	10.03	1079.9	0.0202	2.1527
44	0.1419	0.01602	2112.8	12.04	1025.2	12.04	1080.7	0.0242	2.1459
46	0.1531	0.01602	1965.7	14.05	1025.9	14.05	1081.6	0.0282	2.1393
48	0.1651	0.01602	1830.0	16.05	1026.6	16.05	1082.5	0.0321	2.1327
50	0.1780	0.01602	1704.8	18.05	1027.2	18.05	1083.4	0.0361	2.1262
52	0.1916	0.01602	1589.2	20.06	1027.9	20.06	1084.2	0.0400	2.1197
54	0.2063	0.01603	1482.4	22.06	1028.5	22.06	1085.1	0.0439	2.1134
56	0.2218	0.01603	1383.6	24.06	1029.2	24.06	1086.0	0.0478	2.1070
58	0.2384	0.01603	1292.2	26.06	1029.8	26.06	1086.9	0.0516	2.1008
60	0.2561	0.01603	1207.6	28.06	1030.5	28.06	1087.7	0.0555	2.0946
62	0.2749	0.01604	1129.2	30.06	1031.2	30.06	1088.6	0.0593	2.0885
64	0.2950	0.01604	1056.5	32.06	1031.8	32.06	1089.5	0.0632	2.0824
66	0.3163	0.01604	989.1	34.06	1032.5	34.06	1090.4	0.0670	2.0764
68	0.3389	0.01605	926.5	36.05	1033.1	36.05	1091.2	0.0708	2.0704
70	0.3629	0.01605	868.4	38.05	1033.8	38.05	1092.1	0.0745	2.0645
72	0.3884	0.01605	814.3	40.05	1034.4	40.05	1093.0	0.0783	2.0587
74	0.4155	0.01606	764.1	42.05	1035.1	42.05	1093.8	0.0821	2.0529
76	0.4442	0.01606	717.4	44.04	1035.7	44.04	1094.7	0.0858	2.0472
78	0.4746	0.01607	673.9	46.04	1036.4	46.04	1095.6	0.0895	2.0415
80	0.5068	0.01607	633.3	48.03	1037.0	48.04	1096.4	0.0932	2.0359
82	0.5409	0.01608	595.6	50.03	1037.7	50.03	1097.3	0.0969	2.0303
84	0.5770	0.01608	560.3	52.03	1038.3	52.03	1098.2	0.1006	2.0248

(continued)

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Table F1 (continued)

T (°F)	P^{sat} (psia)	Spec. vol. V (ft^3/lb)		U (Btu/lb)		Enthalpy H (Btu/lb)		Entropy S (Btu/lb R)	
		V_l	V_g	U_l	U_g	H_l	H_g	S_l	S_g
86	0.6152	0.01609	527.5	54.02	1039.0	54.03	1099.0	0.1043	2.0193
88	0.6555	0.01609	496.8	56.02	1039.6	56.02	1099.9	0.1079	2.0139
90	0.6981	0.01610	468.1	58.02	1040.3	58.02	1100.8	0.1115	2.0086
92	0.7431	0.01610	441.3	60.01	1040.9	60.01	1101.6	0.1152	2.0033
94	0.7906	0.01611	416.3	62.01	1041.6	62.01	1102.5	0.1188	1.9980
96	0.8407	0.01612	392.9	64.00	1042.2	64.01	1103.3	0.1224	1.9928
98	0.8936	0.01612	370.9	66.00	1042.9	66.00	1104.2	0.1260	1.9876
100	0.9492	0.01613	350.4	68.00	1043.5	68.00	1105.1	0.1295	1.9825
102	1.0079	0.01614	331.1	69.99	1044.2	70.00	1105.9	0.1331	1.9775
104	1.0697	0.01614	313.1	71.99	1044.8	71.99	1106.8	0.1366	1.9725
106	1.1347	0.01615	296.2	73.98	1045.4	73.99	1107.6	0.1402	1.9675
108	1.2030	0.01616	280.3	75.98	1046.1	75.98	1108.5	0.1437	1.9626
110	1.2750	0.01617	265.4	77.98	1046.7	77.98	1109.3	0.1472	1.9577
112	1.3510	0.01617	251.4	79.97	1047.4	79.98	1110.2	0.1507	1.9528
114	1.4300	0.01618	238.2	81.97	1048.0	81.97	1111.0	0.1542	1.9480
116	1.5130	0.01619	225.9	83.97	1048.6	83.97	1111.9	0.1577	1.9433
118	1.6010	0.01620	214.2	85.96	1049.3	85.97	1112.7	0.1611	1.9386
120	1.6930	0.01620	203.3	87.96	1049.9	87.97	1113.6	0.1646	1.9339
122	1.7890	0.01621	193.0	89.96	1050.6	89.96	1114.4	0.1680	1.9293
124	1.8900	0.01622	183.2	91.96	1051.2	91.96	1115.3	0.1715	1.9247
126	1.9960	0.01623	174.1	93.95	1051.8	93.96	1116.1	0.1749	1.9202
128	2.1070	0.01624	165.5	95.95	1052.4	95.96	1117.0	0.1783	1.9157
130	2.2230	0.01625	157.3	97.95	1053.1	97.96	1117.8	0.1817	1.9112
132	2.345	0.01626	149.66	99.95	1053.7	99.95	1118.6	0.1851	1.9068
134	2.472	0.01626	142.41	101.94	1054.3	101.95	1119.5	0.1884	1.9024
136	2.605	0.01627	135.57	103.94	1055.0	103.95	1120.3	0.1918	1.8980
138	2.744	0.01628	129.11	105.94	1055.6	105.95	1121.1	0.1951	1.8937
140	2.889	0.01629	123.00	107.94	1056.2	107.95	1122.0	0.1985	1.8895
142	3.041	0.01630	117.22	109.94	1056.8	109.95	1122.8	0.2018	1.8852
144	3.200	0.01631	111.76	111.94	1057.5	111.95	1123.6	0.2051	1.8810
146	3.365	0.01632	106.59	113.94	1058.1	113.95	1124.5	0.2084	1.8769
148	3.538	0.01633	101.70	115.94	1058.7	115.95	1125.3	0.2117	1.8727
150	3.718	0.01634	97.07	117.94	1059.3	117.95	1126.1	0.2150	1.8686
152	3.906	0.01635	92.68	119.94	1059.9	119.95	1126.9	0.2183	1.8646
154	4.102	0.01636	88.52	121.94	1060.5	121.95	1127.7	0.2216	1.8606
156	4.307	0.01637	84.57	123.94	1061.2	123.95	1128.6	0.2248	1.8566
158	4.520	0.01638	80.83	125.94	1061.8	125.96	1129.4	0.2281	1.8526
160	4.741	0.01640	77.29	127.94	1062.4	127.96	1130.2	0.2313	1.8487
162	4.972	0.01641	73.92	129.95	1063.0	129.96	1131.0	0.2345	1.8448
164	5.212	0.01642	70.72	131.95	1063.6	131.96	1131.8	0.2377	1.8409
166	5.462	0.01643	67.68	133.95	1064.2	133.97	1132.6	0.2409	1.8371
168	5.722	0.01644	64.80	135.95	1064.8	135.97	1133.4	0.2441	1.8333
170	5.993	0.01645	62.06	137.96	1065.4	137.97	1134.2	0.2473	1.8295

(continued)

Table F1 (continued)

T (°F)	P^{sat} (psia)	Spec. vol. V (ft^3/lb)		U (Btu/lb)		Enthalpy H (Btu/lb)		Entropy S (Btu/lb R)	
		V_l	V_g	U_l	U_g	H_l	H_g	S_l	S_g
172	6.274	0.01646	59.45	139.96	1066.0	139.98	1135.0	0.2505	1.8258
174	6.566	0.01647	56.97	141.96	1066.6	141.98	1135.8	0.2537	1.8221
176	6.869	0.01649	54.61	143.97	1067.2	143.99	1136.6	0.2568	1.8184
178	7.184	0.01650	52.36	145.97	1067.8	145.99	1137.4	0.2600	1.8147
180	7.511	0.01651	50.22	147.98	1068.4	148.00	1138.2	0.2631	1.8111
182	7.850	0.01652	48.19	149.98	1069.0	150.01	1139.0	0.2662	1.8075
184	8.203	0.01653	46.25	151.99	1069.6	152.01	1139.8	0.2694	1.8040
186	8.568	0.01655	44.40	153.99	1070.2	154.02	1140.5	0.2725	1.8004
188	8.947	0.01656	42.64	156.00	1070.7	156.03	1141.3	0.2756	1.7969
190	9.340	0.01657	40.96	158.01	1071.3	158.04	1142.1	0.2787	1.7934
192	9.747	0.01658	39.35	160.02	1071.9	160.05	1142.9	0.2818	1.7900
194	10.168	0.01660	37.82	162.02	1072.5	162.05	1143.7	0.2848	1.7865
196	10.605	0.01661	36.36	164.03	1073.1	164.06	1144.4	0.2879	1.7831
198	11.058	0.01662	34.97	166.04	1073.6	166.08	1145.2	0.2910	1.7798
200	11.526	0.01664	33.64	168.05	1074.2	168.09	1146.0	0.2940	1.7764
202	12.011	0.01665	32.37	170.06	1074.8	170.10	1146.7	0.2971	1.7731
204	12.512	0.01666	31.15	172.07	1075.3	172.11	1147.5	0.3001	1.7698
206	13.031	0.01668	29.99	174.08	1075.9	174.12	1148.2	0.3031	1.7665
208	13.568	0.01669	28.88	176.09	1076.5	176.14	1149.0	0.3061	1.7632
210	14.123	0.01670	27.82	178.11	1077.0	178.15	1149.7	0.3091	1.7600
212	14.696	0.01672	26.80	180.12	1077.6	180.17	1150.5	0.3121	1.7568
215	15.592	0.01674	25.36	183.14	1078.4	183.19	1151.6	0.3166	1.7520
220	17.186	0.01678	23.15	188.18	1079.8	188.23	1153.4	0.3241	1.7442
225	18.912	0.01681	21.17	193.22	1081.2	193.28	1155.3	0.3315	1.7365
230	20.780	0.01685	19.38	196.27	1082.5	198.33	1157.1	0.3388	1.7290
235	22.790	0.01689	17.77	203.32	1083.9	203.39	1158.8	0.3461	1.7215
240	24.970	0.01693	16.32	208.37	1085.2	208.45	1160.6	0.3533	1.7142
245	27.310	0.01697	15.01	213.43	1086.5	213.52	1162.3	0.3606	1.7070
250	29.820	0.01701	13.82	218.50	1087.8	218.59	1164.0	0.3677	1.7000

Source: Smith et al. [8]

Table F2 Superheated steam tables in English units

T (°F)	*V* (ft^3/lb)	*U* (Btu/lb)	*H* (Btu/lb)	*S* (Btu/lb R)	*V* (ft^3/lb)	*U* (Btu/lb)	*H* (Btu/lb)	*S* (Btu/lb R)
	P = 1 psia, T_{sat} = 101.74 °F				P = 5 psia, T_{sat} = 162.24 °F			
Sat liq.	0.016	69.7	69.7	0.1326	0.016	130.2	130.2	0.2349
Sat. vap.	333.6	1044.1	1105.8	1.9781	73.53	1063.1	1131.1	1.8443
200	392.5	1077.5	1150.2	2.0509	78.14	1076.3	1148.6	1.8716
250	422.4	1094.7	1172.9	2.0841	84.21	1093.8	1171.7	1.9054
300	452.3	1112.0	1195.7	2.1152	90.24	1111.3	1194.8	1.9369
350	452.3	1129.5	1218.7	2.1445	96.25	1128.9	1218.0	1.9664
400	511.9	1147.1	1241.8	2.1722	102.20	1146.7	1241.3	1.9943
450	541.7	1164.9	1265.1	2.1985	108.20	1164.5	1264.7	2.0208
500	571.5	1182.8	1288.6	2.2237	114.20	1182.6	1288.2	2.0460
600	631.1	1219.3	1336.1	2.2708	126.10	1219.2	1335.9	2.0932
700	690.7	1256.7	1384.5	2.3144	138.10	1256.5	1384.3	2.1369
800	750.3	1294.9	1433.7	2.3551	150.00	1294.8	1433.6	2.1776
900	809.9	1334.0	1483.8	2.3934	161.90	1333.9	1483.7	2.2159
1000	869.5	1374.0	1534.9	2.4296	173.90	1373.9	1534.7	2.2521
1100	929.0	1414.9	1586.8	2.4640	185.80	1414.8	1586.7	2.2866
1200	988.6	1456.7	1639.7	2.4969	197.70	1456.7	1639.6	2.3194
	P = 10 psia, T_{sat} = 193.21 °F				P = 14.696 psia, T_{sat} = 212.0 °F			
Sat liq.	0.017	161.2	161.3	0.2836	0.017	180.1	180.2	0.3121
Sat. vap	38.42	1072.3	1143.3	1.7879	26.80	1077.6	1150.5	1.7568
200	38.84	1074.7	1146.6	1.7928	…..	…..	…..	…..
250	41.93	1092.6	1170.2	1.8273	28.42	1091.5	1168.8	1.7833
300	44.98	1110.4	1193.7	1.8593	30.52	1109.6	1192.6	1.8158
350	48.02	1128.3	1217.1	1.8892	32.60	1127.6	1216.3	1.8460
400	51.03	1146.1	1240.6	1.9173	34.67	1145.7	1239.9	1.8743
450	54.04	1164.1	1264.1	1.9439	36.72	1163.7	1263.6	1.9010
500	57.04	1182.2	1287.8	1.9692	38.77	1181.9	1287.4	1.9265
600	63.03	1218.9	1335.5	2.0166	42.86	1218.7	1335.2	1.9739
700	69.00	1256.4	1384.0	2.0603	46.93	1256.2	1383.8	2.0177
800	74.98	1294.6	1433.4	2.1011	51.00	1294.5	1433.2	2.0585
900	80.94	1333.7	1483.5	2.1394	55.06	1333.6	1483.4	2.0969
1000	86.91	1373.8	1534.6	2.1757	59.13	1373.7	1534.5	2.1331
1100	92.87	1414.7	1586.6	2.2101	63.19	1414.6	1586.5	2.1676
1200	98.84	1456.6	1639.5	2.2430	67.25	1456.5	1639.4	2.2005
	P = 15 psia, T_{sat} = 213.03 °F				P = 20 psia, T_{sat} = 227.96 °F			
Sat liq.	0.017	181.2	181.2	0.3137	0.017	196.2	196.3	0.3358
Sat. vap	26.29	1077.9	1150.9	1.7552	20.09	1082.0	1156.3	1.7320
250	27.84	1091.4	1168.7	1.7809	20.79	1090.2	1167.1	1.7475
300	29.90	1109.5	1192.5	1.8134	22.36	1108.6	1191.4	1.7805
350	31.94	1127.6	1216.2	1.8436	23.90	1126.9	1215.4	1.8111
400	33.96	1145.6	1239.9	1.8720	25.43	1145.1	1239.2	1.8397
450	35.98	1163.7	1263.6	1.8988	26.95	1163.3	1263.0	1.8666

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
500	37.98	1181.9	1287.3	1.9242	28.46	1181.6	1286.9	1.8921
600	41.99	1218.7	1335.2	1.9717	31.47	1218.4	1334.9	1.9397
700	45.98	1256.2	1383.8	2.0155	34.46	1256.0	1383.5	1.9836
800	49.96	1294.5	1433.2	2.0563	37.46	1294.3	1432.9	2.0244
900	53.95	1333.6	1483.4	2.0946	40.45	1333.5	1483.2	2.0628
1000	57.93	1373.7	1534.5	2.1309	43.43	1373.6	1534.3	2.0991
1100	61.90	1414.6	1586.5	2.1653	46.42	1414.5	1586.3	2.1336
1200	65.88	1456.5	1639.4	2.1982	49.40	1456.4	1639.3	2.1665
	P = 25 psia, T_{sat} = 240.07 °F				P = 30 psia, T_{sat} = 250.34 °F			
Sat liq.	0.017	208.4	208.5	0.3535	0.017	218.8	218.9	0.3692
Sat. vap	16.30	1085.2	1160.6	1.7141	13.74	1087.9	1164.1	1.6995
250	16.56	1089.0	1165.6	1.7212	…..	…..	…..	…..
300	17.83	1107.7	1190.2	1.7547	14.81	1106.8	1189.0	1.7334
350	19.08	1126.2	1214.5	1.7856	15.86	1125.5	1213.6	1.7647
400	20.31	1144.6	1238.5	1.8145	16.89	1144.0	1237.8	1.7937
450	21.53	1162.9	1262.5	1.8415	17.91	1162.5	1261.9	1.8210
500	22.74	1181.2	1286.4	1.8672	18.93	1180.9	1286.0	1.8467
600	25.15	1218.2	1334.6	1.9149	20.95	1218.0	1334.2	1.8946
700	27.56	1255.8	1383.3	1.9588	22.95	1255.6	1383.0	1.9386
800	29.95	1294.2	1432.7	1.9997	24.95	1294.0	1432.5	1.9795
900	32.35	1333.4	1483.0	2.0381	26.95	1333.2	1482.8	2.0179
1000	34.74	1373.5	1534.2	2.0744	28.94	1373.3	1534.0	2.0543
1100	37.13	1414.4	1586.2	2.1089	30.94	1414.3	1586.1	2.0888
1200	39.52	1456.3	1639.2	2.1418	32.93	1456.3	1639.0	2.1217
	P = 35 psia, T_{sat} = 259.29 °F				P = 40 psia, T_{sat} = 267.25 °F			
Sat liq.	0.017	227.9	228.0	0.3809	0.017	236.0	236.1	0.3921
Sat. vap	11.90	1090.1	1167.1	1.6872	10.50	1092.1	1169.8	1.6765
300	12.65	1105.9	1187.8	1.7152	11.04	1104.9	1186.6	1.6992
350	13.56	1124.8	1212.7	1.7468	11.84	1124.1	1211.7	1.7312
400	14.45	1143.5	1237.1	1.7761	12.62	1142.9	1236.4	1.7608
450	15.33	1162.0	1261.3	1.8035	13.40	1161.6	1260.8	1.7883
500	16.21	1180.5	1285.5	1.8294	14.16	1180.2	1285.0	1.8143
600	17.94	1217.7	1333.9	1.8774	15.68	1217.5	1333.6	1.8624
700	19.66	1255.4	1382.8	1.9214	17.19	1255.3	1382.5	1.9065
800	21.38	1293.9	1432.3	1.9624	18.70	1293.7	1432.1	1.9476
900	23.09	1333.1	1482.7	2.0009	20.20	1333.0	1482.5	1.9860
1000	24.80	1373.2	1533.9	2.0372	21.70	1373.1	1533.7	2.0224
1100	26.51	1414.3	1586.0	2.0717	23.19	1414.2	1585.8	2.0569
1200	28.22	1456.2	1638.9	2.1046	24.69	1456.1	1638.8	2.0899
	P = 45 psia, T_{sat} = 274.44 °F				P = 50 psia, T_{sat} = 281.01 °F			
Sat liq.	0.017	243.3	243.5	0.4021	0.017	250.1	250.2	0.4112
Sat. vap	9.40	1093.8	1172.0	1.6671	8.51	1095.3	1174.1	1.6586

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
300	9.78	1104.0	1185.4	1.6849	8.77	1103.0	1184.1	1.6720
350	10.50	1123.4	1210.8	1.7173	9.42	1122.7	1209.9	1.7048
400	11.20	1142.4	1235.7	1.7471	10.06	1141.8	1234.9	1.7349
450	11.89	1161.2	1260.2	1.7749	10.69	1160.7	1259.6	1.7628
500	12.58	1179.8	1284.6	1.8009	11.31	1179.5	1284.1	1.7890
600	13.93	1217.2	1333.3	1.8492	12.53	1217.0	1332.9	1.8374
700	15.28	1255.1	1382.3	1.8934	13.74	1254.9	1382.0	1.8816
800	16.61	1293.6	1431.9	1.9345	14.95	1293.4	1431.7	1.9227
900	17.95	1332.9	1482.3	1.9730	16.15	1332.7	1482.2	1.9613
1000	19.28	1373.0	1533.6	2.0093	17.35	1372.9	1533.4	1.9977
1100	20.61	1414.1	1585.7	2.0439	18.55	1414.0	1585.6	2.0322
1200	21.94	1456.0	1638.7	2.0768	19.75	1455.9	1638.6	2.0652
	P = 55 psia, T_{sat} = 287.08 °F				P = 60 psia, T_{sat} = 292.71 °F			
Sat liq.				0.4196	0.017	262.0	262.2	0.4273
Sat. vap	7.79	1096.7	1175.9	1.6510	7.174	1098.0	1177.6	1.6440
300	7.95	1102.0	1182.8	1.6601	7.257	1101.0	1181.6	1.6492
350	8.55	1121.9	1208.9	1.6934	7.815	1121.2	1208.0	1.6829
400	9.13	1141.3	1234.2	1.7237	8.354	1140.7	1233.5	1.7134
450	9.70	1160.3	1259.1	1.7518	8.881	1159.9	1258.5	1.7417
500	10.27	1179.1	1283.6	1.7781	9.400	1178.8	1283.2	1.7681
600	11.38	1216.8	1332.6	1.8266	10.420	1216.5	1332.3	1.8168
700	12.48	1254.7	1381.8	1.8710	11.440	1254.5	1381.5	1.8612
800	13.58	1293.3	1431.5	1.9121	12.450	1293.1	1431.3	1.9024
900	14.68	1332.6	1482.0	1.9507	13.450	1332.5	1481.8	1.9410
1000	15.77	1372.8	1533.3	1.9871	14.450	1372.7	1533.2	1.9774
1100	16.86	1413.9	1585.5	2.0216	15.450	1413.8	1585.3	2.0120
1200	17.95	1455.8	1638.5	2.0546	16.450	1455.8	1638.4	2.0450
	P = 65 psia, T_{sat} = 297.98 °F				P = 70 psia, T_{sat} = 302.93 °F			
Sat liq.	0.02	267.4	267.6	0.4344	0.018	272.5	272.7	0.4411
Sat. vap	6.65	1099.1	1179.1	1.6375	6.205	1100.2	1180.6	1.6316
300	6.68	1100.0	1180.3	1.6390	…..	…..	…..	…..
350	7.20	1120.4	1207.0	1.6731	6.664	1119.7	1206.0	1.6640
400	7.70	1140.2	1232.7	1.7040	7.133	1139.6	1232.0	1.6951
450	8.19	1159.4	1257.9	1.7324	7.590	1159.0	1257.3	1.7237
500	8.67	1178.4	1282.7	1.7589	8.039	1178.1	1282.2	1.7504
600	9.62	1216.3	1331.9	1.8077	8.922	1216.0	1331.6	1.7993
700	10.55	1254.3	1381.3	1.8522	9.793	1254.1	1381.0	1.8439
800	11.48	1293.0	1431.1	1.8935	10.660	1292.8	1430.9	1.8852
900	12.41	1332.4	1481.6	1.9321	11.520	1332.2	1481.5	1.9238
1000	13.34	1372.6	1533.0	1.9685	12.380	1372.5	1532.9	1.9603
1100	14.26	1413.7	1585.2	2.0031	13.240	1413.6	1585.1	1.9949
1200	15.18	1455.7	1638.3	2.0361	14.100	1455.6	1638.2	2.0279

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
	P = 75 psia, T_{sat} = 307.61 °F							
Sat liq.	0.02	277.3	277.6	0.4474				
Sat. vap	5.81	1101.2	1181.9	1.6260				
350	6.20	1118.9	1205.0	1.6554				
400	6.65	1139.0	1231.2	1.6868				
450	7.08	1158.5	1256.7	1.7156				
500	7.49	1177.7	1281.7	1.7424				
600	8.32	1215.8	1331.3	1.7915				
700	9.14	1254.0	1380.7	1.8361				
800	9.95	1292.7	1430.7	1.8774				
900	10.75	1332.1	1481.3	1.9161				
1000	11.55	1372.4	1532.7	1.9526				
1100	12.35	1413.5	1585.0	1.9872				
1200	13.15	1455.5	1638.1	2.0202				
	P = 80 psia, T_{sat} = 312.04				P = 85 psia, T_{sat} = 316.26			
Sat liq.	0.018	281.9	282.2	0.4534	0.018	286.2	286.5	0.4590
Sat. vap	5.471	1102.1	1183.1	1.6208	5.167	1102.9	1184.2	1.6159
340	5.715	1114.0	1198.6	1.6405	5.364	1113.1	1197.5	1.6328
360	5.885	1122.3	1209.4	1.6539	5.525	1121.5	1208.4	1.6463
380	6.053	1130.4	1220.0	1.6667	5.684	1129.7	1219.1	1.6592
400	6.218	1138.4	1230.5	1.6790	5.840	1137.8	1229.7	1.6716
420	6.381	1146.3	1240.8	1.6909	5.995	1145.8	1240.1	1.6836
450	6.622	1158.1	1256.1	1.7080	6.223	1157.6	1255.5	1.7008
500	7.018	1177.4	1281.3	1.7349	6.597	1177.0	1280.8	1.7279
600	7.794	1215.5	1330.9	1.7842	7.330	1215.3	1330.6	1.7772
700	8.560	1253.8	1380.5	1.8289	8.052	1253.6	1380.2	1.8220
800	9.319	1292.5	1430.5	1.8702	8.768	1292.4	1430.3	1.8634
900	10.080	1332.0	1481.1	1.9089	9.480	1331.9	1481.0	1.9021
1000	10.830	1372.3	1532.6	1.9454	10.190	1372.2	1532.4	1.9386
1100	11.580	1413.4	1584.9	1.9800	10.900	1413.3	1584.7	1.9733
1200	12.330	1455.4	1638.0	2.0131	11.600	1455.4	1637.9	2.0630
	P = 90 psia, T_{sat} = 320.28 °F				P = 95 psia, T_{sat} = 324.13 °F			
Sat liq.	0.018	290.4	290.7	0.4643	0.018	294.4	294.7	0.4694
Sat. vap	4.895	1103.7	1185.3	1.6113	4.651	1104.5	1186.2	1.6069
340	5.051	1112.3	1196.4	1.6254	4.771	1111.4	1195.3	1.6184
360	5.205	1120.8	1207.5	1.6391	4.919	1120.0	1206.5	1.6322
380	5.356	1129.1	1218.3	1.6521	5.063	1128.4	1217.4	1.6453
400	5.505	1137.2	1228.9	1.6646	5.205	1136.6	1228.1	1.6580
420	5.652	1145.3	1239.4	1.6767	5.345	1144.7	1238.7	1.6701
450	5.869	1157.2	1254.9	1.6940	5.551	1156.7	1254.3	1.6876
500	6.223	1176.7	1280.3	1.7212	5.889	1176.3	1279.8	1.7149
600	6.917	1215.0	1330.2	1.7707	6.548	1214.8	1329.9	1.7645
700	7.600	1253.4	1380.0	1.8156	7.196	1253.2	1379.7	1.8094

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
800	8.277	1292.2	1430.1	1.8570	7.838	1292.1	1429.9	1.8509
900	8.950	1331.7	1480.8	1.8957	8.477	1331.6	1480.6	1.8897
1000	9.621	1372.0	1532.3	1.9323	9.113	1371.9	1532.1	1.9262
1100	10.290	1413.2	1584.6	1.9669	9.747	1413.1	1584.5	1.9609
1200	10.960	1455.3	1637.8	2.0000	10.380	1455.2	1637.7	1.9940
	P = 100 psia, T_{sat} = 327.82 °F				P = 105 psia, T_{sat} = 331.37 °F			
Sat liq.	0.018	298.2	298.5	0.4743	0.018	301.9	302.2	0.4790
Sat. vap	4.431	1105.2	1187.2	1.6027	4.231	1105.8	1188.0	1.5988
340	4.519	1110.6	1194.2	1.6116	4.291	1109.7	1193.1	1.6051
360	4.660	1119.2	1205.5	1.6255	4.427	1118.5	1204.5	1.6192
380	4.799	1127.7	1216.5	1.6389	4.560	1127.0	1215.6	1.6326
400	4.935	1136.0	1227.4	1.6516	4.690	1135.4	1226.6	1.6455
420	5.068	1144.2	1238.0	1.6638	4.818	1143.7	1237.3	1.6578
450	5.266	1156.3	1253.7	1.6814	5.007	1155.8	1253.1	1.6755
500	5.588	1175.9	1279.3	1.7088	5.315	1175.6	1278.8	1.7031
600	6.216	1214.5	1329.6	1.7586	5.915	1214.3	1329.2	1.7530
700	6.833	1253.0	1379.5	1.8036	6.504	1252.8	1379.2	1.7981
800	7.443	1291.9	1429.7	1.8451	7.086	1291.8	1429.4	1.8396
900	8.050	1331.5	1480.4	1.8839	7.665	1331.3	1480.3	1.8785
1000	8.655	1371.8	1532.0	1.9205	8.241	1371.7	1531.8	1.9151
1100	9.258	1413.0	1584.4	1.9552	8.816	1412.9	1584.2	1.9498
1200	9.860	1455.1	1637.6	1.9883	9.389	1455.0	1637.5	1.9828
	P = 110 psia, T_{sat} = 334.79 °F				P = 115 psia, T_{sat} = 338.08 °F			
Sat liq.	0.018	305.4	305.8	0.4834	0.018	308.9	309.3	0.4877
Sat. vap	4.048	1106.5	1188.9	1.5950	3.881	1107.0	1189.6	1.5913
40	4.083	1108.8	1191.9	1.5988	3.894	1107.9	1190.8	1.5928
360	4.214	1117.7	1203.5	1.6131	4.020	1116.9	1202.5	1.6072
380	4.343	1126.4	1214.7	1.6267	4.144	1125.7	1213.8	1.6209
400	4.468	1134.8	1225.8	1.6396	4.265	1134.2	1225.0	1.6340
420	4.591	1143.1	1236.6	1.6521	4.383	1142.6	1235.8	1.6465
450	4.772	1155.3	1252.5	1.6698	4.558	1154.8	1251.8	1.6644
500	5.068	1175.2	1278.3	1.6975	4.841	1174.8	1277.9	1.6922
600	5.642	1214.0	1328.9	1.7476	5.392	1213.8	1328.6	1.7425
700	6.205	1252.7	1378.9	1.7928	5.932	1252.5	1378.7	1.7877
800	6.761	1291.6	1429.2	1.8344	6.465	1291.5	1429.0	1.8294
900	7.314	1331.2	1480.1	1.8732	6.994	1331.1	1479.9	1.8682
1000	7.865	1371.6	1531.7	1.9099	7.521	1371.5	1531.6	1.9049
1100	8.413	1412.8	1584.1	1.9446	8.046	1412.8	1584.0	1.9396
1200	8.961	1455.0	1637.4	1.9777	8.570	1454.9	1637.2	1.9727
	P = 120 psia, T_{sat} = 341.27 °F				P = 125 psia, T_{sat} = 344.35 °F			
Sat liq.	0.018	312.2	312.6	0.4919	0.018	315.4	315.8	0.4959
Sat. vap	3.728	1107.6	1190.4	1.5879	3.586	1108.1	1191.1	1.5845

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
360	3.842	1116.1	1201.4	1.6015	3.679	1115.3	1200.4	1.5960
380	3.962	1124.9	1212.9	1.6154	3.794	1124.2	1212.0	1.6100
400	4.079	1133.6	1224.1	1.6286	3.907	1132.9	1223.3	1.6233
420	4.193	1142.0	1235.1	1.6412	4.018	1141.4	1234.4	1.6360
450	4.361	1154.4	1251.2	1.6592	4.180	1153.9	1250.6	1.6541
500	4.634	1174.5	1277.4	1.6872	4.443	1174.1	1276.9	1.6823
600	5.164	1213.5	1328.2	1.7376	4.953	1213.3	1327.9	1.7328
700	5.681	1252.3	1378.4	1.7829	5.451	1252.1	1378.2	1.7782
800	6.193	1291.3	1428.8	1.8246	5.943	1291.2	1428.6	1.8199
900	6.701	1331.0	1479.8	1.8635	6.431	1330.8	1479.6	1.8589
1000	7.206	1371.4	1531.4	1.9001	6.916	1371.3	1531.3	1.8955
1100	7.710	1412.7	1583.9	1.9349	7.400	1412.6	1583.7	1.9303
1200	8.212	1454.8	1637.1	1.9680	7.882	1454.7	1637.0	1.9634
	P = 130 psia, T_{sat} = 347.33 °F				P = 135 psia, T_{sat} = 350.23 °F			
Sat liq.	0.018	318.5	319.0	0.4998	0.018	321.6	322.0	0.5035
Sat. vap	3.454	1108.6	1191.7	1.5813	3.332	1109.1	1192.4	1.5782
360	3.527	1114.5	1199.4	1.5907	3.387	1113.7	1198.3	1.5855
380	3.639	1123.5	1211.1	1.6048	3.496	1122.8	1210.1	1.5997
400	3.749	1132.3	1222.5	1.6182	3.602	1131.7	1221.6	1.6133
420	3.856	1140.9	1233.6	1.6310	3.706	1140.3	1232.9	1.6262
450	4.013	1153.4	1249.9	1.6493	3.858	1152.9	1249.3	1.6446
500	4.267	1173.7	1276.4	1.6775	4.104	1173.3	1275.8	1.6730
600	4.759	1213.0	1327.5	1.7283	4.579	1212.8	1327.2	1.7239
700	5.238	1251.9	1377.9	1.7737	5.042	1251.7	1377.7	1.7694
800	5.712	1291.0	1428.4	1.8155	5.498	1290.9	1428.2	1.8112
900	6.181	1330.7	1479.4	1.8545	5.951	1330.6	1479.2	1.8502
1000	6.649	1371.2	1531.1	1.8911	6.401	1371.1	1531.0	1.8869
1100	7.114	1412.5	1583.6	1.9259	6.849	1412.4	1583.5	1.9217
1200	7.578	1454.6	1636.9	1.9591	7.296	1454.5	1636.8	1.9548
	P = 140 psia, T_{sat} = 353.04 °F				P = 145 psia, T_{sat} = 355.77 °F			
Sat liq.	0.018	324.5	325.0	0.5071	0.018	327.4	327.8	0.5107
Sat. vap	3.219	1109.6	1193.0	1.5752	3.113	1110.0	1193.5	1.5723
360	3.257	1112.9	1197.2	1.5804	3.135	1112.0	1196.1	1.5755
380	3.363	1122.1	1209.2	1.5948	3.239	1121.3	1208.2	1.5901
400	3.466	1131.0	1220.8	1.6085	3.339	1130.4	1220.0	1.6039
420	3.567	1139.7	1232.1	1.6215	3.437	1139.1	1231.4	1.6170
450	3.714	1152.4	1248.7	1.6400	3.580	1151.9	1248.0	1.6356
500	3.953	1172.9	1275.3	1.6686	3.812	1172.6	1274.8	1.6643
600	4.412	1212.5	1326.8	1.7196	4.256	1212.3	1326.5	1.7155
700	4.859	1251.5	1377.4	1.7652	4.689	1251.3	1377.1	1.7612
800	5.299	1290.7	1428.0	1.8071	5.115	1290.6	1427.8	1.8031
900	5.736	1330.5	1479.1	1.8461	5.537	1330.3	1478.9	1.8421
1000	6.171	1371.0	1530.8	1.8828	5.957	1370.9	1530.7	1.8789

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
1100	6.604	1412.3	1583.4	1.9176	6.375	1412.2	1583.2	1.9137
1200	7.035	1454.5	1636.7	1.9508	6.791	1454.4	1636.6	1.9469
	P = 150 psia, T_{sat} = 358.43 °F				P = 155 psia, T_{sat} = 361.02 °F			
Sat liq.	0.018	330.2	330.7	0.5141	0.018	332.9	333.4	0.5174
Sat. vap	3.014	1110.4	1194.1	1.5695	2.921	1110.8	1194.6	1.5668
360	3.022	1111.2	1195.1	1.5707	…..	…..	…..	…..
380	3.123	1120.6	1207.3	1.5854	3.014	1119.8	1206.3	1.5809
400	3.221	1129.7	1219.1	1.5993	3.110	1129.0	1218.2	1.5949
420	3.316	1138.6	1230.6	1.6126	3.203	1138.0	1229.8	1.6083
450	3.455	1151.4	1247.4	1.6313	3.339	1150.9	1246.7	1.6271
500	3.680	1172.2	1274.3	1.6602	3.557	1171.8	1273.8	1.6561
600	4.111	1212.0	1326.1	1.7115	3.975	1211.8	1325.8	1.7077
700	4.530	1251.1	1376.9	1.7573	4.381	1251.0	1376.6	1.7535
800	4.942	1290.4	1427.6	1.7992	4.781	1290.3	1427.4	1.7955
900	5.351	1330.2	1478.7	1.8383	5.177	1330.1	1478.6	1.8346
1000	5.757	1370.7	1530.5	1.8751	5.570	1370.6	1530.4	1.8714
1100	6.161	1412.1	1583.1	1.9099	5.961	1412.0	1583.0	1.9062
1200	6.564	1454.3	1636.5	1.9431	6.352	1454.2	1636.4	1.9394
	P = 160 psia, T_{sat} = 363.55 °F							
Sat liq.	0.018	335.5	336.1	0.5206				
Sat. vap	2.834	1111.2	1195.1	1.5641				
380	2.913	1119.1	1205.3	1.5764				
400	3.006	1128.4	1217.4	1.5906				
420	3.097	1137.4	1229.1	1.6041				
450	3.229	1150.4	1246.0	1.6231				
500	3.441	1171.4	1273.3	1.6522				
600	3.848	1211.5	1325.4	1.7039				
700	4.242	1250.8	1376.4	1.7499				
800	4.629	1290.1	1427.2	1.7919				
900	5.013	1330.0	1478.4	1.8310				
1000	5.395	1370.5	1530.3	1.8678				
1100	5.774	1411.9	1582.9	1.9027				
1200	6.152	1454.1	1636.3	1.9359				
	P = 165 psia, T_{sat} = 366.02 °F				P = 170 psia, T_{sat} = 368.42 °F			
Sat liq.	0.018	338.1	338.7	0.5238	0.018	340.7	341.2	0.5269
Sat. vap	2.751	1111.6	1195.6	1.5616	2.674	1111.9	1196.0	1.5591
400	2.908	1127.7	1216.5	1.5864	2.816	1127.0	1215.6	1.5823
420	2.997	1136.8	1228.3	1.6000	2.903	1136.2	1227.5	1.5960
440	3.083	1145.6	1239.7	1.6129	2.987	1145.1	1239.0	1.6090
460	3.168	1154.2	1251.0	1.6252	3.070	1153.7	1250.3	1.6214
480	3.251	1162.7	1261.9	1.6370	3.151	1162.3	1261.4	1.6333
500	3.333	1171.0	1272.8	1.6484	3.231	1170.6	1272.2	1.6447

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
550	3.533	1191.3	1299.2	1.6753	3.425	1191.0	1298.8	1.6717
600	3.728	1211.3	1325.1	1.7003	3.616	1211.0	1324.7	1.6968
700	4.111	1250.6	1376.1	1.7463	3.988	1250.4	1375.8	1.7428
800	4.487	1289.9	1427.0	1.7884	4.354	1289.8	1426.8	1.7850
900	4.860	1329.8	1478.2	1.8275	4.715	1329.7	1478.0	1.8241
1000	5.230	1370.4	1530.1	1.8643	5.075	1370.3	1530.0	1.8610
1100	5.598	1411.8	1582.7	1.8992	5.432	1411.7	1582.6	1.8959
1200	5.965	1454.1	1636.2	1.9324	5.789	1454.0	1636.1	1.9291
	P = 175 psia, T_{sat} = 370.77 °F				P = 180 psia, T_{sat} = 373.08 °F			
Sat liq.	0.018	343.2	343.7	0.5299	0.018	345.6	346.2	0.5328
Sat. vap	2.601	1112.2	1196.4	1.5567	2.531	1112.5	1196.9	1.5543
400	2.729	1126.3	1214.7	1.5783	2.647	1125.6	1213.8	1.5743
420	2.814	1135.6	1226.7	1.5921	2.730	1134.9	1225.9	1.5882
440	2.897	1144.5	1238.3	1.6051	2.811	1144.0	1237.6	1.6014
460	2.977	1153.3	1249.7	1.6176	2.890	1152.8	1249.0	1.6140
480	3.056	1161.8	1260.8	1.6296	2.967	1161.4	1260.2	1.6260
500	3.134	1170.2	1271.7	1.6411	3.043	1169.8	1271.2	1.6376
550	3.224	1190.7	1298.4	1.6882	3.229	1190.4	1297.9	1.6647
600	3.510	1210.7	1324.4	1.6933	3.409	1210.5	1324.0	1.6900
700	3.872	1250.2	1375.6	1.7395	3.762	1250.0	1375.3	1.7362
800	4.227	1289.6	1426.5	1.7816	4.108	1289.5	1426.3	1.7784
900	4.579	1329.6	1477.9	1.8208	4.451	1329.4	1477.7	1.8176
1000	4.929	1370.2	1529.8	1.8577	4.791	1370.1	1529.7	1.8545
1100	5.276	1411.6	1582.5	1.8926	5.129	1411.5	1582.4	1.8894
1200	5.623	1453.9	1636.0	1.9258	5.466	1453.8	1635.9	1.9227
	P = 185 psia, T_{sat} = 375.33 °F				P = 190 psia, T_{sat} = 377.53 °F			
Sat liq.	0.018	348.0	348.6	0.5356	0.018	350.3	350.94	0.5384
Sat. vap	2.465	1112.8	1197.2	1.5520	2.403	1113.1	1197.6	1.5498
400	2.570	1124.9	1212.9	1.5705	2.496	1124.2	1212.0	1.5667
420	2.651	1134.3	1225.1	1.5845	2.576	1133.7	1224.3	1.5808
440	2.730	1143.4	1236.9	1.5978	2.654	1142.9	1236.2	1.5942
460	2.807	1152.3	1248.4	1.6104	2.729	1151.8	1247.7	1.6069
480	2.883	1160.9	1259.6	1.6225	2.803	1160.5	1259.0	1.6191
500	2.957	1169.4	1270.7	1.6341	2.876	1169.0	1270.1	1.6307
550	3.138	1190.1	1297.5	1.6614	3.052	1189.8	1297.1	1.6581
600	3.314	1210.2	1323.7	1.6867	3.225	1209.9	1323.3	1.6835
700	3.658	1249.8	1375.1	1.7330	3.560	1249.6	1374.8	1.7299
800	3.996	1289.3	1426.1	1.7753	3.889	1289.2	1425.9	1.7722
900	4.329	1329.3	1477.5	1.8145	4.214	1329.2	1477.4	1.8115
1000	4.660	1370.0	1529.5	1.8514	4.536	1369.9	1529.4	1.8484
1100	4.989	1411.4	1582.3	1.8864	4.857	1411.3	1582.1	1.8834
1200	5.317	1453.7	1635.8	1.9196	5.177	1453.7	1635.7	1.9166

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
	P = 195 psia, T_{sat} = 379.69 °F				P = 200 psia, T_{sat} = 381.80 °F			
Sat liq.	0.018	352.6	353.2	0.5412	0.018	354.8	355.5	0.5438
Sat. vap	2.344	1113.4	1198.0	1.5476	2.287	1113.7	1198.3	1.5454
400	2.426	1123.5	1211.1	1.5630	2.360	1122.8	1210.1	1.5593
420	2.505	1133.1	1223.4	1.5772	2.437	1132.4	1222.6	1.5737
440	2.581	1142.3	1235.4	1.5907	2.511	1141.7	1234.7	1.5872
460	2.655	1151.3	1247.1	1.6035	2.584	1150.8	1246.4	1.6001
480	2.727	1160.0	1258.4	1.6157	2.655	1159.6	1257.9	1.6124
500	2.798	1168.6	1269.6	1.6274	2.725	1168.2	1269.0	1.6242
550	2.971	1189.4	1296.6	1.6549	2.894	1189.1	1296.2	1.6518
600	3.139	1209.7	1323.0	1.6804	3.058	1209.4	1322.6	1.6773
700	3.467	1249.4	1374.5	1.7269	3.378	1249.2	1374.3	1.7329
800	3.788	1289.0	1425.7	1.7692	3.691	1288.9	1425.5	1.7663
900	4.105	1329.1	1477.2	1.8085	4.001	1328.9	1477.0	1.8057
1000	4.419	1369.8	1529.2	1.8455	4.308	1369.7	1529.1	1.8426
1100	4.732	1411.3	1582.0	1.8804	4.613	1411.2	1581.9	1.8776
1200	5.043	1453.6	1635.6	1.9137	4.916	1453.5	1635.4	1.9109
	P = 205 psia, T_{sat} = 383.88 °F				P = 210 psia, T_{sat} = 385.92 °F			
Sat liq.	0.018	357.0	357.7	0.5465	0.018	359.2	359.9	0.5490
Sat. vap	2.233	1113.9	1198.7	1.5434	2.182	1114.2	1199.0	1.5413
400	2.297	1122.1	1209.2	1.5557	2.236	1121.3	1208.2	1.5522
420	2.372	1131.8	1221.8	1.5702	2.311	1131.2	1221.0	1.5668
440	2.446	1141.2	1234.0	1.5839	2.383	1140.6	1233.2	1.5806
460	2.517	1150.3	1245.8	1.5969	2.453	1149.8	1245.1	1.5936
480	2.587	1159.1	1257.3	1.6092	2.521	1158.7	1256.7	1.6061
500	2.655	1167.8	1268.5	1.6211	2.588	1167.4	1268.0	1.6180
550	2.820	1188.8	1295.8	1.6488	2.750	1188.5	1295.3	1.6458
600	2.981	1209.2	1322.3	1.6744	2.908	1208.9	1321.9	1.6715
700	3.294	1249.0	1374.0	1.7210	3.214	1248.8	1373.7	1.7182
800	3.600	1288.7	1425.3	1.7635	3.513	1288.6	1425.1	1.7607
900	3.902	1328.8	1476.8	1.8028	3.808	1328.7	1476.7	1.8001
1000	4.202	1369.6	1528.9	1.8398	4.101	1369.4	1528.8	1.8371
1100	4.499	1411.1	1581.8	1.8748	4.392	1411.0	1581.6	1.8721
1200	4.796	1453.4	1635.3	1.9081	4.681	1453.3	1635.2	1.9054
	P = 215 psia, T_{sat} = 387.91 °F				P = 220 psia, T_{sat} = 389.88 °F			
Sat liq.	0.019	361.3	362.1	0.5515	0.019	363.4	364.2	0.5540
Sat. vap	2.133	1114.4	1199.3	1.5393	2.086	1114.6	1199.6	1.5374
400	2.179	1120.6	1207.3	1.5487	2.124	1119.9	1206.3	1.5453
420	2.252	1130.5	1220.1	1.5634	2.196	1129.9	1219.3	1.5601
440	2.323	1140.0	1232.5	1.5773	2.266	1139.5	1231.7	1.5741
460	2.392	1149.3	1244.4	1.5905	2.333	1148.7	1243.7	1.5873
480	2.459	1158.2	1256.0	1.6030	2.399	1157.8	1255.4	1.5999

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
500	2.524	1167.0	1267.4	1.6149	2.464	1166.6	1266.9	1.6120
550	2.684	1188.1	1294.9	1.6429	2.620	1187.8	1294.5	1.6400
600	2.838	1208.6	1321.5	1.6686	2.771	1208.4	1321.2	1.6658
700	3.137	1248.7	1373.5	1.7155	3.064	1248.5	1373.2	1.7128
800	3.430	1288.4	1424.9	1.7580	3.350	1288.3	1424.7	1.7553
900	3.718	1328.6	1476.5	1.7974	3.633	1328.4	1476.3	1.7948
1000	4.004	1369.3	1528.7	1.8344	3.912	1369.2	1528.5	1.8318
1100	4.289	1410.9	1581.5	1.8694	4.190	1410.8	1581.4	1.8668
1200	4.572	1453.2	1635.1	1.9028	4.467	1453.2	1635.0	1.9002
	P = 225 psia, T_{sat} = 391.80 °F				P = 230 psia, T_{sat} = 393.70 °F			
Sat liq.	0.019	365.5	366.2	0.5564	0.019	367.5	368.3	0.5588
Sat. vap	2.041	1114.9	1199.9	1.5354	1.999	1115.1	1200.1	1.5336
400	2.071	1119.1	1205.4	1.5419	2.021	1118.4	1204.4	1.5385
420	2.143	1129.2	1218.4	1.5569	2.091	1128.5	1217.5	1.5537
440	2.211	1138.9	1230.9	1.5710	2.159	1138.3	1230.2	1.5679
460	2.278	1148.2	1243.1	1.5843	2.224	1147.7	1242.4	1.5813
480	2.342	1157.3	1254.8	1.5969	2.288	1156.8	1254.2	1.5940
500	2.406	1166.1	1266.3	1.6090	2.350	1165.7	1265.7	1.6062
550	2.559	1187.5	1294.0	1.6372	2.501	1187.2	1293.6	1.6344
600	2.707	1208.1	1320.8	1.6631	2.646	1207.8	1320.4	1.6604
700	2.994	1248.3	1372.9	1.7101	2.928	1248.1	1372.7	1.7075
800	3.275	1288.1	1424.5	1.7527	3.202	1288.0	1424.2	1.7502
900	3.551	1328.3	1476.1	1.7922	3.473	1328.2	1476.0	1.7897
1000	3.825	1369.1	1528.4	1.8293	3.741	1369.0	1528.2	1.8268
1100	4.097	1410.7	1581.3	1.8643	4.007	1410.6	1581.1	1.8618
1200	4.367	1453.1	1634.9	1.8977	4.272	1453.0	1634.8	1.8952
	P = 235 psia, T_{sat} = 395.56 °F				P = 240 psia, T_{sat} = 397.39 °F			
Sat liq.	0.019	369.5	370.3	0.5611	0.019	371.5	372.3	0.5634
Sat. vap	1.957	1115.3	1200.4	1.5317	1.918	1115.5	1200.6	1.5299
400	1.973	1117.6	1203.4	1.5353	1.927	1116.8	1202.4	1.5320
420	2.042	1127.9	1216.7	1.5505	1.995	1127.2	1215.8	1.5474
440	2.109	1137.7	1229.4	1.5648	2.061	1137.1	1228.6	1.5618
460	2.173	1147.2	1241.7	1.5783	2.124	1146.6	1241.0	1.5754
480	2.236	1156.4	1253.6	1.5911	2.186	1155.9	1253.0	1.5883
500	2.297	1165.3	1265.2	1.6033	2.246	1164.9	1264.6	1.6006
550	2.445	1186.8	1293.1	1.6317	2.391	1186.5	1292.7	1.6291
600	2.588	1207.6	1320.1	1.6578	2.532	1207.3	1319.7	1.6552
700	2.864	1247.9	1372.4	1.7050	2.802	1247.7	1372.1	1.7025
800	3.133	1287.8	1424.0	1.7477	3.066	1287.7	1423.8	1.7452
900	3.398	1328.0	1475.8	1.7872	3.326	1327.9	1475.6	1.7848
1000	3.660	1368.9	1528.1	1.8243	3.583	1368.8	1527.9	1.8219
1100	3.921	1410.5	1581.0	1.8594	3.839	1410.4	1580.9	1.8570
1200	4.180	1452.9	1634.7	1.8928	4.093	1452.8	1634.6	1.8904

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
	P = 245 psia, T_{sat} = 399.19 °F							
Sat liq.	0.019	373.4	374.2	0.5657				
Sat. vap	1.880	1115.6	1200.9	1.5281				
400	1.882	1116.1	1201.4	1.5288				
420	1.950	1126.5	1214.9	1.5443				
440	2.015	1136.5	1227.8	1.5588				
460	2.077	1146.1	1240.3	1.5725				
480	2.138	1155.4	1252.3	1.5855				
500	2.197	1164.4	1264.1	1.5978				
550	2.340	1186.2	1292.3	1.6265				
600	2.478	1207.0	1319.4	1.6527				
700	2.744	1247.5	1371.9	1.7000				
800	3.002	1287.5	1423.6	1.7428				
900	3.257	1327.8	1475.5	1.7824				
1000	3.509	1368.7	1527.8	1.8196				
1100	3.760	1410.3	1580.8	1.8547				
1200	4.009	1452.8	1634.5	1.8881				
	P = 250 psia, T_{sat} = 400.97 °F				P = 255 psia, T_{sat} = 402.72 °F			
Sat liq.	0.019	375.3	376.1	0.5679	0.019	377.2	378.0	0.5701
Sat. vap	1.843	1115.8	1201.1	1.5264	1.808	1116.0	1201.3	1.5247
420	1.907	1125.8	1214.0	1.5413	1.865	1125.1	1213.1	1.5383
440	1.970	1135.9	1227.1	1.5559	1.928	1135.3	1226.3	1.5530
460	2.032	1145.6	1239.6	1.5697	1.989	1145.0	1238.9	1.5669
480	2.092	1154.9	1251.7	1.5827	2.048	1154.5	1251.1	1.5800
500	2.150	1164.0	1263.5	1.5951	2.105	1163.6	1262.9	1.5925
520	2.207	1172.9	1275.0	1.6070	2.161	1172.5	1274.5	1.6044
550	2.291	1185.8	1291.8	1.6239	2.244	1185.5	1291.4	1.6214
600	2.426	1206.7	1319.0	1.6502	2.377	1206.5	1318.6	1.6477
700	2.687	1247.3	1371.6	1.6976	2.633	1247.1	1371.3	1.6953
800	2.941	1287.3	1423.4	1.7405	2.882	1287.2	1423.2	1.7382
900	3.191	1327.7	1475.3	1.7801	3.127	1327.5	1475.1	1.7778
1000	3.438	1368.6	1527.6	1.8173	3.370	1368.5	1527.5	1.8150
1100	3.684	1410.2	1580.6	1.8524	3.611	1410.1	1580.5	1.8502
1200	3.928	1452.7	1634.4	1.8858	3.850	1452.6	1634.3	1.8836
	P = 260 psia, T_{sat} = 404.44				P = 265 psia, T_{sat} = 406.13°F			
Sat liq.	0.019	379.0	379.9	0.5722	0.019	380.8	381.7	0.5743
Sat. vap	1.774	1116.2	1201.5	1.5230	1.742	1116.3	1201.7	1.5214
420	1.825	1124.5	1212.2	1.5353	1.786	1123.8	1211.3	1.5324
440	1.887	1134.7	1225.5	1.5502	1.848	1134.1	1224.7	1.5474
460	1.947	1144.5	1238.2	1.5642	1.907	1144.0	1237.5	1.5614
480	2.005	1154.0	1250.4	1.5774	1.964	1153.5	1249.8	1.5747
500	2.062	1153.1	1262.4	1.5899	2.020	1162.7	1261.8	1.5873

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
520	2.117	1172.1	1274.0	1.6019	2.075	1171.7	1273.4	1.5993
550	2.198	1185.1	1290.9	1.6189	2.154	1184.8	1290.4	1.6165
600	2.329	1206.2	1318.2	1.6453	2.283	1205.9	1317.9	1.6430
700	2.581	1246.9	1371.1	1.6930	2.531	1246.7	1370.8	1.6907
800	2.826	1287.0	1423.0	1.7359	2.771	1286.9	1422.8	1.7337
900	3.066	1327.4	1474.9	1.7756	3.007	1327.3	1474.8	1.7734
1000	3.304	1368.4	1527.3	1.8128	3.241	1368.2	1527.2	1.8106
1100	3.541	1410.0	1580.4	1.8480	3.473	1409.9	1580.3	1.8458
1200	3.776	1452.5	1634.2	1.8814	3.704	1452.4	1634.1	1.8792
	P = 270 psia, T_{sat} = 407.80 °F				P = 275 psia, T_{sat} = 409.45 °F			
Sat liq.	0.019	382.6	383.6	0.5764	0.019	384.4	385.4	0.5784
Sat. vap	1.710	1116.5	1201.9	1.5197	1.680	1116.6	1202.1	1.5181
420	1.749	1123.1	1210.4	1.5295	1.713	1122.3	1209.5	1.5266
440	1.810	1133.5	1223.9	1.5446	1.773	1132.8	1223.1	1.5419
460	1.868	1143.4	1236.7	1.5588	1.831	1142.9	1236.0	1.5561
480	1.925	1153.0	1249.2	1.5721	1.887	1152.5	1248.5	1.5696
500	1.980	1152.3	1261.2	1.5848	1.941	1161.8	1260.6	1.5823
520	2.034	1171.3	1272.9	1.5969	1.994	1170.9	1272.4	1.5944
550	2.112	1184.5	1290.0	1.6140	2.071	1184.1	1289.5	1.6117
600	2.239	1205.6	1317.5	1.6406	2.196	1206.4	1317.1	1.6384
700	2.482	1246.5	1370.5	1.6885	2.436	1246.3	1370.3	1.6863
800	2.719	1286.7	1422.6	1.7315	2.668	1286.6	1422.4	1.7294
900	2.951	1327.2	1474.6	1.7713	2.896	1327.0	1474.4	1.7691
1000	3.181	1368.1	1527.0	1.8085	3.122	1368.0	1526.9	1.8064
1100	3.408	1409.8	1580.1	1.8437	3.346	1409.8	1580.0	1.8416
1200	3.635	1452.3	1634.0	1.8771	3.568	1452.3	1633.9	1.8750
	P = 280 psia, T_{sat} = 411.07 °F				P = 285 psia, T_{sat} = 412.67 °F			
Sat liq.	0.019	386.2	387.1	0.5805	0.019	387.9	388.9	0.5824
Sat. vap	1.651	1116.7	1202.3	1.5166	1.622	1116.9	1202.4	1.5150
420	1.678	1121.6	1208.6	1.5238	1.645	1120.9	1207.6	1.5210
440	1.738	1132.2	1222.2	1.5391	1.704	1131.6	1221.4	1.5365
460	1.795	1142.3	1235.3	1.5535	1.760	1141.7	1234.6	1.5509
480	1.850	1152.0	1247.9	1.5670	1.815	1151.5	1247.2	1.5645
500	1.904	1161.4	1260.0	1.5798	1.868	1160.9	1259.4	1.5774
520	1.956	1170.5	1271.9	1.5920	1.919	1170.1	1271.3	1.5897
550	2.032	1183.8	1289.1	1.6093	1.994	1183.4	1288.6	1.6070
600	2.155	1205.1	1316.8	1.6361	2.115	1204.8	1316.4	1.6339
700	2.391	1246.1	1370.0	1.6841	2.348	1245.9	1369.7	1.6820
800	2.619	1286.4	1422.1	1.7273	2.572	1286.3	1421.9	1.7252
900	2.844	1326.9	1474.2	1.7671	2.793	1326.8	1474.1	1.7650
1000	3.066	1367.9	1526.8	1.8043	3.011	1367.8	1526.6	1.8023
1100	3.286	1409.7	1579.9	1.8395	3.227	1409.6	1579.8	1.8375
1200	3.504	1452.2	1633.8	1.8730	3.442	1452.1	1633.6	1.8710

(continued)

Table F2 (continued)

T (°F)	*V* (ft^3/lb)	*U* (Btu/lb)	*H* (Btu/lb)	*S* (Btu/lb R)	*V* (ft^3/lb)	*U* (Btu/lb)	*H* (Btu/lb)	*S* (Btu/lb R)
	P = 290 psia, T_{sat} = 414.25 °F				P = 295 psia, T_{sat} = 415.81 °F			
Sat liq.	0.019	389.6	390.6	0.5844	0.019	391.3	392.3	0.5863
Sat. vap	1.595	1117.0	1202.6	1.5135	1.568	1117.1	1202.7	1.5120
420	1.612	1120.2	1206.7	1.5182	1.581	1119.5	1205.8	1.5155
440	1.671	1130.9	1220.6	1.5338	1.639	1130.3	1219.7	1.5312
460	1.727	1141.2	1233.8	1.5484	1.694	1140.6	1233.1	1.5458
480	1.780	1151.0	1246.6	1.5621	1.747	1150.5	1245.9	1.5596
500	1.833	1160.5	1258.9	1.5750	1.799	1160.0	1258.3	1.5726
520	1.884	1169.7	1270.8	1.5873	1.849	1169.3	1270.2	1.5850
550	1.958	1183.1	1288.1	1.6048	1.922	1182.7	1287.7	1.6025
600	2.077	1204.5	1316.0	1.6317	2.040	1204.3	1315.6	1.6295
700	2.306	1245.7	1369.5	1.6799	2.265	1245.5	1369.2	1.6779
800	2.527	1286.1	1421.7	1.7232	2.483	1286.0	1421.5	1.7211
900	2.744	1326.6	1473.9	1.7630	2.697	1326.5	1473.7	1.7610
1000	2.958	1367.7	1526.5	1.8003	2.908	1367.6	1526.3	1.7984
1100	3.171	1409.5	1579.6	1.8356	3.117	1409.4	1579.5	1.8336
1200	3.382	1452.0	1633.5	1.8690	3.325	1451.9	1633.4	1.8671
	P = 300 psia, T_{sat} = 39417.359.19 °F				P = 310 psia, T_{sat} = 420.36 °F			
Sat liq.	0.019	392.9	394.0	0.5882	0.019	396.2	397.3	0.5920
Sat. vap	1.543	1117.2	1202.9	1.5105	1.494	1117.5	1203.2	1.5076
420	1.551	1118.7	1204.8	1.5127	…..	…..	…..	…..
440	1.608	1129.6	1218.9	1.5286	1.549	1128.3	1217.2	1.5234
460	1.663	1140.0	1232.3	1.5433	1.603	1138.9	1230.8	1.5384
480	1.715	1150.0	1245.2	1.5572	1.655	1149.0	1243.9	1.5525
500	1.766	1159.6	1257.7	1.5703	1.704	1158.7	1256.5	1.5657
520	1.816	1168.9	1269.7	1.5827	1.753	1168.1	1268.6	1.5782
550	1.888	1182.4	1287.2	1.6003	1.823	1181.7	1286.3	1.5960
600	2.004	1204.0	1315.2	1.6274	1.936	1203.4	1314.5	1.6233
700	2.226	1245.3	1368.9	1.6758	2.152	1244.9	1368.4	1.6719
800	2.441	1285.8	1421.3	1.7192	2.360	1285.5	1420.9	1.7153
900	2.651	1326.4	1473.6	1.7591	2.564	1326.1	1473.2	1.7553
1000	2.859	1367.5	1526.2	1.7964	2.765	1367.3	1525.9	1.7927
1100	3.064	1409.3	1579.4	1.8317	2.964	1409.1	1579.2	1.8280
1200	3.269	1451.9	1633.3	1.8652	3.162	1451.7	1633.1	1.8615
	P = 320 psia, T_{sat} = 423.31 °F				P = 330 psia, T_{sat} = 426.18 °F			
Sat liq.	0.019	399.4	400.5	0.5956	0.019	402.5	403.7	0.5991
Sat. vap	1.448	1117.7	1203.4	1.5048	1.405	1117.8	1203.6	1.5021
440	1.494	1127.0	1215.5	1.5184	1.442	1125.7	1213.8	1.5134
460	1.547	1137.7	1229.3	1.5336	1.494	1136.6	1227.8	1.5289
480	1.597	1147.9	1242.5	1.5478	1.544	1146.9	1241.2	1.5433
500	1.646	1157.8	1255.2	1.5612	1.591	1156.8	1254.0	1.5568
520	1.694	1167.2	1267.5	1.5739	1.638	1166.4	1266.4	1.5696

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
550	1.762	1181.0	1285.3	1.5918	1.705	1180.2	1284.4	1.5876
600	1.873	1202.8	1313.7	1.6192	1.813	1202.3	1313.0	1.6153
700	2.082	1244.5	1367.8	1.6680	2.017	1244.1	1367.3	1.6643
800	2.284	1285.2	1420.4	1.7116	2.213	1284.9	1420.0	1.7079
900	2.482	1325.9	1472.9	1.7516	2.405	1325.6	1472.5	1.7480
1000	2.677	1367.0	1525.6	1.7890	2.595	1366.8	1525.3	1.7855
1100	2.871	1408.9	1578.9	1.8243	2.783	1408.7	1578.7	1.8208
1200	3.063	1451.5	1632.9	1.8579	2.969	1451.4	1632.7	1.8544
	P = 340 psia, T_{sat} = 428.98 °F				P = 350psia, T_{sat} = 431.73 °F			
Sat liq.	0.019	405.6	406.8	0.6026	0.019	408.6	409.8	0.6059
Sat. vap	1.364	1118.0	1203.8	1.4994	1.326	1118.1	1204.0	1.4968
440	1.393	1124.3	1212.0	1.5086	1.347	1123.0	1210.2	1.5038
460	1.444	1135.4	1226.2	1.5242	1.397	1134.2	1224.7	1.5197
480	1.493	1145.8	1239.8	1.5388	1.445	1144.8	1238.4	1.5344
500	1.540	1155.9	1252.8	1.5525	1.491	1154.9	1251.5	1.5483
520	1.585	1165.6	1265.3	1.5654	1.536	1164.7	1264.2	1.5613
550	1.651	1179.5	1283.4	1.5836	1.600	1178.8	1282.4	1.5797
600	1.756	1201.7	1312.2	1.6114	1.703	1201.1	1311.4	1.6077
700	1.955	1243.7	1366.7	1.6606	1.897	1243.3	1366.2	1.6571
800	2.146	1284.6	1419.6	1.7044	2.083	1284.2	1419.2	1.7009
900	2.333	1325.4	1472.2	1.7445	2.265	1325.1	1471.8	1.7411
1000	2.518	1366.6	1525.0	1.7820	2.444	1366.4	1524.7	1.7787
1100	2.700	1408.5	1578.4	1.8174	2.622	1408.3	1578.2	1.8141
1200	2.881	1451.2	1632.5	1.8510	2.798	1451.0	1632.3	1.8477
	P = 360 psia, T_{sat} = 434.41 °F							
Sat liq.	0.019	411.5	412.8	0.6092				
Sat. vap	1.289	1118.3	1204.1	1.4943				
440	1.303	1121.6	1208.4	1.4990				
460	1.353	1132.9	1223.1	1.5152				
480	1.400	1143.7	1237.0	1.5301				
500	1.445	1154.0	1250.3	1.5441				
520	1.489	1163.9	1263.1	1.5573				
550	1.552	1178.1	1281.5	1.5758				
600	1.652	1200.5	1310.6	1.6040				
700	1.842	1242.9	1365.6	1.6536				
800	2.024	1283.9	1418.7	1.6976				
900	2.201	1324.8	1471.5	1.7379				
1000	2.375	1366.2	1524.4	1.7754				
1100	2.548	1408.2	1577.9	1.8109				
1200	2.720	1450.9	1632.1	1.8445				
	P = 370 psia, T_{sat} = 437.04 °F				P = 380 psia, T_{sat} = 439.61 °F			
Sat. liq.	0.019	414.4	415.7	0.6130	0.019	417.2	418.6	0.6156
Sat. vap.	1.255	1118.4	1204.3	1.4918	1.222	1118.5	1204.4	1.4894

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
460	1.311	1131.7	1221.4	1.5107	1.271	1130.4	1219.8	1.5063
480	1.357	1142.6	1235.5	1.5259	1.317	1141.5	1234.1	1.5217
500	1.402	1153.0	1249.0	1.5401	1.361	1152.0	1247.7	1.5360
520	1.445	1163.0	1261.9	1.5534	1.403	1162.1	1260.8	1.5495
540	1.486	1172.6	1274.4	1.5660	1.444	1171.8	1273.3	1.5622
560	1.527	1182.0	1286.5	1.5780	1.483	1181.2	1285.5	1.5743
580	1.566	1191.0	1298.3	1.5894	1.522	1190.4	1297.4	1.5858
600	1.605	1199.9	1309.8	1.6004	1.560	1199.3	1309.0	1.5669
700	1.790	1242.5	1365.1	1.6503	1.741	1242.1	1364.5	1.6470
800	1.967	1283.6	1418.3	1.6943	1.914	1283.3	1417.9	1.6911
900	2.140	1324.6	1471.1	1.7346	2.082	1324.3	1470.8	1.7315
1000	2.310	1366.0	1524.1	1.7723	2.248	1365.7	1523.8	1.7692
1100	2.478	1408.0	1577.7	1.8077	2.412	1407.8	1577.4	1.8047
1200	2.645	1450.7	1631.8	1.8414	2.575	1450.6	1631.6	1.8384
	P = 390 psia, T_{sat} = 442.13 °F				P = 400 psia, T_{sat} = 444.60 °F			
Sat liq.	0.019	420.0	421.4	0.6187	0.019	422.7	424.2	0.6217
Sat. vap	1.191	1118.6	1204.5	1.4870	1.161	1118.7	1204.6	1.4847
460	1.233	1129.2	1218.2	1.5020	1.197	1127.9	1216.5	1.4978
480	1.278	1140.4	1232.6	1.5176	1.242	1139.3	1231.2	1.5136
500	1.321	1151.0	1246.4	1.5321	1.284	1150.0	1245.1	1.5282
520	1.363	1161.2	1259.6	1.5457	1.325	1160.3	1258.4	1.5420
540	1.403	1171.0	1272.3	1.5585	1.364	1170.2	1271.2	1.5549
560	1.442	1180.5	1284.6	1.5707	1.403	1179.8	1283.6	1.5672
580	1.480	1189.7	1296.5	1.5823	1.440	1189.1	1295.7	1.5789
600	1.517	1198.8	1308.2	1.5935	1.476	1198.2	1307.4	1.5901
700	1.694	1241.7	1364.0	1.6437	1.650	1241.3	1363.4	1.6406
800	1.863	1283.0	1417.5	1.6880	1.815	1282.7	1417.0	1.6850
900	2.028	1324.1	1470.4	1.7285	1.976	1323.8	1470.1	1.7255
1000	2.190	1365.5	1523.5	1.7662	2.134	1365.3	1523.3	1.7632
1100	2.350	1407.6	1577.2	1.8017	2.290	1407.4	1576.9	1.7988
1200	2.508	1450.4	1631.4	1.8354	2.445	1450.2	1631.2	1.8325
	P = 410 psia, T_{sat} = 447.02 °F				P = 420 psia, T_{sat} = 449.40 °F			
Sat liq.	0.019	425.4	426.9	0.6247	0.019	428.1	429.6	0.6276
Sat. vap	1.133	1118.7	1204.7	1.4825	1.106	1118.8	1204.7	1.4802
460	1.163	1126.6	1214.8	1.4936	1.130	1125.3	1213.1	1.4894
480	1.207	1138.1	1229.7	1.5096	1.173	1137.0	1228.2	1.5056
500	1.249	1149.0	1243.8	1.5244	1.215	1148.0	1242.4	1.5206
520	1.289	1159.4	1257.2	1.5383	1.254	1158.5	1256.0	1.5347
540	1.328	1169.4	1270.2	1.5514	1.293	1168.6	1289.1	1.5479
560	1.365	1179.1	1282.7	1.5637	1.330	1178.3	1281.7	1.5603
580	1.402	1188.4	1294.8	1.5755	1.366	1187.8	1293.9	1.5722
600	1.438	1197.6	1306.6	1.5868	1.401	1196.9	1305.8	1.5835
700	1.608	1240.8	1362.8	1.6375	1.568	1240.4	1362.3	1.6345

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
800	1.769	1282.4	1416.6	1.6820	1.726	1282.0	1416.2	1.6791
900	1.926	1323.6	1469.7	1.7226	1.879	1323.3	1469.4	1.7197
1000	2.081	1365.1	1523.0	1.7603	2.030	1364.9	1522.7	1.7575
1100	2.233	1407.2	1576.7	1.7959	2.180	1407.0	1576.4	1.7932
1200	2.385	1450.1	1631.0	1.8297	2.327	1449.9	1630.8	1.8269
	P = 430 psia, T_{sat} = 451.74 °F				P = 440 psia, T_{sat} = 454.03 °F			
Sat liq.	0.020	430.6	432.2	0.6304	0.020	433.2	434.8	0.6332
Sat. vap	1.080	1118.8	1204.8	1.4781	1.055	1118.8	1204.8	1.4759
460	1.099	1123.9	1211.4	1.4853	1.069	1122.6	1209.6	1.4812
480	1.142	1135.8	1226.6	1.5017	1.111	1134.6	1225.1	1.4979
500	1.183	1147.0	1241.1	1.5169	1.152	1145.9	1239.7	1.5132
520	1.222	1157.6	1254.8	1.5311	1.190	1156.7	1253.6	1.5276
540	1.259	1167.8	1268.0	1.5444	1.227	1167.0	1266.9	1.5410
560	1.296	1177.6	1280.7	1.5570	1.263	1176.9	1279.7	1.5537
580	1.331	1187.1	1293.0	1.5689	1.298	1186.4	1292.1	1.5657
600	1.366	1196.3	1305.0	1.5804	1.332	1195.7	1304.2	1.5772
700	1.529	1240.0	1361.7	1.6315	1.493	1239.6	1361.1	1.6286
800	1.684	1281.7	1415.7	1.6762	1.644	1281.4	1415.3	1.6734
900	1.835	1323.0	1469.0	1.7169	1.792	1322.8	1468.7	1.7142
1000	1.982	1364.6	1522.4	1.7548	1.936	1364.4	1522.1	1.7521
1100	2.128	1406.8	1576.2	1.7904	2.079	1406.6	1575.9	1.7878
1200	2.273	1449.7	1630.6	1.8242	2.220	1449.6	1630.4	1.8216
	P =450 psia, T_{sat} = 456.28 °F				P = 460 psia, T_{sat} = 458.50 °F			
Sat liq.	0.020	435.7	437.3	0.6360	0.020	438.2	439.8	0.6387
Sat. vap	1.032	1118.9	1204.8	1.4738	1.009	1118.9	1204.8	1.4718
460	1.040	1121.2	1207.8	1.4771	1.012	1119.8	1206.0	1.4731
480	1.082	1133.4	1223.5	1.4940	1.054	1132.2	1222.0	1.4903
500	1.122	1144.9	1238.3	1.5096	1.094	1143.8	1236.9	1.5060
520	1.160	1155.8	1252.4	1.5241	1.132	1154.8	1251.1	1.5207
540	1.197	1166.1	1265.8	1.5377	1.168	1165.3	1264.7	1.5344
560	1.232	1176.1	1278.7	1.5505	1.203	1175.4	1277.7	1.5473
580	1.266	1185.7	1291.2	1.5626	1.236	1185.1	1290.3	1.5595
600	1.300	1195.1	1303.3	1.5742	1.269	1194.5	1302.5	1.5711
700	1.458	1239.2	1360.6	1.6258	1.424	1238.8	1360.0	1.6230
800	1.607	1281.1	1414.9	1.6707	1.570	1280.8	1414.4	1.6680
900	1.751	1322.5	1468.3	1.7115	1.712	1322.3	1468.0	1.7089
1000	1.892	1364.2	1521.8	1.7495	1.850	1364.0	1521.5	1.7469
1100	2.032	1406.5	1575.7	1.7852	1.987	1406.3	1575.4	1.7826
1200	2.170	1449.4	1630.1	1.8190	2.123	1449.3	1629.9	1.8165
	P = 470 psia, T_{sat} = 460.68 °F				P = 480 psia, T_{sat} = 462.82 °F			
Sat liq.	0.020	440.6	442.3	0.6413	0.020	443.0	444.8	0.6439
Sat. vap	0.988	1118.9	1204.8	1.5697	0.967	1118.9	1204.8	1.4677

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
480	1.028	1131.0	1220.4	1.4865	1.002	1129.8	1218.8	1.4828
500	1.067	1142.8	1235.5	1.5025	1.041	1141.7	1234.1	1.4990
520	1.104	1153.9	1249.9	1.5173	1.078	1152.9	1248.6	1.5139
540	1.140	1164.5	1263.6	1.5311	1.113	1163.6	1262.4	1.5279
560	1.174	1174.6	1276.7	1.5441	1.147	1173.8	1275.7	1.5410
580	1.207	1184.4	1289.4	1.5564	1.180	1183.7	1288.5	1.5534
600	1.240	1193.9	1301.7	1.5681	1.211	1193.2	1300.8	1.5652
700	1.392	1238.3	1359.4	1.6202	1.361	1237.9	1358.8	1.6176
800	1.536	1280.4	1414.0	1.6654	1.502	1280.1	1413.6	1.6628
900	1.674	1322.0	1467.6	1.7064	1.638	1321.7	1467.3	1.7038
1000	1.810	1363.8	1521.2	1.7444	1.772	1363.5	1520.9	1.7419
1100	1.944	1406.1	1575.2	1.7802	1.903	1405.9	1574.9	1.7777
1200	2.077	1449.1	1629.7	1.8141	2.033	1448.9	1629.5	1.8116
	P = 490 psia, T_{sat} = 464.93 °F				P = 500 psia, T_{sat} = 467.01 °F			
Sat liq.	0.020	445.4	447.2	0.6465	0.020	447.7	449.5	0.6490
Sat. vap	0.947	1118.9	1204.7	1.4658	0.928	1118.8	1204.7	1.4639
480	0.977	1128.5	1217.1	1.4791	0.954	1127.2	1215.5	1.4755
500	1.016	1140.6	1232.7	1.4955	0.992	1139.5	1231.2	1.4921
520	1.052	1151.9	1247.4	1.5106	1.028	1151.0	1246.1	1.5074
540	1.087	1162.7	1261.3	1.5247	1.062	1161.9	1260.2	1.5216
560	1.121	1173.1	1274.7	1.5380	1.095	1172.3	1273.6	1.5349
580	1.153	1183.0	1287.5	1.5504	1.127	1182.3	1286.6	1.5475
600	1.184	1192.6	1300.0	1.5623	1.158	1192.0	1299.1	1.5595
700	1.332	1237.5	1358.3	1.6149	1.304	1237.1	1357.7	1.6123
800	1.470	1279.8	1413.1	1.6603	1.440	1279.5	1412.7	1.6578
900	1.604	1321.5	1466.9	1.7014	1.571	1321.2	1466.6	1.6990
1000	1.735	1363.3	1520.6	1.7395	1.699	1363.1	1520.3	1.7371
1100	1.864	1405.7	1574.7	1.7753	1.826	1405.5	1574.4	1.7730
1200	1.991	1448.8	1629.3	1.8093	1.951	1448.6	1629.1	1.8069
	P = 510 psia, T_{sat} = 469.05 °F				P = 520 psia, T_{sat} = 471.07 °F			
Sat liq.	0.020	450.0	451.9	0.6515	0.020	452.3	454.2	0.6539
Sat. vap	0.909	1118.8	1204.6	1.4620	0.891	1118.8	1204.5	1.4601
480	0.931	1126.0	1213.8	1.4718	0.909	1124.7	1212.1	1.4682
500	0.969	1138.4	1229.8	1.4886	0.947	1137.2	1228.3	1.4853
520	1.005	1150.0	1244.8	1.5041	0.982	1149.0	1243.5	1.5009
540	1.039	1161.0	1259.0	1.5185	1.016	1160.1	1257.8	1.5154
560	1.071	1171.5	1272.6	1.5319	1.048	1170.7	1271.5	1.5290
580	1.103	1181.6	1285.7	1.5446	1.079	1180.9	1284.7	1.5418
600	1.133	1191.3	1298.3	1.5567	1.109	1190.7	1297.4	1.5539
700	1.277	1236.6	1357.1	1.6097	1.250	1236.2	1356.5	1.6072
800	1.410	1279.2	1412.2	1.6554	1.382	1278.8	1411.8	1.6530
900	1.539	1321.0	1466.2	1.6966	1.509	1320.7	1465.9	1.6943
1000	1.665	1362.9	1520.0	1.7348	1.632	1362.7	1519.7	1.7325

(continued)

Table F2 (continued)

T (°F)	*V* (ft^3/lb)	*U* (Btu/lb)	*H* (Btu/lb)	*S* (Btu/lb R)	*V* (ft^3/lb)	*U* (Btu/lb)	*H* (Btu/lb)	*S* (Btu/lb R)
1100	1.789	1405.3	1574.2	1.7707	1.754	1405.1	1573.9	1.7684
1200	1.912	1448.4	1628.9	1.8047	1.875	1448.3	1628.7	1.8024
	P = 530 psia, T_{sat} = 473.05 °F							
Sat liq.	0.020	454.5	456.5	0.6564				
Sat. vap	0.874	1118.7	1204.5	1.4583				
480	0.888	1123.4	1210.4	1.4646				
500	0.925	1136.1	1226.8	1.4819				
520	0.960	1148.0	1242.2	1.4977				
540	0.994	1159.2	1256.7	1.5124				
560	1.026	1169.9	1270.5	1.5261				
580	1.056	1180.1	1283.8	1.5390				
600	1.086	1190.0	1296.5	1.5512				
700	1.225	1235.8	1355.9	1.6047				
800	1.355	1278.5	1411.4	1.6506				
900	1.479	1320.4	1465.5	1.6920				
1000	1.601	1362.4	1519.4	1.7302				
1100	1.720	1404.9	1573.7	1.7662				
1200	1.839	1448.1	1628.4	1.8002				
	P = 540 psia, T_{sat} = 475.01 °F				P = 550 psia, T_{sat} = 476.94 °F			
Sat liq.	0.020	456.7	458.7	0.6587	0.020	458.9	460.9	0.0611
Sat. vap	0.858	1118.7	1204.4	1.4565	0.842	1118.6	1204.3	1.4547
500	0.905	1134.9	1225.3	1.4786	0.885	1133.8	1223.8	1.4753
520	0.939	1147.0	1240.8	1.4946	0.919	1145.8	1239.5	1.4915
540	0.973	1158.3	1255.5	1.5094	0.952	1157.4	1254.3	1.5064
560	1.004	1169.1	1269.4	1.5232	0.983	1168.3	1268.4	1.5203
580	1.035	1179.4	1282.8	1.5362	1.013	1178.7	1281.8	1.5334
600	1.064	1189.4	1295.7	1.5484	1.042	1188.7	1294.8	1.5458
650	1.134	1213.0	1326.3	1.5767	1.112	1212.4	1325.6	1.5742
700	1.201	1235.3	1355.3	1.6023	1.178	1234.9	1354.7	1.5999
750	1.266	1257.0	1383.4	1.6260	1.241	1256.6	1382.9	1.6237
800	1.328	1278.2	1410.9	1.6483	1.303	1277.9	1410.5	1.6460
900	1.451	1320.2	1465.1	1.6897	1.424	1319.9	1464.8	1.6875
1000	1.570	1362.2	1519.1	1.7280	1.541	1362.0	1518.9	1.7259
1100	1.888	1404.8	1573.4	1.7640	1.657	1404.6	1573.2	1.7619
1200	1.804	1447.9	1682.2	1.7981	1.771	1447.8	1628.0	1.7959
	P = 560 psia, T_{sat} = 478.84 °F				P = 570 psia, T_{sat} = 480.72 °F			
Sat liq.	0.020	461.1	463.1	0.6634	0.020	463.2	465.3	0.6657
Sat. vap	0.826	1118.5	1204.2	1.4529	0.812	1118.5	1204.1	1.4512
500	0.865	1132.6	1222.2	1.4720	0.847	1131.4	1220.7	1.4687
520	0.900	1144.9	1238.1	1.4884	0.881	1143.9	1236.8	1.4853
540	0.932	1156.5	1253.1	1.5035	0.913	1155.6	1251.9	1.5005
560	0.963	1167.5	1267.3	1.5175	0.944	1166.6	1266.2	1.5147

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
580	0.993	1178.0	1280.9	1.5307	0.973	1177.2	1279.9	1.5280
600	1.022	1188.0	1293.9	1.5431	1.002	1187.4	1293.0	1.5405
650	1.090	1211.9	1324.9	1.5717	1.069	1211.4	1324.2	1.5693
700	1.155	1234.4	1354.2	1.5975	1.133	1234.0	1353.6	1.5952
750	1.218	1256.2	1382.4	1.6214	1.195	1255.8	1381.9	1.6191
800	1.279	1277.5	1410.0	1.6438	1.255	1277.2	1409.6	1.6415
900	1.397	1319.6	1464.4	1.6853	1.372	1319.4	1464.1	1.6832
1000	1.513	1361.8	1518.6	1.7237	1.486	1361.6	1518.3	1.7216
1100	1.627	1404.4	1572.9	1.7598	1.597	1404.2	1572.7	1.7577
1200	1.739	1447.6	1627.8	1.7939	1.708	1447.5	1627.6	1.7918
	P = 580 psia, T_{sat} = 482.57 °F				P = 590 psia, T_{sat} = 484.40 °F			
Sat liq.	0.020	465.3	467.5	0.6679	0.020	467.4	469.6	0.6701
Sat. vap	0.797	1118.4	1203.9	1.4495	0.783	1118.3	1203.8	1.4478
500	0.829	1130.2	1219.1	1.4654	0.811	1129.0	1217.5	1.4622
520	0.863	1142.8	1235.4	1.4822	0.845	1141.7	1234.0	1.4792
540	0.895	1154.6	1250.7	1.4976	0.877	1153.7	1249.4	1.4948
560	0.925	1165.8	1265.1	1.5120	0.907	1165.0	1264.0	1.5092
580	0.954	1176.5	1278.9	1.5254	0.936	1175.7	1277.9	1.5227
600	0.982	1186.7	1292.1	1.5380	0.964	1186.0	1291.2	1.5354
650	1.049	1210.8	1323.4	1.5668	1.030	1210.3	1322.7	1.5645
700	1.112	1233.6	1353.0	1.5929	1.092	1233.1	1352.4	1.5906
750	1.173	1255.5	1381.4	1.6169	1.152	1255.1	1380.9	1.6147
800	1.232	1276.9	1409.2	1.6394	1.210	1276.5	1408.7	1.6372
900	1.347	1319.1	1463.7	1.6811	1.324	1318.9	1463.4	1.6790
1000	1.459	1361.3	1518.0	1.7196	1.434	1361.1	1517.7	1.7175
1100	1.569	1404.0	1572.4	1.7556	1.542	1403.8	1572.2	1.7536
1200	1.678	1447.3	1627.4	1.7898	1.649	1447.1	1627.2	1.7879
	P = 600 psia, T_{sat} = 486.20 °F				P = 610 psia, T_{sat} = 487.98 °F			
Sat liq.	0.020	469.5	471.7	0.6723	0.020	471.5	473.8	0.6745
Sat. vap	0.770	1118.2	1203.7	1.4461	0.757	1118.1	1203.5	1.4445
500	0.794	1127.7	1215.9	1.4590	0.778	1126.5	1214.3	1.4558
520	0.828	1140.7	1232.6	1.4762	0.811	1139.6	1231.2	1.4732
540	0.860	1152.8	1248.2	1.4919	0.843	1151.8	1246.9	1.4891
560	0.889	1164.1	1262.9	1.5065	0.872	1163.3	1261.8	1.5038
580	0.918	1175.0	1276.9	1.5201	0.901	1174.2	1275.9	1.5175
600	0.946	1185.3	1290.3	1.5329	0.928	1184.7	1289.4	1.5304
650	1.011	1209.8	1322.0	1.5621	0.993	1209.2	1321.3	1.5598
700	1.073	1232.7	1351.8	1.5884	1.054	1232.2	1351.2	1.5861
750	1.132	1254.7	1380.4	1.6125	1.112	1254.3	1379.9	1.6104
800	1.189	1276.2	1408.3	1.6351	1.169	1275.9	1407.8	1.6330
900	1.301	1318.6	1463.0	1.6769	1.279	1318.3	1462.7	1.6749
1000	1.409	1360.9	1517.4	1.7155	1.386	1360.7	1517.1	1.7135
1100	1.516	1403.6	1571.9	1.7517	1.491	1403.4	1571.7	1.7497
1200	1.621	1447.0	1627.0	1.7859	1.594	1446.8	1626.7	1.7839

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
	P = 620 psia, T_{sat} = 489.74 °F				P = 630 psia, T_{sat} = 491.48 °F			
Sat liq.	0.020	473.5	475.8	0.6766	0.020	475.5	477.9	0.6787
Sat. vap	0.744	1118.0	1203.4	1.4428	0.732	1117.9	1203.2	1.4412
500	0.762	1125.2	1212.7	1.4526	0.747	1123.9	1211.0	1.4494
520	0.795	1138.5	1229.7	1.4702	0.780	1137.4	1228.3	1.4672
540	0.827	1150.8	1245.7	1.4863	0.811	1149.9	1244.4	1.4835
560	0.856	1162.4	1260.7	1.5011	0.840	1161.6	1259.5	1.4985
580	0.884	1173.5	1274.9	1.5150	0.868	1172.7	1273.9	1.5124
600	0.911	1184.0	1288.5	1.5279	0.895	1183.3	1287.6	1.5255
650	0.975	1208.7	1320.5	1.5575	0.958	1208.1	1319.8	1.5552
700	1.035	1231.8	1350.6	1.5839	1.017	1231.3	1350.0	1.5818
750	1.093	1253.9	1379.3	1.6082	1.074	1253.6	1378.8	1.6062
800	1.149	1275.6	1407.4	1.6310	1.130	1275.2	1406.9	1.6289
900	1.257	1318.1	1462.3	1.6729	1.236	1317.8	1461.9	1.6710
1000	1.363	1360.5	1516.8	1.7116	1.340	1360.2	1516.5	1.7097
1100	1.466	1403.2	1571.4	1.7478	1.442	1403.1	1571.2	1.7459
1200	1.568	1446.6	1626.5	1.7820	1.543	1446.5	1626.3	1.7802
	P = 640 psia, T_{sat} = 493.19 °F				P = 650 psia, T_{sat} = 494.89 °F			
Sat liq.	0.020	477.5	479.9	0.6808	0.0203	479.5	481.9	0.6828
Sat. vap	0.720	1117.8	1203.0	1.4396	0.7084	1117.6	1202.8	1.4381
500	0.732	1122.7	1209.3	1.4462	0.7173	1121.3	1207.6	1.4430
520	0.765	1136.3	1226.8	1.4643	0.7501	1135.1	1225.4	1.4614
540	0.796	1148.9	1243.1	1.4807	0.7808	1147.9	1241.8	1.4780
560	0.825	1160.7	1258.4	1.4959	0.8096	1159.8	1257.2	1.4932
580	0.852	1171.9	1272.8	1.5099	0.8371	1171.1	1271.8	1.5074
600	0.879	1182.6	1286.7	1.5231	0.8634	1181.9	1285.7	1.5207
650	0.942	1207.6	1319.1	1.5530	0.9254	1207.0	1318.3	1.5507
700	1.000	1230.9	1349.3	1.5797	0.9835	1230.4	1348.7	1.5775
750	1.056	1253.2	1378.3	1.6041	1.0390	1252.8	1377.8	1.6021
800	1.111	1274.9	1406.5	1.6269	1.0930	1274.6	1406.0	1.6249
900	1.216	1317.5	1461.6	1.6690	1.1970	1317.3	1461.2	1.6671
1000	1.319	1360.0	1516.2	1.7078	1.2980	1359.8	1515.9	1.7059
1100	1.419	1402.9	1570.9	1.7441	1.3970	1402.7	1570.7	1.7422
1200	1.518	1446.3	1.626.1	1.7783	1.4940	1446.1	1625.9	1.7765
	P = 660 psia, T_{sat} = 496.57 °F				P = 670 psia, T_{sat} = 498.22 °F			
Sat liq.	0.0204	481.4	483.9	0.6849	0.0204	483.3	485.8	0.6869
Sat. vap	0.6972	1117.5	1202.7	1.4365	0.6864	1117.4	1202.5	1.4350
500	0.7031	1120.0	1205.9	1.4399	0.6894	1118.7	1204.2	1.4367
520	0.7359	1134.0	1223.9	1.4584	0.7221	1132.8	1222.4	1.4555
540	0.7664	1146.9	1240.5	1.4752	0.7525	1145.9	1239.2	1.4725
560	0.7951	1159.0	1256.1	1.4907	0.7810	1158.1	1254.9	1.4881
580	0.8224	1170.3	1270.8	1.5049	0.8080	1169.6	1269.7	1.5025

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
600	0.8485	1181.2	1284.8	1.5183	0.8339	1180.5	1283.9	1.5159
650	0.9098	1206.5	1317.6	1.5485	0.8947	1205.9	1316.8	1.5463
700	0.9673	1230.0	1348.1	1.5755	0.9516	1229.5	1347.5	1.5734
750	1.0220	1252.4	1377.3	1.6001	1.0060	1252.0	1376.7	1.5981
800	1.0750	1274.2	1405.6	1.6230	1.0580	1273.9	1405.1	1.6211
900	1.1780	1317.0	1460.9	1.6652	1.1600	1316.7	1460.5	1.6634
1000	1.2780	1359.6	1515.6	1.7041	1.2580	1359.3	1515.3	1.7023
1100	1.3750	1402.5	1570.4	1.7404	1.3540	1402.3	1570.2	1.7387
1200	1.4710	1446.0	1625.7	1.7748	1.4490	1445.8	1625.5	1.7730
	P = 680 psia, T_{sat} = 499.86 °F				P = 690 psia, T_{sat} = 501.48 °F			
Sat liq.	0.0204	485.2	487.8	0.6889	0.0205	487.1	489.7	0.6908
Sat. vap	0.6758	1117.2	1202.3	1.4334	0.6655	1117.1	1202.1	1.4319
500	0.6760	1117.3	1202.4	1.4336	…..	…..	…..	…..
520	0.7087	1131.7	1220.8	1.4526	0.6956	1130.5	1219.3	1.4497
540	0.7389	1144.9	1237.9	1.4698	0.7257	1143.9	1236.5	1.4671
560	0.7673	1157.2	1253.7	1.4855	0.7539	1156.3	1252.5	1.4830
580	0.7941	1168.8	1268.7	1.5000	0.7806	1168.0	1267.6	1.4976
600	0.8198	1179.8	1282.9	1.5136	0.8061	1179.0	1282.0	1.5113
650	0.8801	1205.3	1316.1	1.5442	0.8658	1204.8	1315.3	1.5421
700	0.9364	1229.1	1346.9	1.5714	0.9216	1228.6	1346.3	1.5693
750	0.9900	1251.6	1376.2	1.5961	0.9746	1251.3	1375.7	1.5942
800	1.0420	1273.6	1404.7	1.6192	1.0260	1273.2	1404.2	1.6173
900	1.1420	1316.5	1460.2	1.6616	1.1250	1316.2	1459.8	1.6598
1000	1.2390	1359.1	1515.0	1.7005	1.2200	1358.9	1514.7	1.6987
1100	1.3340	1402.1	1569.9	1.7369	1.3140	1401.9	1569.7	1.7352
1200	1.4270	1445.7	1625.3	1.7713	1.4060	1445.5	1625.0	1.7696
	P = 700 psia, T_{sat} = 503.08 °F							
Sat liq.	0.0205	489.0	491.6	0.6928				
Sat. vap	0.6556	1116.9	1201.8	1.4304				
520	0.6829	1129.3	1217.8	1.4468				
540	0.7129	1142.8	1235.2	1.4644				
560	0.7409	1155.4	1251.3	1.4805				
580	0.7675	1167.1	1266.6	1.4952				
600	0.7928	1178.3	1281.0	1.5090				
650	0.8520	1204.2	1314.6	1.5399				
700	0.9072	1228.1	1345.6	1.5673				
750	0.9596	1250.9	1375.2	1.5923				
800	1.0100	1272.9	1403.7	1.6154				
900	1.1080	1315.9	1459.4	1.6580				
1000	1.2020	1358.7	1514.4	1.6970				
1100	1.2950	1401.7	1569.4	1.7335				
1200	1.3860	1445.3	1624.8	1.7679				

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
	P =725 psia, T_{sat} = 507.01 °F				P = 750 psia, T_{sat} = 510.84 °F			
Sat liq.	0.0206	493.5	496.3	0.6975	0.0207	498.0	500.9	0.7022
Sat. vap	0.6318	1116.5	1201.3	1.4268	0.6095	1116.1	1200.7	1.4232
520	0.6525	1126.3	1213.8	1.4396	0.6240	1123.1	1209.7	1.4325
540	0.6823	1140.2	1231.7	1.4578	0.6536	1137.5	1228.2	1.4511
560	0.7100	1153.1	1248.3	1.4742	0.6811	1150.7	1245.2	1.4680
580	0.7362	1165.1	1263.9	1.4893	0.7069	1163.0	1261.1	1.4835
600	0.7610	1176.5	1278.6	1.5033	0.7313	1174.6	1276.1	1.4977
620	0.7848	1187.3	1292.6	1.5164	0.7547	1185.6	1290.4	1.5111
650	0.8190	1202.8	1312.6	1.5347	0.7882	1201.3	1310.7	1.5296
700	0.8729	1227.0	1344.1	1.5624	0.8409	1225.8	1342.5	1.5577
750	0.9240	1249.9	1373.8	1.5876	0.8907	1248.9	1372.5	1.5830
800	0.9732	1272.0	1402.6	1.6109	0.9386	1271.2	1401.5	1.6065
900	1.0680	1315.3	1458.5	1.6536	1.0310	1314.6	1457.6	1.6494
1000	1.1590	1358.1	1513.7	1.6927	1.1190	1357.6	1512.9	1.6886
1100	1.2490	1401.3	1568.8	1.7293	1.2060	1400.8	1568.2	1.7252
1200	1.3370	1444.9	1624.3	1.7638	1.2920	1444.5	1623.8	1.7598
	P =775 psia, T_{sat} = 514.57 °F				P = 800 psia, T_{sat} = 518.21 °F			
Sat liq.	0.0208	502.4	505.4	0.7067	0.0209	506.7	509.8	0.7111
Sat. vap	0.5886	1115.6	1200.1	1.4197	0.5690	1115.2	1199.4	1.4163
520	0.5971	1119.9	1205.6	1.4253	0.5717	1116.6	1201.2	1.4182
540	0.6267	1134.7	1224.6	1.4446	0.6013	1131.9	1220.9	1.4381
560	0.6539	1148.3	1242.1	1.4619	0.6283	1145.9	1238.9	1.4558
580	0.6794	1160.9	1258.3	1.4777	0.6536	1158.8	1255.5	1.4720
600	0.7035	1172.7	1273.6	1.4923	0.6774	1170.8	1271.1	1.4868
620	0.7265	1183.9	1288.1	1.5058	0.7000	1182.2	1285.9	1.5007
650	0.7594	1199.9	1308.8	1.5247	0.7323	1198.4	1306.8	1.5198
700	0.8109	1224.6	1340.9	1.5530	0.7828	1223.4	1339.3	1.5484
750	0.8595	1247.9	1371.2	1.5786	0.8303	1246.9	1369.8	1.5742
800	0.9062	1270.3	1400.3	1.6022	0.8759	1269.5	1399.1	1.5980
900	0.9957	1313.9	1456.7	1.6453	0.9631	1313.2	1455.8	1.6413
1000	1.0820	1357.0	1512.2	1.6846	1.0470	1356.4	1511.4	1.6807
1100	1.1660	1400.3	1567.6	1.7213	1.1290	1399.8	1566.9	1.7175
1200	1.2490	1444.1	1623.2	1.7559	1.2090	1443.7	1622.7	1.7522
	P = 825 psia, T_{sat} = 521.76 °F				P =850 psia, T_{sat} = 525.24 °F			
Sat liq.	0.0210	510.9	514.1	0.7155	0.0211	515.1	518.4	0.7197
Sat. vap	0.5505	1114.6	1198.7	1.4129	0.5330	1114.1	1198.0	1.4096
540	0.5773	1129.0	1217.1	1.4315	0.5546	1126.0	1213.3	1.4250
560	0.6042	1143.4	1235.6	1.4498	0.5815	1140.8	1232.2	1.4439
580	0.6293	1156.6	1252.6	1.4664	0.6063	1154.3	1249.7	1.4608
600	0.6528	1168.9	1268.5	1.4815	0.6296	1166.9	1265.9	1.4763
620	0.6751	1180.5	1283.6	1.4956	0.6516	1178.7	1281.2	1.4906

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
650	0.7069	1196.9	1304.8	1.5150	0.6829	1195.3	1302.8	1.5102
700	0.7564	1222.2	1337.7	1.5440	0.7315	1221.0	1336.0	1.5396
750	0.8029	1245.9	1368.5	1.5700	0.7770	1244.9	1367.1	1.5658
800	0.8473	1268.6	1398.0	1.5939	0.8205	1267.7	1396.8	1.5899
900	0.9323	1312.6	1454.9	1.6374	0.9034	1311.9	1454.0	1.6336
1000	1.0140	1355.9	1510.7	1.6770	0.9830	1355.3	1510.0	1.6733
1100	1.0940	1399.3	1566.3	1.7138	1.0610	1398.9	1565.7	1.7102
1200	1.1720	1443.3	1622.2	1.7485	1.1370	1442.9	1621.6	1.7450
	P = 875 psia, T_{sat} = 528.63 °F				P = 900 psia, T_{sat} = 531.95 °F			
Sat liq.	0.0211	519.2	522.6	0.7238	0.0212	523.2	526.7	0.7279
Sat. vap	0.5165	1113.6	1197.2	1.4064	0.5009	1113.0	1196.4	1.4032
540	0.5330	1123.0	1209.3	1.4185	0.5126	1119.8	1205.2	1.4120
560	0.5599	1138.2	1228.8	1.4379	0.5394	1135.5	1225.3	1.4320
580	0.5846	1152.0	1246.7	1.4553	0.5640	1149.7	1243.6	1.4498
600	0.6077	1164.9	1263.3	1.4711	0.5869	1162.8	1260.6	1.4659
620	0.6294	1176.9	1278.8	1.4856	0.6084	1175.1	1276.4	1.4807
650	0.6602	1193.8	1300.7	1.5056	0.6388	1192.2	1298.6	1.5010
700	0.7080	1219.7	1334.4	1.5353	0.6858	1218.5	1332.7	1.5311
750	0.7526	1243.9	1365.7	1.5618	0.7296	1242.8	1364.3	1.5578
800	0.7952	1266.9	1395.6	1.5860	0.7713	1266.0	1394.4	1.5822
900	0.8762	1311.2	1453.1	1.6299	0.8504	1310.5	1452.2	1.6263
1000	0.9538	1354.8	1509.2	1.6697	0.9262	1354.2	1508.5	1.6662
1100	1.0290	1398.4	1565.1	1.7067	0.9998	1397.9	1564.4	1.7033
1200	1.1030	1442.5	1621.1	1.7416	1.0720	1442.0	1620.6	1.7382
	P = 925 psia, T_{sat} = 535.21 °F				P = 950 psia, T_{sat} = 538.39 °F			
Sat liq.	0.0213	527.1	530.8	0.7319	0.0214	531.0	534.7	0.7358
Sat. vap	0.4861	1112.4	1195.6	1.4001	0.4721	1111.7	1194.7	1.3970
540	0.4930	1116.5	1200.9	1.4054	0.4744	1113.2	1196.6	1.3988
560	0.5200	1132.7	1221.7	1.4260	0.5014	1129.9	1218.0	1.4201
580	0.5445	1147.3	1240.5	1.4443	0.5259	1144.9	1237.4	1.4389
600	0.5672	1160.8	1257.8	1.4608	0.5485	1158.6	1255.1	1.4557
620	0.5885	1173.2	1274.0	1.4759	0.5696	1171.4	1271.5	1.4711
650	0.6186	1190.7	1296.6	1.4965	0.5993	1189.1	1294.4	1.4921
700	0.6648	1217.2	1331.0	1.5269	0.6449	1216.0	1329.3	1.5228
750	0.7078	1241.8	1362.9	1.5539	0.6871	1240.7	1361.5	1.5500
800	0.7486	1265.1	1393.2	1.5784	0.7272	1264.2	1392.0	1.5748
900	0.8261	1309.8	1451.2	1.6227	0.8030	1309.1	1450.3	1.6193
1000	0.9001	1353.6	1507.7	1.6628	0.8753	1353.1	1507.0	1.6595
1100	0.9719	1397.4	1563.8	1.7000	0.9455	1397.0	1563.2	1.6967
1200	1.0420	1441.6	1620.0	1.7349	1.0140	1441.2	1619.5	1.7317
	P = 975 psia, T_{sat} = 541.52 °F				P = 1000psia, T_{sat} = 544.58 °F			
Sat liq.	0.0215	534.8	538.7	0.7396	0.0216	538.6	542.6	0.7434
Sat. vap	0.4587	1111.1	1193.8	1.3940	0.4460	1110.4	1192.9	1.3910

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
560	0.4837	1127.0	1214.3	1.4142	0.4668	1124.0	1210.4	1.4082
580	0.5082	1142.4	1234.1	1.4335	0.4913	1139.9	1230.8	1.4281
600	0.5307	1156.5	1252.2	1.4507	0.5137	1154.3	1249.3	1.4457
620	0.5517	1169.5	1269.0	1.4664	0.5346	1167.5	1266.5	1.4617
650	0.5810	1187.5	1292.3	1.4877	0.5636	1185.8	1290.1	1.4833
700	0.6259	1214.7	1327.6	1.5188	0.6080	1213.4	1325.9	1.5149
750	0.6675	1239.7	1360.1	1.5463	0.6489	1238.6	1358.7	1.5426
800	0.7068	1263.3	1390.8	1.5712	0.6875	1262.4	1389.6	1.5677
900	0.7811	1308.5	1449.4	1.6159	0.7603	1307.8	1448.5	1.6126
1000	0.8518	1352.5	1506.2	1.6562	0.8295	1351.9	1505.4	1.6530
1100	0.9204	1396.5	1562.5	1.6936	0.8966	1396.0	1561.9	1.6905
1200	0.9875	1440.8	1619.0	1.7286	0.9621	1440.4	1618.4	1.7256
	$P = 1025$ psia, $T_{\text{sat}} = 547.58$ °F				$P = 1050$ psia, $T_{\text{sat}} = 550.53$ °F			
Sat liq.	0.0217	542.3	546.4	0.7471	0.0218	545.9	550.1	0.7507
Sat. vap	0.4338	1109.7	1192.0	1.3880	0.4222	1109.0	1191.0	1.3851
560	0.4506	1120.9	1206.4	1.4022	0.4350	1117.8	1202.3	1.3962
580	0.4752	1137.3	1227.4	1.4227	0.4597	1134.7	1224.0	1.4173
600	0.4975	1152.0	1246.4	1.4407	0.4821	1149.8	1234.4	1.4358
620	0.5183	1165.6	1263.9	1.4571	0.5027	1163.6	1261.2	1.4524
650	0.5471	1184.2	1287.9	1.4791	0.5312	1182.5	1285.7	1.4748
700	0.5908	1212.1	1324.2	1.5110	0.5745	1210.8	1322.4	1.5072
750	0.6311	1237.5	1357.3	1.5389	0.6142	1236.5	1355.8	1.5354
800	0.6690	1261.5	1388.4	1.5642	0.6515	1260.6	1387.2	1.5608
900	0.7405	1307.1	1447.5	1.6094	0.7216	1306.4	1446.6	1.6062
1000	0.8083	1351.4	1504.7	1.6499	0.7881	1350.8	1503.9	1.6469
1100	0.8739	1395.5	1561.3	1.6874	0.8524	1395.0	1560.7	1.6845
1200	0.9380	1440.0	1617.9	1.7226	0.9151	1439.6	1617.4	1.7197
	$P = 1075$ psia, $T_{\text{sat}} = 553.43$ °F				$P = 1100$ psia, $T_{\text{sat}} = 556.28$ °F			
Sat liq.	0.0219	549.5	553.9	0.7543	0.0220	553.1	557.5	0.7578
Sat. vap	0.4112	1108.3	1190.1	1.3822	0.4006	1107.5	1189.1	1.3794
560	0.4200	1114.5	1198.1	1.3901	0.4056	1111.2	1193.7	1.3840
580	0.4449	1131.9	1220.4	1.4118	0.4307	1129.1	1216.8	1.4064
600	0.4673	1147.4	1240.4	1.4308	0.4531	1145.1	1237.3	1.4259
620	0.4878	1161.5	1258.6	1.4479	0.4735	1159.5	1255.9	1.4433
650	0.5161	1180.8	1283.5	1.4706	0.5017	1179.1	1281.2	1.4664
700	0.5589	1209.4	1320.6	1.5034	0.5440	1208.1	1318.8	1.4996
750	0.5981	1235.4	1354.4	1.5319	0.5826	1234.3	1352.9	1.5284
800	0.6348	1259.7	1386.0	1.5575	0.6188	1258.8	1384.7	1.5542
900	0.7037	1305.7	1445.7	1.6031	0.6885	1305.0	1444.7	1.6000
1000	0.7688	1350.2	1503.2	1.6439	0.7505	1349.7	1502.4	1.6410
1100	0.8318	1394.6	1560.0	1.6816	0.8121	1394.1	1559.4	1.6787
1200	0.8932	1439.2	1616.8	1.7169	0.8723	1438.7	1616.3	1.7141

(continued)

Table F2 (continued)

T (°F)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)	V (ft^3/lb)	U (Btu/lb)	H (Btu/lb)	S (Btu/lb R)
		P = 1125 psia, T_{sat} = 559.07 °F						
Sat liq.	0.0220	556.6	561.2	0.7613				
Sat. vap	0.3904	1106.8	1188.0	1.3766				
560	0.3917	1107.7	1189.2	1.3778				
580	0.4170	1126.3	1213.1	1.4009				
600	0.4394	1142.6	1234.1	1.4210				
620	0.4599	1157.4	1253.1	1.4387				
650	0.4879	1177.3	1278.9	1.4623				
700	0.5298	1206.7	1317.0	1.4959				
750	0.5679	1233.2	1351.4	1.5250				
800	0.6035	1257.8	1383.5	1.5509				
900	0.6701	1304.3	1443.8	1.5970				
1000	0.7329	1349.1	1501.7	1.6381				
1100	0.7934	1393.6	1558.8	1.6759				
1200	0.8523	1438.3	1615.8	1.7114				

Source: Smith et al. [8]

Table F3 Saturated steam tables in SI units

T (K)	P^{sat} (kPa)	Spec. vol. V (cm^3/g)		Int. energy U (kJ/kg)		Enthalpy H (kJ/kg)		Entropy S (kJ/kg K)	
		V_l	V_g	U_l	U_g	H_l	H_g	S_l	S_g
273.15	0.611	1.000	206300.0	-0.04	2375.6	-0.04	2501.6	0.0000	9.1578
273.16	0.611	1.000	206200.0	0.00	2375.6	0.00	2501.6	0.0000	9.1575
274.15	0.657	1.000	192600.0	4.17	2376.9	4.17	2503.4	0.0153	9.1311
275.15	0.705	1.000	179900.0	8.39	2378.3	8.39	2505.2	0.0306	9.1047
276.15	0.757	1.000	168200.0	12.60	2379.7	12.60	2507.1	0.0459	9.0785
277.15	0.813	1.000	157300.0	16.80	2381.1	16.80	2508.9	0.0611	9.0526
278.15	0.872	1.000	147200.0	21.01	2382.4	21.01	2510.7	0.0762	9.0269
279.15	0.935	1.000	137800.0	25.21	2383.8	25.21	2512.6	0.0913	9.0014
280.15	1.001	1.000	129100.0	29.41	2385.2	29.41	2514.4	0.1063	8.9762
281.15	1.072	1.000	121000.0	33.60	2386.6	33.60	2516.2	0.1213	8.9513
282.15	1.147	1.000	113400.0	37.80	2387.9	37.80	2518.1	0.1362	8.9265
283.15	1.227	1.000	106400.0	41.99	2389.3	41.99	2519.9	0.1510	8.9020
284.15	1.312	1.000	99910.0	46.18	2390.7	46.19	2521.7	0.1658	8.8776
285.15	1.401	1.000	93840.0	50.38	2392.1	50.38	2523.6	0.1805	8.8536
286.15	1.497	1.001	88180.0	54.56	2393.4	54.57	2525.4	0.1952	8.8297
287.15	1.597	1.001	82900.0	58.75	2394.8	58.75	2527.2	0.2098	8.8060
288.15	1.704	1.001	77980.0	62.94	2396.2	62.94	2529.1	0.2243	8.7826
289.15	1.817	1.001	73380.0	67.12	2397.6	67.13	2530.9	0.2388	8.7593
290.15	1.936	1.001	69090.0	71.31	2398.9	71.31	2532.7	0.2533	8.7363
291.15	2.062	1.001	65090.0	75.49	2400.3	75.50	2534.5	0.2677	8.7135
292.15	2.196	1.002	61340.0	79.68	2401.7	79.68	2536.4	0.2820	8.6908
293.15	2.337	1.002	57840.0	83.86	2403.0	83.86	2538.2	0.2963	8.6684
294.15	2.485	1.002	54560.0	88.04	2404.4	88.04	2540.0	0.3105	8.6462
295.15	2.642	1.002	51490.0	92.22	2405.8	92.23	2541.8	0.3247	8.6241
296.15	2.808	1.002	48620.0	96.40	2407.1	96.41	2543.6	0.3389	8.6023

(continued)

Table F3 (continued)

T (K)	P^{sat} (kPa)	Spec. vol. V (cm^3/g)		Int. energy U (kJ/kg)		Enthalpy H (kJ/kg)		Entropy S (kJ/kg K)	
		V_l	V_g	U_l	U_g	H_l	H_g	S_l	S_g
297.15	2.982	1.003	45930.0	100.60	2408.5	100.60	2545.5	0.3530	8.5806
298.15	3.166	1.003	43400.0	104.80	2409.9	104.80	2547.3	0.3670	8.5592
299.15	3.360	1.003	41030.0	108.90	2411.2	108.90	2549.1	0.3810	8.5379
300.15	3.564	1.003	38810.0	113.10	2412.6	113.10	2550.9	0.3949	8.5168
301.15	3.778	1.004	36730.0	117.30	2414.0	117.30	2552.7	0.4088	8.4959
302.15	4.004	1.004	34770.0	121.50	2415.3	121.50	2554.5	0.4227	8.4751
303.15	4.241	1.004	32930.0	125.70	2416.7	125.70	2556.4	0.4365	8.4546
304.15	4.491	1.005	31200.0	129.80	2418.0	129.80	2558.2	0.4503	8.4342
305.15	4.753	1.005	29570.0	134.00	2419.4	134.00	2560.0	0.4640	8.4140
306.15	5.029	1.005	28040.0	138.20	2420.8	138.20	2561.8	0.4777	8.3939
307.15	5.318	1.006	26600.0	142.40	2422.1	142.40	2563.6	0.4913	8.3740
308.15	5.622	1.006	25240.0	146.60	2423.5	146.60	2565.4	0.5049	8.3543
309.15	5.940	1.006	23970.0	150.70	2424.8	150.70	2567.2	0.5184	8.3348
310.15	6.274	1.007	22760.0	154.90	2426.2	154.90	2569.0	0.5319	8.3154
311.15	6.624	1.007	21630.0	159.10	2427.5	159.10	2570.8	0.5453	8.2962
312.15	6.991	1.007	20560.0	163.30	2428.9	163.30	2572.6	0.5588	8.2772
313.15	7.375	1.008	19550.0	167.40	2430.2	167.50	2574.4	0.5721	8.2583
314.15	7.777	1.008	18590.0	171.60	2431.6	171.60	2576.2	0.5854	8.2395
315.15	8.198	1.009	17690.0	175.80	2432.9	175.80	2577.9	0.5987	8.2209
316.15	8.639	1.009	16840.0	180.00	2434.2	180.00	2579.7	0.6120	8.2025
317.15	9.100	1.009	16040.0	184.20	2435.6	184.20	2581.5	0.6252	8.1842
318.15	9.582	1.010	15280.0	188.30	2436.9	188.40	2583.3	0.6383	8.1661
319.15	10.090	1.010	14560.0	192.50	2438.3	192.50	2585.1	0.6514	8.1481
320.15	10.610	1.011	13880.0	196.70	2439.6	196.70	2586.9	0.6645	8.1302
321.15	11.160	1.011	13230.0	200.90	2440.9	200.90	2588.6	0.6776	8.1125

(continued)

Table F3 (continued)

T (K)	P^{sat} (kPa)	Spec. vol. V (cm^3/g)		Int. energy U (kJ/kg)		Enthalpy H (kJ/kg)		Entropy S (kJ/kg K)	
		V_l	V_g	U_l	U_g	H_l	H_g	S_l	S_g
322.15	11.74	1.012	12620.0	205.1	2442.3	205.1	2590.4	0.6906	8.0950
323.15	12.34	1.012	12050.0	209.2	2443.6	209.3	2592.2	0.7035	8.0776
324.15	12.96	1.013	11500.0	213.4	2444.9	213.4	2593.9	0.7164	8.0603
325.15	13.61	1.013	10980.0	217.6	2446.2	217.6	2595.7	0.7293	8.0432
326.15	14.29	1.014	10490.0	221.8	2447.6	221.8	2597.5	0.7422	8.0262
327.15	15.00	1.014	10020.0	226.0	2448.9	226.0	2599.2	0.7550	8.0093
328.15	15.74	1.015	9578.9	230.2	2450.2	230.2	2601.0	0.7677	7.9925
329.15	16.51	1.015	9158.7	234.3	2451.5	234.4	2602.7	0.7804	7.9759
330.15	17.31	1.016	8759.8	238.5	2452.8	238.5	2604.5	0.7931	7.9595
331.15	18.15	1.016	8380.8	242.7	2454.1	242.7	2606.2	0.8058	7.9431
332.15	19.02	1.017	8020.8	246.9	2455.4	246.9	2608.0	0.8184	7.9269
333.15	19.92	1.017	7678.5	251.1	2456.8	251.1	2609.7	0.8310	7.9108
334.15	20.86	1.018	7353.2	255.3	2458.1	255.3	2611.4	0.8435	7.8948
335.15	21.84	1.018	7043.7	259.4	2459.4	259.5	2613.2	0.8560	7.8790
336.15	22.86	1.019	6749.3	263.6	2460.7	263.6	2614.9	0.8685	7.8633
337.15	23.91	1.019	6469.0	267.8	2462.0	267.8	2616.6	0.8809	7.8477
338.15	25.01	1.020	6202.3	272.0	2463.2	272.0	2618.4	0.8933	7.8322
339.15	26.15	1.020	5948.2	276.2	2464.5	276.2	2620.1	0.9057	7.8168
340.15	27.33	1.021	5706.2	280.4	2465.8	280.4	2621.8	0.9180	7.8015
341.15	28.56	1.022	5475.6	284.6	2467.1	284.6	2623.5	0.9303	7.7864
342.15	29.84	1.022	5255.8	288.8	2468.4	288.8	2625.2	0.9426	7.7714
343.15	31.16	1.023	5046.3	292.9	2469.7	293.0	2626.9	0.9548	7.7565
344.15	32.53	1.023	4846.4	297.1	2470.9	297.2	2628.6	0.9670	7.7417
345.15	33.96	1.024	4655.7	301.3	2472.2	301.4	2630.3	0.9792	7.7270
346.15	35.43	1.025	4473.7	305.5	2473.5	305.5	2632.0	0.9913	7.7124

(continued)

Table F3 (continued)

T (K)	P^{sat} (kPa)	Spec. vol. V (cm^3/g)		Int. energy U (kJ/kg)		Enthalpy H (kJ/kg)		Entropy S (kJ/kg K)	
		V_l	V_g	U_l	U_g	H_l	H_g	S_l	S_g
347.15	36.96	1.025	4300.0	309.7	2474.8	309.7	2633.7	1.0034	7.6979
348.15	38.55	1.026	4134.1	313.9	2476.0	313.9	2635.4	1.0154	7.6835
349.15	40.19	1.027	3975.7	318.1	2477.3	318.1	2637.1	1.0275	7.6693
350.15	41.89	1.027	3824.3	322.3	2478.5	322.3	2638.7	1.0395	7.6551
351.15	43.65	1.028	3679.6	326.5	2479.8	326.5	2640.4	1.0514	7.6410
352.15	45.47	1.029	3541.3	330.7	2481.1	330.7	2642.1	1.0634	7.6271
353.15	47.36	1.029	3409.1	334.9	2482.3	334.9	2643.8	1.0753	7.6132
354.15	49.31	1.030	3282.6	339.1	2483.5	339.1	2645.4	1.0871	7.5995
355.15	51.33	1.031	3161.6	343.3	2484.8	343.3	2647.1	1.0990	7.5858
356.15	53.42	1.031	3045.8	347.5	2486.0	347.5	2648.7	1.1108	7.5722
357.15	55.57	1.032	2935.0	351.7	2487.3	351.7	2650.4	1.1225	7.5587
358.15	57.80	1.033	2828.8	355.9	2488.5	355.9	2652.0	1.1343	7.5454
359.15	60.11	1.033	2727.2	360.1	2489.7	360.1	2653.6	1.1460	7.5321
360.15	62.49	1.034	2629.8	364.3	2490.9	364.3	2655.3	1.1577	7.5189
361.15	64.95	1.035	2536.5	368.5	2492.2	368.5	2656.9	1.1693	7.5058
362.15	67.49	1.035	2447.0	372.7	2493.4	372.7	2658.5	1.1809	7.4928
363.15	70.11	1.036	2361.3	376.9	2494.6	376.9	2660.1	1.1925	7.4799
364.15	72.81	1.037	2279.1	381.1	2495.8	381.1	2661.7	1.2041	7.4670
365.15	75.61	1.038	2200.2	385.3	2497.0	385.4	2663.4	1.2156	7.4543
366.15	78.49	1.038	2124.5	389.5	2498.2	389.6	2665.0	1.2271	7.4416
367.15	81.46	1.039	2051.9	393.7	2499.4	393.8	2666.6	1.2386	7.4291
368.15	84.53	1.040	1982.2	397.9	2500.6	398.0	2668.1	1.2501	7.4166
369.15	87.69	1.041	1915.3	402.1	2501.8	402.2	2669.7	1.2615	7.4042
370.15	90.94	1.041	1851.0	406.3	2503.0	406.4	2671.3	1.2729	7.3919
371.15	94.30	1.042	1789.3	410.5	2504.1	410.6	2672.9	1.2842	7.3796

Source: Smith et al. [8]

Table F4 Superheated steam tables in SI units

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
	P = 1 kPa, T_{sat} = 6.98 °C				P = 10 kPa, T_{sat} = 45.83 °C			
Sat liq	1.000	29.334	29.335	0.1060	1.010	191.8	191.8	0.6493
Sat. vap	129200.0	2385.2	2514.4	8.9767	14670.0	2438.0	2584.8	8.1511
75	160640.0	2480.8	2641.5	9.3828	16030.0	2479.7	2640.0	8.3168
100	172180.0	2516.4	2688.6	9.5136	17190.0	2515.6	2687.5	8.4486
125	183720.0	2552.3	2736.0	9.6365	18350.0	2551.6	2735.2	8.5722
150	195270.0	2588.5	2783.7	9.7527	19510.0	2588.0	2783.1	8.6888
175	206810.0	2624.9	2831.7	9.8629	20660.0	2624.5	2831.2	8.7994
200	218350.0	2661.7	2880.1	9.9679	21820.0	2661.4	2879.6	8.9045
225	229890.0	2698.8	2928.7	10.0681	22980.0	2698.6	2928.4	9.0049
250	241430.0	2736.3	2977.7	10.1641	24130.0	2736.1	2977.4	9.1010
300	264500.0	2812.3	3076.8	10.3450	26440.0	2812.2	3076.6	9.2820
350	287580.0	2889.9	3177.5	10.5133	28750.0	2889.8	3177.3	9.4504
400	310660.0	2969.1	3279.7	10.6711	31060.0	2969.0	3279.6	9.6083
450	333730.0	3049.9	3383.6	10.8200	33370.0	3049.8	3383.5	9.7572
500	356810.0	3132.4	3489.2	10.9612	35670.0	3132.3	3489.1	9.8984
550	379880.0	3216.7	3596.5	11.0957	37980.0	3216.6	3596.5	10.0329
	P = 20 kPa, T_{sat} = 60.09 °C				P = 30 kPa T_{sat} = 69.12 °C			
Sat liq	1.017	251.4	251.5	0.8321	1.022	289.3	289.3	0.9441
Sat. vap	7649.8	2456.9	2609.9	7.9094	5229.3	2468.6	2625.4	7.7695
75	8000.0	2478.4	2638.4	7.9933	5322.0	2477.1	2636.8	7.8024
100	8584.7	2514.6	2686.3	8.1261	5714.4	2513.6	2685.1	7.9363
125	9167.1	2550.9	2734.2	8.2504	6104.6	2550.2	2733.3	8.0614
150	9748.0	2587.4	2782.3	8.3676	6493.2	2586.8	2781.6	8.1791
175	10320.0	2624.1	2830.6	8.4785	6880.8	2623.6	2830.0	8.2903
200	10900.0	2661.0	2879.2	8.5839	7267.5	2660.7	2878.7	8.3960
225	11480.0	2698.3	2928.0	8.6844	7653.8	2698.0	2927.6	8.4967
250	12060.0	2735.8	2977.1	8.7806	8039.7	2735.6	2976.8	8.5930
300	13210.0	2812.0	3076.4	8.9618	8810.8	2811.8	3076.1	8.7744
350	14370.0	2889.6	3177.1	9.1303	9581.2	2889.5	3176.9	8.9430
400	15520.0	2968.9	3279.4	9.2882	10350.0	2968.7	3279.3	9.1010
450	16680.0	3049.7	3383.4	9.4372	11120.0	3049.6	3383.3	9.2499
500	17830.0	3132.3	3489.0	9.5784	11890.0	3132.2	3488.9	9.3912
550	18990.0	3216.5	3596.4	9.7130	12660.0	3216.5	3596.3	9.5257
	P = 40 kPa, T_{sat} = 75.89 °C				P = 50 kPa, T_{sat} = 81.35 °C			
Sat liq	1.027	317.6	317.7	1.0261	1.030	340.5	340.6	1.0912
Sat. vap	3993.4	2477.1	2636.9	7.6709	3240.2	2484.0	2646.0	7.5947
100	4279.2	2512.6	2683.8	7.8009	3418.1	2511.7	2682.6	7.6953
125	4573.3	2549.4	2732.3	7.9268	3654.5	2548.6	2731.4	7.8219
150	4865.8	2586.2	2780.9	8.0450	3889.3	2585.6	2780.1	7.9406
175	5157.2	2623.2	2829.5	8.1566	4123.0	2622.7	2828.9	8.0526
200	5447.8	2660.3	2878.2	8.2624	4356.0	2659.9	2877.7	8.1587

(continued)

Table F4 (continued)

T (°C)	*V* (cm^3/g)	*U* (kJ/kg)	*H* (kJ/kg)	*S* (kJ/kg K)	*V* (cm^3/g)	*U* (kJ/kg)	*H* (kJ/kg)	*S* (kJ/kg K)
225	5738.0	2697.7	2827.2	8.3633	4588.5	2697.4	2926.8	8.2598
250	6027.7	2735.4	2976.5	8.4598	4820.5	2735.1	2976.1	8.3564
300	6606.5	2811.6	3075.9	8.6413	5283.9	2811.5	3075.7	8.5380
350	7184.6	2889.4	3176.8	8.8100	5746.7	2889.2	3176.6	8.7068
400	7762.5	2968.6	3279.1	8.9680	6209.1	2968.5	3279.0	8.8649
450	8430.1	3049.5	3383.1	9.1170	6671.4	3049.4	3383.0	9.0139
500	8917.6	3132.1	3488.8	9.2583	7133.5	3132.0	3488.7	9.1552
550	9494.9	3216.4	3596.2	9.3929	7595.5	3216.3	3596.1	9.2898
	P = 75 kPa, T_{sat} = 91.79 °C				*P* = 100 kPa T_{sat} = 99.63 °C			
Sat liq	1.037	384.4	384.5	1.2131	1.043	417.4	417.5	1.3027
Sat. vap	2216.9	2496.7	2663.0	7.4570	1693.7	2506.1	2675.4	7.3598
100	2269.8	2509.2	2679.4	7.5014	1695.5	2506.6	2676.2	7.3618
125	2429.4	2546.7	2728.9	7.6300	1816.7	2544.8	2726.5	7.4923
150	2587.3	2584.2	2778.2	7.7500	1936.3	2582.7	2776.3	7.6137
175	2744.2	2621.6	2827.4	7.8629	2054.7	2620.4	2825.9	7.7275
200	2900.2	2659.0	2876.6	7.9697	2172.3	2658.1	2875.4	7.8349
225	3055.8	2696.7	2925.8	8.0712	2289.4	2695.9	2924.9	7.9369
250	3210.9	2734.5	2975.3	8.1681	2406.1	2733.9	2974.5	8.0342
300	3520.5	2811.0	3075.1	8.3502	2638.7	2810.6	3074.5	8.2166
350	3829.4	2888.9	3176.1	8.5191	2870.8	2888.6	3175.6	8.3858
400	4138.0	2968.2	3278.6	8.6773	3102.5	2968.0	3278.2	8.5442
450	4446.4	3049.2	3382.7	8.8265	3334.0	3049.0	3382.4	8.6934
500	4754.7	3131.8	3488.4	8.9678	3565.3	3131.6	3488.1	8.8348
550	5062.8	3216.1	3595.8	9.1025	3796.5	3216.0	3595.6	8.9695
600	5370.9	3302.2	3705.0	9.2312	4027.7	3302.0	3704.8	9.0982
	P = 101.325 kPa T_{sat} = 100.00 °C				*P* = 125 kPa, T_{sat} = 105.99 °C			
Sat liq	1.044	419.0	419.1	1.3069	1.049	444.2	444.4	1.3740
Sat. vap	1673.0	2506.5	2676.0	7.3554	1374.6	2513.4	2685.2	7.2847
125	1792.7	2544.7	2726.4	7.4860	1449.1	2542.9	2724.0	7.3844
150	1910.7	2582.6	2776.2	7.6075	1545.6	2581.2	2774.4	7.5072
175	2027.7	2620.4	2825.8	7.7213	1641.0	2619.3	2824.4	7.6219
200	2143.8	2658.1	2875.3	7.8288	1735.6	2657.2	2874.2	7.7300
225	2259.3	2695.9	2924.8	7.9308	1829.6	2695.2	2923.9	7.8324
250	2374.5	2733.9	2974.5	8.0280	1923.2	2733.3	2973.7	7.9300
300	2604.2	2810.6	3074.4	8.2105	2109.7	2810.2	3073.9	8.1129
350	2833.2	2888.5	3175.6	8.3797	2295.6	2888.2	3175.2	8.2823
400	3061.9	2968.0	3278.2	8.5381	2481.2	2967.7	3277.8	8.4408
450	3290.3	3048.9	3382.3	8.6873	2666.5	3048.7	3382.0	8.5901
500	3518.7	3131.6	3488.1	8.8287	2851.7	3131.4	3487.9	8.7316
550	3746.9	3215.9	3595.6	8.9634	3036.8	3215.8	3595.4	8.8663
600	3975.0	3302.0	3704.8	9.0922	3221.8	3301.9	3704.6	8.9951

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
	P = 150 kPa, T_{sat} = 111.37 °C				P =75 kPa, T_{sat} = 116.06 °C			
Sat liq	1.053	467.0	467.1	1.4336	1.057	486.8	487.0	1.4849
Sat. vap	1159.0	2519.5	2693.4	7.2234	1003.3	2524.7	2700.3	7.1716
125	1204.0	2540.9	2721.5	7.2953	1028.8	2538.9	2719.0	7.2191
150	1285.2	2579.7	2772.5	7.4194	1099.1	2578.2	2770.5	7.3447
175	1365.2	2618.1	2822.9	7.5352	1168.2	2616.9	2821.3	7.4614
200	1444.4	2656.3	2872.9	7.6439	1236.4	2655.3	2871.7	7.5708
225	1523.0	2694.4	2922.9	7.7458	1304.1	2693.7	2921.9	7.6741
250	1601.3	2732.7	2972.9	7.8447	1371.3	2732.1	2972.0	7.7724
300	1757.0	2809.7	3073.3	8.0280	1505.1	2809.3	3072.7	7.9561
350	1912.2	2887.9	3174.7	8.1976	1638.3	2887.5	3174.2	8.1259
400	2066.9	2967.4	3277.5	8.3562	1771.1	2967.1	3277.1	8.2847
450	2221.5	3048.5	3381.7	8.5056	1903.7	3048.3	3381.4	8.4341
500	2375.9	3131.2	3487.6	8.6472	2036.1	3131.0	3487.3	8.5758
550	2530.2	3215.6	3595.1	8.7819	2168.4	3215.4	3594.9	8.7106
600	2684.5	3301.7	3704.4	8.9108	2300.7	3301.6	3704.2	8.8394
	P = 200 kPa, T_{sat} = 120.23 °C				P =225 kPa, T_{sat} = 123.99 °C			
Sat liq	1.061	504.5	504.7	1.5301	1.064	520.5	520.7	1.5705
Sat. vap	885.4	2529.2	2706.3	7.1268	792.97	2533.2	2711.6	7.0873
125	897.5	2536.9	2716.4	7.1523	795.25	2534.8	2713.8	7.0928
150	959.5	2576.6	2768.5	7.2794	850.97	2575.1	2766.5	7.2213
175	1020.4	2615.7	2819.8	7.3971	905.44	2614.5	2818.2	7.3400
200	1080.4	2654.4	2870.5	7.5072	959.06	2653.5	2869.3	7.4508
225	1139.8	2692.9	2920.9	7.6110	1012.10	2692.2	2919.9	7.5551
250	1198.9	2731.4	2971.2	7.7096	1064.70	2730.8	2970.4	7.6540
300	1316.2	2808.8	3072.1	7.8937	1169.20	2808.4	3071.5	7.8385
350	1432.8	2887.2	3173.8	8.0638	1273.10	2886.9	3173.3	8.0088
400	1549.2	2966.9	3276.7	8.2226	1376.60	2966.6	3276.3	8.1679
450	1665.3	3048.0	3381.1	8.3722	1479.90	3047.8	3380.8	8.3175
500	1781.2	3130.8	3487.0	8.5139	1583.00	3130.6	3486.8	8.4593
550	1897.1	3215.3	3594.7	8.6487	1686.00	3215.1	3594.4	8.5942
600	2012.9	3301.4	3704.0	8.7776	1789.00	3301.2	3703.8	8.7231
650	2128.6	3389.2	3815.0	8.9012	1891.90	3389.1	3814.8	8.8467
	P = 250 kPa, T_{sat} = 127.43 °C				P = 275 kPa, T_{sat} = 130.60 °C			
Sat liq	1.068	535.1	535.34	1.6071	1.071	548.6	548.9	1.6407
Sat. vap	718.4	2536.8	2716.4	7.0520	657.04	2540.0	2720.7	7.0201
150	764.1	2573.5	2764.5	7.1689	693.00	2571.9	2762.5	7.1211
175	813.5	2613.3	2816.7	7.2886	738.21	2612.1	2815.1	7.2419
200	862.0	2652.5	2868.0	7.4001	782.55	2651.6	2866.8	7.3541
225	910.0	2691.4	2918.9	7.5050	826.29	2690.7	2917.9	7.4594
250	957.4	2730.2	2969.6	7.6042	869.61	2729.6	2968.7	7.5590
300	1051.6	2808.0	3070.9	7.7891	955.45	2807.5	3070.3	7.7444

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
350	1145.2	2886.5	3172.8	7.9597	1040.70	2886.2	3172.4	7.9151
400	1238.5	2966.3	3275.9	8.1188	1125.50	2966.0	3275.5	8.0744
450	1331.5	3047.6	3380.4	8.2686	1210.20	3047.3	3380.1	8.2243
500	1424.4	3130.4	3486.5	8.4104	1294.70	3130.2	3486.2	8.3661
550	1517.2	3214.9	3594.2	8.5453	1379.00	3214.7	3594.0	8.5011
600	1609.9	3301.1	3703.6	8.6743	1463.30	3300.9	3703.4	8.6301
650	1702.5	3389.0	3814.6	8.7980	1547.60	3388.8	3814.4	8.7538
	P = 300 kPa, T_{sat} = 133.54 °C				P = 325 kPa, T_{sat} = 136.29 °C			
Sat liq	1.073	561.1	561.4	1.6716	1.076	572.8	573.2	1.7004
Sat. vap	605.6	2543.0	2724.7	6.9909	561.75	2545.7	2728.3	6.9640
150	633.7	2570.3	2760.4	7.0771	583.58	2568.7	2758.4	7.0363
175	675.5	2610.8	2813.5	7.1990	622.41	2609.6	2811.9	7.1592
200	716.4	2650.6	2865.5	7.3119	660.33	2649.6	2864.2	7.2729
225	756.6	2689.9	2916.9	7.4177	690.22	2681.2	2905.6	7.3585
250	796.4	2729.0	2967.9	7.5176	719.81	2712.7	2946.6	7.4400
300	875.3	2807.1	3069.7	7.7034	749.18	2744.0	2987.5	7.5181
350	953.5	2885.8	3171.9	7.8744	778.39	2775.3	3028.2	7.5933
400	1031.4	2965.8	3275.2	8.0338	807.47	2806.6	3069.0	7.6657
450	1109.0	3047.1	3379.8	8.1838	843.68	2845.9	3120.1	7.7530
500	1186.5	3130.0	3486.0	8.3257	879.78	2885.5	3171.4	7.8369
550	1263.9	3214.5	3593.7	8.4608	951.73	2965.5	3274.8	7.9965
600	1341.2	3300.8	3703.2	8.5898	1023.50	3046.9	3379.5	8.1465
650	1418.5	3388.7	3814.2	8.7135	1095.00	3129.8	3485.7	8.2885
	P = 350 kPa T_{sat} = 138.87 °C				P = 375 kPa, T_{sat} = 141.31 °C			
Sat liq	1.079	583.9	584.3	1.7273	1.081	594.3	594.7	1.7526
Sat. vap	524.00	2548.2	2731.6	6.9392	491.13	2550.6	2734.7	6.9160
150	540.58	2567.1	2756.3	6.9982	503.29	2565.4	2754.1	6.9624
175	576.90	2608.3	2810.3	7.1222	537.46	2607.1	2808.6	7.0875
200	612.31	2648.6	2863.0	7.2366	570.69	2647.7	2861.7	7.2027
220	640.18	2680.4	2904.5	7.3226	596.81	2679.6	2903.4	7.2891
240	667.75	2712.0	2945.7	7.4045	622.62	2711.3	2944.8	7.3713
260	695.09	2743.4	2986.7	7.4828	648.22	2742.8	2985.9	7.4499
280	722.27	2774.8	3027.6	7.5581	673.64	2774.3	3026.9	7.5254
300	749.33	2806.2	3068.4	7.6307	698.94	2805.7	3067.8	7.5981
325	783.01	2845.6	3119.6	7.7181	730.42	2845.2	3119.1	7.6856
350	816.57	2885.1	3170.9	7.8022	761.79	2884.8	3170.5	7.7698
400	883.45	2965.2	3274.4	7.9619	824.28	2964.9	3274.0	7.9296
450	950.11	3046.6	3379.2	8.1120	886.54	3046.4	3378.8	8.0798
500	1016.60	3129.6	3485.4	8.2540	948.66	3129.4	3485.1	8.2219
550	1083.00	3214.2	3593.3	8.3892	1010.70	3214.0	3593.0	8.3571
	P = 400 kPa T_{sat} = 143.62 °C							
Sat liq	1.084	604.2	604.7	1.7764				
Sat. vap	462.22	2552.7	2737.6	6.8943				

(continued)

Table F4 (continued)

T (°C)	V (cm³/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm³/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
150	470.66	2563.7	2752.0	6.9285				
175	502.93	2605.8	2807.0	7.0548				
200	534.26	2646.7	2860.4	7.1708				
220	558.85	2678.8	2902.3	7.2576				
240	583.14	2710.6	2943.9	7.3402				
260	607.20	2742.2	2985.1	7.4190				
280	631.09	2773.7	3026.2	7.4947				
300	654.85	2805.3	3067.2	7.5675				
325	684.41	2844.8	3118.5	7.6552				
350	713.85	2884.5	3170.0	7.7395				
400	772.50	2964.6	3273.6	7.8994				
450	830.92	3046.2	3378.5	8.0497				
500	889.19	3129.2	3484.9	8.1919				
550	947.35	3213.8	3592.8	8.3271				
	P = 425 kPa, T_{sat} = 145.82 °C				P = 450 kPa, T_{sat} = 147.92 °C			
Sat liq	1.086	613.7	614.1	1.7990	1.088	622.7	623.2	1.8204
Sat. vap	436.61	2554.8	2740.3	6.8739	413.75	2556.7	2742.9	6.8547
150	441.85	2562.0	2749.8	6.8965	416.24	2560.3	2747.7	6.8660
175	472.47	2604.5	2805.3	7.0239	445.38	2603.2	2803.7	6.9946
200	502.12	2645.7	2859.1	7.1407	473.55	2644.7	2857.8	7.1121
220	525.36	2678.0	2901.2	7.2280	495.59	2677.1	2900.2	7.1999
240	548.30	2709.9	2942.9	7.3108	517.33	2709.2	2942.0	7.2831
260	571.01	2741.6	2984.3	7.3899	538.83	2741.0	2983.5	7.3624
280	593.54	2773.2	3025.5	7.4657	560.17	2772.7	3024.8	7.4384
300	615.95	2804.8	3066.6	7.5388	581.37	2804.4	3066.0	7.5116
325	643.81	2844.4	3118.0	7.6265	607.73	2844.0	3117.5	7.5995
350	671.56	2884.1	3169.5	7.7109	633.97	2883.8	3169.1	7.6840
400	726.81	2964.4	3273.3	7.8710	686.20	2964.1	3272.9	7.8442
450	781.84	3045.9	3378.2	8.0214	738.21	3045.7	3377.9	7.9947
500	836.72	3129.0	3484.6	8.1636	790.07	3128.8	3484.3	8.1370
550	891.49	3213.7	3592.5	8.2989	841.83	3213.5	3592.3	8.2723
	P = 475 kPa, T_{sat} = 149.92 °C				P = 500 kPa T_{sat} = 151.84 °C			
Sat liq	1.091	631.3	631.8	1.8408	1.093	639.6	640.1	1.8604
Sat. vap	393.22	2558.5	2745.3	6.8365	374.68	2560.2	2747.5	6.8192
175	421.14	2601.9	2802.0	6.9667	399.31	2600.6	2800.3	6.9400
200	447.97	2643.7	2856.5	7.0850	424.96	2642.7	2855.1	7.0592
220	468.95	2676.3	2899.1	7.1732	444.97	2675.5	2896.0	7.1478
240	489.62	2708.5	2941.1	7.2567	464.67	2707.8	2940.1	7.2317
260	510.05	2740.4	2982.7	7.3363	484.14	2739.8	2981.9	7.3115
280	530.30	2772.2	3024.1	7.4125	503.43	2771.7	3023.4	7.3879
300	550.43	2803.9	3065.4	7.4858	522.58	2803.5	3064.8	7.4614
325	575.44	2843.6	3116.9	7.5739	546.38	2843.2	3116.4	7.5496
350	600.33	2883.4	3168.6	7.6585	570.05	2883.1	3168.1	7.6343

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
400	649.87	2963.8	3272.5	7.8189	617.16	2963.5	3272.1	7.7948
450	699.18	3045.4	3377.6	7.9694	664.05	3045.2	3377.2	7.9454
500	748.34	3128.6	3484.0	8.1118	710.78	3128.4	3483.8	8.0879
550	797.40	3213.3	3592.1	8.2472	757.41	3213.1	3591.8	8.2233
600	846.37	3299.7	3701.7	8.3765	803.95	3299.5	3701.5	8.3526
650	895.27	3387.7	3813.0	8.5004	850.42	3387.6	3812.8	8.4766
	P = 525 kPa, T_{sat} = 153.69 °C				P = 550 kPa, T_{sat} = 155.47 °C			
Sat liq	1.095	647.5	648.1	1.8790	1.097	655.2	655.8	1.8970
Sat. vap	357.84	2561.8	2749.7	6.8027	342.48	2563.3	2751.7	6.7870
175	379.56	2599.3	2798.6	6.9145	361.60	2598.0	2796.8	6.8900
200	404.13	2641.6	2853.8	7.0345	385.19	2640.6	2852.5	7.0108
220	423.28	2674.6	2896.8	7.1236	403.55	2673.8	2895.7	7.1004
240	442.11	2707.1	2939.2	7.2078	421.59	2706.4	2938.3	7.1849
260	460.70	2739.2	2981.1	7.2879	439.38	2738.6	2980.3	7.2653
280	479.11	2771.2	3022.7	7.3645	457.00	2770.6	3022.0	7.3421
300	497.38	2803.0	3064.1	7.4381	474.48	2802.6	3063.5	7.4158
325	520.08	2842.8	3115.9	7.5264	496.18	2842.4	3115.3	7.5043
350	542.66	2882.7	3167.6	7.6112	517.76	2882.4	3167.2	7.5892
400	587.58	2963.2	3271.7	7.7719	560.68	2963.0	3271.3	7.7500
450	632.26	3045.0	3376.9	7.9226	603.37	3044.7	3376.6	7.9008
500	676.80	3128.2	3483.5	8.0651	645.91	3128.0	3483.2	8.0433
550	721.23	3213.0	3591.6	8.2006	688.34	3212.8	3591.4	8.1789
600	765.57	3299.4	3701.3	8.3299	730.68	3299.2	3701.1	8.3083
	P = 575 kPa, T_{sat} = 157.18 °C				P = 600 kPa, T_{sat} = 158.84 °C			
Sat liq	1.099	662.6	663.2	1.9142	1.101	669.8	670.4	1.9308
Sat. vap	328.41	2584.8	2753.6	6.7720	315.47	2566.2	2755.5	6.7575
175	345.20	2596.6	2795.1	6.8664	330.16	2595.3	2793.3	6.8437
200	367.90	2639.6	2851.1	6.9880	352.04	2638.5	2849.7	6.9662
220	385.54	2672.9	2894.6	7.0781	369.03	2672.1	2893.5	7.0567
240	402.85	2705.7	2937.3	7.1630	385.68	2705.0	2936.4	7.1419
260	419.92	2738.0	2979.5	7.2436	402.08	2737.4	2978.7	7.2228
280	436.81	2770.1	3021.3	7.3206	418.31	2769.6	3020.6	7.3000
300	453.56	2802.1	3062.9	7.3945	434.39	2801.6	3062.3	7.3740
325	474.36	2842.0	3114.8	7.4831	454.35	2841.6	3114.3	7.4628
350	495.03	2882.1	3166.7	7.5681	474.19	2881.7	3166.2	7.5479
400	536.12	2962.7	3271.0	7.7290	513.61	2962.4	3270.6	7.7090
450	576.98	3044.5	3376.3	7.8799	552.80	3044.3	3376.0	7.8600
500	617.70	3127.8	3482.9	8.0226	591.84	3127.6	3482.7	8.0027
550	658.30	3212.6	3591.1	8.1581	630.78	3212.4	3590.9	8.1383
600	698.83	3299.1	3700.9	8.2876	669.63	3298.9	3700.7	8.2678
	P = 625 kPa, T_{sat} = 160.44 °C				P = 650 kPa, T_{sat} = 161.99 °C			
Sat liq	1.103	676.7	677.4	1.9469	1.105	683.4	684.1	1.9623
Sat. vap	303.54	2567.5	2757.2	6.7437	292.49	2568.7	2758.9	6.7304

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
175	316.31	2593.9	2791.6	6.8217	303.53	2592.5	2789.8	6.8004
200	337.45	2637.5	2848.4	6.9451	323.98	2636.4	2847.0	6.9247
220	353.83	2671.2	2892.3	7.0361	339.80	2670.3	2891.2	7.0162
240	369.87	2704.2	2935.4	7.1217	355.29	2703.5	2934.4	7.1021
260	385.67	2736.8	2977.8	7.2028	370.52	2736.2	2977.0	7.1835
280	401.28	2769.1	3019.9	7.2802	385.56	2768.5	3019.2	7.2611
300	416.75	2801.2	3061.7	7.3544	400.47	2800.7	3061.0	7.3355
325	435.94	2841.2	3113.7	7.4433	418.95	2840.9	3113.2	7.4245
350	455.01	2881.4	3165.7	7.5285	437.31	2881.0	3165.3	7.5099
400	492.89	2962.1	3270.2	7.6897	473.78	2961.8	3269.8	7.6712
450	530.55	3044.0	3375.6	7.8408	510.01	3043.8	3375.3	7.8224
500	568.05	3127.4	3482.4	7.9836	546.10	3127.2	3482.1	7.9652
550	605.45	3212.2	3590.7	8.1192	582.07	3212.1	3590.4	8.1009
600	642.76	3298.8	3700.5	8.2488	617.96	3298.6	3700.3	8.2305
	P = 675 kPa, T_{sat} = 163.49 °C				P = 700 kPa, T_{sat} = 164.96 °C			
Sat liq	1.106	689.9	690.7	1.9773	1.108	696.3	697.1	1.9918
Sat. vap	282.23	2570.0	2760.5	6.7176	272.68	2571.1	2762.0	6.7052
175	291.69	2591.1	2788.0	6.7798	280.89	2589.7	2786.2	6.7598
200	311.51	2635.4	2845.6	6.9050	299.92	2634.3	2844.2	6.8859
220	326.81	2669.5	2890.1	6.9970	314.75	2668.6	2888.9	6.9784
240	341.78	2702.8	2933.5	7.0833	329.23	2702.1	2932.5	7.0651
260	356.49	2735.6	2976.2	7.1650	343.46	2735.0	2975.4	7.1470
280	371.01	2768.0	3018.5	7.2428	357.50	2767.5	3017.7	7.2250
300	385.39	2800.3	3060.4	7.3173	371.39	2799.8	3059.8	7.2997
325	403.22	2840.5	3112.6	7.4064	388.61	2840.1	3112.1	7.3890
350	420.92	2880.7	3164.8	7.4919	405.71	2880.3	3164.3	7.4745
400	456.07	2961.6	3269.4	7.6534	439.64	2961.3	3269.0	7.6362
450	491.00	3043.6	3375.0	7.8046	473.34	3043.3	3374.7	7.7875
500	525.77	3127.0	3481.8	7.9475	506.89	3126.8	3481.6	7.9305
550	560.43	3211.9	3590.2	8.0833	540.33	3211.7	3589.9	8.0663
600	595.00	3298.5	3700.1	8.2129	573.68	3298.3	3699.9	8.1959
	P = 725 kPa, T_{sat} = 166.38 °C							
Sat liq	1.110	702.5	703.3	2.0059				
Sat. vap	263.77	2572.2	2763.4	6.6932				
175	270.45	2588.3	2784.4	6.7404				
200	289.13	2633.2	2842.8	6.8673				
220	303.51	2667.7	2887.7	6.9604				
240	317.55	2701.3	2931.5	7.0474				
260	331.33	2734.3	2974.6	7.1296				
280	344.92	2767.0	3017.0	7.2078				
300	358.36	2799.3	3059.1	7.2827				
325	375.01	2839.7	3111.5	7.3721				
350	391.54	2880.0	3163.8	7.4578				

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
400	424.33	2961.0	3268.7	7.6196				
450	456.90	3043.1	3374.3	7.7710				
500	489.31	3126.6	3481.3	7.9140				
550	521.61	3211.5	3589.7	8.0499				
600	553.83	3298.1	3699.7	8.1796				
	P = 750 kPa, T_{sat} = 167.76 °C				P = 775 kPa, T_{sat} = 169.10 °C			
Sat liq	1.112	708.5	709.3	2.0195	1.113	714.3	715.2	2.0328
Sat. vap	255.43	2573.3	2764.8	6.6817	247.61	2574.3	2766.2	6.6705
175	260.88	2586.9	2782.5	6.7215	251.93	2585.4	2780.7	6.7031
200	279.05	2632.1	2841.4	6.8494	269.63	2631.0	2840.0	6.8319
220	293.03	2666.8	2886.6	6.9429	283.22	2665.9	2885.4	6.9259
240	306.65	2700.6	2930.6	7.0303	296.45	2699.8	2929.6	7.0137
260	320.01	2733.7	2973.7	7.1128	309.41	2733.1	2972.9	7.0965
280	333.17	2766.4	3016.3	7.1912	322.19	2765.9	3015.6	7.1751
300	346.19	2798.9	3058.5	7.2662	334.81	2798.4	3057.9	7.2502
325	362.32	2839.3	3111.0	7.3558	350.44	2838.9	3110.5	7.3400
350	378.31	2879.6	3163.4	7.4416	365.94	2879.3	3162.9	7.4259
375	394.22	2920.1	3215.7	7.5240	381.35	2919.8	3215.3	7.5084
400	410.05	2960.7	3268.3	7.6035	396.69	2960.4	3267.9	7.5880
450	441.55	3042.9	3374.0	7.7550	427.20	3042.6	3373.7	7.7396
500	472.90	3126.3	3481.0	7.8981	457.56	3126.1	3480.8	7.8827
550	504.15	3211.4	3589.5	8.0340	487.81	3211.2	3589.2	8.0187
	P = 800 kPa, T_{sat} = 170.4 °C				P = 825 kPa, T_{sat} = 171.69 °C			
Sat liq	1.115	720.0	720.9	2.0457	1.117	725.6	726.5	2.0583
Sat. vap	240.26	2575.3	2767.5	6.6596	233.34	2576.2	2768.7	6.6491
175	243.53	2584.0	2778.8	6.6851	235.64	2582.5	2776.9	6.6675
200	260.79	2629.9	2838.6	6.8148	252.48	2628.8	2837.1	6.7982
220	274.02	2665.0	2884.2	6.9094	265.37	2664.1	2883.1	6.8933
240	286.88	2699.1	2928.6	6.9976	277.90	2698.4	2927.6	6.9819
260	299.48	2732.5	2972.1	7.0807	290.15	2731.8	2971.2	7.0653
280	311.89	2765.4	3014.9	7.1595	302.21	2764.8	3014.1	7.1443
300	324.14	2797.9	3057.3	7.2348	314.12	2797.5	3056.6	7.2197
325	339.31	2838.5	3109.9	7.3247	328.85	2838.1	3109.4	7.3098
350	354.34	2878.9	3162.4	7.4107	343.45	2878.6	3161.9	7.3959
375	369.29	2919.5	3214.9	7.4932	357.96	2919.1	3214.5	7.4786
400	384.16	2960.2	3267.5	7.5729	372.39	2959.9	3267.1	7.5583
450	413.74	3042.4	3373.4	7.7246	401.10	3042.2	3373.1	7.7101
500	443.17	3125.9	3480.5	7.8678	429.65	3125.7	3480.2	7.8533
550	472.49	3211.0	3589.0	8.0038	458.10	3210.8	3588.8	7.9894
	P = 850 kPa, T_{sat} = 172.94 °C				P = 875 kPa, T_{sat} = 174.16 °C			
Sat liq	1.118	731.1	732.0	2.0705	1.120	736.4	737.4	2.0825
Sat. vap	226.81	2577.1	2769.9	6.6388	220.65	2578.0	2771.0	6.6289

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
175	228.21	2581.1	2775.1	6.6504	221.20	2579.6	2773.1	6.6336
200	244.66	2627.7	2835.7	6.7820	237.29	2626.6	2834.2	6.7662
220	257.24	2663.2	2881.9	6.8777	249.56	2662.3	2880.7	6.8624
240	269.44	2697.6	2926.6	6.9666	261.46	2696.8	2925.6	6.9518
260	281.37	2731.2	2970.4	7.0503	273.09	2730.6	2969.5	7.0357
280	293.10	2764.3	3013.4	7.1295	284.51	2763.7	3012.7	7.1152
300	304.68	2797.0	3056.0	7.2051	295.79	2796.5	3055.3	7.1909
325	319.00	2837.7	3108.8	7.2954	309.72	2837.3	3108.3	7.2813
350	333.20	2878.2	3161.4	7.3815	323.53	2877.9	3161.0	7.3676
375	347.29	2918.8	3214.0	7.4643	337.24	2918.5	3213.6	7.4504
400	361.31	2959.6	3266.7	7.5441	350.87	2959.3	3266.3	7.5303
450	389.20	3041.9	3372.7	7.6960	377.98	3041.7	3372.4	7.6823
500	416.93	3125.5	3479.9	7.8393	404.94	3125.3	3479.7	7.8257
550	444.56	3210.7	3588.5	7.9754	431.79	3210.5	3588.3	7.9618
	P = 900 kPa, T_{sat} = 175.36 °C				P = 925 kPa, T_{sat} = 176.53 °C			
Sat liq	1.121	741.6	742.6	2.0941	1.123	746.8	747.8	2.1055
Sat. vap	214.81	2578.8	2772.1	6.6192	209.28	2579.6	2773.2	6.6097
200	230.32	2625.5	2832.7	6.7508	223.73	2624.3	2831.3	6.7357
220	242.31	2661.4	2879.5	6.8475	235.46	2660.5	2878.3	6.8329
240	253.93	2696.1	2924.6	6.9373	246.80	2695.3	2923.6	6.9231
260	265.27	2729.9	2968.7	7.0215	257.87	2729.3	2967.8	7.0076
280	276.40	2763.2	3012.0	7.1012	268.73	2762.6	3011.2	7.0875
300	287.39	2796.1	3054.7	7.1771	279.44	2795.6	3054.1	7.1636
325	300.96	2836.9	3107.7	7.2676	292.66	2836.5	3107.2	7.2543
350	314.40	2877.5	3160.5	7.3540	305.76	2877.2	3160.2	7.3408
375	327.74	2918.2	3213.2	7.4370	318.75	2917.9	3212.7	7.4238
400	341.01	2959.0	3266.0	7.5169	331.68	2958.8	3265.6	7.5038
450	367.39	3041.4	3372.1	7.6689	357.36	3041.2	3371.8	7.6560
500	393.61	3125.1	3479.4	7.8124	382.90	3124.9	3479.1	7.7995
550	419.73	3210.3	3588.1	7.9486	408.32	3210.1	3587.8	7.9357
600	445.76	3297.1	3698.2	8.0785	433.66	3296.9	3698.0	8.0657
	P = 950 kPa, T_{sat} = 177.67 °C				P = 975 kPa, T_{sat} = 178.79 °C			
Sat liq	1.124	751.8	752.8	2.1166	1.126	756.7	757.8	2.1275
Sat. vap	204.03	2580.4	2774.2	6.6005	199.04	2581.1	2775.2	6.5916
200	217.48	2623.2	2829.8	6.7209	211.55	2622.0	2828.3	6.7064
220	228.96	2659.5	2877.0	6.8187	222.79	2658.6	2875.8	6.8048
240	240.05	2694.6	2922.6	6.9093	233.64	2693.8	2921.6	6.8958
260	250.86	2728.7	2967.0	6.9941	244.20	2728.0	2966.1	6.9809
280	261.46	2762.1	3010.5	7.0742	254.56	2761.5	3009.7	7.0612
300	271.91	2795.1	3053.4	7.1505	264.76	2794.6	3052.8	7.1377
325	284.81	2836.0	3106.6	7.2413	277.35	2835.6	3106.1	7.2286
350	297.57	2876.8	3159.5	7.3279	289.81	2876.5	3159.0	7.3154
375	310.24	2917.6	3212.3	7.4110	302.17	2917.3	3211.9	7.3986

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
400	322.84	2958.5	3265.2	7.4911	314.45	2958.2	3264.8	7.4787
450	347.87	3041.0	3371.5	7.6433	338.86	3040.7	3371.1	7.6310
500	372.74	3124.7	3478.8	7.7869	363.11	3124.5	3478.6	7.7747
550	397.51	3209.9	3587.6	7.9232	387.26	3209.8	3587.3	7.9110
600	422.19	3296.7	3697.8	8.0532	411.32	3296.6	3697.6	8.0410
	P = 1000 kPa, T_{sat} = 179.88 °C				P = 1050 kPa, T_{sat} = 182.02 °C			
Sat liq	1.127	761.5	762.6	2.1382	1.130	770.8	772.0	2.1588
Sat. vap	194.29	2581.9	2776.2	6.5828	185.45	2583.3	2778.0	6.5659
200	205.92	2620.9	2826.8	6.6922	195.45	2618.5	2823.8	6.6645
220	216.93	2657.7	2874.6	6.7911	206.04	2655.8	2872.1	6.7647
240	227.55	2693.0	2920.6	6.8825	216.24	2691.5	2918.5	6.8569
260	237.89	2727.4	2965.2	6.9680	226.15	2726.1	2963.5	6.9430
280	248.01	2761.0	3009.0	7.0485	235.84	2759.9	3007.5	7.0240
300	257.98	2794.2	3052.1	7.1251	245.37	2793.2	3050.8	7.1009
325	270.27	2835.2	3105.5	7.2163	257.12	2834.4	3104.4	7.1924
350	282.43	2876.1	3158.5	7.3031	268.74	2875.4	3157.6	7.2795
375	294.50	2917.0	3211.5	7.3864	280.25	2916.3	3210.6	7.3629
400	306.49	2957.9	3264.4	7.4665	291.69	2957.4	3263.6	7.4432
450	330.30	3040.5	3370.8	7.6190	314.41	3040.0	3370.2	7.5958
500	353.96	3124.3	3478.3	7.7627	336.97	3123.9	3477.7	7.7397
550	377.52	3209.6	3587.1	7.8991	359.43	3209.2	3586.6	7.8762
600	400.98	3296.4	3697.4	8.0292	381.79	3296.1	3697.0	8.0063
	P = 1100 kPa, T_{sat} = 184.07 °C				P = 1150 kPa, T_{sat} = 186.05 °C			
Sat liq	1.133	779.9	781.1	2.1786	1.136	788.6	789.9	2.1977
Sat. vap	177.38	2584.5	2779.7	6.5497	169.99	2585.8	2781.3	6.5342
200	185.92	2616.2	2820.7	6.6379	177.22	2613.8	2817.6	6.6122
220	196.14	2653.9	2869.6	6.7392	187.10	2651.9	2867.1	6.7147
240	205.96	2689.9	2916.4	6.8323	196.56	2688.3	2914.4	6.8066
260	215.47	2724.7	2961.8	6.9190	205.73	2723.4	2960.0	6.8959
280	224.77	2758.8	3006.0	7.0005	214.67	2757.7	3004.5	6.9779
300	233.91	2792.2	3049.6	7.0778	223.44	2791.3	3048.2	7.0556
325	245.16	2833.6	3103.3	7.1695	234.25	2832.8	3102.2	7.1476
350	256.28	2874.7	3156.6	7.2569	244.91	2874.0	3155.6	7.2352
375	267.30	2915.7	3209.7	7.3405	255.47	2915.1	3208.9	7.3190
400	278.24	2956.8	3262.9	7.4209	265.96	2956.2	3262.1	7.3995
450	299.96	3039.6	3369.5	7.5737	286.77	3039.1	3368.9	7.5525
500	321.53	3123.5	3477.2	7.7177	307.42	3123.1	3476.6	7.6966
550	342.98	3208.9	3586.2	7.8543	327.97	3208.5	3585.7	7.8333
600	364.35	3295.8	3696.6	7.9845	348.42	3295.5	3696.2	7.9636
	P = 1200 kPa, T_{sat} = 187.96 °C				P = 1250 kPa, T_{sat} = 189.81 °C			
Sat liq	1.139	797.1	798.4	2.2161	1.141	805.3	806.7	2.2338
Sat. vap	163.20	2586.9	2782.7	6.5194	156.93	2588.0	2784.1	6.5050

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
200	169.23	2611.3	2814.4	6.5872	161.88	2608.9	2811.2	6.5630
220	178.80	2650.0	2864.5	6.6909	171.17	2648.0	2861.9	6.6680
240	187.95	2686.7	2912.2	6.7858	180.02	2685.1	2910.1	6.7637
260	196.79	2722.1	2958.2	6.8738	188.56	2720.8	2956.5	6.8523
280	205.40	2756.5	3003.0	6.9562	196.88	2755.4	3001.5	6.9353
300	213.85	2790.3	3046.9	7.0342	205.02	2789.3	3045.6	7.0136
325	224.24	2832.0	3101.0	7.1266	215.03	2831.1	3099.9	7.1064
350	234.49	2873.3	3154.6	7.2144	224.90	2872.5	3153.7	7.1944
375	244.63	2914.4	3208.0	7.2983	234.66	2913.8	3207.1	7.2785
400	254.70	2955.7	3261.3	7.3790	244.35	2955.1	3260.5	7.3593
450	274.68	3038.6	3368.2	7.5323	263.55	3038.1	3367.6	7.5128
500	294.50	3122.7	3476.1	7.6765	282.60	3122.3	3475.5	7.6571
550	314.20	3208.2	3585.2	7.8132	301.54	3207.8	3584.7	7.7940
600	333.82	3295.2	3695.8	7.9436	320.39	3294.9	3695.4	7.9244
	P = 1300 kPa, T_{sat} = 191.61 °C							
Sat liq	1.144	813.2	814.7	2.2510				
Sat. vap	151.13	2589.0	2785.4	6.4913				
200	155.09	2606.4	2808.0	6.5394				
220	164.11	2646.0	2859.3	6.6457				
240	172.70	2683.5	2908.0	6.7424				
260	180.97	2719.4	2954.7	6.8316				
280	189.01	2754.3	3000.0	6.9151				
300	196.87	2788.4	3044.3	6.9938				
325	206.53	2830.3	3098.8	7.0869				
350	216.05	2871.8	3152.7	7.1751				
375	225.46	2913.2	3206.3	7.2594				
400	234.79	2954.5	3259.7	7.3404				
450	253.28	3037.7	3366.9	7.4940				
500	271.62	3121.9	3475.0	7.6385				
550	289.85	3207.5	3584.3	7.7754				
600	307.99	3294.6	3695.0	7.9060				
	P = 1350 kPa, T_{sat} = 193.35 °C				P = 1400 kPa, T_{sat} = 195.04 °C			
Sat liq	1.146	820.9	822.5	2.2676	1.149	828.5	830.1	2.2837
Sat. vap	145.74	2589.9	2786.6	6.4780	140.72	2590.8	2787.8	6.4651
200	148.79	2603.9	2804.7	6.5165	142.94	2601.3	2801.4	6.4941
225	159.70	2653.6	2869.2	6.6493	153.57	2651.7	2866.7	6.6285
250	169.96	2700.1	2929.5	6.7675	163.55	2698.6	2927.6	6.7477
275	179.79	2744.4	2987.1	6.8750	173.08	2743.2	2985.5	6.8560
300	189.33	2787.4	3043.0	6.9746	182.32	2786.4	3041.6	6.9561
325	198.66	2829.5	3097.7	7.0681	191.35	2828.6	3096.5	7.0499
350	207.85	2871.1	3151.7	7.1566	200.24	2870.4	3150.7	7.1386
375	216.93	2912.5	3205.4	7.2410	209.02	2911.9	3204.5	7.2233
400	225.94	2953.9	3259.0	7.3221	217.72	2953.4	3258.2	7.3045

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
425	234.88	2995.5	3312.6	7.4003	226.35	2994.9	3311.8	7.3828
450	243.78	3037.2	3366.3	7.4759	234.95	3036.7	3365.6	7.4585
475	252.63	3079.2	3420.2	7.5493	243.50	3078.7	3419.6	7.5319
500	261.46	3121.5	3474.4	7.6205	252.02	3121.1	3473.9	7.6032
550	279.03	3207.1	3583.8	7.7576	268.98	3206.8	3583.3	7.7404
	P = 1450 kPa, T_{sat} = 196.69 °C				P = 1500 kPa, T_{sat} = 198.29 °C			
Sat liq	1.151	835.8	837.5	2.2993	1.154	842.9	844.7	2.3145
Sat. vap	136.04	2591.6	2788.9	6.4526	131.66	2592.4	2789.9	6.4406
200	137.48	2598.7	2798.1	6.4722	132.38	2596.1	2794.7	6.4508
225	147.86	2649.7	2864.1	6.6082	142.53	2647.7	2861.5	6.5885
250	157.57	2697.1	2925.5	6.7286	151.99	2695.5	2923.5	6.7099
275	166.83	2742.0	2983.9	6.8376	161.00	2740.8	2982.3	6.8196
300	175.79	2785.4	3040.3	6.9381	169.70	2784.4	3038.9	6.9207
325	184.54	2827.8	3095.4	7.0322	178.19	2826.9	3094.2	7.0152
350	193.15	2869.7	3149.7	7.1212	186.53	2868.9	3148.7	7.1044
375	201.65	2911.3	3203.6	7.2061	194.77	2910.6	3202.8	7.1894
400	210.06	2952.8	3257.4	7.2874	202.92	2952.2	3256.6	7.2709
425	218.42	2994.4	3311.1	7.3658	211.01	2993.9	3310.4	7.3494
450	226.72	3036.2	3365.0	7.4416	219.05	3035.8	3364.3	7.4253
475	234.99	3078.3	3419.0	7.5151	227.06	3077.9	3418.4	7.4989
500	243.23	3120.7	3473.3	7.5865	235.03	3120.3	3472.8	7.5703
550	259.62	3206.4	3582.9	7.7237	250.89	3206.0	3582.4	7.7077
	P = 1550 kPa, T_{sat} = 199.85 °C				P = 1600 kPa, T_{sat} = 201.37 °C			
Sat liq	1.156	849.9	851.7	2.3292	1.159	856.7	858.6	2.3436
Sat. vap	127.55	2593.2	2790.8	6.4289	123.69	2593.8	2791.7	6.4175
200	127.61	2593.5	2791.3	6.4298	….	…..	….	….
225	137.54	2645.8	2858.9	6.5692	132.85	2643.7	2856.3	6.5503
250	146.77	2694.0	2921.5	6.6917	141.87	2692.4	2919.4	6.6740
275	155.54	2739.5	2980.6	6.8022	150.42	2738.3	2979.0	6.7852
300	164.00	2783.4	3037.6	6.9038	158.66	2782.4	3036.2	6.8873
325	172.25	2826.1	3093.1	6.9986	166.68	2825.2	3091.9	6.9825
350	180.34	2868.2	3147.7	7.0881	174.54	2867.5	3146.7	7.0723
375	188.33	2910.0	3201.9	7.1733	182.30	2909.3	3201.0	7.1577
400	196.24	2951.7	3255.8	7.2550	189.97	2951.1	3255.0	7.2394
425	204.08	2993.4	3309.7	7.3336	197.58	2992.9	3309.0	7.3182
450	211.87	3035.3	3363.7	7.4095	205.15	3034.8	3363.0	7.3942
475	219.63	3077.4	3417.8	7.4832	212.67	3077.0	3417.2	7.4679
500	227.35	3119.8	3472.2	7.5547	220.16	3119.4	3471.7	7.5395
550	242.72	3205.7	3581.9	7.6921	235.06	3205.3	3581.4	7.6770
	P = 1650 kPa, T_{sat} = 202.86 °C				P = 1700 kPa, T_{sat} = 204.31 °C			
Sat liq	1.161	863.4	865.3	2.3576	1.163	869.9	871.8	2.3713
Sat. vap	120.05	2594.5	2792.6	6.4065	116.62	2595.1	2793.4	6.3957

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
225	128.45	2641.7	2853.6	6.5319	124.31	2639.6	2851.0	6.5138
250	137.27	2690.9	2917.4	6.6567	132.94	2689.3	2915.3	6.6398
275	145.61	2737.1	2977.3	6.7687	141.09	2735.8	2975.6	6.7526
300	153.64	2781.3	3034.8	6.8713	148.91	2780.3	3033.5	6.8557
325	161.44	2824.4	3090.8	6.9669	156.51	2823.5	3089.6	6.9516
350	169.09	2866.7	3145.7	7.0569	163.96	2866.0	3144.7	7.0419
375	176.63	2908.7	3200.1	7.1425	171.30	2908.0	3199.2	7.1277
400	184.09	2950.5	3254.2	7.2244	178.55	2949.9	3253.5	7.2098
425	191.48	2992.3	3308.3	7.3032	185.74	2991.8	3307.6	7.2887
450	198.82	3034.3	3362.4	7.3794	192.87	3033.9	3361.7	7.3649
475	206.13	3076.5	3416.7	7.4531	199.97	3076.1	3416.1	7.4388
500	213.40	3119.0	3471.1	7.5248	207.04	3118.6	3470.6	7.5105
550	227.86	3205.0	3581.0	7.6624	221.09	3204.6	3580.5	7.6482
600	242.24	3292.4	3692.1	7.7934	235.06	3292.1	3691.7	7.7793
	P = 1750 kPa, T_{sat} = 205.72 °C				P = 1800 kPa, T_{sat} = 207.11 °C			
Sat liq	1.166	876.2	878.3	2.3846	1.168	882.5	884.6	2.3976
Sat. vap	113.38	2595.7	2794.1	6.3853	110.32	2596.3	2794.8	6.3751
225	120.39	2637.6	2848.2	6.4961	116.69	2635.5	2845.5	6.4787
250	128.85	2687.7	2913.2	6.6233	124.99	2686.1	2911.0	6.6071
275	136.82	2734.5	2974.0	6.7368	132.78	2733.3	2972.3	6.7214
300	144.45	2779.3	3032.1	6.8405	140.24	2778.2	3030.7	6.8257
325	151.87	2822.7	3088.4	6.9368	147.48	2821.8	3087.3	6.9223
350	159.12	2865.3	3143.7	7.0273	154.55	2864.5	3142.7	7.0131
375	166.27	2907.4	3198.4	7.1133	161.51	2906.7	3197.5	7.0993
400	173.32	2949.3	3252.7	7.1955	168.39	2948.8	3251.9	7.1816
425	180.32	2991.3	3306.9	7.2746	175.20	2990.8	3306.1	7.2608
450	187.26	3033.4	3361.1	7.3509	181.97	3032.9	3360.4	7.3372
475	194.17	3075.7	3415.5	7.4248	188.69	3075.2	3414.9	7.4112
500	201.04	3118.2	3470.0	7.4965	195.38	3117.8	3469.5	7.4830
550	214.71	3204.3	3580.0	7.6344	208.68	3203.9	3579.5	7.6209
600	228.28	3291.8	3691.3	7.7656	221.89	3291.5	3690.9	7.7522
	P = 1850 kPa, T_{sat} = 208.47 °C				P = 1900 kPa, T_{sat} = 209.80 °C			
Sat liq	1.170	888.6	890.8	2.4103	1.172	894.6	896.8	2.4228
Sat. vap	107.41	2596.8	2795.5	6.3651	104.65	2597.3	2796.1	6.3554
225	113.19	2633.3	2842.8	6.4616	109.87	2631.2	2840.0	6.4448
250	121.33	2684.4	2908.9	6.5912	117.87	2682.8	2906.7	6.5757
275	128.96	2732.0	2970.6	6.7064	125.35	2730.7	2968.8	6.6917
300	136.26	2777.2	3029.3	6.8112	132.49	2776.2	3027.9	6.7970
325	143.33	2820.9	3086.1	6.9082	139.39	2820.1	3084.9	6.8944
350	150.23	2863.8	3141.7	6.9993	146.14	2863.0	3140.7	6.9857
375	157.02	2906.1	3196.6	7.0856	152.76	2905.4	3195.7	7.0723
400	163.73	2948.2	3251.1	7.1681	159.30	2947.6	3250.3	7.1550
425	170.37	2990.3	3305.4	7.2474	165.78	2989.7	3304.7	7.2344

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
450	176.96	3032.4	3359.8	7.3239	172.21	3031.9	3359.1	7.3109
475	183.50	3074.8	3414.3	7.3980	178.59	3074.3	3413.7	7.3851
500	190.02	3117.4	3468.9	7.4698	184.94	3117.0	3468.4	7.4570
550	202.97	3203.6	3579.1	7.6079	197.57	3203.2	3578.6	7.5951
600	215.84	3291.1	3690.4	7.7392	210.11	3290.8	3690.0	7.7265
	P = 1950 kPa, T_{sat} = 211.10 °C				P = 2000 kPa, T_{sat} = 212.37 °C			
Sat liq	1.174	900.5	902.8	2.4349	1.177	906.2	908.6	2.4469
Sat. vap	102.03	2597.7	2796.7	6.3459	99.54	2598.2	2797.2	6.3366
225	106.72	2629.0	2837.1	6.4283	103.72	2626.9	2834.3	6.4120
250	114.58	2681.1	2904.6	6.5604	111.45	2679.5	2902.4	6.5454
275	121.91	2729.4	2967.1	6.6772	118.65	2728.1	2965.4	6.6631
300	128.90	2775.1	3026.5	6.7831	125.50	2774.0	3025.0	6.7696
325	135.66	2819.2	3083.7	6.8809	132.11	2818.3	3082.5	6.8677
350	142.25	2862.3	3139.7	6.9725	138.56	2861.5	3138.6	6.9596
375	148.72	2904.8	3194.8	7.0593	144.89	2904.1	3193.9	7.0466
400	155.11	2947.0	3249.5	7.1421	151.13	2946.4	3248.7	7.1296
425	161.43	2989.2	3304.0	7.2216	157.30	2988.7	3303.3	7.2092
450	167.70	3031.5	3358.5	7.2983	163.42	3031.0	3357.8	7.2859
475	173.93	3073.9	3413.1	7.3725	169.51	3073.5	3412.5	7.3602
500	180.13	3116.6	3467.8	7.4445	175.55	3116.2	3467.3	7.4323
550	192.44	3202.9	3578.1	7.5827	187.57	3202.5	3577.6	7.5706
600	204.67	3290.5	3689.6	7.7142	199.50	3290.2	3689.2	7.7022
	P = 2100 kPa, T_{sat} = 214.85 °C				P = 2200 kPa, T_{sat} = 217.24 °C			
Sat liq	1.181	917.5	920.0	2.4700	1.185	928.3	931.0	2.4922
Sat. vap	94.89	2598.9	2798.2	6.3187	90.65	2599.6	2799.1	6.3015
225	98.15	2622.4	2828.5	6.3802	93.07	2617.9	2822.7	6.3492
250	105.64	2676.1	2897.9	6.5162	100.35	2672.7	2893.4	6.4879
275	112.59	2725.4	2961.9	6.6356	107.07	2722.7	2958.3	6.6091
300	119.18	2771.9	3022.2	6.7432	113.43	2769.7	3019.3	6.7179
325	125.53	2816.5	3080.1	6.8422	119.53	2814.7	3077.7	6.8177
350	131.70	2860.0	3136.6	6.9347	125.47	2858.5	3134.5	6.9107
375	137.76	2902.8	3192.1	7.0220	131.28	2901.5	3190.3	6.9985
400	143.73	2945.3	3247.1	7.1053	137.00	2944.1	3245.5	7.0821
425	149.63	2987.6	3301.8	7.1851	142.65	2986.6	3300.4	7.1621
450	155.48	3030.0	3356.5	7.2621	148.25	3029.1	3355.2	7.2393
475	161.28	3072.6	3411.3	7.3365	153.81	3071.7	3410.1	7.3139
500	167.06	3115.3	3466.2	7.4087	159.34	3114.5	3465.1	7.3862
550	178.53	3201.8	3576.7	7.5472	170.30	3201.1	3575.7	7.5249
600	189.91	3289.6	3688.4	7.6789	181.19	3289.0	3687.6	7.6568
	P = 2300 kPa, T_{sat} = 219.55 °C							
Sat liq	1.189	938.9	941.6	2.5136				
Sat. vap	86.77	2600.2	2799.8	6.2849				

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
225	88.42	2613.3	2816.7	6.3190				
250	95.51	2669.2	2888.9	6.4605				
275	102.03	2720.0	2954.7	6.5835				
300	108.18	2767.6	3016.4	6.6935				
325	114.06	2812.9	3075.3	6.7941				
350	119.77	2857.0	3132.4	6.8877				
375	125.36	2900.2	3188.5	6.9759				
400	130.85	2942.9	3243.9	7.0598				
425	136.28	2985.5	3299.0	7.1401				
450	141.65	3028.1	3353.9	7.2174				
475	146.99	3070.8	3408.9	7.2922				
500	152.28	3113.7	3464.0	7.3646				
550	162.80	3200.4	3574.8	7.5035				
600	173.22	3288.3	3686.7	7.6355				
	P = 2400 kPa, T_{sat} = 221.78 °C				P = 2500 kPa, T_{sat} = 223.94 °C			
Sat liq	1.193	949.1	951.9	2.5343	1.197	959.0	962.0	2.5543
Sat. vap	83.20	2600.7	2800.4	6.2690	79.91	2601.2	2800.9	6.2536
225	84.15	2608.6	2810.6	6.2894	80.21	2603.8	2804.3	6.2604
250	91.08	2665.6	2884.2	6.4338	86.99	2662.0	2879.5	6.4077
275	97.41	2717.3	2951.1	6.5586	93.15	2714.5	2947.4	6.5345
300	103.36	2765.4	3013.4	6.6699	98.93	2763.1	3010.4	6.6470
325	109.05	2811.1	3072.8	6.7714	104.43	2809.3	3070.4	6.7494
350	114.55	2855.4	3130.4	6.8656	109.75	2853.9	3128.2	6.8442
375	119.93	2898.8	3186.7	6.9542	114.94	2897.5	3184.8	6.9333
400	125.22	2941.7	3242.3	7.0384	120.04	2940.6	3240.7	7.0178
425	130.44	2984.5	3297.5	7.1189	125.07	2983.4	3296.1	7.0986
450	135.61	3027.1	3352.6	7.1964	130.04	3026.2	3351.3	7.1763
475	140.73	3069.9	3407.7	7.2713	134.97	3069.0	3406.5	7.2513
500	145.82	3112.9	3462.9	7.3439	139.87	3112.1	3461.7	7.3240
525	150.88	3156.1	3518.2	7.4144	144.74	3155.4	3517.2	7.3946
550	155.91	3199.6	3573.8	7.4830	149.58	3198.9	3572.9	7.4633
	P = 2600 kPa, T_{sat} = 226.04 °C				P = 2700 kPa, T_{sat} = 228.07 °C			
Sat liq	1.201	968.6	971.7	2.5736	1.205	978.0	981.2	2.5924
Sat. vap	76.86	2601.5	2801.4	6.2387	74.03	2601.8	2801.7	6.2244
250	83.21	2658.4	2874.7	6.3823	79.70	2654.7	2869.9	6.3575
275	89.22	2711.7	2943.6	6.5110	85.58	2708.8	2939.8	6.4882
300	94.83	2760.9	3007.4	6.6249	91.04	2758.6	3004.4	6.6034
325	100.17	2807.4	3067.9	6.7281	96.22	2805.6	3065.4	6.7075
350	105.32	2852.3	3126.1	6.8236	101.21	2850.7	3124.0	6.8036
375	110.33	2896.1	3183.0	6.9131	106.07	2894.8	3181.2	6.8935
400	115.26	2939.4	3239.0	6.9979	110.83	2938.2	3237.4	6.9787
425	120.11	2982.3	3294.6	7.0789	115.52	2981.2	3293.1	7.0600
450	124.91	3025.2	3349.9	7.1568	120.15	3024.2	3348.6	7.1381

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
475	129.66	3068.1	3405.3	7.2320	124.74	3067.2	3404.0	7.2134
500	134.38	3111.2	3460.6	7.3048	129.30	3110.4	3459.5	7.2863
525	139.07	3154.6	3516.2	7.3755	133.82	3153.8	3515.2	7.3571
550	143.74	3198.2	3571.9	7.4443	138.33	3197.5	3571.0	7.4260
600	153.01	3286.5	3684.3	7.5768	147.27	3285.8	3683.5	7.5587
	P = 2800 kPa, T_{sat} = 230.05 °C				P = 2900 kPa, T_{sat} = 231.97 °C			
Sat liq	1.209	987.1	990.5	2.6106	1.213	996.0	999.5	2.6283
Sat. vap	71.39	2602.1	2802.0	6.2104	68.93	2602.3	2802.2	6.1969
250	76.44	2650.9	2864.9	6.3331	73.40	2647.1	2859.9	6.3092
275	82.19	2705.9	2936.0	6.4659	79.03	2702.9	2932.1	6.4441
300	87.51	2756.3	3001.3	6.5824	84.23	2754.0	2998.2	6.5621
325	92.55	2803.7	3062.8	6.6875	89.13	2801.8	3060.3	6.6681
350	97.40	2849.2	3121.9	6.7842	93.84	2847.6	3119.7	6.7654
375	102.10	2893.4	3179.3	6.8746	98.41	2892.0	3177.4	6.8563
400	106.71	2937.0	3235.8	6.9601	102.88	2935.8	3234.1	6.9421
425	111.25	2980.2	3291.7	7.0416	107.28	2979.1	3290.2	7.0239
450	115.74	3023.2	3347.3	7.1199	111.62	3022.3	3346.0	7.1024
475	120.17	3066.3	3402.8	7.1954	115.92	3065.5	3401.6	7.1780
500	124.58	3109.6	3458.4	7.2685	120.18	3108.8	3457.3	7.2512
525	128.95	3153.1	3514.1	7.3394	124.42	3152.3	3513.1	7.3222
550	133.30	3196.8	3570.0	7.4084	128.62	3196.1	3569.1	7.3913
600	141.94	3285.2	3682.6	7.5412	136.97	3284.6	3681.8	7.5243
	P = 3000 kPa, T_{sat} = 233.84 °C				P = 3100 kPa, T_{sat} = 235.67 °C			
Sat liq	1.216	1004.7	1008.4	2.6455	1.220	1013.2	1017.0	2.6623
Sat. vap	66.63	2602.4	2802.3	6.1837	64.47	2602.5	2802.3	6.1709
250	70.55	2643.2	2854.8	6.2857	67.89	2639.2	2849.6	6.2626
275	76.08	2700.0	2928.2	6.4228	73.32	2697.0	2924.2	6.4019
300	81.16	2751.6	2995.1	6.5422	78.29	2749.2	2991.9	6.5227
325	85.94	2799.9	3057.7	6.6491	82.96	2797.9	3055.1	6.6307
350	90.53	2846.0	3117.5	6.7471	87.42	2844.3	3115.4	6.7294
375	94.97	2890.7	3175.6	6.8385	91.75	2889.3	3173.7	6.8212
400	99.31	2934.6	3232.5	6.9246	95.97	2933.4	3230.8	6.9077
425	103.58	2978.0	3288.7	7.0067	100.11	2976.9	3287.3	6.9900
450	107.79	3021.3	3344.6	7.0854	104.20	3020.3	3343.3	7.0689
475	111.95	3064.6	3400.4	7.1612	108.24	3063.7	3399.2	7.1448
500	116.08	3107.9	3456.2	7.2345	112.24	3107.1	3455.1	7.2183
525	120.18	3151.5	3512.1	7.3056	116.22	3150.8	3511.0	7.2895
550	124.26	3195.4	3568.1	7.3748	120.17	3194.7	3567.2	7.3588
600	132.34	3284.0	3681.0	7.5079	128.01	3283.3	3680.2	7.4920
	P = 3200 kPa, T_{sat} = 237.45 °C				P = 3300 kPa, T_{sat} = 239.18 °C			
Sat liq	1.224	1021.5	1025.4	2.6786	1.227	1029.7	1033.7	2.6945
Sat. vap	62.44	2602.5	2802.3	6.1585	60.53	2602.5	2802.3	6.1463

(continued)

Table F4 (continued)

T (°C)	V (cm³/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm³/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
250	65.38	2635.2	2844.4	6.2398	63.02	2631.1	2839.0	6.2173
275	70.27	2693.9	2920.2	6.3815	68.28	2690.8	2916.1	6.3614
300	75.59	2746.8	2988.7	6.5037	73.06	2744.4	2985.5	6.4851
325	80.16	2796.0	3052.5	6.6127	77.53	2794.0	3049.9	6.5951
350	84.51	2842.7	3113.2	6.7120	81.78	2841.1	3110.9	6.6952
375	88.72	2887.9	3171.8	6.8043	85.88	2886.5	3169.9	6.7879
400	92.83	2932.1	3229.2	6.8912	89.88	2930.9	3227.5	5.8752
425	96.86	2975.9	3285.8	6.9738	93.81	2974.8	3284.3	6.9580
450	100.83	3019.3	3342.0	7.0528	97.67	3018.3	3340.6	7.0373
475	104.76	3062.8	3398.0	7.1290	101.49	3061.9	3396.8	7.1136
500	108.65	3106.3	3454.0	7.2026	105.27	3105.5	3452.8	7.1873
525	112.51	3150.0	3510.0	7.2739	109.02	3149.2	3509.0	7.2588
550	116.34	3193.9	3566.2	7.3433	112.74	3193.2	3565.3	7.3282
600	123.95	3282.7	3679.3	7.4767	120.13	3282.1	3678.5	7.4618
	P = 3400 kPa, T_{sat} = 240.88 °C				P = 3500 kPa, T_{sat} = 242.54 °C			
Sat liq	1.231	1037.6	1041.8	2.7101	1.235	1045.4	1049.8	2.7253
Sat. vap	58.73	3602.5	2802.1	6.1344	57.03	2602.4	2802.0	6.1228
250	60.80	2626.9	2833.6	6.1951	58.69	2622.7	2828.1	6.1732
275	65.98	2687.7	2912.0	6.3416	63.81	2684.5	2907.8	6.3221
300	70.68	2741.9	2982.2	6.4669	68.42	2739.5	2979.0	6.4491
325	75.05	2792.0	3047.2	6.5779	72.71	2790.0	3044.5	6.5611
350	79.20	2839.4	3108.7	6.6787	76.78	2837.8	3106.5	6.6626
375	83.21	2885.1	3168.0	6.7719	80.69	2883.7	3166.1	6.7563
400	87.11	2929.7	3225.9	6.8595	84.49	2928.4	3224.2	6.8443
425	90.93	2973.7	3282.8	6.9426	88.22	2972.6	3281.3	6.9277
450	94.69	3017.4	3339.3	7.0221	91.89	3016.4	3338.0	7.0074
475	98.41	3061.0	3395.5	7.0986	95.51	3060.1	3394.3	7.0840
500	102.09	3104.6	3451.7	7.1724	99.09	3103.8	3450.6	7.1580
525	105.74	3148.4	3507.9	7.2440	102.64	3147.7	3506.9	7.2297
550	109.36	3192.5	3564.3	7.3136	106.17	3191.8	3563.4	7.2993
600	116.54	3281.5	3677.7	7.4473	113.15	3280.8	3676.9	7.4332
	P = 3600 kPa, T_{sat} = 244.16 °C				P = 3700 kPa, T_{sat} = 245.75 °C			
Sat liq	1.238	1053.1	1057.6	2.7401	1.242	1060.6	1065.2	2.7547
Sat. vap	55.415	2602.2	2801.7	6.1115	53.888	2602.1	2801.4	6.1004
250	56.702	2618.4	2822.5	6.1514	54.812	2614.0	2816.8	6.1299
275	61.759	2681.3	2903.6	6.3030	59.814	2678.0	2899.3	6.2841
300	66.297	2737.0	2975.6	6.4315	64.282	2734.4	2972.3	6.4143
325	70.501	2788.0	3041.8	6.5446	68.410	2786.0	3039.1	6.5284
350	74.482	2836.1	3104.2	6.6468	72.311	2834.4	3102.0	6.6314
375	78.308	2882.3	3164.2	6.7411	76.055	2880.8	3162.2	6.7262
400	82.024	2927.2	3222.5	6.8294	79.687	2926.0	3220.8	6.8149
425	85.660	2971.5	3279.8	6.9131	83.238	2970.4	3278.4	6.8989
450	89.236	3015.4	3336.6	6.9930	86.728	3014.4	3335.3	6.9790

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
475	92.764	3059.2	3393.1	7.0698	90.171	3058.2	3391.9	7.0559
500	96.255	3103.0	3449.5	7.1439	93.576	3102.1	3448.4	7.1302
525	99.716	3146.9	3505.9	7.2157	96.950	3146.1	3504.9	7.2021
550	103.150	3191.1	3562.4	7.2854	100.300	3190.4	3561.5	7.2719
600	109.960	3280.2	3676.1	7.4195	106.930	3279.6	3675.2	7.4061
	P = 3800 kPa, T_{sat} = 247.31 °C				P = 3900 kPa, T_{sat} = 248.84 °C			
Sat liq	1.245	1068.0	1072.7	2.7689	1.249	1075.3	1080.1	2.7828
Sat. vap	52.438	2601.9	2801.1	6.0896	51.061	2601.6	2800.8	6.0789
250	53.017	2609.5	2811.0	6.1085	51.308	2605.0	2805.1	6.0872
275	57.968	2674.7	2895.0	6.2654	56.215	2671.4	2890.6	6.2470
300	62.372	2731.9	2968.9	6.3973	60.558	2729.3	2965.5	6.3806
325	66.429	2783.9	3036.4	6.5126	64.547	2781.9	3033.6	6.4970
350	70.254	2832.7	3099.7	6.6163	68.302	2831.0	3097.4	6.6015
375	73.920	2879.4	3160.3	6.7117	71.894	2877.9	3158.3	6.6974
400	77.473	2924.7	3219.1	6.8007	75.372	2923.5	3217.4	6.7868
425	80.944	2969.3	3276.8	6.8849	78.767	2968.2	3275.3	6.8713
450	84.353	3013.4	3333.9	6.9653	82.099	3012.4	3332.6	6.9519
475	87.714	3057.3	3390.7	7.0424	85.383	3056.4	3389.4	7.0292
500	91.038	3101.3	3447.2	7.1168	88.629	3100.5	3446.1	7.1037
525	94.330	3145.4	3503.8	7.1888	91.844	3144.6	3502.8	7.1759
550	97.596	3189.6	3560.5	7.2587	95.033	3188.9	3559.5	7.2459
600	104.060	3279.0	3674.4	7.3931	101.350	3278.3	3673.6	7.3804
	P = 4000 kPa, T_{sat} = 250.33 °C							
Sat liq	1.252	1082.4	1087.4	2.7965				
Sat. vap	49.749	2601.3	2800.3	6.0685				
275	54.546	2668.0	2886.1	6.2288				
300	58.833	2726.7	2962.0	6.3642				
325	62.759	2779.8	3030.8	6.4817				
350	66.446	2829.3	3095.1	6.5870				
375	69.969	2876.5	3156.4	6.6834				
400	73.376	2922.2	3215.7	6.7733				
425	76.698	2967.0	3273.8	6.8581				
450	79.958	3011.4	3331.2	6.9388				
475	83.169	3055.5	3388.2	7.0163				
500	86.341	3099.6	3445.0	7.0909				
525	89.483	3143.8	3501.7	7.1632				
550	92.598	3188.2	3558.6	7.2333				
600	98.763	3277.7	3672.8	7.3680				
650	104.860	3368.4	3787.9	7.4961				
	P = 4100 kPa, T_{sat} = 251.80 °C				P = 4200 kPa, T_{sat} = 253.24 °C			
Sat liq	1.256	1089.4	1094.6	2.8099	1.259	1096.3	1101.6	2.8231
Sat. vap	48.500	2601.0	2799.9	6.0583	47.307	2600.7	2799.4	6.0482

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
260	50.150	2624.6	2830.3	6.1157	48.654	2620.4	2824.8	6.0962
275	52.955	2664.5	2881.6	6.2107	51.438	2661.0	2877.1	6.1929
300	57.191	2724.0	2958.5	6.3480	55.625	2721.4	2955.0	6.3320
325	61.057	2777.7	3028.0	6.4667	59.435	2775.6	3025.2	6.4519
350	64.680	2827.6	3092.8	6.5727	62.998	2825.8	3090.4	6.5587
375	68.137	2875.0	3154.4	6.6697	66.392	2873.6	3152.4	6.6563
400	71.476	2920.9	3214.0	6.7600	69.667	2919.7	3212.3	6.7469
425	74.730	2965.9	3272.3	6.8450	72.856	2964.8	3270.8	6.8323
450	77.921	3010.4	3329.9	6.9260	75.981	3009.4	3328.5	6.9135
475	81.062	3054.6	3387.0	7.0037	79.056	3053.7	3385.7	6.9913
500	84.165	3098.8	3443.9	7.0785	82.092	3097.9	3442.7	7.0662
525	87.236	3143.0	3500.7	7.1508	85.097	3142.3	3499.7	7.1387
550	90.281	3187.5	3557.6	7.2210	88.075	3186.8	3556.7	7.2090
575	93.303	3232.1	3614.7	7.2893	91.030	3231.5	3613.8	7.2774
	P = 4300 kPa, T_{sat} = 254.66 °C				P = 4400 kPa, T_{sat} = 256.05 °C			
Sat liq	1.262	1103.1	1108.5	2.8360	1.266	1109.8	1115.4	2.8487
Sat. vap	46.168	2600.3	2798.9	6.0383	45.079	2599.9	2798.3	6.0286
260	47.223	2616.2	2819.2	6.0768	45.853	2611.8	2813.6	6.0575
275	49.988	2657.5	2872.4	6.1752	48.601	2653.9	2867.8	6.1577
300	54.130	2718.7	2951.4	6.3162	52.702	2716.0	2947.8	6.3006
325	57.887	2773.4	3022.3	6.4373	56.409	2771.3	3019.5	6.4230
350	61.393	2824.1	3088.1	6.5450	59.861	2822.3	3085.7	6.5315
375	64.728	2872.1	3150.4	6.6431	63.139	2870.6	3148.4	6.6301
400	67.942	2918.4	3210.5	6.7341	66.295	2917.1	3208.8	6.7216
425	71.069	2963.7	3269.3	6.8198	69.363	2962.5	3267.7	6.8076
450	74.131	3008.4	3327.1	6.9012	72.365	3007.4	3325.8	6.8892
475	77.143	3052.8	3384.5	6.9792	75.317	3051.9	3383.3	6.9674
500	80.116	3097.1	3441.6	7.0543	78.229	3096.3	3440.5	7.0426
525	83.057	3141.5	3498.6	7.1269	81.110	3140.7	3497.6	7.1153
550	85.971	3186.0	3555.7	7.1973	83.963	3185.3	3554.7	7.1858
575	88.863	3230.8	3612.9	7.2658	86.794	3230.1	3612.0	7.2544
	P = 4500 kPa, T_{sat} = 257.41 °C				P = 4600 kPa, T_{sat} = 258.75 °C			
Sat liq	1.269	1116.4	1122.1	2.8612	1.272	1122.9	1128.8	2.8735
Sat. vap	44.037	2599.5	2797.7	6.0191	43.038	2599.1	2797.0	6.0097
260	44.540	2607.4	2807.9	6.0382	43.278	2602.9	2802.0	6.0190
275	47.273	2650.3	2863.0	6.1403	46.000	2646.6	2858.2	6.1230
300	51.336	2713.2	2944.2	6.2852	50.027	2710.4	2940.5	6.2700
325	54.996	2769.1	3016.6	6.4088	53.643	2766.9	3013.7	6.3949
350	58.396	2820.5	3083.3	6.5182	56.994	2818.7	3080.9	6.5050
375	61.620	2869.1	3146.4	6.6174	60.167	2867.6	3144.4	6.6049
400	64.721	2915.8	3207.1	6.7093	63.215	2914.5	3205.3	6.6972
425	67.732	2961.4	3266.2	6.7955	66.172	2960.3	3264.7	6.7838
450	70.677	3006.3	3324.4	6.8774	69.063	3005.3	3323.0	6.8659

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
475	73.572	3050.9	3382.0	6.9558	71.903	3050.0	3380.8	6.9444
500	76.427	3095.4	3439.3	7.0311	74.702	3094.6	3438.2	7.0199
525	79.249	3139.9	3496.6	7.1040	77.469	3139.2	3495.5	7.0928
550	82.044	3184.6	3553.8	7.1746	80.209	3183.9	3552.8	7.1636
575	84.817	3229.5	3611.1	7.2432	82.926	3228.8	3610.2	7.2323
	P = 4700 kPa, T_{sat} = 260.07 °C				P = 4800 kPa, T_{sat} = 261.37 °C			
Sat liq	1.276	1129.3	1135.3	2.8555	1.279	1135.6	1141.8	2.8974
Sat. vap	42.081	2598.6	2796.4	6.0004	41.161	2598.1	2795.7	5.9913
275	44.778	2642.9	2853.3	6.1058	43.604	2639.1	2848.4	6.0887
300	48.772	2707.6	2936.8	6.2549	47.569	2704.8	2933.1	6.2399
325	52.346	2764.7	3010.7	6.3811	51.103	2762.5	3007.8	6.3675
350	55.651	2816.9	3078.5	6.4921	54.364	2815.1	3076.1	6.4794
375	58.775	2866.1	3142.3	6.5926	57.441	2864.6	3140.3	6.5805
400	61.773	2913.2	3203.6	6.6853	60.390	2911.9	3201.8	6.6736
425	64.679	2959.1	3263.1	6.7722	63.247	2958.0	3261.6	6.7608
450	67.517	3004.3	3321.6	6.8545	66.036	3003.3	3320.3	6.8434
475	70.304	3049.1	3379.5	6.9332	68.773	3048.2	3378.3	6.9223
500	73.051	3093.7	3437.1	7.0089	71.469	3092.9	3435.9	6.9981
525	75.765	3138.4	3494.5	7.0819	74.132	3137.6	3493.4	7.0712
550	78.452	3183.1	3551.9	7.1527	76.768	3182.4	3550.9	7.1422
575	81.116	3228.1	3609.3	7.2215	79.381	3227.4	3608.5	7.2110
600	83.760	3273.3	3667.0	7.2885	81.973	3272.7	3666.2	7.2781
	P = 4900 kPa, T_{sat} = 262.55 °C				P = 5000 kPa, T_{sat} = 263.91 °C			
Sat liq	1.282	1141.9	1148.2	2.9091	1.286	1148.0	1154.5	2.9206
Sat. vap	40.278	2597.6	2794.9	5.9823	39.429	2597.0	2794.2	5.9735
275	42.475	2635.2	2843.3	6.0717	41.388	2631.3	2838.2	6.0547
300	46.412	2701.9	2929.3	6.2252	45.301	2699.0	2925.5	6.2105
325	49.909	2760.2	3004.8	6.3541	48.762	2758.0	3001.8	6.3408
350	53.128	2813.3	3073.6	6.4669	51.941	2811.5	3071.2	6.4545
375	56.161	2863.0	3138.2	6.5685	54.932	2861.5	3136.2	6.5568
400	59.064	2910.6	3200.0	6.6621	57.791	2909.3	3198.3	6.6508
425	61.874	2956.9	3260.0	6.7496	60.555	2955.7	3258.5	6.7386
450	64.615	3002.3	3318.9	6.8324	63.250	3001.2	3317.5	6.8217
475	67.303	3047.2	3377.0	6.9115	65.893	3046.3	3375.8	6.9009
500	69.951	3092.0	3434.8	6.9874	68.494	3091.2	3433.7	6.9770
525	72.565	3136.8	3492.4	7.0607	71.061	3136.0	3491.3	7.0504
550	75.152	3181.7	3549.9	7.1318	73.602	3181.0	3549.0	7.1215
575	77.716	3226.8	3607.6	7.2007	76.119	3226.1	3606.7	7.1906
600	80.260	3272.0	3665.3	7.2678	78.616	3271.4	3664.5	7.2578
	P = 5100 kPa, T_{sat} = 265.15 °C				P = 5200 kPa, T_{sat} = 268.37 °C			
Sat liq	1.289	1154.1	1160.7	2.9319	1.292	1160.1	1166.8	2.9431
Sat. vap	38.611	2596.5	2793.4	5.9648	37.824	2595.9	2792.6	5.9561

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
275	40.340	2627.3	2833.1	6.0378	39.330	2623.3	2827.8	6.0210
300	44.231	2696.1	2921.7	6.1960	43.201	2693.1	2917.8	6.1815
325	47.660	2755.7	2998.7	6.3277	46.599	2753.4	2995.7	6.3147
350	50.801	2809.6	3068.7	6.4423	49.703	2807.8	3066.2	6.4302
375	53.750	2860.0	3134.1	6.5452	52.614	2858.4	3132.0	6.5338
400	56.567	2908.0	3196.5	6.6396	55.390	2906.7	3194.7	6.6287
425	59.288	2954.5	3256.9	6.7278	58.070	2953.4	3255.4	6.7172
450	61.940	3000.2	3316.1	6.8111	60.679	2999.2	3314.7	6.8007
475	64.537	3045.4	3374.5	6.8905	63.234	3044.5	3373.3	6.8803
500	67.094	3090.3	3432.5	6.9668	65.747	3089.5	3431.4	6.9567
525	69.616	3135.3	3490.3	7.0403	68.227	3134.5	3489.3	7.0304
550	72.112	3180.2	3548.0	7.1115	70.679	3179.5	3547.1	7.1017
575	74.584	3225.4	3605.8	7.1807	73.108	3224.7	3604.9	7.1709
600	77.035	3270.8	3663.7	7.2479	75.516	3270.2	3662.8	7.2382
	P = 5300 kPa, T_{sat} = 267.58 °C				P = 5400 kPa, T_{sat} = 268.76 °C			
Sat liq	1.296	1166.1	1172.9	2.9541	1.299	1171.9	1178.9	2.9650
Sat. vap	37.066	2595.3	2791.7	5.9476	36.334	2594.6	2790.8	5.9392
275	38.354	2619.2	2822.5	6.0041	37.411	2615.0	2817.0	5.9873
300	42.209	2690.1	2913.8	6.1672	41.251	2687.1	2909.8	6.1530
325	45.577	2751.0	2992.6	6.3018	44.591	2748.7	2989.5	6.2891
350	48.647	2805.9	3063.7	6.4183	47.628	2804.0	3061.2	6.4066
375	51.520	2856.9	3129.9	6.5225	50.486	2855.3	3127.8	6.5114
400	54.257	2905.3	3192.9	6.6179	53.166	2904.0	3191.1	6.6072
425	56.897	2952.2	3253.8	6.7067	55.768	2951.1	3252.2	6.6963
450	59.466	2998.2	3313.3	6.7905	58.297	2997.1	3311.9	6.7804
475	61.980	3043.5	3372.0	6.8703	60.772	3042.6	3370.8	6.8604
500	64.452	3088.6	3430.2	6.9468	63.204	3087.8	3429.1	6.9371
525	66.890	3133.7	3488.2	7.0206	65.603	3132.9	3487.2	7.0110
550	69.300	3178.8	3546.1	7.0920	67.973	3178.1	3545.1	7.0825
575	71.687	3224.1	3604.0	7.1613	70.320	3223.4	3603.1	7.1519
600	74.054	3269.5	3662.0	7.2287	72.646	3268.9	3661.2	7.2194
	P = 5500 kPa, T_{sat} = 269.93 °C				P = 5600 kPa, T_{sat} = 271.09 °C			
Sat liq	1.302	1177.7	1184.9	2.9757	1.306	1183.5	1190.8	2.9863
Sat. vap	35.628	2594.0	2789.9	5.9309	34.946	2593.3	2789.0	5.9227
275	36.499	2610.8	2811.5	5.9705	35.617	2606.5	2805.9	5.9537
300	40.327	2684.0	2905.8	6.1388	39.434	2680.9	2901.7	6.1248
325	43.641	2746.3	2986.4	6.2765	42.724	2744.0	2983.2	6.2640
350	46.647	2802.1	3058.7	6.3949	45.700	2800.2	3056.1	6.3834
375	49.450	2853.7	3125.7	6.5004	48.470	2852.1	3123.6	6.4896
400	52.115	2902.7	3189.3	6.5967	51.100	2901.3	3187.5	6.5863
425	54.679	2949.9	3250.6	6.6862	53.630	2948.7	3249.0	6.6761
450	57.171	2996.1	3310.5	6.7705	56.085	2995.0	3309.1	6.7607
475	59.608	3041.7	3369.5	6.8507	58.486	3040.7	3368.2	6.8411

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
500	62.002	3086.9	3427.9	6.9275	60.843	3086.1	3426.8	6.9181
525	64.362	3132.1	3486.1	7.0015	63.165	3131.3	3485.1	6.9922
550	66.694	3177.3	3544.2	7.0731	65.460	3176.6	3543.2	7.0639
575	69.002	3222.7	3602.2	7.1426	67.731	3222.0	3601.3	7.1335
600	71.289	3268.3	3660.4	7.2102	69.981	3267.6	3659.5	7.2011
	P = 5700 kPa, T_{sat} = 272.2 °C							
Sat liq	1.309	1189.1	1196.6	2.9968				
Sat. vap	34.288	2592.6	2788.0	5.9146				
275	34.761	2602.1	2800.2	5.9369				
300	38.571	2677.8	2897.6	6.1108				
325	41.838	2741.6	2980.0	6.2516				
350	44.785	2798.3	3053.5	6.3720				
375	47.525	2850.5	3121.4	6.4789				
400	50.121	2899.9	3185.6	6.5761				
425	52.617	2947.5	3247.5	6.6663				
450	55.038	2994.0	3307.7	6.7511				
475	57.403	3039.8	3367.0	6.8316				
500	59.724	3085.2	3425.6	6.9088				
525	62.011	3130.5	3484.0	6.9831				
550	64.270	3175.9	3542.2	7.0549				
575	66.504	3221.3	3600.4	7.1245				
600	68.719	3267.0	3658.7	7.1923				
	P = 5800 kPa, T_{sat} = 273.35 °C				P = 5900 kPa, T_{sat} = 274.46 °C			
Sat liq	1.312	1194.7	1202.3	3.0071	1.315	1200.3	1208.0	3.0172
Sat. vap	33.651	2591.9	2787.0	5.9066	33.034	2591.1	2786.0	5.8986
280	34.756	2614.4	2816.0	5.9592	33.953	2610.2	2810.5	5.9431
290	36.301	2645.7	2856.3	6.0314	35.497	2642.1	2851.5	6.0166
300	37.736	2674.6	2893.5	6.0969	36.928	2671.4	2889.3	6.0830
325	40.982	2739.1	2976.8	6.2393	40.154	2736.7	2973.6	6.2272
350	43.902	2796.3	3051.0	6.3608	43.048	2794.4	3048.4	6.3496
375	46.611	2848.9	3119.3	6.4683	45.728	2847.3	3117.1	6.4578
400	49.176	2898.6	3183.8	6.5660	48.252	2897.2	3182.0	6.5560
425	51.638	2946.4	3245.9	6.6565	50.693	2945.2	3244.3	6.6469
450	54.026	2992.9	3306.3	6.7416	53.048	2991.9	3304.9	6.7322
475	56.357	3038.8	3365.7	6.8223	55.346	3037.9	3364.4	6.8132
500	58.644	3084.4	3424.5	6.8996	57.600	3083.5	3423.3	6.8906
525	60.896	3129.8	3483.0	6.9740	59.819	3129.0	3481.9	6.9652
550	63.120	3175.2	3541.2	7.0460	62.010	3174.4	3540.3	7.0372
575	65.320	3220.7	3599.5	7.1157	64.176	3220.0	3598.6	7.1070
	P = 6000 kPa, T_{sat} = 275.55 °C				P = 6100 kPa, T_{sat} = 276.63 °C			
Sat liq	1.319	1205.8	1213.7	3.0273	1.322	1211.2	1219.3	3.0372
Sat. vap	32.438	2590.4	2785.0	5.8908	31.860	2589.6	2783.9	5.8830

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
280	33.173	2605.9	2804.9	5.9270	32.415	2601.5	2799.3	5.9108
290	34.718	2638.4	2846.7	6.0017	33.962	2634.6	2841.8	5.9869
300	36.145	2668.1	2885.0	6.0692	35.386	2664.8	2880.7	6.0555
325	39.353	2734.2	2970.4	6.2151	38.577	2731.7	2967.1	6.2031
350	42.222	2792.4	3045.8	6.3386	41.422	2790.4	3043.1	6.3277
375	44.874	2845.7	3115.0	6.4475	44.048	2844.1	3112.8	6.4373
400	47.379	2895.8	3180.1	6.5462	46.524	2894.5	3178.3	6.5364
425	49.779	2944.0	3242.6	6.6374	48.895	2942.8	3241.0	6.6280
450	52.103	2990.8	3303.5	6.7230	51.189	2989.8	3302.0	6.7139
475	54.369	3036.9	3363.2	6.8041	53.424	3036.0	3361.9	6.7952
500	56.592	3082.6	3422.2	6.8818	55.616	3081.8	3421.0	6.8730
525	58.778	3128.2	3480.8	6.9564	57.771	3127.4	3479.8	6.9478
550	60.937	3173.7	3539.3	7.0285	59.898	3173.0	3538.3	7.0200
575	63.071	3219.3	3597.7	7.0985	62.001	3218.6	3596.8	7.0900
	P = 6200 kPa, T_{sat} = 277.70 °C				P = 6300 kPa, T_{sat} = 278.75 °C			
Sat liq	1.325	1216.6	1224.8	3.0471	1.328	1221.9	1230.3	3.0568
Sat. vap	31.300	2588.8	2782.9	5.8753	30.757	2588.0	2781.8	5.8677
280	31.679	2597.1	2793.5	5.8946	30.962	2592.6	2787.6	5.8783
290	33.227	2630.8	2836.8	5.9721	32.514	2626.9	2831.7	5.9573
300	34.650	2661.5	2876.3	6.0418	33.935	2658.1	2871.9	6.0281
325	37.825	2729.2	2963.8	6.1911	37.097	2726.7	2960.4	6.1793
350	40.648	2788.5	3040.5	6.3168	39.898	2786.5	3037.8	6.3061
375	43.248	2842.4	3110.6	6.4272	42.473	2840.8	3108.4	6.4172
400	45.697	2893.1	3176.4	6.5268	44.895	2891.7	3174.5	6.5173
425	48.039	2941.6	3239.4	6.6188	47.210	2940.4	3237.8	6.6096
450	50.304	2988.7	3300.6	6.7049	49.447	2987.7	3299.2	6.6960
475	52.510	3035.0	3360.6	6.7864	51.624	3034.1	3359.3	6.7778
500	54.671	3080.9	3419.9	6.8644	53.757	3080.1	3418.7	6.8559
525	56.797	3126.6	3478.7	6.9393	55.853	3125.8	3477.7	6.9309
550	58.894	3172.2	3537.4	7.0116	57.921	3171.5	3536.4	7.0034
575	60.966	3218.0	3595.9	7.0817	59.964	3217.3	3595.0	7.0735
	P = 6400 kPa, T_{sat} = 279.79 °C				P = 6500 kPa, T_{sat} = 280.82 °C			
Sat liq	1.332	1227.2	1235.7	3.0664	1.335	1232.5	1241.1	3.0759
Sat. vap	30.230	2587.2	2780.6	5.8601	29.719	2586.3	2779.5	5.8527
280	30.265	2587.9	2781.6	5.8619	….	….	….	….
290	31.821	2623.0	2826.6	5.9425	31.146	2619.0	2821.4	5.9277
300	33.241	2654.7	2867.5	6.0144	32.567	2651.2	2862.9	6.0008
325	36.390	2724.2	2957.1	6.1675	35.704	2721.6	2953.7	6.1558
350	39.170	2784.4	3035.1	6.2955	38.465	2782.4	3032.4	6.2849
375	41.722	2839.1	3106.2	6.4072	40.994	2837.5	3103.9	6.3974
400	44.119	2890.3	3172.7	6.5079	43.366	2888.9	3170.8	6.4986
425	46.407	2939.2	3236.2	6.6006	45.629	2938.0	3234.5	6.5917
450	48.617	2986.6	3297.7	6.6872	47.812	2985.5	3296.3	6.6786

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
475	50.767	3033.1	3358.0	6.7692	49.935	3032.2	3356.8	6.7608
500	52.871	3079.2	3417.6	6.8475	52.012	3078.3	3416.4	6.8392
525	54.939	3125.0	3476.6	6.9226	54.053	3124.2	3475.6	6.9145
550	56.978	3170.8	3535.4	6.9952	56.065	3170.0	3534.4	6.9871
575	58.993	3216.6	3594.1	7.0655	58.052	3215.9	3593.2	7.0575
	P = 6600 kPa, T_{sat} = 281.84 °C				P = 6700 kPa, T_{sat} = 282.84 °C			
Sat liq	1.338	1237.6	1246.5	3.0853	1.432	1242.8	1251.8	3.0946
Sat. vap	29.223	2585.5	2778.3	5.8452	28.741	2584.6	2777.1	5.8379
290	30.490	2614.9	2816.1	5.9129	29.850	2610.8	2810.8	5.8980
300	31.911	2647.7	2858.4	5.9872	31.273	2644.2	2853.7	5.9736
325	35.038	2719.0	2950.2	6.1442	34.391	2716.4	2946.8	6.1326
350	37.781	2780.4	3029.7	6.2744	37.116	2778.3	3027.0	6.2640
375	40.287	2835.8	3101.7	6.3877	39.601	2834.1	3099.5	6.3781
400	42.636	2887.5	3168.9	6.4894	41.927	2886.1	3167.0	6.4803
425	44.874	2936.7	3232.9	6.5828	44.141	2935.5	3231.3	6.5741
450	47.031	2984.5	3294.9	6.6700	46.274	2983.4	3293.4	6.6616
475	49.129	3031.2	3355.5	6.7524	48.346	3030.3	3354.2	6.7442
500	51.180	3077.4	3415.2	6.8310	50.372	3076.6	3414.1	6.8229
525	53.194	3123.4	3474.5	6.9064	52.361	3122.6	3473.4	6.8985
550	55.179	3169.3	3533.5	6.9792	54.320	3168.6	3532.5	6.9714
575	57.139	3215.2	3592.3	7.0497	56.254	3214.5	3591.4	7.0419
600	59.079	3261.3	3651.2	7.1181	58.168	3260.7	3650.4	7.1104
	P = 6800 kPa, T_{sat} = 283.84 °C				P = 7000 kPa, T_{sat} = 285.79 °C			
Sat liq	1.345	1247.9	1257.0	3.1038	1.351	1258.0	1267.4	3.1219
Sat. vap	28.272	2583.7	2775.9	5.8306	27.373	2581.8	2773.5	5.8162
290	29.226	2606.6	2805.3	5.8830	28.024	2597.9	2794.1	5.8530
300	30.652	2640.6	2849.0	5.9599	29.457	2633.2	2839.4	5.9327
325	33.762	2713.7	2943.3	6.1211	32.556	2708.4	2936.3	6.0982
350	36.470	2776.2	3024.2	6.2537	35.233	2772.1	3018.7	6.2333
375	38.935	2832.4	3097.2	6.3686	37.660	2829.0	3092.7	6.3497
400	41.239	2884.7	3165.1	6.4713	39.922	2881.8	3161.2	6.4536
425	43.430	2934.3	3229.6	6.5655	42.068	2931.8	3226.3	6.5485
450	45.539	2982.3	3292.0	6.6532	44.131	2980.1	3289.1	6.6368
475	47.587	3029.3	3352.9	6.7361	46.133	3027.4	3350.3	6.7201
500	49.588	3075.7	3412.9	6.8150	48.086	3074.0	3410.6	6.7993
525	51.552	3121.8	3472.4	6.8907	50.003	3120.2	3470.2	6.8753
550	53.486	3167.8	3531.5	6.9636	51.889	3166.3	3529.6	6.9485
575	55.395	3213.9	3590.5	7.0343	53.750	3212.5	3588.7	7.0193
600	57.283	3260.0	3649.6	7.1028	55.590	3258.8	3647.9	7.0880
	P = 7200 kPa, T_{sat} = 287.70 °C				P = 7400 kPa, T_{sat} = 289.57 °C			
Sat liq	1.358	1267.9	1277.6	3.1397	1.364	1277.6	1287.7	3.1571
Sat. vap	26.522	2579.9	2770.9	5.8020	25.715	2578.0	2768.3	5.7880

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
290	26.878	2589.0	2782.5	5.8226	25.781	2579.7	2770.5	5.7919
300	28.321	2625.6	2829.5	5.9054	27.238	2617.8	2819.3	5.8779
325	31.413	2702.9	2929.1	6.0755	30.328	2697.3	2921.8	6.0530
350	34.063	2767.8	3013.1	6.2132	32.954	2763.5	3007.4	6.1933
375	36.454	2825.6	3088.1	6.3312	35.312	2822.1	3083.4	6.3130
400	38.676	2878.9	3157.4	6.4362	37.497	2876.0	3153.5	6.4190
425	40.781	2929.4	3223.0	6.5319	39.564	2926.9	3219.6	6.5156
450	42.802	2978.0	3286.1	6.6208	41.544	2975.8	3283.2	6.6050
475	44.759	3025.4	3347.7	6.7044	43.460	3023.5	3345.1	6.6892
500	46.668	3072.2	3408.2	6.7840	45.327	3070.4	3405.9	6.7691
525	48.540	3118.6	3468.1	6.8602	47.156	3117.0	3466.0	6.8456
550	50.381	3164.9	3527.6	6.9337	48.954	3163.4	3525.7	6.9192
575	52.197	3211.1	3586.9	7.0047	50.727	3209.8	3585.1	6.9904
600	53.991	3257.5	3646.2	7.0735	52.478	3256.2	3644.5	7.0594
	P = 7600 kPa, T_{sat} = 291.41 °C				P = 7800 kPa, T_{sat} = 293.21 °C			
Sat liq	1.371	1287.2	1297.6	3.1742	1.378	1296.7	1307.4	3.1911
Sat. vap	24.949	2575.9	2765.5	5.7742	24.220	2573.8	2762.8	5.7605
300	26.204	2609.7	2808.8	5.8503	25.214	2601.3	2798.0	5.8224
325	29.297	2691.7	2914.3	6.0306	28.315	2685.9	2906.7	6.0082
350	31.901	2759.2	3001.6	6.1737	30.900	2754.8	2995.8	6.1542
375	34.229	2818.6	3078.7	6.2950	33.200	2815.1	3074.0	6.2773
400	36.380	2873.1	3149.6	6.4022	35.319	2870.1	3145.6	6.3857
425	38.409	2924.3	3216.3	6.4996	37.314	2921.8	3212.9	6.4839
450	40.351	2973.6	3280.3	6.5896	39.220	2971.4	3277.3	6.5745
475	42.228	3021.5	3342.5	6.6742	41.060	3019.6	3339.8	6.6596
500	44.056	3068.7	3403.5	6.7545	42.850	3066.9	3401.1	6.7402
525	45.845	3115.4	3463.8	6.8312	44.601	3113.8	3461.7	6.8172
550	47.603	3161.9	3523.7	6.9051	46.320	3160.4	3521.7	6.8913
575	49.335	3208.4	3583.3	6.9765	48.014	3207.0	3581.5	6.9629
600	51.045	3254.9	3642.9	7.0457	49.686	3253.7	3641.2	7.0322
650	54.413	3348.5	3762.1	7.1784	52.976	3347.4	3760.6	7.1652
	P = 8000 kPa, T_{sat} = 294.97 °C							
Sat liq	1.384	1306.0	1317.1	3.2076				
Sat. vap	23.525	2571.7	2759.9	5.7471				
300	24.264	2592.7	2786.8	5.7942				
325	27.378	2679.9	2899.0	5.9860				
350	29.948	2750.3	2989.9	6.1349				
375	32.222	2811.5	3069.2	6.2599				
400	34.310	2867.1	3141.6	6.3694				
425	36.273	2919.3	3209.5	6.4684				
450	38.145	2969.2	3274.3	6.5597				
475	39.950	3017.6	3337.2	6.6452				

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
500	41.704	3065.1	3398.8	6.7262				
525	43.419	3112.2	3459.5	6.8035				
550	45.102	3158.9	3519.7	6.8778				
575	46.759	3205.6	3579.7	6.9496				
600	48.394	3252.4	3639.5	7.0191				
650	51.611	3346.3	3759.2	7.1523				
	P = 8200 kPa, T_{sat} = 296.70 °C				P = 8400 kPa, T_{sat} = 298.39 °C			
Sat liq	1.391	1315.2	1326.6	3.2239	1.398	1324.3	1336.1	3.2399
Sat. vap	22.863	2569.5	2757.0	5.7338	22.231	2567.2	2754.0	5.7207
300	23.350	2583.7	2775.2	5.7656	22.469	2574.4	2763.1	5.7366
320	25.916	2657.7	2870.2	5.9288	25.058	2651.1	2861.6	5.9056
340	28.064	2718.5	2948.6	6.0588	27.203	2713.4	2941.9	6.0388
360	29.968	2771.5	3017.2	6.1689	29.094	2767.3	3011.7	6.1509
380	31.715	2819.5	3079.5	6.2659	30.821	2816.0	3074.8	6.2491
400	33.350	2864.1	3137.6	6.3534	32.435	2861.1	3133.5	6.3376
425	35.282	2916.7	3206.0	6.4532	34.337	2914.1	3202.6	6.4383
450	37.121	2966.9	3271.3	6.5452	36.147	2964.7	3268.3	6.5309
475	38.893	3015.6	3334.5	6.6311	37.887	3013.6	3331.9	6.6173
500	40.614	3063.3	3396.4	6.7124	39.576	3061.6	3394.0	6.6990
525	42.295	3110.5	3457.3	6.7900	41.224	3108.9	3455.2	6.7769
550	43.943	3157.4	3517.8	6.8646	42.839	3155.9	3515.8	6.8516
575	45.566	3204.3	3577.9	6.9365	44.429	3202.9	3576.1	6.9238
600	47.166	3251.1	3637.9	7.0062	45.996	3249.8	3636.2	6.9936
	P = 8600 kPa, T_{sat} = 300.06 °C				P = 8800 kPa, T_{sat} = 301.70 °C			
Sat liq	1.404	1333.3	1345.4	3.2557	1.411	1342.2	1354.6	3.2713
Sat. vap	21.627	2564.9	2750.9	5.7076	21.049	2562.6	2747.8	5.6948
320	24.236	2644.3	2852.7	5.8823	23.446	2637.3	2843.6	5.8590
340	26.380	2708.1	2935.0	6.0189	25.592	2702.8	2928.0	5.9990
360	28.258	2763.1	3006.1	6.1330	27.459	2758.8	3000.4	6.1152
380	29.968	2812.4	3070.1	6.2326	29.153	2808.8	3065.3	6.2162
400	31.561	2858.0	3129.4	6.3220	30.727	2854.9	3125.3	6.3067
425	33.437	2911.5	3199.1	6.4236	32.576	2908.9	3195.6	6.4092
450	35.217	2962.4	3265.3	6.5168	34.329	2960.1	3262.2	6.5030
475	36.928	3011.6	3329.2	6.6037	36.011	3009.6	3326.5	6.5904
500	38.586	3059.8	3391.6	6.6858	37.640	3058.0	3389.2	6.6728
525	40.202	3107.3	3453.0	6.7639	39.228	3105.6	3450.8	6.7513
550	41.787	3154.4	3513.8	6.8390	40.782	3152.9	3511.8	6.8265
575	43.345	3201.5	3574.3	6.9113	42.310	3200.1	3572.4	6.8990
600	44.880	3248.5	3634.5	6.9813	43.815	3247.2	3632.8	6.9692
625	46.397	3295.7	3694.7	7.0492	45.301	3294.5	3693.1	7.0373
	P = 9000 kPa, T_{sat} = 303.31 °C				P = 9200 kPa, T_{sat} = 304.89 °C			
Sat liq	1.418	1351.0	1363.7	3.2867	1.425	1359.7	1372.8	3.3018
Sat. vap	20.495	2560.1	2744.6	5.6820	19.964	2557.7	2741.3	5.6694

(continued)

Table F4 (continued)

T (°C)	V (cm³/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm³/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
320	22.685	2630.1	2834.3	5.8355	21.952	2622.7	2824.7	5.8118
340	24.836	2697.4	2920.9	5.9792	24.110	2691.9	2913.7	5.9594
360	26.694	2754.4	2994.7	6.0976	25.961	2750.0	2988.9	6.0801
380	28.372	2805.2	3060.5	6.2000	27.625	2801.5	3055.7	6.1840
400	29.929	2851.8	3121.2	6.2915	29.165	2848.7	3117.0	7.2765
425	31.754	2906.3	3192.0	6.3949	30.966	2903.6	3188.5	6.3808
450	33.480	2957.8	3259.2	6.4894	32.668	2955.5	3256.1	6.4760
475	35.136	3007.6	3323.8	6.5773	34.298	3005.6	3321.1	6.5644
500	36.737	3056.1	3386.8	6.6600	35.872	3054.3	3384.4	6.6475
525	38.296	3104.0	3448.7	6.7388	37.405	3102.3	3446.5	6.7266
550	39.822	3151.4	3509.8	6.8143	38.904	3149.9	3507.8	6.8023
575	41.321	3198.7	3570.6	6.8870	40.375	3197.3	3568.8	6.8752
600	42.798	3246.0	3631.1	6.9574	41.824	3244.7	3629.5	6.9457
625	44.255	3293.3	3691.6	7.0256	43.254	3292.1	3690.0	7.0141
	P = 9400 kPa, T_{sat} = 306.44 °C				P = 9600 kPa, T_{sat} = 307.97 °C			
Sat liq	1.432	1368.2	1381.7	3.3168	1.439	1376.7	1390.6	3.3315
Sat. vap	19.455	2555.2	2738.0	5.6568	18.965	2552.6	2734.7	5.6444
320	21.245	2615.1	2814.8	5.7879	20.561	2607.3	2804.7	5.7637
340	23.412	2686.3	2906.3	5.9397	22.740	2680.5	2898.8	5.9199
360	25.257	2745.6	2983.0	6.0627	24.581	2741.0	2977.0	6.0454
380	26.909	2797.8	3050.7	6.1681	26.221	2794.1	3045.8	6.1524
400	28.433	2845.5	3112.8	6.2617	27.731	2842.3	3108.5	6.2470
425	30.212	2900.9	3184.9	6.3669	29.489	2898.2	3181.3	6.3532
450	31.891	2953.2	3253.0	6.4628	31.145	2950.9	3249.9	6.4498
475	33.495	3003.5	3318.4	6.5517	32.726	3001.5	3315.6	6.5392
500	35.045	3052.5	3381.9	6.6352	34.252	3050.7	3379.5	6.6231
525	36.552	3100.7	3444.3	6.7146	35.734	3099.0	3442.1	6.7028
550	38.024	3148.4	3505.9	6.7906	37.182	3146.9	3503.9	6.7790
575	39.470	3195.9	3566.9	6.8637	38.602	3194.5	3565.1	6.8523
600	40.892	3243.4	3627.8	6.9343	39.999	3242.1	3626.1	6.9231
	P = 9800 kPa, T_{sat} = 309.48 °C				P = 10000 kPa, T_{sat} = 310.96 °C			
Sat liq	1.446	1385.2	1399.3	3.3461	1.453	1393.5	1408.0	3.3605
Sat. vap	18.494	2550.0	2731.2	5.6321	18.041	2547.3	2727.7	5.6198
320	19.899	2599.2	2794.3	5.7393	19.256	2590.9	2783.5	5.7145
340	22.093	2674.7	2891.2	5.9001	21.468	2668.7	2883.4	5.8803
360	23.931	2736.4	2971.0	6.0282	23.305	2731.8	2964.8	6.0110
380	25.561	2790.3	3040.8	6.1368	24.926	2786.4	3035.7	6.1213
400	27.056	2839.1	3104.2	6.2325	26.408	2835.8	3099.9	6.2182
425	28.795	2895.5	3177.7	6.3397	28.128	2892.8	3174.1	6.3264
450	30.429	2948.6	3246.8	6.4369	29.742	2946.2	3243.6	6.4243
475	31.988	2999.4	3312.9	6.5268	31.280	2997.4	3310.1	6.5147
500	33.491	3048.8	3377.0	6.6112	32.760	3047.0	3374.6	6.5994
525	34.949	3097.4	3439.9	6.6912	34.196	3095.7	3437.7	6.6797

(continued)

Table F4 (continued)

T (°C)	V (cm³/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm³/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
550	36.373	3145.4	3501.9	6.7676	35.597	3143.9	3499.8	6.7564
575	37.769	3193.1	3563.3	6.8411	36.970	3191.7	3561.4	6.8302
600	39.142	3240.8	3624.4	6.9121	38.320	3239.5	3622.7	6.9013
	P = 10200 kPa, T_{sat} = 312.42 °C				P = 10400 kPa, T_{sat} = 313.86 °C			
Sat liq	1.460	1401.8	1416.7	3.3748	1.467	1410.0	1425.2	3.3889
Sat. vap	17.605	2544.6	2724.2	5.6076	17.184	2541.8	2720.6	5.5955
320	18.632	2582.3	2772.3	5.6894	18.024	2573.4	2760.8	5.6638
340	20.865	2662.6	2875.4	5.8604	20.282	2656.3	2867.2	5.8404
360	22.702	2727.0	2958.6	5.9940	22.121	2722.2	2952.3	5.9769
380	24.315	2782.6	3030.6	6.1059	23.726	2778.7	3025.4	6.0907
400	25.785	2832.6	3095.6	6.2040	25.185	2829.3	3091.2	6.1899
425	27.487	2890.0	3170.4	6.3131	26.870	2887.3	3166.7	6.3001
450	29.081	2943.9	3240.5	6.4118	28.446	2941.5	3237.3	6.3994
475	30.599	2995.3	3307.4	6.5027	29.943	2993.2	3304.6	6.4909
500	32.058	3045.2	3372.1	6.5879	31.382	3043.3	3369.7	6.5765
525	33.472	3094.0	3435.5	6.6685	32.776	3092.4	3433.2	6.6574
550	34.851	3142.3	3497.8	6.7454	34.134	3140.8	3495.8	6.7346
575	36.202	3190.3	3559.6	6.8194	35.464	3188.9	3557.8	6.8087
600	37.530	3238.2	3621.0	6.8907	36.770	3236.9	3619.3	6.8803
	P = 10600 kPa, T_{sat} = 315.27 °C				P = 10800 kPa, T_{sat} = 316.67 °C			
Sat liq	1.474	1418.1	1433.7	3.4029	1.481	1426.2	1442.4	3.4167
Sat. vap	16.778	2539.0	2716.9	5.5835	16.385	2536.2	2713.1	5.5715
320	17.432	2564.1	2748.9	5.6376	16.852	2554.5	2736.5	5.6109
340	19.717	2649.9	2858.9	5.8203	19.170	2643.4	2850.4	5.8000
360	21.560	2717.4	2945.9	5.9599	21.018	2712.4	2939.4	5.9429
380	23.159	2774.7	3020.2	6.0755	22.612	2770.7	3014.9	6.0604
400	24.607	2825.9	3086.8	6.1759	24.050	2822.6	3082.3	6.1621
425	26.276	2884.5	3163.0	6.2872	25.703	2881.7	3159.3	6.2744
450	27.834	2939.1	3234.1	6.3872	27.245	2936.7	3230.9	6.3752
475	29.313	2991.1	3301.8	6.4793	28.706	2989.0	3299.0	6.4678
500	30.732	3041.4	3367.2	6.5652	30.106	3039.6	3364.7	6.5542
525	32.106	3090.7	3431.0	6.6465	31.461	3089.0	3428.8	6.6357
550	33.444	3139.3	3493.8	6.7239	32.779	3137.8	3491.8	6.7134
575	34.753	3187.5	3555.9	6.7983	34.069	3186.1	3554.1	6.7880
600	36.039	3235.6	3617.6	6.8700	35.335	3234.3	3615.9	6.8599
625	37.304	3283.6	3679.1	6.9394	36.580	3282.4	3677.5	6.9294
	P = 11000 kPa, T_{sat} = 318.5 °C				P = 11200 kPa, T_{sat} = 319.40 °C			
Sat liq	1.489	1434.2	1450.6	3.4304	1.496	1442.1	1458.9	3.4440
Sat. vap	16.006	2533.2	2709.3	5.5595	15.639	2530.3	2705.4	5.5476
320	16.285	2544.4	2723.5	5.5835	15.726	2533.8	2710.0	5.5553
340	18.639	2636.7	2841.7	5.7797	18.124	2629.8	2832.8	5.7591
360	20.494	2707.4	2932.8	5.9259	19.987	2702.2	2926.1	5.9090

(continued)

Table F4 (continued)

T (°C)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)	V (cm^3/g)	U (kJ/kg)	H (kJ/kg)	S (kJ/kg K)
380	22.083	2766.7	3009.6	6.0454	21.573	2762.6	3004.2	6.0305
400	23.512	2819.2	3077.8	6.1483	22.993	2815.8	3073.3	6.1347
425	25.151	2878.9	3155.5	6.2617	24.619	2876.0	3151.7	6.2491
450	26.676	2934.3	3227.7	6.3633	26.128	2931.8	3224.5	6.3515
475	28.120	2986.9	3296.2	6.4564	27.555	2984.8	3293.4	6.4452
500	29.503	3037.7	3362.2	6.5432	28.921	3035.8	3359.7	6.5324
525	30.839	3087.3	3426.5	6.6251	30.240	3085.6	3424.3	6.6147
550	32.139	3136.2	3489.7	6.7031	31.521	3134.7	3487.7	6.6929
575	33.410	3184.7	3552.2	6.7779	32.774	3183.3	3550.4	6.7679
600	34.656	3233.0	3614.2	6.8499	34.002	3231.7	3612.5	6.8401
625	35.882	3281.2	3675.9	6.9196	35.210	3280.0	3674.4	6.9099
	P = 11400 kPa, T_{sat} = 320.74 °C							
Sat liq	1.504	1450.0	1467.2	3.4575				
Sat. vap	15.284	2527.2	2701.5	5.5357				
340	17.622	2622.7	2823.6	5.7383				
360	19.495	2697.0	2919.3	5.8920				
380	21.079	2758.4	2998.7	6.0156				
400	22.492	2812.3	3068.7	6.1211				
425	24.104	2873.1	3147.9	6.2367				
450	25.599	2929.4	3221.2	6.3399				
475	27.010	2982.6	3290.5	6.4341				
500	28.359	3033.9	3357.2	6.5218				
525	29.661	3083.9	3422.1	6.6043				
550	30.925	3133.1	3485.7	6.6828				
575	32.160	3181.9	3548.5	6.7580				
600	33.370	3230.4	3610.8	6.8304				
625	34.560	3278.8	3672.8	6.9004				
650	35.733	3327.2	3734.6	6.9683				

Source: Smith et al. [8]

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