Problem 1.1A

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

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

c. $$\frac{80.0\ \text{lb}_f}{} \Bigg| \frac{32.174\ (\text{lb}_m)(\text{ft})}{(\text{lb}_f)(\text{s})^2} \Bigg| \frac{1\ \text{kg}}{2.20\ \text{lb}_m} \Bigg| \frac{1\ \text{m}}{3.2808\ \text{ft}} \Bigg| \frac{1\ \text{N}}{1\ (\text{kg})(\text{m})(\text{s})^{-2}} = \mathbf{356\ N}$$

Problem 1.1 B

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

Solution

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

Problem 1.1 C

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.

NOZZLES

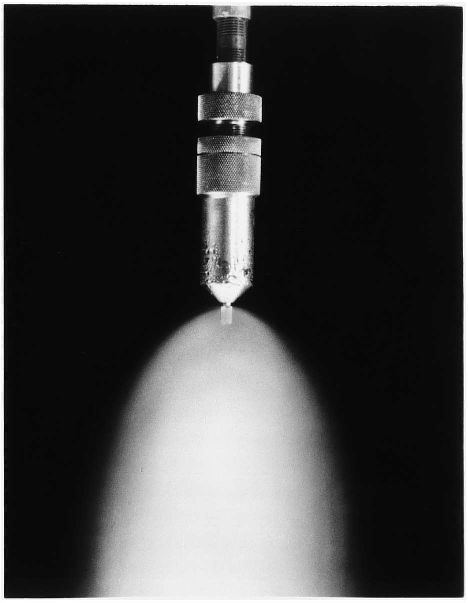


Fig. 1a. Ultrasonic nozzle *(courtesy of Misonix Inc., Farmingdale, N.J.)*

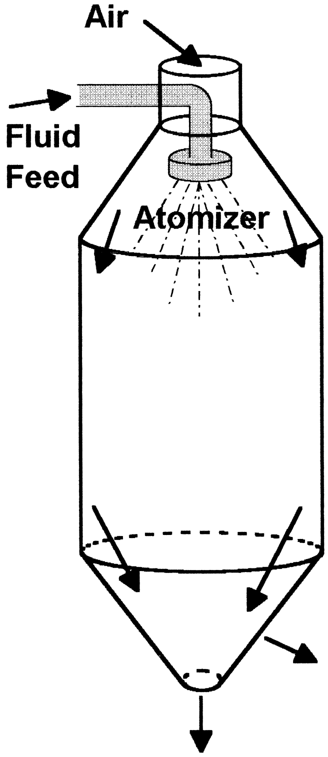


Fig. 1b. A conventional nozzle spraying a fluid of suspended particles in a flash dryer.

Spray nozzles are used for dust control, water aeration, dispersing a particular pattern of drops, coating, paintings, cleaning surfaces of tanks and vats, and numerous other applications. They develop a large interface between a gas and liquid, and can provide uniform round drops of liquid. Atomization occurs by a combination of gas and liquid pressure differences. The Figure below (courtesy of Misonix Inc.) compares the particle sizes from the ultrasonic nozzle with those from the conventional nozzle.

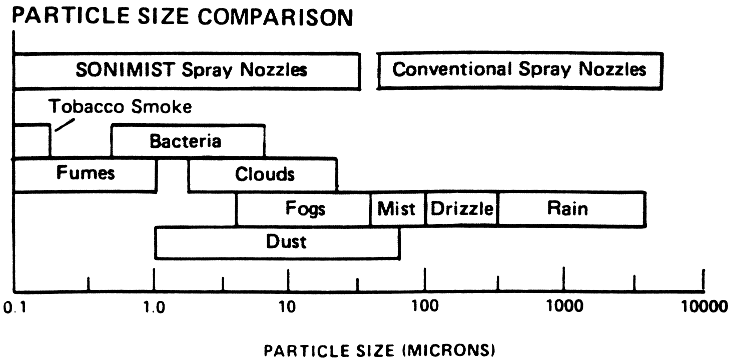


Fig. 1c

Solution

a. Calculation of the constant.

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

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

We want to find a set of units that convert units on the right hand side of the above expression to units on the left hand side of the expression. Such a set can be set up directly by multiplication.

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

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

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.

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

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

Substituting pressure and temperature in SI units

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

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

Problem 1.1 D

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, $\mathrm{Btu/(hr)(ft)^2(°F)}$
G = mass velocity of the liquid, $\mathrm{lb_m/(hr)(ft)^2}$
K = thermal conductivity of the liquid, $\mathrm{Btu/(hr)(ft)(°F)}$
C_p = heat capacity of the liquid, $\mathrm{Btu/(lb_m)(°F)}$
μ = Viscosity of the liquid, $\mathrm{lb_m/(ft)(hr)}$
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:

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

Next we consolidate like units

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

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

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.

Problem 1.2 A

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. $$\begin{array}{c|c|c|c} 50 \text{ g mol CaCO}_3 & 100 \text{ g CaCO}_3 & 1 \text{ lb CaCO}_3 & 1 \text{ lb mol CaCO}_3 \\ \hline & 1 \text{ g mol CaCO}_3 & 454 \text{ g CaCO}_3 & 100 \text{ lb CaCO}_3 \end{array} = \mathbf{0.11\ lb\ mol}$$

b. $$\begin{array}{c|c|c} 150 \text{ kg CaCO}_3 & 2.205 \text{ lb CaCO}_3 & 1 \text{ lb mol CaCO}_3 \\ \hline & 1 \text{ kg CaCO}_3 & 100 \text{ lb CaCO}_3 \end{array} = \mathbf{3.30\ lb\ mol}$$

c. $$\begin{array}{c|c} 100 \text{ lb CaCO}_3 & 1 \text{ lb mol CaCO}_3 \\ \hline & 100 \text{ lb CaCO}_3 \end{array} = \mathbf{1.00\ lb\ mol\ CaCO_3}$$

Problem 1.2 B

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. $$\begin{array}{c|c|c} 13.0 \text{ lb mol AgNO}_3 & 170 \text{ lb AgNO}_3 & 1 \text{ kg} \\ \hline & 1 \text{ lb mol AgNO}_3 & 2.205 \text{ lb} \end{array} = 1002 \text{ kg } \mathbf{or\ 1000\ kg}$$

b. $$\begin{array}{c|c|c} 55.0 \text{ g mol AgNO}_3 & 170 \text{ g AgNO}_3 & 1 \text{ kg} \\ \hline & 1 \text{ g mol AgNO}_3 & 1000 \text{ g} \end{array} = \mathbf{9.35\ kg}$$

Problem 1.3 A

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

a. the mol fraction composition of this mixture.

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

Solution

a. Basis: 100 g of 10 wt% solution

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

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

The density of the solution is

$$\frac{1.10\ \text{g soln/cm}^3\ \text{soln}}{1.00\ \text{g H}_2\text{O/cm}^3}\Bigg|\frac{1.00\ \text{g H}_2\text{O/cm}^3}{} = 1.10\ \frac{\text{g soln}}{\text{cm}^3}$$

$$\frac{1\ \text{cm}^3\ \text{soln}}{1.10\ \text{g soln}}\Bigg|\frac{1\ \text{g soln}}{0.1\ \text{g H}_3\text{PO}_4}\Bigg|\frac{97.97\ \text{g H}_3\text{PO}_4}{1\ \text{g mol H}_3\text{PO}_4}\Bigg|\frac{264.2\ \text{gal}}{10^6\ \text{cm}^3} = \mathbf{0.24\ gal/g\ mol}$$

Problem 1.3 B

The density of a liquid is 1500 kg/m^3 at 20 °C.

a. What is the specific gravity 20°C/4°C of this material.

b. What volume (ft^3) does 140 lb_m of this material occupy at 20°C.

Solution

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

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

b.

$$\frac{1\ \text{m}^3\ \text{liquid}}{1500\ \text{kg}}\Bigg|\frac{1\ \text{kg}}{2.20\ \text{lb}}\Bigg|\frac{35.31\ \text{ft}^3}{1\ \text{m}^3}\Bigg|\frac{140\ \text{lb}_m}{} = \mathbf{1.50\ ft^3}$$

Problem 1.3 C

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

The problem may be solved by either converting the EPA standards to ppb or vice versa. We will convert the EPA standards to ppb; ppb is a ratio, and therefore it is necessary for the numerator and denominator to have same mass or mole units. The mass and volume that the Sb contributes to the water solution is negligible.

Antimony

$$\frac{0.006\ \text{mg Sb}}{1\text{L soln}}\Bigg|\frac{1\ \text{L soln}}{1000\ \text{cm}^3\ \text{soln}}\Bigg|\frac{1\ \text{cm}^3\ \text{soln}}{1.00\ \text{g H}_2\text{O}}\Bigg|\frac{1\ \text{g}}{1000\ \text{mg}} = \frac{6\ \text{g Sb}}{10^9\ \text{g soln}} = \mathbf{6\ ppb}$$

Nickel

$$\frac{0.1\ \text{mg Ni}}{1\ \text{L soln}}\Bigg|\frac{1\ \text{L soln}}{1000\ \text{cm}^3\ \text{soln}}\Bigg|\frac{1\ \text{cm}^3\ \text{soln}}{1.0\ \text{g H}_2\text{O}}\Bigg|\frac{1\ \text{g}}{1000\ \text{mg}} = \frac{9\ \text{g Ni}}{10^9\ \text{g soln}} = \mathbf{100\ ppb}$$

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

Problem 1.3 D

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

b. $$\frac{1.075\text{ g soln/cm}^3}{1.0\text{ g }H_2O\text{/cm}^3}\bigg|\frac{1.00\text{ g }H_2O\text{/cm}^3}{}\bigg|\frac{1\text{ lb}}{454\text{ g}}\bigg|\frac{2.832\times10^4\text{ cm}^3}{\text{ft}^3} = \mathbf{67.1}\ \frac{\textbf{lb soln}}{\mathbf{ft^3}\textbf{ soln}}$$

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

Problem 1.4 A

A liquified mixture of n-butane, n-pentane and n-hexane has the following composition in percent.

n - C_4H_{10}	50
n - C_5H_{12}	30
n - C_6H_{14}	20

Calculate the weight fraction, mol fraction and mol percent of each component and also the average molecular weight of the mixture.

Solution

Note that the hydrocarbon mixture is liquid so that the composition is therefore in weight percent. It is convenient to use a weight basis and set up a table to make the calculations.

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**

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

Problem 1.5 A

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

Problem 1.5 B

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.

$$C_p = \begin{array}{c|c|c|c} [20.869 + 5.293 \times 10^{-2}\ (T_{°F})]\quad \text{Btu} & 252\ \text{cal} & 1\ \text{lb mol} & 1.8\ °\text{F} \\ \hline 1\ (\text{lb mol})\ (°\text{F}) & 1\ \text{Btu} & 454\ \text{g mol} & 1\ \text{K} \end{array}$$

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

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.

MEASURING TANK PRESSURE

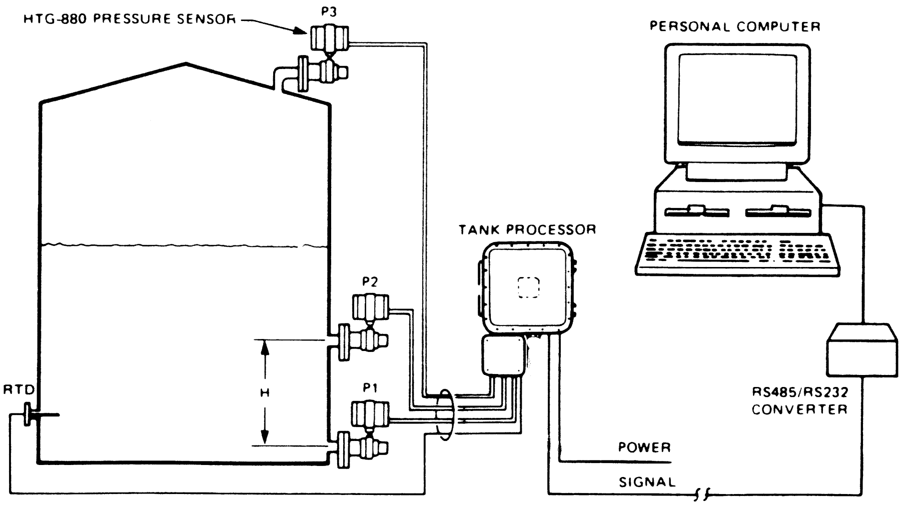


Fig. 2

The measurement of pressure at the bottom (at P1) of a large tank of fluid enables you to determine the level of fluid in the tank. A sensor at P2 measures the density of the fluid, and the sensor at P3 measures the pressure of the gas above the fluid. A digital signal is sent to the remote control room where the sensor readings and calculations for volume can be displayed on a PC. The volume of fluid in the tank is determined by multiplying the known area by the height of fluid calculated from the pressure and density measurements. Level can be determined to an accuracy of ± 1/8 inch, a value that leads to an accuracy of about 0.2% in the volume. In a tank containing 300,000 bbl of crude oil, the error roughly corresponds to about $12,000 in value.

$$T_{°F} = (T_K - 273)\,1.8 + 32$$

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

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

Problem 1.6 A

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.

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

$$= 15.0\text{ m}\;\frac{0.909\text{ g styrene/cm}^3}{1.0\text{ g }H_2O\text{/cm}^3}\;\Bigg|\;\frac{1.0\text{ g }H_2O\text{/cm}^3}{}\;\Bigg|\;\frac{10^3\text{ kg/m}^3}{1\text{ g/cm}^3}\;\Bigg|\;\frac{9.80\text{ m/s}^2}{}\;\Bigg|\;\frac{1\text{ Pa}}{1\text{ (kg)(m)}^{-1}\text{(s)}^{-2}}$$

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

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

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

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

U-TUBE MANOMETER

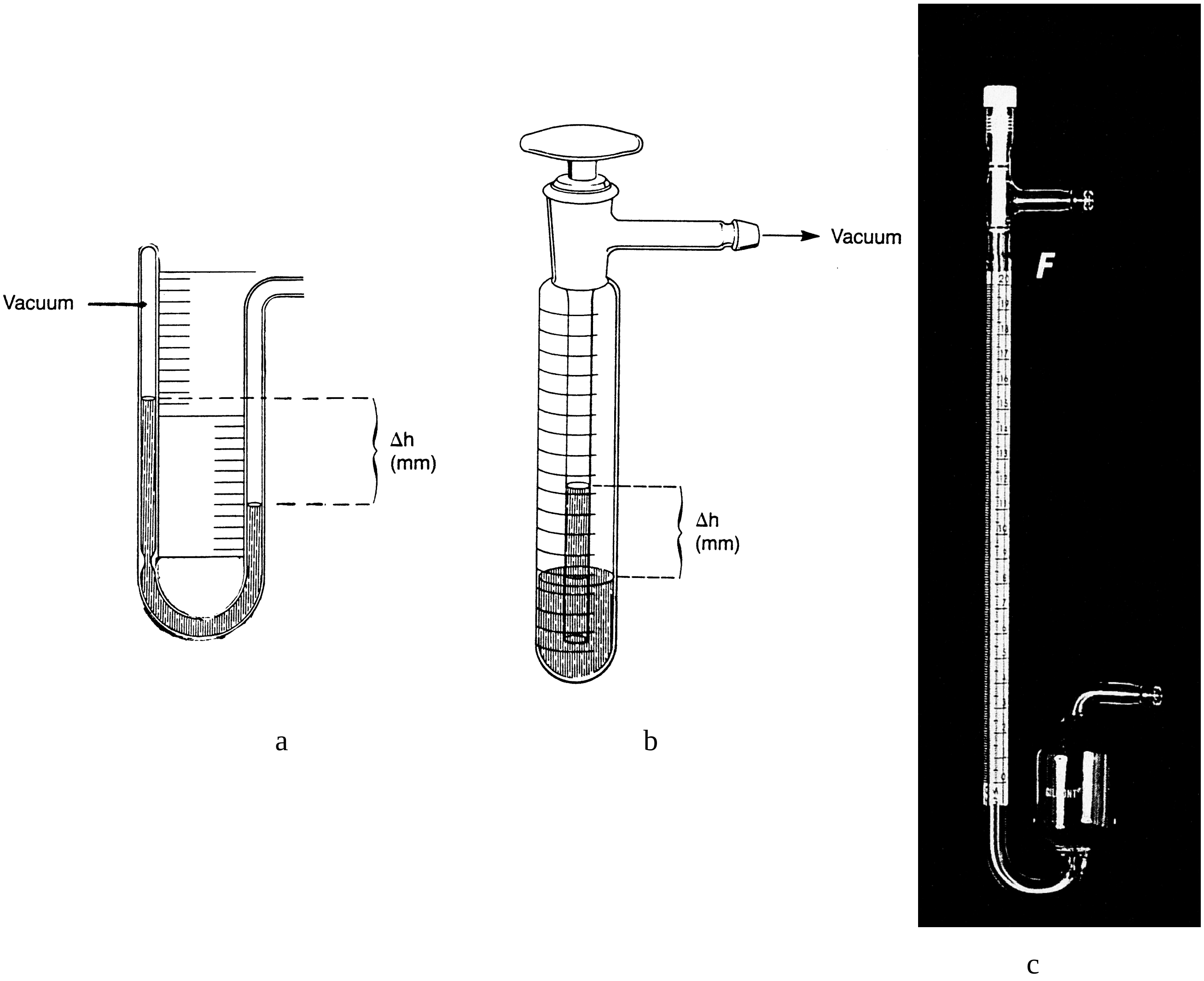


Fig. 3 Various forms of manometers

Typical liquid manometers consist of a U-shaped tube of glass or polycarbonate plastic partially filled with what is called a manometer fluid. The size and height of the manometer, and the manometer fluid, are selected so as to measure the desired pressure over the expected pressure range. Typical manometer fluids are mercury, water, the fluid in the system being measured, and heavy oils with very low vapor pressure. A manometer with the reference end open to the atmosphere makes gage measurements, i.e., measurements relative to the existing barometric pressure. A manometer with the reference end sealed so as to contain only the manometer fluid vapor measures roughly absolute pressure, but more precisely the reference pressure is the vapor pressure of the manometer fluid, hence the use of mercury which has an especially low vapor pressure at room temperature (2×10^{-3} mm Hg; 3×10^{-4} kPa). The sensitivity of a manometer can be increased by using special oils of specific gravity of 0.8 to 1.0 that also have very low vapor pressures. The accuracy of manometers depends on how closely you can read the meniscus in the glass tube.

Problem 1.6 B

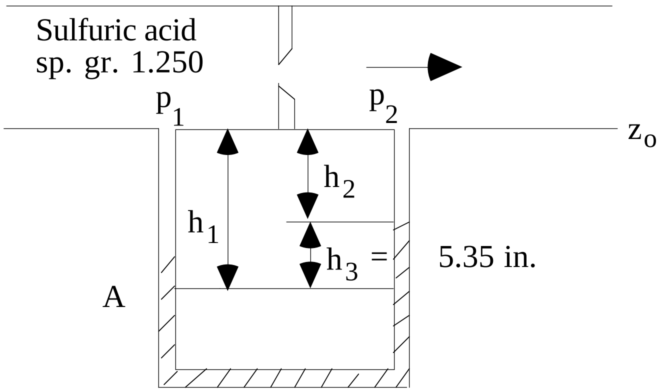
A U-tube manometer is used to determine the pressure drop across an orifice meter. The liquid flowing in the pipe line is a sulfuric acid solution having a specific gravity (60°/60°) of 1.250. The manometer liquid is mercury, with a specific gravity (60°/60°) of 13.56. The manometer reading is 5.35 inches,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

$$\rho_{acid} = \begin{array}{c|c|c} 1.250 & 62.4\ \text{lb/ft}^3 & 1\ \text{ft}^3 \\ \hline & & 1.728 \times 10^3\ \text{in}^3 \end{array} = 0.0451\ \text{lb/in}^3$$

$$\rho_{Hg} = \begin{array}{c|c|c} 13.56 & 62.4\ \text{lb/ft}^3 & 1\ \text{ft}^3 \\ \hline & & 1.728 \times 10^3\ \text{in}^3 \end{array} = 0.490\ \text{lb/in}^3$$



The procedure is to start with p_1 at z_o and add up the incremental pressure contributions. The pressures of the Hg in the left and right columns below A in the tube cancel each other, so we stop adding at level A.

$$\begin{array}{llcl} & \textit{left column} & & \textit{right column} \\ \text{At } z_o & p_1 + \rho_a h_1 g & = & p_2 + \rho_a h_2 g + \rho_{Hg} h_3 g \\ & p_1 - p_2 + \rho_a (h_1 - h_2) g & = & \rho_{Hg} h_3 g \\ & p_1 - p_2 + \rho_a h_3 g & = & \rho_{Hg} h_3 g \\ & p_1 - p_2 & = & (\rho_{Hg} - \rho_a) h_3 g \end{array}$$

Substitute the densities in the final equation

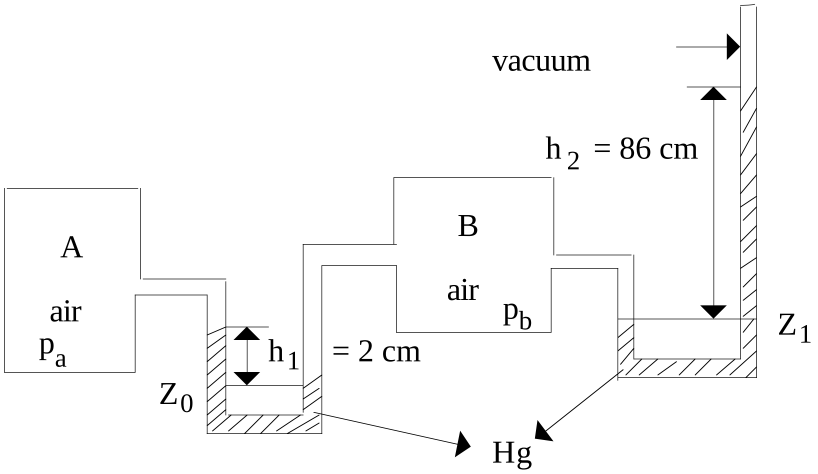
$$p_1 - p_2 = \begin{array}{c|c|c} (0.490 - 0.0451)\ \text{lb}_f & (5.35)\ \text{in} & 32.2\ \text{ft/s}^2 \\ \hline \text{in}^2 & & 32.174\ (\text{ft})(\text{lb}_m)/(\text{s}^2)(\text{lb}_f) \end{array} = \mathbf{2.38\ lb_f/in^2\ (psi)}$$

Problem 1.6 C

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



Tank A is connected to tank B through a U - tube and Tank B is connected to the vertical U - tube. The vertical tube can be used to measure the pressure in tank B and the U - tube can be used to relate the pressures of tanks A and B.

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

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

Problem 1.7 A

Gypsum (plaster of Paris : $CaSO_4 \cdot 2H_2O$) is produced by the reaction of calcium carbonate and sulfuric acid. A certain lime stone analyzes: $CaCO_3$ 96.89 %; $MgCO_3$ 1.41 %; inerts 1.70 %. For 5 metric tons of limestone reacted completely, determine:

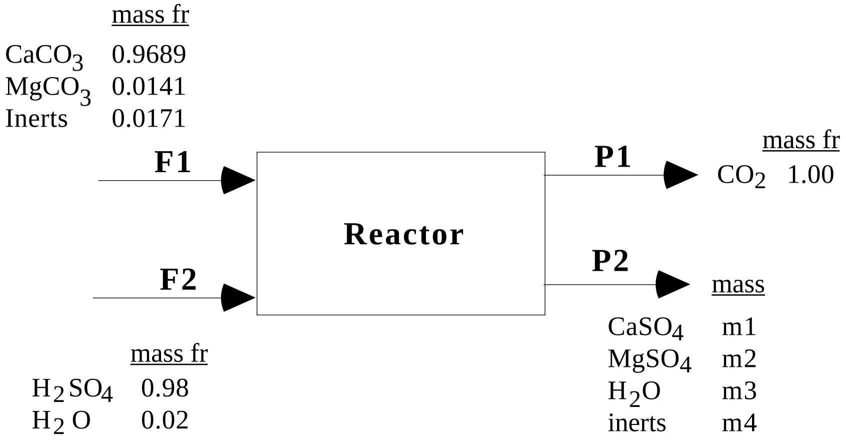
a. kg of anhydrous gypsum ($CaSO_4$) produced.
b. kg of sulfuric acid solution (98 wt%) required.
c. kg of carbon dioxide produced.
(MW : $CaCO_3$ 100.1; $MgCO_3$ 84.32; H_2SO_4 98; $CaSO_4$ 136; $MgSO_4$ 120;
H_2O 18; CO_2 44)

Solution

The problem involves 2 reactions. Both calcium carbonate and magnesium carbonate react with sulfuric acid. The stoichiometric equations are

$$CaCO_3 + H_2SO_4 \text{ ------> } CaSO_4 + H_2O + CO_2 \qquad (1)$$

$$MgCO_3 + H_2SO_4 \text{ ------> } MgSO_4 + H_2O + CO_2 \qquad (2)$$



Basis : 5000 kg limestone

a. $CaSO_4$ produced

5000 kg limestone	96.89 kg $CaCO_3$	1 kg mol $CaCO_3$	1 kg mol $CaSO_4$	136 kg $CaSO_4$
	100 kg limestone	100.1 kg $CaCO_3$	1 kg mol $CaCO_3$	1 kg mol $CaSO_4$

= **6600 kg $CaSO_4$**

b. Sulfuric acid required

Both $CaCO_3$ and $MgCO_3$ react with sulfuric acid in a 1 to 1 molar ratio.

5000 kg limestone	96.89 kg $CaCO_3$	1 kg mol $CaCO_3$	1 kg mol H_2SO_4	98 kg H_2SO_4
	100 kg limestone	100.1 kg $CaCO_3$	kg mol $CaCO_3$	kg mol H_2SO_4

= 4740 kg H_2SO_4

$$\begin{array}{l|l|l|l|l} \text{5000 kg limestone} & \text{1.41 kg MgCO}_3 & \text{1 kg mol MgCO}_3 & \text{1 kg mol H}_2\text{SO}_4 & \text{98.0 kg H}_2\text{SO}_4 \\ \hline & \text{100 kg limestone} & \text{84.32 kg MgCO}_3 & \text{kg mol MgCO}_3 & \text{kg mol H}_2\text{SO}_4 \end{array}$$

$= 81.94 \text{ kg } H_2SO_4$

total acid required = 4739.9 + 81.94 kg = 4822 kg 100 % acid.

We need to correct for the fact that acid is available as a 98 % solution.

$$\begin{array}{l|l} \text{4821.84 kg H}_2\text{SO}_4 & \text{100 kg acid solution} \\ \hline & \text{98.0 kg H}_2\text{SO}_4 \end{array} = \mathbf{4920 \text{ kg } H_2SO_4 \text{ solution}}$$

c. Carbon dioxide generated

Both $CaCO_3$ and $MgCO_3$ react with sulfuric acid to produce carbon dioxide.

$$\begin{array}{l|l|l|l|l} \text{5000 kg limestone} & \text{96.83 kg CaCO}_3 & \text{1 kg mol CaCO}_3 & \text{1 kg mol CO}_2 & \text{44 kg CO}_2 \\ \hline & \text{100 kg CaCO}_3 & \text{100.1 kg CaCO}_3 & \text{1 kg mol CaCO}_3 & \text{1 kg mol CO}_2 \end{array} +$$

$$\begin{array}{l|l|l|l|l} \text{5000 kg limestone} & \text{1.41 kg MgCO}_3 & \text{1 kg MgCO}_3 & \text{1 kg mol CO}_2 & \text{44 kg CO}_2 \\ \hline & \text{100 kg MgCO}_3 & \text{84.32 kg MgCO}_3 & \text{1 kg mol MgCO}_3 & \text{1kg mol CO}_2 \end{array}$$

$= \quad 2128.1 + 36.8 = \mathbf{2165 \text{ kg } CO_2}$

Problem 1.7 B

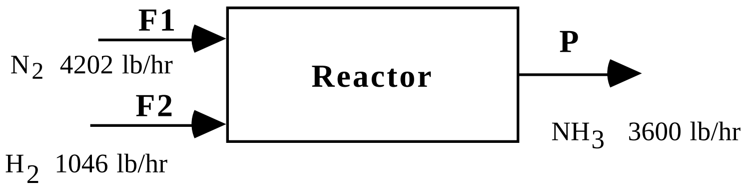
The synthesis of ammonia proceeds according to the following reaction

$$N_2 + 3 H_2 \text{ -----> } 2 NH_3$$

In a given plant, 4202 lb of nitrogen and 1046 lb of hydrogen are fed to the synthesis reactor per hour. Production of pure ammonia from this reactor is 3060 lb per hour.

a. What is the limiting reactant.
b. What is the percent excess reactant.
c. What is the percent conversion obtained (based on the limiting reactant).

Solution



AMMONIA SYNTHESIS REACTOR

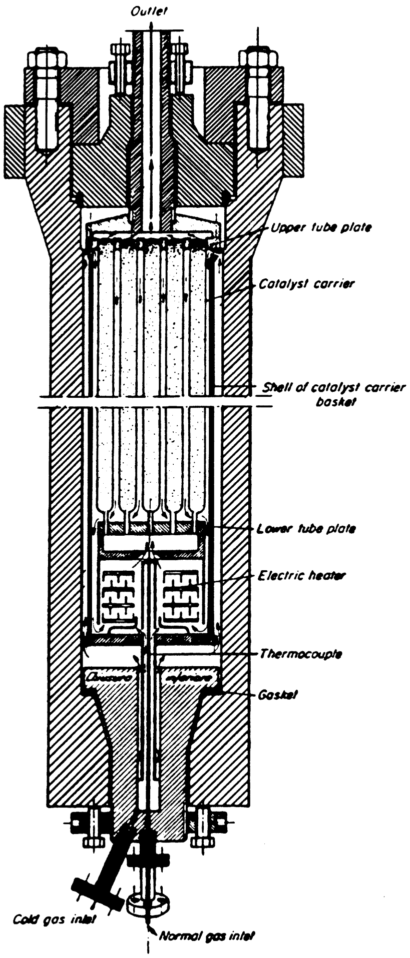


Fig. 4 Claude ammonia converter, a continuous flow reactor

Ammonia is a commodity chemical produced in millions of tons each year for fertilizer, explosives, plastics, chemicals, and many other uses. Figure 4 shows an ammonia reactor that is 1.2 m in diameter and 7 m high, and operates at 1000 atm pressure, hence the gases are not ideal. An ammonia plant is comprised of a sequence of reactors. Each reactor product discharges into a cooling and condensing process from which liquid ammonia is removed. Some of the unreacted gas is fed back to the start of the reactor, and the rest is passed on to the next reactor in sequence. Entering gas contains some inert components, mainly argon and methane, that do not react, and at the end of the process have to be purged from the system. Every effort is made in the design of the overall plant to keep the ratio of the hydrogen to the nitrogen at 3 to 1 at the entrance of the reactor. Various types of catalyst have been developed to enhance the fraction conversion of the H_2/N_2 to NH_3 on flow through the reactor.

a. $$\frac{4202 \text{ lb } N_2}{} \left| \frac{1 \text{ lb mol } N_2}{28 \text{ lb } N_2} \right| \frac{2 \text{ lb mol } NH_3}{1 \text{ lb mol } N_2} = 300 \text{ lb mol } NH_3$$

$$\frac{1046 \text{ lb } H_2}{} \left| \frac{1 \text{ lb mol } H_2}{2 \text{ lb } H_2} \right| \frac{2 \text{ lb mol } NH_3}{3 \text{ lb mol } H_2} = 348.6 \text{ lb mol } NH_3$$

If all of the N_2 were to react, 300 lb mol of ammonia would be produced while if all of the hydrogen were to react, 348.6 lb mol ammonia would be produced. **N_2 is the limiting reactant.**

b. H_2 required : based on the limiting reactant

$$\frac{4202 \text{ lb } N_2}{} \left| \frac{1 \text{ lb mol } N_2}{28 \text{ lb } N_2} \right| \frac{3 \text{ lb mol } H_2}{1 \text{ lb mol } N_2} = 450 \text{ lb mol } H_2 \text{ required}$$

H_2 available : $$\frac{1046 \text{ lb } H_2}{} \left| \frac{1 \text{ lb mol } H_2}{2 \text{ lb } H_2} \right. = 523 \text{ lb mol } H_2$$

$$\% \text{ excess reactant} = \frac{\text{mol in excess}}{\text{mol required to react with limiting reactant}} \times 100$$

$$\% \text{ excess } H_2 = \frac{(523 - 450)}{450} \times 100 = \mathbf{16.2\ \%}$$

c. $$\text{Percentage conversion} = \frac{\text{moles (or mass) of feed that react}}{\text{moles (or mass) of feed introduced}} \times 100$$

$$N_2 \text{ reacted} = \frac{3060 \text{ lb } NH_3}{} \left| \frac{1 \text{ lb mol } NH_3}{17 \text{ lb } NH_3} \right| \frac{1 \text{ lb mol } N_2}{2 \text{ lb mol } NH_3} \left| \frac{28 \text{ lb } N_2}{1 \text{ lb mol } N_2} \right. = 2520 \text{ lb } N_2$$

$$\% \text{ conversion} = \frac{2520 \text{ lb}}{4202 \text{ lb}} \times 100 = \mathbf{60.0\ \%}$$

Problem 1.7 C

Five pounds of bismuth (MW = 209) is heated along with one pound of sulfur to form Bi_2S_3 (MW = 514). At the end of the reaction, the mass is extracted and the free sulfur recovered is 5 % of the reaction mass. Determine

a. the limiting reactant.
b. the percent excess reactant.
c. the percent conversion of sulfur to Bi_2S_3.

$$2\text{ Bi} \quad + \quad 3\text{ S} \quad \text{----->} \quad Bi_2S_3$$

Solution

a. Find the Limiting reactant

Ratio in the feed

$$\frac{\text{Bi}}{\text{S}} \quad = \quad \frac{\left.\dfrac{5.00\text{ lb Bi}}{}\right|\dfrac{1\text{ lb mol Bi}}{209\text{ lb Bi}}}{\left.\dfrac{1.00\text{ lb S}}{}\right|\dfrac{1\text{ lb mol S}}{32\text{ lb S}}} \quad = \quad \frac{0.0239\text{ mol Bi}}{0.0313\text{ mol S}} = 0.774$$

$$\text{Ratio in the chemical equation} = \frac{2\text{ lb mol Bi}}{3\text{ lb mol S}} \quad = \quad 0.667$$

Compare the two ratios; **S is the limiting reactant.**

b. % Excess reactant

$$\text{Bi required} = \left.\frac{1\text{ lb S}}{}\right|\left.\frac{1\text{ lb mol S}}{32\text{ lb S}}\right|\frac{2\text{ mol Bi}}{3\text{ mol S}} \quad = \quad 0.0208\text{ lb mol Bi}$$

$$\%\text{ excess Bi} \quad = \quad \frac{(0.0239 - 0.028)}{0.028} \quad \times \quad 100 \quad = \quad \mathbf{14.9\ \%}$$

c. We will assume that no gaseous products are formed, so that the total mass of the reaction mixture is conserved at 6 lb (5 lb Bi + 1 lb S). The free sulfur at the end of the reaction = 5%.

$$\left.\frac{6.00\text{ lb rxn mass}}{}\right|\left.\frac{5.00\text{ lb S}}{100\text{ lb rxn mass}}\right|\frac{1\text{ lb mol S}}{32.0\text{ lb S}} = 0.00938\text{ lb mol S}$$

$$\%\text{ Conversion} \quad = \quad \frac{\text{moles of feed that react}}{\text{moles of feed introduced}} \quad \times \quad 100$$

$$= \quad \frac{0.0313 - 0.00938}{0.0313} \quad \times \quad 100 \quad = \quad \mathbf{70.0\ \%}$$

CHAPTER 1 – ADDITIONAL PROBLEMS
(Answers will be found in Appendix A)

Section 1.1

1.1A Convert the following to the desired units:

(a) 60 mi/hr to m/s (b) 30 N/m^2 to lb$_f$/ft^2
(c) 16.3 J to Btu (d) 4.21 kW to J/s

1.1B Change the following to the desired units:

(a) 235 g to pounds. (b) 610 L to cubic feet.
(c) 30 g/L to pounds/cubic feet. (d) 14.7 lb/in^2 to kg/cm^2

1.1C Find the kinetic energy of a ton of water moving at 60 min/hr expressed as (ft)(lb$_f$).

1.1D An elevator which weights 10,000 lb is pulled up 10 ft between the first and second floors of a building 100 ft high. The greatest velocity the elevator attains is 3 ft/s. How much kinetic energy does the elevator have in (ft)(lb$_f$) at this velocity?

1.1E The Colburn equation for heat transfer is

$$\left(\frac{h}{CG}\right)\left(\frac{C\mu}{k}\right)^{2/3} = \frac{0.023}{\left(DG/\mu\right)^{0.2}}$$

where C = heat capacity, Btu/(lb of fluid)(°F); μ = viscosity, lb/(hr)(ft); k = thermal conductivity, Btu/(hr)(ft^2)(°F)/ft; D = pipe diameter, ft; and G = mass velocity, lb/(hr)(ft^2) of cross section. What are the units of the heat transfer coefficient h?

1.1F Countercurrent gas centrifuges have been used to separate ^{235}U from ^{238}U. The rate of diffusive transport is $K = 2\pi D\rho\bar{r}$. If K = rate of transport of light component to the center of the centrifuge, in g mol/(s)(cm of height); D = diffusion coefficient; ρ = molar density, g moles/cm^3; and $\bar{r}$ = log mean radius, $(r_2 - r_1)/\ln(r_2/r_1)$, with r in cm, what are the units of D?

1.1G The density of a certain liquid is given an equation of the following form:

$$\rho = (A + BT)e^{Cp}$$

where ρ = density in g/cm^3, t = temperature in °C, and P = pressure in atm.

(a) The equation is dimensionally consistent. What are the units of A, B, and C?
(b) In the units above, A = 1.096, B = 0.00086, and C = 0.000953. Find A, B, and C if ρ is expressed in lb/ft^3, T in °R, and p in lb$_f$/in^2.

Section 1.2

1.2A (a) How many g moles are represented by 100 g of CO_2?
(b) Calculate the weight in pounds of 3.5 g moles of nitrogen.

1.2B Convert the following:
(a) 120 lb mol of NaCl to g. (b) 120 g mol of NaCl to lb.
(c) 120 lb of NaCl to g mol. (d) 120 g of NaCl to lb mol.

Section 1.3

1.3A A solution of sulfuric acid at 60°F is found to have a sp gr of 1.22. From the tables in Perry's *Chemical Engineer's Handbook*, the solution is found to be 30 percent by weight H_2SO_4. What is the concentration of H_2SO_4 in the following units: (a) lb mol/gal, (b) lb/ft^3, (c) g/L, (d) lb H_2SO_4/lb H_2O, and (e) lb mol H_2O/lb mol total solution?

1.3B A mixture of liquid hydrocarbons contains 10.0 percent *n*-heptane, 40.0 percent *n*-octane, and 50.0 percent *i*-pentane by weight. The specific gravities $\left(\frac{60^\circ \text{F}}{60^\circ \text{F}}\right)$ of the pure components are

n-heptane = 0.685 *n*-octane = 0.705 *i*-pentane = 0.622

(a) What is the sp gr $\left(\frac{60^\circ \text{F}}{60^\circ \text{F}}\right)$ of 93 lb of this mixture?
(b) How many U.S. gallons will be occupied by 130 lb of this mixture?

1.3C Convert 17.2 ppm NH_3 in water to the equivalent number of ppm of NH_3 gas in water vapor.

1.3D Five thousand barrels of 28°API gas oil are blended with 20,000 bbl of 15° API fuel oil. What is the °API (API gravity) of the mixture? What is the density in lb/gal and lb/ft^3?

Section 1.4

1.4A A mixture of gases is analyzed and found to have the following composition:

CO_2	12.0%
CO	6.0
CH_4	27.3
H_2	9.9
N_2	44.8

How much will 3 lb moles of this gas mixture weight?

1.4B You have 100 lb of gas of the following composition:

CH_4	30%
H_2	10%
N_2	60%

What is the average molecular weight of this gas?

1.4C What is the composition of the gas in Problem 1.4A on a nitrogen free basis (no N_2 in the analysis)?

Section 1.5

1.5A Two thermometers are to be checked against a standard thermometer. The standard reads –22°F. What should the other two thermometers read if they are calibrated in °C and K, respectively?

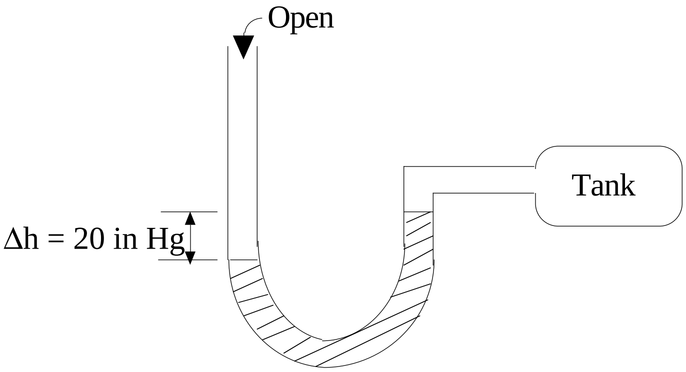
1.5B Mercury boils at 630K. What is its boiling temperature expressed in °C? In °F? In °R?

Section 1.6

1.6A What is the gauge pressure at a depth of 4.50 mi below the surface of the sea if the water temperature averages 60°F? Give your answer in lb (force) per sq. in. The sp gr of sea water at 60°F/60°F is 1.042 and is assumed to be independent of pressure.

1.6B The pressure gauge on the steam condenser for a turbine indicates 26.2 in. Hg of vacuum. The barometer reading is 30.4 in. Hg. What is the pressure in the condenser in psia?

1.6C Examine the figure



The barometer reads 740 mm Hg. Calculate tank pressure in psia.

1.6D (a) An orifice is used to measure the flow rate of a gas through a pipe as shown in Fig. P1.6D. The pressure drop across the orifice is measured with a mercury manometer, both legs of which are constructed of $\frac{1}{4}$ - in. inner diameter (ID) glass tubing. If the pressure drop across the orifice is equivalent to 4.65 in. Hg, calculate h_2 and h_3 (both in inches) if h_1 is equal to 13.50 in.

(b) The right glass leg of the manometer in Fig. P1.6D becomes corroded and is replaced with glass tubing which is $\frac{3}{8}$ - in. ID. The manometer is again filled with a sufficient volume of mercury. For the same pressure drop as in part (a), calculate h_2 and h_3 (both in inches).

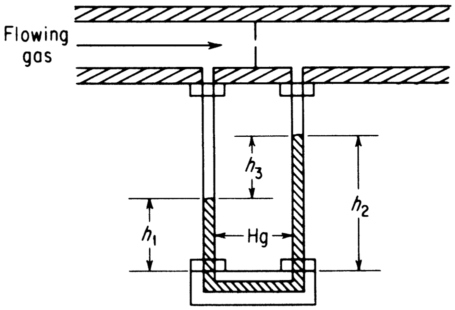


Figure P1.6D

Section 1.7

1.7A How many grams of chromic sulfide will be formed from 0.718 grams of chromic oxide according to the equation

$$2Cr_2O_3 + 3CS_2 \rightarrow 2Cr_2S_3 + 3CO_2$$

1.7B A barytes composed of 100 percent $BaSO_4$ is fused with carbon in the form of coke containing 6 percent ash (which is infusible). The composition of the fusion mass is

$BaSO_4$	11.1%
BaS	72.8
C	13.9
Ash	2.2
	100.%

Reaction:

$$BaSO_4 + 4C \rightarrow BaS + 4CO$$

Find the excess reactant, the percentage of the excess reactant, and the degree of completion of the reaction.