الجامعة التكنولوجية

قسم الهندسة الكيمياوية

المرحلة الاولى

مباديء الهندسة الكيمياوية

م.د. خالد تركي راشد

Chapter 1

Dimensions, Units, and Their Conversion

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, and hours or seconds for time.

In this lectures you will use the two most commonly used systems of units:

1. **SI**, formally called Le Systeme Internationale d'Unites, and informally called SI or more often (redundantly) the SI system of units.
2. **AE**, or American Engineering system of units.

Dimensions and their respective units are classified as fundamental or derived:

- **Fundamental** (or basic) dimensions/units are those that can be measured independently and are sufficient to describe essential physical quantities.
- **Derived** dimensions/units are those that can be developed in terms of the fundamental dimensions/units.

Tables 1.1 and 1.2 list both basic, derived, and alternative units in the SI and AE systems. Figure 1.1 illustrates the relation between the basic dimensions and some of the derived dimensions.

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 **prefix** indicated in Table 1.3.

1.2 Operations with Units

The rules for handling units are essentially quite simple:

1.2.1 Addition, Subtraction, Equality

You can add, subtract, or equate numerical quantities only if the associated units of the quantities are the same. Thus, the operation

5 kilograms + 3 joules

cannot be carried out because the units as well as 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, grams, or ounces, or some other mass unit.

Table 1.1 SI Units

Physical Quantity	Name of Unit	Symbol for Unit*	Definition of Unit
	Basic SI Units		
Length	metre, meter	m	
Mass	kilogramme, kilogram	kg	
Time	second	s	
Temperature	kelvin	K	
Molar amount	mole	mol	
	Derived SI Units		
Energy	joule	J	$kg \cdot m^2 \cdot s^{-2} \rightarrow Pa \cdot m^3$
Force	newton	N	$kg \cdot m \cdot s^{-2} \rightarrow J \cdot m^{-1}$
Power	watt	W	$kg \cdot m^2 \cdot s^{-3} \rightarrow J \cdot s^{-1}$
Density	kilogram per cubic meter		$kg \cdot m^{-3}$
Velocity	meter per second		$m \cdot s^{-1}$
Acceleration	meter per second squared		$m \cdot s^{-2}$
Pressure	newton per square meter, pascal		$N \cdot m^{-2}$, Pa
Heat capacity	joule per (kilogram · kelvin)		$J \cdot kg^{-1} \cdot K^{-1}$
	Alternative Units		
Time	minute, hour, day, year	min, h, d, y	
Temperature	degree Celsius	°C	
Volume	litre, liter (dm^3)	L	
Mass	tonne, ton (Mg), gram	t, g	

Table 1.2 American Engineering (AE) System Units

Physical Quantity	Name of Unit	Symbol
	Some Basic Units	
Length	foot	ft
Mass	pound (mass)	lb_m
Time	second, minute, hour, day	s, min, h (hr), day
Temperature	degree Rankine or degree Fahrenheit	°R or °F
Molar amount	pound mole	lb mol
	Derived Units	
Force	pound (force)	lb_f
Energy	British thermal unit, foot pound (force)	Btu, $(ft)(lb_f)$
Power	horsepower	hp
Density	pound (mass) per cubic foot	lb_m/ft^3
Velocity	feet per second	ft/s
Acceleration	feet per second squared	ft/s^2
Pressure	pound (force) per square inch	$lb_f/in.^2$, psi
Heat capacity	Btu per pound (mass) per degree F	$Btu/(lb_m)(°F)$

Figure 1.1 Relation between the basic dimensions (in boxes) and various derived dimensions (in ellipses).

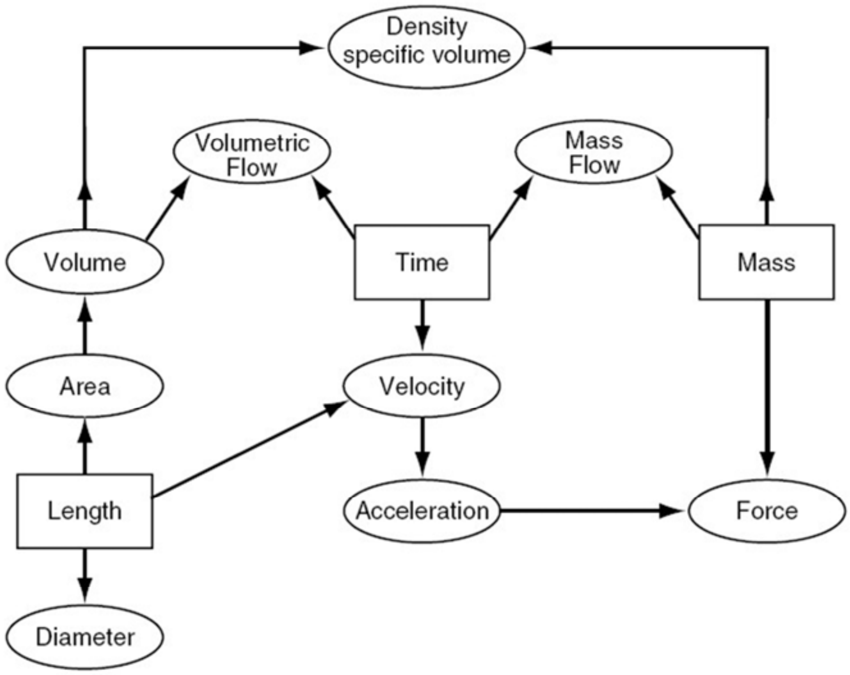

Table 1.3 SI Prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^9	giga	G	10^{-1}	deci	d
10^6	mega	M	10^{-2}	centi	c
10^3	kilo	k	10^{-3}	milli	m
10^2	hecto	h	10^{-6}	micro	μ
10^1	deka	da	10^{-9}	nano	n

1.2.2 Multiplication and Division

You can multiply or divide unlike units at will such as

50(kg)(m)/(s)

but you cannot cancel or merge units unless they are identical. Thus, 3 m^2/60 cm can be converted to 3 m^2/0.6 m, and then to 5 m, but in m/s^2, the units cannot be cancelled or combined.

Example 1.1

Add the following:

(a) 1 foot + 3 seconds (b) 1 horsepower + 300 watts

Solution

The operation indicated by

$$1 \text{ ft} + 3 \text{ s}$$

has no meaning since the dimensions of the two terms are not the same. In the case of

$$1 \text{ hp} + 300 \text{ watts}$$

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 or watts, before the addition can be carried out. Since 1 hp = 746 watts,

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

1.3 Conversion of Units and Conversion Factors

The procedure for converting one set of units to another is simply to multiply any number and its associated units by ratios termed **conversion factors** to arrive at the desired answer and its associated 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?

We formulate the conversion as follows

$$\frac{2 \times 1100 \text{ ft}}{\text{s}} \left| \frac{1 \text{ mi}}{5280 \text{ ft}} \right| \frac{60 \text{ s}}{1 \text{ min}} \left| \frac{60 \text{ min}}{1 \text{ hr}} \right.$$

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

Example 1.2

(a) Convert 2 km to miles. (b) Convert 400 in.^{3}/day to cm^3/min.

Solution

(a) One way to carry out the conversion is to look up a direct conversion factor, namely 1.61 km = 1 mile:

$$\frac{2 \text{ km}}{} \left| \frac{1 \text{ mile}}{1.61 \text{ km}} \right. = 1.24 \text{ mile}$$

Another way is to use conversion factors you know

$$\frac{2 \cancel{\text{km}}}{} \left| \frac{10^5 \cancel{\text{cm}}}{1 \cancel{\text{km}}} \right| \frac{1 \cancel{\text{in.}}}{2.54 \cancel{\text{cm}}} \left| \frac{1 \cancel{\text{ft}}}{12 \cancel{\text{in.}}} \right| \frac{1 \text{ mile}}{5280 \cancel{\text{ft}}} = 1.24 \text{ mile}$$

(b) $$\frac{400 \text{ in.}^3}{\text{day}}\left|\left(\frac{2.54 \text{ cm}}{1 \text{ in.}}\right)^3\right|\frac{1 \text{ day}}{24 \text{ hr}}\left|\frac{1 \text{ hr}}{60 \text{ min}} = 4.55\frac{\text{cm}^3}{\text{min}}\right.$$

In part (b) note that not only are the numbers in the conversion of inches to centimeters raised to a power, but the units also are raised to the same power.

Example 1.3

An example of a semiconductor is ZnS with a particle diameter of 1.8 nanometers. Convert this value to (a) dm (decimeters) and (b) inches.

Solution

$$\text{(a)}\quad \frac{1.8\ \text{nm}}{}\left|\frac{10^{-9}\ \text{m}}{1\ \text{nm}}\right|\frac{10\ \text{dm}}{1\ \text{m}} = 1.8 \times 10^{-8}\ \text{dm}$$

$$\text{(b)}\quad \frac{1.8\ \text{nm}}{}\left|\frac{10^{-9}\ \text{m}}{1\ \text{nm}}\right|\frac{39.37\ \text{in.}}{1\ \text{m}} = 7.09 \times 10^{-8}\ \text{in.}$$

In the AE system the conversion of terms involving pound **mass** and pound **force** deserve special attention. Let us start the discussion with Newton's Law:

$$F = Cma \qquad (1.1)$$

Where:

F = force

C = a constant whose numerical value and its units depend on those selected for F, m, and a, m = mass

a = acceleration

In the SI system in which the unit of force is defined to be the Newton (N) when 1 kg is accelerated at 1 m/s^2, a conversion factor $C = 1\ N/(Kg)(m)/s^2$ must be introduced to have the force be 1 N:

$$F = \underset{\widetilde{C}}{\frac{1\ \text{N}}{\frac{(\text{kg})(\text{m})}{\text{s}^2}}}\left|\underset{\widetilde{m}}{\frac{1\ \text{kg}}{}}\right|\underset{\widetilde{a}}{\frac{1\ \text{m}}{\text{s}^2}} = 1\ \text{N} \qquad (1.1)$$

Because the numerical value associated with the conversion factor is **1**, the conversion factor seems simple, even nonexistent, and the units are ordinarily ignored.

In the **AE** system an analogous conversion factor is required. If a mass of 1 $1b_m$ is hypothetically accelerated at g ft/s^2, where g is the acceleration that would be caused by gravity (about 32.2 ft/s^2 depending on the location of the mass), we can make the force be 1 $1b_f$ by choosing the proper numerical value and units for the conversion factor C:

$$F = \underbrace{\left(\frac{1(\text{lb}_f)(s^2)}{32.174(\text{lb}_m)(\text{ft})}\right)}_{\widetilde{C}}\left(\underbrace{\frac{1\ \text{lb}_m}{}}_{\widetilde{m}}\Bigg|\underbrace{\frac{g\ \text{ft}}{s^2}}_{\widetilde{g}}\right) = 1\ \text{lb}_f \qquad (1.2)$$

The inverse of the conversion factor with the numerical value **32.174** included is given the special symbol $\mathbf{g_c}$ (Note: in eq. [1.2], g=32.2 ft/s^2)

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

But never forget that the pound (**mass**) and pound (**force**) are not the same units in the **AE** system.

1 lbf= 32.174 lbm ft/s^2

Example 1.4

What is the potential energy in (ft)(1b$_f$) of a 100 lb drum hanging 10 ft above the surface of the earth with reference to the surface of the earth?

Solution

Potential energy = P = m g h

Assume that the 100 lb means 100 lb mass; *g* = acceleration of gravity = 32.2 ft/s^2. Figure E1.4 is a sketch of the system.

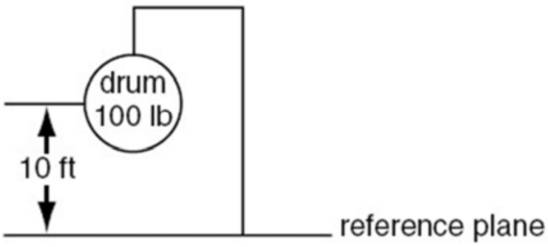

Figure E1.4

$$P = \frac{100\ \text{lb}_m}{}\Bigg|\frac{32.2\ \text{ft}}{\text{s}^2}\Bigg|\frac{10\ \text{ft}}{}\Bigg|\frac{(\text{s}^2)(\text{lb}_f)}{32.174(\text{ft})(\text{lb}_m)} = 1000\ (\text{ft})(\text{lb}_f)$$

Notice that in the ratio of **32.2 ft/s^2** divided by **32.174[(ft)(lb_m)]/[(s^2)(lb_f)]**, the numerical values are almost equal. Many engineers would solve the problem by saying that **100 lb × 10 ft = 1000 (ft)(1b)** without realizing that, in effect, they are canceling out the numbers in the **g/g_c** ratio, and that the lb in the solution means lb_f.

Example 1.5

In biological systems, production rate of glucose is 0.6 μg mol/(mL)(min). Determine the production rate of glucose for this system in the units of lb mol/(ft^3)(day).

Solution

Basis: 1 min

$$\frac{0.6\ \mu\text{g mol}}{(\text{mL})(\text{min})}\left|\frac{1\text{ g mol}}{10^6\ \mu\text{g mol}}\right|\frac{1\text{ lb mol}}{454\text{ g mol}}\left|\frac{1000\text{ mL}}{1\text{ L}}\right|\frac{1\text{ L}}{3.531\times 10^{-2}\text{ ft}^3}\left|\frac{60\text{ min}}{\text{hr}}\right|\frac{24\text{ hr}}{\text{day}}$$

$$= 0.0539\frac{\text{lb mol}}{(\text{ft}^3)(\text{day})}$$

1.4 Dimensional Consistency (Homogeneity)

The concept of dimensional consistency can be illustrated by an equation that represents the pressure/volume/temperature behavior of a gas, and is known as van der Waals's equation.

$$\left(p + \frac{a}{V^2}\right)(V - b) = RT$$

Inspection of the equation shows that the constant **a** must have the units of **[(pressure)(volume)^2]** for the expression in the first set of parentheses to be consistent throughout. If the units of pressure are **atm** and those of volume are **cm^3**, a will have the units of **[(atm)(cm)^6]**. Similarly, **b** must have the same units as **V**, or in this particular case the units of **cm^3**.

Example 1.6

Your handbook shows that microchip etching roughly follows the relation

$$d = 16.2 - 16.2e^{-0.021t} \quad t < 200$$

where d is the depth of the etch in microns (micrometers, μm) and t is the time of the etch in seconds. What are the units associated with the numbers 16.2 and 0.021? Convert the relation so that d becomes expressed in inches and t can be used in minutes.

Solution

Both values of **16.2** must have the associated units of microns (**μm**). The **exponential** must be **dimensionless** so that **0.021** must have the associated units of **s^{-1}**.

$$d_{\text{in}} = \frac{16.2\ \mu\text{m}}{}\left|\frac{1\ \text{m}}{10^6\ \mu\text{m}}\right|\frac{39.27\ \text{in.}}{1\ \text{m}}\left[1 - \exp\frac{-0.021}{s}\left|\frac{60s}{1\ \text{min}}\right|\frac{t_{\text{min}}}{}\right]$$
$$= 6.38 \times 10^{-4}(1 - e^{-1.26t_{\text{min}}})\ \text{inches}$$

Nondimensional Groups:

As you proceed with the study of chemical engineering, you will find that groups of symbols may be put together, either by theory or based on experiment, that have no net units. Such collections of variables or parameters are called **dimensionless** or **nondimensional groups**. One example is the Reynolds number (group) arising in fluid mechanics.

$$\text{Reynolds number} = \frac{Dv\rho}{\mu} = N_{RE}$$

where ***D*** is the pipe diameter, say in cm; ***v*** is the fluid velocity, say in cm/s; ***ρ*** is the fluid density, say in g/cm^3; and ***μ*** is the viscosity, say in centipoise, units that can be converted to **g/(cm)(s)**. Introducing the consistent set of units for ***D***, ***v***, ***ρ***, and ***μ*** into ***Dvρ/μ***, you will find that all the units cancel out so that the numerical value of **1** is the result of the cancellation of the units.

$$\frac{\not{cm}}{}\left|\frac{\not{cm}}{\not{s}}\right|\frac{\not{g}}{\not{cm}^3}\left|\frac{(\not{cm})\ (\not{s})}{\not{g}}\right.$$

Example 1.7

Explain without differentiating why the following differentiation cannot be correct:

$$\frac{d}{dx}\sqrt{1 + (x^2/a^2)} = \frac{2ax}{\sqrt{1 + (x^2/a^2)}}$$

where *x* is length and *a* is a constant.

Solution

- Observe that x and a must have the same units because the ratio x^2/a^2 must be dimensionless (because 1 is dimensionless).
- Thus, the left-hand side of the equation has units of $1/x$ (from d/dx). However, the right-hand side of the equation has units of x^2 (the product of ax).
- Consequently, something is wrong as the equation is not dimensionally consistent.

Questions

1. Which of the following best represents the force needed to lift a heavy suitcase?

   a. 25 N b. 25 kN c. 250 N d. 250 kN

2. Pick the correct answer(s); a watt is

   a. one joule per second b. equal to 1 (kg)(m^2)/s^2 c. the unit for all types of power

   d. all of the above e. none of the above

3. Is kg/s a basic or derived unit in SI?
4. Answer the following questions yes or no. Can you

   a. divide ft by s? **b.** divide m by cm? **c.** multiply ft by s? **d.** divide ft by cm? **e.** divide m by (deg) K? **f.** add ft and s? **g.** subtract m and (deg) K **h.** add cm and ft? **i.** add cm and m^2? **j.** add 1 and 2 cm?

5. Why is it not possible to add 1 ft and 1 ft^2?
6. What is g_c?
7. Is the ratio of the numerator and denominator in a conversion factor equal to unity?
8. What is the difference, if any, between pound force and pound mass in the AE system?
9. Could a unit of force in the SI system be kilogram force?
10. Contrast the procedure for converting units within the SI system with that for the A E system.
11. What is the weight of a one pound mass at sea level? Would the mass be the same at the center of Earth? Would the weight be the same at the center of Earth?
12. What is the mass of an object that weighs 9.80 kN at sea level?
13. Explain what dimensional consistency means in an equation.
14. Explain why the so-called dimensionless group has no net dimensions.
15. If you divide all of a series of terms in an equation by one of the terms, will the resulting series of terms be dimensionless?
16. How might you make the following variables dimensionless:

    a. Length (of a pipe). b. Time (to empty a tank full of water).

Answers:

1. (c)
2. (a)
3. Derived.

4. (a) - (e) yes; (f) and (g) no; (h) and (i) no; (j) no.

5. The dimensions are not the same.
6. A conversion factor in the American Engineering system of units.
7. Yes.
8. lb_f is force and lb_m is mass, and the dimensions are different.
9. The unit is not legal in SI.
10. In SI the magnitudes of many of the units are scaled on the basis of 10, in AE. Consequently, the units are often ignored in making conversion in SI.
11. (a) 1 lb_f in the AE system of units; (b) yes; (c) no.
12. 1000 kg.
13. All additive terms on the right-hand side of an equation must have the same dimensions as those on the left-hand side.
14. All of the units cancel out.
15. Yes.
16. (a) Divide by the radius or diameter; (b) divide by the total time to empty the tank, or by a fixed unit of time.

Problems

1. Classify the following units as correct or incorrect units in the SI system:

   a. nm b. K c. sec d. N/mm e. kJ/(s)(m3)
2. Add 1 cm and 1 m.
3. Subtract 3 ft from 4 yards.
4. Divide 3 $m^{1.5}$ by 2 $m^{0.5}$.
5. Multiply 2 ft by 4 lb.
6. What are the value and units of g_c in the SI system?
7. Electronic communication via radio travels at approximately the speed of light (186,000 miles/second). The edge of the solar system is roughly at Pluto, which is 3.6 × 109 miles from Earth at its closest approach. How many hours does it take for a radio signal from Earth to reach Pluto?
8. Determine the kinetic energy of one pound of fluid moving in a pipe at the speed of 3 feet per second.
9. Convert the following from AE to SI units:

   a. 4 lb_m/ft to kg/m b. 1.00 $lb_m/(ft^3)(s)$ to $kg/(m^3)(s)$
10. Convert the following 1.57×10^{-2} g/(cm)(s) to lb_m/(ft)(s)

11. Convert 1.1 gal to ft^3.

12. Convert 1.1 gal to m^3.

13. An orifice meter is used to measure the rate of flow of a fluid in pipes. The flow rate is related to the pressure drop by the following equation

$$u = c\sqrt{\frac{\Delta P}{\rho}}$$

Where u = fluid velocity

Δp = pressure drop 1force per unit area^2

ρ = density of the flowing fluid

c = constant

What are the units of **c** in the SI system of units?

14. The thermal conductivity *k* of a liquid metal is predicted via the empirical equation

$$k = A \exp(B/T)$$

where *k* is in J/(s)(m)(K) and *A* and *B* are constants. What are the units of *A* and *B*?

Answers:

1. (a), (s), (d), (e) are correct**.**
2. Change units to get 101 cm.
3. Change units to get 9 ft.
4. 1.5 m.
5. 8 (ft)(lb).
6. 1, dimensionless.
7. 5.38 hr.
8. 0.14 (ft) (lb_f).
9. a. 5.96 kg/m; b. 16.0 kg/(m^3)(s)
10. $1.06 * 10^{-3}$ lb_m/(ft)(s)
11. 0.15 ft^3
12. $4.16 * 10^{-3}$ m^3.
13. c is dimensionless
14. *A* has the same units as *k*; B has the units of T

Supplementary Problems (Chapter One):

Problem 1

Convert the following quantities to the ones designated :

a. 42 ft^2/hr to cm^2/s.
b. 25 psig to psia.
c. 100 Btu to hp-hr.

Solution

a. $$\frac{42.0\ ft^2}{hr}\left|\left(\frac{1.0\ m}{3.2808\ ft}\right)^2\right|\frac{10^4\ cm^2}{1.0\ m^2}\left|\frac{1\ hr}{3600\ s}\right. = \mathbf{10.8\ cm^2/s}$$

b. $$\frac{100\ Btu}{}\left|\frac{3.93\times 10^{-4}\ hp\text{-}hr}{1\ Btu}\right. = \mathbf{3.93\times 10^{-2}\ hp\text{-}hr}$$

c. $$\frac{80.0\ lb_f}{}\left|\frac{32.174\ (lb_m)(ft)}{(lb_f)(s)^2}\right|\frac{1\ kg}{2.20\ lb_m}\left|\frac{1\ m}{3.2808\ ft}\right|\frac{1\ N}{1\ (kg)(m)(s)^{-2}} = \mathbf{356\ N}$$

Problem 2

Convert the ideal gas constant : $R = 1.987\ \frac{cal}{(gmol)(K)}$ to $\frac{Btu}{(lb\ mol)(°R)}$

Solution

$$\frac{1.987\ cal}{(gmol)(K)}\left|\frac{1\ Btu}{252\ cal}\right|\frac{454\ gmol}{1\ lb\ mol}\left|\frac{1\ K}{1.8\ °R}\right. = \mathbf{1.98\ \frac{Btu}{(lb\ mol)(°R)}}$$

Problem 3

Mass flow through a sonic nozzle is a function of gas pressure and temperature. For a given pressure p and temperature T, mass flow rate through the nozzle is given by

$$m = 0.0549\ p\ /(T)^{0.5} \quad \text{where m is in lb/min, p is in psia and T is in °R}$$

a. Determine what the units for the constant 0.0549 are.
b. What will be the new value of the constant, now given as 0.0549, if the variables in the equation are to be substituted with SI units and m is calculated in SI units.

Solution

a. Calculation of the constant.

The first step is to substitute known units into the equation.

$$\frac{lb_m}{min} = 0.0549 \; \frac{lb_f}{(in^2)(°R)^{0.5}}$$

$$\frac{lb_f}{(in^2)(°R)^{0.5}} \left| \frac{(lb_m)(in)^2(°R)^{0.5}}{(min)(lb_f)} \right. \quad \text{------>} \quad \frac{(lb_m)}{(min)}$$

Units for the constant 0.0549 are $\frac{(lb_m)(in)^2(°R)^{0.5}}{(min)(lb_f)}$

b. To determine the new value of the constant, we need to change the units of the constant to appropriate SI units using conversion factors.

$$\frac{0.0549\ (lb_m)(in^2)(°R)^{0.5}}{(lb_f)(min)} \left| \frac{(0.454\ kf)}{(1\ lb_m)} \right| \frac{(14.7\ lb_f / in^2)}{101.3\ \times\ 10^3 N/m^2} \left| \frac{(1\ min)}{(60\ s)} \right| \frac{(1K)^{0.5}}{(1.8\ °R)^{0.5}} \left| \frac{(p)}{(T)^{0.5}} \right.$$

$$\mathbf{m \quad = \quad 4.49 \ \times \ 10^{-8}\ (m)\ (s)\ (K)^{0.5}\ \frac{(p)}{(T)^{0.5}}}$$

Substituting pressure and temperature in SI units

$$m \quad = \quad 4.49 \ \times \ 10^{-8}\ (m)\ (s)\ (K)^{0.5}\ \frac{(p)(N/\ m^2)}{(T)^{0.5}(K)^{0.5}} \left| \frac{1\ kg/(m)(s)^2}{1\ N/m^2} \right.$$

$$\mathbf{m\ \frac{(kg)}{(s)} \quad = \quad 4.49 \ \times \ 10^{-8} \frac{(p)}{(T)^{0.5}}}$$ where p is in N/m^2 and T is in K

<u>Problem 4</u>

An empirical equation for calculating the inside heat transfer coefficient, h_i, for the turbulent flow of liquids in a pipe is given by:

$$h_i = \frac{0.023\ G^{0.8}\ K^{0.67}\ Cp^{0.33}}{D^{0.2}\ \mu^{0.47}}$$

where h_i = heat transfer coefficient, Btu/(hr)(ft)^2(°F)
G = mass velocity of the liquid, lb_m/(hr)(ft)^2
K = thermal conductivity of the liquid, Btu/(hr)(ft)(°F)
C_p = heat capacity of the liquid, Btu/(lb_m)(°F)
μ = Viscosity of the liquid, lb_m/(ft)(hr)
D = inside diameter of the pipe, (ft)

a. Verify if the equation is dimensionally consistent.
b. What will be the value of the constant, given as 0.023, if all the variables in the equation are inserted in SI units and h_i is in SI units.

Solution

a. First we introduce American engineering units into the equation:

$$h_i = \frac{0.023\left[(lb_m)/(ft)^2(hr)\right]^{0.80}}{(ft)^{0.2}} \frac{\left[Btu/(hr)(ft)(°F)\right]^{0.67}\left[Btu/(lb_m)(°F)\right]^{0.33}}{\left[lb_m/(ft)(hr)\right]^{0.47}}$$

$$h_i = \frac{0.023(Btu)^{0.67} \quad (lb_m)^{0.8}}{[(lb_m)^{0.33}(lb_m)^{0.47}]} \left| \frac{(ft)^{0.47}}{[(ft)^{1.6}(ft)^{0.67}(ft)^{0.2}]} \right| \frac{(1)}{[(°F)^{0.67}(°F)^{0.33}]} \left| \frac{(hr)^{0.47}}{[(hr)^{0.8}(hr)^{0.67}]} \right.$$

$$h_i = 0.023 \quad \frac{Btu}{(hr)(ft)^2\ (°F)}$$

The equation is dimensionally consistent.

b. The constant 0.023 is dimensionless; a change in units of the equation parameters will not have any effect on the value of this constant.

Chapter 2

2.1 The Mole Moles, Density and Concentration

In the SI system a mole is composed of 6.022 x 10^{23} molecules (**Avogadro's number**). To convert the number of moles to mass and the mass to moles, we make use of the **molecular weight** – the mass per mole:

$$\text{Molecular Weight (MW)} = \frac{\text{Mass}}{\text{Mole}}$$

Thus, the calculations you carry out are

$$\text{the g mol} = \frac{\text{mass in g}}{\text{molecular weight}}$$

$$\text{the lb mol} = \frac{\text{mass in lb}}{\text{molecular weight}}$$

and

$$\text{Mass in g} = (\text{MW})\ (\text{g mol})$$

$$\text{Mass in lb} = (\text{MW})\ (\text{lb mol})$$

For example

$$\frac{100.0 \text{ g } H_2O}{} \left| \frac{1 \text{ g mol } H_2O}{18.0 \text{ g } H_2O} \right. = 5.56 \text{ g mol } H_2O$$

$$\frac{6.0 \text{ lb mol } O_2}{} \left| \frac{32.0 \text{ lb } O_2}{1 \text{ lb mol } O_2} \right. = 192 \text{ lb } O_2$$

- **The atomic weight** of an element is the mass of an atom based on the scale that assigns a mass of exactly 12 to the carbon isotope ^{12}C.
- A **compound** is composed of more than one atom, and the molecular weight of the compound is nothing more than the sum of the weights of atoms of which it is composed.

Example 2.1

What is the molecular weight of the following cell of a superconductor material? (The figure represents one cell of a larger structure.)

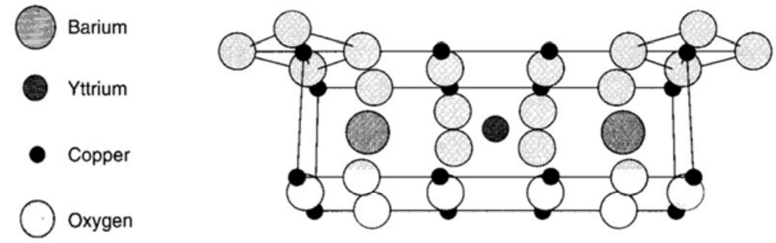

Figure E2.1

Solution

Element	Number of atoms	Atomic weights	Mass (g)
Ba	2	137.34	2(137.34)
Cu	16	63.546	16(63.546)
O	24	16.00	24(16.00)
Y	1	88.905	1(88.905)
		Total	1764.3

The molecular weight of the cell for each mole is 1764.3 g/g mol.

Example 2.2

If a bucket holds 2.00 lb of NaOH (MW=40), how many

a) Pound moles of NaOH does it contain?

b) Gram moles of NaOH does it contain?

Solution

$$\textbf{(a)}\quad \frac{2.00 \text{ lb NaOH}}{}\left|\frac{1 \text{ lb mol NaOH}}{40.0 \text{ lb NaOH}}\right. = 0.050 \text{ lb mol NaOH}$$

$$\textbf{(b}_1\textbf{)}\quad \frac{2.00 \text{ lb NaOH}}{}\left|\frac{1 \text{ lb mol NaOH}}{40.0 \text{ lb NaOH}}\right|\frac{454 \text{ g mol}}{1 \text{ lb mol}} = 22.7 \text{ g mol}$$

$$\textbf{(b}_2\textbf{)}\quad \frac{2.00 \text{ lb NaOH}}{}\left|\frac{454 \text{ g}}{1 \text{ lb}}\right|\frac{1 \text{ g mol NaOH}}{40.0 \text{ g NaOH}} = 22.7 \text{ g mol}$$

Example 2.3

How many pounds of NaOH (MW=40) are in 7.50 g mol of NaOH?

Solution

$$\frac{7.50 \text{ g mol NaOH}}{}\left|\frac{1 \text{ lb mol}}{454 \text{ g mol}}\right|\frac{40.0 \text{ lb NaOH}}{1 \text{ lb mol NaOH}} = 0.661 \text{ lb NaOH}$$

2.2 Density

Density is the ratio of mass per unit volume, as for example, kg/m^3 or lb/ft^3. Density has both a numerical value and units. **Specific volume** is the inverse of density, such as cm^3/g or ft^3/lb.

$$\rho = \text{density} = \frac{\text{mass}}{\text{volume}} = \frac{m}{V}$$

$$\hat{V} = \text{specific volume} = \frac{\text{volume}}{\text{mass}} = \frac{V}{m}$$

For example, given that the density of n-propyl alcohol is 0.804 g/cm^3, what would be the volume of 90.0 g of the alcohol? The calculation is

$$\frac{90.0\ \text{g}}{} \left| \frac{1\ \text{cm}^3}{0.804\ g} \right. = 112\ \text{cm}^3$$

❖ In a packed bed of solid particles containing void spaces, the bulk density is

$$\rho_B = \text{bulk density} = \frac{\text{total mass of solids}}{\text{total empty bed volume}}$$

❖ A homogeneous mixture of two or more components, whether solid, liquid, or gaseous, is called a **solution**.

For some solutions, the density of the solution is

$$V = \sum_{i=1}^{n} V_i \qquad \text{where } n = \text{number of components}$$

$$m = \sum_{i=1}^{n} m_i$$

$$\rho_{\text{solution}} = \frac{m}{V}$$

For others you cannot.

2.3 Specific Gravity الثقل النوعي

Specific gravity is commonly thought of as a dimensionless ratio.

$$\text{sp.gr. of } A = \textbf{specific gravity} \text{ of } A = \frac{(\text{g/cm}^3)_A}{(\text{g/cm}^3)_{ref}} = \frac{(\text{kg/m}^3)_A}{(\text{kg/m}^3)_{ref}} = \frac{(\text{lb/ft}^3)_A}{(\text{lb/ft}^3)_{ref}}$$

- The reference substance for **liquids** and **solids** normally is **water**.
- The density of water is **1.000 g/cm^3, 1000 kg/m^3, or 62.43 lb/ft^3 at 4°C**.
- The specific gravity of **gases** frequently is referred to **air**, but may be referred to other gases.

For Example If dibromopentane (DBP) has a specific gravity of 1.57, what is the density in (a) g/cm^3? (b) lb$_m$/ft^3? and (c) kg/m^3?

(a)

$$\frac{1.57\dfrac{\text{g DBP}}{\text{cm}^3}}{1.00\dfrac{\text{g H}_2\text{O}}{\text{cm}^3}}\left|\frac{1.00\dfrac{\text{g H}_2\text{O}}{\text{cm}^3}}{}\right. = 1.57\frac{\text{g DBP}}{\text{cm}^3}$$

(b)

$$\frac{1.57\dfrac{\text{lb DBP}}{\text{ft}^3}}{1.00\dfrac{\text{lb H}_2\text{O}}{\text{ft}^3}}\left|\frac{62.4\dfrac{\text{lb H}_2\text{O}}{\text{ft}^3}}{}\right. = 97.97\frac{\text{lb DBP}}{\text{ft}^3}$$

(c)

$$\frac{1.57\text{g DBP}}{\text{cm}^3}\left|\left(\frac{100\text{ cm}}{1\text{ m}}\right)^3\right|\frac{1\text{ kg}}{1000\text{ g}} = 1.57\times10^3\frac{\text{kg DBP}}{\text{m}^3}$$

or

$$\frac{1.57\dfrac{\text{kg DBP}}{\text{m}^3}}{1.00\dfrac{\text{kg H}_2\text{O}}{\text{m}^3}}\left|\frac{\dfrac{1.00\times10^3\text{kg H}_2\text{O}}{\text{m}^3}}{}\right. = 1.57\times10^3\frac{\text{kg DBP}}{\text{m}^3}$$

<u>Example 2.4</u>

If a 70% (by weight) solution of glycerol has a specific gravity of 1.184 at 15°C, what is the density of the solution in (a) g/cm^3? (b) lbm/ft^3? and (c) kg/m^3?

Solution

(a) (1.184 g glycerol/ cm^3)/(1 g water/ cm^3) * (1 g water/ cm^3) = 1.184 g solution/cm^3.

(b) (1.184 lb glycerol/ft^3)/(1 lb water/ft^3) * (62.4 lb water/ft^3) = 73.9 lb solution/ft^3.

(c) (1.184 kg glycerol/m^3)/(1 kg water/m^3) * (1000 kg water/m^3) = 1.184 * 10^3 kg solution/m^3.

The specific gravity of petroleum products is often reported in terms of a hydrometer scale called °API (American Petroleum Institute). The equation for the API scale is

$$°\text{API} = \frac{141.5}{\text{sp.gr.}\frac{60°\text{F}}{60°\text{F}}} - 131.5 \qquad (\text{API gravity}) \qquad (2.1)$$

or

$$\text{sp.gr.}\frac{60°}{60°} = \frac{141.5}{°\text{API} + 131.5} \quad . \qquad (2.2)$$

60 °F = 15 °C Note: T°F = 1.8 T°C +32T°C= T°F -32/1.8

The **volume** and therefore the **<u>density</u>** of petroleum products vary with **<u>temperature</u>**, and the petroleum industry has established 60 °F as the standard temperature for volume and API gravity.

<u>Example 2.5</u>

In the production of a drug having a molecular weight of 192, the exit stream from the reactor flows at a rate of 10.5 L/min. The drug concentration is 41.2% (in water), and the specific gravity of the solution is 1.024. Calculate the concentration of the drug (in kg/L) in the exit stream, and the flow rate of the drug in kg mol/min.

Solution

Take 1 kg of the exit solution as a basis for convenience.

Basis: 1 kg solution

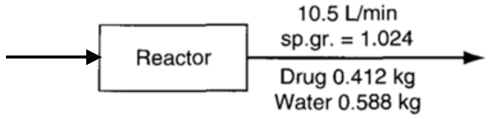

Figure E2.5

$$\text{density of solution} = \frac{1.024\,\frac{\text{g soln}}{\text{cm}^3}}{1.000\,\frac{\text{g } H_2O}{\text{cm}^3}} \left| \frac{1.000\,\frac{\text{g } H_2O}{\text{cm}^3}}{} \right. = 1.024\,\frac{\text{g soln}}{\text{cm}^3}$$

$$\frac{0.412 \text{ kg drug}}{1.000 \text{ kg soln}} \left| \frac{1.024 \text{ g soln}}{1 \text{ cm}^3} \right| \frac{1 \text{ kg}}{10^3 \text{ g}} \left| \frac{10^3 \text{cm}^3}{1 \text{ L}} \right. = 0.422 \text{ kg drug/L soln}$$

To get the flow rate, take a different basis, namely 1 minute.

Basis: 1 min = 10.5 L solution

$$\frac{10.5 \text{ L soln}}{1 \text{ min}}\left|\frac{0.422 \text{ kg drug}}{1 \text{ L soln}}\right|\frac{1 \text{ kg mol drug}}{192 \text{ kg drug}} = 0.023 \text{ kg mol/min}$$

2.4 Flow Rate

For continuous processes the **flow rate** of a process stream is the rate at which material is transported through a pipe. The **mass flow rate** (**$\dot{m}$**) of a process stream is the **mass** (**m**) transported through a line per unit **time** (**t**).

$$\dot{m} = \frac{m}{t}$$

The **volumetric flow rate (F)** of a process stream is the **volume (V)** transported through a line per unit **time**.

$$F = \frac{V}{t}$$

The **molar flow (ṇ) rate** of a process stream is the number of **moles** (**n**) of a substance transported through a line per unit **time**.

$$\dot{n} = \frac{n}{t}$$

2.5 Mole Fraction and Mass (Weight) Fraction

- ☒ **Mole fraction** is simply the number of moles of a particular compound in a mixture or solution divided by the total number of moles in the mixture or solution.
- ☒ This definition holds for **gases**, **liquids**, and **solids**.
- ☒ Similarly, the **mass (weight) fraction** is nothing more than the **mass (weight)** of the compound divided by the total mass (weight) of all of the compounds in the mixture or solution.

Mathematically, these ideas can be expressed as

$$\text{mole fraction of } A = \frac{\text{moles of } A}{\text{total moles}}$$

$$\text{mass (weight) fraction of } A = \frac{\text{mass of } A}{\text{total mass}}$$

Mole percent and **mass (weight) percent** are the respective fractions times **100**.

Example 2.6

An industrial-strength drain cleaner contains 5 kg of water and 5 kg of NaOH. What are the mass (weight) fractions and mole fractions of each component in the drain cleaner container?

Solution

Basis: 10 kg of total solution

Component	kg	Weight fraction	Mol. Wt.	kg mol	Mole fraction
H_2O	5.00	$\frac{5.00}{10.0} = 0.500$	18.0	0.278	$\frac{0.278}{0.403} = 0.69$
NaOH	5.00	$\frac{5.00}{10.00} = 0.500$	40.0	0.125	$\frac{0.125}{0.403} = 0.31$
Total	10.00	1.000		0.403	1.00

The kilogram moles are calculated as follows:

$$\frac{5.00 \text{ kg } H_2O}{} \Big| \frac{1 \text{ kg mol } H_2O}{18.0 \text{ kg } H_2O} = 0.278 \text{ kg mol } H_2O$$

$$\frac{5.00 \text{ kg NaOH}}{} \Big| \frac{1 \text{ kg mol NaOH}}{40.0 \text{ kg NaOH}} = 0.125 \text{ kg mol NaOH}$$

Adding these quantities together gives the total kilogram moles.

Example 2.7

In normal living cells, the nitrogen requirement for the cells is provided from protein metabolism (i.e., consumption of the protein in the cells). When individual cells are commercially grown, $(NH_4)_2SO_4$ is usually used as the source of nitrogen. Determine the amount of $(NH_4)_2SO_4$ consumed in a fermentation medium in which the final cell concentration is 35 g/L in a 500 L volume of the fermentation medium. Assume that the cells contain 9 wt. % N, and that $(NH_4)_2SO_4$ is the only nitrogen source.

Solution

Basis: 500 L solution containing 35 g/L

$$\frac{500 \text{ L}}{} \Big| \frac{35 \text{ g cell}}{\text{L}} \Big| \frac{0.09 \text{ g N}}{1 \text{ g cell}} \Big| \frac{1 \text{ g mol N}}{14 \text{ g N}} \times \Big| \frac{1 \text{ g mol } (NH_4)_2SO_4}{2 \text{ g mol N}} \Big| \frac{132 \text{ g } (NH_4)_2SO_4}{1 \text{ g mol } (NH_4)_2SO_4} = 7425 \text{ g } (NH_4)_2SO_4$$

2.6 Analyses of Multicomponent Solutions and Mixtures

The **composition of gases** will always be assumed to be given in **mole percent** or **fraction** unless specifically stated otherwise.

The **composition of liquids** and **solids** will be given by **mass (weight) percent** or **fraction** unless otherwise specifically stated.

For Example Table below lists the detailed composition of dry air (composition of air 21% O_2 and 79% N_2). Calculate the average molecular weight of air?

Basis 100 mol of air

Component	Moles = percent	Mol. wt.	Lb or kg	Weight %
O_2	21.0	32	672	23.17
N_2	79.0	28.2	2228	76.83
Total	100		2900	100.00
The average molecular weight is 2900 lb/100 lb mol = 29.0, or 2900 kg/100 kg mol = 29				

2.7 Concentration

Concentration generally refers to the quantity of some substance per unit volume.

a. Mass per unit volume (lb of solute/ft^3 of solution, g of solute/L, lb of solute/barrel, kg of solute/m^3).

b. Moles per unit volume (lb mol of solute/ft^3 of solution, g mol of solute/L, g mol of solute/cm^3).

c. Parts per million (**ppm**); parts per billion (**ppb**), a method of expressing the concentration of extremely dilute solutions; **ppm is equivalent to a mass (weight) fraction for solids and liquids** because the total amount of material is of a much higher order of magnitude than the amount of solute; it is a **mole fraction for gases**.

d. Parts per million by volume (ppmv) and parts per billion by volume (ppbv)

e. Other methods of expressing concentration with which you may be familiar are molarity (g mol/L), molality (mole solute/kg solvent), and normality (equivalents/L).

Example 2.8

The current Occupational Safety and Health Administration (OSHA) 8-hour limit for Hydrogen cyanide (HCN) (boils at 25.6 °C) (MW = 27.03) in air is 10.0 ppm. A lethal dose of HCN in air is (from the Merck Index) 300 mg/kg of air at room temperature. How many mg HCN/kg air is 10 ppm? What fraction of the lethal dose is 10.0 ppm?

Solution

Basis: 1 kg mol of the air/HCN mixture

$$\text{The 10.0 ppm is } \frac{10.0 \text{ g mol HCN}}{10^6(\text{air} + \text{HCN})\text{g mol}} = \frac{10.0 \text{ g mol HCN}}{10^6 \text{ g mol air}}$$

$$\text{a. } \frac{10.0 \text{ g mol HCN}}{10^6 \text{ g mol air}} \left| \frac{27.03 \text{ g HCN}}{1 \text{ g mol HCN}} \right| \frac{1 \text{ g mol air}}{29 \text{ g air}} \left| \frac{1000 \text{ mg HCN}}{1 \text{ g HCN}} \right. \times \frac{1000 \text{ g air}}{1 \text{ kg air}} = 9.32 \text{ mg HCN/kg air}$$

$$\text{b. } \frac{9.32}{300} = 0.031$$

Example 2.9

A solution of HNO_3 in water has a specific gravity of 1.10 at 25°C. The concentration of the HNO_3 is 15 g/L of solution. What is the

a. Mole fraction of HNO_3 in the solution?

b. ppm of HNO_3 in the solution?

Solution

Basis: 1 L of solution

Density= 1.1 × 1g/cm^3 = 1.1 g/cm^3 (density of solution)

$$\frac{15 \text{ g } HNO_3}{1 \text{ L soln}}\left|\frac{1 \text{ L}}{1000 \text{ cm}^3}\right|\frac{1 \text{ cm}^3}{1.10 \text{ g soln}} = 0.01364\frac{\text{g } HNO_3}{\text{g soln}}$$

Basis: 100 g solution

The mass of water in the solution is: 100 – 1.364 = 98.636 g H_2O.

	g	**MW**	**gmol**	**mol fraction**
HNO_3	1.364	63.02	0.02164	0.00394
H_2O	98.636	18.016	5.475	0.99606
Total			5.4966	1

b. $$\frac{0.01364}{1} = \frac{13{,}640}{10^6} \text{ or } 13{,}640 \text{ ppm}$$

Example 2.10

Sulfur trioxide (SO_3) can be absorbed in sulfuric acid solution to form more concentrated sulfuric acid. If the gas to be absorbed contains 55% SO_3, 41% N_2, 3% SO_2, and 1% O_2, how many parts per million of O_2 are there in the gas? What is the composition of the gas on a N_2 free basis?

Solution

(a) $$\frac{1 \text{ mol } O_2}{100 \text{ mol gas}} \Rightarrow \frac{10^4 \text{mol } O_2}{10^6 \text{ mol gas}} \text{ or } 10^4 \text{ ppm}$$

(b) Basis: 100 mol gas

Comp.	% = mol	mol fr. (answer)	or mol %
SO_3	55	0.932	93.2
SO_2	3	0.051	5.1
O_2	1	0.017	1.7
Total	59	1.000	100.0

Example 2.11

To avoid the possibility of explosion in a vessel containing gas having the composition of 40% N_2, 45% O_2, and 15% CH_4, the recommendation is to dilute the gas mixture by adding an equal amount of pure N_2. What is the final mole fraction of each gas?

Solution

The basis is 100 moles of initial gas

Composition	Original Mixture mol%		After Addition N_2	Final Mixture Mole Fraction
N_2	40	+ 100 →	140	140/200 = 0.70
O_2	45		45	45/200 = 0.23
CH_4	15		15	15/200 = 0.07
Total	100		200	1.00

Example 2.12

Calculate the empirical formula of an organic compound with the following mass analysis: carbon, 26.9%; hydrogen, 2.2%; and oxygen as the only other element present.

Solution

Basis: 100 g of compound

	C	H	O
Mass (m) combining / g	26.9	2.2	70.9
Molar mass (M) / g mol^{-1}	12	1	16
Number of moles combining (mass ÷ molar mass)	26.9 / 12 = 2.24	2.2 / 1 = 2.20	70.9 / 16 = 4.43
Ratio of number of moles	2.24 / 2.20 = 1.02	2.20 / 2.20 = 1.00	4.43 / 2.20 = 2.01
Simplest ratio	1	1	2

The empirical formula of this organic compound is $C_1H_1O_2$.

Questions

1. Answer the following questions true or false:
    a. The pound mole is comprised of 2.73 x 10^{26} molecules
    b. The kilogram mole is comprised of 6.022 x 10^{26} molecules.
    c. Molecular weight is the mass of a compound or element per mole.
2. What is the molecular weight of acetic acid (CH3COOH)?
3. For numbers such as 2 mL of water + 2 mL of ethanol, does the sum equal to 4 mL of the solution?
4. Answer the following questions true or false:
    a. The inverse of the density is the specific volume.

b. Density of a substance is the mass per unit volume.
c. The density of water is less than the density of mercury.

5. A cubic centimeter of mercury has a mass of 13.6 g at Earth's surface. What is the density of mercury?
6. What is the approximate density of water at room temperature in kg/m^3?
7. For liquid HCN, a handbook gives: sp. gr. $10^{\circ}C/4^{\circ}C = 1.2675$. What does this statement mean?
8. Answer the following questions true or false:
   a. The density and specific gravity of mercury are the same.
   b. Specific gravity is the ratio of two densities.
   c. If you are given the value of a reference density, you can determine the density of a substance of interest by multiplying by the specific gravity.
   d. The specific gravity is a dimensionless quantity.
9. A mixture is reported as 15% water and 85% ethanol. Should the percentages be deemed to be by mass, mole, or volume?
10. Answer the following questions true or false:
    a) In engineering practice the compositions of liquids and solids are usually denoted in weight (mass) fraction or percent.
    b) In engineering practice the composition of gases is usually denoted in mole fraction or percent.
    c) e. A pseudo-average molecular weight can be calculated for a mixture of pure components whether solid, liquid, or gases.
11. Do parts per million denote a concentration that is a mole ratio?
12. Does the concentration of a component in a mixture depend on the amount of the mixture?
13. Pick the correct answer. How many ppm are there in 1 ppb? (a) 1000, (b) 100, (c) 1, (d) 0.1, (e) 0.01, (f) 0.001?
14. How many ppb are there in 1 ppm?
15. Does 50 ppm represent an increase of five times a value of 10 ppm?

Answers:

1. (a) T; (b) T; (c) T
2. 60.05
3. No
4. (a) T; (b) T; (c) T

5. 13.6 g/cm^3
6. 1000 kg/m^3

7. The statement means that the density at 10°C of liquid HCN is 1.2675 times the density of water at 4°C.
8. (a) F – the units differ; (b) T; (c) T; (d) F.
9. Mass
10. (a) T; (b) T; (c) T
11. For gases but not for liquids or solids.
12. No
13. 0.001
14. 1000
15. No (4 times)

Problems

1. Convert the following:
    a) 120 g mol of NaCl to g.
    b) 120 g of NaCl to g mol.
    c) 120 lb mol of NaCl to lb.
    d) 120 lb of NaCl to lb mol.
2. Convert 39.8 kg of NaCl per 100 kg of water to kg mol of NaCl per kg mol of water.
3. How many lb mol of $NaNO_3$ are there in 100 lb?
4. The density of a material is 2 kg/m^3. What is its specific volume?
5. An empty 10 gal tank weighs 4.5 lb. What is the total weight of the tank plus the water when it is filled with 5 gal of water?
6. If you add 50 g of sugar to 500 mL of water, how do you calculate the density of the sugar solution?
7. For ethanol, a handbook gives: sp. gr. 60°F = 0.79389. What is the density of ethanol at 60°F?
8. The specific gravity of steel is 7.9. What is the volume in cubic feet of a steel ingot weighing 4000 lb?
9. The specific gravity of a solution is 0.80 at 70°F. How many cubic feet will be occupied by 100 lb of the solution at 70°F?
10. A solution in water contains 1.704 kg of HNO_3/kg H_2O, and the solution has a specific gravity of 1.382 at 20°C. What is the mass of HNO_3 in kg per cubic meter of solution at

20°C?

11. Forty gal/min of a hydrocarbon fuel having a specific gravity of 0.91 flows into a tank truck with a load limit of 40,000 lb of fuel. How long will it take to fill the tank in the truck?
12. Pure chlorine enters a process. By measurement it is found that 2.4 kg of chlorine pass into the process every 3.1 minutes. Calculate the molar flow rate of the chlorine in kg mol/hr.
13. Commercial sulfuric acid is 98% H_2SO_4 and 2% H_2O. What is the mole ratio of H_2SO_4 to H_2O?
14. A compound contains 50% sulfur and 50% oxygen by mass. Is the empirical formula of the compound (1) SO, (2) SO_2, (3) SO_3, or (4) SO_4?
15. How many kg of activated carbon (a substance used in removing trace impurities) must be mixed with 38 kg of sand so that the final mixture is 28% activated carbon?
16. A gas mixture contains 40 lb of O_2, 25 lb of SO_2, and 30 lb of SO_3. What is the composition of the mixture in mole fractions?
17. Saccharin, an artificial sweetener that is 3000 times sweeter than sucrose, is composed of 45.90% carbon, 2.73% hydrogen, 26.23% oxygen, 7.65% nitrogen, and 17.49% sulfur. Is the molecular formula of saccharin (a) $C_{14}H_{10}O_6N_2S_2$, (b) $C_5H_7O_3NS$, (c) $C_8H_9O_2NS$, and (d) $C_7H_5O_3NS$?
18. A mixture of gases is analyzed and found to have the following composition: CO_2 12.0%, CO 6.0%, CH_4 27.3%, H_2 9.9% and N_2 44.8%. How much will 3 lb mol of this gas weigh?
19. A liquefied mixture of n-butane, n-pentane, and n-hexane has the following composition: n-C_4H_{10} 50%, n-C_5H_{12} 30%, and n-C_6H_{14} 20%. For this mixture, calculate:
    a) The weight fraction of each component.
    b) The mole fraction of each component.
    c) The mole percent of each component.
    d) The average molecular weight of the mixture.
20. How many mg/L is equivalent to a 1.2% solution of a substance in water?

Answers:

1. (a) 7010 g; (b) 2.05 g mol; (c) 7010 lb; (d) 2.05 lb mol
2. 0.123 kg mol NaCl/kg mol H_2O
3. 1.177 lb mol
4. 0.5 m^3/kg
5. 46.2 lb

6. Measure the mass of water (should be about 500g) and add it to 50 g. Measure the volume of the solution (will not be 450 mL). Divide the mass by the volume.

7. 0.79389 g/cm^3 (assuming the density of water is also at 60°F)
8. 8.11 ft^3
9. 2 ft^3
10. 870 kg HNO_3/m^3 solution.
11. 132 min
12. 0.654 kg mol/hr
13. 9
14. SO_2
15. 14.8 kg
16. O_2 0.62; SO_2 0.19; SO_3 0.19
17. (d)
18. 72.17 lb
19. (a) C_4: 0.50, C_5: 0.30, C_6: 0.20; (b) C_4: 0.57, C_5: 0.28, C_6: 0.15; (c) C_4: 57, C_5: 28, C_6: 15; (d) 66.4 kg/kg mol
20. 12000 mg/L

Supplementary Problems (Chapter Two):

Problem 1

Calcium carbonate is a naturally occuring white solid used in the manufacture of lime and cement. Calculate the number of lb mols of calcium carbonate in:

a. 50 g mol of $CaCO_3$.
b. 150 kg of $CaCO_3$.
c. 100 lb of $CaCO_3$.

Solution

a. $$\frac{50 \text{ g mol } CaCO_3}{} \left| \frac{100 \text{ g } CaCO_3}{1 \text{ g mol } CaCO_3} \right| \frac{1 \text{ lb } CaCO_3}{454 \text{ g } CaCO_3} \left| \frac{1 \text{ lb mol } CaCO_3}{100 \text{ lb } CaCO_3} \right. = \mathbf{0.11 \text{ lb mol}}$$

b. $$\frac{150 \text{ kg } CaCO_3}{} \left| \frac{2.205 \text{ lb } CaCO_3}{1 \text{ kg } CaCO_3} \right| \frac{1 \text{ lb mol } CaCO_3}{100 \text{ lb } CaCO_3} = \mathbf{3.30 \text{ lb mol}}$$

c. $$\frac{100 \text{ lb } CaCO_3}{} \left| \frac{1 \text{ lb mol } CaCO_3}{100 \text{ lb } CaCO_3} \right. = \mathbf{1.00 \text{ lb mol } CaCO_3}$$

Problem 2

Silver nitrate (lunar caustic) is a white crystalline salt, used in marking inks, medicine and chemical analysis. How many kilograms of silver nitrate ($AgNO_3$) are there in :

a. 13.0 lb mol $AgNO_3$.

b. 55.0 g mol $AgNO_3$

Solution

a.

$$\frac{13.0 \text{ lb mol } AgNO_3}{} \left| \frac{170 \text{ lb } AgNO_3}{1 \text{ lb mol } AgNO_3} \right| \frac{1 \text{ kg}}{2.205 \text{ lb}} = 1002 \text{ kg } \textbf{or 1000 kg}$$

b.

$$\frac{55.0 \text{ g mol } AgNO_3}{} \left| \frac{170 \text{ g } AgNO_3}{1 \text{ g mol } AgNO_3} \right| \frac{1 \text{ kg}}{1000 \text{ g}} = \textbf{9.35 kg}$$

Problem 3

Phosphoric acid is a colorless deliquescent acid used in the manufacture of fertilizers and as a flavoring agent in drinks. For a given 10 wt % phosphoric acid solution of specific gravity 1.10 determine:

a. the mol fraction composition of this mixture.

b. the volume (in gallons) of this solution which would contain 1 g mol H_3PO_4.

Solution

a. Basis: 100 g of 10 wt% solution

	g	MW	g mol	mol fr
H_3PO_4	10	97.97	0.102	0.020
H_2O	90	18.01	5.00	0.980

b. Specific gravity $= \dfrac{\rho_{soln}}{\rho_{ref}}$ The ref. liquid is water

The density of the solution is

$$\frac{1.10 \text{ g soln/cm}^3 \text{ soln}}{1.00 \text{ g } H_2O/\text{cm}^3} \left| \frac{1.00 \text{ g } H_2O/\text{cm}^3}{} \right. = 1.10 \frac{\text{g soln}}{\text{cm}^3}$$

$$\frac{1 \text{ cm}^3 \text{ soln}}{1.10 \text{ g soln}} \left| \frac{1 \text{ g soln}}{0.1 \text{ g } H_3PO_4} \right| \frac{97.97 \text{ g } H_3PO_4}{1 \text{ g mol } H_3PO_4} \left| \frac{264.2 \text{ gal}}{10^6 \text{ cm}^3} \right. = \textbf{0.24 gal/g mol}$$

Problem 4

The density of a liquid is 1500 kg/m^3 at 20 °C.
a. What is the specific gravity 20°C/4°C of this material.
b. What volume (ft^3) does 140 lb$_m$ of this material occupy at 20°C.

Solution

Assume the reference substance is water which has a density of 1000 kg/m^3 at 4°C.

a. Specific gravity $= \dfrac{\rho_{soln}}{\rho_{ref}} = \dfrac{(kg/m^3)soln}{(kg/m^3)ref} = \dfrac{1500\ kg/m^3}{1000\ kg/m^3}$ = **1.50**

b. $\dfrac{1\ m^3\ liquid}{1500\ kg} \left| \dfrac{1\ kg}{2.20\ lb} \right| \dfrac{35.31\ ft^3}{1\ m^3} \left| \dfrac{140\ lb_m}{} \right.$ = **1.50 ft^3**

Problem 5

The 1993 Environmental Protection Agency (EPA) regulation contains standards for 84 chemicals and minerals in drinking water. According to the EPA one of the most prevalent of the listed contaminants is naturally occuring antimony. The maximum contaminant level for antimony and nickel has been set at 0.006 mg/L and 0.1 mg/L respectively.

A laboratory analysis of your household drinking water shows the antimony concentration to be 4 ppb (parts per billion) and that of nickel to be 60 ppb. Determine if the drinking water is safe with respect to the antimony and nickel levels.

Assume density of water to be 1.00 g/cm^3

Solution

Antimony

$$\frac{0.006\ mg\ Sb}{1L\ soln}\left|\frac{1\ L\ soln}{1000\ cm^3\ soln}\right|\frac{1\ cm^3\ soln}{1.00\ g\ H_2O}\left|\frac{1\ g}{1000\ mg}\right. = \frac{6\ g\ Sb}{10^9\ g\ soln} = \mathbf{6\ ppb}$$

Nickel

$$\frac{0.1\ mg\ Ni}{1\ L\ soln}\left|\frac{1\ L\ soln}{1000\ cm^3\ soln}\right|\frac{1\ cm^3\ soln}{1.0\ g\ H_2O}\left|\frac{1\ g}{1000\ mg}\right. = \frac{9\ g\ Ni}{10^9\ g\ soln} = \mathbf{100\ ppb}$$

House hold drinking water contains less than the EPA mandated tolerance levels of antimony and nickel. Drinking water is therefore safe.

Problem 6

Wine making involves a series of very complex reactions most of which are performed by microorganisms. The starting concentration of sugars determines the final alcohol content and sweetness of the wine. The specific gravity of the starting stock is therefore adjusted to achieve desired quality of wine.
A starting stock solution has a specific gravity of 1.075 and contains 12.7 wt% sugar. If all the sugar is assumed to be $C_{12}H_{22}O_{11}$, determine

a. kg sugar/kg H_2O
b. lb solution/ft^3 solution
c. g sugar/L solution

Solution

Basis: 100 kg starting stock solution

a. $$\frac{12.7 \text{ kg sugar}}{100 \text{ kg soln}} \left| \frac{100 \text{ kg solution}}{87.3 \text{ kg } H_2O} \right. = .145 \ \frac{\textbf{kg sugar}}{\textbf{kg } H_2O}$$

b. $$\frac{1.075 \text{ g soln/cm}^3}{1.0 \text{ g } H_2O\text{/cm}^3} \left| \frac{1.00 \text{ g } H_2O\text{/cm}^3}{} \right| \frac{1 \text{ lb}}{454 \text{ g}} \left| \frac{2.832 \times 10^4 \text{ cm}^3}{\text{ft}^3} \right. = 67.1 \ \frac{\textbf{lb soln}}{\textbf{ft}^3 \textbf{ soln}}$$

c. $$\frac{1.075 \text{ g soln/cm}^3}{1.0 \text{ g } H_2O\text{/cm}^3} \left| \frac{1.0 \text{ g } H_2O\text{/cm}^3}{} \right| \frac{12.7 \text{ g sugar}}{100 \text{ g soln}} \left| \frac{1000 \text{ cm}^3}{1 \text{ L}} \right. = 136 \ \frac{\textbf{g sugar}}{\textbf{L soln}}$$

Problem 7

How many ppb are there in 1 ppm? Does the system of units affect your answer? Does it make any difference if the material for which the ppb are measured is a gas, liquid, or solid?

Solution

a) 1000

b) No

c) **Yes, because for solids and liquids the ratio in ppb is mass whereas for gases the ratio is in moles.**

Chapter 3

Choosing a Basis

- A **basis** is a reference chosen by you for the calculations you plan to make in any particular problem, and a proper choice of basis frequently makes the problem much easier to solve.
- The **basis** may be a **period of time** such as **hours**, or a given **mass of material**, such as **5 kg** of CO_2, or some other convenient quantity.

❖ For **<u>liquids</u>** and **<u>solids</u>** in which a **<u>mass (weight)</u>** analysis applies, a convenient basis is often **<u>1 or 100 lb or kg</u>**; similarly, **<u>1 or 100 moles</u>** is often a good choice for a **<u>gas</u>**.

Example 3.1

Gas mixture 10.0% H_2, 40.0% CH_4, 30.0% CO, and 20.0% CO_2, what is the average molecular weight of the gas?

Solution

Basis: 100 kg mol or lb mol of gas

Component	Percent = kg mol or lb mol	Mol wt.	Kg or lb
CO_2	20.0	44.0	880
CO	30.0	28.0	840
CH_4	40.0	16.04	642
H_2	10.0	2.02	20
Total	100.0		2382

$$\text{Average molecular weight} = \frac{2382 \text{ kg}}{100 \text{ kg mol}} = 23.8 \text{ kg/kg mol}$$

<u>Other Method for Solution</u>:

Average molecular weight = 0.2 * 44 + 0.3 * 28 + 0.4 * 16.04 + 0.1 * 2.02 = 23.8 kg/kg mol

Example 3.2

A liquefied mixture has the following composition: (Butane) n-C_4H_{10} 50% (MW=58), (Pentane) n-C_5H_{12} 30% (MW=72), and (hexane) n-C_6H_{14} 20% (MW=86). For this mixture, calculate: (a) mole fraction of each component. (b) Average molecular weight of the mixture.

Solution

Basis: 100 kg

	% = kg	wt fr	MW	kg mol	mol fr
n - C_4H_{10}	50	**0.50**	58	0.86	**0.57**
n - C_5H_{12}	30	**0.30**	72	0.42	**0.28**
n - C_6H_{14}	20	**0.20**	86	0.23	**0.15**
	100	**1.00**		1.51	**1.00**

$$\text{Average molecular weight} = \frac{\text{total mass}}{\text{total mol}} = \frac{100 \text{ kg}}{1.51 \text{ kg mol}} = \mathbf{66}$$

Example 3.3

A medium-grade bituminous coal analyzes as follows:

Component	Percent
S	2
N	1
O	6
Ash	11
Water	3
Residuum	77

The residuum is C and H, and the mole ratio in the residuum is H/C = 9. Calculate the weight (mass) fraction composition of the coal with the ash and the moisture omitted (ash – and moisture – free).

Solution

Take as a basis 100 kg of coal because then percent = kilograms.

Basis: 100 kg of coal

The sum of the S + N + O + ash + water is   2 + 1 + 6 + 11 + 3 = 23 kg

We need to determine the individual kg of **C** and of **H** in the **77 kg** total residuum.

To determine the kilograms of C and H, you have to select a new basis.

Basis: 100 kg mol (Because the H/C ratio is given in terms of moles, not weight)

Component	Mole fraction	kg mol	Mol. wt.	kg	Mass fraction
H	$\frac{9}{1+9} = 0.90$	90	1.008	90.7	0.43
C	$\frac{1}{1+9} = \frac{0.10}{1.00}$	$\frac{10}{100}$	12	$\frac{120}{210.7}$	$\frac{0.57}{1.00}$

H: (77kg) (0.43) = 33.15 kg

C: (77kg) (0.57) = 43.85 kg

Finally, we can prepare a table summarizing the results on the basis of **1 kg of the coal <u>ash-free and water-free</u>**.

Component	kg	Wt. fraction
C	43.85	0.51
H	33.15	0.39
S	2	0.02
N	1	0.01
O	6	0.07
Total	86.0	1.00

Supplementary Problems (Chapter Three):

Problem 1

1 mol of gas containing O_2 20%, N_2 78%, and SO_2 2%, find the composition of the gas on an SO_2 – free basis, meaning gas without the SO_2 in it.

Solution

Basis: 1.00 mol gas

Components	Mol fraction	Mol	Mol SO_2 free	Mol fraction SO_2 free
O_2	0.20	0.20	0.20	0.20
N_2	0.78	0.78	0.78	0.80
SO_2	0.02	0.02		
	1.00	1.00	0.98	1.00

Problem 2

In a ternary alloy such as $Nd_{4.5}Fe_{77}B_{18.5}$ the average grain size is about 30 nm. By replacing 0.2 atoms of Fe with atoms of Cu, the grain size can be reduced (improved) to 17 nm.

(a) What is the molecular formula of the alloy after adding the Cu to replace the Fe?

(b) What is the mass fraction of each atomic species in the improved alloy?

Solution

Basis: 100 g mol (or atoms) of $Nd_{4.5}Fe_{77}B_{18.5}$

(a) The final alloy is $Nd_{4.5}Fe_{76.8}B_{18.5}Cu_{0.2}$.

(b) Use a table to calculate the respective mass fractions.

Component	Original g mol	Final g mol	MW	g	Mass fraction
Nd	4.5	4.5	144.24	649.08	0.126
Fe	77	76.8	55.85	4289.28	0.833
B	18.5	18.5	10.81	199.99	0.039
Cu		0.2	63.55	12.71	0.002
Total	100.0	100.0		5151.06	1.000

Problem 3 (Basic Principles…. Book, Page 87)

Read each of the following problems and select a suitable basis for solving each one. Do not solve the problems.

a. You have 130 kg of gas of the following composition: 40% N_2, 30% CO_2, and 30% CH_4 in a tank. What is the average molecular weight of the gas?

b. You have 25 lb of a gas of the following composition: CH_4 80%, C_2H_4 10%, and C_2H_6 10%. What is the average molecular weight of the mixture? What is the weight (mass) fraction of each of the components in the mixture?

c. The proximate and ultimate analysis of coal is given in the following table. What is the composition of the "Volatile combustible material" (VCM)? Present your answer in the form of the mass percent of each element in the VCM.

Proximate Analysis (%)		Ultimate Analysis (%)	
Moisture	3.2	Carbon	79.90
Volatile combustible material	21.0	Hydrogen	4.85
Fixed carbon	69.3	Sulfur	0.69
Ash	6.5	Nitrogen	1.30
		Ash	6.50
		Oxygen	6.76
Total	100.0	Total	100.00

d. A fuel gas is reported to analyze, on a mole basis, 20% methane, 5% ethane, and the remainder CO_2. Calculate the analysis of the fuel gas on a mass percentage basis.

Solution

(a) A gas requires a convenient basis of 1 or 100 g moles or kg moles (if use SI units).

(b) A gas requires a convenient basis of 1 or 100 lb moles (if use AE units).

(c) Use 1 or 100 kg of coal, or 1 or 100 lb of coal because the coal is a solid and mass is a convenient basis.

(d) Use 1 or 100 moles (SI or AE) as a convenient basis as you have a gas.

<u>**Problem 4**</u> (Basic Principles…. Book, Page 88)

Choose a basis for the following problem: Chlorine usage at a water treatment plant averages 134.2 lb/day. The average flow rate of water leaving the plant is 10.7 million gal/day. What is the average chlorine concentration in the treatment water leaving the plant (assuming no reaction of the chlorine), expressed in milligrams per liter?

Solution

Pick one day as a basis which is equivalent to what is given - - two numbers:

(a) 134.2 lb Cl (b) 10.7×10^6 gal water.