هندسة كيماوية وصناعات نفطية
المرحلة الأولى
مبادئ الهندسة الكيماوية

I

INTRODUCTION TO ENGINEERING CALCULATIONS

1

The chemical engineering profession encompasses a wide variety of activities and is engaged in resolving problems that occur in industry, government, and academia. Problems encountered by chemical engineers are found in design, operation, control, troubleshooting, research, and even politics, the latter because of environmental and economic concerns. Chemical engineers work in numerous areas besides petroleum refining and the chemical and petrochemical industries because their background and experience are easily portable and found useful. You will find chemical engineers solving problems in industries such as

Drugs and pharmaceutics
Microelectronics
Biotechnology
Explosives and fireworks
Fats and oils
Fertilizer and agricultural chemicals
Foods and beverages
Leather tanning and finishing
Lime and cement
Man-make fibers
Metallurgical and metal products
Paints, varnishes, and pigments
Pesticides and herbicides
Plastic materials, synthetic resins

Rubber products
Soap and toiletries
Solid-state materials
Stone, clay, glass, and ceramics
Wood, pulp, paper, and board

Table 1.0 gives you some idea of the vast industrial capacity in the United States in which chemical engineers participate.

For you to learn how to appreciate and treat the problems that will arise in our modern technology, especially in the technology of the future, it is necessary to learn certain basic principles and practice their application. This text describes the principles of making material and energy balances and illustrates their application in a wide variety of ways.

We begin in this chapter with a review of certain background information. You have already encountered most of the concepts to be presented in basic chemistry and physics courses. Why, then, the need for a review? First, from experience we

TABLE 1.0 U.S. Production in 1986

Chemicals (in 10^9 lb)		Fertilizers (in 10^6 tons)	
Sulfuric acid	73.64	Nitrogen	10.4
Nitrogen	48.62	Phosphate (P_2O_5)	8.6
Oxygen	33.03	Potash (K_2O)	1.0
Ethylene	32.81		
Lime	30.34	Pesticides and herbicides (in 10^6 lb)	
Ammonia	28.01	Herbicides	756
Sodium hydroxide	22.01	Insecticides	370
Chlorine	20.98	Fungicides	109
Phosphoric acid	18.41		
Propylene	17.34	Plastics (in 10^6 lb)	
Sodium carbonate	17.20	Thermosetting resins	5.8
Ethylene dichloride	14.53	(phenols, urea,	
Nitric acid	13.12	polyesters, epoxies)	
Urea	12.06	Thermoplastic resins	33.6
Ammonium nitrate	11.11	(polyetheyne, polystyrene,	
Benzene	10.23	polypropylene, copolymers)	
Ethylbenzene	8.92	Synthetic fibers	
Carbon dioxide	8.50	Cellulosics (rayon, acetate)	0.6
Vinyl chloride	8.42	Polyester	3.3
Styrene	7.84	Nylon	2.5
Minerals (in 10^6 tons)		Olefinic and acrylic	3.0
Phosphate rock	1.2		
Salt	36.8		
Sulfur	12.2		
Synthetic rubber (in metric tons)	4380		

have found it necessary to restate these familiar basic concepts in a somewhat more general and clearer fashion; second, you will need practice to develop your ability to analyze and work engineering problems. To read and understand the principles discussed in this chapter is relatively easy; to apply them to different unfamiliar situations is not. An engineer becomes competent in his or her profession by mastering the techniques developed by one's predecessors—thereafter comes the time to pioneer new ones.

The chapter begins with a discussion of units, dimensions, and conversion factors, and then goes on to review some terms you should already be acquainted with, such as:

(a) Mole and mole fraction
(b) Density and specific gravity
(c) Measures of concentration
(d) Temperature
(e) Pressure

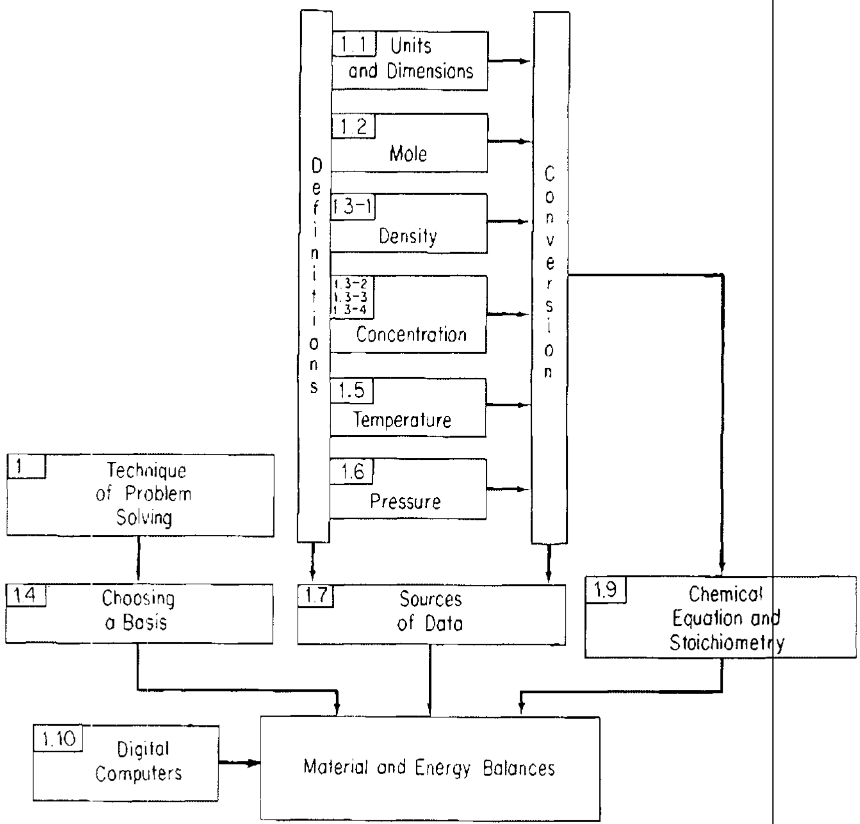

Figure 1.0 Hierarchy of topics to be studied in this chapter (section numbers are in the upper left-hand corner of the boxes).

It then provides some clues on "how to solve problems," which should be of material aid in all the remaining portions of your career. Finally, the principles of stoichiometry are reviewed, and the technique of handling incomplete reactions is illustrated. Figure 1.0 shows the relation of the topics to be discussed to each other and to the ultimate goal of being able to solve problems involving both material and energy balances.

1.1 UNITS AND DIMENSIONS

Your objectives in studying this section are to be able to:

1. Add, subtract, multiply, and divide units associated with numbers.
2. Convert one set of units in a function or equation into another equivalent set for mass, length, area, volume, time, energy, and force.
3. Specify the basic and derived units in the SI and American engineering systems for mass, length, volume, density, and time, and their equivalences.
4. Explain the difference between weight and mass.
5. Define and know how to use the gravitational conversion factor g_c.
6. Apply the concepts of dimensional consistency to determine the units of any term in a function.

"Take care of your units and they will take care of you."

At some time in every student's life comes the exasperating sensation of frustration in problem solving. Somehow, the answers or the calculations do not come out as expected. Often this outcome arises because of inexperience in the handling of units. The use of units or dimensions along with the numbers in your calculations requires more attention than you probably have been giving to your computations in the past, but paying attention will help avoid such annoying experiences. The proper use of dimensions in problem solving is not only sound from a logical viewpoint—it will also be helpful in guiding you along an appropriate path of analysis from what is at hand through what has to be done to the final solution.

1.1-1 Units and Dimensions

Dimensions are our basic concepts of measurement such as *length*, *time*, *mass*, *temperature*, and so on; **units** are the means of expressing the dimensions, such as *feet* or *centimeters* for length, or *hours* or *seconds* for time. Units are associated with some quantities you may have previously considered to be dimensionless. A good example is *molecular weight*, which is really the mass of one substance per mole of that substance. This method of attaching units to all numbers which are not fundamentally dimensionless has the following very practical benefits:

(a) It diminishes the possibility of inadvertent inversion of any portion of the calculation.
(b) It reduces the calculation in many cases to simple ratios, which can be easily manipulated on a hand-held calculator.
(c) It reduces the intermediate calculations and eliminates considerable time in problem solving.
(d) It enables you to approach the problem logically rather than by remembering a formula and plugging numbers into the formula.
(e) It demonstrates the physical meaning of the numbers you use.

Every freshman knows that what you get from adding apples to oranges is fruit salad! The rule for handling units is essentially quite simple: **treat the units as you would algebraic symbols. You can add, subtract, or equate numerical quantities only if the units of the quantities are the same.** Thus the operation

5 kilograms + 3 joules

is meaningless because the dimensions of the two terms are different. The numerical operation

10 pounds + 5 grams

can be performed (because the dimensions are the same, mass) *only* after the units are transformed to be the same, either pounds, or grams, or ounces, and so on. **In multiplication and division, you can multiply or divide different units,** such as (10 centimeters ÷ 4 seconds) = 2.5 centimeters/second, **but you cannot cancel them out unless they are the same.** For example, 3 m^2/60 cm must first be converted to 3 m^2/0.6 m and then to 5 m. The units contain a significant amount of information content that cannot be ignored. They also serve as guides in efficient problem solving, as you will see shortly.

EXAMPLE 1.1 Dimensions and Units

Add the following:

(a) 1 foot + 3 seconds

(b) 1 horsepower + 300 watts

Solution

The operation indicated by

1 ft + 3 s

has no meaning since the dimensions of the two terms are not the same. One foot has the dimensions of length, whereas 3 seconds has the dimensions of time. In the case of

1 hp + 300 watts

the dimensions are the same (energy per unit time) but the units are different. You must transform the two quantities into like units, such as horsepower, watts, or something else, before the addition can be carried out. Since 1 hp = 746 watts,

$$746 \text{ watts} + 300 \text{ watts} = 1046 \text{ watts}$$

1.1-2 Conversion of Units and Conversion Factors

In this book, to help you follow the calculations, we will frequently make use of what is called the *dimensional equation*. It contains both units and numbers. One quantity is multiplied by a number of ratios termed **conversion factors** of equivalent values of combinations of time, distance, and so on, to arrive at the final desired answer. The ratios used are simple well-known values and thus the conversion itself should present no great problem. Examine Example 1.2.

EXAMPLE 1.2 Conversion of Units

If a plane travels at twice the speed of sound (assume that the speed of sound is 1100 ft/s), how fast is it going in miles per hour?

Solution

$$\begin{array}{c|c|c|c|c} 2 & 1100\text{ ft} & 1\text{ mi} & 60\text{ s} & 60\text{ min} \\ \hline & \text{s} & 5280\text{ ft} & 1\text{ min} & 1\text{ hr} \end{array} = 1500\,\frac{\text{mi}}{\text{hr}}$$

or

$$\begin{array}{c|c|c} 2 & 1100\text{ ft} & 60\,\frac{\text{mi}}{\text{hr}} \\ \hline & \text{s} & 88\,\frac{\text{ft}}{\text{s}} \end{array} = 1500\,\frac{\text{mi}}{\text{hr}}$$

Of course, it is possible to look up conversion ratios, which will enable the length of the calculation to be reduced; for instance, in Example 1.2 we could have used the conversion factor of 60 mi/hr equals 88 ft/s. However, it usually takes less time to use values you know than to look up shortcut conversion factors in a handbook. Common conversion ratios are listed on the inside front cover.

We have set up the dimensional equation with vertical lines to separate each ratio, and these lines retain the same meaning as an × or multiplication sign placed between each ratio. The dimensional equation will be retained in this form throughout most of this text to enable you to keep clearly in mind the significance of units in problem solving. It is recommended that you always write down the units next to the associated numerical value (unless the calculation is very simple) until you become quite familiar with the use of units and dimensions and can carry them in your head.

At any point in the dimensional equation you can determine the consolidated net units and see what conversions are still required. This may be carried out formally, as shown below by drawing slanted lines below the dimensional equation and writing the consolidated units on these lines, or it may be done by eye, mentally canceling and accumulating the units, or, you can strike out pairs of units as you proceed:

$$\begin{array}{c|c|c|c} 2 \times 1100\ \text{ft} & 1\ \text{mi} & 60\ \text{sec} & 60\ \text{min} \\ \hline \text{s} & 5280\ \text{ft} & 1\ \text{min} & 1\ \text{hr} \end{array}$$

$$\frac{\text{ft}}{\text{s}} \qquad \frac{\text{mi}}{\text{s}} \qquad \frac{\text{mi}}{\text{min}}$$

Consistent use of dimensional equations throughout your professional career will assist you in avoiding silly mistakes such as converting 10 centimeters to inches by multiplying by 2.54:

$$\begin{array}{c|c} 10\ \text{cm} & 2.54\ \text{cm} \\ \hline & \text{in.} \end{array} \neq 25.4\ \text{cm} \quad \text{but instead} \quad = 25.4\,\frac{\text{cm}^2}{\text{in.}}$$

Note how easily you discover that a blunder has occurred by including the units in the calculations.

Here is another example of the conversion of units.

EXAMPLE 1.3 Use of Units

Change 400 $\text{in.}^3/\text{day}$ to cm^3/min.

Solution

$$\begin{array}{c|c|c|c} 400\ \text{in.}^3 & \left(2.54\ \text{cm}\right)^3 & 1\ \text{day} & 1\ \text{hr} \\ \hline \text{day} & \left(1\ \text{in.}\right) & 24\ \text{hr} & 60\ \text{min} \end{array} = 4.56\,\frac{\text{cm}^3}{\text{min}}$$

In this example note that not only are the numbers raised to a power, but the units also are raised to the same power.

> There shall be one measure of wine throughout our kingdom, and one measure of ale, and one measure of grain . . . and one breadth of cloth. . . . And of weights it shall be as of measures.

So reads the standard measures clause of the *Magna Carta* (June 1215). The standards mentioned were not substantially revised until the nineteenth century. When the American colonies separated from England, they retained, among other things, the weights and measures then in use. It is probable that at that time these were the most firmly established and widely used weights and measures in the world.

No such uniformity of weights and measures existed on the European continent. Weights and measures differed not only from country to country but even from town to town and from one trade to another. This lack of uniformity led the National Assembly of France during the French Revolution to enact a decree (May 8, 1790) that called upon the French Academy of Sciences to act in concert with the Royal Society of London to "deduce an invariable standard for all of the measures and all weights." Having already an adequate system of weights and measures, the English

TABLE 1.1 Common Systems of Units

	Length	Time	Mass	Force	Energy*	Temperature	Remarks
Absolute (dynamic) systems							
Cgs	centimeter	second	gram	dyne*	erg, joule, or calorie	K, °C	Formerly common scientific
Fps (ft-lb-s or English absolute)	foot	second	pound	poundal*	ft poundal	°R, °F	
SI	meter	second	kilogram	newton*	joule	K, °C	Internationally adopted units for ordinary and scientific use
Gravitational systems							
British engineering	foot	second	slug*	pound weight	Btu(ft)(lb_f)	°R, °F	
American engineering	foot	second, hour	pound mass (lb_m)	pound force (lb_f)	Btu or (hp)(hr)	°R, °F	Used by chemical and petroleum engineers in the United States

*Unit derived from basic units; all energy units are derived.

TABLE 1.2 SI Units Encountered in this Book

Basic SI units

Physical quantity	Name of unit	Symbol for unit*
Length	metre, meter	m
Mass	kilogramme, kilogram	kg
Time	second	s
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol

Derived SI units

Physical quantity	Name of unit	Symbol for unit*	Definition of unit
Energy	joule	J	$kg \cdot m^2 \cdot s^{-2}$
Force	newton	N	$kg \cdot m \cdot s^{-2} \Leftrightarrow J \cdot m^{-1}$
Power	watt	W	$kg \cdot m^2 \cdot s^{-3} \Leftrightarrow J \cdot s^{-1}$
Frequency	hertz	Hz	cycle/s
Area	square meter		m^2
Volume	cubic meter		m^3
Density	kilogram per cubic meter		$kg \cdot m^{-3}$
Velocity	meter per second		$m \cdot s^{-1}$
Angular velocity	radian per second		$rad \cdot s^{-1}$
Acceleration	meter per second squared		$m \cdot s^{-2}$
Pressure	newton per square meter, pascal		$N \cdot m^{-2}$, Pa
Specific heat	joule per (kilogram · kelvin)		$J \cdot kg^{-1} \cdot K^{-1}$

Alternative units

Physical quantity	Allowable unit	Symbol for unit*
Time	minute	min
	hour	h
	day	d
	year	a
Temperature	degree Celsius	°C
Volume	litre, liter (dm^3)	L
Mass	tonne, ton (Mg)	t
	gram	g
Pressure	bar (10^5Pa)	bar

*Symbols for units do not take a plural form, but plural forms are used for the unabbreviated names.

cm gm s

In the cgs system the unit of force is defined as the dyne; hence if C is selected to be $C = 1 \text{ dyne}/(\text{g})(\text{cm})/\text{s}^2$, then when 1 g is accelerated at 1 cm/s²

$$F = \frac{1 \text{ dyne}}{\frac{(\text{g})(\text{cm})}{\text{s}^2}} \left| \frac{1 \text{ g}}{} \right| \frac{1 \text{ cm}}{\text{s}^2} = 1 \text{ dyne}$$

Similarly, in the SI system in which the unit of force is defined to be the newton (N), if $C = 1 \text{ N}/(\text{kg})(\text{m})/\text{s}^2$, then when 1 kg is accelerated at 1 m/s²,

$$F = \frac{1 \text{ N}}{\frac{(\text{kg})(\text{m})}{\text{s}^2}} \left| \frac{1 \text{ kg}}{} \right| \frac{1 \text{ m}}{\text{s}^2} = 1 \text{ N}$$

However, in the American engineering system we ask that the numerical value of the force and the mass be essentially the same at the earth's surface. Hence, if a mass of 1 lb_m is accelerated at g ft/s², where g is the acceleration of gravity (about 32.2 ft/s² depending on the location of the mass), we can make the force be 1 lb_f by choosing the proper numerical value and units for C:

$$F = (C)\frac{1 \text{ lb}_m}{} \left| \frac{g \text{ ft}}{\text{s}^2} \right. = 1 \text{ lb}_f \tag{1.2}$$

Observe that for Eq. (1.2) to hold, the units of C have to be

$$C \approx \frac{\text{lb}_f}{\text{lb}_m\left(\frac{\text{ft}}{\text{s}^2}\right)}$$

A numerical value of 1/32.174 has been chosen for the constant because 32.174 is the numerical value of the average acceleration of gravity (g) at sea level at 45° latitude when g is expressed in ft/s². The acceleration of gravity, you may recall, varies a few tenths of 1% from place to place on the surface of the earth and changes considerably as you rise up from the surface as in a rocket. With this selection of units and with the number 32.174 employed in the denominator of the conversion factor,

$$F = \left(\frac{1 \, (\text{lb}_f)(\text{s}^2)}{32.174(\text{lb}_m)(\text{ft})}\right)\left(\frac{1 \text{ lb}_m}{} \left| \frac{g \text{ ft}}{\text{s}^2} \right.\right) = 1 \text{ lb}_f$$

The inverse of C is given the special symbol g_c:

$$g_c = 32.174\frac{(\text{ft})(\text{lb}_m)}{(\text{s}^2)(\text{lb}_f)} \tag{1.3}$$

Division by g_c achieves exactly the same result as multiplication by C in Newton's law. You can see, therefore, that in the American engineering system we have the convenience that the numerical value of a pound mass is also that of a pound force if the numerical value of the ratio g/g_c is equal to 1, as it is approximately in most cases. A nonstandard usage sometimes encountered analogous to lb_f and lb_m is kg_f

and kg_m; a conversion factor not equal to unity is involved in the transformation by an equation similar to Eq. (1.2).

Furthermore, a one pound mass is said to weigh one pound if the mass is in static equilibrium on the surface of earth. We can define **weight** as the opposed force required to support a mass. For the concept of weight for masses that are not stationary at earth's surface, or are affected by the earth's rotation (a factor of only 0.002 times the force exerted by gravity), or are located away from the earth's surface as in a rocket or satellite, consult your physics text.

To sum up, always keep in mind that the two quantities g and g_c are **not** the same. Also, **never forget that the pound (mass) and pound (force) are not the same units in the American engineering system** even though we speak of *pounds* to express force, weight, or mass. Nearly all teachers and writers in physics, engineering, and related fields in technical communications are careful to use the terms "mass," "force," and "weight" properly. On the other hand, in ordinary language most people, including scientists and engineers, omit the designation of "force" or "mass" associated with the pound or kilogram but pick up the meaning from the context of the statement. No one gets confused by the fact that a man is 6 feet tall but has only two feet. Similarly, you should interpret the statement that a bottle "weighs" 5 kg as meaning that the bottle has a mass of 5 kg and is attracted to the earth's surface with a force equal to

$$(5 \text{ kg})(9.80 \text{ m/s}^2) = 49(\text{kg})(\text{m})(\text{s}^{-2}) \qquad \text{if } g = 9.80 \text{ m/s}^2$$

Perhaps one of these days people will speak of "massing" instead of "weighing" and "mass-minding" instead of "weight-watching," but probably not soon. **In this book, we will not subscript the symbol lb with m (for mass) or f (for force)** unless it becomes essential to do so to avoid confusion. **We will always mean by the unit lb without a subscript the quantity pound mass.**

EXAMPLE 1.4 Use of g_c

One hundred pounds of water is flowing through a pipe at the rate of 10.0 ft/s. What is the kinetic energy of this water in $(\text{ft})(\text{lb}_f)$?

Solution

$$\text{kinetic energy} = K = \tfrac{1}{2}mv^2$$

Assume that the 100 lb of water means the mass of the water.

$$K = \frac{1}{2}\left|\frac{100 \text{ lb}_m}{}\right|\left(\frac{10 \text{ ft}}{\text{s}}\right)^2\left|\frac{}{32.174\dfrac{(\text{ft})(\text{lb}_m)}{(\text{s}^2)(\text{lb}_f)}}\right| = 155 \ (\text{ft})(\text{lb}_f)$$

EXAMPLE 1.5 Use of g_c

What is the potential energy in $(\text{ft})(\text{lb}_f)$ of a 100-lb drum hanging 10 ft above the surface of the earth with reference to the surface of the earth?

Solution

$$\text{potential energy} = P = mgh$$

Assume that the 100 lb means 100 lb mass; g = acceleration of gravity = 32.2 ft/s^2.

$$P = \frac{100\ \text{lb}_m \mid 32.2\ \text{ft} \mid 10\ \text{ft} \mid}{\mid \text{s}^2 \mid \mid 32.174\dfrac{(\text{ft})(\text{lb}_m)}{(\text{s}^2)(\text{lb}_f)}} = 1001\ (\text{ft})(\text{lb}_f)$$

Notice that in the ratio of g/g_c, or 32.2 ft/s^2 divided by 32.174 (ft/s^2)(lb$_m$/lb$_f$), the numerical values are almost equal. A good many people would solve the problem by saying that 100 lb × 10 ft = 1000 (ft)(lb) without realizing that in effect they are canceling out the numbers in the g/g_c ratio.

EXAMPLE 1.6 Weight

What is the difference in the weight in newtons of a 100-kg rocket at height of 10 km above the surface of the earth, where g = 9.76 m/s^2, as opposed to its weight on the surface of the earth, where g = 9.80 m/s^2?

Solution

The weight in newtons can be computed in each case from Eq. (1.1) with $a = g$ if we ignore the tiny effect of centripetal acceleration resulting from the rotation of the earth (less than 0.3%):

$$\text{weight difference} = \frac{100\ \text{kg} \mid (9.80 - 9.76)\,\text{m} \mid 1\ \text{N}}{\mid \text{s}^2 \mid \dfrac{(\text{kg})(\text{m})}{\text{s}^2}} = 4.00\ \text{N}$$

Note that the concept of weight is not particularly useful in treating the dynamics of long-range ballistic missiles or of earth satellites because the earth is both round and rotating.

You should develop some facility in converting units from the SI system into the American engineering system, and vice versa, since these are the two sets of units in this text. Certainly you are familiar with the **common conversions** in both the American engineering and the SI systems. If you have forgotten, Table 1.3 lists a short selection of essential conversion factors. Memorize them. Common abbreviations and symbols also appear in this table.

The distinction between uppercase and lowercase letters should be followed, even if the symbol appears in applications where the other lettering is in uppercase style. Unit abbreviations have the same form for both singular and plural, and they are not followed by a period (except in the case of inches).

Other useful conversion factors are discussed in subsequent sections of this book.

One of the best features of the SI system is that (except for time) units and their multiples and submultiples are related by standard factors designated by the prefixes indicated in Table 1.4. Prefixes are not preferred for use in denominators (except for

TABLE 1.3 Basic Conversion Factors*

Dimension	American engineering	SI	Conversion: American engineering to SI
Length	12 in. = 1 ft 3 ft = 1 yd 5280 ft = 1 mi	10 mm† = 1 cm† 100 cm† = 1 m	1 in. = 2.54 cm 3.28 ft = 1 m
Volume	1 ft^3 = 7.48 gal	1000 cm^3† = 1 L†	35.31 ft^3 = 1.00 m^3
Density	1 ft^3 H_2O = 62.4 lb_m	1 cm^3† H_2O = 1 g 1 m^3 H_2O = 1000 kg	—
Mass	1 ton_m = 2000 lb_m‡	1000 g = 1 kg	1 lb = 0.454 kg
Time	1 min = 60 s 1 hr = 60 min	1 min† = 60 s 1 h† = 60 min†	—

*Some conversion factors in this table are approximate but have sufficient precision for engineering calculations.
†An acceptable but not preferred unit in the SI system.
‡2000 lb_m is the "short ton"; 2240 lb_m is the "long ton"; 1000 kg = 2204.6 lb_m is the "metric ton."

TABLE 1.4 SI Prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{18}	exa	E	10^{-1}	deci*	d
10^{15}	penta	P	10^{-2}	centi*	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto*	h	10^{-15}	femto	f
10^{1}	deka*	da	10^{-18}	atto	a

*Avoid except for areas and volumes.

kg). Do not use double prefixes; that is, use nanometer, not millimicrometer. The strict use of these prefixes leads to some amusing combinations of noneuphonious sounds, such as nanonewton, nembujoule, and so forth. Also, some confusion is certain to arise because the prefix M can be confused with m as well as with M = 1000 derived from the Roman numerical. When a compound unit is formed by multiplication of two or more other units, its symbol consists of the symbols for the separate units joined by a centered dot (e.g., N · m for newton meter). The dot may be omitted in the case of familiar units such as watthour (symbol Wh) if no confusion will result, or if the symbols are separated by exponents, as in $N \cdot m^2 kg^{-2}$. Hy-