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Chapter1

Dimensions, Units, and TheirConversion

1.1 Units and Dimensions

Dimensions are our basic concepts of measurement such as length, time, mass, temperature, andso on;**units**arethemeansofexpressingthedimensions,suchasfeetorcentimetersforlength,and hours or seconds fortime.

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

1. **SI**,formallycalledLeSystemeInternationaled'Unites,andinformallycalledSIormore often (redundantly) the SI system ofunits.
2. **AE**, or American Engineering system ofunits.

Dimensions and their respective units are classified as fundamental orderived:

- **Fundamental** (or basic) dimensions/units are those that can be measured independentlyand are sufficient to describe essential physicalquantities.
- **Derived**dimensions/unitsarethosethatcanbedevelopedintermsofthefundamental dimensions/units.

Tables1.1and1.2listbothbasic,derived,andalternativeunitsintheSIandAEsystems.Figure 1.1 illustrates the relation between the basic dimensions and some of the deriveddimensions. OneofthebestfeaturesoftheSIsystemisthat(exceptfortime)unitsandtheirmultiplesand submultiples are related by standard factors designated by the **prefix** indicated in Table1.3.

1.2 Operations withUnits

The rules for handling units are essentially quitesimple:

1.2.1 Addition, Subtraction,Equality

Youcanadd,subtract,orequatenumericalquantitiesonlyiftheassociatedunitsofthequantities are the same. Thus, theoperation

5 kilograms + 3joules

cannot be carried out because the units as well as the dimensions of the two terms are different.The numericaloperation

10 pounds + 5grams

can be performed (because the dimensions are the same, mass) only after the units aretransformed to be the same, either pounds, grams, or ounces, or some other massunit.

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) SystemUnits

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 deriveddimensions (in ellipses).

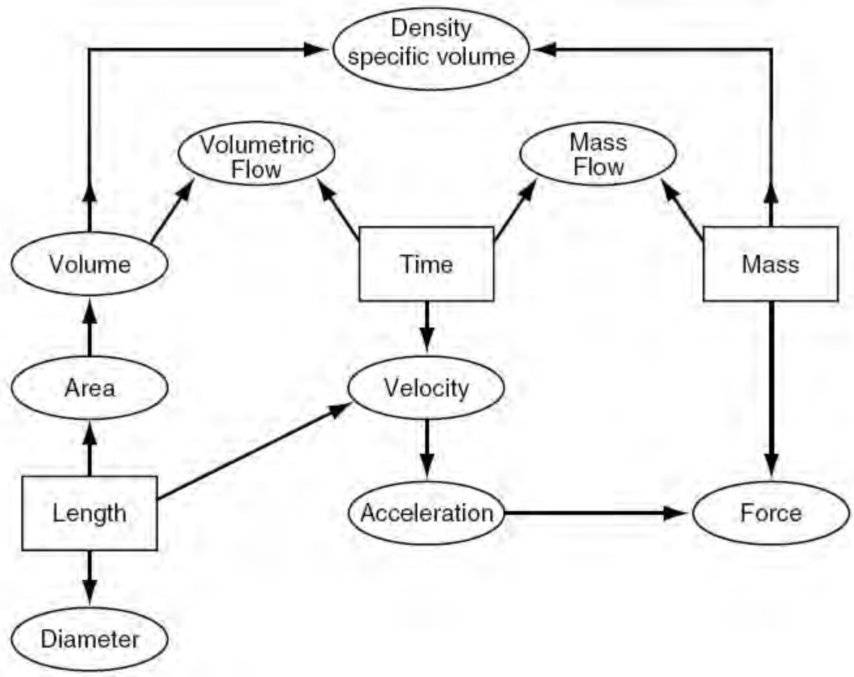


Table 1.3 SIPrefixes

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 suchas

50(kg)(m)/(s)

butyoucannotcancelormergeunitsunlesstheyareidentical.Thus,3m^2/60cmcanbeconverted to 3 m^2/0.6 m, and then to 5 m, but in m/s^2, the units cannot be cancelled orcombined.

<u>Example1.1</u>

Add thefollowing:

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

Solution

The operation indicatedby

1 ft + 3s

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

1 hp + 300watts

the dimensions are the same (energy per unit time), but the units are different. You musttransform thetwoquantitiesintolikeunits,suchashorsepowerorwatts,beforetheadditioncanbecarried out. Since 1 hp = 746watts,

746 watts + 300 watts = 1046watts

1.3 Conversion of Units and ConversionFactors

Theprocedureforconvertingonesetofunitstoanotherissimplytomultiplyanynumberandits associated units by ratios termed **conversion factors** to arrive at the desired answer andits associatedunits.

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

We formulate the conversion asfollows

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

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

<u>Example1.2</u>

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

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

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

Inpart(b)notethatnotonlyarethenumbersintheconversionofinchestocentimetersraisedtoa power, but the units also are raised to the samepower.

Example1.3

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

Solution

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

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

IntheAEsystemtheconversionoftermsinvolvingpound**mass**andpound**force**deservespecial attention. Let us start the discussion with Newton'sLaw:

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

Where:

F =force

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

anda,   m =mass

a =acceleration

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

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

Because the numerical value associated with the conversion factor is **1**, the conversion factorseems simple, even nonexistent, and the units are ordinarilyignored.

Inthe**AE**systemananalogousconversionfactorisrequired.Ifamassof11b$_m$ishypothetically acceleratedat*g*ft/s^2,where*g*istheaccelerationthatwouldbecausedbygravity(about32.2ft/s^{2}depending on the location of the mass), we can make the force be 1 1b$_f$ by choosing theproper numerical value and units for the conversion factorC:

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

Theinverseoftheconversionfactorwiththenumericalvalue**32.174**includedisgiventhespecial 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 lbmft/s^2

Example1.4

Whatisthepotentialenergyin(ft)(1b$_f$)ofa100lbdrumhanging10ftabovethesurfaceofthe earth with reference to the surface of theearth?

Solution

Potential energy = P = m gh

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

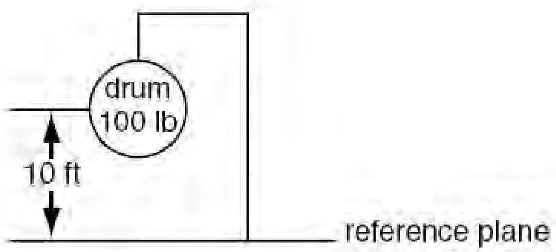


Figure E1.4

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

Notice that in the ratio of **32.2 ft/s^2** divided by **32.174[(ft)(lb_m)]/[(s^2)(lb_f)]**, the numerical valuesare almostequal.Manyengineerswouldsolvetheproblembysayingthat**100lb×10ft=1000 (ft)(1b)**withoutrealizingthat,ineffect,theyarecancelingoutthenumbersinthe**g/g_c**ratio,and that the lb in the solution meanslb$_f$.

<u>**Example1.5**</u>

In biological systems, production rate of glucose is 0.6 µgmol/(mL)(min). Determinethe production rate of glucose for this system in the units of lbmol/(ft^3)(day).

Solution

Basis: 1min

$$\frac{0.6\ \mu\text{g mol}}{(\text{mL})(\text{min})}\bigg|\frac{1\ \text{g mol}}{10^6\ \mu\text{g mol}}\bigg|\frac{1\ \text{lb mol}}{454\ \text{g mol}}\bigg|\frac{1000\ \text{mL}}{1\ \text{L}}\bigg|\frac{1\ \text{L}}{3.531\times10^{-2}\ \text{ft}^3}\bigg|\frac{60\ \text{min}}{\text{hr}}\bigg|\frac{24\ \text{hr}}{\text{day}}$$

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

1.4 Dimensional Consistency(Homogeneity)

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

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

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

<u>**Example1.6**</u>

Your handbook shows that microchip etching roughly follows therelation

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

wheredisthedepthoftheetchinmicrons(micrometers,µm)andtisthetimeoftheetchin seconds.Whataretheunitsassociatedwiththenumbers16.2and0.021?Converttherelationso that d becomes expressed in inches and t can be used inminutes.

Solution

Bothvaluesof**16.2**musthavetheassociatedunitsofmicrons(**µm**).The**exponential**mustbe **dimensionless**so that **0.021** must have the associated units of**s^{-1}**.

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

NondimensionalGroups:

Asyouproceedwiththestudyofchemicalengineering,youwillfindthatgroupsofsymbolsmay be put together, either by theory or based on experiment, that have no net units. Such collectionsof variablesorparametersarecalled**dimensionless**or**nondimensionalgroups**.Oneexampleisthe Reynolds number (group) arising in fluidmechanics.

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

where***D***isthepipediameter,sayincm;***v***isthefluidvelocity,sayincm/s;***ρ***isthefluiddensity, say in g/cm^3; and ***μ*** is the viscosity, say in centipoise, units that can be converted to**g/(cm)(s)**. Introducingtheconsistentsetofunitsfor***D***,***v***,***ρ***,and***μ***into***Dvρ/μ***,youwillfindthatalltheunits cancel out so that the numerical value of **1** is the result of the cancellation of theunits.

$$\frac{\cancel{cm}}{}\left|\frac{\cancel{cm}}{\cancel{s}}\right|\frac{\cancel{g}}{\cancel{cm^3}}\left|\frac{(\cancel{cm})(\cancel{s})}{\cancel{g}}\right.$$

Example1.7

Explain without differentiating why the following differentiation cannot becorrect:

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

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

Solution

- Observe that *x* and *a* must have the same units because the ratio x^2/a^2 must bedimensionless (because 1 isdimensionless).
- Thus, the left-hand side of the equation has units of 1/*x* (from *d/dx*). However, theright-hand side of the equation has units of x^2 (the product of*ax*).
- Consequently, something is wrong as the equation is not dimensionallyconsistent.

Questions

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

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

2. Pick the correct answer(s); a wattis

a. one joule persecond b. equal to $1(kg)(m^2)/s^2$ c. the unit for all types ofpower

d. all of theabove e. none of theabove

3. Is kg/s a basic or derived unit inSI?

4. Answer the following questions yes or no. Canyou

a.divideftbys?**b.**dividembycm?**c.**multiplyftbys?**d.**divideftbycm? **e.**dividem by (deg) K? **f.** add ft and s? **g.** subtract m and (deg) K **h.** add cm and ft? **i.** add cm andm^2?

j. add 1 and 2cm?

5. Why is it not possible to add 1 ft and $1ft^2$?

6. What isg_c?

7. Is the ratio of the numerator and denominator in a conversion factor equal tounity?

8. What is the difference, if any, between pound force and pound mass in the AEsystem?

9. Could a unit of force in the SI system be kilogramforce?

10. Contrast the procedure for converting units within the SI system with that for the A E system.

11. Whatistheweightofaonepoundmassatsealevel?Wouldthemassbethesameatthe center of Earth? Would the weight be the same at the center ofEarth?

12. What is the mass of an object that weighs 9.80 kN at sea level?

13. Explain what dimensional consistency means in anequation.

14. Explain why the so-called dimensionless group has no net dimensions.

15. Ifyoudivideallofaseriesoftermsinanequationbyoneoftheterms,willtheresulting series of terms bedimensionless?

16. How might you make the following variablesdimensionless:

a. Length (of apipe). b. Time (to empty a tank full ofwater).

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 thesame.
6. A conversion factor in the American Engineering system ofunits.
7. Yes.
8. $lb_f$is force and lb_m is mass, and the dimensions aredifferent.
9. The unit is not legal inSI.
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 inSI.
11. (a) 1 lb_f in the AE system of units; (b) yes; (c)no.
12. 1000kg.
13. Alladditivetermsontheright-handsideofanequationmusthavethesamedimensionsas those on the left-hand side.
14. All of the units cancel out.
15. Yes.
16. (a)Dividebytheradiusordiameter;(b)dividebythetotaltimetoemptythetank,orbya fixed unit oftime.

Problems

1. Classify the following units as correct or incorrect units in the SIsystem:
   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 4yards.
4. Divide 3 $m^{1.5}$by 2$m^{0.5}$.
5. Multiply 2 ft by 4lb.
6. What are the value and units of $g_c$in the SIsystem?
7. Electroniccommunicationviaradiotravelsatapproximatelythespeedoflight(186,000 miles/second).TheedgeofthesolarsystemisroughlyatPluto,whichis3.6×109miles fromEarthatitsclosestapproach.Howmanyhoursdoesittakeforaradiosignalfrom Earth to reachPluto?
8. Determinethekineticenergyofonepoundoffluidmovinginapipeatthespeedof3feet per second.
9. Convert the following from AE to SIunits:
   a. 4 lb_m/ft tokg/m b. 1.00 $lb_m/(ft^3)(s)$ tokg/$(m^3)(s)$
10. Convert the following 1.57×10^{-2} g/(cm)(s) tolb_m/(ft)(s)
11. Convert 1.1 gal toft^3.

12. Convert 1.1 gal tom^3.

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

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

Where u = fluidvelocity

Δp = pressure drop 1force per unitarea^2

ρ = density of the flowingfluid

c =constant

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

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

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

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) arecorrect**.**

2. Change units to get 101cm.

3. Change units to get 9ft.

4. 1.5 m.

5. 8(ft)(lb).

6. 1,dimensionless.

7. 5.38hr.

8. 0.14 (ft)(lb_f).

9. a. 5.96 kg/m; b. 16.0kg/(m^3)(s)

10. $1.06 * 10^{-3}$ lb_m/(ft)(s)

11. 0.15ft^3

12. $4.16 * 10^{-3} m^3$.

13. c isdimensionless

14. *A* has the same units as *k*; B has the units of T

Supplementary Problems (ChapterOne):

Problem1

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

Problem2

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

Solution

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

Problem3

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

$m = 0.0549\ p/(T)^{0.5}$ 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.

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

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

Substituting pressure and temperature in SI units

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

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

Problem4

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.

Chapter2

Moles, Density andConcentration

2.1 TheMole

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 outare

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

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

and

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

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

Forexample

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

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

- **Theatomicweight**ofanelementisthemassofanatombasedonthescalethatassignsa mass of exactly 12 to the carbon isotope ^{12}C.
- A **compound** is composed of more than one atom, and the molecular weight ofthe compound is nothing more than the sum of the weights of atoms of which it iscomposed.

Example2.1

Whatisthemolecularweightofthefollowingcellofasuperconductormaterial?(Thefigure represents one cell of a largerstructure.)

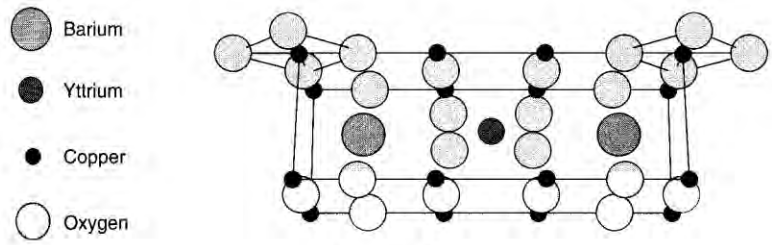


Figure E2.1

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 moleis 1764.3 g/gmol.

Example2.2

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

a) Pound moles of NaOH does it contain?

b) Gram moles of NaOH does itcontain?

Solution

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

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

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

Example2.3

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

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

Densityistheratioofmassperunitvolume,asforexample,kg/m^{3}orlb/ft^3.Densityhas both a numerical value and units. **Specific volume** is the inverse of density, such as cm^3/g orft^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 thevolume of 90.0 g of the alcohol? The calculationis

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

- In a packed bed of solid particles containing void spaces, the bulk densityis

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

- Ahomogeneousmixtureoftwoormorecomponents,whethersolid,liquid,orgaseous,is called a **solution**.

For some solutions, the density of the solutionis

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

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

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

For others youcannot.

2.3 Specific Gravityالثقل النوعي

Specific gravity is commonly thought of as a dimensionlessratio.

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

- 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 at4°C**.
- The specific gravity of **gases** frequently is referred to **air**, but may be referred to othergases.

ForExampleIfdibromopentane(DBP)hasaspecificgravityof1.57,whatisthedensityin(a) g /cm^3? (b) lb_m/ft^3? and (c)kg/m^3?

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

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

$$\textbf{(c)} \quad \frac{1.57\text{g DBP}}{\text{cm}^3}\left|\left(\frac{100\text{ cm}}{1\text{ m}}\right)^3\right|\frac{1\text{ kg}}{1000\text{ g}} = 1.57 \times 10^3\frac{\text{kg DBP}}{\text{m}^3}$$

or

$$\frac{1.57\dfrac{\text{kg DBP}}{\text{m}^3}}{1.00\dfrac{\text{kg H}_2\text{O}}{\text{m}^3}} \left| \frac{1.00 \times 10^3\text{kg H}_2\text{O}}{\text{m}^3} \right. = 1.57 \times 10^3\frac{\text{kg DBP}}{\text{m}^3}$$

Example2.4

If a 70% (by weight) solution of glycerol has a specific gravity of 1.184 at 15°C, what is thedensity 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 gsolution/cm^3.

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

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

Thespecificgravityofpetroleumproductsisoftenreportedintermsofahydrometerscalecalled °API(American Petroleum Institute). The equation for the API scaleis

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

or

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

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

The **volume** and therefore the **density** of petroleum products vary with **temperature**, andthe petroleum industry has established 60 °F as the standard temperature for volume and APIgravity.

Example2.5

In the production of a drug having a molecular weight of 192, the exit stream from the reactorflows atarateof10.5L/min.Thedrugconcentrationis41.2%(inwater),andthespecificgravityofthe solutionis1.024.Calculatetheconcentrationofthedrug(inkg/L)intheexitstream,andtheflow r ate of t he drug in kgmol/min.

Solution

Take 1 kg of the exit solution as a basis forconvenience.

Basis: 1 kgsolution

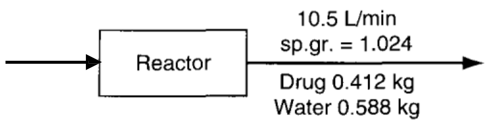


Figure E2.5

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

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

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

Basis: 1 min = 10.5 Lsolution

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

2.4 FlowRate

For c ontinuous pr ocesses t he **flow rate** of a process s tream i s t he r ate at w hich materialis 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 lineper unit**time**.

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

The **molar flow ($\dot{n}$) rate** of a process stream is the number of **moles** (**n**) of a substancetransported through a line per unit**time**.

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

2.5 Mole Fraction and Mass (Weight)Fraction

- **Molefraction**issimplythenumberofmolesofaparticularcompoundinamixtureor solution divided by the total number of moles in the mixture orsolution.
- Thisdefinitionholdsfor**gases**,**liquids**,and**solids**.
- Similarly, the **mass (weight) fraction** is nothing m ore t han t he **mass (weight)** ofthe compounddividedbythetotalmass(weight)ofallofthecompoundsinthemixtureor solution.

Mathematically, these ideas can be expressedas

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

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

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

Example2.6

Anindustrial-strengthdraincleanercontains5kgofwaterand5kgofNaOH.Whatarethemass (weight) fractions and mole fractions of each component in the drain cleanercontainer?

Solution

Basis: 10 kg of totalsolution

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 asfollows:

$$\frac{5.00 \text{ kg } H_2O}{} \left| \frac{1 \text{ kg mol } H_2O}{18.0 \text{ kg } H_2O} \right. = 0.278 \text{ kg mol } H_2O$$

$$\frac{5.00 \text{ kg NaOH}}{} \left| \frac{1 \text{ kg mol NaOH}}{40.0 \text{ kg NaOH}} \right. = 0.125 \text{ kg mol NaOH}$$

Adding these quantities together gives the total kilogrammoles.

Example2.7

Innormallivingcells,thenitrogenrequirementforthecellsisprovidedfromproteinmetabolism (i.e.,consumptionoftheproteininthecells).Whenindividualcellsarecommerciallygrown, ($NH_4)_2SO_4$ is usually us ed a s t he source of ni trogen. D etermine t he amount of ($NH_4)_2SO_4$consumed inafermentationmediuminwhichthefinalcellconcentrationis35g/Lina500Lvolumeofthe fermentationmedium.Assumethatthecellscontain9wt.%N,andthat$(NH_4)_2SO_4$istheonly nitrogensource.

Solution

Basis: 500 L solution containing 35 g/L

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

2.6 Analyses of Multicomponent Solutions andMixtures

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

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

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 ofair

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 unitvolume.

a. Massperunitvolume(lbofsolute/ft^3ofsolution,gofsolute/L,lbofsolute/barrel, kg ofsolute/m^3).

b. Molesperunitvolume(lbmolofsolute/ft^3ofsolution,gmolofsolute/L,gmolof solute/cm^3).

c. Parts pe r million (**ppm**); pa rts pe r bi llion (**ppb**), a m ethod of e xpressingthe concentration of e xtremely di lute s olutions; **ppm is equivalent to a mass(weight)fractionforsolidsandliquids**becausethetotalamountofmaterialisofamuc h hi gher o rder o f m agnitude t han t he a mount of s olute; i t i s a **mole fraction forgases**.

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

e. Other m ethods o f e xpressing concentration w ith w hich you may be familiarare molarity (g mol/L), molality (mole solute/kg solvent), and normality(equivalents/L).

Example2.8

The cu rrent Occupational Safety and Health Administration (OSHA) 8-hour limit f or Hydrogen cyanide(HCN)(boils a t 25.6 °C) (MW = 27.0 3) i n a ir i s 10.0 ppm . A l ethal dos e of H CNin airis(fromtheMerckIndex)300mg/kgofairatroomtemperature.HowmanymgHCN/kgairis 10 ppm? W hat fraction of the lethal dose is 10.0ppm?

Solution

Basis: 1 kg mol of the air/HCNmixture

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

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

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

Example2.9

A solution of HNO_3 in water has a specific gravity of 1.10 at 25°C. The concentration of theHNO_3 is 15 g/L of solution. What isthe

a. Mole fraction of HNO_3 in thesolution?

b. ppm of HNO_3 in thesolution?

Solution

Basis: 1 L ofsolution

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 gsolution

The mass of water in the solution is: 100 – 1.364 = 98.636 gH_2O.

	g	**MW**	**gmol**	**molfraction**
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. $$\frac{0.01364}{1} = \frac{13{,}640}{10^6} \text{ or } 13{,}640 \text{ ppm}$$

Example2.10

Sulfurtrioxide(SO_3)canbeabsorbedinsulfuricacidsolutiontoformmoreconcentratedsulfuric acid. If the gas to be absorbed contains 55% SO_3, 41% N_2, 3% SO_2, and 1% O_2, how many partsper million of O_2 are there in the gas? What is the composition of the gas on a N_2 freebasis?

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

Example2.11

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 equalamount of pure N_2. What is the final mole fraction of eachgas?

Solution

The basis is 100 moles of initialgas

Composition	OriginalMixture mol%	AfterAddition N_2	Final Mixture MoleFraction
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

Example2.12

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 elementpresent.

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 orfalse:
   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. Fornumberssuchas2mLofwater+2mLofethanol,doesthesumequalto4mLofthe solution?
4. Answer the following questions true orfalse:
   a. The inverse of the density is the specificvolume.
   b. Density of a substance is the mass per unitvolume.
   c. The density of water is less than the density ofmercury.

5. A cubic centimeter of mercury has a mass of 13.6 g at Earth's surface. What is the densityof mercury?
6. What is the approximate density of water at room temperature inkg/m^3?
7. ForliquidHCN,ahandbookgives:sp.gr.$10^{\circ}C/4^{\circ}C$=1.2675.Whatdoesthisstatement mean?
8. Answer the following questions true orfalse:
    a. The density and specific gravity of mercury are thesame.
    b. Specific gravity is the ratio of twodensities.
    c. Ifyouaregiventhevalueofareferencedensity,youcandeterminethedensityofa substance of interest by multiplying by the specific gravity.
    d. The specific gravity is a dimensionlessquantity.
9. A mixture is reported as 15% water and 85% ethanol. Should the percentages be deemedto be by mass, mole, orvolume?
10. Answer the following questions true orfalse:
    a) In engineering practice the compositions of liquids and solids are usually denotedin weight (mass) fraction orpercent.
    b) In engineering practice the composition of gases is usually denoted in molefraction orpercent.
    c) e. A pseudo-average molecular weight can be calculated for a mixture ofpure components whether solid, liquid, orgases.
11. Do parts per million denote a concentration that is a moleratio?
12. Does the concentration of a component in a mixture depend on the amount of themixture?
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 10ppm?

Answers:

1. (a) T; (b) T; (c)T
2. 60.05
3. No
4. (a) T; (b) T; (c)T
5. 13.6g/cm^3
6. 1000kg/m^3

7. Thestatementmeansthatthedensityat10 $^\circ$CofliquidHCNis1.2675timesthedensityof water at4 $^\circ$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 orsolids.
12. No
13. 0.001
14. 1000
15. No (4 times)

Problems

1. Convert thefollowing:
    a) 120 g mol of NaCl tog.
    b) 120 g of NaCl to gmol.
    c) 120 lbmol of NaCl tolb.
    d) 120 lb of NaCl to lbmol.
2. Convert 39.8 kg of NaCl per 100 kg of water to kg mol of NaCl per kg mol ofwater.
3. How many lbmol of $NaNO_3$ are there in 100lb?
4. The density of a material is 2 kg/m^3. What is its specificvolume?
5. An empty 10 gal tank weighs 4.5 lb. What is the total weight of the tank plus the waterwhen it is filled with 5 gal of water?
6. Ifyouadd50gofsugarto500mLofwater,howdoyoucalculatethedensityofthesugar solution?
7. Forethanol,ahandbookgives:sp.gr.60°F=0.79389.Whatisthedensityofethanolat 60°F?
8. The specific gravity of steel is 7.9. What is the volume in cubic feet of a steelingot weighing 4000lb?
9. The specific gravity of a solution is 0.80 at 70°F. How many cubic feet will be occupiedby 100 lb of the solution at70°F?
10. Asolutioninwatercontains1.704kgofHNO_3/kgH_2O,andthesolutionhasaspecific gravityof1.382at20°C.WhatisthemassofHNO_3inkgpercubicmeterofsolutionat 20°C?

11. Forty gal/min of a hydrocarbon fuel having a specific gravity of 0.91 flows into a tanktruck with a load limit of 40,000 lb of fuel. How long will it take to fill the tank in thetruck?
12. Pure chlorine enters a process. By measurement it is found that 2.4 kg of chlorine passinto the process every 3.1 minutes. Calculate the molar flow rate of the chlorine in kgmol/hr.
13. Commercialsulfuricacidis98%H_2SO_4and2%H_2O.WhatisthemoleratioofH$_2$SO$_4$to H_2O?
14. A compound contains 50% sulfur and 50% oxygen by mass. Is the empirical formula ofthe compound (1) SO, (2) SO_2, (3) SO_3, or (4)SO_4?
15. Howmanykgofactivatedcarbon(asubstanceusedinremovingtraceimpurities)mustbe mixed with 38 kg of sand so that the final mixture is 28% activatedcarbon?
16. A gas mixture contains 40 lb of O_2, 25 lb of SO_2, and 30 lb of SO_3. What is thecomposition of the mixture in molefractions?
17. Saccharin,anartificialsweetenerthatis3000timessweeterthansucrose,iscomposedof 45.90%carbon,2.73%hydrogen,26.23%oxygen,7.65%nitrogen,and17.49%sulfur.Is themolecularformulaofsaccharin(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. Amixtureofgasesisanalyzedandfoundtohavethefollowingcomposition:$CO_2$12.0%, CO 6.0%, CH_4 27.3%, H_2 9.9% and N_2 44.8%. How much will 3 lbmol of this gasweigh?
19. Aliquefiedmixtureofn-butane,n-pentane,andn-hexanehasthefollowingcomposition: 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 eachcomponent.
    b) The mole fraction of eachcomponent.
    c) The mole percent of eachcomponent.
    d) The average molecular weight of themixture.
20. How many mg/L is equivalent to a 1.2% solution of a substance inwater?

Answers:

1. (a) 7010 g; (b) 2.05 g mol; (c) 7010 lb; (d) 2.05 lbmol
2. 0.123 kg molNaCl/kg molH_2O
3. l.l77lbmol
4. 0.5m^3/kg 5.

46.2 lb

6. Measurethemassofwater(shouldbeabout500g)andadditto50g.Measurethevolume of the solution (will not be 450 mL). Divide the mass by thevolume.

7. 0.79389 g/cm^3 (assuming the density of water is also at60°F)
8. 8.11ft^3
9. 2 ft^3
10. 870 kg HNO_3/m^{3}solution.
11. 132 min
12. 0.654 kgmol/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/kgmol
20. 12000mg/L

Supplementary Problems (ChapterTwo):

Problem1

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

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

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

Problem2

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

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

Problem3

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 $= \frac{\rho_{soln}}{\rho_{ref}}$ The ref. liquid is water

The density of the solution is $\frac{1.10 \text{ g soln/cm}^3 \text{ soln}}{1.00 \text{ g } H_2O\text{/cm}^3} \left| \frac{1.00 \text{ g } H_2O\text{/cm}^3}{} \right. = 1.10 \frac{\text{g soln}}{\text{cm}^3}$

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

Problem4

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. $$\text{Specific gravity} = \frac{\rho_{soln}}{\rho_{ref}} = \frac{(kg/m^3)soln}{(kg/m^3)ref} = \frac{1500\ kg/m^3}{1000\ kg/m^3} = \mathbf{1.50}$$

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

Problem5

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.

Problem6

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

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

Problem7

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.

Chapter3

Choosing aBasis

- A **basis** is a reference chosen by you for the calculations you plan to make in anyparticular problem, and a proper choice of basis frequently makes the problem much easier tosolve.
- The**basis**maybea**periodoftime**suchas**hours**,oragiven**massofmaterial**,suchas**5kg** of CO_2, or some other convenientquantity.
- For **liquids** and **solids** in which a **mass (weight)** analysis applies, a convenient basis isoften **1 or 100 lb or kg**; similarly, **1 or 100 moles** is often a good choice for a**gas**.

Example3.1

Gasmixture10.0%H_2,40.0%CH_4,30.0%CO,and20.0%CO_2,whatistheaveragemolecular weight of thegas?

Solution

Basis: 100 kg mol or lbmol ofgas

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

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

Other Method forSolution:

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

Example3.2

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).Forthismixture,calculate:(a)molefractionofeach component. (b) A verage molecular weight of themixture.

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**

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

Example3.3

A medium-grade bituminous coal analyzes asfollows:

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

TheresiduumisCandH,andthemoleratiointheresiduumisH/C=9.Calculatetheweight (mass) f raction 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 ofcoal

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

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

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, notweight)

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) = 33.15kg

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

Finally,wecanprepareatablesummarizingtheresultsonthebasisof**1kgofthecoalash-freeandwater-free**.

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 (ChapterThree):

Problem1

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 init.

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

Problem2

Inaternaryalloysuchas$Nd_{4.5}Fe_{77}B_{18.5}$theaveragegrainsizeisabout30nm.Byreplacing0.2 atoms of Fe with atoms of Cu, the grain size can be reduced (improved) to 17nm.

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

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

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 massfractions.

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, Page87)

Readeachofthefollowingproblemsandselectasuitablebasisforsolvingeachone.Donotsolve theproblems.

a. Youhave130kgofgasofthefollowingcomposition:40%N_2,30%CO_2,and30%CH_4ina tank. What is the average molecular weight of thegas?

b. Youhave25lbofagasofthefollowingcomposition:$CH_4$80%,$C_2H_4$10%,and$C_2H_6$10%. W hat is the average m olecular w eight of t he m ixture? What i s t he w eight (mass) f raction of eachof t he components in themixture?

c. The pr oximate a nd ul timate a nalysis of coal i s g iven in the f ollowing table. What is the composition of the "Volatile combustible material" (VCM)? Present your answer in the form ofthe mass percent of each element in theVCM.

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. Afuelgasisreportedtoanalyze,onamolebasis,20%methane,5%ethane,andtheremainder CO_2. Calculate the analysis of the fuel gas on a mass percentagebasis.

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.

Problem 4 (Basic Principles…. Book, Page88)

Choose a basis for the following problem: Chlorine usage at a water treatment plant averages134.2 lb/day. The average flow rate of water leaving the plant is 10.7 million gal/day. What is theaverage chlorine c oncentration in the tr eatment w ater leaving the pl ant (assuming no reaction ofthe chlorine), expressed in milligrams perliter?

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.

Chapter4Te mperature

- **Temperature** is a measure of the energy (mostly kinetic) of the molecules in a system.This definition tells us about the amount ofenergy.
- Other s cientists pr efer to say th at **Temperature** is a p roperty o f t he s tate of thermal equilibriumofthesystemwithrespecttoothersystemsbecausetemperaturetellsusabout the capability of a system to transfer energy (asheat).

☒ **Fourtypesoftemperature:**

Twobasedona**relativescale**,**degreesFahrenheit(°F)**and**Celsius(°C)**,andtwobasedonan **absolute scale**, **degree Rankine (°R)** and **Kelvin(K)**.

☒ **TemperatureConversion**

$$\Delta°F = \Delta°R$$

$$\Delta°C = \Delta K$$

Also, the Δ°C is larger than theΔ°F

$$\frac{\Delta°C}{\Delta°F} = 1.8 \quad \text{or} \quad \Delta°C = 1.8\ \Delta°F$$

$$\frac{\Delta K}{\Delta°R} = 1.8 \quad \text{or} \quad \Delta K = 1.8\ \Delta°R$$

Also, because of the temperature difference between boiling water and ice (Celsius: 100°C – 0°C =100°C; Fahrenheit: 212°F – 32°F = 180°F), the following relationships hold:

Δ°C = 1.8000 Δ°F and Δ K = 1.8000 Δ°F

Thepropermeaningofthesymbols°**C,°F,K,**and°**R,**aseitherthetemperatureortheunit temperaturedifference,mustbeinterpretedfromthecontextoftheequationorsentencebeing examined. Suppose you have therelation:

$$T_{°F} = a + bT_{°C}$$

Whataretheunitsof**a**and**b**?Theunitsof**a**mustbe°**F**forconsistency.Thecorrectunitsfor**b** mustinvolvetheconversionfactor**(1.8Δ°F\Δ°C)**,thefactorthatconvertsthesizeofanintervalon one temperaturescale

$$T_{°F} = a_{°F} + \underbrace{\left(\frac{1.8\ \Delta°F}{\Delta°C}\right)}_{b} T_{°C}$$

Unfortunately, the units for b are usually ignored; just the value of b (1.8) isemployed.

- The relations between **°C, °F, K,** and °**R**are:

$$T_{°R} = T_{°F}\left(\frac{1\ \Delta°R}{1\ \Delta°F}\right) + 460°R$$ Or $$\boxed{T_{°R} = T_{°F} + 460}$$

$$T_K = T_{°C}\left(\frac{1\ \Delta K}{1\ \Delta°C}\right) + 273\ K$$ Or $$\boxed{T_K = T_{°C} + 273}$$

$$T_{°F} - 32°F = T_{°C}\left(\frac{1.8\ \Delta°F}{1\ \Delta°C}\right)$$

$$T_{°C} = (T_{°F} - 32°F)\left(\frac{1\ \Delta°C}{1.8\ \Delta°F}\right)$$ Or $$\boxed{T_{°F} = 1.8\ T_{°C} + 32}$$

Example4.1

Convert 100 °C to (a) K, (b) °F, and (c)°R.

Solution

(a) $$(100 + 273)°C \frac{1\ \Delta K}{1\ \Delta°C} = 373\ K$$

or with suppression of the **Δ** symbol,

$$(100 + 273)°C \frac{1\ K}{1°C} = 373\ K$$

(b) $$(100°C)\frac{1.8\ \Delta°F}{1\ \Delta°C} + 32°F = 212°F$$

(c) $$(212 + 460)°F \frac{1\ \Delta°R}{1\ \Delta°F} = 672°R$$

or

$$(373\ K)\frac{1.8\ \Delta°R}{1\ \Delta K} = 672°R$$

Example4.2

The heat capacity of sulfuric acid has the units J/(g mol)(°C), and is given by therelation

Heat capacity = 139.1 + 1.56 * 10^{-1}T

whereTisexpressedin°C.Modifytheformulasothattheresultingexpressionhastheassociated units of Btu/(lbmol) (°R) and T is in°R.

Solution

$T_{°F} = 1.8\ T_{°C} + 32 \rightarrow T_{°C} = (T_{°F} - 32)/1.8$

$T_{°R} = T_{°F} + 460 \rightarrow T_{°F} = T_{°R} - 460$

$\therefore\ T_{°C} = [T_{°R} - 460 - 32]/1.8$

$$\text{heat capacity} = \left\{139.1 + 1.56 \times 10^{-1}\left[\overbrace{(T_{°R} - 460 - 32)\frac{1}{1.8}}^{T_{°C}}\right]\right\} \times \underbrace{\frac{1\ \text{J}}{(\text{g mol})(°\text{C})}\left|\frac{1\ \text{Btu}}{1055\ \text{J}}\right|\frac{454\ \text{g mol}}{1\ \text{lb mol}}\left|\frac{1°\text{C}}{1.8°\text{R}}\right.}_{\text{conversion factors}} =$$

$$= 23.06 + 2.07 \times 10^{-2} T_{°R}$$

Note the suppression of the Δ symbol in the conversion between °C and°R.

Problems

1. Complete the following table with the proper equivalenttemperatures:

°C	°F	K	°R
−40	_____	_____	_____
_____	77.0	_____	_____
_____	_____	698	_____
_____	_____	_____	69.8

2. The heat capacity of sulfur is $C_p = 15.2 + 2.68T$, where C_p is in J/(g mol)(K) and T is inK. Convert this expression so that C_p is in cal/(g mol)(°F) with T in°F.

Answers:

1.

°C	°F	K	°R
−40.0	−40.0	233	420
25.0	77.0	298	537
425	796	698	1256
−234	−390	38.8	69.8

2. $C_p = 93.2 + 0.186 T_{°F}$

Supplementary Problems (ChapterFour):

Problem1

Complete the table below with the proper equivalent temperatures.

°C	°F	K	°R
- 40.0	----------	------------	-----------
----------	77.0	------------	-----------
----------	----------	698	-----------
----------	----------	------------	69.8

Solution

The conversion relations to use are:

°F	=	1.8 °C	+	32
K	=	°C	+	273
°R	=	°F	+	460
°R	=	1.8 K		

°C	°F	K	°R
- 40.0	**- 40.0**	**233**	**420**
25.0	77.0	**298**	**437**
425	**797**	698	**1257**
- 235	**-390**	**38.4**	69.8

Problem2

The specific heat capacity of toluene is given by following equation

$C_p = 20.869 + 5.293 \times 10^{-2}\,T$ where C_p is in Btu/(LB mol) (° F) and T is in ° F

Express the equation in cal/(g mol) (K) with T in K.

Solution

First, conversion of the units for the overall equation is required.

$$C_p = \frac{[20.869 + 5.293 \times 10^{-2}\,(T_{°F})]\quad \text{Btu}}{1\ (\text{lb mol})\ (°F)}\left|\frac{252\ \text{cal}}{1\ \text{Btu}}\right|\frac{1\ \text{lb mol}}{454\ \text{g mol}}\left|\frac{1.8\ °F}{1\ \text{K}}\right.$$

$$= [\,20.869 + 5.293 \times 10^{-2}\,(T_{°F})]\,\frac{\text{cal}}{(\text{g mol})\ (\text{K})}$$

Note that the coefficients of the equation remain unchanged in the new units for this particular conversion. The T of the equation is still in °F, and must be converted to kelvin.

$$T_{°F} = (T_K - 273)\,1.8 + 32$$

$$C_p = 20.69 + 5.293 \times 10^{-2}\,[(T_K - 273)\,1.8 + 32]$$

Simplifying $C_p = -3.447 + 9.527 \times 10^{-2}\,T_K$

Chapter5

Pressure

5.1 Pressure and ItsUnits

Pressureisdefinedas"thenormal(perpendicular)**force**perunit**area**(Figure5.1).The pressure at the bottom of the static (nonmoving) column of mercury exerted on the sealing plateis

$$p = \frac{F}{A} = \rho g h + p_0 \qquad \ldots 5.1$$

Where p = pressure at the bottom of the column of the fluid, F = force, A = area, ρ = density offluid g = acceleration of gravity, h = height of the fluid column, and p_0 = pressure at thetop ofthe column offluid

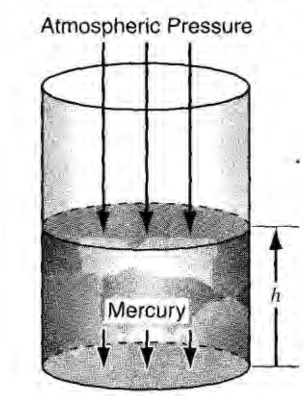


Figure 5.1 Pressure is the normal force per unit area. Arrows show the force exerted onthe respectiveareas

ForExample,supposethatthecylinderoffluidinFigure5.1isacolumnofmercurythathasan areaof1cm^{2}andis50cmhigh.ThedensityoftheHgis13.55g/cm^3.Thus,theforceexertedby t he m ercury alone on the 1 cm^2 section of the bottom plate by the column of mercuryis

$$F = \frac{13.55\ \text{g}}{\text{cm}^3}\left|\frac{980\ \text{cm}}{\text{s}^2}\right|\frac{50\ \text{cm}}{}\left|\frac{1\ \text{cm}^2}{}\right|\frac{1\ \text{kg}}{1000\ \text{g}}\left|\frac{1\ \text{m}}{100\ \text{cm}}\right|\frac{1(\text{N})(\text{s}^2)}{1(\text{kg})(\text{m})}$$

$$= 6.64\ \text{N}$$

P=F/A …. F= P* A = ρ g h*A

Thepressureonthesectionoftheplatecoveredbythemercuryistheforceperunitareaofthe mercury plus the pressure of theatmosphere

$$p = \frac{6.64\ \text{N}}{1\ \text{cm}^2}\left|\left(\frac{100\ \text{cm}}{1\ \text{m}}\right)^2\right|\frac{(1\ \text{m}^2)(1\ \text{Pa})}{(1\ \text{N})}\left|\frac{1\ \text{kPa}}{1000\ \text{Pa.}}\right. + p_0 = 66.4\ \text{kPa} + p_0$$

IfwehadstartedwithunitsintheAEsystem,thepressurewouldbecomputedas[thedensityof mercury is 845.5 lb_m/ft^3]

$$p = \frac{845.5\ lb_m}{1\ ft^3}\left|\frac{32.2\ ft}{s^2}\right|\frac{50\ cm}{}\left|\frac{1\ in.}{2.54\ cm}\right|\frac{1 ft}{12\ in.}\left|\frac{(s)^2(lb_f)}{32.174(ft)(lb_m)}\right. + p_0$$

$$= 1388\frac{lb_f}{ft^2} + p_0$$

5.2 Measurement of Pressure

Pressure, like temperature, can be expressed using either an **absolute** or a **relativescale**.

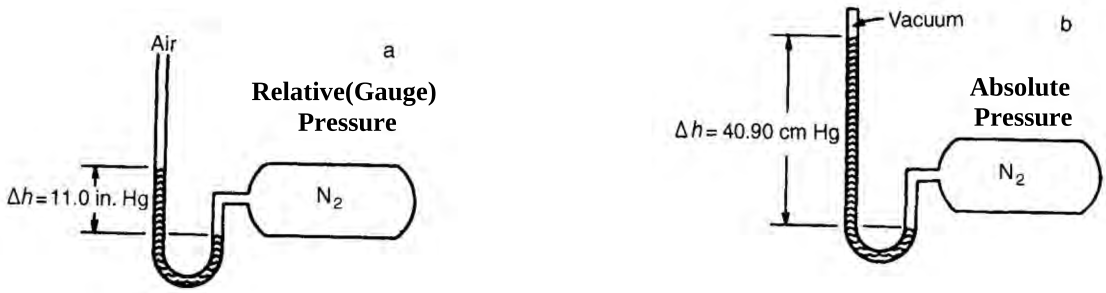


Figure 5.2 (a) **Open-end manometer** showing a pressure above atmospheric pressure.(b) **Manometer** measuring an **absolutepressure**.

The relationship between **relative** and **absolute pressure** is given by the followingexpression:

Gauge Pressure + Barometer Pressure (atmospheric)= AbsolutePressure …5.2

$$P_{vacuum} = p_{atmospheric} - p_{absolute}$$

- Thestandardatmosphereisdefinedasthepressure(inastandardgravitationalfield) equivalent to 1 atm or 760 mm Hg at 0°C or otherequivalent.

The **standard atmosphere** is equalto

- 1.00 atmospheres(atm)
- 33.91 feet of water (ftH_2O)
- 14.7 pounds (force) per square inch absolute(psia)
- 29.92 inches of mercury (in.Hg)
- 760.0 millimeters of mercury (mmHg)
- 1.013 * 10^5 pascal (Pa) or newtons per square meter (N/m^2); or 101.3kPa

For Example, convert 35 psia to inches of mercury andkPa.

$$\frac{35\ psia}{}\left|\frac{29.92\ in.\ Hg}{14.7\ psia}\right. = 71.24\ in\ Hg$$ And, $$\frac{35\ psia}{}\left|\frac{101.3\ kPa}{14.7\ psia}\right. = 241\ kPa$$

<u>For Example</u>, What is the equivalent **pressure** to **1 kg/cm²** (i.e., **kg_f/cm²**) in pascal ($g = 9.8 m/s^2$)

$[1\ kg/cm^2] * [9.8\ m/s^2] * [(100\ cm/1\ m)^2] = 9.8 * 10^4\ N/m^2$ (orPa)

<u>Example5.1</u>

What is the equivalent pressure to 60 Gpa (gigapascal)in

(a)atmospheres (b)psia (c) inches ofHg (d) mm ofHg

Solution

Basis: 60 GPa

(a) $\frac{60\ \text{GPa}}{} \Big| \frac{10^6\ \text{kPa}}{1\ \text{GPa}} \Big| \frac{1\ \text{atm}}{101.3\ \text{kPa}} = 0.59 \times 10^6\ \text{atm}$

(b) $\frac{60\ \text{GPa}}{} \Big| \frac{10^6\ \text{kPa}}{1\ \text{GPa}} \Big| \frac{14.696\ \text{psia}}{101.3\ \text{kPa}} = 8.70 \times 10^6\ \text{psia}$

(c) $\frac{60\ \text{GPa}}{} \Big| \frac{10^6\ \text{kPa}}{1\ \text{GPa}} \Big| \frac{29.92\ \text{in. Hg}}{101.3\ \text{kPa}} = 1.77 \times 10^7\ \text{in. Hg}$

(d) $\frac{60\ \text{GPa}}{} \Big| \frac{10^6\ \text{kPa}}{1\ \text{GPa}} \Big| \frac{760\ \text{mm Hg}}{101.3\ \text{kPa}} = 4.50 \times 10^8\ \text{mm Hg}$

<u>Example5.2</u>

The pressure gauge on a tank of CO_2 used to fill soda-water bottles reads 51.0 psi. At the sametime the barometer reads 28.0 in. Hg. What is the absolute pressure in the tank in psia? See FigureE5.2.

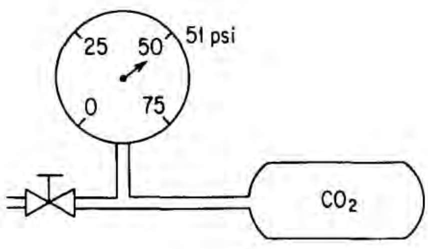


Figure E5.2

Solution

$$\text{Atmospheric pressure} = \frac{28.0\ \text{in. Hg}}{} \Big| \frac{14.7\ \text{psia}}{29.92\ \text{in Hg}} = 13.76\ \text{psia}$$

The absolute pressure in the tankis

51.0 psia + 13.76 psia = 64.8psia

Example5.3

Small animals such as mice can live (although not comfortably) at reduced air pressures down to20 kPa absolute. In a test, a mercury manometer attached to a tank, as shown in Figure E5.3, reads64.5 cm Hg and the barometer reads 100 kPa. Will the micesurvive?

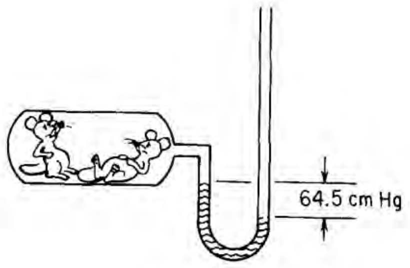


Figure E5.3

Solution

Youareexpectedtorealizefromthefigurethatthetankis**belowatmosphericpressure**because the**leftleg**ofthe**manometerishigher**thanthe**rightleg**,whichisopentotheatmosphere. Consequently,togetthe**absolutepressure**you**subtract**the**64.5cmHg**fromthe**barometer reading**. The **absolute pressure** in the tankis

$$100\text{ kPa} - \frac{64.5\text{ cm Hg}}{}\left|\frac{101.3\text{ kPa}}{76.0\text{ cm Hg}}\right. = 100 - 86 = 14\text{ kPa absolute}$$

The mice probably will **notsurvive**.

5.3 Differential PressureMeasurements

Whenthecolumnsoffluidsareatequilibrium(seeFigure5.3),therelationshipamongρ_1,ρ_2,ρ_3, and the heights of the various columns of fluid is asfollows:

$$\mathbf{P_1 + \rho_1 d_1 g = P_2 + \rho_2 d_2 g + \rho_3 d_3\ g} \qquad \ldots 5.3$$

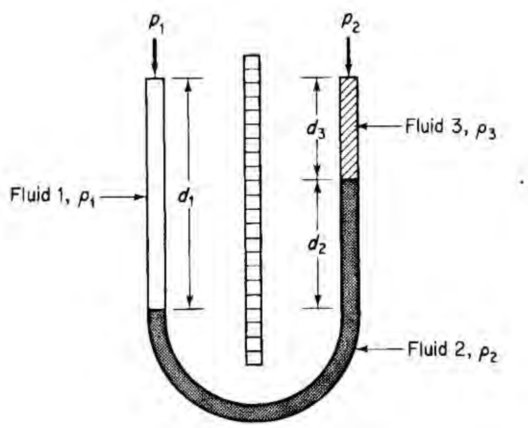


Figure 5.3 Manometer with threefluids.

Note

Iffluids1and3are**gases**,andfluid2is**mercury**,thedensityofthe**gas**is**somuchless**thanthat of **mercury** that you can **ignore** the term involving the gas in Equation (5.3) forpractical applications.

- Canyoushowforthecaseinwhichρ_1=ρ_3=ρthatthemanometerexpressionreducesto the differential manometerequation:

$$P_1 - P_2 = (\rho_2 - \rho)\, g\, d_2 \quad \text{… 5.4}$$

Example5.4

Inmeasuringtheflowoffluidinapipelineasshowninfigure E5.4,adifferentialmanometerwas us ed t o determine the pressure difference across the orifice plate. The flow rate was to becalibrated with the observed pressure dr op (difference). C alculate t he **pressure drop p_1 - p_2** in pa scals f orthe manometer reading in FigureE5.4.

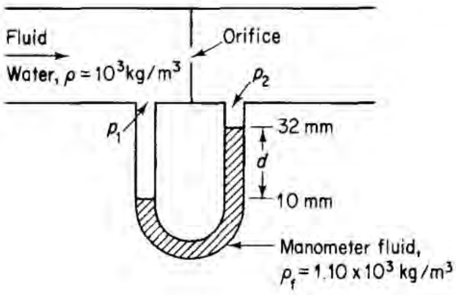


Figure E5.4

Solution

In this problem you **cannot ignore the water density** above the manometerfluid.

$$p_1 - p_2 = (\rho_f - \rho)gd$$

$$= \frac{(1.10 - 1.00)10^3\ \text{kg}}{\text{m}^3}\left|\frac{9.807\ \text{m}}{\text{s}^2}\right|\frac{(22)(10^{-3})\text{m}}{}\left|\frac{1(\text{N})(\text{s}^2)}{(\text{kg})(\text{m})}\right|\frac{1(\text{Pa})(\text{m}^2)}{1(\text{N})}$$

$$= 21.6\ \text{Pa}$$

Example5.5

Airisflowingthroughaduct**under**adraftof4.0cmH_2O.Thebarometerindicatesthatthe at mospheric pressure i s 730 m m H g. W hat i s t he a bsolute pr essure o f t he a ir i n i nches of mercury? S ee FigureE5.5

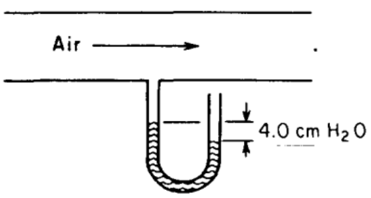


Figure E5.5

Solution

Inthisproblemyou**canignorethegasdensity**abovethemanometerfluidandtheairabovethe open end of themanometer.

$$\text{Atmospheric pressure} = \frac{730 \text{ mm Hg}}{} \bigg| \frac{29.92 \text{ in. Hg}}{760 \text{ mm Hg}} = 28.7 \text{ in. Hg}$$

Next, convert 4.0 cm H_2O to in.Hg:

$$\frac{4.0 \text{ cm } H_2O}{} \bigg| \frac{1 \text{ in.}}{2.54 \text{ cm}} \bigg| \frac{1 \text{ ft}}{12 \text{ in.}} \bigg| \frac{29.92 \text{ in. Hg}}{33.91 \text{ ft } H_2O} = 0.12 \text{ in. Hg}$$

Sincethereadingis4.0cmH_2Odraft(**underatmospheric**),theabsolutereadinginuniformunits is

$$28.7 \text{ in. Hg} - 0.12 \text{ in. Hg} = 28.6 \text{ in. Hg absolute}$$

Questions

1. Figure SAT5.1Q2 shows four closed containers completely filled with water. Orderthe containers from the one exerting the highest pressure to the lowest on their respectivebase.

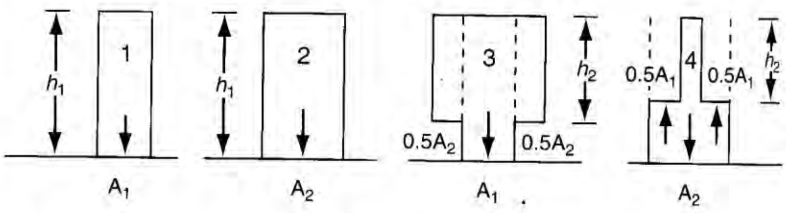


Figure SAT5.1Q2

2. Answer the following questions true orfalse:
   a. Atmospheric pressure is the pressure of the air surrounding us and changes fromday to day
   b. Thestandardatmosphereisaconstantreferenceatmosphereequalto1.000atmor the equivalent pressure in other units.
   c. Absolute pressure is measured relative to a vacuum.
   d. Gauge pressure is measured upward relative to atmospheric pressure.
   e. Vacuum and draft pressures are measured downward from atmosphericpressure.
   f. You can convert from one type of pressure measurement to another usingthe standard atmosphere.
   g. Amanometermeasuresthepressuredifferenceintermsoftheheightoffluid(s)in the manometer tube.

3. What is the equation to convert gauge pressure to absolutepressure?
4. Whatarethevaluesandunitsofthestandardatmosphereforsixdifferentmethodsof expressingpressure?
5. What is the equation to convert vacuum pressure to absolutepressure?

Answers:

1. 3isthehighestpressure;nextare1and2,whicharethesame;and4islast.Thedecisions are made by dividing the weight of water by the basearea.
2. All are true
3. Gauge pressure + barometric pressure = absolutepressure
4. Seelectures
5. Barometric pressure - vacuum pressure = absolutepressure

Problems

1. Convert a pressure of 800 mm Hg to the followingunits:

   a. psia b.kPa c.atm d. ft H_2O
2. Your textbook lists five types of pressures: atmospheric pressure, barometric pressure, gauge pressure, absolute pressure, and vacuumpressure.

   a. What kind of pressure is measured by the device in FigureSAT5.2P2A?

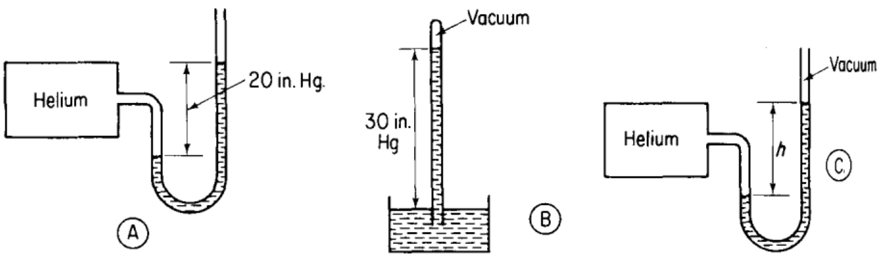


Figure SAT5.2P2A

   b. What kind of pressure is measured by the device in FigureSAT5.2P2B?
   c. What would be the reading in Figure SAT5.2P2C assuming that the pressureand temperature inside and outside the helium tank are the same as in parts (a) and(b)?
3. Anevaporatorshowsareadingof40kPavacuum.Whatistheabsolutepressureinthe evaporator inkPa?
4. AU-tubemanometerfilledwithmercuryisconnectedbetweentwopointsinapipeline.If the manometer reading is 26 mm of Hg, calculate the pressure difference in kPa betweenthe points when (a) water is flowing through the pipeline, and (b) also when air atatmospheric pressure and 20°C with a density of 1.20 kg/m^3 is flowing in thepipeline.

5. ABourdongaugeandamercurymanometerareconnectedtoatankofgas,asshownin Figure SAT5.3P2. If the reading on the pressure gauge is 85 kPa, what is h in centimetersof Hg?

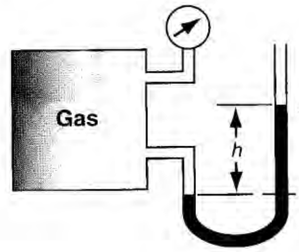


Figure SAT5.3P2

Answers:

1. (a) 15.5; (b) 106.6; (c) 1.052; (d)35.6
2. (A) Gauge pressure; (B) barometric pressure, absolute pressure; (C) 50 in.Hg
3. Intheabsenceofabarometricpressurevalue,assume101.3kPa.Theabsolutepressureis 61.3kPa.
4. The Hg is static. (a) 3.21 kPa; (b) 3.47kPa
5. 63.8 cm Hg

Supplementary Problems (ChapterFive):

Problem1

A solvent storage tank, 15.0 m high contains liquid styrene (sp. gr. 0.909). A pressure gauge is fixed at the base of the tank to be used to determine the level of styrene.

a. Determine the gage pressure when the tank is full of styrene.
b. If the tank is to be used for storage of liquid hexane (sp. gr. 0.659), will the same pressure gage calibration be adequate ? What is the risk in using the same calibration to determine the level of hexane in the tank.
c. What will be the new pressure with hexane to indicate that the tank is full.

Solution

a. The liquid in full tank will exert a gage pressure at the bottom equal to 15.0 m of styrene. The tank has to operate with atmospheric pressure on it and in it, or it will break on expansion at high pressure or collapse at lower pressure.

$$p = h\,\rho\,g$$

$$= 15.0\text{ m}\ \frac{0.909\text{ g styrene/cm}^3}{1.0\text{ g H}_2\text{O/cm}^3}\left|\frac{1.0\text{ g H}_2\text{O/cm}^3}{}\right|\frac{10^3\text{ kg/m}^3}{1\text{ g/cm}^3}\left|\frac{9.80\text{ m/s}^2}{}\right|\frac{1\text{ Pa}}{1\text{ (kg)(m)}^{-1}\text{(s)}^{-2}}$$

$$= 134 \times 10^3\text{ Pa} = \mathbf{134\ kPa\ gage}$$

b. Hexane is a liquid of specific gravity lower than that of styrene; therefore a tank full of hexane would exert a proportionally lower pressure. If the same calibration is used the tank may overflow while the pressure gage was indicating only a partially full tank.

c. New p = h ρ g

$$= 15.0\ \text{m}\ \frac{0.659\ \text{g hexane/cm}^3}{1.0.0\ \text{g}\ H_2O/\text{cm}^3}\ \Bigg|\ \frac{1.0\ \text{g}\ H_2O/\text{cm}^3}{}\ \Bigg|\ \frac{10^3\ \text{kg/m}^3}{}\ \Bigg|\ \frac{9.8\ \text{m/s}^2}{}\ \Bigg|\ \frac{1\ \text{Pa}}{1(\text{kg})(\text{m})^{-1}(\text{s})^{-2}}$$

$$= \quad 96900\ \text{Pa} = \mathbf{96.9\ kPa}$$

Problem2

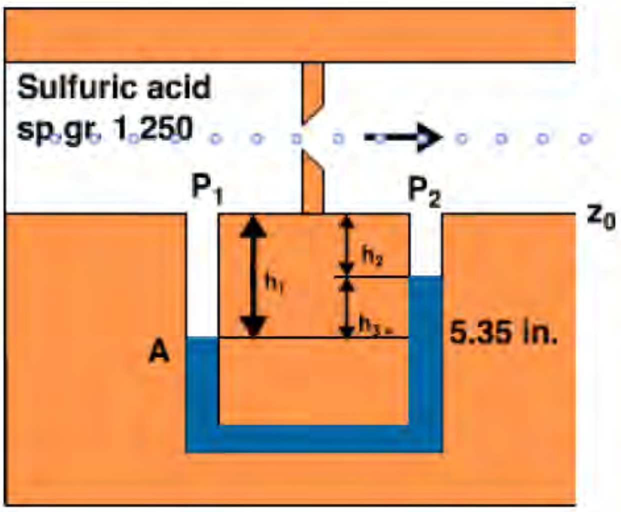
A U-tube manometer is used to determine the pressure drop across an orifice meter. The liquid flowing in the pipe line is a sulfuric acid solution having a specific gravity (60°/60°) of 1.250. The manometer liquid is mercury, with a specific gravity (60°/60°) of 13.56. The manometer reading is 5.35 inches, and all parts of the system are at a temperature of 60°F. What is the pressure drop across the orifice meter in psi.

Solution

First we calculate density of acid and mercury.

$$\rho_{acid} = \frac{1.250}{}\ \Bigg|\ \frac{62.4\ \text{lb/ft}^3}{}\ \Bigg|\ \frac{1\ \text{ft}^3}{1.728\times10^3\ \text{in}^3} = 0.0451\ \text{lb/in}^3$$

$$\rho_{Hg} = \frac{13.56}{}\ \Bigg|\ \frac{62.4\ \text{lb/ft}^3}{}\ \Bigg|\ \frac{1\ \text{ft}^3}{1.728\times10^3\ \text{in}^3} = 0.490\ \text{lb/in}^3$$



	left column		*right column*
At z_o	$p_1 + \rho_a h_1 g$	=	$p_2 + \rho_a h_2 g + \rho_{Hg} h_3 g$

$$p_1 - p_2 + \rho_a (h_1 - h_2) g = \rho_{Hg} h_3 g$$

$$p_1 - p_2 + \rho_a h_3 g = \rho_{Hg} h_3 g$$

$$p_1 - p_2 = (\rho_{Hg} - \rho_a) h_3 g$$

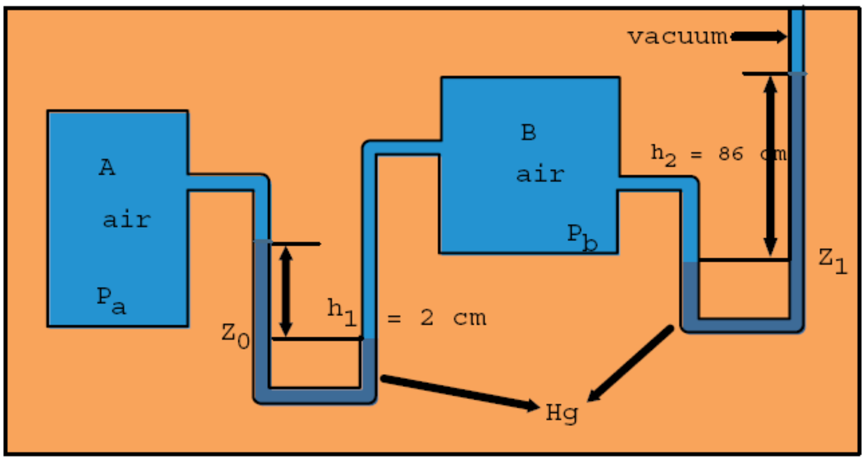
$$p_1 - p_2 = \frac{(0.490 - 0.0451)\ lb_f}{in^2} \left| \frac{(5.35)\ in}{} \right| \frac{32.2\ ft/s^2}{32.174\ (ft)(lb_m)/(s^2)(lb_f)} = \mathbf{2.38\ lb_f/in^2\ (psi)}$$

Problem3

The pressure difference between two air tanks A and B is measured by a U - tube manometer, with mercury as the manometer liquid. The barometric pressure is 700 mm Hg.

a. What is the absolute pressure in the tank A ?
b. What is the gauge pressure in the tank A ?

Solution



a. At Z_0 $\quad p_a + h_1 \rho_{Hg} g = p_b$ (neglecting the effect of air in the U - tube) (1)

at Z_1 $\quad p_b = h_2 \rho_{Hg} g$ (2)

Eliminate p_b from the equations

$$p_a + h_1 \rho_{Hg} g = h_2 \rho_{Hg} g$$

$$p_a = (h_2 - h_1) \rho_{Hg} g$$

= 840 mm Hg absolute

The pressure measured by this manometer system is the absolute pressure because the reference (pressure above the mercury) in the vertical tube is a vacuum.

b. $p_a = 840 - 700 = 140$ mm Hg

Chapter6

Introduction to MaterialBalances

6.1 The Concept of a Material Balance

A **material balance** is nothing more than the application of the law of the **conservationof mass**:

"Matter is neither created nordestroyed"

6.2 Open and Closed Systems

a. System

By**system**wemeananyarbitraryportionoforawhole**process**thatyouwanttoconsider for analysis. You can define a **system** such as a **reactor**, a **section of a pipe**. O r, you can definethe **limits**ofthe**system**bydrawingthe**systemboundary**,namelyalinethatenclosestheportionof the pr ocess that you want toanalyze.

b. ClosedSystem

Figure6.1showsatwo-dimensionalviewofathree-dimensionalvesselholding**1000kgofH_2O**. **Notethatmaterialneitherentersnorleavesthevessel**,thatis,**nomaterialcrossesthesystem boundary**. Changes can take place **inside the system**, but for a **closed system**, **no massexchange occurs with thesurroundings**.

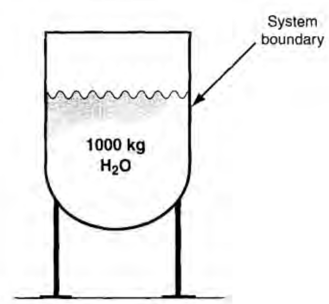


Figure 6.1 A closedsystem.

c. Open System

Figure6.2isanexampleofan**opensystem**(alsocalleda**flowsystem**)becausematerialcrosses the systemboundary.

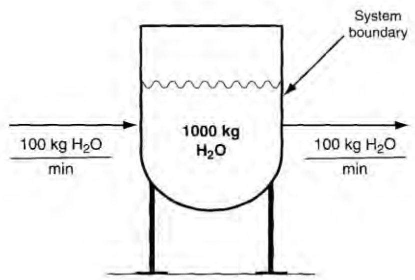


Figure 6.2 An open steady–statesystem.

6.3 Steady-State and Unsteady-State Systems

a. Steady–State System

Because the rate of addition of water is equal to the rate of removal, the amount of waterin thevesselshowninFigure6.2remainsconstantatitsoriginalvalue(**1000kg**).Wecall such a **process** or **system** a **steady–state process** or a **steady–state system**because

1. The**conditions**insidetheprocess(specificallytheamountofwaterinthevesselin Figure 6.2) **remain unchanged with time**,and
2. The **conditions** of the flowing streams **remain constant withtime**.

✶ Thus,ina**steady-stateprocess**,bydefinitionalloftheconditionsintheprocess**(e.g., temperature,pressure,massofmaterial,flowrate,etc.)**remainconstantwithtime.A **continuous process** is one in which material enters and/or leaves the systemwithout interruption.

b. Unsteady–State System

Because the amount of water in the system **changes with time (Figure 6.3)**, the **process**and**system** are deemed to be an **unsteady–state** (**transient**) **process orsystem**.

✶ For an **unsteady-state process**, not all of the **conditions** in the **process (e.g.,temperature, pressure, mass of material, etc.)** remain constant with time, and/or the **flows** in and outof the **system** can **vary withtime**.

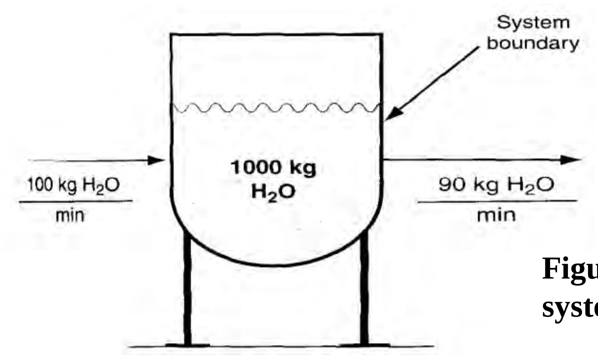


Figure 6.3 Initial conditions for an open unsteady–state system withaccumulation.

✶ Figure 6.4 shows the system after 50 minutes of accumulation (Fifty minutesof accumulation at 10 kg/min amounts to 500 kg of totalaccumulation).

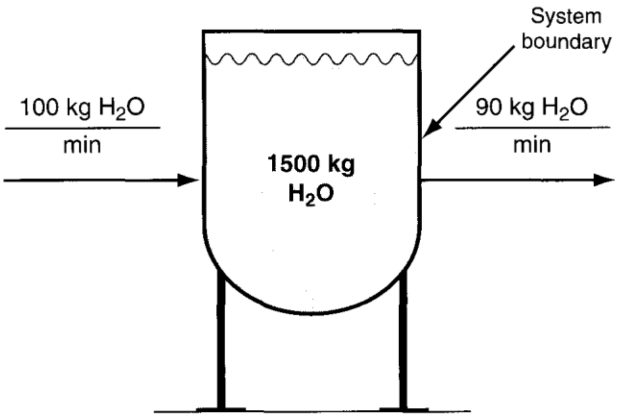


Figure 6.4 The condition of the open unsteady–state system with accumulation after50 minutes.

- **Figures 6.5** and **6.6** demonstrate **negativeaccumulation**.
  Notethattheamountofwaterinthesystemdecreaseswithtimeattherateof**10kg/min**. Figure 6.6 shows the system after **50 minutes** ofoperation.

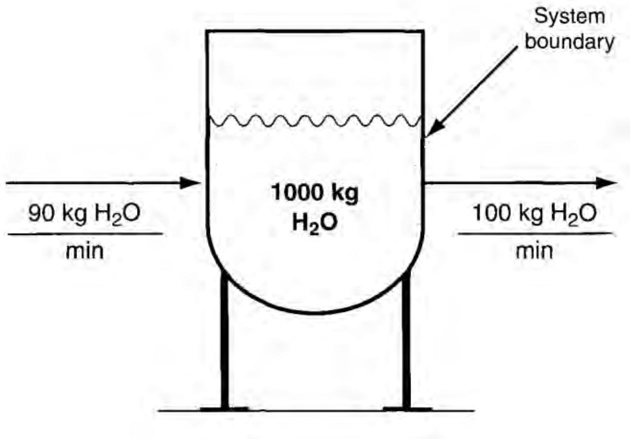


Figure 6.5 Initial conditions for an unsteady–state process with negativeaccumulation.

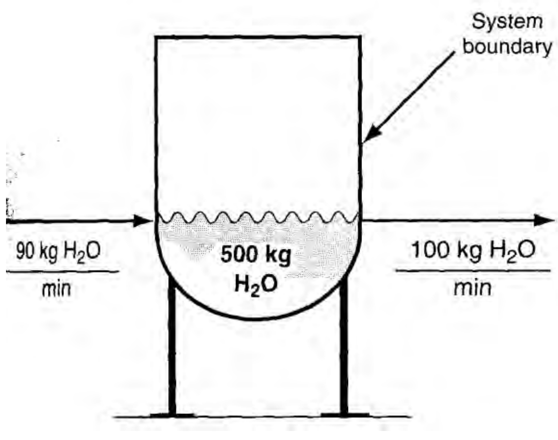


Figure 6.6 Condition of the open unsteady–state system with negative accumulation after50 minutes.

- **The material balance for a single component process is**

$$\begin{Bmatrix}\text{Accumulation of material}\\ \text{within the system}\end{Bmatrix} = \begin{Bmatrix}\text{Total flow into}\\ \text{the system}\end{Bmatrix} - \begin{Bmatrix}\text{Total flow out}\\ \text{of the system}\end{Bmatrix} \quad ...6.1$$

Equation 6.1 can apply to **moles** or any **quantity** that is **conserved**. As an example, look at**Figure 6.7** in which we have converted all of the mass quantities in **Figure 6.2** to their equivalent valuesin moles.

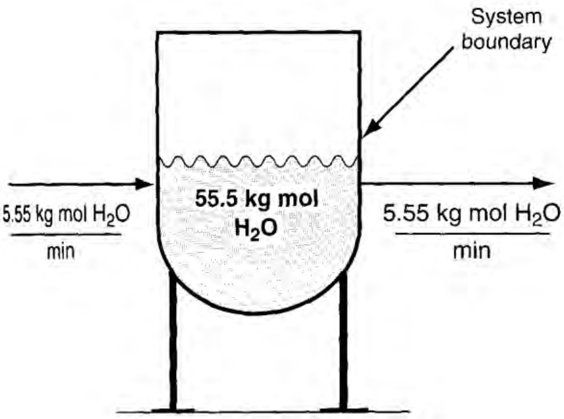


Figure 6.7 The system in Figure 6.2 with the flow rates shown in kgmol.

If the process is in the **steady state**, the **accumulation** term by definition is **zero**, and **Equation6.1** simplifies to a famoustruism

What goes in must come out (In =Out) ...6.2

Ifyouareanalyzinganunsteady-stateprocess,theaccumulationtermoveratimeintervalcanbe calculatedas

$$\{\text{Accumulation}\} = \begin{Bmatrix}\text{Final material}\\ \text{in the system}\end{Bmatrix} - \begin{Bmatrix}\text{Initial material}\\ \text{in the system}\end{Bmatrix} \quad (6.3)$$

The**times**youselectforthefinalandinitialconditionscanbeanything,butyouusuallyselectan **interval**such as **1 minute** or **1 hour** rather than specifictimes.

- Whenyoucombine**Equations6.1and6.3**yougetthe**generalmaterialbalance**fora component in the system in the **absence ofreaction**

$$\begin{Bmatrix}\text{Final material}\\ \text{in the system}\\ \text{at } t_2\end{Bmatrix} - \begin{Bmatrix}\text{Initial material}\\ \text{in the system}\\ \text{at } t_1\end{Bmatrix} = \begin{Bmatrix}\text{Flow into}\\ \text{the system}\\ \text{from } t_1 \text{ to } t_2\end{Bmatrix} - \begin{Bmatrix}\text{Flow out of}\\ \text{the system}\\ \text{from } t_1 \text{ to } t_2\end{Bmatrix} \quad ...6.4$$

Example6.1

Will you save money if instead of buying premium 89 octane gasoline at \$1.269 per gallon thathas theoctaneyouwant,youblendsufficient93octanesupremegasolineat\$l.349pergallonwith87 oc tane regular gasoline at \$1.149 pergallon?

Solution

Chooseа**basis**of**1gallonof89octanegasoline**,thedesiredproduct.Thesystemisthegasoline tank.

- Forsimplicity,assumethat**nogasolineexists**inthetankatthestartoftheblending,and **one gallon exists** in the tank at the end of theblending.
- This arrangement corresponds to an **unsteady-state process**. Clearly it is an **opensystem**.

The **initial number of gallons** in the system is **zero** and the **final number of gallons** is**one**.

Let **x** = the number of gallons of **87** octane gasoline added,and

y = the number of gallons of **93** octane added to theblend.

Since **x + y = 1** is the total flow into thetank,

$\therefore$ y = 1 –x

According to Equation (6.4) the balance on the octane numberis

$$\underbrace{\frac{89\text{ octane}}{1\text{ gal}}\,\Big|\,1\text{ gal} - 0}_{\textit{Accumulation}} = \underbrace{\frac{87\text{ octane}}{1\text{ gal}}\,\Big|\,x\text{ gal} + \frac{93\text{ octane}}{1\text{ gal}}\,\Big|\,(1-x)\text{ gal}}_{\textit{Inputs}}$$

The solution is x = 2/3 gal and thus y = 1 – x = 1/3gal.

The cost of the blended gasoline is (2/3) (\$l.l49) + (1/3) (\$l.349) = \$1.216

A value less than the cost of the 89 octane gasoline(\$l.269).

6.4 Multiple ComponentSystems

Suppose the input to a vessel contains **more than one component**, such as 100 kg/min ofa 50%waterand50%sugar(sucrose,$C_{12}H_{22}O_{11}$,MW=342.3)mixture(seeFigure6.8).Themass ba lances with respect to the **sugar and water**, balances that we call **componentbalances**.

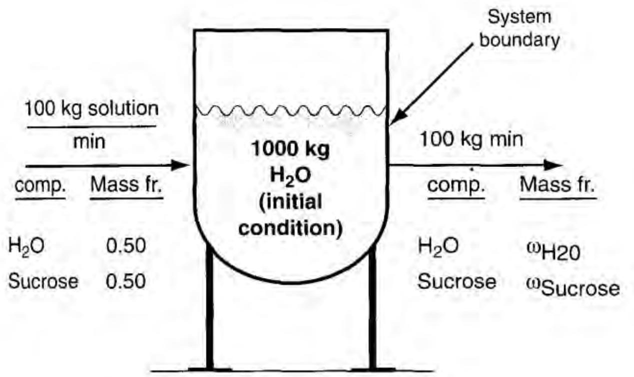


Figure 6.8 An open system involving twocomponents.

<u>ForExample</u>,lookatthemixershowninFigure6.9,anapparatusthatmixestwostreamsto increasetheconcentrationofNaOHinadilutesolution.**Themixerisasteady–stateopen system**. I nitially the mixer is empty, and after 1 hour it is emptyagain.

<u>Basis = 1 hour</u> for con venience. A s an alternate t o the **basis** we s elected you could select **<u>F_1 =9000kg/hrasthebasis,orF_2=1000kg/hrasthebasis</u>**;the**numbers**forthisexamplewouldnot c hange – just the **units** would change. Here are the components and total balances in**kg**:

Balances	Flow in F_1	Flow in F_2	Flow out	Accum.
NaOH	450	500	950	= 0
H_2O	8,550	500	9,050	= 0
Total	9,000	1,000	10,000	= 0

We can convert the kg shown in Figure 6.9 to kg moles by dividing each compound byits respective molecular weight (NaOH = 40 and H_2O =18).

$$\text{NaOH:}\quad \frac{450}{40} = 11.25 \qquad \frac{500}{40} = 12.50 \qquad \frac{950}{40} = 23.75$$

$$H_2O\text{:}\quad \frac{8550}{18} = 475 \qquad \frac{500}{18} = 27.78 \qquad \frac{9050}{18} = 502.78$$

Then the component and total balances in **kg mol**are:

Balances	Flow in F_1	Flow in F_2	Flow out	Accum.
NaOH	11.25	12.50	23.75	= 0
H_2O	475	27.78	502.78	= 0
Total	486.25	40.28	536.53	= 0

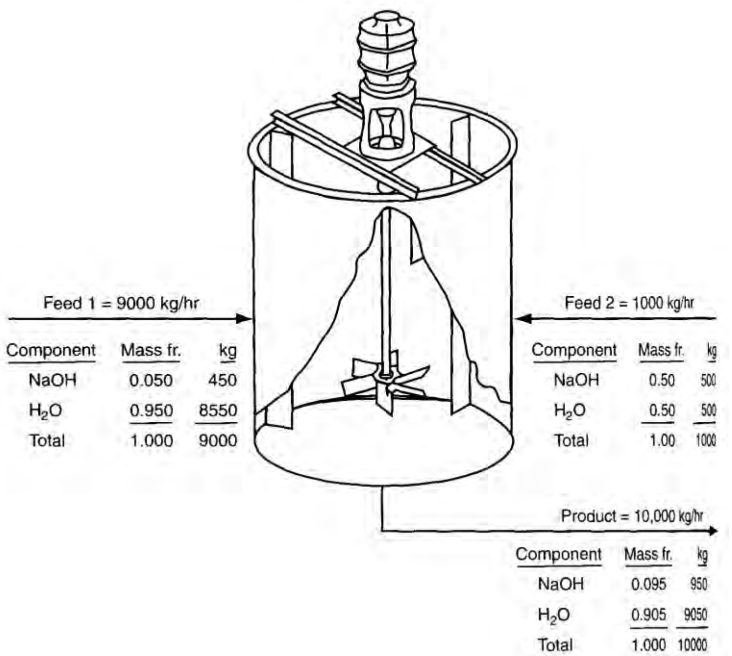


Figure 6.9 Mixing of a dilutestream of NaOH with a concentratedstream of NaOH. Values below thestream arrows are based on 1 hourof operation.

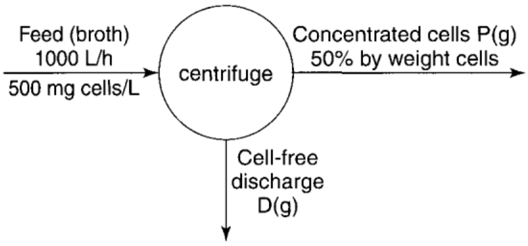
Example6.2

Centrifugesareusedtoseparateparticlesintherangeof0.1to100μmindiameterfromaliquid usingcentrifugalforce.Yeastcellsarerecoveredfromabroth(aliquidmixturecontainingcells) usingatubularcentrifuge(acylindricalsystemrotatingaboutacylindricalaxis).Determinethe amountofthecell-freedischargeperhourif1000L/hrisfedtothecentrifuge,thefeedcontains 500mgcells/L,andtheproductstreamcontains50wt.%cells.Assumethatthefeedhasadensity of $1 g/cm^3$.

Solution

This problem involves a **steady state**, **open (flow)** system **withoutreaction**.

Basis = 1hour



FigureE6.2

M.B. oncells

In (mass) = Out(mass)

$$\frac{1000 \text{ L feed}}{} \left| \frac{500 \text{ mg cells}}{1 \text{ L feed}} \right| \frac{1 \text{ g}}{1000 \text{ mg}} = \frac{0.5 \text{ g cells}}{1 \text{ g } P} \left| \frac{P \text{ g}}{} \right.$$

P = 1000g

M.B. on fluid

In (mass) = Out(mass)

$$\frac{1000 \text{ L}}{} \left| \frac{1000 \text{ cm}^3}{1 \text{ L}} \right| \frac{1 \text{ g fluid}}{1 \text{ cm}^3} = \frac{1000 \text{ g } P}{} \left| \frac{0.50 \text{ g fluid}}{1 \text{ g } P} \right. + D \text{ g fluid}$$

$D = (10^6 - 500)g$

6.5 Accounting for Chemical Reactions in MaterialBalances

Chemicalreactioninasystemrequirestheaugmentationof**Equation6.4**totakeinto accountthe**effectsofthereaction**.Toillustratethispoint,lookat**Figure6.10**,whichshowsa s teady–state system in which **HCl**reacts with **NaOH**by the followingreaction:

$$\textbf{NaOH + HCl} \longrightarrow \textbf{NaCl + H}_2\textbf{O}$$

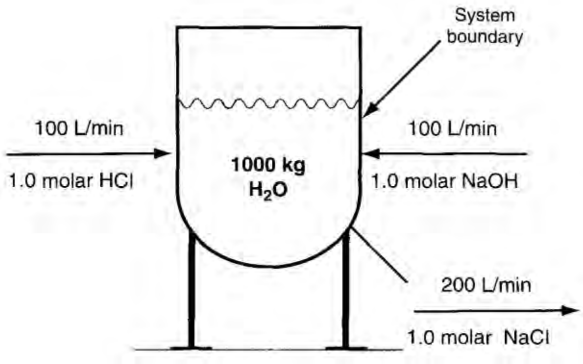


Figure 6.10 Reactor for neutralizing HCl withNaOH.

Equation 6.4 must be augmented to include terms for the **generation** and **consumption**of components by the **chemical reaction** in the system asfollows

$$\left\{\begin{matrix}\text{Accumulation}\\ \text{within the}\\ \text{system}\end{matrix}\right\} = \left\{\begin{matrix}\text{Input}\\ \text{through}\\ \text{the system}\\ \text{boundaries}\end{matrix}\right\} - \left\{\begin{matrix}\text{Output}\\ \text{through}\\ \text{the system}\\ \text{boundaries}\end{matrix}\right\} + \left\{\begin{matrix}\text{Generation}\\ \text{within the}\\ \text{system}\end{matrix}\right\} - \left\{\begin{matrix}\text{Consumption}\\ \text{within the}\\ \text{system}\end{matrix}\right\} \quad ...6.5$$

6.6 Material Balances for Batch and Semi-BatchProcesses

- A **batchprocess** isusedtoprocessa **fixedamount** ofmaterialeachtimeitisoperated. **Initially**, the material to be processed is charged into the system. After processing ofthe material is complete, the products are **removed**.
- **Batch processes** are used **industrially** for specialty processing applications(e.g., producing **pharmaceutical** products), which typically operate at relatively **lowproduction rates**.
- LookatFigure6.11athatillustrateswhatoccursatthestartofabatchprocess,andafter thorough mixing, the final solution remains in the system (Figure6.11b).

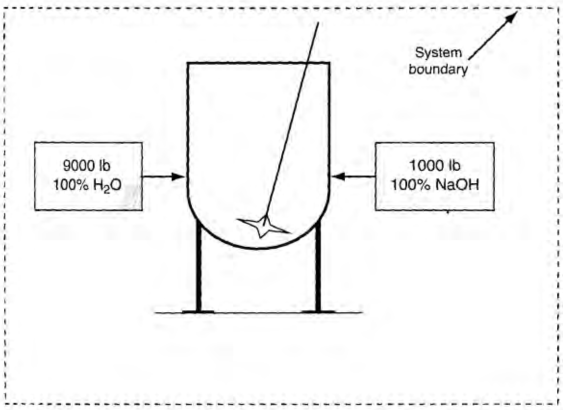


Figure 6.11a The initial state of a batch mixingprocess.

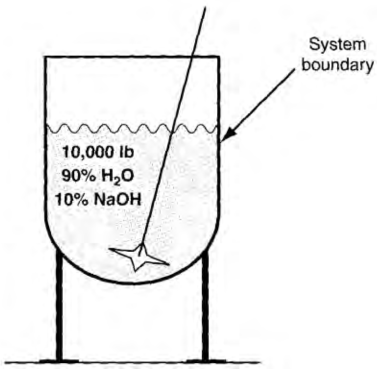


Figure 6.11b The finalstate of a batch mixingprocess.

♦ We can summarize the **hypothetical operation** of the **batch** as a flow system (opensystem) as follows (**Figure6.12**):

Final conditions: All values =0

Flowsout:

NaOH =
1,000lbH_2O =
9,000lb
Total = 10,000lb

Initial conditions: All value =0

Flows in:

NaOH =
1,000lbH_2O =
9,000lb
Total 10,000lb

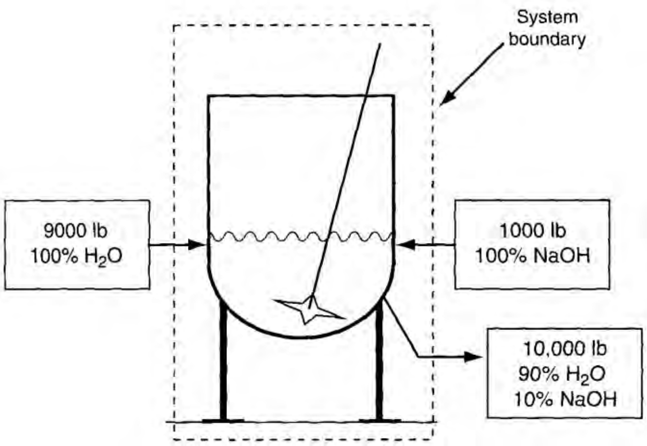


Figure 6.12 The batch process in Figure 6.11 represented as an opensystem.

☒ In a **semi-batch process** material **enters** the pr ocess dur ing i ts op eration, but doe s**not leave**.Instead,massisallowedtoaccumulateintheprocessvessel.Productis**withdrawn** only a fter the process isover.

☒ **AFigure6.13 illustrates**a**semi-batchmixingprocess**. Initiallythevessel i s em pty(**Figure 6.13a**). **Figure 6.13b** shows the **semi-batch system** after **1 hour** of operation.**Semi-batch processes** are **open** and **unsteady –state**.

☒ Only flows **enter** the systems, and **none leave**, hence the system is an **unsteady state** –one that you can treat as having **continuous flows**, asfollows:

Finalconditions:

NaOH = 1,000 lb
H_2O = 9,000lb
Total = 10,000 lb

Flows out: All values =0

Flows in:

NaOH = 1,000lb
H_2O = 9,000lb
Total = 10,000lb

Initial conditions: All values =0