SUPPLEMENTARY PROBLEMS FOR BASIC PRINCIPLES AND CALCULATIONS IN CHEMICAL ENGINEERING 6TH EDITION

David M. Himmeblau
The University of Texas

CONTENTS

LIST OF FIGURES

PREFACE

For a long time students have sought out solved problems in addition to those provided as examples in the textbook. Sources of such problems are related texts and old homework and examination files, but these alternate sources are usually inconvenient to find and use.

To meet this demand I compiled in this supplement additional problems with detailed solutions, problems that are quite similar to those in the text. In addition, I have added numerous unsolved problems with answers (a frequent request for homework problem assignments). Each set of problems conforms to the arrangement in my book "Basic Principles and Calculations in Chemical Engineering, 6th edition, published by Prentice Hall, Englewood Cliffs, N.J. The notation used in the problems and solutions is the same as in the textbook.

To acquaint students with process equipment usually shown as black boxes in example problems, a series of pictures, line diagrams, and short explanations have been inserted at appropriate places in the supplement.

How can you use this supplement? For those individuals who after reading a problem look first for a similar problem with a worked out solution, this supplement offers numerous examples to follow. For those who have some confidence in their ability to solve problems but just want to hone their skills by comparing their answers with known solutions, enough problems with answers are given to make it impractical to solve all of them before moving on to the next topic. Students who want to prepare for exams will find the problems with answers helpful. Finally, those individuals who have trouble in developing consistent and fruitful strategies for problem solving can make use of the detail solutions provided to improve their particular abilities.

David M. Himmelblau
Austin, Texas

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

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

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

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

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

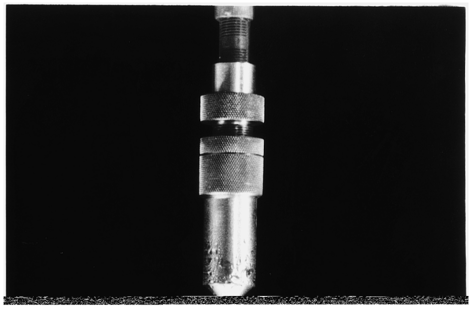
Problem 1.1 C

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

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

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

NOZZLES



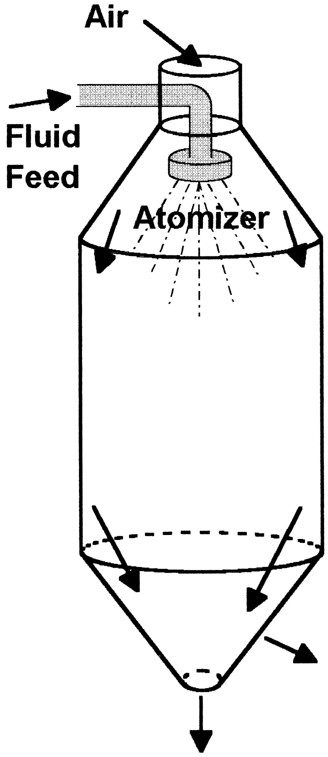


Fig. 1a. Ultrasonic nozzle
(courtesy of Misonix Inc., Farmingdale, N.J.)

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.

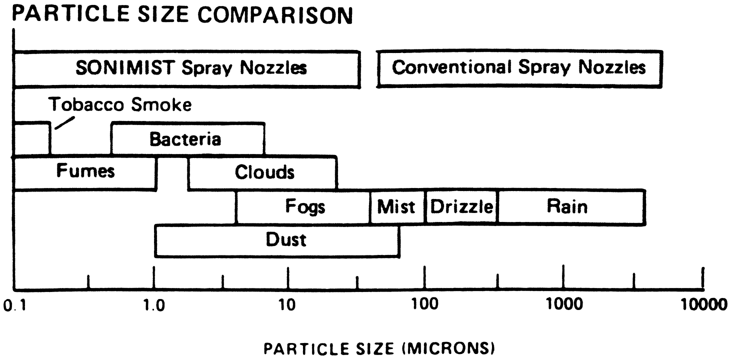


Fig. 1c

Solution

a. Calculation of the constant.

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

$$\frac{\text{lb}_\text{m}}{\text{min}} = 0.0549\ \frac{\text{lb}_\text{f}}{(\text{in}^2)(°\text{R})^{0.5}}$$

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.

$$\frac{\text{lb}_\text{f}}{(\text{in}^2)(°\text{R})^{0.5}}\Bigg|\frac{(\text{lb}_\text{m})(\text{in})^2(°\text{R})^{0.5}}{(\text{min})(\text{lb}_\text{f})} \quad \text{------>} \quad \frac{(\text{lb}_\text{m})}{(\text{min})}$$

Units for the constant 0.0549 are $\dfrac{(\text{lb}_\text{m})(\text{in})^2(°\text{R})^{0.5}}{(\text{min})(\text{lb}_\text{f})}$

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.

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

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

Substituting pressure and temperature in SI units

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

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

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, 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:

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

Next we consolidate like units

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

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

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

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

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

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

b. $$\frac{55.0\text{ g mol }AgNO_3}{} \Bigg| \frac{170\text{ g }AgNO_3}{1\text{ g mol }AgNO_3} \Bigg| \frac{1\text{ kg}}{1000\text{ g}} = \mathbf{9.35\ kg}$$

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

$$\begin{array}{c|c} 1.10\text{ g soln/cm}^3\text{ soln} & 1.00\text{ g H}_2\text{O/cm}^3 \\ \hline 1.00\text{ g H}_2\text{O/cm}^3 & \end{array} = 1.10\ \frac{\text{g soln}}{\text{cm}^3}$$

$$\begin{array}{c|c|c|c} 1\text{ cm}^3\text{ soln} & 1\text{ g soln} & 97.97\text{ g H}_3\text{PO}_4 & 264.2\text{ gal} \\ \hline 1.10\text{ g soln} & 0.1\text{ g H}_3\text{PO}_4 & 1\text{ g mol H}_3\text{PO}_4 & 10^6\text{ cm}^3 \end{array} = \mathbf{0.24\ gal/g\ mol}$$

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.

$$\begin{array}{c|c|c|c} 1\text{ m}^3\text{ liquid} & 1\text{ kg} & 35.31\text{ ft}^3 & 140\text{ lb}_m \\ \hline 1500\text{ kg} & 2.20\text{ lb} & 1\text{ m}^3 & \end{array} = \mathbf{1.50\ ft^3}$$

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**

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

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:

$$
\begin{array}{lcll}
°F & = & 1.8\,°C & +\ 32 \\
K & = & °C & +\ 273 \\
°R & = & °F & +\ 460 \\
°R & = & 1.8\ K &
\end{array}
$$

°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.

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

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

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

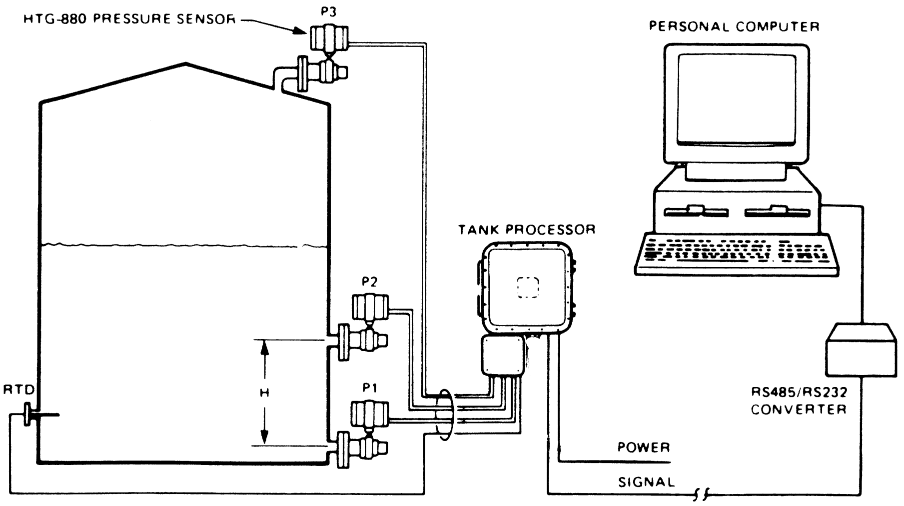


Fig. 2

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.

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

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

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

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

$$= 15.0\text{ m}\;\frac{0.659\text{ g hexane/cm}^3}{1.0.0\text{ g H}_2\text{O/cm}^3}\Bigg|\;\frac{1.0\text{ g H}_2\text{O/cm}^3}{}\;\Bigg|\;\frac{10^3\text{ kg/m}^3}{}\;\Bigg|\;\frac{9.8\text{ m/s}^2}{}\;\Bigg|\;\frac{1\text{ Pa}}{1\text{(kg)(m)}^{-1}\text{(s)}^{-2}}$$

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

U-TUBE MANOMETER

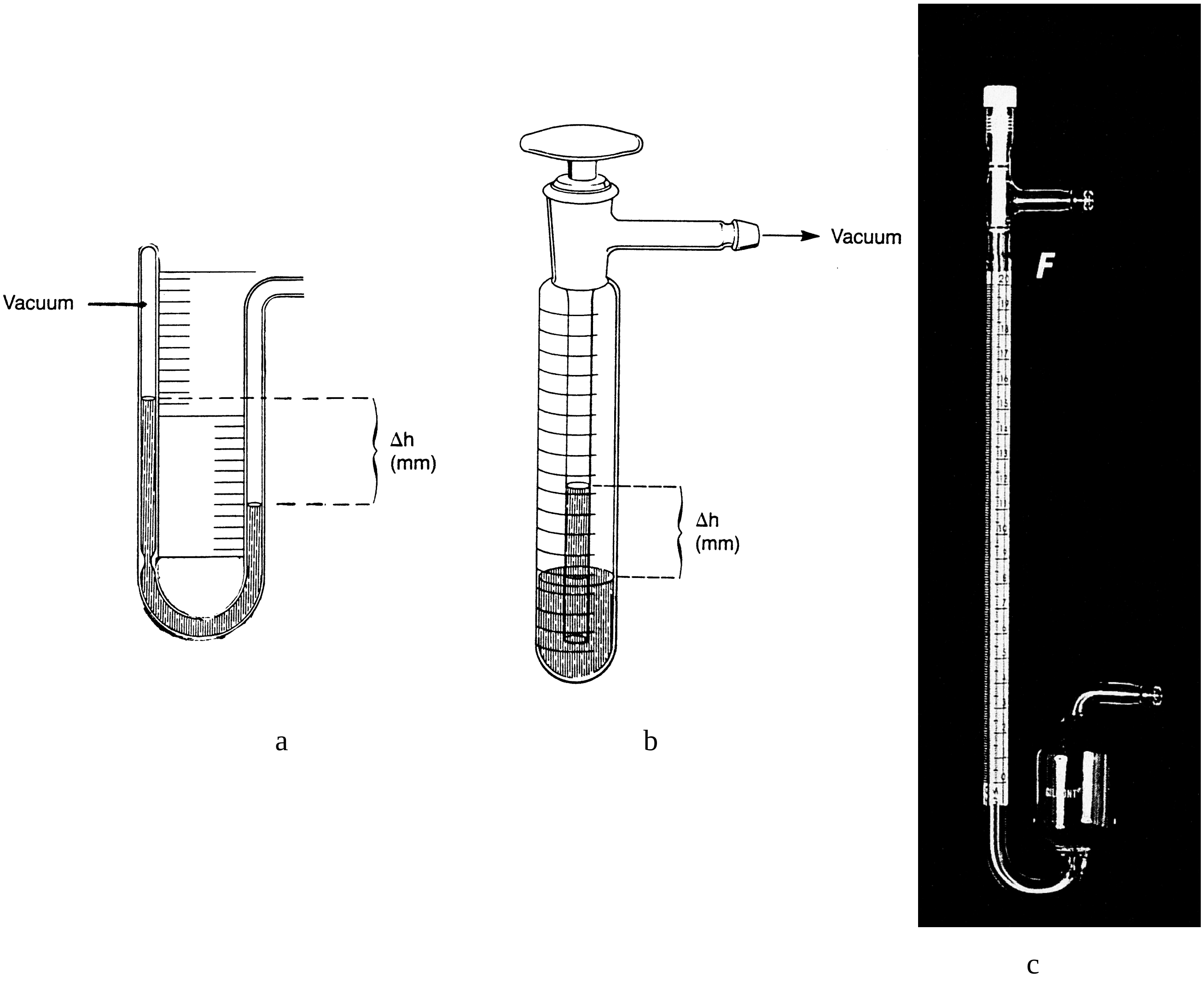


Fig. 3 Various forms of manometers

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

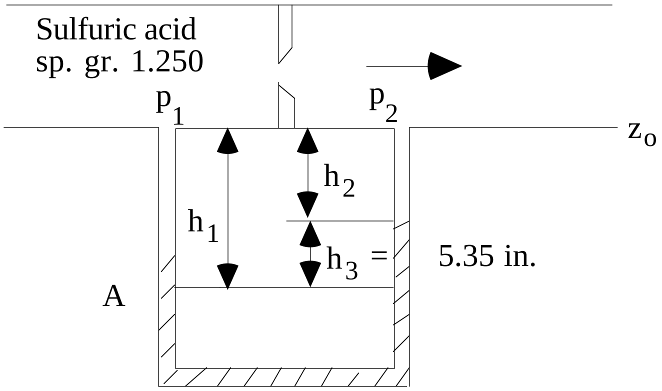
A U-tube manometer is used to determine the pressure drop across an orifice meter. The liquid flowing in the pipe line is a sulfuric acid solution having a specific gravity (60°/60°) of 1.250. The manometer liquid is mercury, with a specific gravity (60°/60°) of 13.56. The manometer reading is 5.35 inches,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

$$\rho_{acid} = \frac{1.250}{} \Big| \frac{62.4\ \text{lb/ft}^3}{} \Big| \frac{1\ \text{ft}^3}{1.728 \times 10^3\ \text{in}^3} = 0.0451\ \text{lb/in}^3$$

$$\rho_{Hg} = \frac{13.56}{} \Big| \frac{62.4\ \text{lb/ft}^3}{} \Big| \frac{1\ \text{ft}^3}{1.728 \times 10^3\ \text{in}^3} = 0.490\ \text{lb/in}^3$$



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.

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

Substitute the densities in the final equation

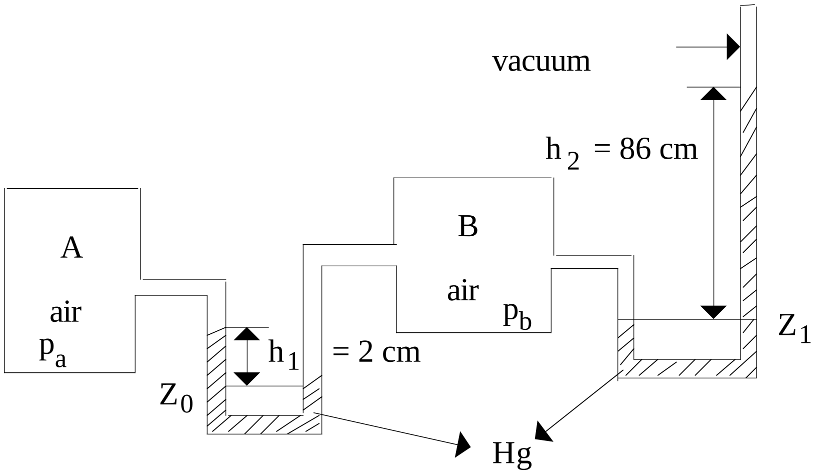
$$p_1 - p_2 = \frac{(0.490 - 0.0451)\ \text{lb}_f}{\text{in}^2} \Big| \frac{(5.35)\ \text{in}}{} \Big| \frac{32.2\ \text{ft/s}^2}{32.174\ (\text{ft})(\text{lb}_m)/(\text{s}^2)(\text{lb}_f)} = \mathbf{2.38\ lb_f/in^2\ (psi)}$$

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 $\quad p_a + h_1 \rho_{Hg} g = p_b$ (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

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:

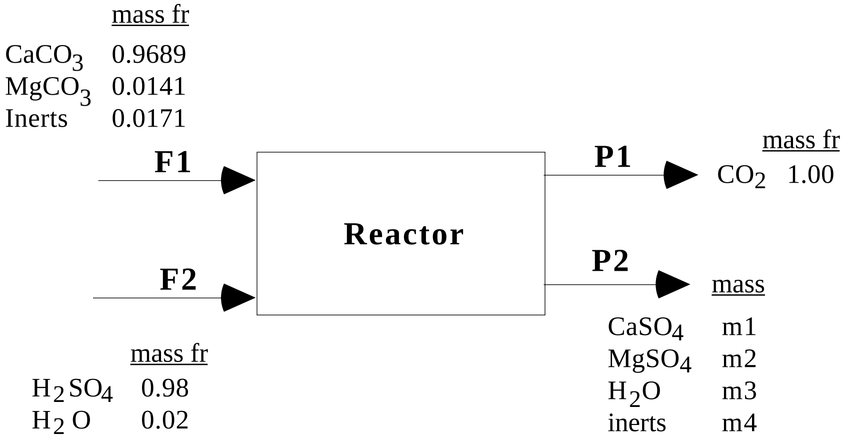
a. kg of anhydrous gypsum ($CaSO_4$) produced.
b. kg of sulfuric acid solution (98 wt%) required.
c. kg of carbon dioxide produced.
(MW : $CaCO_3$ 100.1; $MgCO_3$ 84.32; H_2SO_4 98; $CaSO_4$ 136; $MgSO_4$ 120;
H_2O 18; CO_2 44)

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

5000 kg limestone	1.41 kg $MgCO_3$	1 kg mol $MgCO_3$	1 kg mol H_2SO_4	98.0 kg H_2SO_4
	100 kg limestone	84.32 kg $MgCO_3$	kg mol $MgCO_3$	kg mol H_2SO_4

= 81.94 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.

4821.84 kg H_2SO_4	100 kg acid solution
	98.0 kg H_2SO_4

= **4920 kg H_2SO_4 solution**

c. Carbon dioxide generated

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

5000 kg limestone	96.83 kg $CaCO_3$	1 kg mol $CaCO_3$	1 kg mol CO_2	44 kg CO_2
	100 kg $CaCO_3$	100.1 kg $CaCO_3$	1 kg mol $CaCO_3$	1 kg mol CO_2

+

5000 kg limestone	1.41 kg $MgCO_3$	1 kg $MgCO_3$	1 kg mol CO_2	44 kg CO_2
	100 kg $MgCO_3$	84.32 kg $MgCO_3$	1 kg mol $MgCO_3$	1kg mol CO_2

= 2128.1 + 36.8 = **2165 kg CO_2**

Problem 1.7 B

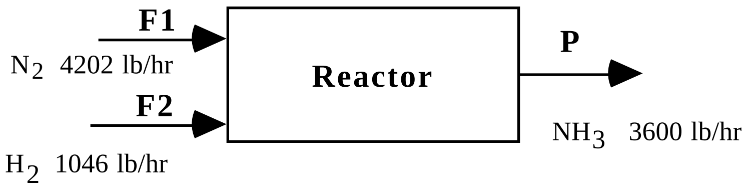
The synthesis of ammonia proceeds according to the following reaction

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

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

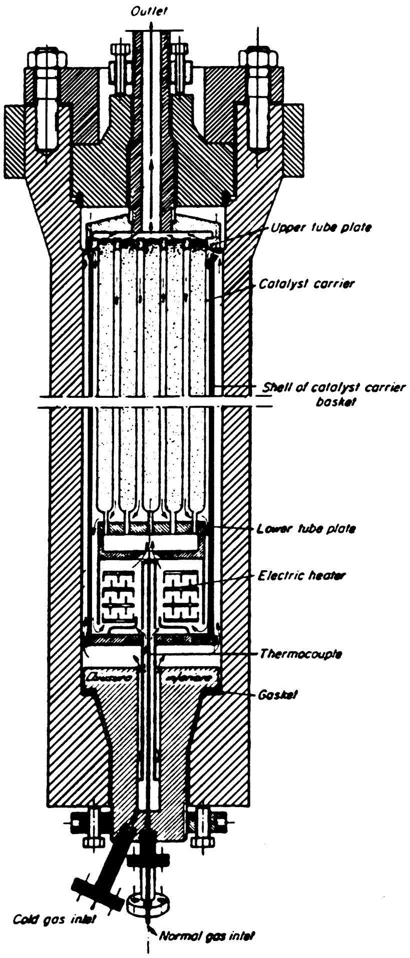


Fig. 4 Claude ammonia converter, a continuous flow reactor

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.

$$\begin{array}{c|c|c} 4202\ \text{lb N}_2 & 1\ \text{lb mol N}_2 & 2\ \text{lb mol NH}_3 \\ \hline & 28\ \text{lb N}_2 & 1\ \text{lb mol N}_2 \end{array} = 300\ \text{lb mol NH}_3$$

$$\begin{array}{c|c|c} 1046\ \text{lb H}_2 & 1\ \text{lb mol H}_2 & 2\ \text{lb mol NH}_3 \\ \hline & 2\ \text{lb H}_2 & 3\ \text{lb mol H}_2 \end{array} = 348.6\ \text{lb mol NH}_3$$

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

$$\begin{array}{c|c|c} 4202\ \text{lb N}_2 & 1\ \text{lb mol N}_2 & 3\ \text{lb mol H}_2 \\ \hline & 28\ \text{lb N}_2 & 1\ \text{lb mol N}_2 \end{array} = 450\ \text{lb mol H}_2\ \text{required}$$

H_2 available :

$$\begin{array}{c|c} 1046\ \text{lb H}_2 & 1\ \text{lb mol H}_2 \\ \hline & 2\ \text{lb H}_2 \end{array} = 523\ \text{lb mol H}_2$$

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

$$\%\ \text{excess H}_2 = \frac{(523 - 450)}{450} \times 100 = \mathbf{16.2\ \%}$$

c. Percentage conversion

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

$$\text{N}_2\ \text{reacted} = \begin{array}{c|c|c|c} 3060\ \text{lb NH}_3 & 1\ \text{lb mol NH}_3 & 1\ \text{lb mol N}_2 & 28\ \text{lb N}_2 \\ \hline & 17\ \text{lb NH}_3 & 2\ \text{lb mol NH}_3 & 1\ \text{lb mol N}_2 \end{array} = 2520\ \text{lb N}_2$$

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

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.

$$2\,\text{Bi} + 3\,\text{S} \text{ ----> } \text{Bi}_2\text{S}_3$$

Solution

a. Find the Limiting reactant

Ratio in the feed

$$\frac{\text{Bi}}{\text{S}} = \frac{\begin{array}{c|c} 5.00\text{ lb Bi} & 1\text{ lb mol Bi} \\ \hline & 209\text{ lb Bi}\end{array}}{\begin{array}{c|c} 1.00\text{ lb S} & 1\text{ lb mol S} \\ \hline & 32\text{ lb S}\end{array}} = \frac{0.0239\text{ mol Bi}}{0.0313\text{ mol S}} = 0.774$$

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

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

b. % Excess reactant

$$\text{Bi required} = \begin{array}{c|c|c} 1\text{ lb S} & 1\text{ lb mol S} & 2\text{ mol Bi} \\ \hline & 32\text{ lb S} & 3\text{ mol S}\end{array} = 0.0208\text{ lb mol Bi}$$

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

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%.

$$\begin{array}{c|c|c} 6.00\text{ lb rxn mass} & 5.00\text{ lb S} & 1\text{ lb mol S} \\ \hline & 100\text{ lb rxn mass} & 32.0\text{ lb S}\end{array} = 0.00938\text{ lb mol S}$$

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

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

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 $K = 2\pi \mathrm{D}\rho\bar{r}$. 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 $\left(\dfrac{60^\circ\text{F}}{60^\circ\text{F}}\right)$ of the pure components are

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

(a) What is the sp gr $\left(\dfrac{60^\circ\text{F}}{60^\circ\text{F}}\right)$ 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?

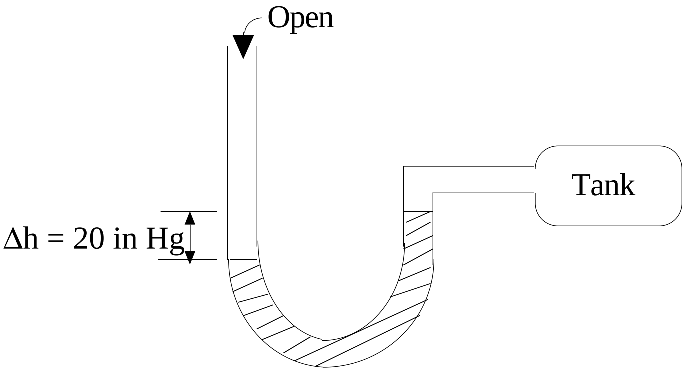
1.5B Mercury boils at 630K. What is its boiling temperature expressed in °C? In °F? In °R?

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).

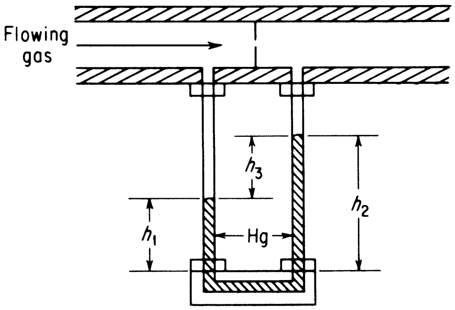


Figure P1.6D

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.

Problem 2.1A

When Bob came home he found a disaster. Bill and Mary were both lying dead in a puddle on the floor. Pieces of broken glass were all over the floor. What caused the disaster?

Solution

One way to approach this type of novel problem is to set up a matrix in which the columns are possible options for solution and the rows are comprised first of the constraints followed by the criteria for evaluation. The last row would be the decision as to the best option based on the weight of evidence presented in the matrix.

If the problem is not novel, then you can recognize valid patterns of successful solution for related problems, and follow those patterns. With novel problems and lack of data, you often make assumptions that prove to be incorrect. In this problem you might assume that Bill and Mary drowned in the water from a waterbed as one option. But what about the glass? A second option might be that Bill and Mary were in a bathroom or kitchen where both water and glass exist. A third option would require a distinct stretch of the imagination, but is the simplest solution: Bill and Mary were goldfish and the glass came from the broken goldfish bowl. Various options can be evaluated in terms of the constraints in the problem: presence of broken glass, water on the floor, Bill and Mary dead, and so on. A decision based on the data would eliminate options such as Bill and Mary drowned in a swimming pool or in a river as the constraints are violated by the meager data available.

Problem 2.1B

Why are 1994 new dimes worth more than 1984 dimes that have been in circulation?

Solution

In this novel problem you must focus on what the problem is. Think about it. What is the unknown? What do the words mean? Perhaps draw a figure. Can you rephrase the problem?

If you assume that the numbers refer to the year of minting, the question seems to be nonsense as a dime is worth 10 cents no matter what the year of issue. Does the question mean that circulated dimes, being worn, have less numismatic value than new dimes? Or do the number simply refer to the number of dimes? Clarifying a problem statement is always the first step in problem solving. Why solve the wrong problem well?

Problem 2.2A

Solve the four linear material balances

$$x_1 - x_2 + x_3 - 4x_4 = 20$$
$$2x_1 + x_3 - x_4 = 15$$
$$3x_2 + x_3 = 30$$
$$2x_1 - x_3 + 2x_4 = -10$$

using a computer program

Solution

A number of standard computer programs easily handle problems of this type such as spreadsheet packages, Matlab, Mathcad, Polymath, and so on as well as symbolic manipulators such as Mathematica, Maple, Derive, etc. Most statistic packages and equation solvers will also solve linear equations and have a simple user interface.

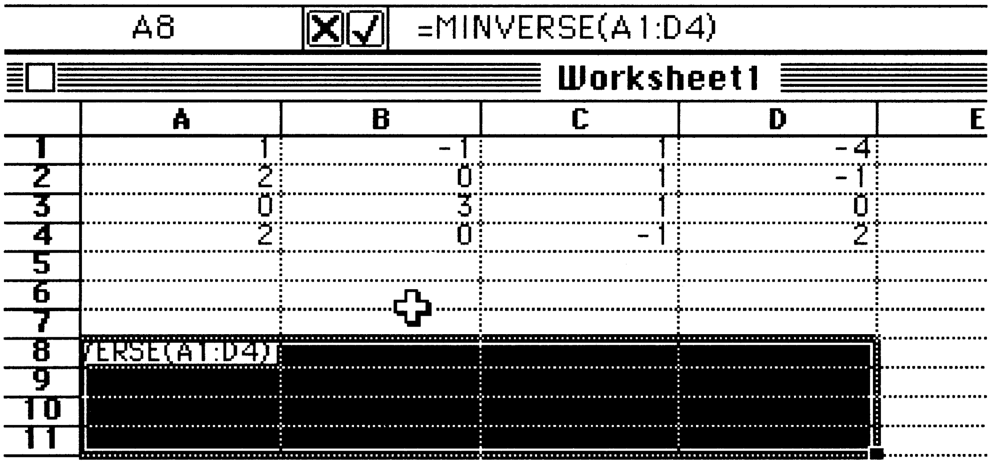
The solution for this example was obtained via the Excel spreadsheet. The equations can be represented in the matrix notation **Ax** = **b** where the arrays are

$$\mathbf{A} = \begin{array}{cccc} 1 & -1 & 1 & -4 \\ 2 & 0 & 1 & -1 \\ 0 & 3 & 1 & 0 \\ 2 & 0 & -1 & 2 \\ \multicolumn{4}{c}{4 \text{ x } 4} \\ \multicolumn{4}{c}{\text{(4 rows, 4 columns)}} \end{array} \qquad \mathbf{x} = \begin{array}{c} \text{x1} \\ \text{x2} \\ \text{x3} \\ \text{x4} \\ 4 \text{ x } 1 \\ \text{(4 rows, 1 col)} \end{array} \qquad \mathbf{b} = \begin{array}{c} 20 \\ 15 \\ 30 \\ -10 \\ 4 \text{ x } 1 \\ \text{(4 rows, 1 col)} \end{array}$$

To solve for the elements in **x**, you need to form the matrices (arrays) **A**, **b**, and **x**; calculate the inverse of **A**, $\mathbf{A}^{-1}$; and multiply as follows:

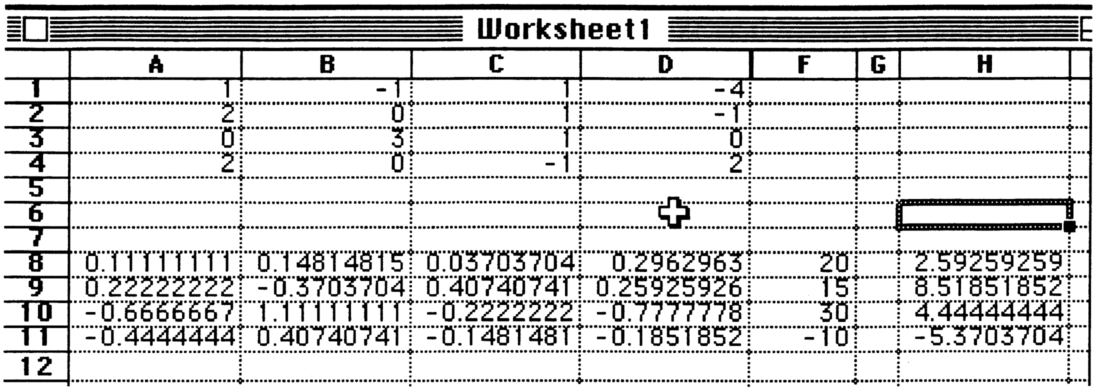
$$\mathbf{A}^{-1}\mathbf{b} = \mathbf{x}$$

Excel carries out these operations transparently for you. The first screen shows the worksheet with the data entered along with the dark cells reserved for the elements of the inverse matrix $\mathbf{A}^{-1}$. The next figure show the elements of the inverse matrix $\mathbf{A}^{-1}$ and the solution (in column H).



A8 =MINVERSE(A1:D4)

	A	B	C	D	E
1	1	-1	1	-4	
2	2	0	1	-1	
3	0	3	1	0	
4	2	0	-1	2	
5					
6					
7					
8	VERSE(A1:D4)				
9					
10					
11					



	A	B	C	D	F	G	H
1	1	-1	1	-4			
2	2	0	1	-1			
3	0	3	1	0			
4	2	0	-1	2			
5							
6							
7							
8	0.11111111	0.14814815	0.03703704	0.2962963	20		2.59259259
9	0.22222222	-0.3703704	0.40740741	0.25925926	15		8.51851852
10	-0.6666667	1.11111111	-0.2222222	-0.7777778	30		4.44444444
11	-0.4444444	0.40740741	-0.1481481	-0.1851852	-10		-5.3703704
12							

Problem 2.2B

In the back of the book is a disk containing the program Broyden that can solve sets of nonlinear equations. (It is actually a minimization program that minimize the sums of the squares of the deviations between the function values and zero). Solve the following two equations using Broyden or another program. You must compile the subroutine containing these equations via Fortran compiler on your computer before executing the program if you use Broyden.

$$25 - x_1^2 - x_2^2 = 0$$

$$x_1 + x_2 - 2 = 0$$

Solution

The output shows

```
ITER  NFUNCT  NDRV    FN VALUE          X-VALUES

  0      5      2   0.457000E+03 -0.200000E+01  0.000000E+00
  1     21      4   0.440910E+03  0.199082E+01 -0.199541E+00
  2     45      6   0.602136E+02 -0.847026E+00 -0.478122E+01
  3     56      8   0.598039E+02 -0.845112E+00 -0.483793E+01
  4     70     10   0.417177E+02  0.825930E+00 -0.508889E+01
  5     80     12   0.365274E+02  0.1570[illegible]9E+01 -0.501562E+01
  6     93     14   0.102013E+02  0.33869[illegible]E+01 -0.393178E+01
  7    103     16   0.686787E+01  0.322017E+01 -0.383872E+01
  8    116     18   0.230040E+01  0.397599E+01 -0.318019E+01
  9    130     20   0.167794E+00  0.427840E+01 -0.252328E+01
 10    146     22   0.110081E-02  0.438222E+01 -0.241096E+01
 11    156     24   0.288763E-04  0.439219E+01 -0.239034E+01
 12    163     26   0.229370E-08  0.439115E+01 -0.239120E+01
 13    170     28   0.933623E-12  0.439116E+01 -0.239117E+01
 14    173     28   0.932459E-12  0.439116E+01 -0.239117E+01
```

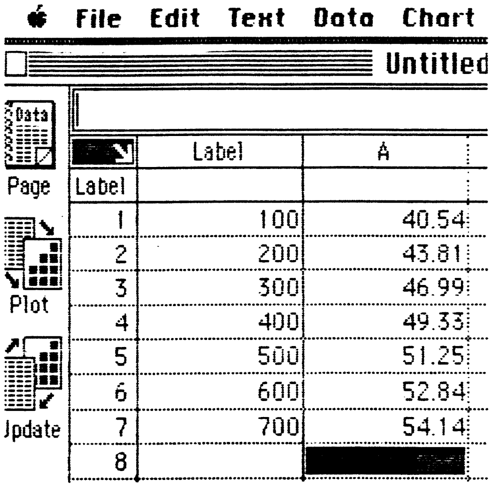
Problem 2.2C

You are asked to plot the following data and fit the best curve to it to relate C_p, the heat capacity, to the temperature.

	T(°C)		C_p[J/(g mol) (°C)]
	100		40.54
	200		43.81
X Axis	300	Y Axis	46.99
(horizontal)	400	(vertical)	49.33
	500		51.25
	600		52.84
	700		54.14

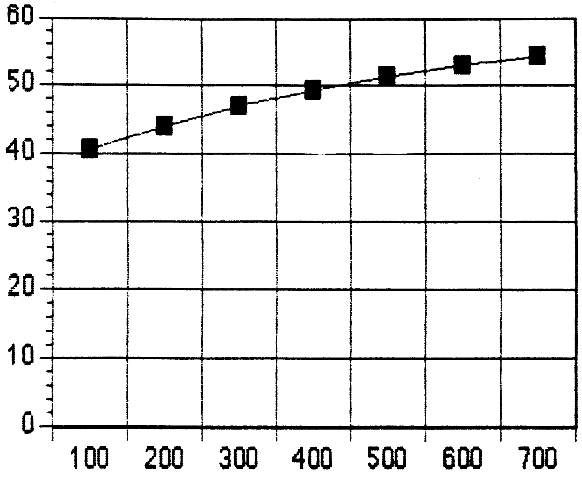
Solution

A program called DeltaGraph was used to carryout this assignment. The screen after entry of the data is



	Label	A
Label		
1	100	40.54
2	200	43.81
3	300	46.99
4	400	49.33
5	500	51.25
6	600	52.84
7	700	54.14
8		

and the graph with a superimposed plot of a third order polynominal looks as follows



CHAPTER 2 – ADDITIONAL PROBLEMS
(Answers will be found in Appendix A)

Section 2.1

2.1A The following experiment is carried out in a laboratory. A 1.45 kg copper ball (sp. gr. 8.92) is allowed to fall from 100 cm height into a tall vessel containing phenol (sp. gr. 0.789). Will the ball move more rapidly through the phenol if the material is at 25°C or at 100°C? Explain why.

2.1B Six beakers are aligned next to each other in a row on a table. The first three beakers are one-half full of ethanol. The second three beakers are empty. How can you arrange the beakers so that the half full and empty vessels alternate in the row by moving only 1 beaker?

2.1C One evening a man at work saw behind him two masked men. He turned right and ran straight ahead. Then he turned left and continued running straight ahead, and kept running while turning left twice more. As soon as he turned the last time he saw in the distance the two masked mean waiting for him. Who were they?

Section 2.2

2.2A Solve the following set of linear equations using a spread sheet program, MathCad, Matlab, or a related package:

$$\begin{gathered} 2x + y + z = 7 \\ x - y + z = 2 \\ x + y - z = 0 \end{gathered}$$

2.2B Solve the following set of nonlinear equations using a spread sheet program, MathCad, or Matlab, or a related package:

$$\begin{gathered} y = 48 - x^2 \\ x^5 = y^2 \end{gathered}$$

2.2C Create an x-y graph for the following data points, labeling the axes properly, via a spread sheet, MathCad, or a related program

time(s)	3	7	12	22	45	78
distance(min)	10	5	8	2	17	21

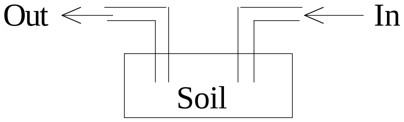
Problem 3.1A

Bioremediation is a method of cleaning up contaminated groundwater and soil. If a dilute solution of nutrients is pumped via a well into a closed soil layer underground at the rate of 1.5 kg/hr, and a recovery well removes 1.2 kg of depleted solution per hour, answer the following questions:

a. What is the system (draw a picture)?
b. What is the value of the input per hour?
c. What is the value of the output per hour?
d. What is the value of the accumulation per hour?
e. What assumption has to be made to answer (d)?

Solution

a. The system is the soil.



b. The input is 1.5 kg in one hour.

c. The output is 1.2 kg in one hour.

d. Assume the process is unsteady state. Then the accumulation in the soil is 0.3 kg in one hour.

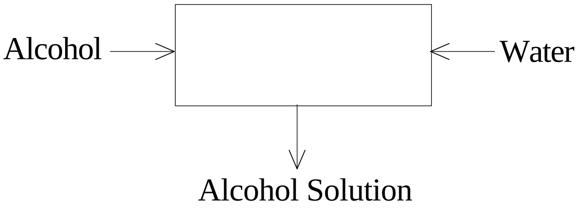
e. Assume unsteady state. If not, the accumulation would be zero and perhaps some leak from the closed system occurred (as would likely occur in the field).

Problem 3.1B

If 1 L of ethy alcohol is mixed with l L of water, how many kilograms of solution result? How many liters?

Solution

The densities of alcohol and water at 20°C are 0.789 and 0.998 g/cm^3, respectively.



Basis: 1 L of each compound

$$\frac{0.789\text{g}}{\text{cm}^3}\bigg|\frac{1000\text{ cm}^3}{} = 789\text{ g} \qquad \frac{0.998\text{ g}}{\text{cm}^3}\bigg|\frac{1000\text{ cm}^3}{} = 998\text{g}$$

The total kg are 789 + 998 = **1787 g.**

The volumes are not additive. For a 789/1789 = 0.442 mass fraction solution of alcohol in water, the density at 20°C is 0.929 g/cm^3.

$$\frac{1787\text{ g}}{}\bigg|\frac{\text{cm}^3}{0.929\text{ g}} = \mathbf{1923\ cm^3}$$

Problem 3.2A

A solution composed of 50% ethanol (EtOH), 10% methanol (MeOH), and 40% water (H_2O) is fed at the rate of 100 kg/hr into a separator that produces one stream at the rate of 60 kg/hr with the composition of 80% EtOH, 15% MeOH, and 5% H_2O, and a second stream of unknown composition. Calculate the composition (in %) of the three compounds in the unknown stream and its flowrate in kg/hr.

Solution

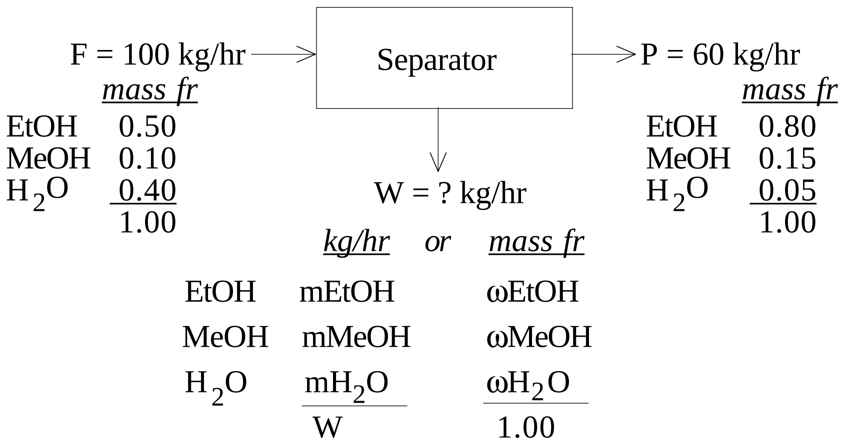
We will follow the steps in Table 3.1 in the analysis and solution of this problem.

Step 1

The problem is to calculate the percent of the three components in the unknown stream and its flow rate. Assume the process in the steady state over a sufficiently long period of time.

Steps 2, 3, and 4

The figure is shown with all known values entered as numbers (with units) and all unknown values entered as symbols.



Step 5

An obvious basis is one hour.

SEPARATION BY PRESSURE SWING ADSORPTION

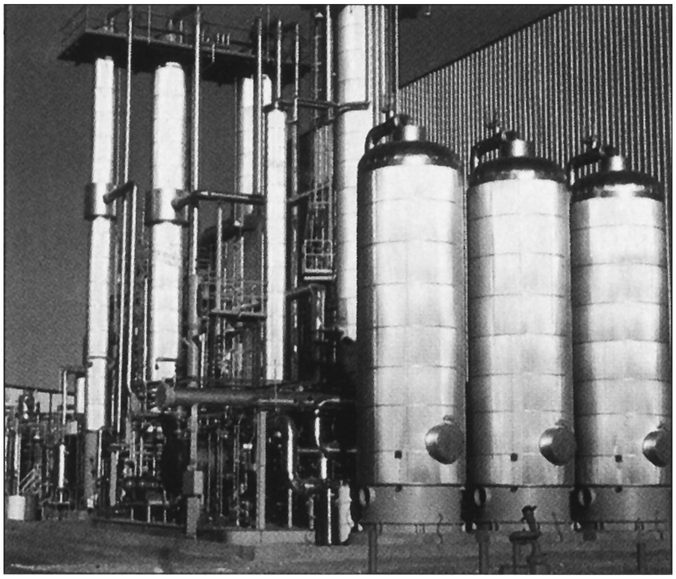


Fig. 5a. Pressure swing absorption beds for the dehydration of alcohols (*courtesy of Howe-Baker Engineers*)

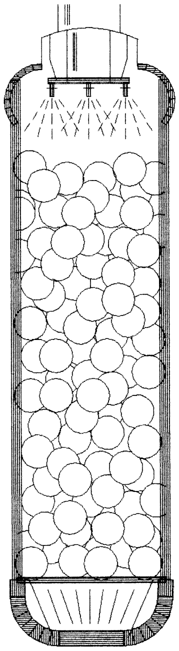


Fig. 5b. Packed bed used in adsorber.

Pressure swing adsorption is a commercial process for separating fluids based on their different affinities for an adsorbent. A sequence of steps involves more than one vessel ("bed") packed with adsorbent. Bed No. 1 receives the feed at the high supply pressure while bed No. 2 is opened to the low exhaust pressure. When Bed No. 1 becomes saturated with desired product (the undesired product leaves the bed at the exit), the supply is switched to Bed No. 2, and Bed No. 1 is opened to the low pressure so that the desired product is recovered. In the meantime desired product collects in Bed No. 2. After Bed No. 2 is saturated, the supply is again shifted back to Bed No. 1, and so on. More than two beds can be employed, and the specific design of the system and operating conditions are based on economical operation to conserve compression energy.

Step 6

The variables whose values are unknown are either (a) m_{EtOH}, m_{MeOH}, and m_{H_2O} plus W, or (b) ω_{EtOH}, ω_{MeOH}, and ω_{H_2O} plus W. Either set of four is acceptable as they are equivalent. We have four unknowns, and need four independent equations.

Step 7

Four mass balances can be written for each set of variables, one total and three component balances, but only three of the balances are independent.

$$\begin{array}{lrclcl c rclcl}
\text{Total:} & F & = & P & + & W & & F & = & P & + & W \\
\text{EtOH:} & 0.50F & = & 0.80P & + & m_{EtOH} & & 0.50F & = & 0.80P & + & \omega_{EtOH}W \\
\text{MeOH:} & 0.10F & = & 0.15P & + & m_{MeOH} & \text{or} & 0.10F & = & 0.15P & + & \omega_{MeOH}W \\
H_2O\text{:} & 0.40F & = & 0.05P & + & m_{H_2O} & & 0.40F & = & 0.05P & + & \omega_{H2O}W
\end{array}$$

In addition you know one more independent equation holds for the components in W

$$m_{EtOH} + m_{MeOH} + m_{H2O} = W \qquad \text{or} \qquad \omega_{EtOH} + \omega_{MeOH} + \omega_{H2O} = 1$$

Thus, we have four independent equations, and can get a unique solution.

Step 8

Because the equations involving the product of ω and W are nonlinear, the equations involving m are often selected for solution of the problem, but if W is calculated first, then both sets of equations are linear and uncoupled (can be solved independently).

Step 9

The solution of the equations is (using the total and first two component balances)

	m_i (kg/hr)	*ω_i (mass fr)*
EtOH	2	0.050
MeOH	1	0.025
H_2O	37	0.925
	40	1.00

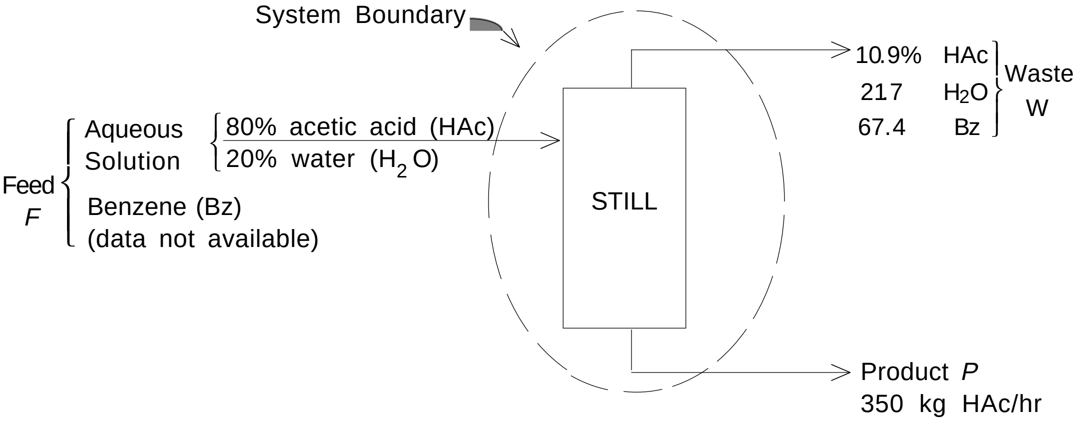
Step 10

As a check, we will use the third component balance, the one for H_2O, a redundant equation

$$\begin{array}{rcl c rcl}
0.40(100) & \overset{?}{=} & 0.05(60) + 37 & \text{or} & 0.40(100) & = & 0.05(60) + 0.925(40) \\
40 & = & 3 + 37 & & 40 & = & 3 + 37
\end{array}$$

Problem 3.2B

A continuous still is to be used to separate acetic acid, water, and benzene from each other. On a trial run, the calculated data were as shown in the figure. Data recording the benzene composition of the feed were not taken because of an instrument defect. The problem is to calculate the benzene flow in the feed per hour. How many independent material balance equations can be formulated for this problem? How many variables whose values are unknown exist in the problem?



Solution

No reaction occurs in this problem and the process is in the steady state. Values of two streams, W and F, are not known if 1 hr is taken as a basis, nor is the concentration of the benzene in F, $\omega_{Bz,F}$. (If you know the concentration of benzene in F, you know all the concentrations in the aqueous feed. Thus, we have three unknowns.

Three components exist in the problem, hence three mass balances can be written down (the units are kg):

Balance	*F in*		*W out*		*P out*	
HAc:	$0.80(1 - \omega_{Bz,F})F$	=	$0.109W$	+	350	(a)
H_2O:	$0.20(1 - \omega_{Bz,F})F$	=	$0.217W$	+	0	(b)
Benzene:	$\omega_{Bz,F}F$	=	$0.67W$	+	0	(c)

The total balance would be: F = W + 350 (in kg). Are the three component balances independent? Because of the zero terms in the right-hand sides of Eqs. (b) and (c), no variation or combination of Eqs. (b) and (c) will lead to Eq. (a). Are Eqs. (b) and (c) redundant equations? No constant exists that when multiplied into Eq. (b) gives Eq. (c), hence the three mass balances are independent.

A more formal way of establishing independence is to form the coefficient matrix of the equations (when equated to zero) and determine its rank

$$\begin{array}{c} \begin{array}{ccc} F & \omega_{Bz,F}F & W \end{array} \\ \begin{bmatrix} 0.80 & -0.80 & -0.109 \\ 0.20 & -0.20 & -0.217 \\ 0 & 1 & -0.674 \end{bmatrix} \end{array}$$

Can you show by elementary operations that the matrix is of full rank, hence the three component mass balances are independent?

SEPARATION BY DISTILLATION

Fig. 6a. Distillation column (*courtesy of Eickmeyer and Assoc.*)

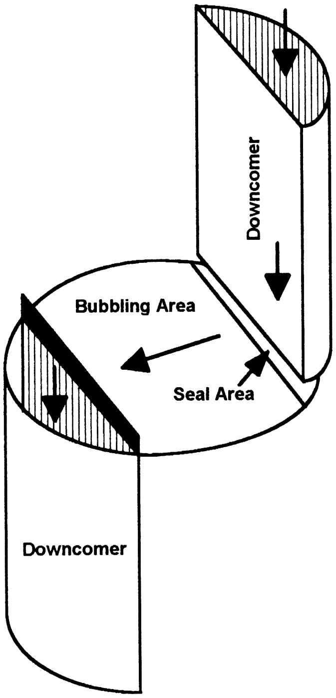


Fig. 6b. Flow of liquid down the column and across a tray through which vapor bubbles upward

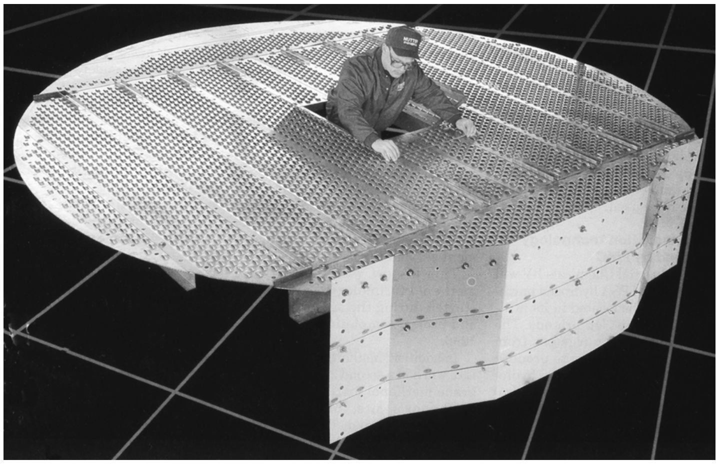


Fig. 6c. One distillation tray in the column (*courtesy of Nutter Engineering*)

In a distillation column, vapor and liquid flow in countercurrent directions to each other. Liquid is vaporized at the bottom, and vapor is condensed from the top product and withdrawn from the column. A number of trays are placed in the column, or the column is packed with open material, so that the vapor phase contacts the liquid phase, and components are transferred from one phase to the other. As you proceed up the column the temperature decreases, and the net effect is an increase in the more volatile component(s) in the vapor and a decrease in the less volatile components in the liquid. Vapor is withdrawn from the top of the column and liquid from the bottom. Feed to the column usually enters part way up the column.

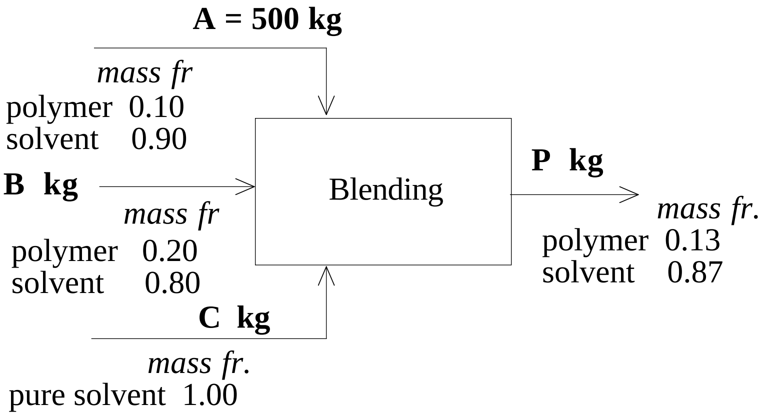
Problem 3.3 A

A liquid adhesive, which is used to make laminated boards, consists of a polymer dissolved in a solvent. The amount of polymer in the solution has to be carefully controlled for this application. When the supplier of the adhesive receives an order for 3000 kg of an adhesive solution containing 13 wt % polymer, all it has on hand is (1) 500 kg of a 10 wt % solution, (2) a very large quantity of a 20 wt % solution, and (3) pure solvent.

Calculate the weight of each of the three stocks that must be blended together to fill the order. Use all of the 10 wt % solution.

Solution

Steps 1, 2, 3 and 4 This is a steady state process without reaction.



Step 5 Basis: 3000 kg 13 wt % polymer solution

Step 6 Two unknowns: B and C . (A is not an unknown since all of it must be used).

Step 7 and 8 Two component balances and one total balance can be made. Only 2 of the balances are independent.

Total balance: $500 + B + C = 3000$ (1)

Polymer balance: $0.10\,(500) + 0.20\,B + 0.00\,(C) = 0.13\,(3000)$ (2)

Solvent balance: $0.90\,(500) + 0.80\,B + 1.00\,(C) = 0.87\,(3000)$ (3)

We will use equations (1) and (2).

Step 9

from (2) $0.1\,(500) + 0.20\,B = 0.13\,(3000)$

B = 1700 kg

from (1) $500 + 1700 + C = 3000$

C = 800 kg

Step 10

Equation (3) can be used as a check,

$0.90\,A + 0.80\,B + C = 0.87\,P$

$0.90\,(500) + 0.80\,(1700) + 800 = 2610 = 0.87\,(3000) = 2610$

MIXING (BLENDING)

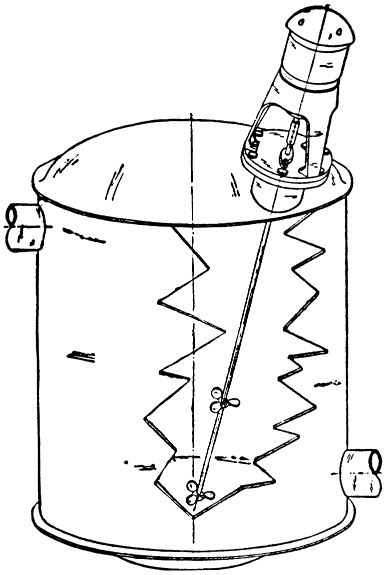


Fig. 7a. Mixing tank and agitator (*courtesy of Mixing Equipment Co.*)

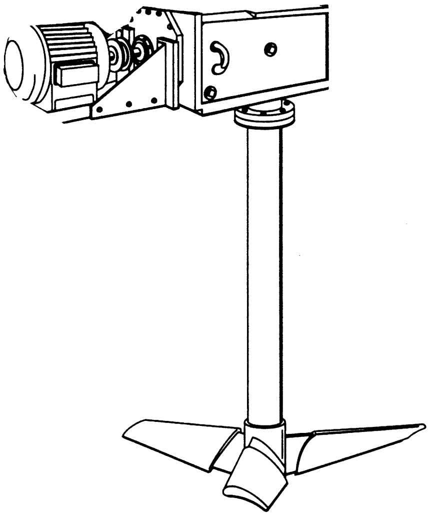


Fig. 7b. Impeller and motor for a mixing tank

In mixing and blending various mechanical devices are used to produce agitation. In addition to rotating impellers illustrated above, mixing can be accomplished with pumps and recirculation of fluid to the tank, air bubbles, jet mixing, and even flow through a packed pipe as shown in Figure 7c.

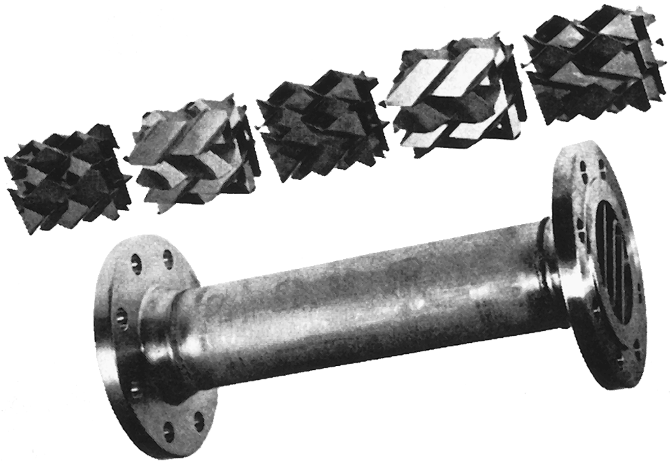


Fig. 7c. Corrugated plate type elements alongside the flanged static mixer body

Problem 3.3 B

You are asked to measure the rate at which waste gases are being discharged from a stack. The gases entering contain 2.1 % carbon dioxide. Pure carbon dioxide is introduced into the bottom of the stack at a measured rate of 4.0 lb per minute. You measure the discharge of gases leaving the stack, and find the concentration of carbon dioxide is 3.2 %. Calculate the rate of flow, in lb mol/minute, of the entering waste gases.

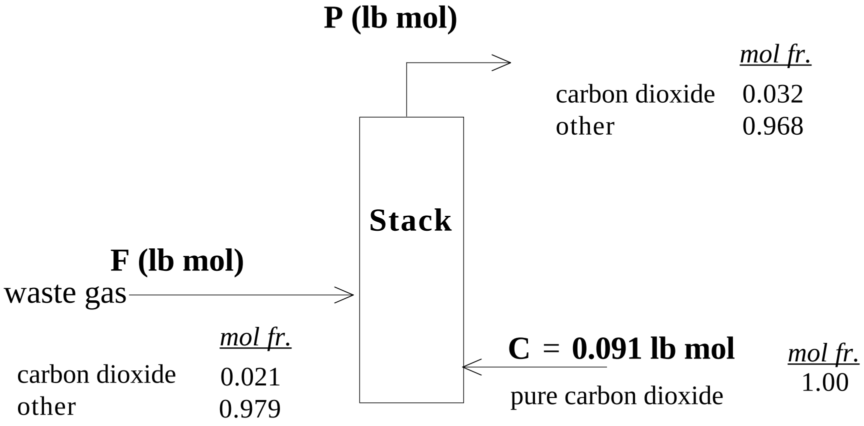
Solution

Step 5

A convenient basis to use is 1 minute of operation, equivalent to 0.091 lb mol of pure CO_2 feed.

Steps 1, 2, 3 and 4 This is a steady state problem without reaction.

$$\frac{4 \text{ lb } CO_2}{} \left| \frac{1 \text{ lb mol } CO_2}{44 \text{ lb } CO_2} \right. = 0.091 \text{ lb mol } CO_2$$



Step 6

The unknowns are F and P (all compositions are known).

Steps 7 and 8

The "other" balance (a tie component) and the CO_2 balance are independent equations. We will use mole balances since all of the compositions are in mole fractions.

CO_2 balance : $0.021 F + 0.091 = 0.032 P$ (1)

waste gas balance: $0.979 F = 0.968 P$ (2)

Step 9

Solving (1) and (2) **P = 8.10 lb mol/min** **F = 8.01 lb mol/min**

Step 10

To check above values, substitute them in the total balance

$$F + 0.091 = 8.00 = P = 8.00$$

GAS FLOW MEASUREMENT

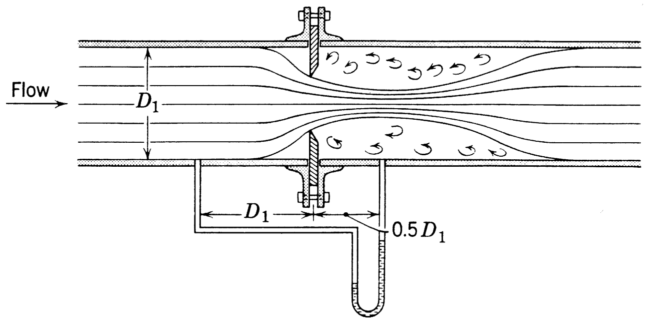
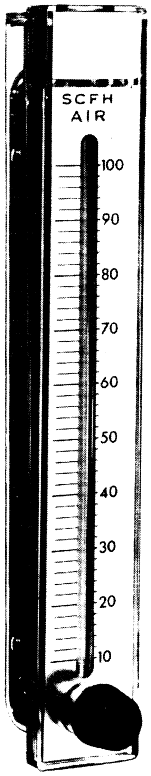


Fig. 8a. Sharp-edged orifice meter. The pressure loss in the converging-diverging flow can be related to the mass flow rate through the pipe.



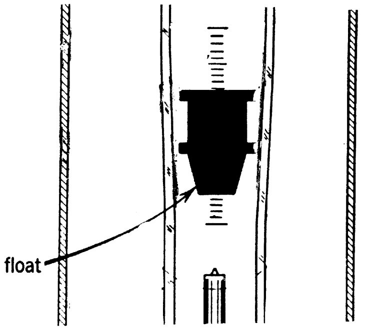


Fig. 8b. A rotameter consists of a tapered tube, glass or plastic, enclosing a small float. The fluid flow (adjusted by a valve at the bottom) causes the float to rise. Calibration may be necessary for different fluids.

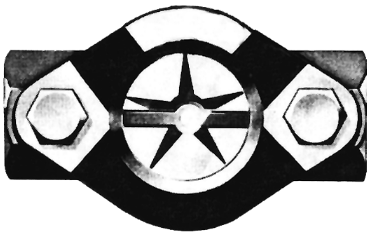


Fig. 8c. Positive displacement meter. The rotating wheel counts the volume passing through the pipe.

Both gas flow rates and liquid flow rates can be measured by a wide variety of devices such as bellow meters, Venturi nozzles, nutating disk meters, orifice meters, rotameters, weirs (for liquids), Pitot tubes, and magnetic meters among others. Some devices measure volumetric flow directly as with meters in which the space between rotating paddles incorporates small volumetric displacements of fluid. Other device measure the flows indirectly by measuring the pressure drop caused by an orifice between two different sites in the pipe, or the change in voltage of a heated wire.

MEASUREMENT OF GAS CONCENTRATION

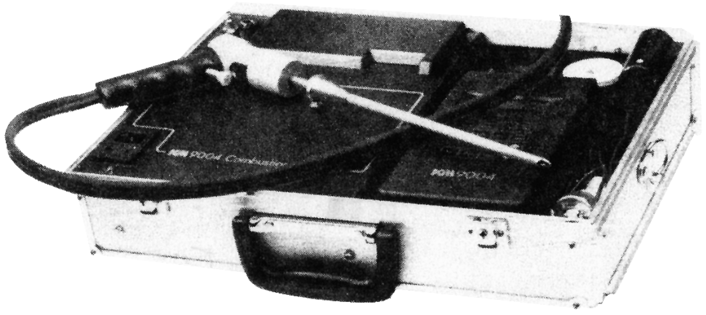


Fig. 9a. Portable combustion gas analyzer uses fuel cell technology to measure oxygen, carbon monoxide and carbon dioxide with 0.2% accuracy for O_2 and CO_2, and 1% for CO.

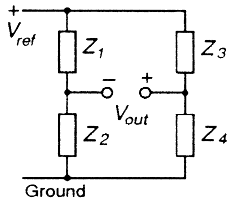


Fig. 9b. A Wheatstone bridge circuit as used in power plants for CO_2. It operates by balancing the output voltage of two circuits, one in a reference gas concentration, and the other in the gas to be measured.

Different combustion gases require different instruments for analysis. In addition to the instruments shown above, carbon dioxide and carbon monoxide can be measured by infrared analyzers--an infrared source is passed through a cell containing the sample gas, and the absorption at specific wavelengths is related to concentration. Accuracy is about 1%. Water vapor has to be eliminated for analysis. Oxygen concentration can be measured by using its paramagnetic properties or the electric potential developed in an oxidation-reduction reaction at high temperature. Hydrocarbons can be measured by flame ionization, hot wire detectors, and infrared analysis. Preprocessing scrubbing, etc. is needed to prevent interference in the analysis.

Problem 3.3 C

A laundry can purchase soap containing 30.0 wt % water at a price of \$ 7.00 per kg. The same manufacturer offers a soap containing 5.0 wt % water. If the freight rate is \$ 6.00 per 100 kg, what is the maximum price that the laundry should pay the manufacturer for the soap containing 5.0 wt % water ? Note that the buyer has to pay the freight.

Solution

Step 1, 2, 3 and 4

The final cost of the dry soap to the laundry includes the price paid to the manufacturer for the dry soap plus the cost of shipping the wet soap. When buying the dilute soap (30 wt % water) the laundry pays more freight on the water whereas buying the more concentrated soap (5 wt % water) would reduce the freight paid on the water. In this problem a sketch of the process is not required. The balance is to be made on dollars, not mass.

Step 5

You can use 100 kg of dilute soap (30 wt % water) as a basis, but it is probably clearer to use 100 kg of dry soap.

Basis : 100 kg dry soap

Step 6

The only unknown is C, the cost of the 95 wt % soap per kg. The balance is in dollars.

Steps 7, 8 and 9 The idea is to equate the total cost of two sources of soap.

cost of soap in the 95% soln:

$$\frac{\$\ C}{1\text{ kg wet soap}}\left|\frac{1\text{ kg wet soap}}{0.95\text{ kg dry soap}}\right|\frac{100\text{ kg dry soap}}{} = \$\ 105.26\ C$$

cost of shipping the 95 wt % soap:

$$\frac{100\text{ kg dry soap}}{}\left|\frac{1\text{ kg wet soap}}{0.95\text{ kg dry soap}}\right|\frac{\$\ 6.00}{100\text{ kg wet soap}} = \$\ 6.32$$

cost of soap in the 70 wt% soln:

$$\frac{\$\ 7.00}{1\text{ kg wet soap}}\left|\frac{1\text{ kg wet soap}}{0.70\text{ kg dry soap}}\right|\frac{100\text{ kg dry soap}}{} = \$\ 1000.00$$

cost of shipping the 70 wt % soap

$$\frac{100\text{ kg dry soap}}{}\left|\frac{1\text{ kg wet soap}}{0.70\text{ kg dry soap}}\right|\frac{\$\ 6.00}{100\text{ kg wet soap}} = \$\ 8.57$$

Cost balance:

cost of 95 w% soap + cost of shipping = cost of 70 wt % soap + cost of shipping

$$105.26\ C + 6.32 = 1000 + 8.57$$

solving for C **C = \$ 9.52 / kg wet soap**

Note that the cost of shipping is a very small factor in the final cost.

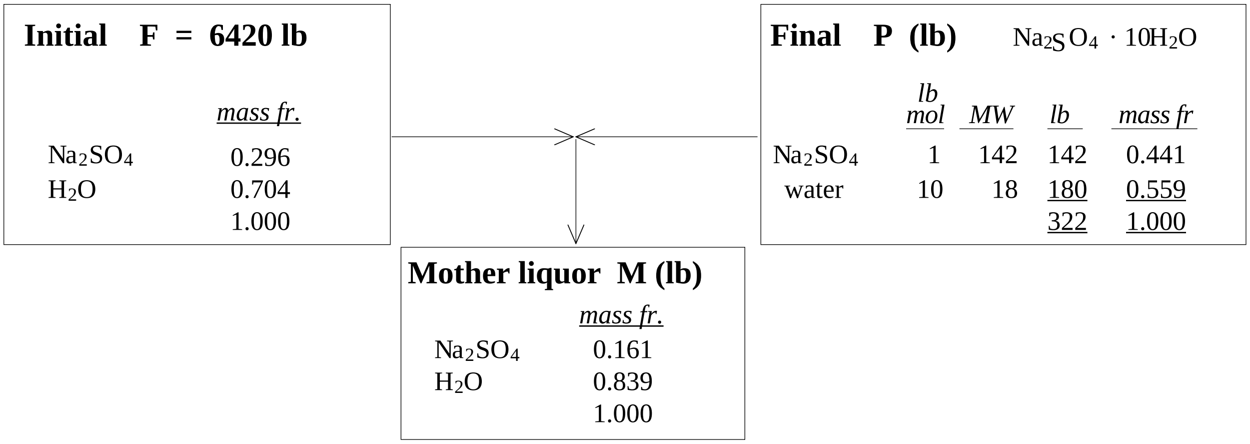
Problem 3.3 D

A crystallizer contains 6420 lb of aqueous solution of anhydrous sodium sulfate (concentration 29.6 wt %) at 104 °C. The solution is cooled to 20 °C to crystallize out the desired Na_2SO_4. 10 H_2O. The remaining solution (the mother liquor) is found to contain 16.1 % anhydrous sodium sulfate. What is the weight of this mother liquor.

Solution

Steps 1, 2, 3 and 4

This problem will be analyzed as unsteady state problem although it could be treated as a steady state problem with flows. The concentrations have to be calculated for some consistent components. Na_2SO_4 and H_2O are the easiest to use here rather than $Na_2SO_4 \cdot 10H_2O$ and H_2O.



Initial F = 6420 lb

	mass fr.
Na_2SO_4	0.296
H_2O	0.704
	1.000

Final P (lb) $Na_2SO_4 \cdot 10H_2O$

	lb mol	*MW*	*lb*	*mass fr*
Na_2SO_4	1	142	142	0.441
water	10	18	180	0.559
			322	1.000

Mother liquor M (lb)

	mass fr.
Na_2SO_4	0.161
H_2O	0.839
	1.000

Step 5 Basis : 6420 lb of 29.6 wt% Na_2SO_4 solution

Step 6 The unknowns are the weight of crystals P (lb) and weight of mother liquor M (lb).

Step 7 and 8

We need 2 independent balances, and will pick the total balance plus the Na_2SO_4 balance.

$$\text{Accumulation} = \text{In} - \text{out}$$

$$\text{Total:} \quad P - F = 0 - M \qquad (1)$$

$$Na_2SO_4\text{:} \quad 0.441P - 0.296\,F = 0 - 0.161\,M \qquad (2)$$

Step 9

from (1) $P = 6240 - M$

Substituting in (2) $0.441\,(6240 - M) - 6240\,(0.296) = -\,0.161\,M$

M = 3330 lb **P = 3100 lb**

Step 10

Use H_2O balance as a check

H_2O balance : $0.704\,F = 0.551\,P + 0.839\,M$

$0.704\,(6420) = 4520$ lb $0.551\,(3100) + 0.839\,(3330) = 4500$ lb

The calculated values do not exactly match, but they are close enough. The difference can be attributed to rounding errors given the number of significant figures in the problem.

CRYSTALLIZATION

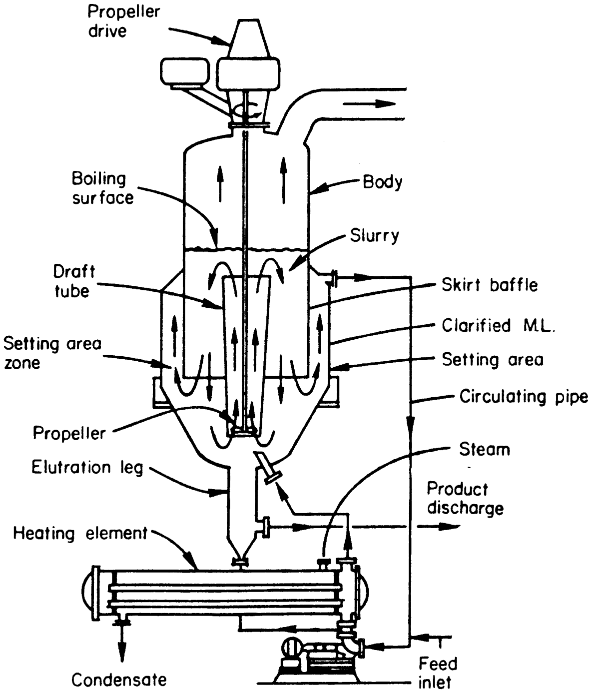


Fig. 10a. Continuous crystallizer (*courtesy of Swenson Process Equipment*). Fine crystals are brought from the bottom to the surface where the rate is higher.

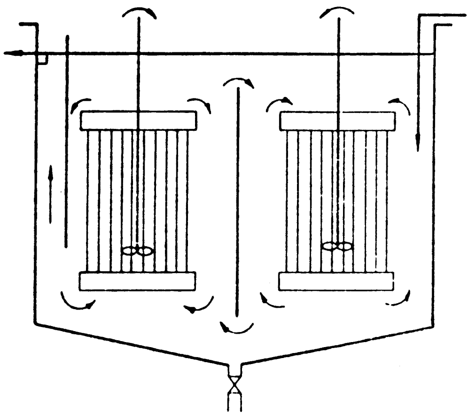


Fig. 10b. Batch crystallizer

Crystallization from an overall viewpoint represents transfer of a material from solution (or even a gas) to a solid phase by cooling, evaporation, or a combination of both. But there is more to it. Of considerable importance are economics, crystal size distribution, purity, and the shape of the crystals. Impurities or mother solution are carried along only in the surface or occlusions in the crystals. The partical size distribution depends on the distribution of seed crystals, which are injected into the crystallizer prior to initiation of crystallization (batch) or continuously from recycled undersized particles, the mixing in the system, the crystal growth rate, and the degree of supersaturation of the mother liquor. As in shown in the figures, both batch and continuous crystallization are used in industry.

Problem 3.4 A

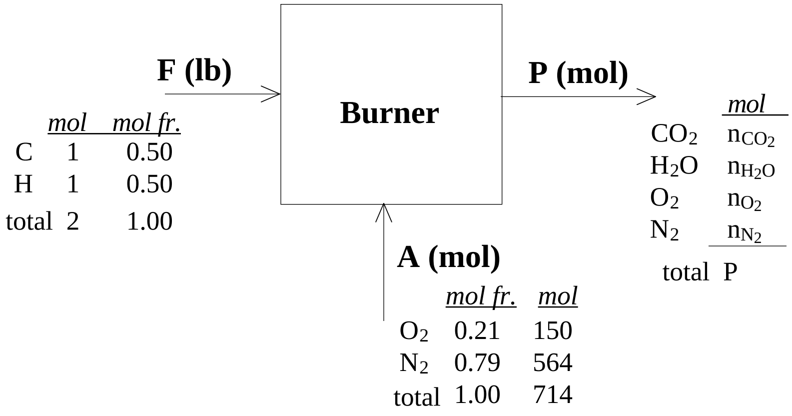
A furnace used to provide heat to anneal steel burns a fuel oil whose composition can be represented as $(CH_2)_n$. It is planned to burn this fuel with stoichiometric air.

a. Assume complete combustion and calculate the Orsat analysis of the flue gas.
b. Recalculate the Orsat analysis assuming that 5 % of the carbon in the fuel burns to CO only.

Solution

Steps 1, 2, 3 and 4

This problem is a steady state problem with reaction. The subscript n in the $(CH_2)_n$ merely indicates that the oil is made up of a long chain of CH_2 units or molecules. The carbon to hydrogen ratio remains 1 to 2 in the fuel. All of the known compositions are placed in the figure for part (a).



Step 5 In this problem no flow rates are given. A convenient basis can be selected either F, A, or P in moles. We will pick

$$F = 100 \text{ mol fuel oil}$$

a.

Step 4 Calculate A

$$CH_2 + 1.5\ O_2 \text{ -------> } CO_2 + H_2O$$

oxygen required

$$\begin{array}{c|c} 100 \text{ mol oil} & 1.5 \text{ mol } O_2 \\ \hline & 1 \text{ mol oil} \end{array} = 150 \text{ mol } O_2$$

Nitrogen entering

$$\begin{array}{c|c} 150 \text{ mol } O_2 & 79 \text{ mol } N_2 \\ \hline & 21 \text{ mol } O_2 \end{array} = 564 \text{ mol } N_2$$

Step 6 The unknowns are P and n_{CO_2}, n_{H_2O}, n_{O_2}, n_{N_2}. Since $\sum n_i = P$ is an independent equation, only 4 unknowns exists.

A FURNACE

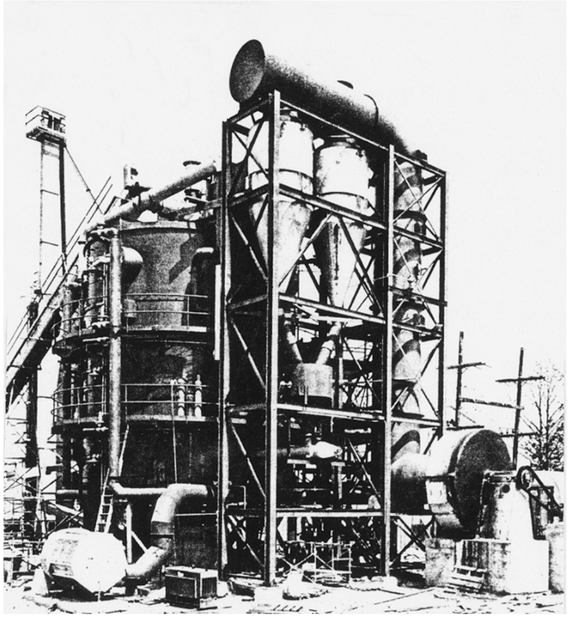
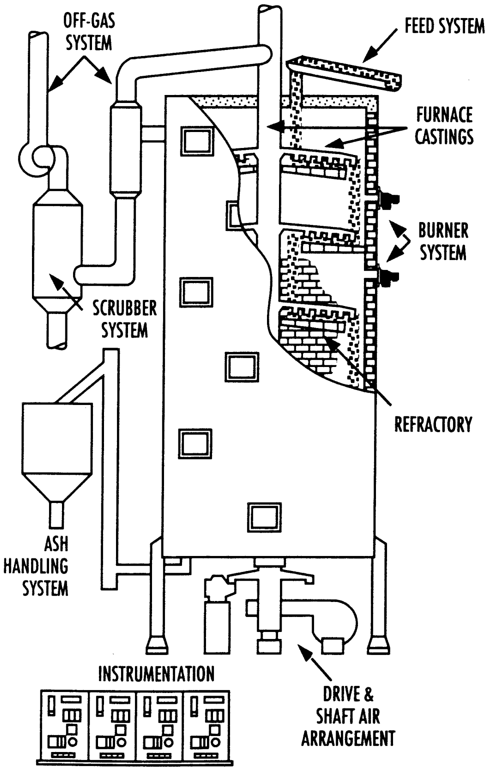


Fig. 11. Multiple hearth furnace (*courtesy of BSP Thermal Systems*)

Indirect or direct fired heaters are widely used in the process industries. Heat loss is kept to a minimum by refractory coatings on the furnace wall. Any material in the fuel that is corrosive or forms excess soot has to be avoided. Usually 20-25% excess air is required for fuel oil vs. 5-10% for gaseous fuel, hence the latter is more economic. Energy in the exit flue gas not used to heat water or a product can be recovered by heat exchangers that generate additional steam or preheat the entering air.



Steps 7, 8 and 9

The compound balances are in moles. Gas combustion problems can be presented in tabular form for convenience and to save space. The balances can be written as

In - out + generation - consumption = accumulation = 0

										Results	
	In		*Out*		*Generation*		*Consumption*			*n_i mols*	*Orsat anal.*
CH_2 :	100	-	0	+	0	-	100	=	0	0	0
O_2 :	150	-	n_{O_2}	+	0	-	150	=	0	0	0
N_2 :	564	-	n_{N_2}	+	0	-	0	=	0	564	0.849
CO_2:	0	-	n_{CO_2}	+	100	-	0	=	0	100	0.151
H_2O :	0	-	n_{H_2O}	+	100	-	0	=	0	100	0
										764	1.000

Step 10

As a check we will redo the problem using element balances. For steady state systems if element balances are used, they are just

in = out

Element	*In*	*Out*
C	100	100
H2	100	100
O2	150	100 + 100/2 = 150
N2	564	564
	914	**914**

b.

Steps 7, 8 and 9 Now we have 5 mol of CO in the exit gas and 95 mol of CO_2.

	In		*Out*		*Generation*		*Consumption*	*n_i mols*	*Orsat analysis(in%).*
CH_2	100	-	0	+	0	-	100	0	0
O_2	150	-	n_{O_2}	+	0	-	$2.5 + 95 + \frac{1}{2}(100)$	2.5	0.4
N_2	564	-	n_{N_2}	+	0	-	0	564	84.6
CO	0	-	n_{CO}	+	5	-	0	5	0.8
CO_2	0	-	n_{CO_2}	+	95	-	0	95	14.2
H_2O	0	-	n_{H_2O}	+	100	-	0	0	0
								666.5	100.0

Step 10 (b) A check via element balances gives

Element	*In*	*Out*
C	100	95 + 5 = 100
H2	100	100
O2	150	95 + 5/2 + 5/2 + 100/2 = 150
N2	564	564
	914	914

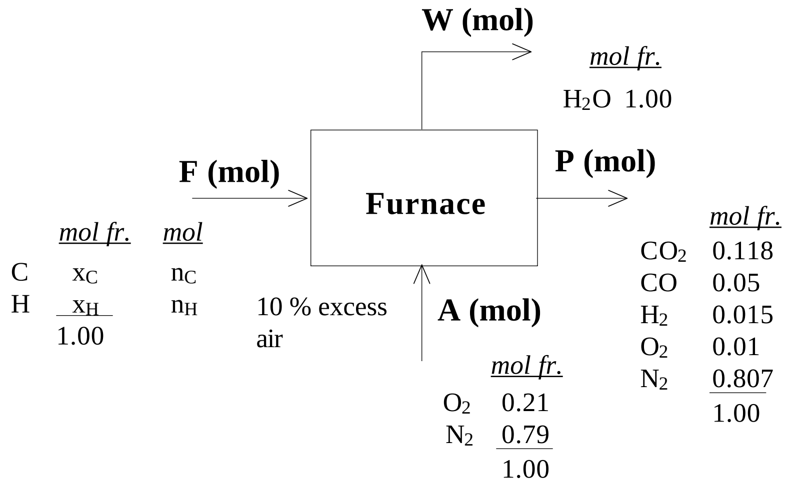
Problem 3.4 B

Your assistant reports the following experimental data for the exit Orsat gas analysis from the combustion of a hydrocarbon oil in a furnace: CO_2 11.8 %; CO 5.0 %; H_2 1.5 %; O_2 1.0 % and N_2 by difference. The oil is being burned with 10 % excess air. Would you compliment him on his work ?

Solution

Steps 1, 2, 3 and 4

The process is a steady state process with reaction. With 10 % excess air it is unlikely that there is any H_2 in the exit gases. Based on the given exit gas analysis and given excess air, we can calculate the fuel analysis and see if it is reasonable. Do not forget the water in the exit gas!



Step 5: A convenient basis is the exit stream. Basis : P = 100 mol exit gas.

Step 6 : Unknowns : A, the moles of air entering; F, the moles of fuel entering; x_C the mol fraction of carbon in the fuel, and x_H the mol fraction of hydrogen in the fuel, or use n_C and n_H instead of x_c and x_H.

Steps 7, 8 and 9: Four element balances can be made; also $n_c + n_H = F$.

	In		*Out*	*Results (mol)*
N2	0.79 A	=	0.807 (100)	A = 102
O2	0.21 (102)	=	(0.118 + 0.05/2 + 0.01) 100 + W/2	W = 12.2
C	$F(x_C) = n_C$	=	(0.118 + 0.05) 100	$n_C = 16.8$
H	$F(x_H) = n_H$	=	(2) (0.015) 100 + 2W	$n_H = 27.4$

Step 9

Oxygen in = 0.21 (102) = 21.4 mol;

Based on the C and H_2 found in the exit gas stream and the water, the oxygen entering the furnace is

Required O_2:

$C + O_2 \longrightarrow CO_2$

$$\begin{array}{l|l} 16.8 \text{ mol C} & 1 \text{mol } O_2 \\ \hline & 1 \text{ mol C} \end{array} = 16.8$$

$H_2 + 1/2\, O_2 \longrightarrow H_2O$

$$\begin{array}{l|l} 13.7 \text{ mol } H_2 & 1 \text{mol } O_2 \\ \hline & 2 \text{ mol } H_2 \end{array} = 6.85$$

$$\begin{aligned} \text{Total required } O_2 &= 23.65 \\ 10\% \text{ excess} &= 2.37 \\ \text{Total } O_2 &= 26.00 \end{aligned}$$

But the total oxygen supplied as per the O_2 balance = 21.4 mol. The answer to the question is **no.** This discrepancy is too large.

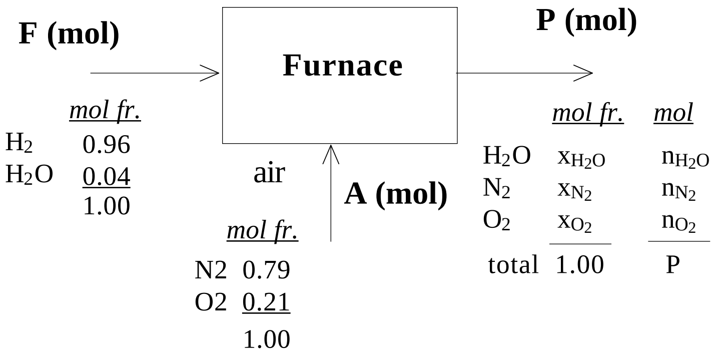
Problem 3.4 C

Moist hydrogen containing 4 mole percent water is burnt completely in a furnace with 32 % excess air. Calculate the Orsat analysis of the resulting flue gas.

Solution

Steps 1, 2, 3 and 4

This is a steady state process with a reaction. The data are placed in the figure.



Step 5 Basis: 100 mol F

Step 4 We first calculate the amount of entering air.

$H_2 + 0.5\, O_2 \longrightarrow H_2O$

Oxygen required:

$$\begin{array}{l|l} 96 \text{ mol } H_2 & 1 \text{ mol } O_2 \\ \hline & 2 \text{ mol } H_2 \end{array} = 48 \text{ mol}$$

Excess O_2

$$\begin{array}{l|l} 48 \text{ mol } O_2 & 32 \text{ mol } O_2 \\ \hline & 100 \text{ mol } O_2 \end{array} = 15 \text{ mol}$$

Total oxygen in $\qquad$ 63 mol

Nitrogen supplied $$\begin{array}{l|l} 63 \text{ mol } O_2 & 79 \text{ mol } N_2 \\ \hline & 21 \text{ mol } O_2 \end{array} = 237 \text{ mol}$$

Step 6 : Unknowns (4): P, the mol of flue gas and n_{H_2O}, n_{N_2}, n_{O_2}.

Step 7, 8 and 9 You can make 3 element balances and know that $\Sigma n_i = P$, a total of 4 balances. The solution can be presented in the tabular form using compound balances.

$$\text{In} - \text{Out} + \text{Generation} - \text{Consumption} = 0 \quad \text{(for a steady state system)}$$

Compound	*In*		*Out*		*Generation*		*Consumption*			*mol n_i*	*Orsat analy(%)*
H_2	96	-	0	+	0	-	96	=	0	0	0.00
H_2O	4	-	n_{H_2O}	+	96	-	0	=	0	100	0.00
O_2	63	-	n_{O_2}	+	0	-	48	=	0	15	5.95
N_2	237	-	n_{N_2}	+	0	-	0	=	0	237	94.05
										352	100.00

Step 10

A check can be made by making element balances in moles.

Balance	*In*	*Out*	*Compound*	*n_i*
H2	96 + 4	n_{H_2O}	H_2O	100
O2	63 + (4/2)	$n_{O_2} + n_{H_2O}/2$	O_2	15
N2	237	n_{N_2}	N_2	237
	400			352

Note: The Orsat analysis is on a moisture free basis.

Problem 3.5 A

A triple effect evaporator is designed to reduce water from an incoming brine (NaCl + H_2O) stream from 25 wt % to 3 wt %. If the evaporator unit is to produce 14,670 lb/hr of NaCl (along with 3 wt % H_2O), determine:

a. the feed rate of brine in lb/hr.
b. the water removed from the brine in each evaporator.

The data are shown in the accompanying figure.

Solution

Steps 1, 2, 3 and 4

This is a steady state problem. The data has been placed on the figure.

EVAPORATORS

Fig. 12a. Multiple effect vertical tube evaporators (*courtesy of APV Crepaco Inc.*)

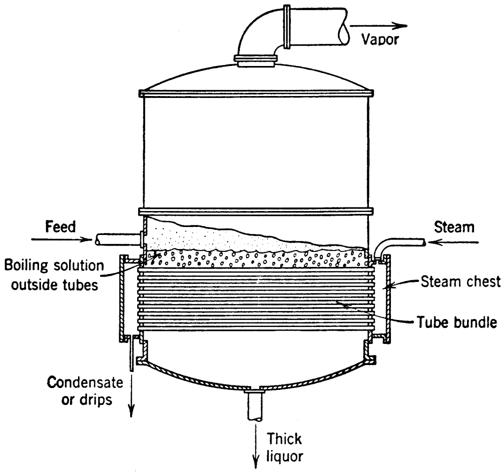
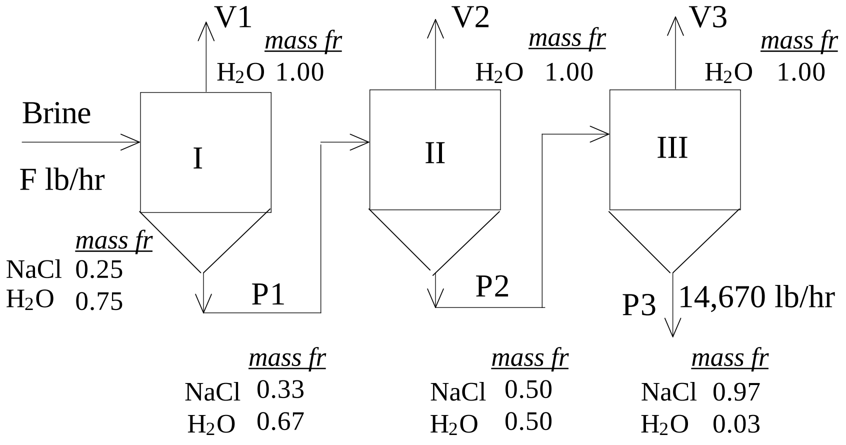


Fig. 12b. Crossection of a single effect evaporator (*courtesy of Swenson Process Equipment Co.*)

Evaporation as a process operation involves the concentration of one more or solutes by transfer of the solvent from the liquid into the vapor phase. Evaporation also may be simply formation of vapor from a liquid. The heating medium, usually steam, is introduced in the steam chest connected to a set of tubes inside the evaporator body. The steam condenses causing some of the liquid outside of the tubes to vaporize. As a matter of economy, often a multiple series of evaporators are connected so that the vapor from one evaporator is introduced (at a lower pressure) into the steam chest of the next evaporator where it condenses, and so on. Dissolved solids can be deposited on the exterior of the heating tubes (scaling) so that different interior evaporator designs are used to reduce scaling.



Step 5: It is best to choose 1 hr of operation or an arbitrary amount of dry salt produced per hour as the basis. We will select

Basis: 14,670 lb = 1 hr

Step 6: There are 6 unknown stream flows: F, V_1, V_2, V_3, P_1, and P_2.

Step 7 and 8

Balances for salt and water and total balance can be written for each unit as a system as well as overall balances (not all of these balances would be independent). We will use the salt and total balances as the simplest ones.

Overall balances

Total balance : $F = V_1 + V_2 + V_3 + 14{,}670$ (1)

Salt balance : $0.25\,F = 0.97\,(14{,}670)$ (2)

Evaporator I

Total balance : $F = V_1 + P_1$ (3)

Salt balance : $0.25\,F = 0.33\,P_1$ (4)

Evaporator II

Total balance : $P_1 = V_2 + P_2$ (5)

Salt balance : $0.33\,P_1 = 0.50\,P_2$ (6)

Evaporator III

Total balance : $P_2 = V_3 + 14{,}670$ (7)

Salt balance : $0.50\,P_2 = 0.97\,(14{,}670)$ (8)

Any set of 6 independent equations can be used to determine the 6 unknowns. We will use equations (1) to (6) to solve for all of the unknowns.

Step 9

By starting the solution with equation (2), the equations become uncoupled.

$$\mathbf{F = 56{,}900\ lb/hr}$$

From equation (4) $0.25\,(56{,}900) = 0.33\,P_1$

$P_1 = 43{,}100$ lb/hr

From equation (3) **V_1 = 13,800 lb/hr**

From equations (5) and (6) P_2 = 28,460 lb/hr ; **V_2 = 14,700 lb/hr**

From equation (1) 56,900 = 13,800 + 14,700 + V_3 + 14,670
V_3 = 13,800 lb/hr

Step 10 Equations (7) and (8) can be used to check the results.

Equation (7) $P_2 = V_3 + P_3$
$28{,}460 \cong 13{,}800 + 14{,}670 = 28{,}470$

Equation (8) $0.5\ P_2 = 0.97\ P_3$
$0.5\ (28{,}460) = 0.97\ (14{,}670)$
14,230 lb = 14,230 lb

Problem 3.5 B

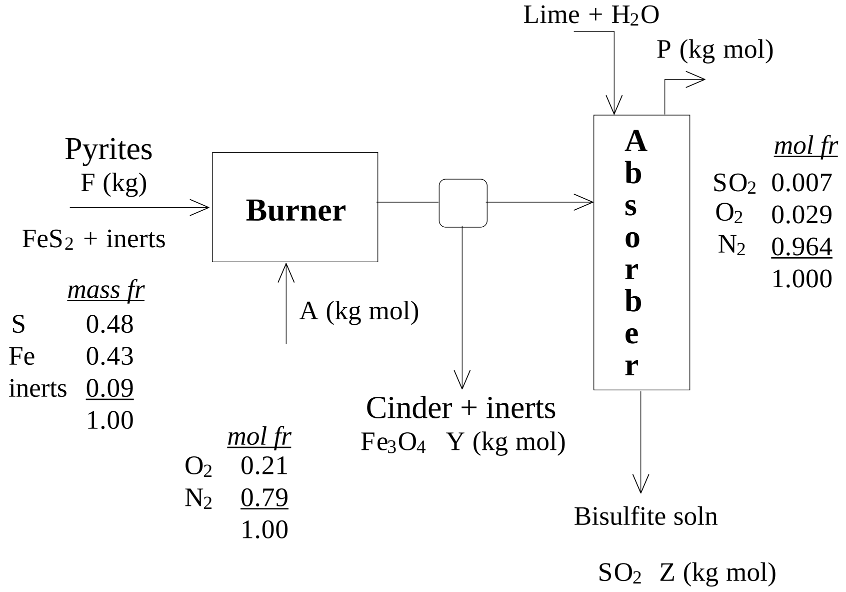
Plants in Europe sometimes use the mineral pyrites (the desired compound in the pyrites is FeS_2) as a source of SO_2 for the production of sulfite pulping liquor. Pyrite rock containing 48.0 % sulfur is burned completely by flash combustion. All of the iron forms Fe_3O_4 in the cinder (the solid product), and a negligible amount of SO_3 occurs in either the cinder or the product gas. The gas from such a furnace is passed through milk of lime (CaO in water) absorbers to produce bisulfite pulping liquor. The exit gas from the absorber analyzes: SO_2 0.7 %, O_2 2.9 % and N_2 96.4 %.

Calculate the kg of air supplied to the burner per kg of the pyrites burned.
(MW : S 32; Fe 56; O 16; N 14)

Solution

Steps 1, 2, 3 and 4 The problem is a steady state one with a reaction occurring, and the system will be the combination of both units. In this problem the oxidation reaction of pyrites can be considered to occur as follows.

$$3\ FeS_2 + 8\ O_2 \dashrightarrow Fe_3O_4 + 6\ SO_2$$



	mass fr
S	0.48
Fe	0.43
inerts	0.09
	1.00

	mol fr
O_2	0.21
N_2	0.79
	1.00

	mol fr
SO_2	0.007
O_2	0.029
N_2	0.964
	1.000

FLASH COMBUSTION

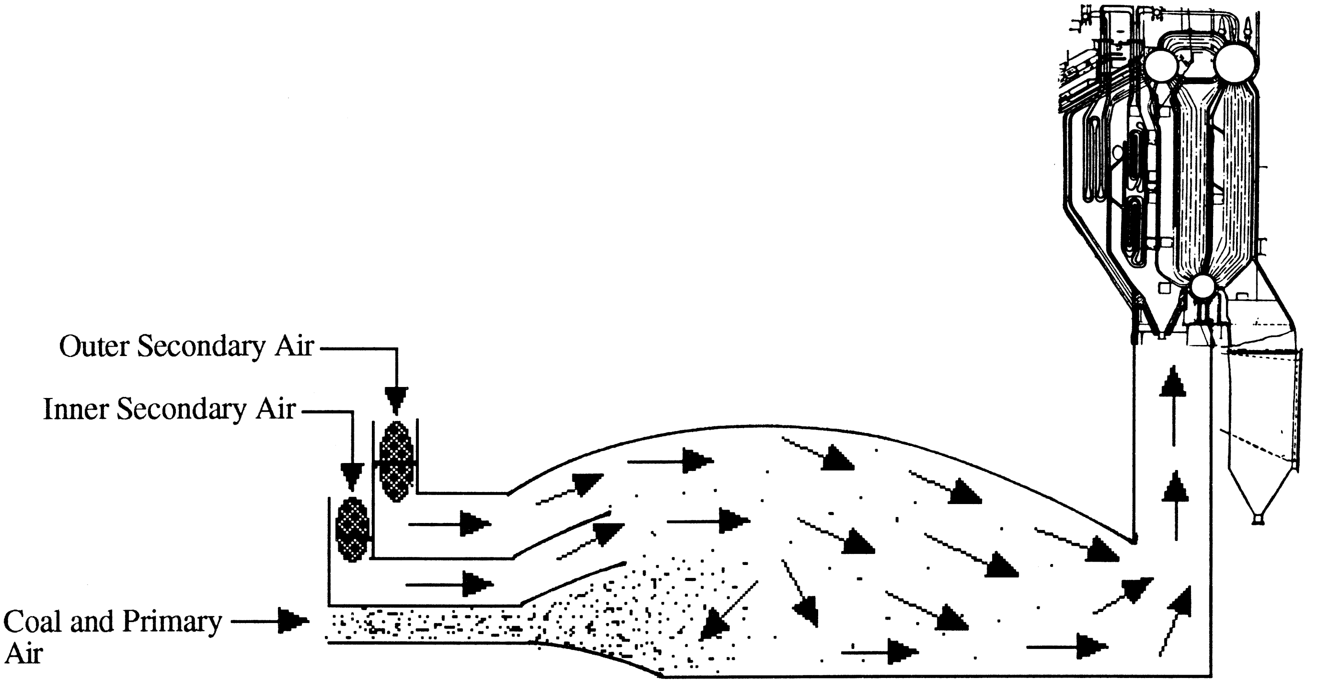


Fig. 13.

Finely divided solids such as coal or pyrites can be burned (or roasted) in a flash combustion chamber which operates as follows. The raw material is fed into a ball mill pulverizer, and the small particles are swept by air into the combustion chamber where they burn. A tangential gas take off duct from the chamber promotes swirling of the gas, and the layer of burnt particles of ash settle to the bottom of the chamber from which they can periodically be removed. The hot gases are cooled in a waste heat boiler where further fines settle out. The cooled gas goes to an SO_2 recovery system in the case of pyrites.

Step 5 Basis : P = 100 kg mol

Step 6 Let F be in kg, A and P in kg mol, Z be the kg mol of SO_2 absorbed in the lime solution, and Y be the moles of Fe_3O_4 in the cinder.

Steps 7 and 8

Element balances (in moles)

$$\text{S:}\quad (0.48/32)\ F = Z + 0.007\ (100) \qquad (1)$$

$$\text{N2}\quad 0.79\ A = 0.964\ (100) \qquad (2)$$

$$\text{O2}\quad 0.21\ A = Z + 100(0.007 + 0.029) + \begin{array}{c|c} Y\ \text{mol}\ Fe_3O_4 & 2\ \text{mol}\ O_2 \\ \hline & 1\ \text{mol}\ Fe_3O_4 \end{array} \qquad (3)$$

$$\text{Fe}\quad (0.43/56)\ F = \begin{array}{c|c} Y\ \text{mol}\ Fe_3O_4 & 3\ \text{mol Fe} \\ \hline & 1\ \text{mol}\ Fe_3O_4 \end{array} \qquad (4)$$

Step 9

From (2) A = 122 kg mol and from (4): 0.00256F = Y

Substitute Z from equation (1) and Y from equation (4) in terms of F into equation (3) to get

$$0.21\ A = (0.015\ F - 0.70) + 100\ (0.036) + (0.00256F)2$$

Solve for F **F = 1130 kg pyrites**

Z = 0.015 (1130) - 0.7 = 16.3 kg mol; Y = 2.90 kg mol

$$\frac{\text{kg air}}{\text{kg pyrites}} = \begin{array}{c|c} 122\ \text{kg mol air} & 29\ \text{kg air} \\ \hline 1130\ \text{kg pyrites} & \text{kg mol air} \end{array} = \mathbf{3.1}\ \frac{\textbf{kg air}}{\textbf{kg pyrites}}$$

Step 10

The flow rates can be checked by applying overall compound balances. The above were mol balances on the elements so the checks will be in moles also.

Accumulation = In - out + generation - consumption = 0

	In		*Out*		*Generation*		*Consumption*		*Accumulation*
FeS_2	[(0.91/120)1130]	–	0	+	0	–	[(0.91/120)1130]	=	0
O_2	0.21 (122)	–	2.9	+	0	–	(2.90) (8)	≈	0
N_2	0.79(122)	–	0.964 (100)	+	0	–	0	=	0
Fe_3O_4	0	–	2.9	+	2.9	–	0	=	0
SO_2	0	–	(16.3 + 0.7)	+	17.0	–	0	=	0

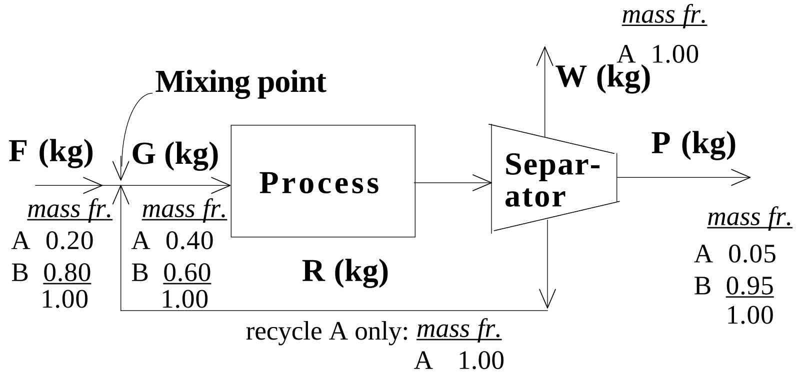
Problem 3.6 A

Based on the process drawn in the diagram, what is the kg recycle / kg feed if the amount of W waste is 100 kg ? The known compositions are inserted on the process diagram.

Solution

Steps 1, 2, 3 and 4

This is a steady state problem without reaction comprised of three subsystems, the process, the separator, and the mixing point.



Step 5 Basis : W = 100 kg

Step 6: The unknowns are F, R, P and G

Steps 7 and 8

We can make two component balances for the mixing point and two for the combined system of the process and separator, as well as overall balances. We start with overall balances as usual. Not all the balances are independent.

Overall balances

$$\begin{array}{llcll}
\text{Total} & F & = & P + 100 & (1)\\
\text{A} & 0.20\,F & = & 0.05\,P + 1.00\,(100) & (2)\\
\text{B} & 0.80\,F & = & 0.95\,P & (3)
\end{array}$$

Mixing point

$$\begin{array}{llcll}
\text{Total} & F + R & = & G & (4)\\
\text{A} & 0.20\,F + (1.00)\,R & = & 0.40\,G & (5)\\
\text{B} & 0.80\,F & = & 0.60\,G & (6)
\end{array}$$

Process + Separator

$$\begin{array}{llcll}
\text{Total} & G & = & P + W + R & (7)\\
\text{A} & 0.40\,G & = & 0.05\,P + (1.00)100 + (1.00)R & (8)\\
\text{B} & 0.60\,G & = & 0.95\,P & (9)
\end{array}$$

Step 9 We have many redundant equations. Overall, process plus separator, and mixing point balances have only 2 independent equations each, and of the 3 sets of equations only 2 sets form an independent equation set . Therefore we can chose a set of four independent equations by choosing two equations each from two sets.

Substitute (1) in (2) $0.20\,(P + 100) = 0.05\,P + 100$

$P = 533$ kg; $F = 633$ kg

Equation (6) $0.80\,(633) = 0.60\,G$

$G = 844$ kg

Equation (4) $633 + R = 844$ $\frac{R}{F} = \frac{211\ \text{kg}}{633\ \text{kg}} = \mathbf{0.33}\ \frac{\textbf{kg R}}{\textbf{kg F}}$

$R = 211$ kg

Step 10 Equations (7) and (8) can be used to verify the results.

Equation (7)

$$G = P + W + R$$
$$844 = 533 + 100 + 211$$
$$844\ \text{kg} = 844\ \text{kg}$$

Equation (8)

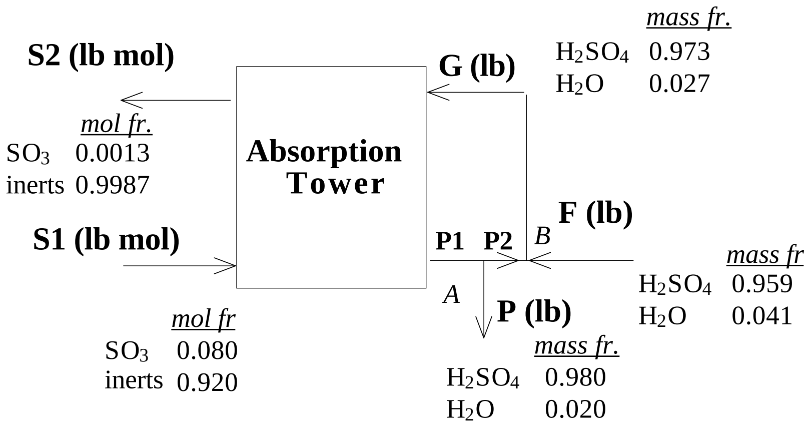
$$0.40\ G = 0.05\ P + W + R$$
$$0.40\ (844) = 0.05\ (533) + 100 + 211$$
$$338\ \text{kg} = 338\ \text{kg}$$

Problem 3.6 B

A contact sulfuric acid plant produces 98.0 % sulfuric acid, by absorbing SO_3 into a 97.3 % sulfuric acid solution. A gas containing 8.00 % SO_3 (remainder inerts) enters the SO_3 absorption tower at the rate of 28 lb mol per hour. 98.5 % of the SO_3 is absorbed in this tower. 97.3 % sulfuric acid is introduced into the top of the tower and 95.9 % sulfuric acid from another part of the process is used as make - up acid. The flow sheet is given in the figure with all of the known data on it.

Calculate the

a. Tons/day of 95.9 % H_2SO_4 make-up acid solution required.
b. Tons/day of 97.3 % H_2SO_4 solution introduced into the top of the tower.
c. Tons/day of 98 % H_2SO_4 solution produced.



Solution

Steps 1, 2, 3 and 4 This is a steady state process. The known data are in the figure. The reaction is

$$H_2O + SO_3 \text{ -----> } H_2SO_4$$

Calculate the SO_3 absorbed in the tower and the composition of S2.

Step 5 Basis : 100 mol S1

Step 4

$$\begin{array}{c|c} 0.08\ \text{mol } SO_3 & 100\ \text{mol S1} \\ \hline 1\ \text{mol S1} & \end{array} = 8\ \text{mol } SO_3$$

ABSORPTION

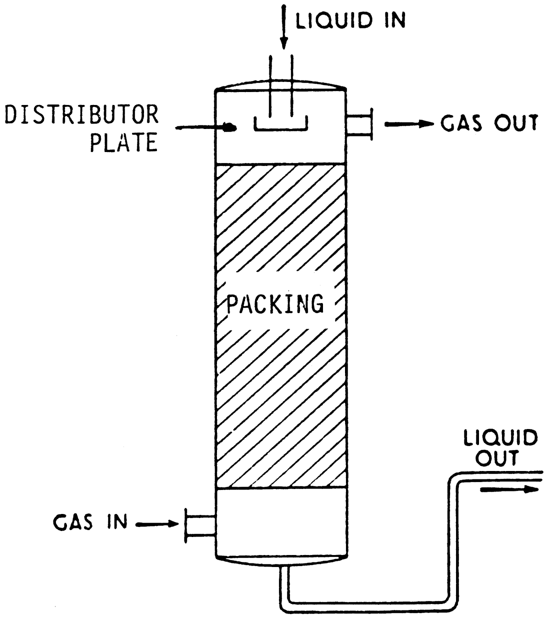


Fig. 14a. Packed column

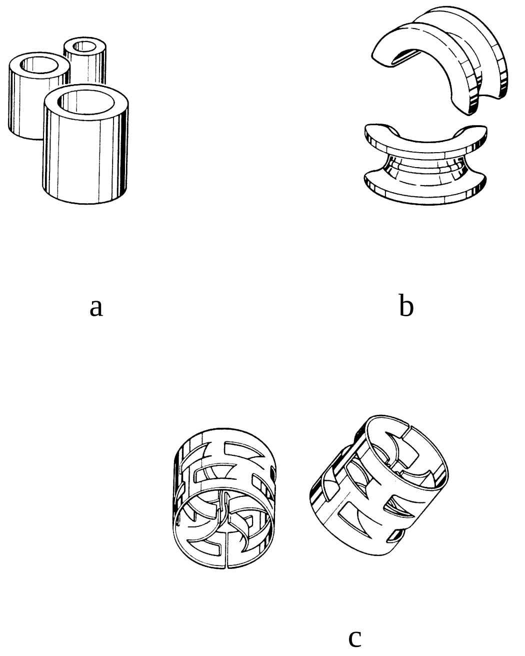


Fig. 14b. Various kinds of packing: (a) Raschig rings, (b) Intalox saddles, (c) Pall rings

In a packed column the liquid comes in at the top, or near the top, and enters the column via a series of nozzles or through a distributor plat. The gas enters below the packing and passes upward. Packing placed in the column is held in place by support plates.

In the manufacture of sulfuric acid, the SO_2 is first catalytically oxidized, to SO_3 which is then absorbed into a H_2SO_4–H_2O-SO_3 solution (absorption directly into H_2O is not feasible because a mist forms with SO_3 that cannot be absorbed). An absorption tower is usually composed of various kinds of packing, but sometimes trays are used as in a distillation column. For sulfuric acid manufacture the steel tower is lined with acid proof masonry, and chemical stoneware is used for the packing. A tower might be 7 or 8 m in diameter and absorb 1,000 tons per day of SO_3. Absorption towers are used to retrieve many other gases from the vapor phase into the liquid phase (not necessarily water).

SO_3 absorbed in the tower = 8 (0.985) = 7.88 mol (the overall absorption)
SO_3 in stream S2 = (8 - 7.88) = 0.12 mol

Inerts in stream S2 = inerts in stream S1 = 92 mol

Calculate the composition of stream S2 (in mole fraction):

$$SO_2 = \frac{0.12}{(92 + 0.12)} = 0.0013 \qquad \text{inerts} = \frac{92}{(92 + 0.12)} = 0.9987$$

Step 5 New Basis : S1 = 28 lb mol gas with 8 % SO_3 (equivalent to 1 hr).

Step 6 6 unknown variables : F, G, P, P1, P2, S2.

Steps 7 and 8

We can make component balances for the overall system, the tower, the mixing point, and the separation point. We will use component balances rather than element balances. Some balances as are in mass and others in moles.

For steady state systems : In - Out + Generated - Consumed = 0

Overall

$$H_2SO_4 : 0.959\ F - 0.980\ P + 28\ (0.08)\ (0.985) \frac{1 \text{ mol } H_2SO_4}{1 \text{ mol } SO_3} \left| \frac{98 \text{ lb } H_2SO_4}{1 \text{ lb mol } H_2SO_4} \right. - 0 = 0 \qquad (1)$$

$$SO_3 : \quad 28\ (0.08) - 28\ (0.08)\ (0.015) \quad + \quad 0 \quad - \quad 28\ (0.08)\ (0.985) \quad = 0 \qquad (2)$$

$$H_2O : \quad 0.041\ F - 0.020\ P + 0 - 28\ (0.08)\ (0.985) \frac{1 \text{ mol } H_2O}{1 \text{ mol } SO_3} \left| \frac{18 \text{ lb } H_2O}{1 \text{ lb mol } H_2O} \right. = 0 \qquad (3)$$

Mixing point B

Total : $F + P2 = G$ (4)
H_2SO_4 : $0.959\ F + 0.980\ P2 = 0.973\ G$ (5)
H_2O : $0.041\ F + 0.020\ P2 = 0.027\ G$ (6)

Separation point A

Total : $P1 = P2 + P$ (7)

Step 9

Equation (1): $0.959\ F - 0.980\ P + 216.22 = 0$ (8)
Equation (3): $0.041\ F - 0.020\ P - 39.72 = 0$ (9)

Solving (8) and (9) **F = 2060 lb** **P = 2240 lb**

Equation (4) : $2060 + P2 = G$ (10)
Equation (5) : $1975 + 0.980\ P2 = 0.973\ G$ (11)

Solving (10) and (11) **G = 6470 lb P2 = 4410 lb**

Step 10

Use equation (6) as a check: $0.041\ (2060) + 0.020\ (4410) \overset{?}{=} 0.027\ (6470)$
$84.4 + 88.2 \cong 175 \text{ lb}$
173 lb ≅ 175 lb

Problem 3.6 C

$TiCl_4$ can be formed by reacting titanium dioxide (TiO_2) with hydrochloric acid. TiO_2 is available as an ore containing 78 % TiO_2 and 22 % inerts. The HCl is available as 45 wt% solution (the balance is water). The per pass conversion of TiO_2 is 75 %. The HCl is fed into the reactor in 20 % excess based on the reaction. Pure unreacted TiO_2 is recycled back to mix with the TiO_2 feed.

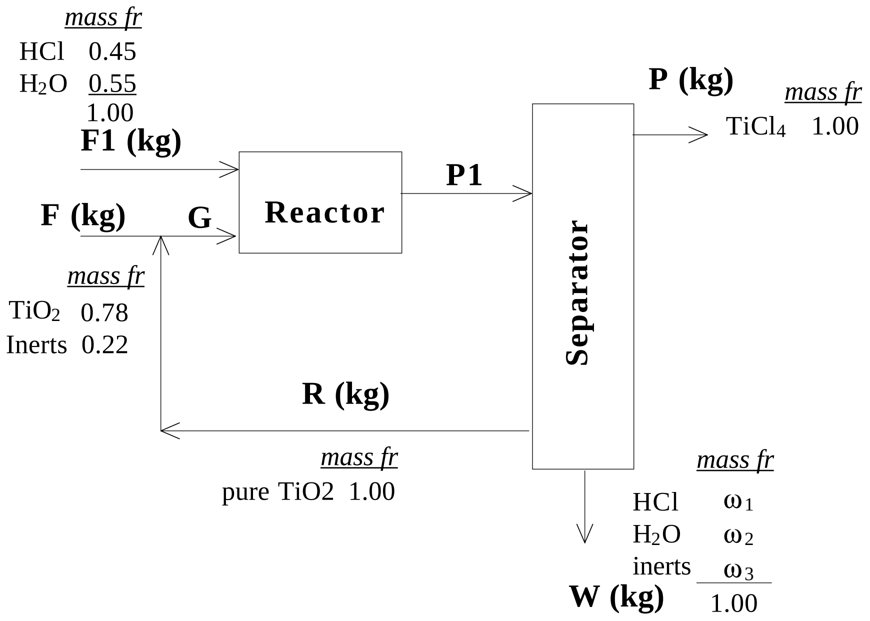
$$TiO_2 + 4\,HCl \;\text{----->}\; TiCl_4 + 2H_2O$$

For 1 kg of $TiCl_4$ produced, determine:

a. the kg of TiO_2 ore fed.
b. the kg of 45 wt % HCl solution fed.
c. the ratio of recycle stream to fresh TiO_2 ore (in kg).
(MW : TiO_2 79.9; HCl 36.47; $TiCl_4$ 189.7)

Solution

Steps 1, 2, 3 and 4 The known data have been inserted into the figure. This is a steady state problem with reaction and recycle.



TiO_2 mass. fr.	
Ti	0.599
O	0.401

HCl mass fr.	
H	0.0274
Cl	0.9726

$TiCl_4$ mass fr.	
Ti	0.252
Cl	0.748

Step 5 Though P could be selected as the basis, it is equally valid and easier to choose F = 100 kg because F1 can then be calculated immediately.

SLURRY REACTOR

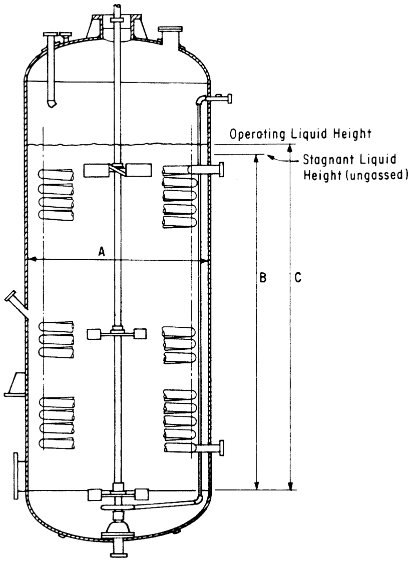


Fig. 15. Slurry reactor (*courtesy of Howard Rase*)

In a reaction between a liquid and the solids, the solids have to be agitated and distributed throughout the liquid either by agitators or by gas bubbles to avoid settling of the solids. Prior to entering the reactor the solids have to be milled to a suitable size so that good contact with the liquid reactants is maintained, but not so fine that it is difficult to remove unreacted solids from the liquid phase in the separator.

SOLID-LIQUID-VAPOR SEPARATORS

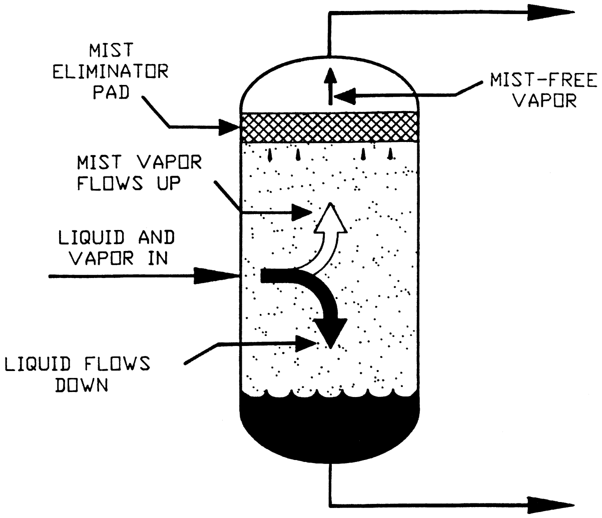


Fig. 16a. A typical vapor-liquid separator

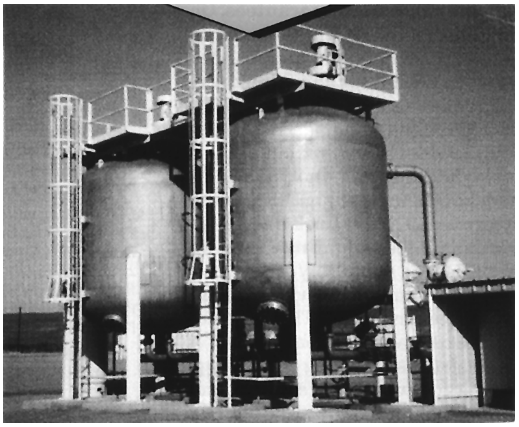


Fig. 16b. Flotation separators remove emulsified oil and suspended solids (*courtesy of EIMCO Process Equipment Co.*)

Fig. 16c. Liquid-vapor separator via centrifugal flow (*courtesy of Wright Austin Co.*)

Separators are used to segregate solids from liquids and gases, and gases from liquids. Examples for gas-solid separation are cyclones, dust collectors, electric precipitators, rotary sprayer scrubbers, and wet separators. The entrainment of liquid drops in evaporators, crystallizers, distillation columns, and other mass transfer equipment can be a serious problem. Drops and mist are eliminated by cyclone separators or by coalescing drops by impingement with baffles or wire mesh pads. Solid-liquid separation is most economical by use of gravity settling or a centrifuge, but finely divided solids can be removed by floatation or filtration. Liquid-gas separation takes place in equipment such as shown in Fig 16a. Mixtures in a single liquid or gas phase are separated by distillation, absorption, adsorption, and membranes.

Step 4 Calculate F1

$$\begin{array}{c|c|c|c|c} 1.00\ \text{kg F} & 0.78\ \text{kg TiO}_2 & 1\ \text{kg mol TiO}_2 & 4\ \text{kg mol HCl} & 1.20 \\ \hline & 1\ \text{kg F} & 79.9\ \text{kg TiO}_2 & 1\ \text{kg mol TiO}_2 & \end{array}$$

$$\times \begin{array}{c|c} 36.47\ \text{kg HCl} & 1\ \text{kg F1} \\ \hline 1\ \text{kg mol HCl} & 0.45\ \text{kg HCl} \end{array} = \text{F1} = 3.80\ \text{kg}$$

System: Let the system be all of the units and mixing points jointly.

Step 6: The unknowns are: P, m^{W}_{HCl} (or ω_1), $m^{W}_{H_2O}$ (or ω_2), m^{W}_{inerts} (or ω_3), and W.

Step 7 The element balances are Ti, O, H, Cl, and also $\sum m_i = W\left(\text{or} \sum \omega_i = 1\right)$ and the inerts balance. If 5 of these are independent, we can solve for the variables whose values are unknown.

Steps 8 and 9 The balances are in kg. The simplest balances to start with are those involving tie components. If selected properly, the equations can be solved sequentially rather than simultaneously.

Ti: $(0.78)\ (1.00)\ (0.599) = (1.00)\ (P)\ (0.252)$

P = 1.85 kg (this value would be sufficient to calculate the answers to parts a and b)

Total: $1.00 + 3.80 = P + W = 1.85 + W$

$$W = 2.94\ \text{kg}$$

O: $$\begin{array}{c|c} (3.80)(0.55) & 16 \\ \hline & 18 \end{array} + (1.00)\ (0.78)\ (0.401) = \begin{array}{c|c} (2.94)(\omega_2) & 16 \\ \hline & 18 \end{array}$$

$$\omega_2 = 0.83$$

Cl: $$\begin{array}{c|c} (3.80)(0.45) & 35.45 \\ \hline & 36.47 \end{array} = \begin{array}{c|c|c|c} 1.85 & & 4 & 35.45 \\ \hline & 189.7 & & 1 \end{array} + \begin{array}{c|c} 2.94\ (\omega_1) & 35.45 \\ \hline 1 & 36.47 \end{array}$$

$$\omega_1 = 0.096$$

Inerts: $\omega_3 = 0.22\ (1.00)/(2.94) = 0.075$

Step 10 As a check, $\Sigma\omega_i = 0.096 + 0.83 + 0.075 = 1.00$

a. $\dfrac{\text{kg F}}{\text{kg P}} = \dfrac{1.00}{1.854} = \mathbf{0.54}\ \dfrac{\mathbf{kg}}{\mathbf{kg}}$

b. $\dfrac{\text{kg F1}}{\text{kg P}} = \dfrac{3.798}{1.854} = \mathbf{2.05}\ \dfrac{\mathbf{kg}}{\mathbf{kg}}$

} These values can be calculated solely from the data given and the Ti balance.

To calculate the third part of the problem, we need to involve the recycle stream in the balances. Let the system be the mixing point. No reaction occurs. The balances are in kg.

Steps 6, 7, 8, and 9

$$\begin{aligned} &\text{Total:} && 100 + R = G \\ &\text{TiO}_2\text{:} && 100\,(0.78) + R\,(1.00) = m^G_{\text{TiO}_2} \\ &\text{Inerts:} && 100\,(0.22) = m^G_{\text{inerts}} \end{aligned}$$

Next use the system of reactor plus separator.

$$\text{Total} \quad G + 3.80 = 1.85 + 2.94 + R$$

The component balances will not add any independent equations, hence the information about the fraction conversion must be used via a compound balance on TiO_2:

$$\text{TiO}_2\text{:} \quad \overset{\textit{In}}{\overline{100(0.78) + R(1.00)}} - \overset{\textit{Out}}{\overline{R(1.00)}} + \overset{\textit{Generation}}{\overline{0}} - \overset{\textit{Consumption}}{\overline{0.75[100(0.78) + R] = 0}}$$

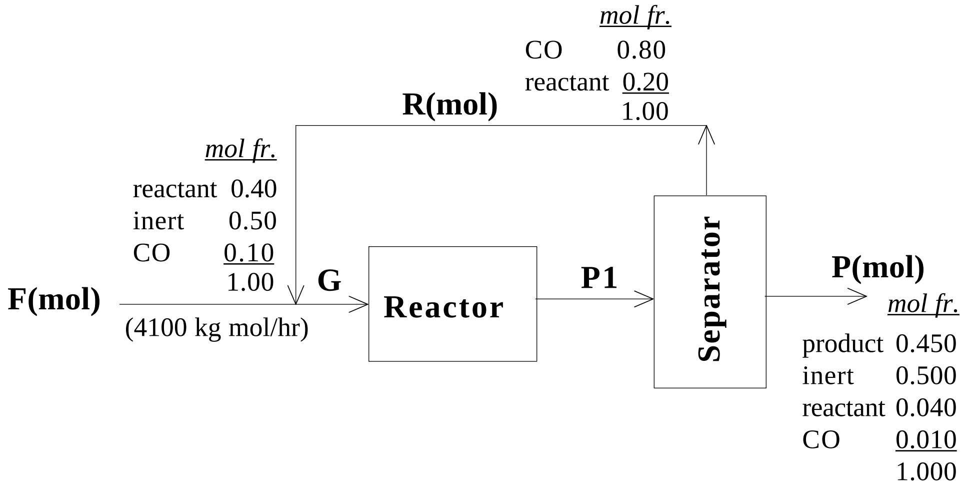
$$R = 26\ \text{kg}$$

c.

$$\frac{\text{kg R}}{\text{kg F}} = \frac{26}{100} = \mathbf{0.26}$$

Problem 3.6 D

Many chemicals generate emissions of volatile compounds that need to be controlled. In the process shown in the accompanying figure, the CO in the exhaust is substantially reduced by separating it from the reactor effluent and recycling the unreacted CO together with the reactant. Although the product is proprietary, information is provided that the fresh feed stream contains 40 % reactant, 50 % inert and 10 % CO, and that on reaction 2 moles of reactant yield 2.5 moles of product. Conversion of the reactant to product is 73 % on one pass through the reactor, and 90 % for the over all process. The recycle stream contains 80% CO and 20% reactant. Calculate the ratio of moles of the recycle stream to moles of the product stream.



Solution

Steps 1, 2, 3 and 4 This is a steady state process with reaction and recycle. The data has been placed in the figure. (The components in P have to be calculated first.) The initial system is the overall process.

Step 5 Basis : 4100 kg mol F

Step 6 Unknowns : P and its components

Calculate the composition of stream P

Product

4100 kg mol F	40 mol reactant	90 mol react	2.5 mol product
	100 mol F	100 mol reactant	2 mol reactant

= 1845 kg mol product

Inert

4100 kg mol F	50 mol inert	= 2050 kg mol inert
	100 mol F	

Reactant

4100 kg mol F	40 mol reactant	0.10 mol unreacted	= 164 kg mol reactant
	100 mol F	1.0 mol reactant	

CO

4100 kg mol F	10 mol CO	0.10 mol unreacted CO	= 41 kg mol CO
	100 mol F	1.0 mol CO	

$$P = 1845 + 2050 + 164 + 41 = 4100 \text{ kg mol}$$

Use of the inerts as a tie component verifies this value.

Steps 7, 8 and 9 The next step is to calculate the recycle stream by picking a system involving the recycle stream. To avoid calculations involving P1, select first the mixing point as the system and then a system composed of the reactor plus the separator.

Mixing point

No reaction occurs so that a total balance is satisfactory: $G = 4100 + R$

Reactor plus separator

Because a reaction occurs, an overall balance is not appropriate, but a reactant balance (a compound balance) is.

Reactant:

$$\overset{\textit{In}}{0.40(4100) + 0.20R} - \overset{\textit{Out}}{(0.20R + 0.040(4100))} + \overset{\textit{Gen.}}{0} - \overset{\textit{Consumption}}{0.73[0.40(4100) + 0.20R]} = \overset{\textit{Accum.}}{0}$$

$$\mathbf{R = 6460 \text{ kg mol}}$$

$$\frac{\mathbf{R}}{\mathbf{P}} = \frac{\mathbf{6460}}{\mathbf{4100}} = \mathbf{1.58}$$

$$\frac{\textbf{mol recycle}}{\textbf{mol product}} = \frac{\mathbf{6460}}{\mathbf{1845}} = \mathbf{3.5}$$

Problem 3.6 E

Perchloric acid ($HClO_4$) can be prepared as shown in the diagram below from $Ba(ClO_4)_2$ and $HClO_4$. Sulfuric acid is supplied in 20% excess to react with $Ba(ClO_4)_2$. If 17,400 lb $HClO_4$ leave the separator and the recycle is 6125 lb $Ba(ClO_4)_2$ over the time period, calculate :

a. The overall conversion of $Ba(ClO_4)_2$.
b. The lb of $HClO_4$ leaving the separator per lb of feed.
c. The lb of H_2SO_4 entering the reactor.
d. The per pass conversion of $Ba(ClO_4)_2$.

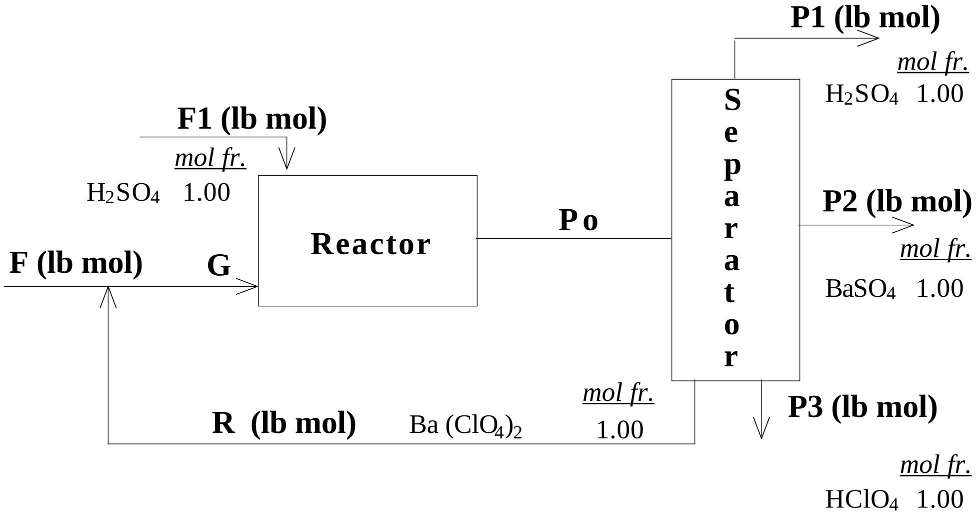
Note : 20 % H_2SO_4 is based on the total $Ba(ClO_4)_2$ entering the reactor.

$$Ba(ClO_4)_2 \quad + \quad H_2SO_4 \quad \text{------>} \quad BaSO_4 \quad + \quad 2HClO_4$$

MW: $Ba(ClO_4)_2$ 336; $BaSO_4$ 233; H_2SO_4 98; $HClO_4$ 100.5

Solution

This is a steady state problem with reaction and recycle.



Composition of feed F (given):

	mass fr.	*M W*	*mol fr*
$Ba(ClO_4)_2$	0.90	336	0.729
$HClO_4$	0.10	100.5	0.271

Steps 1, 2, 3 and 4 All the known data have been placed in the figure. All flows calculated below are in lb mol.

$$\frac{17400 \text{ lb } HClO_4}{} \left| \frac{1 \text{ lb mol } HClO_4}{100.5 \text{ lb } HClO_4} \right. = 173.1 \text{ lb mol } HClO_4$$

$$\frac{6125 \text{ lb } Ba(ClO_4)_2}{} \left| \frac{1 \text{ lb mol } Ba(ClO_4)_2}{336 \text{ lb } Ba(ClO_4)_2} \right. = 18.23 \text{ lb mol } Ba(ClO_4)_2$$

Step 5 This is a steady state process with reaction. Some thought must be given as to the system to pick and the basis to use. No obvious basis appears and since we usually make overall balances first, we will pick P3 = 17,400 lb as the basis equivalent to 17,400/100.5 = 173.13 lb mol.

Step 6 The unknown are: F, F1, P1, and P2.

Step 7 We can make 5 element balances: Ba, Cl, O, H, S, hence if 4 balances are independent, a unique solution exists.

a The overall percent conversion of $Ba(ClO_4)_2$ is **100%** since no $Ba(ClO_4)_2$ leaves the overall system.

Overall element balances (lb mol)

$$\text{Cl:}\quad \frac{\text{F lb mol}}{}\left|\frac{0.729\text{ lb mol Ba(ClO}_4)_2}{1\text{ lb mol F}}\right|\frac{2\text{ lb mol Cl}}{1\text{ lb mol Ba(ClO}_4)_2}$$

$$+\ \frac{\text{F lb mol}}{}\left|\frac{0.271\text{ lb mol HClO}_4}{1\text{ lb mol F}}\right|\frac{1\text{ lb mol Cl}}{1\text{ lb mol HClO}_4}$$

$$=\ \frac{173.13\text{ lb mol P3}}{}\left|\frac{1\text{ lb mol HClO}_4}{1\text{ lb mol P3}}\right|\frac{1\text{ lb mol Cl}}{1\text{ lb mol HClO}_4}$$

$$F = 100.1\text{ lb mol}$$

$$\text{Ba:}\quad \frac{(100.1)\text{ lb mol}}{}\left|\frac{0.729\text{ lb mol Ba(ClO}_4)_2}{1\text{ lb mol F}}\right|\frac{1\text{ lb mol Ba}}{1\text{ lb mol Ba(ClO}_4)_2}$$

$$=\ \frac{\text{P2 lb mol}}{}\left|\frac{1\text{ lb mol Ba}}{1\text{ lb mol P2}}\right.$$

$$P2 = 73.0\text{ lb mol}$$

$$\text{S:}\quad \frac{\text{F1 lb mol}}{}\left|\frac{1\text{ lb mol H}_2\text{SO}_4}{1\text{ lb mol F1}}\right|\frac{1\text{ lb mol S}}{1\text{ lb mol H}_2\text{SO}_4}$$

$$=\ \frac{\text{P1 lb mol}}{}\left|\frac{1\text{ lb mol S}}{1\text{ lb mol P1}}\right. +\ \frac{73.0\text{ lb mol BaSO}_4}{}\left|\frac{1\text{ lb mol S}}{1\text{ lb mol BaSO}_4}\right.$$

The H and O balances are not independent balances from what we have so far. We need one more equation.

Mixing point

$$\text{Total:}\ \ 100.1 + \frac{6125}{336} = G = 118.3\text{ lb mol}$$

Now we can calculate F1 as 1.2 times the $Ba(ClO_4)_2$ in G. The number of moles of $Ba(ClO_4)_2$ in G is

$$Ba(ClO_4)_2\text{:}\qquad 100.1\ (0.729) + \frac{6125}{336} = 91.2$$

$$1.2\ (91.2) = \mathbf{109\ lb\ mol = F1}$$

b.
$$\frac{\text{lb HClO}_4}{\text{lb F}} = \frac{17400 \text{ lb HClO}_4 \text{ exiting}}{100.1(0.729)(336) + 100.1(0.271)(100.5)} = \mathbf{0.64\ \frac{lb\ HClO_4}{lb\ F}}$$

c. F1 = 109 lb mol or **10,700 lb $\mathbf{H_2SO_4}$**

To get the fraction conversion f on one pass through the reactor, we make a compound balance for $Ba(ClO4)_2$ for the system of the reactor plus the separator.

Accum.		*In*		*Out*		*Generation*	*Consumption*
0	=	91.2	–	$\frac{6125}{336}$	+	0	–f(91.2)

f = 0.80

CHAPTER 3 – ADDITIONAL PROBLEMS
(Answers will be found in Appendix A)

Section 3.1

3.1A State whether the following processes represent open or closed systems.

(a) The global carbon cycle of the earth.
(b) The carbon cycle for a forest.
(c) An outboard motor for a boat.
(d) Your home air conditioner with respect to the coolant.

3.1B Give an example of:

(a) An unsteady state process
(b) A steady state process

Draw a picture or explain the process in not more than three sentences. Any type of process you can think of will be acceptable—a chemical engineering process is not required.

Section 3.2

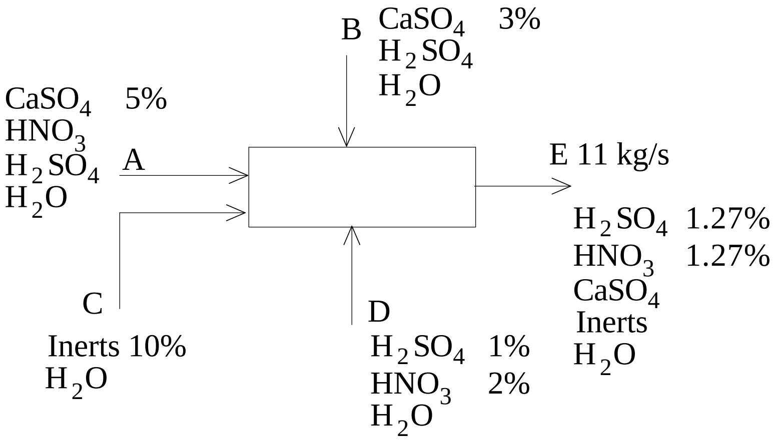
3.2A Determine the rank of the following matrix .

$$\begin{bmatrix} 1 & 0 & 2 \\ 3 & 0 & 4 \\ 2 & -5 & 1 \end{bmatrix}$$

3.2B Do the following set of equations have a unique solution?

$$\begin{aligned} x_1 + x_2 + x_3 &= 4 \\ 2x_1 + 5x_2 - 2x_3 &= 3 \\ x_1 + 7x_2 - 7x_3 &= 5 \end{aligned}$$

3.2C Effluent from a fertiler plant is processed by the system shown in the figure. How many additional concentration and stream flow measurements must be made to completely specify the problem (so that a unique solution exists).



Does only 1 unique set of specifications exist?

Section 3.3

3.3A Paper pulp is sold on the basis that it contains 12 percent moisture; if the moisture exceeds this value, the purchaser can deduct any charges for the excess moisture and also deduct for the freight costs of the excess moisture. A shipment of pulp became wet and was received with a moisture content of 22 percent. If the original price for the pulp was $40/ton of air-dry pulp and if the freight is $1.00/100 lb shipped, what price should be paid per ton of pulp delivered?

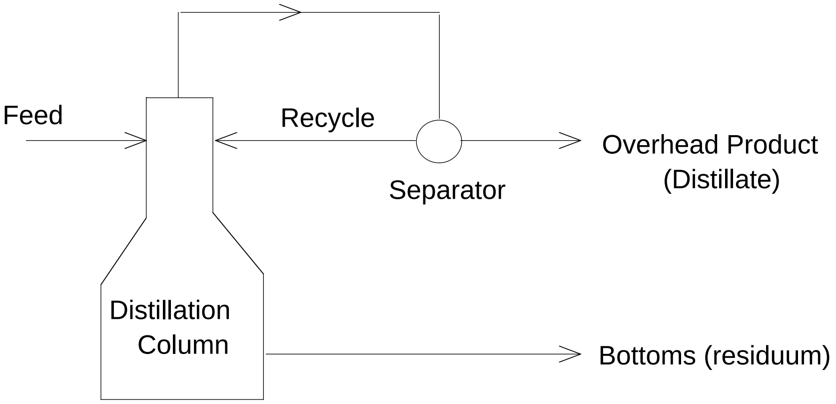
3.3B If 100g of Na_2SO_4 is dissolved in 200g of H_2O and the solution is cooled until 100 g of $Na_2SO_4 \cdot 10H_2O$ crystallizes out, find

(a) The composition of the remaining solution (mother liquor).
(b) The grams of crystals recovered per 100 g of initial solution.

3.3C The feed to a distillation column is separated into net overhead product containing nothing with a boiling point higher than isobutane and bottoms containing nothing with a boiling point below that of propane. See Fig. P3.3C. The composition of the feed is

	mole %
Ethylene	2.0
Ethane	3.0
Propylene	5.0
Propane	15.0
Isobutane	25.0
n-Butane	35.0
n-Pentane	15.0
Total	100.0

The concentration of isobutane in the overhead is 5.0 mole percent, and the concentration of propane in the bottoms is 0.8 mole percent. Calculate the composition of the overhead and bottoms streams per 100 moles of feed.



Hint: In the overhead there is no nC_5H_{12} or nC_4H_{10}, and in the bottoms there in no C_2H_4, C_2H_6, or C_3H_6.

Section 3.4

3.4A A synthesis gas analyzing CO_2, 4.5 percent; CO, 26 percent; H_2, 13 percent; CH_4, 0.5 percent; and N_2, 56 percent, is burned in a furnace with 10 percent excess air. Calculate the Orsat analysis of the flue gas.

3.4B Solvents emitted from industrial operations can become significant pollutants if not disposed of properly. A chromatographic study of the waste exhaust gas from a synthetic fiber plant has the following analysis in mole percent:

CS_2	40%
SO_2	10
H_2O	50

It has been suggested that the gas be disposed of by burning with an excess of air. The gaseous combustion products are then emitted to the air through a smokestack. The local air pollution regulations say that no stack gas is to analyze more than 2 percent SO_2 by an Orsat analysis averaged over a 24-hr period. Calculate the minimum percent excess air that must be used to stay within this regulation.

3.4C A low-grade pyrites containing 32 percent S is mixed with 10 kg of pure sulfur per 100 kg of pyrites so the mixture will burn readily, forming a burner gas that analyzes (Orsat) SO_2, 13.4 percent; O_2. 2.7 percent; and N_2, 83.9 percent. No sulfur is left in the cinder. Calculate the percentage of the sulfur fired that burned to SO_3. (The SO_3 is not detected by the Orsat analysis.)

Section 3.5

3.5A A natural gas analyzes CH_4, 80.0 percent and N_2, 20.0 percent. It is burned under a boiler and most of the CO_2 is scrubbed out of the flue gas for the production of dry ice. The exit gas from the scrubber analyzes CO_2, 1.2 percent; O_2, 4.9 percent; and N_2, 93.9 percent. Calculate the

(a) Percentage of the CO_2 absorbed.
(b) Percent excess air used.

3.5B A solvent dewaxing unit in an oil refinery is separating 3000 bbl/day of a lubricating distillate into 23 vol percent of slack wax and 77 vol percent of dewaxed oil. The charge is mixed with solvent, chilled, and filtered into wax and oil solution streams. The solvent is then removed from the two streams by two banks of stripping columns, the bottoms from each column in a bank being charged to the next column in the bank. The oil bank consists of four columns, and the wax bank of three. A test on the charge and bottoms from each column gave the following results:

	percent solvent by volume				
	to 1st column	*no. 1 bottoms*	*no. 2 bottoms*	*no. 3 bottoms*	*no. 4 bottoms*
Pressed oil	83	70	27	4.0	0.8
Wax	83	71	23	0.5	—

Calculate the following:

(a) Total solution per day charged to the whole unit.
(b) Percentage of total solvent in oil solution removed by each column in oil bank.
(c) Percentage of total solvent in wax solution removed by each column in wax bank.
(b) Barrels of solvent lost per day (in bottoms from last column of each bank).

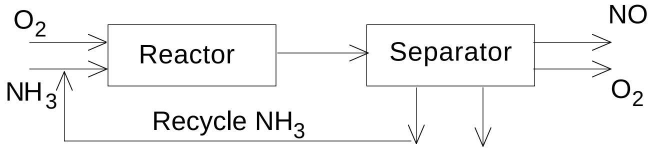
Section 3.6

3.6A In an attempt to provide a means of generating NO cheaply, gaseous NH_3 is burned with 20 per cent excess O_2:

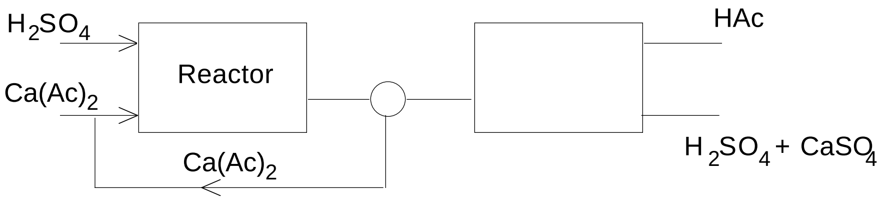
$$4NH_3 + 5O_2 \longrightarrow 4NO + 6H_2O$$

The reaction is 70 percent complete. The NO is separated from the unreacted NH_3, and the latter recycled as shown Fig. P3.6A. Compute the

(a) Moles of NO formed per 100 moles of NH_3 fed.
(b) Moles of NH_3 recycled per mole of NO formed.

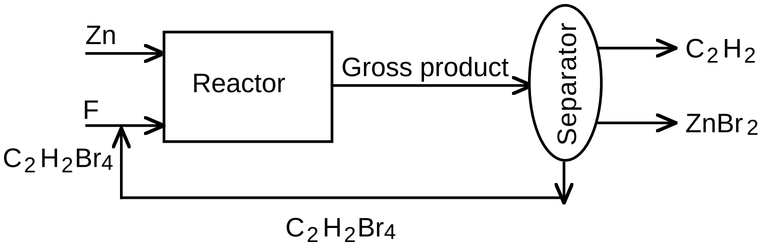


3.6B Acetic acid is to be generated by the addition of 10 percent excess sulfuric acid to calcium acetate. The reaction $Ca(AC)_2 + H_2SO_4 \longrightarrow CaSO_4 + 2HAc$ goes on with 90 percent completion. The unused $Ca(Ac)_2$ and the H_2SO_4 are separated from the products of the reaction, and the excess $Ca(Ac)_2$ is recycled. The acetic acid is separated from the products. Find the amount of recycle per hour based on 1000 lb of feed per hour, and also the pounds of acetic acid manufactured per hour. See Fig. P3.6B.



3.6C The reaction of ethyl-tetrabromide with zinc dust proceeds as shown in the diagram below. The reaction is

$$C_2H_2Br_4 + 2\ Zn \longrightarrow C_2H_2 + 2\ ZnBr_2$$



Based on the $C_2H_2Br_4$, on one pass through the reactor the conversion is 80%, and the unreacted $C_2H_2Br_4$ is recycled. On the basis of l000 kg of $C_2H_2Br_4$ fed to the reactor per hour, calculate

(1) how much C_2H_2 is produced per hour (in lb);
(2) the rate of recycle in lb/hr;
(3) the amount of Zn that has to be added per hour if Zn is to be 20% in excess;
(4) the mole ratio of $ZnBr_2$ to C_2H_2 in the products.

Problem 4.1A

A steel tank having a capacity of 25 m^3 holds carbon dioxide at 30˚C and 1.6 atm. Calculate the weight, in grams, of the carbon dioxide.

Solution

$$T = 30^\circ C = 30 + 273.15 = 303K$$

$$p = 1.6 \text{ atm}$$

$$V = 25 \text{ m}^3$$

Use pV = nRT

The gas constant has to be chosen to be consistent with the units of pressure, temperature, and volume. Use standard conditions to calculate R

$$R = \frac{1.00 \text{ atm}}{} \left| \frac{22.415\text{m}^3}{\text{kg mol}} \right| \frac{}{273.15\text{K}} = 0.08206 \frac{(\text{atm})(\text{m}^3)}{(\text{kg mol})(\text{k})}$$

$$n = \frac{(p)(V)}{(R)(T)} = \frac{(1.6)(25)}{(0.08206)(303)} = 1.608 \text{ kg mol or } 1{,}608 \text{ g mol}$$

$$\text{Weight of carbon dioxide} = \frac{1{,}608 \text{ g mol}}{} \left| \frac{44 \text{ g CO}_2}{\text{g mol CO}_2} \right. = \mathbf{70.7 \times 10^3 \text{ g CO}_2}$$

Alternate Solution:

Use V = 22.415 m^3/kg mol at T = 273K and p = 1 atm abs.

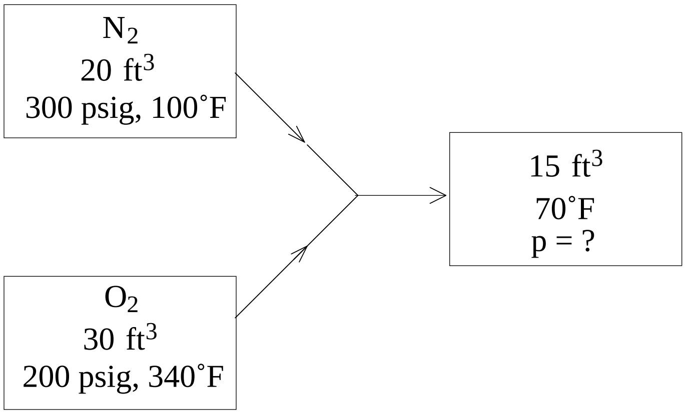
$$\text{and } \left(\frac{p_2}{p_1}\right)\left(\frac{V_2}{V_1}\right) = \left(\frac{n_2}{n_1}\right)\left(\frac{T_2}{T_1}\right)$$

$$\frac{25 \text{ m}^3}{} \left| \frac{1.6 \text{ atm abs}}{1 \text{ atm abs}} \right| \frac{273\text{K}}{303\text{K}} \left| \frac{1 \text{ kg mol}}{22.415 \text{ m}^3} \right| \frac{44 \text{ kg CO}_2}{1 \text{ kg mol CO}_2} \left| \frac{1000 \text{ g}}{1 \text{ kg}} \right. = 70.7 \times 10^3 \text{ g CO}_2$$

Problem 4.1B

20 ft^3 of nitrogen at 300 psig and 100˚F and 30 ft^3 of oxygen at 200 psig and340˚F are injected into a 15 ft^3 vessel. The vessel is then cooled to 70˚F. Find the partial pressure of each component in the 15 ft^3 vessel. Assume that the ideal gas law applies.

Solution



The problem can be solved by determining the number of moles of oxygen and nitrogen and solving for the total pressure at the final conditions. Then the partial pressures are calculated using the mole fractions.

Nitrogen	*Oxygen*
$V = 20\ ft^3$	$V = 30\ ft^3$
p = 300 psig = 314.7 psia	p = 200 psig = 214.7 psia
T = 100˚F = 560˚R	T = 340˚F = 800˚R
$n_{N_2} = \frac{pV}{RT} = \frac{(314.7)(20)}{(10.73)(560)} = 1.05 \text{ lb mol}$	$n_{O_2} = \frac{(214.7)(30)}{(10.73)(800)} = 0.75 \text{ lb mol}$

$$n_T = n_{N_2} + n_{O_2} = 1.80 \text{ lb mol}$$

Final pressure $p_T = \frac{n_T RT}{V} = \frac{(1.80)(10.73)(530)}{15} = 682 \text{ psia}$

	moles	*mole fr*(y_i)	$p_i = p_T(y_i)$
O_2	0.75	0.42	**286**
N_2	1.05	0.58	**396**
	1.80	1.00	682 *psia*

Problem 4.1C

A steel container has a volume of 200 m^3. It is filled with nitrogen at 22˚C and atmospheric pressure. If the container valve is opened and the container heated to 200˚C, calculate the fraction of the nitrogen which leaves the container.

Solution

The solution involves determining the number of moles of nitrogen in the tank at the final given temperature and pressure (T_2 and p_2), and at the initial conditions, and subtracting.

$T_1 = 22^\circ C = 295K$	$T_2 = 200^\circ C = 473K$
$p_1 = 1$ atm	$p_2 = 1$ atm
$V_1 = 200\ m^3$	$V_2 = 200\ m^3$
$n_1 = \frac{p_1V_1}{RT_1}$	$n_2 = \frac{p_2V_2}{RT_2}$
$n_1 = \frac{(1)(200)}{(0.08206)(295)}$	$n_2 = \frac{(1)(200)}{(0.08206)(473)}$
= 8.26 kg mol	= 5.15 kg mol

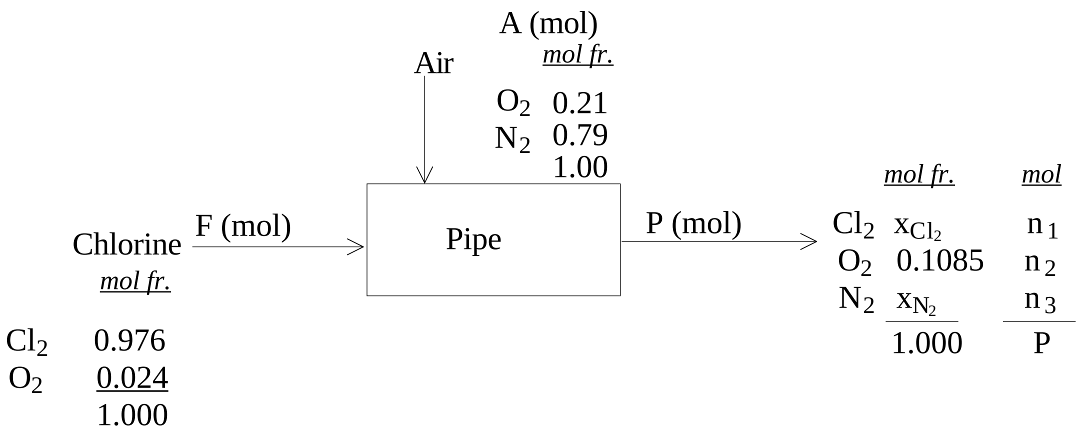
The fraction of N_2 leaving = $\frac{8.26 - 5.15}{5.15}$ = **0.60**

Problem 4.1D

Chlorine gas containing 2.4 percent O_2 is flowing through an earthenware pipe. The gas flow rate is measured by introducing air into it at the rate of 115 m^3/min. Further down the line, after mixing is complete, the gas is found to contain 10.85 percent O_2. How many m^3 of the initial gas were flowing per minute through the pipe?

Solution

The problem is similar to other nonreacting material balance problems. It is convenient to imagine the pipeline between the point of injection of air to the point of sampling as a mixer. The process may be considered to be a steady state process without reaction.



Step 5 We could use F = 100 mol as the basis instead of the given flowrate. All flow rates can be then be converted to the basis of 1 minute at the end of the problem. However, it is easier to use the given flow rate in m^3 assuming that the temperature and pressure are the same for all streams so that moles are proportional to m^3 in each stream.

$$A = 115 \text{ m}^3$$

Step 6 Let x_{Cl_2} and x_{N_2} be the respective mole fractions in P.
The unknowns are: F, P, x_{Cl_2} , and x_{N_2} (or n_1 and n_3).

Step 7 The balances are: Cl_2, O_2, N_2, and $\Sigma x_i = 1$ (or $\Sigma n_i = P$) so the problem has a unique solution.

Step 8	Total	$F + 115 = P$	(1)
	Oxygen Balance	$0.024F + 0.21(115) = 0.1085\ P$	(2)
	Chlorine Balance	$0.976F = x_{Cl_2}\ (P)$	(3)
	Nitrogen Balance	$0.79(115) = x_{N_2}P$	(4)
	$\Sigma x_i = 1.000$	$0.1085 + x_{Cl_2} + x_{N_2} = 1.000$	(5)

Steps 8 and 9

Only 4 of the balances are independent. Substitute the total balance for one component balance and solve (1) and (2) together to get

$$P = 253 \text{ m}^3 \text{ at T and p}$$

$$V_{in} = \mathbf{138\ m^3} \text{ at T and p}$$

Step 10 Use Σx_i as a check

from (4) $x^P_{N_2} = 0.79(115)/253 = 0.359$

from (3)&(1) $x^P_{Cl_2} = (0.976)(138)/253 = 0.532$

from (5) $0.359 + 0.532 + 0.1085 = 1.00$

Problem 4.1E

A synthetic gas generated from coal has the following composition: CO_2, 7.2%; CO, 24.3%; H_2, 14.1%; CH_4, 3.5%; N_2, 50.9%.

(a) Calculate the cubic feet of air necessary for complete combustion per cubic foot of synthetic gas at the same conditions.

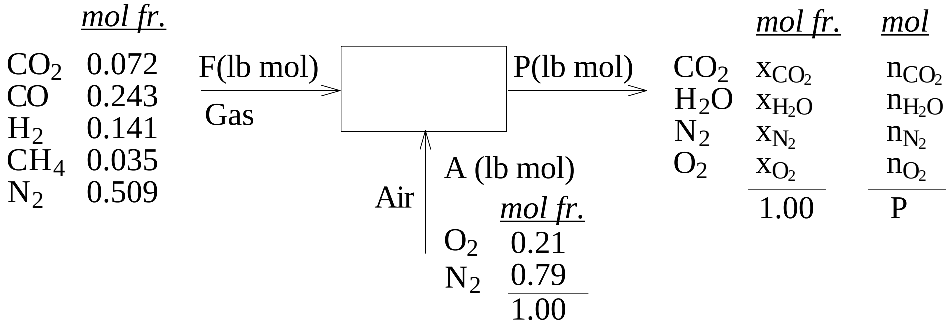
(b) If 38% excess air were used for combustion, what volume of flue gas at 750˚F and 738 mm Hg would be produced per cubic foot of synthetic gas at standard conditions?

(c) Calculate the flue gas analysis for (a) and (b).

Solution

The problem is just a material balance problem with volumes of inlet and outlet gases specified instead of moles. We could select ft^3 or moles as a basis.

Steps 1, 2, 3, and 4 This is a steady state problem with reaction.



Part (a)
Calculate the required air first.

Step 5 Basis 100 mol F

Step 4

Component	*mol*	*Reaction*	*mol reqd O_2*
CO_2	7.2		
CO	24.3	$CO + \frac{1}{2}O_2 \rightarrow CO_2$	12.15
H_2	14.1	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	7.15
CH_4	3.5	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	7.0
N_2	50.9		
	100.0		26.3
Accompanying N_2: 26.3 (79/21)			98.9
		Total	125.2

a. $$\frac{A}{F} = \frac{125.2 \text{ mol air}}{100 \text{ mol feed}} = 1.25 \ \frac{\text{mol air}}{\text{mol feed}} = \frac{\mathbf{1.25\ ft^3\ air}}{\mathbf{1.00\ ft^3\ feed}}$$

(both at same conditions)

Since the temperature and pressure are the same for both streams, the mole ratio and the volume ratio are the same.

Next, let us make a material balance for the case in which the air supplied is 38% in excess. Keep the same basis.

$$A = 125.2\ (1.38) = 172.7 \text{ mol}$$

Part (b)

Step 6 Unknowns: P, and x_{CO_2}, x_{H_2O}, x_{N_2}, x_{O_2} (or $n_{CO_2}, n_{H_2O}, n_{N_2}, n_{O_2}$)

Steps 7, and 8 The element balances are:

Carbon balance: $7.2 + 24.3 + 3.5 = Px_{CO_2} = n_{CO_2}$ (1)

Hydrogen balance: $14.1(2) + 3.5(4) = 2\,Px_{H_2O} = 2n_{H_2O}$ (2)

Oxygen balance: $7.2(2) + 24.3 + 0.21\ (172.7)(2) = 2Px_{CO_2} + Px_{H_2O} + 2Px_{O_2}$ (3)

Nitrogen balance(N2): $50.9 + 0.79\ (172.7) = Px_{N_2} = n_{N_2}$ (4)

Also: $x_{H_2O} + x_{CO_2} + x_{N_2} + x_{O_2} = 1$ (5)

or $n_{H_2O} + n_{CO_2} + n_{N_2} + n_{O_2} = P$

Step 9

From the above equstions we get

Component	*mol*
CO_2	35
H_2O	21.1
O_2	10.1
N_2	187.3
Total	253

Vol. of P @ 750˚F, 738 mm Hg

$$T = 750^\circ F = 1210^\circ R$$

$$p = 738 \text{ mm Hg}$$

$$V_P = \frac{253 \text{ lb mol}}{} \left| \frac{359 \text{ ft}^3}{1 \text{ lb mol}} \right| \frac{1210^\circ R}{492^\circ R} \left| \frac{760 \text{ mm Hg}}{738 \text{ mm Hg}} \right. = 2.30 \times 10^5 \text{ ft}^3$$

$$V_F = \frac{100 \text{ lb mol}}{} \left| \frac{359 \text{ ft}^3}{1 \text{ lb mol}} \right. = 3.59 \times 10^4 \text{ ft}^3$$

$$\frac{V_P}{V_F} = \frac{2.30\times 10^5}{3.59\times 10^4} = \mathbf{6.41}\ \frac{\mathbf{ft^3\ flue\ gas}}{\mathbf{ft^3\ air\ at\ SC}}\ \mathbf{at\ T\ and\ p}$$

Part (c) Flue gas analysis.

a. The water and carbon dioxide are the same as in part b, and there is no O_2 in the flue gas.

	mol	*mol fr*
CO_2	35	**0.23**
H_2O	21.1	**0.14**
N_2	98.9	**0.63**
	155	1.00

b.

	mol	*mol fr*
CO_2	35	**0.14**
H_2O	21.1	**0.08**
N_2	187	**0.74**
O_2	10.1	**0.04**
	253	1.00

Problem 4.1F

An old way of producing hydrogen gas in the laboratory was by the reaction of sulfuric acid with zinc metal

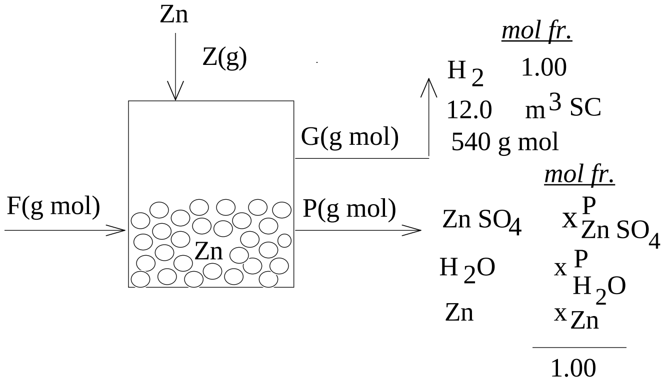
$$H_2SO_4(l) + Zn(s) \rightarrow ZnSO_4(s) + H_2(g)$$

How many grams of sulfuric acid solution (98%) must act on an excess of zinc to produce 12.0 m^3/hr of hydrogen at standard conditions. Assume all the acid used completely reacts.

Solution

Steps 1, 2, 3, and 4 You first must determine the number of moles of hydrogen produced, and then calculate the acid required via stoichiometry. This is a steady state process with reaction except for the Zn (which can be assumed to exit the vessel).

	mass fr.	*MW*	10^3 *g mol*	*mol fr.*
H_2SO_4	0.98	98	10.0	0.90
H_2O	0.02	18	1.111	0.100
	1.00		11.11	1.00



Step 5 Basis 1 hr (12.0 m^3 at SC in G)

$$\text{moles of hydrogen} = n = \frac{pV}{RT}$$

$$\text{vol of hydrogen} = V = \begin{array}{c|c} 12.0\ m^3 & 1000\ L \\ \hline & 1 m^3 \end{array} = 1.20 \times 10^4 L$$

$$n = \frac{(1\ \text{atm})(1.20 \times 10^4)}{(0.08206)\ (273)} = 5.36 \times 10^2 \text{g mol}$$

Step 6 Unknowns are: F, P, $x^P_{ZnSO_4}$, $x^P_{H_2O}$, and x^P_{Zn}. The only unknown we want to solve for is F.

Steps 7 and 8 Balances: We can make H, S, O, and Zn element balances (they may not all be independent) plus $\Sigma x_i = 1$. The easiest balance to make to get F is an H_2SO_4 compound balance, but other reasonable balances can be used.

In		*Out*		*Generation*		*Consumption*		*Accum.*
0.90F	–	0	+	536	–	0	=	0

$$F = 596 \text{ g mol } H_2SO_4$$

$$\begin{array}{c|c} 596 \text{ g mol } H_2SO_4 \text{ soln} & 10.0 \text{ g soln} \\ \hline & 11.11 \times 10^{-3} \text{ g mol } 98\% \text{ soln} \end{array} = \mathbf{5.37 \times 10^4 \text{ g } 98\% \text{ soln}}$$

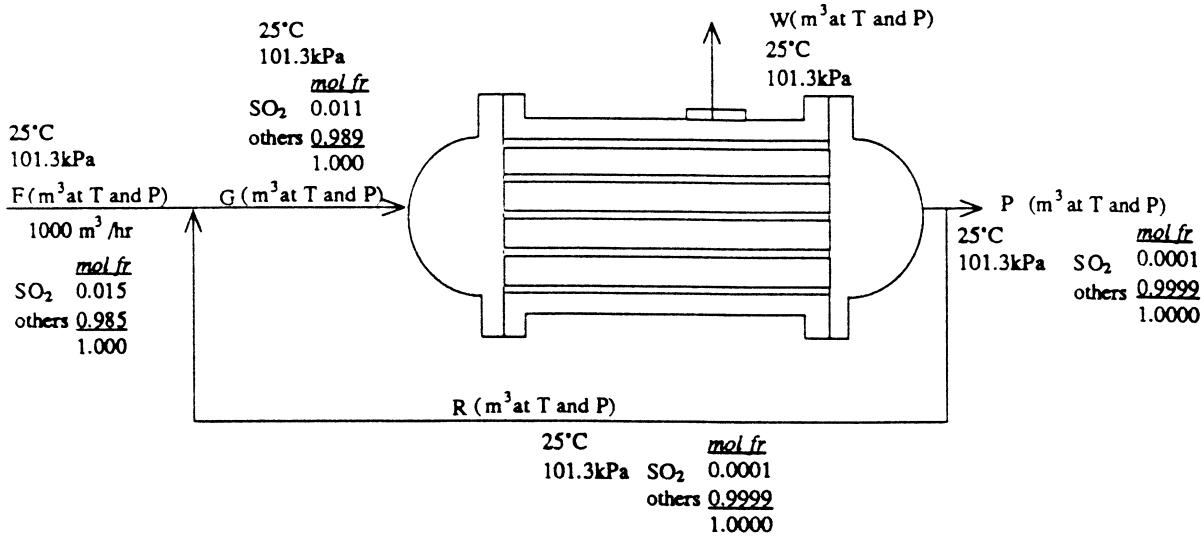
Problem 4.1G

Polymeric membranes are proposed to be used to reduce the SO_2 concentration in the waste gas of a sulfuric acid plant from 1.5% to 0.01%. Hollows fibers (made of polymeric membrane) fill the separations unit. The waste gas containing 1.5% SO_2 is the fresh feed in the amount of 1000 m^3 hr at 25˚C and 1 atm (101.3 kPa). To meet the product gas specifications, part of the product stream has to be recycled to reduce the concentration of SO_2 entering the separator itself to 1.10% SO_2 in G, the process feed. The process is isothermal at 25˚C and isobaric at 1 atm.

(a) Determine the recycle stream flow rate R in m^3/hr.
(b) Determine the waste stream flowrate W in m^3/hr.

Solution

Steps 1, 2, 3, and 4 This is a steady state process with reaction and recycle. All the known data have been placed in the figure. No reaction occurs.



Step 5 Basis: F = 1000 m^3 at 25°C and 101.3kPa (same basis as 1 hr)

Step 6 Ignore the exit stream from the reactor. Then G, P, W, and R are unknowns and their compositions are known.

Since the temperature and pressure are constant throughout, volume balances can be used (mole fraction is the same as volume fraction). The balances could be made in moles and then converted to the basis of 1000 m^3.

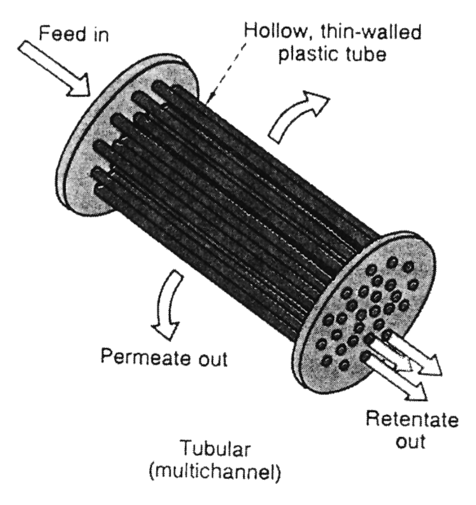
Steps 7, 8, and 9 The system is the overall process. The balances are

Total: 1000 = P + W

SO_2: (0.015)(1000) = 0.0001 P + W (1.000)

Other: (0.985)(1000) = 0.9999 P (a tie component)

SEPARATION BY MEMBRANES



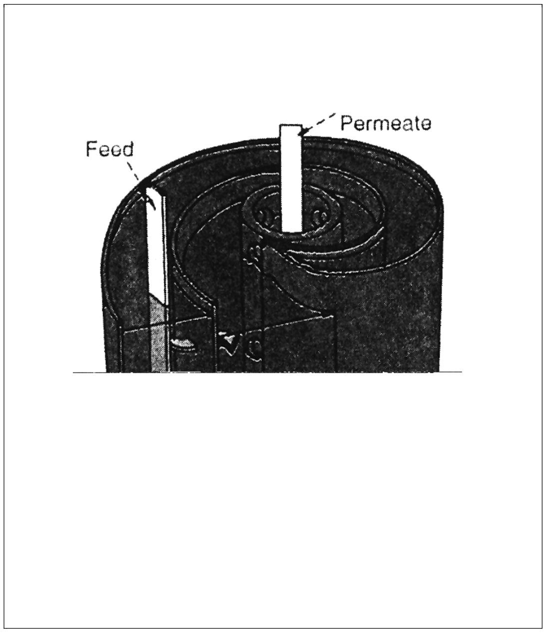


Fig. 17a Tubular membrane separator

Fig. 17b Spiral wound membrane separator

Membranes are used to separate gaseous mixtures or liquid mixtures. Membrane modules can be tubular, spiral-wound, or plate and frame configurations. Membrane materials are usually proprietary plastic films, ceramic or metal tubes, or gels with hole size, thickness, chemical properties, ion potential, and so on appropriate for the separation. Examples of the kinds of separation that can be accomplished are separation of one gas from a gas mixture, separation of proteins from a solution, dialysis of blood of patients with kidney disease, and separation of electrolytes from non electrolytes.

Two of the balances are independent. Solve any two to get

$$P = 985.1\ \text{m}^3\text{/hr at } 25^\circ\text{C and 1 atm}$$
$$\mathbf{W = 14.9\ m^3/hr\ at\ 25^\circ C\ and\ 1\ atm}$$

To get R we make a balance on the mixing point where F and R combine to make G

Total: $1000 + R = G$

SO_2: $0.015(1.000) + 0.0001R = 0.011G$

Other: $(0.985)(1000) + 0.9999R = 0.989G$

(Two of the balances are independent). Solve the first two to get

$$\mathbf{R = 364\ m^3/hr\ at\ 25^\circ C\ and\ 1\ atm}$$
$$G = 1364\ \text{m}^3\text{/hr at } 25^\circ\text{C and 1 atm}$$

Step 10 Check

$$0.15(1000) \overset{?}{=} 0.001\ (985.1) + 14.9$$
$$15 = 15\ \text{OK.}$$

Problem 4.1H

In a sulfuric acid plant, sulfur is burned in the presence of excess oxygen to produce sulfur dioxide which in turn is further reacted in the next step with oxygen in a converter to produce sulfur trioxide.

In the plant SO_2 along with 10% excess air is fed into the converter which operates at 1500˚C and 1 atm. The per pass conversion of SO_2 is 75% and overall conversion is 100%. If 10^6 m^3/hr of SO_3 at 1100˚C and 1 atm is fed to the converter, calculate the:

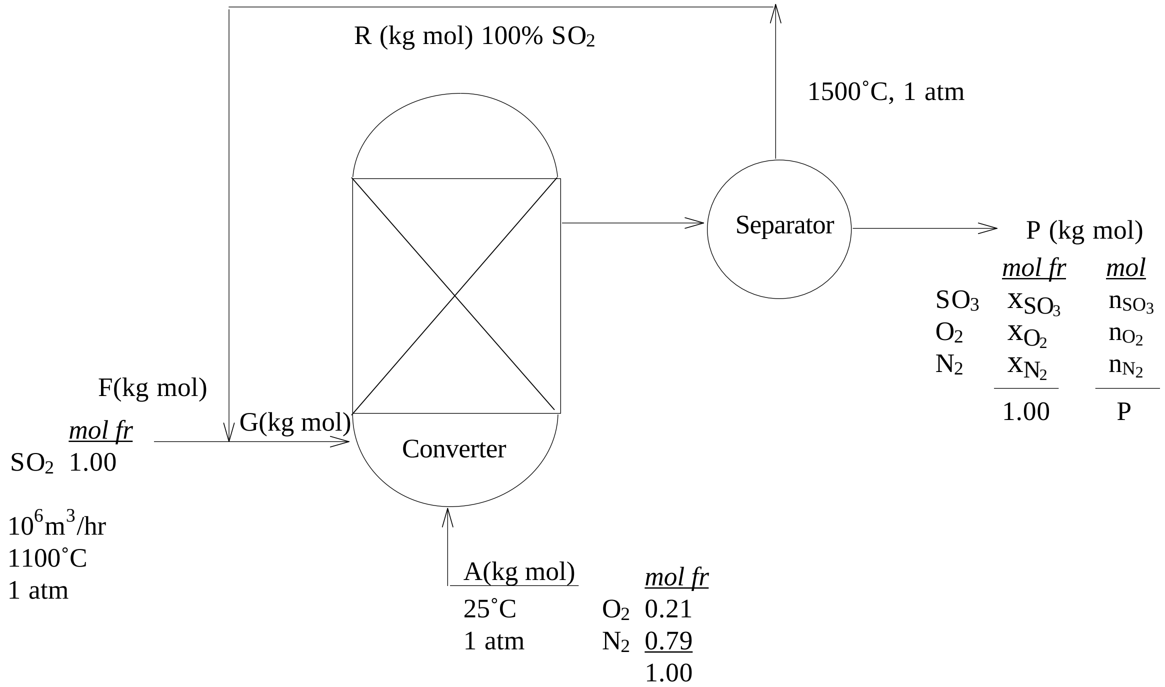
(a) flow rate of the product stream P in m^3/hr at 1500˚C and 1 atm and its composition in mole percent;
(b) flow rate of the recycle stream R in m^3/hr at 1500˚C and 1 atm.

Solution

This is a steady state problem with reaction and recycle.

Steps 1, 2, and 3

$$SO_2 + \frac{1}{2} O_2 \rightarrow SO_3$$



Step 5 Basis: F = 10^6 m^3 at 1100˚C and 101.3kPa (equivalent to 1 hr)

Step 4 We will make the balance in moles (m^3 could also be used if A and F are adjusted to 1 atm and 1500°C).

$$n = \frac{pV}{RT} = \frac{101.3(10^6)}{8.314\,(1100 + 273)} = 8874 \text{ kg mol } SO_2$$

Next, calculate the value of A, the entering air.

		kg mol
Required	O_2:	$8874\left(\frac{1}{2}\right) = 4{,}437$
Excess	O_2:	$0.1(4{,}437) = \underline{\ \ 444}$
	Total	4,881
N_2:	$4881\left(\frac{0.79}{0.21}\right) =$	18,360

Step 6 The system is the overall process. The unknowns are P, n_{SO_3}, n_{O_2}, and n_{N_2} (or P, x_{SO_3}, x_{O_2}, x_{N_2})

Step 7 The balances are: S, O, N, and $\Sigma n_i = P\ \left(\text{or } \Sigma x_i = 1\right)$

Steps 8 and 9 For the overall process the element balances are (units are kg mol):

S: $8{,}874 = P\left(x_{SO_3}\right) = n_{SO_3}$
N2: $18{,}360 = P\left(x_{N_2}\right) = n_{N_2}$
O: $8{,}874\,(2) + 4{,}881(2) = 8{,}874(3) + n_{O_2}(2)$

$n_{SO_3} = 8{,}874$ $n_{N_2} = 18{,}360$ $n_{O_2} = 444$

Thus P = 8,874 + 18,360 + 444 = 27,618 kg mol or 27,620 kg mol

a. Apply pV = nRT

$$V = \frac{(27{,}620)(8.314)(1500 + 273)}{101.3} = \mathbf{4.02 \times 10^6 m^3/hr \text{ at } 1500°C \text{ and } 1 \text{ atm}}$$

At the mixing point of F and R we get G: F + R = G

b. Make the system the reactor plus the separator to avoid having to calculate information about the converter outlet stream. Use an SO_2 balance in kg mol.

In		*Out*		*Gen.*		*Consum.*		*Accum.*
(1.00)(8874+R)	–	R(1.00)	+	0	–	0.75(8874+R)	=	0

R = 2958 kg mol which corresponds **0.43×10^6 m^3/hr at 1500˚C and 1 atm**

Problem 4.2A

Seven pounds of N_2 at 120˚F are stored in a cylinder having a volume of 0.75 ft^3. Calculate the pressure in atmospheres in the cylinder

(a) assuming N_2 to be an ideal gas
(b) assuming the pressure of N_2 can be predicted by van der Waal's equation
(c) using the compressibility factor method
(d) using the Redlich-Kwong equation of state.

Solution

$$\left.\begin{aligned} &V = 0.75\ \text{ft}^3\\ &T = 120^\circ\text{F} = 580^\circ\text{R}\\ &n = \begin{array}{c|c} 7\ \text{lb N}_2 & 1\ \text{lb mol} \\ \hline & 28\ \text{lb N}_2\end{array} \ = \ 0.25\ \text{lb mol N}_2\end{aligned}\right\}\quad \text{Basis}$$

$R = 10.73\ (\text{psia})(\text{ft}^3)/(\text{lb mol})(^\circ\text{R})$

a. Using the ideal gas relation pV = nRT

$$p = \frac{(0.25)(10.73)(580)}{0.75}\left(\frac{1\ \text{atm}}{14.7\ \text{psia}}\right) = \mathbf{141\ atm\ (2074\ psia)}$$

b. Using van der Waals, equation

$$\left(p + \frac{n^2a}{V^2}\right)(V - nb) = nRT$$

From the text for nitrogen $a = 1.347\times 10^6\left(\frac{\text{cm}^3}{\text{g mol}}\right)^2$ and $b = 38.6\left(\frac{\text{cm}^3}{\text{g mol}}\right)$

$$a = 1.347\times\begin{array}{c|c} \left(\frac{\text{cm}^3}{\text{g mol}}\right)^2 & 3.776\ \text{x}\ 10^{-3}\left(\frac{\text{cm}^3}{\text{g mol}}\right)^2 \\ \hline & 1\left(\frac{\text{cm}^3}{\text{g mol}}\right)^2\end{array} \ = \ 5086\left(\frac{\text{ft}^3}{\text{g mol}}\right)^2$$

$$b = \begin{array}{c|c} 38.6\left(\frac{\text{cm}^3}{\text{g mol}}\right)^2 & 1.60\times 10^{-2}\left(\frac{\text{cm}^3}{\text{g mol}}\right)^2 \\ \hline & 1\left(\frac{\text{ft}^3}{\text{g mol}}\right)^2\end{array} = 0.6176\left(\frac{\text{ft}^3}{\text{g mol}}\right)^2$$

Then

$$\left(p + \frac{(0.25)^2\ 5086}{(0.75)^2}\right)[0.75 - 0.25\ (0.6176)] = 0.25\ (10.73)\ (580)$$

$$(p + 565.1)\ [0.596] = 1556$$

$$\mathbf{p = 20.46\ psi\ (139\ atm)}$$

c. Using the compressibility factor

$$pV = znRT$$

From Appendix D in the text the critical properties for nitorgen are

$$p_c = 33.5 \text{ atm and } T_c = 126.2\text{K } (227^\circ\text{R})$$

$$V'_c = \frac{RT_c}{p_c}\ \frac{(0.7302)(227)}{(33.5)} = 4.95 \text{ ft}^3/\text{lb mol}$$

$$T_r = \frac{T}{T_c} = \frac{580^\circ\text{R}}{227^\circ\text{R}} = 2.56$$

$$V'_r = \frac{V}{V'_c} = \frac{0.75 \text{ ft}^3/0.25 \text{ lb mol}}{4.95 \text{ ft}^3/\text{lb mol}} = 0.61$$

On one of the compressibility charts having the right domain determine the intersection of the $V'_r = 0.61$ and the $T_r = 2.56$ lines. Some approximation may be required. From this point you can read z on the vertical and p_r on the horizontal axis:

$z = 1.05$ $\quad$ $p_r = 4.5$

$$p = \frac{znRT}{V} = \frac{(1.05)(0.25)(10.73)(580)}{(0.75)} = 2178 \text{ psia } (148 \text{ atm})$$

or use p_r: $\quad$ $p_r = p/p_c$

$$p = (p_r)(p_c) = 4.5\ (33.5) = 151 \text{ atm}$$

These answers are close enough in view of the accuracy of the original data.

d. Using the Redlich Kwong Equation of State

$$\left[p + \frac{a}{T^{1/2}\ \hat{V}\left(\hat{V} + b\right)}\right]\left(\hat{V} - b\right) = RT$$

where $a = 0.4278\,\dfrac{R^2 T_c^{2.5}}{p_c}$ and $b = 0.0867\,\dfrac{RT_c}{p_c}$

$$a = 0.4278\ \frac{(0.7302)^2\ (227)^{2.5}}{(33.5)}\ =\ 5286\ (°R)^{0.5}\ (atm)\ (ft^3/lb\ mol)^2$$

$$b = 0.0867\ \frac{(0.7302)\ (227)}{(33.5)}\ =\ 0.429\ ft^3/lb\ mol$$

Substitute these values into the equation

$$\left[p + \frac{5286}{(580)^{1/2}\ 3\ \ (3 + 0.429)}\right](3 - 0.429) = (0.7302)\ (580)$$

$$(p + 20.96)\ (2.571) = 4235$$

$$p = 144\ atm$$

The pressures determined by three methods are comparable although not exactly same.

Problem 4.2B

A gas analyzes 60% methane and 40% ethylene by volume. It is desired to store 12.3 kg of this gas mixture in a cylinder having a capacity of $5{\cdot}14 \times 10^{-2}$ m^3 at a maximum temperature of 45˚C. Calculate the pressure inside the cylinder by

(a) assuming that the mixture obeys the ideal gas laws;
(b) using the compressibility factor determined by the pseudo critical point method.

Solution Basis: 12.3 kg

a. *Ideal Gas Law* pV = nRT

$$\text{av mol wt} = \sum y_i MW_i = 0.60\ (16) + 0.40\ (28) = 20.8\ \frac{kg}{kg\ mol}$$

$$n = \frac{12.3\ kg}{}\left|\frac{1\ kg\ mol\ mixture}{20.8\ kg\ mixture}\right. =\ 0.591\ kg\ mol$$

$T = 45˚C = 318K$ $V = 5.14 \times 10^{-2}\ m^3$ $R = 8.314\ (kPa)\ (m^3)/(kg\ mol)(K)$

$$p = \frac{nRT}{V}\ =\ \frac{0.591\ (8.314)(318)}{5.14 \times 10^{-2}}\ =\ 30{,}400\ kPa$$

b. *Pseudocritical method*

$$p_c' = \sum_i p_{ci}\, y_i \qquad T_c' = \sum_i T_{ci}\, y_i \qquad V_c' = \sum_i V_{ci}'\, y_i$$

Methane	*Ethylene*
$T_c = 190.7\text{K}$	$T_c = 283.1\text{ K}$
$p_c = 45.8$ atm (4640 kPa)	$p_c = 50.5$ atm (5116 kPa)
$V_c' = \dfrac{RT_c}{p_c} = 0.342\ \dfrac{\text{m}^3}{\text{kg mol}}$	$V_c' = \dfrac{RT_c}{p_c} = 0.460\ \dfrac{\text{m}^3}{\text{kg mol}}$

$T_c' = 0.60\,(190.7) + 0.40\,(283.1) = 227.7\text{K}$ $\quad p_c' = 0.60\,(4640) + 0.40\,(5116) = 4830$ kPa

$$V_c' = 0.60\,(0.342) + 0.40\,(0.460) = 0.389\ \frac{\text{m}^3}{\text{kg mol}}$$

$$T_r' = \frac{T}{T_c'} = \frac{318\text{K}}{227.7\text{K}} = 1.40$$

$$V_r' = \frac{\hat{V}}{\hat{V}_c'} = \frac{5.14 \times 10^{-2}\ \text{m}^3/0.591\ \text{kg mol}}{0.389\ \text{m}^3/\text{kg mol}} = 0.22$$

Using T_r' and V_r', we get $p_r = 5.3$ (approximately) so that $p = p_r p_c' = (5.3)(4830) = 26{,}000$ kPa

Problem 4.3A

Calculate the vapor pressure of benzene at 50˚C using the Antoine Equation. Also estimate the normal boiling point of benzene (the vapor pressure at 1 atm), and compare it with the experimental value (taken from a handbook).

Solution

Antoine Equation $\ln(p^*) = A - \frac{B}{C + T}$

From Appendix G in the text the coefficients are

Benzene:	A = 15.9008	T = K
	B = 2788.51	p^* = mmHg
	C = –52.36	

a. Vapor Pressure of benzene at 50˚C

$$\ln(p^*) = 15.9008 - \frac{2788.51}{-52.36 + (50 + 273)}$$

p^* = **270 mmHg abs**

b. At the boiling point the vapor pressure is 1 atm (760 mmHg abs.)

$$\ln(760) = 15.9008 - \frac{2788.51}{-52.36 + T}$$

Solving, T = **353.3K**

From Appendix D in the text the normal boiling point of benzene is **353.26K**. The two values agree well.

Problem 4.3B

Prepare a Cox chart for ethyl acetate. The vapor pressure of ethyl acetate is 200 mmHg abs. at 42˚C and 5.0 atm at 126.0˚C. By using the chart estimate the

a. boiling point of ethyl acetate at 760 mmHg and compare with the experimental value (77.1˚C).

b. vapor pressure of ethyl acetate at its critical temperature of 523.1K. Compare with the experimental value of 37.8 atm.

Solution

To construct the temperature scale the following data for the vapor pressure of water are used:

T(˚C):	30.0	50.0	100.0	150.0	200.0	250.0
p(atm):	0.042	0.122	1.00	4.70	15.36	39.22

The procedure is as follows:

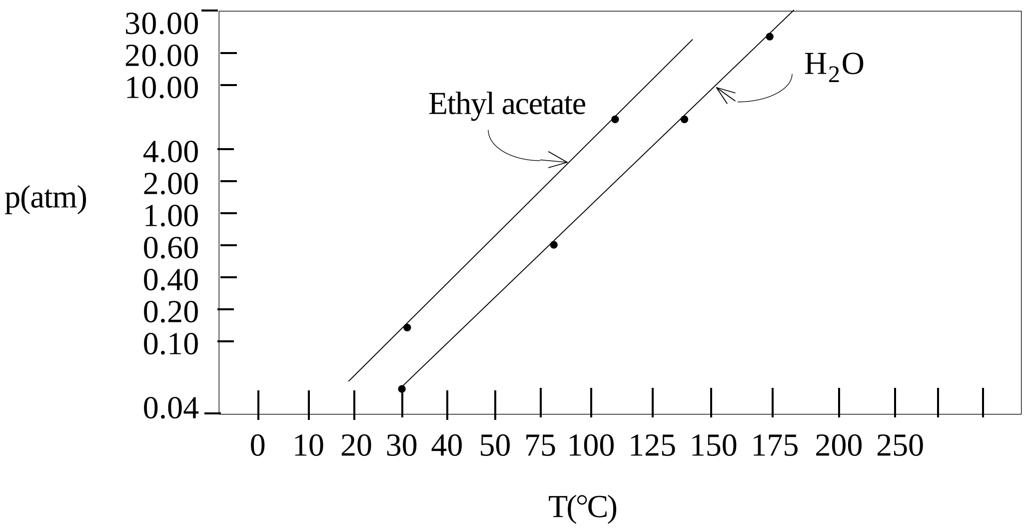
1. First, select a logarithmic vertical scale and place even values of the vapor pressure on the vertical scale to cover the desired pressure range.

2. Then draw a straight line representing the vapor pressure of water at any suitable angle so that you cover the range of temperatures and pressures needed for the problem.

3. To locate each integer value of the water temperature (such as 30, 50, 100, etc.) on the horizontal scale, note the corresponding vapor pressure on the vertical axis, and move horizontally to the line. Then drop vertically down to the temperature axis and mark the axis with the selected temperature (the spacing will not be at even intervals). Repeat to get a series of temperatures.

4. Finally, put the two points given for ethyl acetate on the chart and draw a line between them for ethyl acetate.

Cox Chart

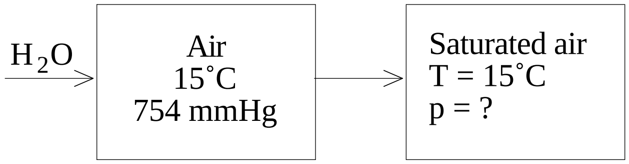


The normal boiling point is estimated to be between 75˚C and 80˚C (a bigger chart would produce a more accurate result), and at the critical point (250˚C), the estimated vapor pressure is about 50 atm.

Problem 4.4A

If sufficient water is placed in a vessel containing a dry gas at 15˚C and 100.5 kPa to thoroughly saturate it, what will be the absolute pressure in the vessel after saturation? The temperature and volume of the vessel remain constant.

Solution



Once the air is saturated with water vapor, the water (if the water vapor is in equilibrium with liquid water) exerts a pressure equal to its vapor pressure at 15˚C.

Basis: Dry gas at 15˚C and 100.5 kPa

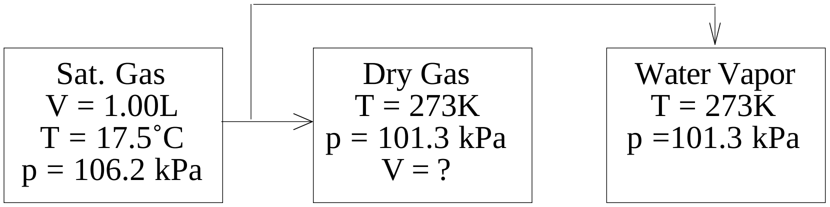
The vapor pressure of H_2O at 15˚C = 1.7 kPa. Since the temperature and volume remain constant

$$p_T = p_{air} + p_{H_2O} = 100.5 + 1.7 = \mathbf{102.2\ kPa}$$

Problem 4.4B

A gas saturated with water vapor in a tank has a volume of 1.00L at 17.5˚C and a pressure of 106.2 kPa. What is the volume of dry gas under standard conditions? How many grams of water vapor are present in the gas?

Solution



At the initial conditions the total pressure is the sum of gas pressure and vapor pressure of the water. The first step in the solution involves determining the pressure of the dry gas assuming constant temperature and volume. Look up: $p_{H_2O} = p^*_{H_2O}$ (at 17.5˚C) = 2.00 kPa

$p_T = 106.2\text{ kPa} = p^*_{H_2O} + p_{gas} = 2.00 + p_{gas}$ $\qquad p_{gas} = 104.2\text{ kPa}$

a. $$\frac{1.00\text{L}}{}\left|\frac{273\text{K}}{290.5\text{K}}\right|\frac{104.2\text{ kPa}}{101.3\text{ kPa}} = \mathbf{0.97L\ at\ SC}$$

b. One solution technique is to apply pV = nRT to the water vapor.

$$\frac{1.00\text{L}}{}\left|\frac{2.00\text{ kPa}}{290.5\text{K}}\right|\frac{1\text{ atm}}{101.3\text{ kPa}}\left|\frac{1\text{ (g mol)(K)}}{0.08206\text{ (L)(atm)}}\right|\frac{18\text{g } H_2O}{1\text{ g mol } H_2O} = \mathbf{0.015\ g\ H_2O}$$

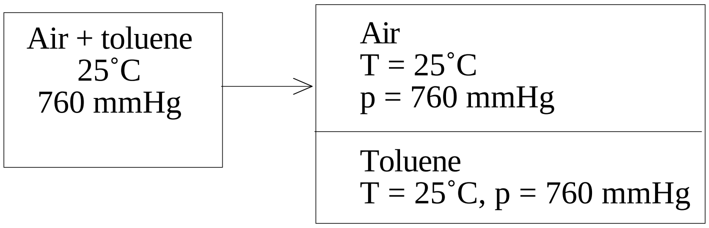
Another approach is to use pV = nRT to calculate the total moles present and multiply the result (0.039 g mol) by the mole fraction water (2.00/106.2).

Problem 4.4C
Dry air at 25˚C is saturated with toluene under a total pressure of 760 mmHg abs. Is there adequate air for complete combustion of all the toluene? If so, determine the percent excess air present for combustion.

Solution

The solution involves first determining the number of moles of toluene and the moles of oxygen in a specified volume

Steps 1, 2, 3 $C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O$



Step 5 Basis: 1 g mol C_7H_8

Step 4 From the chemical equation we see 9 mol of O_2 are need per mol of toluene hence (9/0.21) = 42.86 mol of air is needed per mol of toluene. The mole fraction C_7H_8 would be (1/43.86) = 0.0228.

Steps 6, 7, 8 and 9 At 25˚C, C_7H_8 exerts a vapor pressure of

$$\ln(p^*) = 16.0137 - \frac{3096.52}{-53.67 + (25 + 273.1)}$$

$$p^* = 28.22 \text{ mm Hg abs.}$$

At saturation

$$760 - 28.22 = 731.78 \text{ mm Hg abs.} = p_{air}$$

$$\frac{p_{air}}{p_{toluene}} = \frac{n_{air}}{n_{toluene}} = \frac{731.78}{28.22} = 25.93$$

Since the molar ratio of air/toluene required for complete combustion is 42.9, and under the given conditions the air/toluene ratio is only 25.93, the amount of air available is not adequate.

Problem 4.5A

Assume that Raoult's Law holds for the following mixture

	mole%
n-Hexane	20
Benzene	50
Toluene	30

a. What is the dew point pressure of the mixture if it is at 150˚F?
b. What is the dew point temperature of the mixture if it is at 85 psia?
c. What is the bubble point temperature of the mixture if it is at 70 psig? The barometer reads 780 mmHg.
d. What is the bubble point pressure if the mixture is 150˚F?

Solution

a. The dew point pressure is the pressure of which the vapor first starts to condense at 150˚F. The mixture is assumed to be all vapor and the condensate composition is determined by

$$1 = p_T \sum_{i=1}^{n} \frac{y_i}{p_i^*} \qquad \text{or} \qquad \frac{1}{p_T} = \sum_{i=1}^{n} \frac{y_i}{p_i^*}$$

Assume an ideal solution exists and use the Antonine Equation to determine p_i^* for the pure components

$$\ln (p^*) = A - \frac{B}{C + T} \qquad T = 150˚F = 338.6K$$

	A	B	C	p_i^*	y_i	y_i/p_i^*
n-Hexane	15.8366	2697.55	–48.78	684.67	0.20	2.921×10^{-4}
Benzene	15.9008	2788.51	–52.36	472.93	0.50	1.057×10^{-3}
Toluene	16.0137	3096.52	–53.67	171.75	0.30	1.747×10^{-3}
						3.096×10^{-3}

$$\frac{1}{p_T} = \sum \frac{y_i}{p_i^*} = 3.096 \times 10^{-3}$$

$$\mathbf{p_T = 333\ mmHg}$$

b. The dew point temperature is the temperature at which the vapor first condenses when the vapor and liquid are in equilibrium. For an ideal solution at 85 psia (4395 mmHg) the relation to use is

$$\frac{1}{p_T} = \sum \frac{y_i}{p_i^*}$$

$$p^* = \exp\left[A - \frac{B}{C + T}\right]$$

$$\frac{1}{4394.6} = \left[\frac{0.2}{e^{\left(15.8366 - \frac{2697.55}{-48.78 + T}\right)}} + \frac{0.5}{e^{\left(15.9008 - \frac{2788.51}{-52.36 + T}\right)}} + \frac{0.3}{e^{\left(16.0137 - \frac{3096.52}{-53.67 + T}\right)}}\right]$$

Solve for T by trial and error (or on a computer) to get

T = 500K	p_T = 13105 mmHg	
T = 425K	p_T = 3842 mmHg	**T ~ 435K**
T = 435K	p_T = 4321 mmHg	

c. The bubble point temperature at a given pressure is the temperature at which the liquid mixture vapor pressure equals the total pressure. The mixture is assumed to be all liquid and the vapor composition is assumed to be in equilibrium with the liquid. The relation used under these assumptions for an ideal liquid is

$$p_T = \sum p_i^* x_i$$

$$\frac{70\text{ psi}}{} \left| \frac{760.0\text{ mmHg}}{14.696\text{ psia}} \right. = 3619\text{ mmHg}$$

$$p_T = 3619 + 780 = 4399\text{ mmHg abs.}$$

$$4399 = \left[0.20\, e^{\left(15.8366 - \frac{2697.55}{-48.78 + T}\right)} + 0.5\, e^{\left(15.9008 - \frac{2788.51}{-52.36 + T}\right)} + 0.3\, e^{\left(16.0137 - \frac{3096.52}{-53.67 + T}\right)}\right]$$

Solve for T by trial and error (or on a computer) to get

T = 400K	p = 2372 mmHg	
T = 425K	p = 4070 mmHg	**T = 429K**
T = 430K	p = 4496 mmHg	

d. The bubble point pressure at 150˚F (338.6K) is the pressure at which the liquid first starts to vaporize when the vapor and liquid are in equilibrium

For an ideal liquid

$$p_T = \sum p_i^* x_i$$

	A	B	C	p_i^*	x_i	$p_i^* x_i$
n-Hexane	15.8366	2697.55	–48.78	684.67	0.20	136.93
Benzene	15.9008	2788.51	–52.36	472.93	0.50	236.47
Toluene	16.0137	3096.52	–53.67	171.75	0.30	51.53
						424.9

$$\mathbf{p_T = 425\text{ mmHg}}$$

Problem 4.5B

A natural gas has the following analysis at 400 kPa

	Mole%
Propane	78.0
Butane	12.0
Pentane	10.0

Its temperature must be kept above what value to prevent condensation? If it were cooled, what would be the composition of the liquid that first condenses out of the gas?

Solution

Basis: 1.00 mol gas at 400 kPa.

Assume ideal vapor and liquid at the dew point. $x_i = y_i/K_i$ $\sum x_i = 1$ $K_i = p_i^* / p_T$

$$\sum\left(y_i / K_i\right) = 1 \text{ or } p_T \sum\left(y_i / p_i^*\right) = 1 \text{ for an ideal solution.}$$

Procedure

Assume a temperature and obtain values for p_i^* from the Antonine equation or, a handbook. Calculate $\left(\sum y_i / p_i^*\right)$ p_T to see if the sum equals 1.0. If not, repeat to bracket the value 1.

1st iteration, let T = 310K

	p_i^*(kPa)	y_i / p_i^*	$p_T \sum\left(y_i / p_i^*\right)$
C_3	1269	6.147×10^{-4}	
C_4	343.4	3.494×10^{-4}	$400(1.999 \times 10^{-3}) = 0.768$
C_5	104.7	9.551×10^{-4}	
		$\sum = 1.919 \times 10^{-3} (\text{kPa})^{-1}$	

2nd iteration, let T = 290K

	p_i^*	y_i / p_i^*	$p_T \sum\left(y_i / p_i^*\right)$
C_3	765	1.020×10^{-3}	
C_4	186.5	6.434×10^{-3}	$400\ (3.644 \times 10^{-3}) = 1.457$
C_5	50.5	1.980×10^{-3}	
		$\sum = 3.644 \times 10^{-3} (\text{kPa})^{-1}$	

3rd iteraction T = 300K

	p_i^*	y_i / p_i^*	$p_T \sum\left(y_i / p_i^*\right)$
C_3	993.5	7.851×10^{-4}	$400\ (2.610 \times 10^{-3}) = 1.04$
C_4	255.9	4.689×10^{-4}	close enough
C_5	73.76	1.356×10^{-3}	
		$\sum = 2.610 \times 10^{-3} (\text{kPa})^{-1}$	$T \cong 300\text{K}$

At the dew point temperature, the liquid which first condenses has the composition

$$x_i = y_i p_T / p_i^*$$

$$\frac{y_i p_T}{p_i^*}$$

$$x_{C_3} = \frac{(0.78)(400\ \text{kPa})}{993.5\ \text{kPa}} = 0.314$$

$$x_{C_4} = \frac{(0.12)(400\ \text{kPa})}{255.9\ \text{kPa}} = 0.188$$

$$x_{C_5} = \frac{(0.10)(400\ \text{kPa})}{73.76\ \text{kPa}} = 0.542$$

$$\sum x_i = 1.04$$

Problem 4.6A

A gas mixture contains 0.0083 g mol of water vapor per g mol of dry CH_4 at a temperature of 27˚C and a total pressure of 200 kPa. Calculate the:

a. percent relative saturation of the mixture.
b. percent saturation of the mixture
c. temperature to which the mixture must be heated at 200 kPa in order that the relative saturation will be 0.20.

Solution

Basis: 1 lb mol CH_4

$p^*_{H_2O}$ (27˚C) = 3.536 kPa $\quad p_{total} = 200$ kPa $\quad p_{H_2O} = p_{total}\ y_{H_2O}$

a. Percent relative saturation = $\frac{p_{H_2O}}{p^*_{H_2O}}(100)$

$$y_{H_2O} = \frac{0.0083}{1 + 0.0083} = 0.0082$$

$$p_{H_2O} = (200\text{ kPa})(0.0082) = 1.64\text{ kPa}$$

$$\frac{1.64}{3.536}(100) = \mathbf{46.4\%}$$

b. Percent saturation = (rel. saturation) $\left(\frac{p_T - p^*_i}{p_T - p_i}\right)100$

$$= (0.464)\left(\frac{200 - 3.54}{200 - 1.64}\right)100 = \mathbf{46.0\%}$$

Note that the percent saturation is always less than the percent relative saturation.

c. In the heating at constant pressure, the mole fraction of the water vapor does not change so p_{H_2O} = 1.64 kPa.

$$\frac{p_{H_2O}}{p^*_{H_2O}} = 0.20 \qquad \text{or} \qquad \frac{1.64}{p^*_{H_2O}} = 0.20$$

The vapor pressure has to be calculated to get the temperature.

$p^*_{H_2O} = \frac{1.64}{0.20} = 8.2$ kPa and from stream table **T = 315K (42°C)**

Problem 4.6B

A gas at 200˚F and 30 in Hg abs. has a molal humidity of 0.10. Calculate:

a. the percentage humidity
b. the relative humidity
c. the dew point of the gas (˚F)

Solution

$p^*_{H_2O}$(at 200˚F) = 11.525 psia

p_T = 30 in Hg = 1.003 atm = 14.74 psia

$$\text{molal humidity} = \frac{n_{\text{vapor}}}{n_{\text{vapor free gas}}} = \frac{p_{\text{vapor}}}{p_{\text{vapor gas}}}$$

$$\left.\begin{aligned} \frac{p_{H_2O}}{p_{gas}} &= 0.10 \\ p_T &= p_{H_2O} + p_{gas} \end{aligned}\right\} \qquad \begin{aligned} p_{H_2O} &= 1.34 \text{ psia} \\ p_{gas} &= 13.4 \text{ psia} \end{aligned}$$

a. Percentage humidity $= \dfrac{p_{H_2O}}{p^*_{H_2O}}\left(\dfrac{p_T - p^*_{H_2O}}{p_T - p_{H_2O}}\right) 100 = \mathbf{2.79\%}$

b. Relative humidity $\dfrac{p_{H_2O}}{p^*_{H_2O}}(100) = \mathbf{11.6\%}$

c. The dew point of the gas can be determined from the steam tables. It is the temperature of which the partial pressure is equal to the vapor pressure of vapor (cooling at constant total pressure)

$$p_{H_2O} = 1.34 \text{ psia} = p^*$$

The corresponding T is **T = 112˚F**

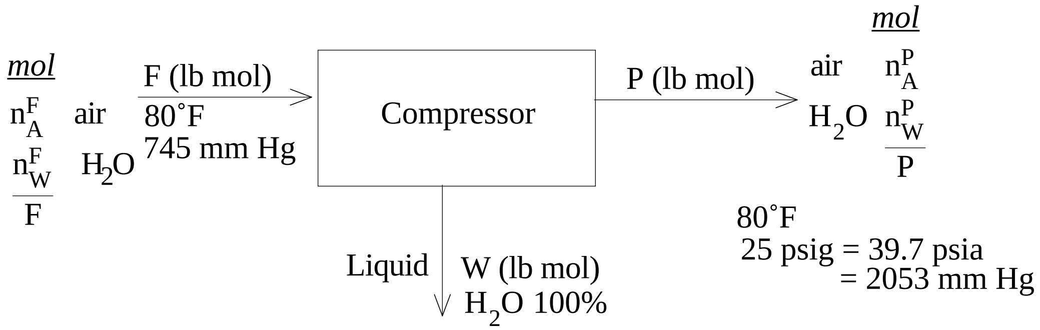
Problem 4.7A

Air saturated with water vapor at 80˚F and 745.0 mm Hg abs. is passed through an air compressor and then stored in a tank at 25.0 psig and 80˚F. What percentage of the water originally in the air was removed during the processing?

Solution

This problem can be treated as a steady state problem without reaction, or as an unsteady state problem. We will carry out the solution as a steady state problem. Recall that the water vapor condenses on compression so that the compressed gas is still saturated.

Steps 1, 2, 3, and 4



Step 5 Several basis can be considered: F = 100 lb mol, P = 100 lb mol, W = 100 lb mol, F = 745 lb mol, and so on, but we will take a tie component as a convenient basis

Basis: F = 1.00 lb mol

Step 4 Calculate the gas compositions.

F	P
p_W^* at 80˚F is 0.5067 psia (26.2 mm Hg abs.)	p_W^* = 26.2 mm Hg
p_A in F = 745 - 26.2 = 718.8 mm Hg	p_A in P = 2053 – 26.2 = 2027 mm Hg
$\frac{n_A^F}{n_T^F} = \frac{p_A^F}{p_T^F} = \frac{718.8}{745}$	$\frac{n_A^P}{n_T^P} = \frac{p_A^P}{p_T^P} = \frac{2027}{2053}$

Steps 6, 7, 8 and 9

We can make two component balances and one total balance (F = P + W) of which two are independent. Two unknowns exist: W and P.

Total balance (lb mol)

$$1.00 = P + W$$

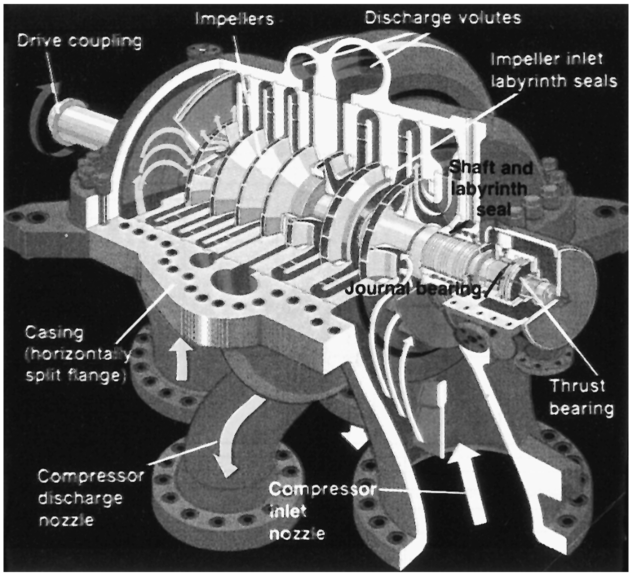
Air balance (lb mol)

$$1.00\left(\frac{718.8}{745}\right) = P\left(\frac{2027}{2053}\right) \text{ so that } P = 0.977 \text{ lb mol}$$

$$W = 1.00 - 0.977 = 0.023 \text{ lb mol}$$

100 (0.023/0.0364) = 63%

GAS COMPRESSORS (TURBO COMPRESSORS)



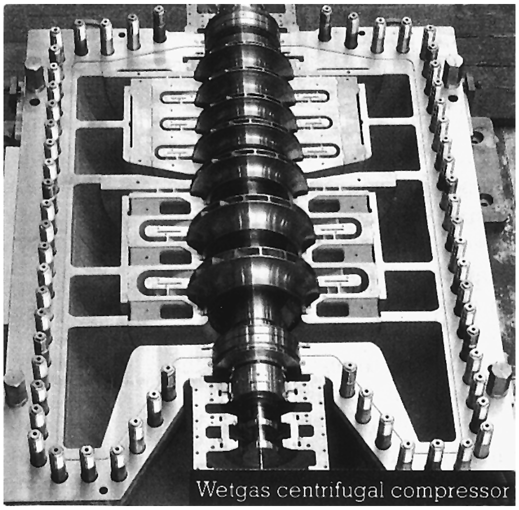


Fig. 18a Centrifugal compressor, quarter section open

Fig. 18b One half section of a wet gas centrifugal compressor (courtesy of Sultzer Turbosystems)

Compressors take in gas at one pressure and release it at a higher pressure. Some axial flow compressors have adjustable guide vanes such as occur in units for natural gas liquification. A minimum flow exists below which the compressor operation becomes unstable (surges) and back flow can occur as well as mechanical damage. A different type of compressor found in common use is the reciprocating compressor which uses pistons to compress gases to higher pressures than can be achieved with axial flow units, but can only handle smaller volumes of gas. Both types of compressors can be used in stages to achieve higher pressures than provided by a single unit. The approximate range of functioning of compressors is in Fig. 18c.

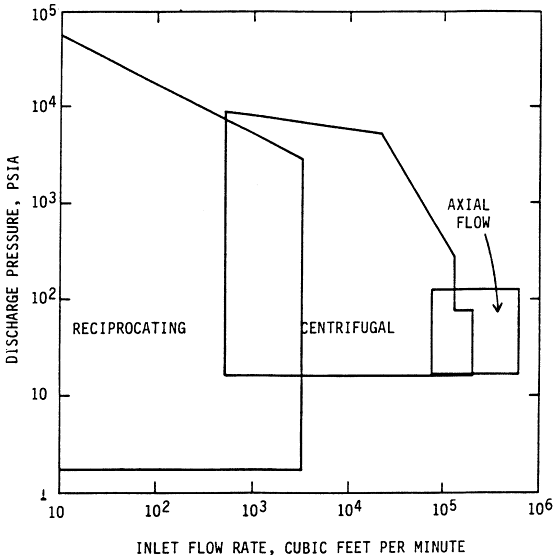


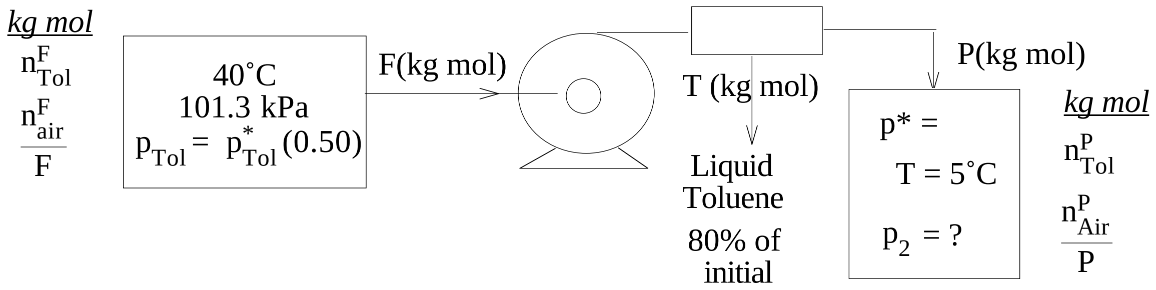
Fig. 18c Range of operation of compressors

Problem 4.7B

Toluene is evaporated into dry air. The resulting mixture at 40˚C and a pressure of 101.3 kPa has a percentage saturation of 50%. It is desired to condense 80% of the toluene in the mixture by a process of cooling and compressing. If the temperature is reduced to 5˚C, determine the pressure to which gas must be compressed.

Solution

Steps 1, 2, and 3, This is a steady state process without reaction.



Step 4 Use the Antoine Equation for toluene to get p^* for toluene

A = 16.0137 B = 3096.52 C = -53.67

$$\ln(p^*) = A - \frac{B}{C + T}$$

at T = 40˚C $p^*_T = 58.71$ mm Hg abs.

at T = 5˚C $p^*_T = 9.118$ mm Hg abs.

p_{Total} = 101.3 kPa = 760 mm Hg. At 40°C

$$P_{Tol} = 0.50\ p^*_{Tol} = 0.50\,(58.71) = 29.36 \text{ mm Hg}$$

Step 5 Basis: F = 100 kg mol

Step 4 The toluene condensed is

$$T = 0.80(100)\,(0.0386) = 3.088 \text{ kg mol}$$

Calculate the composition of the inlet gas.

$$\frac{n^F_{Tol}}{n^F_{Tot}} = \frac{p^F_{Tol}}{p^F_{Tot}} = \frac{29.36}{760} = 0.0386$$

Step 6 Unknown are: n^P_{Air}, n^P_{Tol}, P

Steps 7, 8, and 9

An overall balance, an air balance, and a toluene balance can be written; only two are independent. But $n_A^P + n_{Tol}^P$ = P is the third equation needed.

Air balance (kg mol): $100\,(1 - 0.0386) = n_{Air}^P$

Toluene balance (kg mol): $100\,(0.0386) = 3.088 + n_{Tol}^P$

Note that because of condensation, the toluene in P is saturated, and amounts to 20% of the original toluene, or 0.77 kg mol. The partial pressure of the saturated toluene in P is 9.118 mm Hg abs.

$$\frac{p_{Tol}}{p_{Tot}} = \frac{p^*_{Tol}}{p_{Tot}} = \frac{n_{Tol}}{n_{Tot}} = \frac{0.77}{0.77 + 96.14} = \frac{0.77}{96.91}$$

$$p_{Tot} = 9.118\left(\frac{96.91}{0.77}\right) = \mathbf{1150\ mm\ Hg\ abs.\ (153\ kPa)}$$

Problem 4.7C

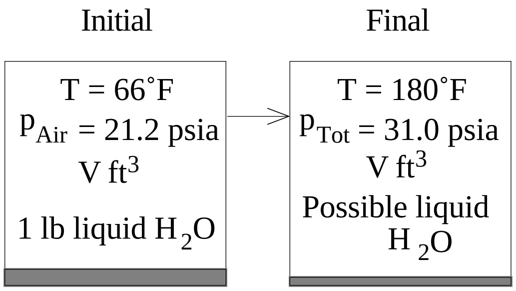
A constant-volume vessel contains dry air at 66˚F and 21.2 psia. One pound of liquid water is introduced into the vessel. The vessel is then heated to a constant temperature of 180˚F. After equilibrium is reached, the pressure in the vessel is 31.0 psia. The vapor pressure of water at 180˚F is 7.51 psia.

a. Did all of the water evaporate?
b. Compute the volume of the vessel in cubic feet.
c. Compute the humidity of the air in the vessel at the final conditions in pounds of water per pound of air.

Solution

Steps 1, 2, and 3 Assume the liquid water occupies a negligible volume in the vessel. The system is the vessel.

Gas	F (lb mol)
H_2O	$n^F_{H_2O}$
Air	n^F_{Air}
Total	n^F_{Tot}



Gas	G (lb mol)
H_2O	$n^G_{H_2O}$
Air	n^G_{Air}
Total	n^G_{Tot}

$p^*_{H_2O}$ (66˚F) = 0.3162 psia

$p^*_{H_2O}$ (180˚F) = 7.51 psia

Step 5 Basis: Initial gas at conditions shown in the Figure.

Steps 6, 7, 8, and 9

First we have to determine if all the water is vaporized or not in the vessel. We can calculate the partial pressure of the air in the vessel at 180°F by applying the ideal gas law to both the initial and final conditions, and using as the material balance the equality of the initial and final moles of air, $n^F_{Air} = n^G_{Air}$.

$$\frac{p^F_{Air}V}{p^G_{Air}V} = \frac{n^F_{Air}RT^F}{n^G_{Air}RT^G}$$

or

$$p^G_{Air} = p^F_{Air}\left(\frac{T^G}{T^F}\right) = 21.2\left(\frac{180+460}{66+460}\right) = 26.9 \text{ psia}$$

Thus, the pressure of the water vapor in the air at the final conditions is

$$p^G_{H_2O} = 31.1 - 26.9 = 4.2 \text{ psia}$$

Because 4.2 < 7.51 psia, the air at the final state is not saturated.

a. All the water vaporizes

b. We can calculate the volume of the vessel from the final given conditions plus the value of the partial pressure of the water vapor in the final state

$$V_{H_2O} = \frac{n^G_{H_2O} R T^G}{p^G_{H_2O}} = \frac{(1/18)(0.73)(640)}{4.2} = \mathbf{90.8\ ft^3}$$

The volume of the water vapor at its partial pressure is the same as the volume of the vessel.

c. The humidity is

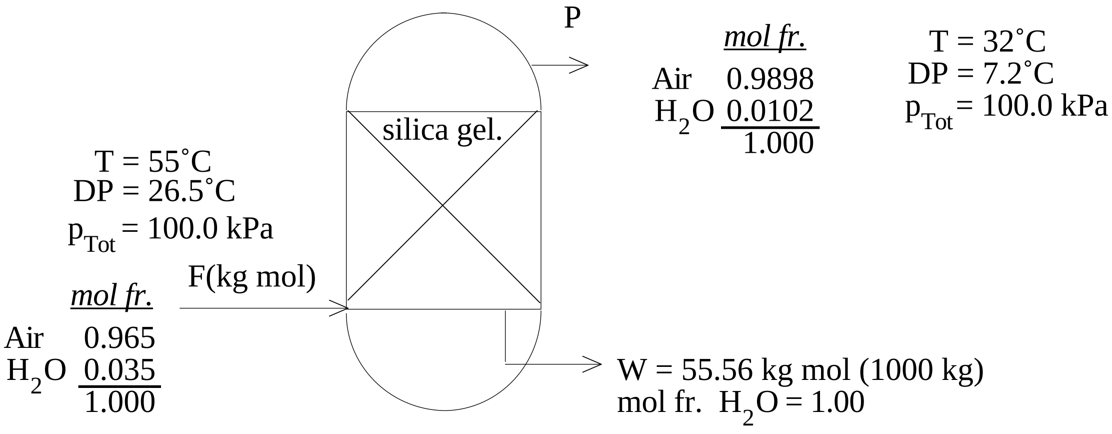
$$\frac{4.2 \text{ lb mol } H_2O}{26.9 \text{ lb mol air}} \left| \frac{18 \text{ lb } H_2O}{1 \text{ lb mol } H_2O} \right| \frac{1 \text{ lb mol air}}{29 \text{ lb air}} = 0.097 \frac{\text{lb } H_2O}{\text{lb air}}$$

Problem 4.7D

A silica gel drier removes 1000 kg of water per hour. Air is supplied at a temperature of 55˚C and a dew point of 26.5˚C. The air leaves the drier at a temperature of 32˚C and a dew point of 7.2˚C. The pressure in the system is constant at 100.0 kPa. Calculate the volume of the wet air (at the initial conditions) which is supplied per hour.

Solution

Steps 1, 2, 3 and 4 Some of the data in the figure have been calculated in Step 4 below. The process is a steady state one without reaction. Because gas are involved, the calculations will be in moles. The systems is the drier.



Step 5 Basis: 1 hour

Step 4 $p^*_{H_2O}(26.5˚C) = 3.50$ kPa

$p^*_{H_2O}(7.2˚C) = 1.02$ kPa

Calculate the stream compositions first.

Inlet air	*Outlet air*
$p_{H_2O} = p^*_{H_2O}(26.5˚C) = 3.50$ kPa	$p_{H_2O} = p^*_{H_2O}(7.2˚C) = 1.02$ kPa
$p_T = 100.0$ kPa	$p_T = 100.0$ kPa

Step 6 Unknowns are F and P

Step 7 Balances are H_2O and air (or total)

Steps 8 and 9

$$\left.\begin{aligned}&\text{Air:} && F(0.965) = P(0.9898)\\ &H_2O\text{:} && F(0.035) = P(0.0102) + 55.56\end{aligned}\right\}\quad F = 2214 \text{ kg mol}$$

$$V = \frac{nRT}{p} = \frac{(2214)(8.314)(328)}{100.0} = \mathbf{6.04\times 10^4\ m^3/hr}$$

at 55°C and 100 kPa

CHAPTER 4 – ADDITIONAL PROBLEMS
(Answers will be found in Appendix A)

Section 4.1

4.1A In a test on an oil-fired boiler, it is not possible to measure the amount of oil burned, but the air used is determined by inserting a venturi meter in the air line. It is found that 5000 ft^3/min of air at 80°F and 10 psig is used. The dry gas analyzes CO_2, 10.7 percent; CO, 0.55 percent; O_2, 4.75 percent; and N_2, 84.0 percent. If the oil is assumed to be all hydrocarbon, calculate the gallons per hour of oil burned. The sp gr of the oil is 0.94.

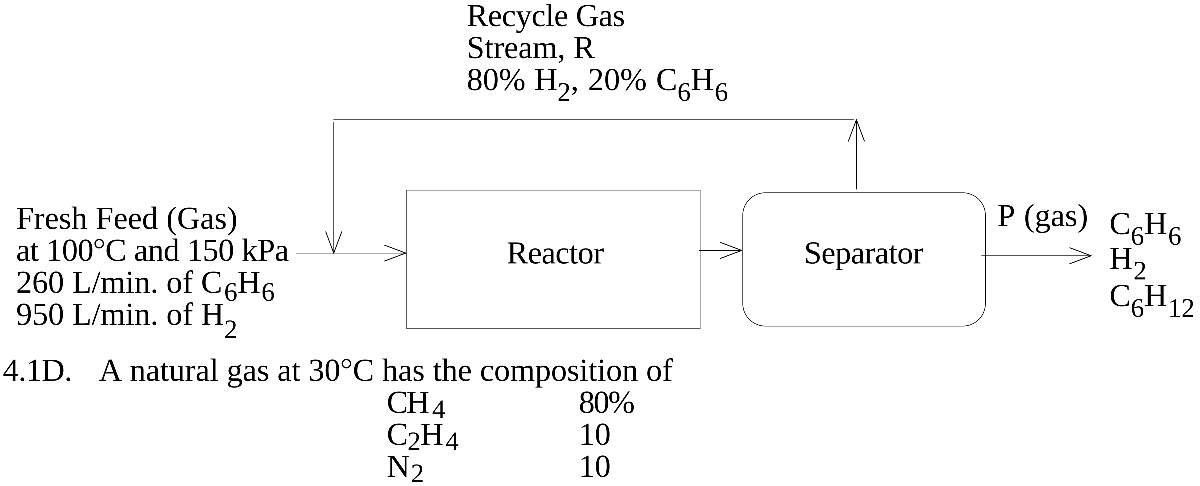
4.1B In the manufacture of dry ice, a fuel is burned to a flue gas which contains 16.2 percent CO_2, 4.8 percent O_2, and the remainder N_2. This flue gas passes through a heat exchanger and then goes to an absorber. The data show that the analysis of the flue gas entering the absorber is 13.1 percent CO_2 with the remainder O_2 and N_2. Apparently something has happened. To check your initial assumption that an air leak has developed in the heat exchanger, you collect the following data with a wet-test meter on the heat exchanger:

Entering flue gas in a 2-min period	47,800 ft^3 at 600°F and 740 mm of Hg
Exit flue gas in a 2-min period	30,000 ft^3 at 60°F and 720 mm of Hg

Was your assumption about an air leak a good one, or was perhaps the analysis of the gas in error? Or both?

4.1C. Benzene (C_6H_6) is converted to cyclohexane (C_6H_{12}) by direct reaction with H_2. The fresh feed to the process is 260 L/min of C_6H_6 plus 950 L/min of H_2 at 100°C and 150 kPa. The single pass conversion of H_2 in the reactor is 48% while the overall conversion of H_2 in the process is 75%. The recycle stream contains 80% H_2 and the remainder benzene (no cyclohexane).

(a) Determine the molar flow rates of H_2, C_6H_6, and C_6H_{12} in the exiting product.
(b) Determine the volumetric flow rates of the product stream if it exits at 100 kPa and 200°C.
(c) Determine the molar flow rate of the recycle stream, and the volumetric flow rate if the recycle stream is at 100°C and 100 kPa.



4.1D. A natural gas at 30°C has the composition of

CH_4	80%
C_2H_4	10
N_2	10

If the pressure in the line is 100 kN/m^2, what are the partial pressures of the three components? If the temperature is raised to 40°C, will the partial pressures change? If so, what will they be?

Section 4.2

4.2A Find the molar volume (in cm^3/g mol) of propane at 375 K and 21 atm. Use the Redlich-Kwong and Peng-Robinson equations, and solve for the molar volume using (1) a nonlinear equation solver, and (2) the compressibility factor method. The acentric factor for propane to use in the Peng-Robinson equation is 0.1487. Also, check your results with the value found in a data base or a handbook.

4.2B What weight of ethane is contained in a gas cylinder of 1.0 ft^3 in volume if the gas is at 100°F and 2000 psig? Use (1) an equation of state and (2) the compressibility factor method.

4.2C Calculate the volume occupied by 2.0 lb air at 735 psia and 392°F.

Section 4.3

4.3A Estimate the vapor pressure of aniline at 350°C from the following vapor pressure data (the experimental vapor pressure is 40 atm):

t(°C)	184.4	212.8	254.8	292.7
p*(atm)	1.00	2.00	5.00	10.00

(a) Prepare a Cox chart to solve this problem.
(b) Fit the coefficients in Antoine equation using a nonlinear optimization code or a nonlinear regression code, and predict the value from the Antoine equation.

4.3B Estimate the vapor pressure of benzene at 125°C from the vapor pressure data

T(°F):	102.6	212
p^* (psia):	3.36	25.5

by preparing a Cox chart.

Section 4.4

4.4A Carbon disulfide (CS_2) at 20°C has a vapor pressure of 352 mm Hg. Dry air is bubbled through the CS_2 at 20°C until 4.45 lb of CS_2 are evaporated. What was the volume of the dry air required to evaporate this CS_2 (assuming that the air is saturated) if the air was initially at 20°C and 10 atm and the final pressure on the air-CS vapor mixture is 750 mm Hg?

4.4B A mixture of acetylene (C_2H_2) with an excess of oxygen measured 350 ft^3 at 25°C and 745 mm pressure. After explosion the volume of the dry gaseous product was 300 ft^3 at 60°C and its partial pressure of 745 mm. Calculate the volume of acetylene and of oxygen in the original mixture. Assume that the final gas was saturated and that only enough water was formed to saturate the gas.

4.4C An 8.00–liter cylinder contains a gas saturated with water vapor at 25.0°C and a pressure of 102.6 kPa. What is the volume of the gas when dry at standard conditions?

4.4D Oxalic acid ($H_2C_2O_4$) is burned with 248 percent excess air, 65 percent of the carbon burning to CO. Calculate the dew point of the flue gas.

Section 4.5

4.5A Equilibrium flash vaporization of a liquid mixture of ethane (15 mol), propane (15 mol), n-butane (15 mol), and pentane (15 mol) at 140°F and 200 psia takes place in a vessel. What ratio of liquid to vapor exists when vaporization is complete. K-values are respectively 3.70, 1.38, 0.57, and 0.21.

4.5B A vapor composed of 30 percent n-hexane, 30% n-heptane, and 40% n-octane is partially condensed at 100 kPa. Assume that the vapor and liquid are ideal solutions. Calculate the mole fractions of the three components in the vapor at equilibrium if 80 percent of the original vapor condenses.

4.5C A solution containing 12 wt percent of dissolved nonvolatile solid is fed to a flash distillation unit. The molecular weight of the solid is 123.0. The effective vapor pressure of the solution is equal to

$$p = p^* x$$

where p = effective vapor pressure of the solution
x = mole fraction of water
p^* = vapor pressure of pure water

The pressure in the flash distillation unit is 1.121 psia and the temperature is 100°F. Calculate the pounds of pure water obtained in the vapor stream per 100 lb of feed solution and the weight percent of the dissolved nonvolatile solid leaving in the liquid stream.

4.5D Consider a tank of water at 0°C under a pressure of 101.3 kPa at the surface of the water. Would it be possible to maintain ice at the bottom of the water tank at 0°C in equilibrium with the water?

Section 4.6

4.6A Toluene is mixed with air at 21°C in such proportions that the partial pressure of the vapor is 1.33 kPa. The total pressure is 99.3 kPa. Calculate the following:
(a) The relative saturation.
(b) The moles of toluene per mole of vapor-free gas.
(c) The weight of toluene per unit weight of vapor-free gas.
(d) The percent saturation.
(e) The percentage of toluene by volume.

4.6B A rigid vessel which is 1 ft^{3}in volume contains 1 lb of N_2 and 1 lb of H_2O at 100F.
(a) What is the pressure (psia) in the vessel?
(b) What is the molal humidity in the vapor phase?
(c) What mass fraction of the water is liquid?

4.6C Around airports jet aircrafts can become major contributors to pollution, and as aircraft activity increases and public concern brings other sources under control, the relative contribution of aircraft to pollution could go up. Recently, federal-, state-, and local-government pressure has speeded the introduction of new combustors in aircraft. In a test for an aircraft fuel with the average composition $C_{1.20}H_{4.40}$, the fuel is completely burned with the exact stochiometric amount of air required. The air is supplied at 24°C and 100 kPa, with a humidity of 80 percent.

For the entering air, compute the following:
(1) The dew point.
(2) The molal humidity.
(3) The relative humidity.

Section 4.7

4.7A Leather containing 100 percent of its own weight of water (i.e., if the dry leather is 1 lb, the water is 1 lb) is dried by means of air. The dew point of the entering air is 40°F, and in the exit air it is 55°F. If 2000 lb of leather are forced through the dryer per hour, how many pounds of water are removed per hour? The barometer reads 750 mm Hg.

The following is the solution to the problem. Explain whether the solution is correct or not. If not, what is the solution?

Basis: 750 lb mol wet air in

$p^*_{H_2O}$ at 40°F = 6.29 mm Hg

$p^*_{H_2O}$ at 55°F = 11.05 mm Hg

lb mol dry air in = 750 – 6.29 – 743.7 lb mol

lb mol dry air out = 750 – 11.05 – 739 lb mol

$$\frac{6.29\ \text{lb mol}}{} \left| \frac{18\ \text{lb}}{1\ \text{lb mol}} \right. = 114\ \text{lb}\ H_2O$$

Dry air balance

$$H_2O_{out} = \frac{11.05\ \text{lb mol}}{} \left| \frac{743.7}{739} \right| \frac{18\ \text{lb}}{1\ \text{lb mol}} = 200\ \text{lb}\ H_2O$$

H_2O absorbed = 200 – 114 = 86 lb H_2O

Comp.	*mol*	*mol fract*	*mol fract*	*M.W.*	*lb*
Dry Air	743.7	0.991	0.991	29	28.7
H_2O	6.29	0.009	0.009	18	0.2
Total	750	1.0	1.0		28.9

Basis: 2000 lb leather (1 hr)

$$\frac{2000\ \text{lb leather}}{1\ \text{hr}}\left|\frac{0.50\ \text{lb}\ H_2O}{1\ \text{lb leather}}\right|\frac{86\ \text{lb}\ H_2O\ \text{removed}}{114\ \text{lb}\ H_2O\ \text{in}} = 75.4\ \text{lb / hr}$$

4.7B Air at 300K and 100 kPa has a dew point of 289K.
- (a) What is the percent relative humidity?
- (b) To what pressure must this air be compressed to cause condensation to start (the temperature remains at 300K)?
- (c) To what temperature must this air be cooled to remove 25 percent of the moisture (the pressure stays constant at 100 kPa)?
- (d) What would be the percent relative humidity of this air after heating to 340K (at constant pressure)?
- (e) Did the molal saturation change during the heating indicated in part (d)?

4.7C Air saturated with water vapor is at 140°F and a pressure of 29.68 in. Hg.
- (a) To what temperature must the air be cooled to separate 68 percent of the water in it as liquid water (pressure is constant)?
- (b) To what pressure must the air be compressed to separate 68 percent of the water in it as liquid water (temperature is constant)?
- (c) If the temperature is reduced to 100°F and the gas is compressed to 25 psia, what percentage of the water separates out as liquid?

4.7D Soybean flakes from an extraction process are reduced from 0.96 lb of C_2HCl_3 per pound of dry flakes to 0.05 lb of C_2HCl_3 per pound of dry flakes in a desolventizer by a stream of N_2 which vaporizes the C_2HCl_3. The entering N_2 contains C_2HCl_3 such that its dew point is 30°C. The N_2 leaves at 90°C with a relative saturation of 60%. The pressure in the desolventizer is 760 mmHg, and 1000 lb/hr of dry flakes pass through the drier.
- (a) Compute the volume of N_2 plus C_2HCl_3 leaving the desolventizer at 90°C and 760 mm Hg in cubic feet per minute.
- (b) The N_2 leaving the desolventizer is compressed and cooled to 40°C, thus condensing out the C_2HCl_3 picked up in the desolventizer. What must the pressure in the condenser be if the gas is to have a dew point of 30°C at the pressure of the desolventizer?

Problem 5.1A

A 100-hp engine is used to pump ground water into an irrigation channel. Calculate the rate at which the pump is doing work in

(a) Btu/hr (b) J/s (c) kW.

Solution Basis: 100 hp

a.

$$\begin{array}{c|c|c} 100\text{ hp} & 0.7068\text{ Btu/s} & 3600\text{ s} \\ \hline & 1\text{ hp} & 1\text{ hr} \end{array} = \mathbf{2.544 \times 10^{5}\ Btu/hr}$$

b.

$$\begin{array}{c|c} 100\text{ hp} & 745.7\text{ J/s} \\ \hline & 1\text{ hp} \end{array} = \mathbf{7.457 \times 10^{4}\ J/s}$$

c.

$$\begin{array}{c|c} 100\text{ hp} & 0.7457\text{ kW} \\ \hline & 1\text{ hp} \end{array} = \mathbf{745.7\ kW}$$

Problem 5.1B

Classify the following variables as intense or extensive.

a) temperature

b) density

c) mass

d) specific heat capacity

e) refractive index

Solution

a. Temperature: **intensive property**

b. Density: **intensive property**

c. Mass: **extensive property**

d. Specific heat capacity: **intensive property**

e. Refractive index: **intensive property**

PUMPS AND BLOWERS

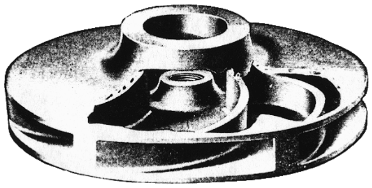


Fig 19a Cutaway view of two-vane impeller with open eye (courtesy of Nagle Pumps)

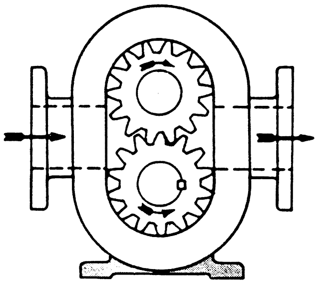


Fig. 19d Gear pump (courtesy of the Hydraulic Institute)

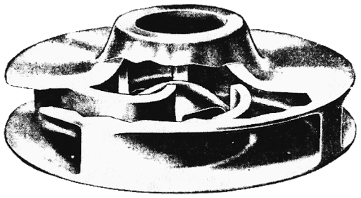


Fig 19b Semi-open impeller for handling fluids containing pulpy solids (courtesy of Nagle Pumps)

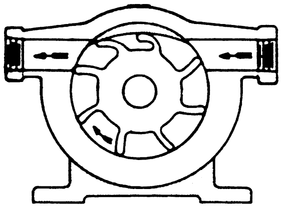


Fig. 19e Flexible impeller pump (courtesy of the Hydraulic Institute)

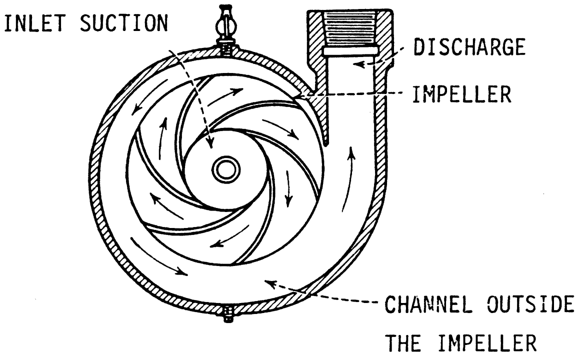


Fig 19c Volute pump

PUMPS

Numerous designs of pumps exist among which a few are illustrated in the figures above for pumping liquids. Centrifugal pumps have fixed impellers with fairly close clearance between the impeller and the casing. Flexible impeller pumps have rubber blades that are squeezed between the shell and the impeller hub. Gear pumps represent a class of positive displacement pumps whose teeth mesh and force liquid into the outlet. Reciprocating piston pumps operate much like the piston in an automobile except the latter pressurizes gases.

Problem 5.1C

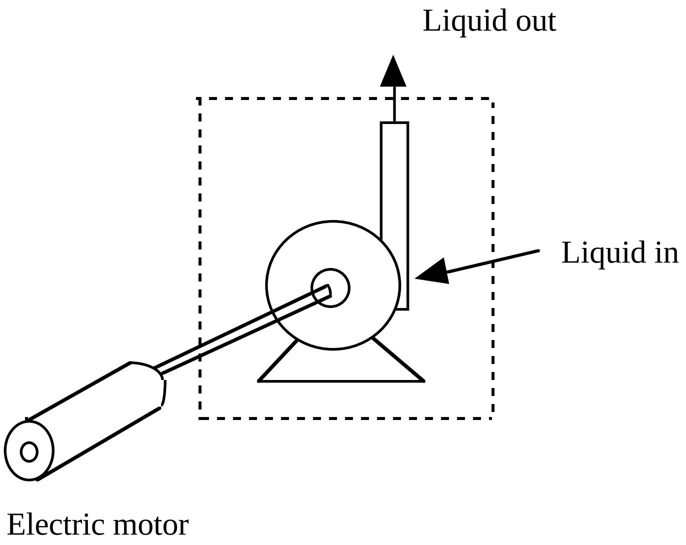
Make a rough sketch of each of the following processes. Show the system boundary, and classify the system as open or closed.

a) pump b) storage tank c) windmill d) internal combustion engine

Solution

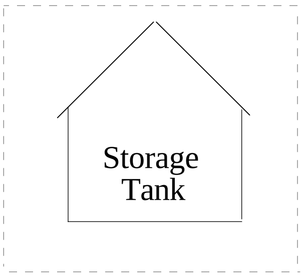
The dashed lines represent the respective system boundaries.

a. pump



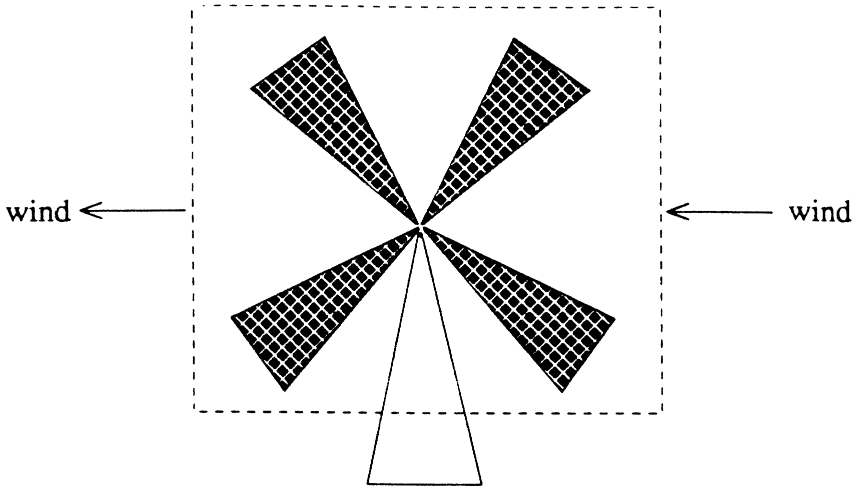
open system: mass is transferred across the system boundary

b. Storage tank



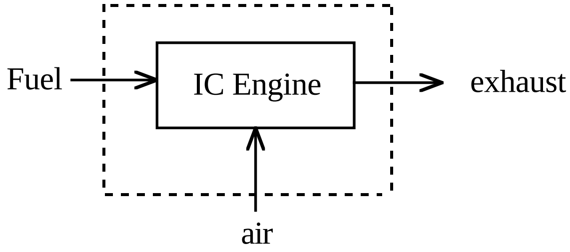
Closed system: the tank does not exchange mass or energy with surroundings (except when it is filled or emptied)

c. Windmill



Open System: wind moves in and out of the system

d.



Open System: fuel and air enter the engine, and exhaust gases leave the engine.

Problem 5.1D

Calculate the potential energy of 1 kg of water located at the surface of a lake that is 100 meters above a water turbine which is 200 meters away and used to generate electricity.

Solution

$$PE = mgh = \frac{1\ \text{kg}}{} \left| \frac{9.80\ \text{m}}{\text{s}^2} \right| \frac{100\ \text{m}}{} \left| \frac{1\ \text{J}}{\frac{1\ (\text{kg})(\text{m}^2)}{\text{s}^2}} \right. = \mathbf{980J}$$

Problem 5.1E

An ideal gas in a tank at 500˚C and 100 kPa is compressed isothermally to 1000 kPa. What was the work (in J/g mol) of compression?

Solution

We have to assume that the work done on the gas represents energy transferred solely to the gas, and no work is done on the equipment containing the gas during the compression.

Basis: 1g mol gas

Isothermal compression

$$\widehat{W} = \int_{\hat{V}_1}^{\hat{V}_2} p\,d\widehat{V} = \int_{\hat{V}_1}^{\hat{V}_2} \frac{nRT}{\widehat{V}}\,d\widehat{V} = nRT \ln \frac{\widehat{V}_2}{\widehat{V}_1}$$

$$\frac{p_2V_2}{p_1V_1} = \frac{n_1RT_1}{n_2RT_2} \text{ so that } \frac{\hat{V}_2}{\hat{V}_1} = \frac{p_1}{p_2} = \frac{100}{1000} = 0.10$$

$$\widehat{W} = \frac{1\text{ g mol}}{}\left|\frac{8.314\text{J}}{1\text{ (g mol)(K)}}\right|\frac{(500 + 273.15)\text{ K}}{}\ \ln(0.10) = \mathbf{14{,}800J}$$

(the positive sign designates work done on the system)

Problem 5.1F

A wall of an annealing oven is made of 10 inch thick forebrick. If the interior of the wall is at 2550°F and the exterior of the wall is at 392°F, what is the heat loss per hour? The relation for heat transfer is $Q = kA\,(T_2 - T_1)/\Delta x$ where k is the thermal conductivity, T is the temperature in °F, and Δx is the wall thickness.

Solution

Basis: 1 hour

You have to look up the thermal conductivity in a handbook. It varies with temperature but assume an average value of 0.81 Btu/(hr)(ft^2)(°F)/ft.

$$\text{Thus,}\quad Q = \frac{0.81\text{(Btu)(ft)}}{\text{(hr)(ft}^2\text{)(°F)}}\left|\frac{(2550 - 392)\text{F}}{}\right|\frac{}{(10/12)\text{ft}}\ ) = \mathbf{2100\ \frac{Btu}{(hr)(ft^2)}}$$

ANNEALING OVENS

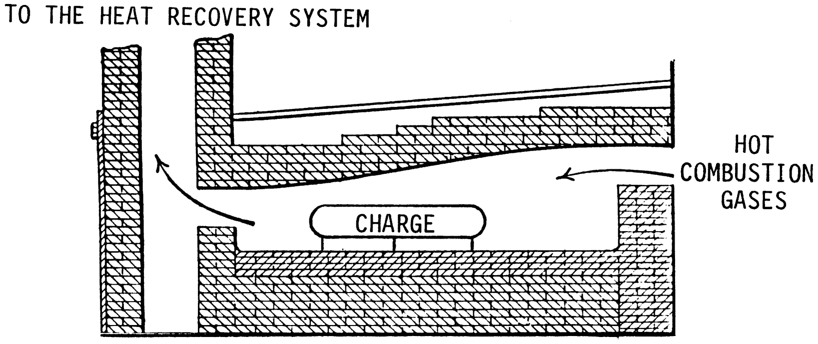


Fig 20 Reverbatory furnace

Ovens, kilns, retorts, and furnaces provide a way of heating a charge of material. Some ovens are fixed with the charge loaded and heated, and then cooled and unloaded as a batch. Others are tunnels in which the charge passes through on trolleys or conveyors with the heating occurring in the entrance region and the cooling taking place in an exit region. In both case the heat of combustion is transferred either by direct contact from the flame or combustion gases, or indirectly by transfer through a containing wall that separates the combustion products from the charge. The use of direct combustion offers cheaper construction, lower cost of operation and maintenance, and more rapid heating and cooling. The disadvantages are that the charge can be contaminated with the dust and components of the combustion gases, and that the charge can be oxidized/reduced depending on the oven conditions.

Problem 5.1G

An ideal gas at 50˚C and 1 atm is heated to 500˚C at constant pressure, and then isothermally compressed to 10 atm. It is then isobarically cooled to 50˚C, and finally is isothermally expanded to back to its initial state. For the overall process, determine ΔH and ΔU.

Solution

Enthalpy ΔH and internal energy ΔU are state functions and since the process returns to its initial state at the end

$$\boldsymbol{\Delta U = \Delta H = 0}$$

Problem 5.1H

A automobile weighing 2500 lb is traveling at 55 miles per hour when the brakes are suddenly applied bringing the vehicle to a stop. After the brakes have cooled to the ambient temperature, how much heat (in Btu) has been transferred from the brakes to the surroundings?

Solution

Let the system be the whole car. The accumulation term in the energy balance is not zero because the kinetic energy of the vehicle is initially not zero but after stopping is zero. Also, energy (heat) is transferred from the vehicle to the surroundings so that the energy transfer term in the energy balance is not zero. The rest of the terms presumably are zero. Consequently we get (in symbols)

$$Q = \Delta K = K_2 - K_1$$

Basis: 2500 lb automobile

$K_2 = 0$

$$K_1 = \left(\tfrac{1}{2}\right) mv^2 = \frac{1}{2}\,\bigg|\,\frac{2500\ \text{lb}_m}{}\,\bigg|\left(\frac{55\ \text{mile}}{\text{hr}}\right)^2\bigg|\left(\frac{1\ \text{hr}}{3600\ \text{S}}\right)^2\bigg|\left(\frac{5280\ \text{ft}}{1\ \text{mile}}\right)^2$$

$$\frac{1\,(\text{s}^2)(\text{lb}_f)}{32.2(\text{ft})(\text{lb}_m)}\,\bigg|\,\frac{1\ \text{Btu}}{778(\text{ft})(\text{lb}_f)} = 325\ \text{Btu}$$

Q = (0 – 325) = **–325 Btu** (the minus sign denotes heat transfer out of system)

Problem 5.1I

In Problem 5.1E, a gas was compressed isothermally. How much heat has to be transferred to or from the compression equipment to keep it isothermal. Was the transfer into or out of the equipment?

Solution

In the energy balance the accumulation term is zero because the internal energy of an ideal gas depends only on the temperature, and the temperature is constant. The energy transport terms involve heat and work

$$0 = Q + W \qquad \text{or here } Q = -W$$

$$Q = \mathbf{-14{,}800J}$$

In other words, the negative sign indicates heat is transferred from the system to the surroundings to keep the temperature constant in the system.

Problem 5.2A

A heat capacity equation for acetylene is given by

$$C_p = 9.89 + 0.8273 \times 10^{-2}T - 0.3783 \times 10^{-5}T^2 + 0.7457 \times 10^{-9}T^3$$

where T is in °F and C_p is in Btu/(lb mol) (°F).

a. Convert the C_p equation so that T can be inserted in the equation in °R, and the units of C_p will be Btu/(lb mol)(°R).

b. Convert the C_p equation so that T can be inserted in the equation in K and the units of C_p will be J/(g mol) (K).

Solution The units of C_p are already Btu/(lb mol) (°F) and since $\Delta°F = \Delta°R$, the units are also Btu/(lb mol) (°R). To change from $T_{°F}$, substitute $T_{°F} = T_{°R} - 460$ in the equation for $C_{p.}$

a. $$C_p = 9.89 + 0.8273 \times 10^{-2} \left(T_{°R} - 460\right) - 0.3783 \times 10^{-5} \left(T_{°R} - 460\right)^2 + 0.7457 \times 10^{-q} \left(T_{°R} - 460\right)^3$$

We will delete the cubic term for simplicity in the answer. The error is small.

$$\begin{aligned} C_p &= 9.89 + 0.8273 \times 10^{-2} (°R - 460) - 0.3783 \times 10^{-5} (°R - 920°R + 2.116 \times 10^5) \\ &= (9.89 - 0.8273 \times 10^{-2} (460) - 0.3783 \times 10^{-5} (2.116 \text{ x } 10^5)) + (0.8273 \times 10^{-2} + 0.3783 \times 10^{-5} \\ &\quad \times (920))°R - 0.3783 \times 10^{-5} °R^2 \end{aligned}$$

$$\mathbf{C_p = 5.284 + 0.1175 \times 10^{-2}\ T_{°R} - 0.3783 \times 10^{-5}\ T^2_{°R}\ \text{Btu/(lb mol) (°R)}}$$

b. First, multiply the entire equation by conversion factors to convert

$$\frac{\text{Btu}}{\text{(lb mol)(°F)}} \rightarrow \frac{\text{J}}{\text{(g mol)(K)}}$$

$$\begin{array}{c|c|c|c} \text{Btu} & 1\text{ lb} & 1.8°\text{F} & 1055\text{ J} \\ \hline \text{(lb mol)(°F)} & 454\text{g} & 1\text{K} & 1\text{ Btu} \end{array} \rightarrow 4.184 \text{ is the multiplier}$$

Then substitute in the equation for C_p the following expression for $T_{°F}$

$$T_{°F} = 1.8\ T_K - 460$$

$$\begin{aligned} C_p = [&9.89 + 0.8273 \times 10^{-2} (1.8\ T_K - 460) - 0.3783 \times 10^{-5} (1.8T_K - 460)^2 + 0.7457 \times 10^{-9} \\ &\times (1.8T_K - 460)^3] [4.184] \text{ J/(g mol) (K)} \end{aligned}$$

$$\mathbf{C_p = 6.01 + 1.86 \times 10^{-2}\ T_K - 1.45 \times 10^{-5}\ T_K^2 + 1.34 \times 10^{-9}\ T_K^3}$$

Problem 5.2B

One of your coworkers has collected experimental values for the heat capacity of air from 0 to 1500°C as follows:

T(°C)	0	18	25	100	200	300	400	500	600	700
C_p (J/g mol) (°C)	29.062	29.075	29.075	29.142	29.292	29.514	29.782	30.083	30.401	30.711
T(°C)	800	900	1000	1100	1200	1300	1400	1500		
C_p(J/(g mol) (°C)	31.020	31.317	31.585	31.865	32.108	32.338	32.556	32.761		

Use the method of least square to estimate values of the coefficients in the following two functions that can be used to calculate C_p in the future.

$$\left.\begin{aligned} C_p &= a + bT + CT^2 \\ C_p &= a' + b'T + c'T^2 + d'T^3 \end{aligned}\right\} \text{ where } T \text{ is in } {}^\circ\mathrm{C}$$

Solution

From a computer program to carry out the least squares procedure you can find

a = 28.936	**a´ = 29.041**
b = 2.39 × 10^{-3}	**b´ = 0.185 × 10^{-2}**
c = 1.62 × 10^{-7}	**c´ = 0.339 × 10^{-5}**
	d´ = -0.270 × 10^{-8}

Problem 5.2C

Two gram moles of carbon dioxide are heated from 400°C to 1100°C. Calculate ΔH by integrating the heat capacity equation for carbon dioxide. Compare your result with the value calculated from the enthalpy tables for the combustion gases.

Solution Basis: 2 g mol CO_2

a.

$$\Delta H = 2\left[\int_{400}^{1100} 36.11(1100-400) + \left(\frac{1}{2}\right)\left(4.233\times10^{-2}\right)\left(1100^2-400^2\right) - \frac{1}{3}\left(2.887\times10^{-5}\right)\left(1100^3-400^3\right) + \frac{1}{4}\left(7.464\times10^{-9}\right)\left(1100^4-400^4\right)\right] = \mathbf{7.598\times10^4\ J}$$

b. By use of the tables of enthalpies we find

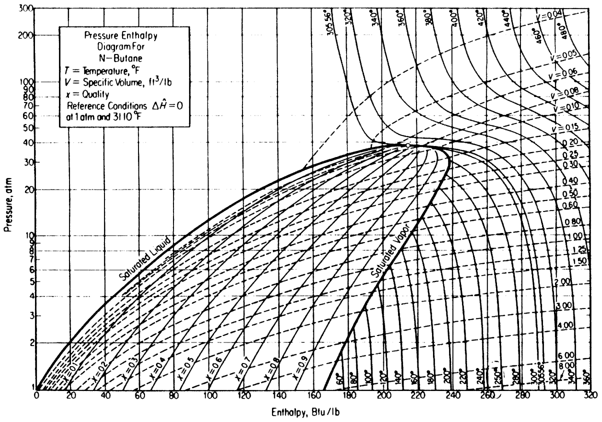
T°(C)	$\Delta\hat{H}$(J/(g mol)	
1100	55,310	
400	<u>17,340</u>	
	37,970	× 2 = **75,940 J**

Problem 5.2D

n-Butane is a common fuel used in locations where natural gas is not available. If 10 lb of n-butane are cooled from 10 atm and 260°F to saturated liquid at 2 atm, (a) determine the enthalpy change in Btu, and (b) if the 10 lb of n-butane were cooled isobarically (at constant pressure) to saturated liquid, determine the enthalpy change in Btu.

Solution

The easiest way to solve this problem is to use the pressure-enthalpy chart for n-butane found in the text. Basis: 10 lb n-butane.



Pressure enthalpy diagram for *n*-butane.

a. The pertinent data are

Initial state (260°F, 10 atm): $\Delta\hat{H} \cong 260$ Btu/lb

Final state (satd. liquid, 2 atm): $\Delta\hat{H} \cong 20$ Btu/lb

For the change

$$\Delta H = (20 - 260)\ 10 = \mathbf{-2400\ Btu}$$

b. The initial specific enthalpy is still the same. The final specific enthalpy is $\Delta\hat{H}$(satd. liq., 10 atm) = 87 Btu/lb

For the change

$$\Delta H = 10\ (87 - 260) = \mathbf{-1730\ Btu}$$

Problem 5.2E

Use the SI data for water to calculate the change of enthalpy that occurs when 5 kg of water at 70°C in a closed vessel of $0.50 m^3$ in volume are heated to 453.1 K and 1000 kPa. Also determine the final quality of the steam in the vessel.

Solution

Even though the initial pressure of the water is not stated (remember, enthalpy is a function of temperature and pressure), the effect of pressure is negligible so that you can assume that the initial conditions are saturated water at 70°C (343K) where the specific liquid enthalpy is $\Delta\widehat{H}$ = 289.9 kJ/kg. The final conditions are 453.1K and 1000 kPa where the water is still saturated, hence at the final conditions the vessel contains a mixture of vapor and liquid. The fraction vapor has to be calculated first (the quality). Data at 453.1K and 1000 kPa are:

$\hat{V}_{liquid}$ = 0.001127 m^3/kg $\hat{V}_{vapor}$ = 0.1944 m^3/kg

$\Delta\hat{H}_{liquid}$ = 762.5 kJ/kg $\Delta\hat{H}_{vapor}$ = 2777.6 kJ/kg

The total volume is comprised of the volume of the liquid plus the volume of the vapor. Let x = fraction vapor.

Basis: 1 kg H_2O

b. $\frac{0.50}{5} = (1 - x)\,(0.001127) + x\,(0.1944)$ **x = 0.51**

The enthalpy of the wet steam is

a. $A\hat{H}$ = 0.49 (762.5) + 0.51 (2777.6) = 1794 kJ/kg so that the change in the enthalpy of the water is $\Delta H_{final} - \Delta H_{initial}$ = (1794 – 289.9) (5) = **7520 kJ**

Problem 5.2F

Use the steam tables in American Engineering units to calculate the quality of 15 lb of wet steam at 120 psia when the enthalpy of the wet steam has been calculated to be 12,000 Btu (relative to liquid water at 32°F which has a value of 0 Btu).

Solution

Basis: 1 lb wet steam at 120 psia

The enthalpy of the wet steam is 12,000/15 = 800 Btu/lb. From the steam tables for saturated steam at 120 psia the specific enthalpies of the liquid and vapor are

$\Delta\hat{H}_L$ = 312.46 Btu/lb $\Delta\hat{H}_V$ = 1190.6 Btu/lb

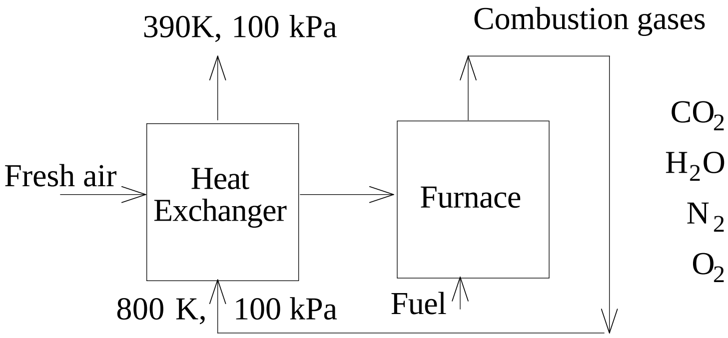
If we let x be the quality (vapor fraction) of the steam

$$312.46\,(1 - x) + 1190.6\,(x) = 800$$

x = 0.56

Problem 5.2G

Energy can be saved by passing the combustion gases from a furnace or boiler through a heat exchanger in which the air entering the furnace is preheated. Examine the figure.



	mol fr.	
CO_2	0.070	3.12×10^5 m^3/hr
H_2O	0.140	830K
N_2	0.730	100 kPa
O_2	0.060	
	1.000	

The air does not contact the combustion gases directly in the heat exchanger; the streams are separated by tube walls. Calculate the enthalpy change in kJ that occurs for the combustion gases on passing through the heat exchanger.

Solution

The system is the heat exchanger. The process is steady state without reaction.

Step 5 Basis: 1 hr

HEAT EXCHANGERS

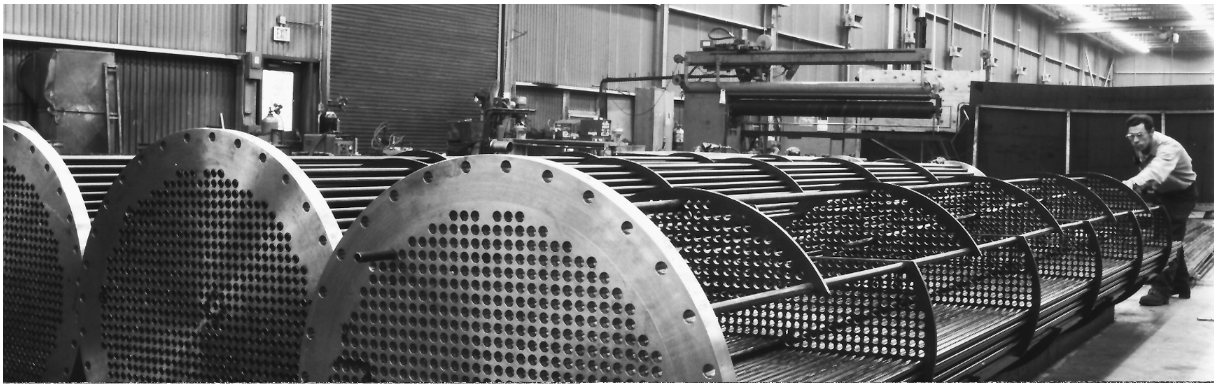


Fig 21a Shell and tube heat exchanger under construction (courtesy of Guston County Dyeing Machine Co.)

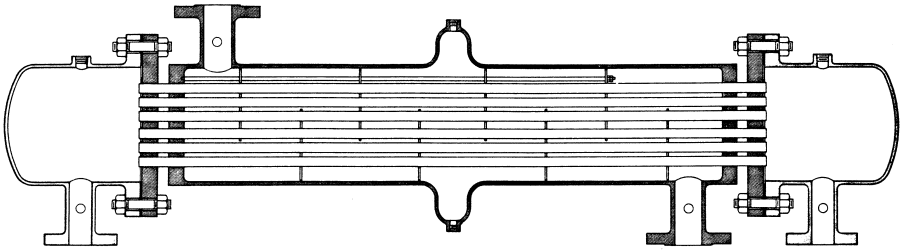


Fig 21b Line drawing of a standard type of shell and tube heat exchanger (courtesy of Patterson-Kelley Co.)

In these types of heat exchangers the two fluids are separated by the tube walls. As one fluid flows through the shell-- the region outside the tubes -- the other fluid flows through the tubes. Heat transfer occurs so as to cool, and perhaps even condense, the hotter fluid, and heat, and even vaporize, the cooler fluid. Heat exchangers are called by various names depending on their function such as chillers, condensers, coolers, heaters, reboilers, steam generators, vaporizes, waste heat boilers, and so on.

$$n = \frac{100\text{ kPa}}{} \left|\, \frac{3.12\times 10^5\text{m}^3}{830\text{K}} \right|\, \frac{1\text{ (kg mol)(K)}}{8.314\text{ (kPa) (m}^3)} = 4.52\times 10^3\text{ kg mol}$$

Steps 1, 2, 3, and 4

All the data needed are in the figure except the specific enthalpy data which are in the third and fourth columns below. Interpolation in the tables in the text is needed to get $\Delta\hat{H}$ at 390K.

	$n(\text{kg mol}\times 10^{-3})$	$\Delta\hat{H}(\text{kJ / kgmol})$ at 390K	$\Delta\hat{H}(\text{kJ / kgmol})$ at 800K	$\Delta H = n\left(\Delta\hat{H}_{390} - \Delta\hat{H}_{800}\right)(\text{kJ})$
$CO_2(g)$	0.316	3404	23,710	–6,420
$H_2O(g)$	0.633	3456	18,823	–9,730
$N_2(g)$	3.30	4511	15,756	–37,110
$O_2(g)$	0.27	3946	16,564	–3,410
				ΔH = –56,670 kJ

Problem 5.2H

The vapor pressure of benzene can be calculated from the Antoine equation.

$$\ln(p^*) = 15.9008 - \frac{2788.51}{-52.36 + T}$$

where p^* is in mm Hg and T is in K. Determine the heat of vaporization of benzene at its normal boiling point, and compare with the experimental value.

Solution

The normal boiling point of benzene = 353.26K. Use the Clausius Clapeyron equation to get ΔH_v

$$\frac{d\ln p^*}{dt} = \frac{\Delta\hat{H}_v}{RT^2}$$

Differentiate the Antoine equation with respect to T

$$\frac{d\ln p^*}{dT} = -2788.51\left(-\frac{1}{(-52.36+T)^2}\right)$$

$$\frac{d\ln p^*}{dT} = \frac{2788.51}{(-52.36+T)^2}$$ (the units of the right hand side are K^{-1})

and equate the result with the right hand side of the Clausion Clapeyron equation to get

$$\frac{\Delta\hat{H}_v}{RT^2} = \frac{2788.51}{(-52.36 + T)^2}$$

Substitute T = 353.26 K and R = 8.314 J/(g mol) (K), and solve for $\Delta\hat{H}_v$

$$\Delta\hat{H}_v = \left.\frac{8.314\text{J}}{(\text{g mol})\ (\text{K})}\right|\left.\frac{(353.26\text{K})^2}{}\right|\frac{2788.51}{(-52.36 + 353.26)^2\text{K}} = \frac{3.195 \times 10^4\text{J}}{\text{g mol}}$$

or **31.95 kJ/g mol** compared with **30.76** from the Appendix in the text.

Problem 5.2I

Lead is used in a number of manufacturing industries. To prevent lead vapor from escaping from a molding unit, the vapors from the unit are passed through a chilling unit to condense the lead vapor. What is the enthalpy change per kg mol of lead if the lead vapor entering the chiller is at 1850°C and the product of the chiller is solid lead at 280°C.

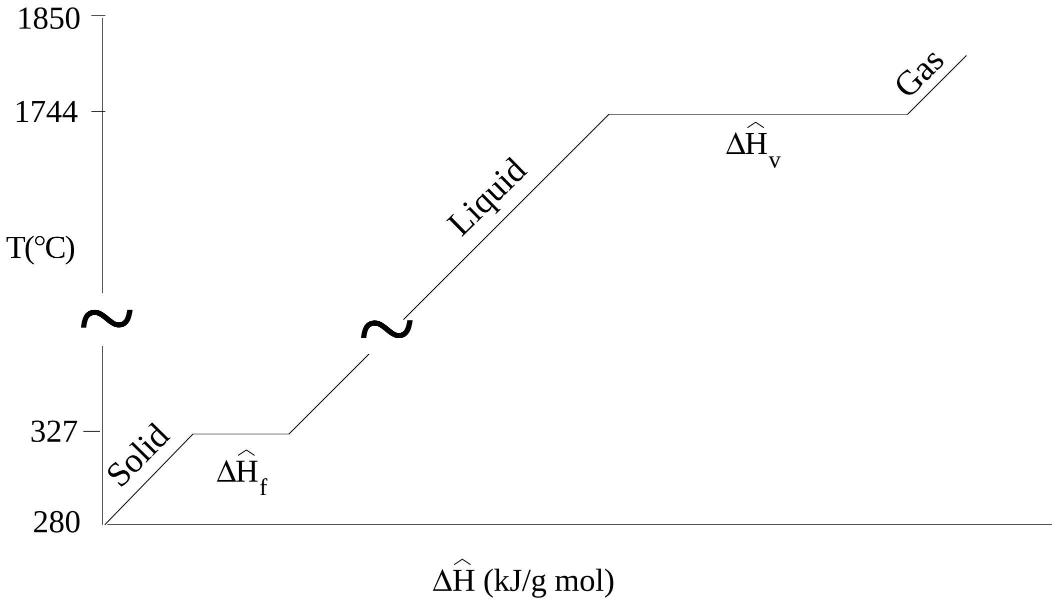
Data:

Melting point of lead:	327.4°C
Boiling point of lead:	1744°C
Heating capacity data:	J/(g mol)(K) with T in K:
Solid	24.1 + 0.049 T
Liquid	6.8
Vapor	20.8
Heat of fusion:	5.121 kJ/g mol
Heat of vaporization:	175.98 kJ/g mol

Solution

Basis: 1 g mol of lead

The diagram shows figuratively (not to scale) the successive calculations that must be carried out to get the overall enthalpy change.



$$\Delta\hat{H} = \int_{1850}^{1744} 20.8\ dT - 175.98\times10^3 + \int_{1744}^{327.4} 6.8\ dT - 5.121\times10^3$$

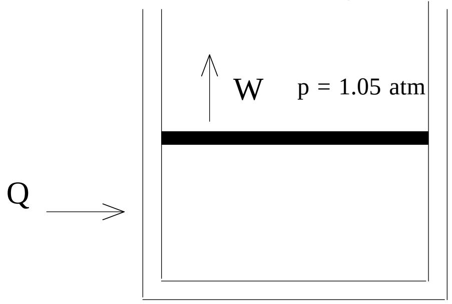
$$+\int_{327.4+273.15}^{280+273.15} (24.1+0.049T)\ dT = \mathbf{-195{,}400\ kJ/gmol}$$

Problem 5.3A

Determine Q, W, ΔU and ΔH for the isothermal expansion of 1.31 mol of an ideal gas against a constant external pressure of 1.05 atm. This initial conditions are: T = 276 K and p_1 = 4.62 atm; the final pressure is p_2 = 2.21 atm for the gas.

Solution

Steps 1, 2, 3 and 4 This is an unsteady state closed process without reaction. The energy balance reduces to Q + W = ΔU. The system is the gas plus the sealing barrier.



	Initial	*Final*
p (atm)	4.62	2.21
T(K)	276	276

Assume that the work done by the gas is done only against the source of the external pressure, and none is done against the cylinder wall (frictionless piston assumption). We will assume that the surface enclosing the gas has no weight so that no change in potential energy is involved.

Step 5 Basis: 1.31 mol of ideal gas at 4.62 atm and 276 K

Step 6 The unknowns are Q, W, ΔU and ΔH

Steps 7, 8 and 9 Because the process is isothermal, **ΔH = ΔU = 0** since the gas is ideal. To calculate W we use

$$W = -\int_{V_1}^{V_2} p dV = -p\Delta V.$$

Use pV = nRT to calculate the initial and final volumes: V = n R T/p

$$V_{initial} = 6.42 \text{ L} \qquad V_{final} = 13.43 \text{ L}$$

$$\mathbf{W} = -p\Delta V = -1.05 \text{ atm } (13.43 - 6.42) \text{ L} = -7.36 \text{ (L) (atm)} = \mathbf{-745 \text{ J}}$$

$$\mathbf{Q = -W = 745 \text{ J}}$$

Note: The work being done by the system is negative and heat being supplied to the system is positive.

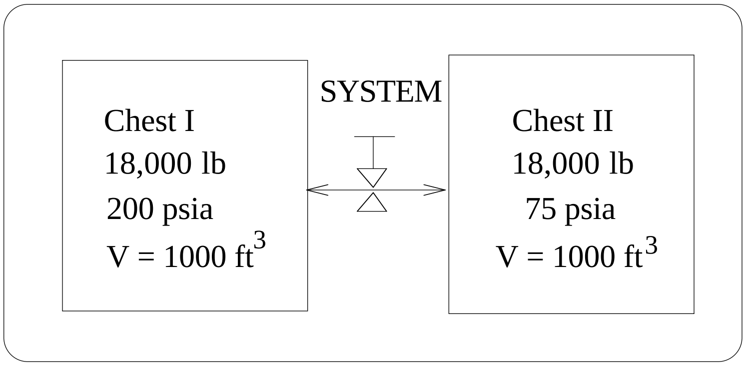
Problem 5.3B

In a paper mill two steam chests are to be operated in parallel. Each has a volumetric capacity of 1000 cu.ft and each contains 18,000 lb of steam and liquid water. The first chests registers a pressure of 200 psia, but owing to an error, it is connected to the second when the pressure in the latter is 75 psia. What will be the pressure in the system after equilibrium has been attained. It may be assumed that no heat is exchanged with the surroundings, and no water exits to the surroundings.

Solution This is a closed system for an unsteady state process without reaction.

Steps 1, 2, 3 and 4

The figure shows the initial conditions of the system.



Data from the steam tables are:

Data: p_s (psia)	T_s (°F)	$V_{Liq.}$ (ft^3/lb)	V_{Gas} (ft^3/lb)	$\Delta H_{Liq.}$ (Btu/lb)	ΔH_{Gas} (Btu/lb)
200	381.8	0.01839	2.288	355.4	1198.7
75	307.6	0.01753	5.820	277.4	1181.9

The initial specific volumes show that the steam is a saturated mixture of liquid and vapor in each steam chest at the initial conditions.

Step 5 Basis: 18,000 lbs water + steam @ 200 psia, and 18,000 lbs water + steam @ 75 psia

Steps 6, 7, 8, and 9

The material balance is: the 36,000 lb of water present initially are present at the final state.

The energy balance is

$$\Delta E = \Delta U + \Delta P + \Delta K = -\Delta\left[\left(\hat{H}+\hat{P}+\hat{K}\right)\ m\right] + Q + W$$

STEAM CHEST

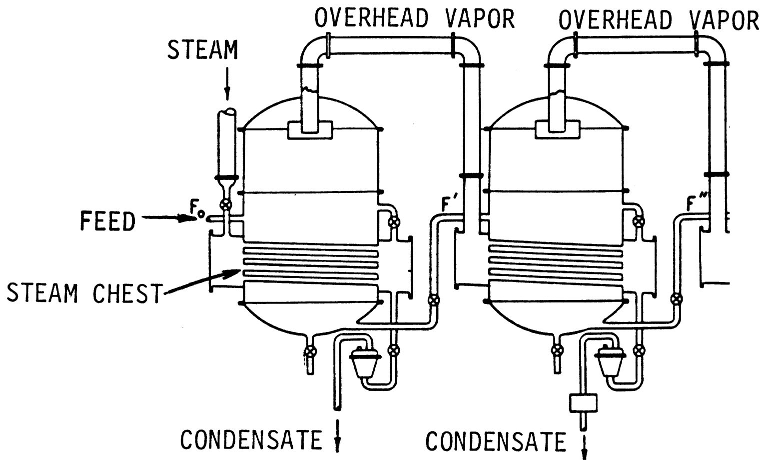


Fig 22 Steam chest in an evaporator

A steam chest is a heat exchanger placed inside another piece of equipment, such as an evaporator. In the figure steam is introduced into a set of tubular coils (or straight tubes) place inside the evaporator shell and submerged in the liquid. Steam condenses and is withdrawn as liquid condensate. A trap at the chest exit prevents the steam itself from escaping.

and the terms that are zero are:

ΔP	(no change from the reference plane)
ΔK	(no velocity)
$\Delta\left[\left(\hat{H} + \hat{P} + \hat{K}\right)m\right]$	(no mass flow in or out)
Q	(assumed zero)
W	(no change in system boundary)

Thus, $\Delta U = 0$, or $\Delta U_{initial} = \Delta U_{final}$.

Step 6 The unknown is the final pressure which will be the equilibrium pressure at the final temperature of the system.

Step 4 Calculate the initial internal energy of the system. If the SI steam tables are used, $\Delta\hat{U}$ can be read directly in the tables. If the American Engineering Tables are used

$$\Delta\hat{U} = \Delta\hat{H} - \Delta(p\hat{V})$$

hence both p and $\hat{V}$ as well as $\Delta\hat{H}$ are needed. Recall that at the reference conditions for the steam tables, p = 0.0886 psia and T = 32°F, $\Delta\hat{H} = 0$.

The specific volume of the water in both steam chests is $\frac{1000\ \text{ft}^3}{18{,}000\ \text{lb}} = 0.0556\ \text{ft}^3/\text{lb}$

Step 5 Basis: 1 lb steam

Step 4

<u>*The system is steam chest I*</u>. The initial fraction vapor comes from a volume balance. Let x_i = fraction vapor in steam chest I

$0.0556 = (1 - x_I)(0.01839) + (x_I)(2.288)$ $\qquad x_I = 0.0164$

$$\Delta\hat{U}_I = \{[0.9836\,(355.4) + 0.0164\,(1198.7)] - [0]\} - \Delta\left(p\hat{V}\right)$$

(Note: $\Delta\hat{H}$ is 0 at 32°F and the vapor pressure of water so that the reference for the pV calculations is at the same conditions.)

$\Delta\left(p\hat{V}\right)$ is a very small quantity as can be seen from the following calculations:

$$\left(p\hat{V}\right)_{32°F}{}^{32°F} = \frac{0.0886\ \text{lb}_f}{\text{in}^2}\left|\frac{144\ \text{in}^2}{1\ \text{ft}^2}\right|\frac{0.01602\ \text{ft}^3}{1\ \text{lb}_m}\left|\frac{1\ \text{Btu}}{778.16\ (\text{ft})(\text{lb}_f)}\right. = 0.00026\ \text{Btu}$$

$\Delta\hat{U}_I = 369.2 - 2.06 = 367.2$ Btu $\qquad \Delta(pV) = 2.06$ Btu

Next, the system is steam chest II.

$$0.0556 = (1 - x_{II})\,(0.01753) + (x_{II})\,(5.820)$$

$$x_{II} = 0.00656 \qquad \Delta\left(p\hat{V}\right) = 0.77\ \text{Btu}$$

$$\Delta\hat{U}_{II} = \left\{\left[0.99346\,(277.4) + 0.00656\,(1181.9)\right] - [0]\right\} - 0.77 = 282.6\ \text{Btu}$$

Steps 7, 8, and 9

Thus, $\Delta U_{\text{final}} = 367.2\,(18{,}000) + 282.6\,(18{,}000) = 1.170 \times 10^7$ Btu

After equilibrium is reached, to get the pressure we need to find two intensive properties to fix the state of the system (from among $\hat{V}$, $\Delta\hat{U}$, T, and x). One is

$$\hat{V} = \frac{2000\,\text{ft}^3}{36{,}000\ \text{lb}} = 0.0556\ \text{ft}^3/\text{lb}$$

We can get an approximate answer by estimating the $\Delta\left(p\hat{V}\right)$ term as about 1 Btu in calculating $\Delta\hat{H}$

$$\Delta\hat{U}_{\text{final}} = \frac{1.170 \times 10^7\,\text{Btu}}{36{,}000\ \text{lb}} = 325.25\ \text{Btu/lb}$$

$$\Delta\hat{H} = 326\ \text{Btu/lb}$$

Assume a final pressure of 120 psia so that $\Delta\hat{H}_L$ = 312.46 Btu/lb and $\Delta\hat{H}_G$ = 1190.6 But/lb; T = 341.26°F; $\hat{V}_L$ = 0.0179 ft^3/lb and $\hat{V}_G$ = 3.728 ft^3/lb; the fraction vapor is

$$0.0556 = (1 - x)\,(0.0179) + (x)\,(3.728)$$
$$x = 0.01016$$

To check the assumption calculate $\Delta\hat{H}$

$$0.98984\,(312.46) + 0.01016\,(1190.6) = 309.3 \neq 326 \qquad \text{Too low.}$$

Assume a final pressure of 130 psia so that $\Delta\hat{H}_L$ = 318.81, and $\Delta\hat{H}_G$ = 1192.0; T = 347.31°F; $\hat{V}_L$ = 0.0180 and $\hat{V}_G$ = 3.455.

$$0.0556 = (1 - x)\,(0.0180) + (x)\,(3.455)$$
$$x = 0.01094$$

Check $\Delta\hat{H}$ again.

$$0.98905\,(318.81) + 0.01094\,(1192.0) = 328.4 \qquad \text{Too high.}$$

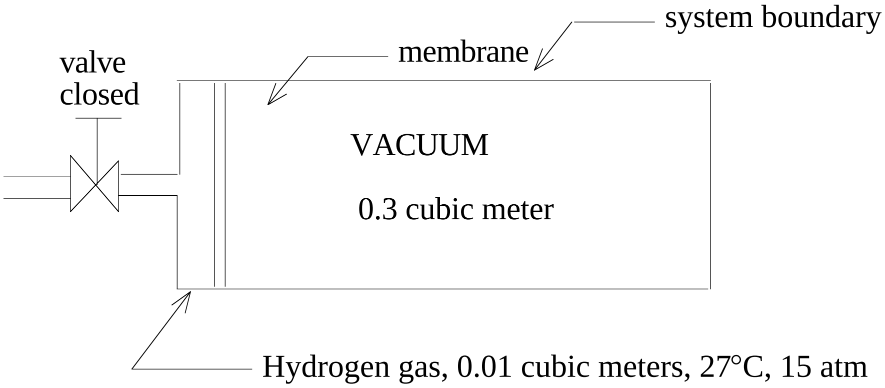
The pressure is about **129 psia.**

Problem 5.3C

A shock tunnel uses hydrogen as its driving gas. The hydrogen at high pressure is restrained by a metallic membrane. When the membrane is ruptured, the hydrogen bursts into the evacuated section and a researcher can study high intensity shock waves. Given the data on the schematic diagram of the tunnel, determine the final temperature and pressure of the gas. The process occurs quickly, before any appreciable heat transfer can occur between the gas and the walls of the chamber.

Solution

Steps 1, 2, 3 and 4 This is an unsteady state process without reaction. The system will be entire chamber, both the high pressure side and the vacuum side. All of the known data have been placed on the figure.



Step 5 Basis: 0.01 m^3 of H_2 at 27°C, 15 atm

Steps 6, 7, and 8

The unknowns are the final temperature and pressure. The mass balance is just the initial mass of H_2 equals the final mass of H_2. The energy balance

$$\Delta E = \Delta U + \Delta P + \Delta K = -\Delta\left[\left(\hat{H} + \hat{P} + \hat{K}\right)\ m\right] + Q + W$$

reduces to $\Delta U = 0$ because $\Delta P = \Delta K = 0$ and all the terms on the right hand side of the equation are zero (no mass flow, no heat transfer, and fixed system boundary.)

Let us check to see if the H_2 can be treated as an ideal gas because we know if $\Delta U = 0$, the final temperature equals the initial temperature for an ideal gas.

$p_c = 12.8$ atm $\qquad T_c = 33.3\text{K}$

use $\quad p_c' = 12.8 + 8 = 20.8$ atm $\qquad T_c' = 33.8 + 8 = 41.8\text{K}$

$$p_r' = \frac{15}{20.8} = 0.72 \qquad T_r' = \frac{300}{41.8} = 7.18$$

From the compressibility charts $z \cong 1.01$ so that the assumption of an ideal gas holds, and $\Delta U = 0$ so the final temperature = 300K = T. At constant temperature.

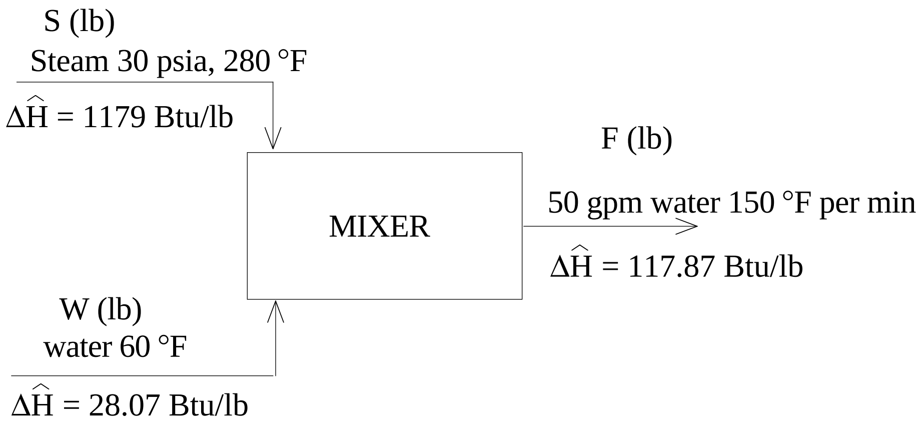
$$p_2 = p_1\left(\frac{V_1}{V_2}\right) = 15\left(\frac{0.01}{0.31}\right) = \mathbf{0.48\ atm}$$

Problem 5.3D

A stream of hot water at 150 °F flowing at a rate of 50 gal/min is to be produced by mixing water at 60 °F and steam at 30 psia and 280 °F in a suitable mixer. What are the required flow rates of steam and cold water. Assume Q = 0.

Solution

Steps 1, 2, 3 and 4 This is a steady state problem. The system is open. No reaction occurs. The stream properties are placed in the figure



$$\frac{50\text{ gal}}{\text{min}}\left|\frac{1\text{ ft}^3}{7.48\text{ gal}}\right|\frac{1\text{ lb}_m}{0.01634\text{ ft}^3} = 409\,\frac{\text{lb}_m}{\text{min}}$$

Step 5 Basis: 50 gpm of hot water at 150 °F (equivalent to 1 min)

Steps 6 and 7 Unknowns are m_W, m_S.

Balances (2): Energy balance and overall mass balance. The mass balance is

$$S + W = F = 409$$

There is no heat exchange with the surroundings, so that Q = 0. The work W = 0, the kinetic and potential energies are constant, hence $\Delta K = \Delta P = 0$, and there is no accumulation in the system so that $\Delta E = 0$. The overall energy balance reduces to

$$\Delta H = 0 = F\,\Delta\hat{H}_F + S\,\Delta\hat{H}_S + W\,\Delta\hat{H}_W$$

Steps 7, 8 and 9

Substitute the enthalpy data from steam tables:

$$28.07\ (W) + 1179\ (S) = 409\ (117.87)$$

Solve the energy balance with the material balance to get

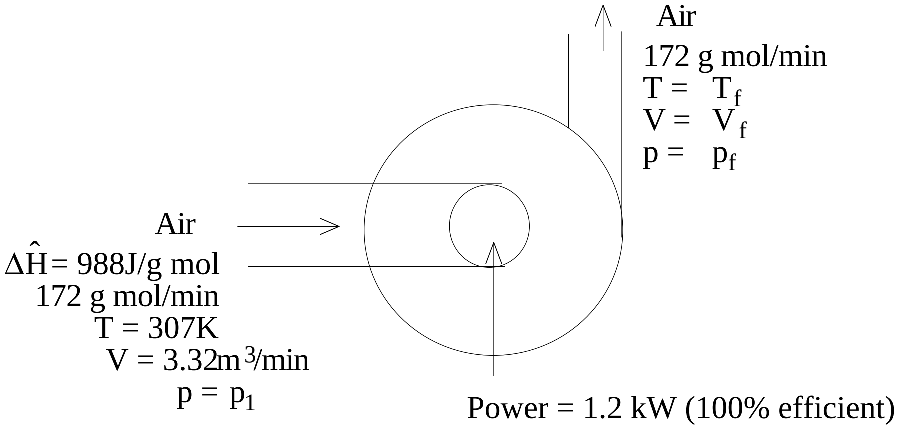
W = 377 lb/min; S = 32 lb/min

Problem 5.3E

In a waste treatment plant, hazardous chemicals are oxidized to less toxic chemicals by bubbling air through the waste solution. This process is known as aeration. The rate of aeration is governed by the COD (chemical oxygen demand). In a pilot unit, an air blower supplies 172 g mol of air/min to the aerator. The blower uses 1.2 kW. The inlet gas flow rate is 3.32 m^3/min at a temperature of 307 K and a pressure of p_1. Determine the final temperature of the gas assuming the process is adiabatic, and that the blower is 100% efficient.

Solution

Steps 1, 2, 3 and 4 This is a steady state flow problem without reaction. The known properties of the air are shown in the figure.



Step 5 Basis: 1 min (172 g mol/air)

Steps 6, 7, 8 and 9

The kinetic and potential energy effects can be neglected (= 0). There is no exchange of heat with the surroundings (Q = 0). The general energy balance reduces to: $\Delta H = W$

Note that the value of W is positive (work done on the system) .

$$W = \frac{1.2\ \text{kW}}{} \left| \frac{1000\ \frac{J}{s}}{1\ \text{kW}} \right| \frac{60\ \text{s}}{1\text{min}} = 7.2 \times 10^4\ \text{J/min}$$

$$\Delta H = \Delta H_{\text{final}} - \Delta H_{\text{initial}} = \left(\Delta\hat{H}_f\right) 172 - 988\,(172) = 7.2 \times 10^4$$

$\Delta\hat{H}_f = 1407$ J/g mol which from tables for the thermodynamic properties air with the same reference state (273K) corresponds to about **321K**

If you assume air is an ideal gas, you can calculate T_1 by

$$\Delta H = n \int_{307}^{T_1} C_p\, dT = 172 \left(\frac{7}{2}\right)(8.314)\,(T - 307) = +7.2 \times 10^4$$

$$T = 321\text{K}$$

Problem 5.4A

Calculate the heat of reaction at standard conditions (T = 25°C and p = 101.3kPa) for 1 mol of HCl(g) for the following reaction:

$$4HCl(g) + O_2\,(g) \leftrightarrows 2\,H_2O(g) + 2Cl_2(g)$$

Solution

The assumption is that stoichiometric amounts of the reactants react completely to form the products shown in the equation at 25°C and 1 atm.

Data	$\Delta\hat{H}^\circ_f(\text{kJ / gmol})$
HCl(g)	-92.311
$O_2(g)$	0
$H_2O(g)$	-241.826
$Cl_2(g)$	0

Basis: 4 g mol HCl(g)

$$\Delta H^\circ_{rxn} = \sum_{\text{products}} \Delta H^\circ_{f,i} - \sum_{\text{reactants}} \Delta H^\circ_{f,i}$$

$$\Delta H^\circ_{rxn} = 2(-241.826) - 4(-92.311) = 114.4 \text{ kJ}$$

$$\Delta\hat{H}^\circ_{rxn} = -\frac{114.4}{4} = \mathbf{-28.6\ kJ/g\ mol\ HCl(g)}$$

Problem 5.4B

Find the standard (25°C and 1 atm) heat of reaction for the following reaction:

$$C_3H_6(g) + 9/2\ O_2(g) \rightarrow 3\ CO_2(g) + 3H_2O(l)$$

Solution

Data	$\Delta\hat{H}^\circ_f(\text{kJ / g mol})$
$C_3H_6(g)$	20.41
$O_2(g)$	0
$CO_2(g)$	-393.51
$H_2O(l)$	-285.840

Basis: 1 g mol $C_3H_6(g)$

$$\Delta H^\circ_{rxn} = \sum_{\text{products}} \Delta H^\circ_{f,i} - \sum_{\text{reactants}} \Delta H^\circ_{f,i}$$

$$\Delta H^\circ_{rxn} = 3(-393.51) + 3\,(-285.840) - 1(20.41)$$

$$\Delta H^\circ_{rxn} = \mathbf{-2058.46\ kJ/g\ mol\ C_3H_6(g)}$$

Problem 5.4C

The corrosion of aluminum in water is normally prevented by the tightly adhering oxide layer that forms on the aluminum. If this layer were absent, as when aluminum is amalgamated with mercury in an anaerobic atmosphere, the following reaction occurs.

$$2Al(s) + 6H_2O(l) \rightarrow 2A1(0H)_3(s) + 3H_2(g)$$

To get the heat of formation of $A1(OH)_3(s)$, the reaction is carried out with stoichiometric quantities of reactants, and after complete reaction occurs you find that heat was liberated. After applying the energy balance, you calculate $\left(\Delta H^\circ_{rxn}\right)$ at standard conditions per 2 moles of A1) was –837.0 kJ. What is the heat of formation of $A1(OH)_3$ (s)?

Solution Basis: 2g mol Al(s)

Data	ΔH°_f(kJ/g mol)
Al(s)	0
$H_2O(l)$	-285.841
$A1(OH)_3(s)$	?
$H_2(g)$	0

$$\Delta H^\circ_{rxn} = \sum_{\text{products}} \Delta H^\circ_{f,i} - \sum_{\text{reactants}} \Delta H^\circ_{f,i} = -837.0$$

$$2\left(\Delta \hat{H}^\circ_f\right) - 6(-285.841) = -837.0$$

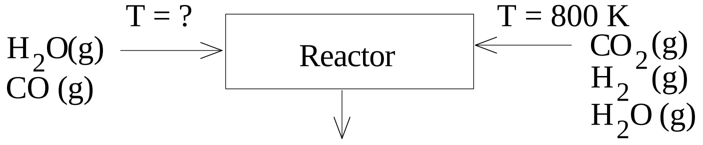
$$\mathbf{\Delta \hat{H}^\circ_f = -1276\ kJ / g\ mol\ A1(OH)_3(s)}$$

Problem 5.4D

Carbon monoxide and 100% excess water are reacted to form hydrogen and carbon dioxide. The heat loss from the reactor is 120.2 kJ per kg mole of CO entering. If the exit temperature is 800K, what is the entering temperature? The pressure is 1.0 atm. Assume complete combustion.

Solution

Steps 1, 2, 3, and 4 This is a steady state process with reaction. The system is the reactor.



heat loss: Q = –120.2 kJ/kg mol CO

$$CO(g) + H_2O(g) \rightleftarrows CO_2(g) + H_2(g)$$

$\Delta\hat{H}^\circ_f$ (kJ/g mol): –110.52 –241.826 –393.51 0

Step 5 Basis: 1.0 g mol CO entering

Steps 6, 7, 8, and 9 The material balance summary is (in g mol)

Compound	In	Out
CO	1	0
H_2O	2	1
CO_2	0	1
H_2	0	1

The enthalpies with respect to 25°C and 1 atm can calculate from the tables of the combustion gases:

Compounds In	g mol	Enthalpies (kJ/g mol)		$\Delta H(\text{kJ})$
		$\Delta\hat{H}^\circ_f$	$\Delta\hat{H}^T_{298K}$	
CO(g)	1	–110.52	$\left(\Delta\hat{H}^T_{CO} - 0.728\right)$	$-110.52(1) + \Delta\hat{H}^T_{CO}(1) - 0.728(1)$
$H_2O(g)$	2	–241.826	$\left(\Delta\hat{H}^T_{H_2O} - 0.837\right)$	$-241.826(2) + \Delta\hat{H}^T_{H_2O}(2) - 0.837(2)$
			Total	$-596.574 + \Delta\hat{H}_{CO} + 2\Delta\hat{H}_{H_2O}$

Compounds Out	g mol	$\Delta\hat{H}^\circ_f$	ΔH^{800K}_{298K}	$\Delta H(\text{kJ})$	
$CO_2(g)$	1	–393.51	(23.710 – 0.912)1	–393.51 + 22.798	= –370.71
$H_2(g)$	1	0	(15.413 – 0.718)1	0 + 14.695	= 14.695
$H_2O(g)$	1	–241.826	(18.823 – 0.837)1	–241.826 + 17.986	= –223.840
			Total		–579.867

The energy balance reduces to

$$Q = -0.1202 \text{ kJ} = \Delta H = \underset{\text{products}}{\Sigma\Delta H_i} - \underset{\text{reactants}}{\Sigma\Delta H_i}$$

so that

$$(-579.867) - \left(-596.574 + \Delta\widehat{H}^{T}_{CO_2} + 2\Delta\widehat{H}^{T}_{H_2O}\right) + 0.1202 = 0$$

By choosing successive temperatures, the energy balance can be made to balance at the desired temperature.

Let T = 500K. Then $\Delta\widehat{H}^{T}_{CO}$ = 6,652J/g mol and $\Delta\widehat{H}^{T}_{H_2O}$ = 7,752J/g mol from the tables.

$$-579.867 + 596.574 - 6.652 - 15.504 + 0.1202 = -5.329 \neq 0 \qquad \text{Too low.}$$

Let T = 400K. Then $\Delta\widehat{H}^{T}_{H_2O}$ = 3,696 J/g mol and $\Delta\widehat{H}^{T}_{H_2O}$ = 4,284 J/g mol.

$$-579.867 + 596.574 - 3.696 - 8.568 + 0.1202 = 4.563 \neq 0 \qquad \text{Too High}$$

However the temperature has been bracketed and linear interpolation gives

$$400 + \frac{4.563 - 0}{4.563-(-5.329)}(100) = \mathbf{446K}$$

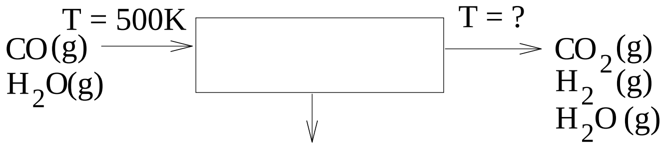
You could use the heat capacity equations to get the enthalpy changes for the gases, $\Delta\widehat{H}^{T}_{i,\ 298}$, i.e., use the sensible heats, but the calculations would take longer than using the tables. However, you would get an equation (fourth order) containing only one variable, the desired temperature T. By dropping terms higher than second order (which contribute little to ΔH), you can solve a quadratic equation for T.

Problem 5.4E

Carbon monoxide is reacts with 100% excess water to form carbon dioxide and hydrogen. The reactants enter the reactor at 500K and 1.0 atm. Because of poor insulation, the heat loss from the reactor is 71.21kJ per g/mol of carbon monoxide entering. Find the temperature of the outlet gas stream from the reactor.

Solution

Steps 1, 2, 3 and 4 This is a steady state problem with reaction. The system is the reactor.



heat loss: $Q = -71.21$ kJ/g mol CO

	$CO(g)$ +	$H_2O(g)$ $\rightarrow$	$CO_2(g)$ +	$H_2(g)$
$\Delta\hat{H}^\circ_f$(kJ/g mol):	–110.52	–241.826	–393.51	0

Step 5 Basis: 1 g mol CO entering

Steps 6, 7, 8 and 9

Material Balance	*In*	*Out*
$CO(g)$	1	0
$H_2O(g)$	2	2 – 1 = 1
$CO_2(g)$	0	1
$H_2(g)$	0	1

Energy Balance

The energy balance reduces to $Q = \Delta H$, and $\Delta H = n \sum_{\text{products}} n_i\left(\Delta\hat{H}^\circ_{f,i} + \Delta\hat{H}^T_{298,i}\right)$ $-\sum_{\text{reactants}} n_i\left(\Delta\hat{H}^\circ_{f,i} + \Delta\hat{H}^{500}_{298,\ i}\right)$. Let T = 298K be the reference temperature.

Heat capacity equations can be used to calculate the "sensible heats", $\Delta\hat{H}^T_{298}$ instead of tables, but use of the tables is quicker.

In

Compound	g mol	$\Delta\hat{H}^\circ_f$ (kJ/g mol)	$\Delta\hat{H}^{500}_{298}$ (kJ/g mol)	ΔH(kJ)
$CO(g)$	1	–110.52	(6.652 – 0.728)	–104.596
$H_2O(g)$	2	–241.826	(7.752 – 0.837)	–469.822
				–574.418

Out

Compound	g mol	$\Delta\hat{H}_f^\circ$ (kJ/g mol)	$\Delta\hat{H}_{298}^T$ (kJ/g mol)	ΔH(kJ)
$CO_2(g)$	1	–393.51	$\left(\Delta\hat{H}^T_{CO_2} - 0.912\right)$	$\Delta\hat{H}^T_{CO_2} - 394.422$
$H_2(g)$	1	0	$\left(\Delta\hat{H}^T_{H_2} - 0.718\right)$	$\Delta\hat{H}^T_{H_2} - 0.718$
$H_2O(g)$	1	–241.826	$\left(\Delta\hat{H}^T_{H_2O} - 0.837\right)$	$\Delta\hat{H}^T_{H_2O} - 242.663$
				$\Sigma\Delta\hat{H}^T_i - 637.803$

We need to assume temperatures until we find the temperature that yields $\Delta\hat{H}^T_i$ values that cause the energy balance to balance:

$$\Delta H - Q = 0 \text{ or}$$

$$\left[(1)\left(\Delta\hat{H}^T_{CO_2}\right) + (1)\left(\Delta\hat{H}^T_{H_2}\right) + (1)\left(\Delta\hat{H}^T_{H_2O}\right) - 637.803 - (-469.822)\right] + 71.21 = 0$$

Let T = 1000K. Then

(1)	$\Delta\hat{H}^T_{CO_2}$	=	34.308
(1)	$\Delta\hat{H}^T_{H_2}$	=	21.388
(1)	$\Delta\hat{H}^T_{H_2O}$	=	26.823
	Total		82.519

Substitute 82.519 in the energy balance and get for the sum of the terms –14.252 kJ. Too low.

Increase the temperature to 1200K:

$$(1)\,\Delta\hat{H}^T_{CO_2} + (1)\,\Delta\hat{H}^T_{H_2} + (1)\,\Delta\hat{H}^T_{H_2O} = 45.404 + 27.509 + 35.312 = 108.225$$

and the energy balance sums to 11.454 kJ: Too high. The temperature is bracketed, however.
Use T = 1100K

$$(1)\,\Delta\hat{H}^T_{CO_2} + (1)\,\Delta\hat{H}^T_{H_2} + (1)\,\Delta\hat{H}^T_{H_2O} = 39.802 + 24.426 + 31.011 = 95.239$$

and the energy balance sums to –1.53kJ.

The temperature is $1100 + 100\,\dfrac{0-(-1.53)}{11.454-(-1.53)} = \mathbf{1112K}$

FURNACE

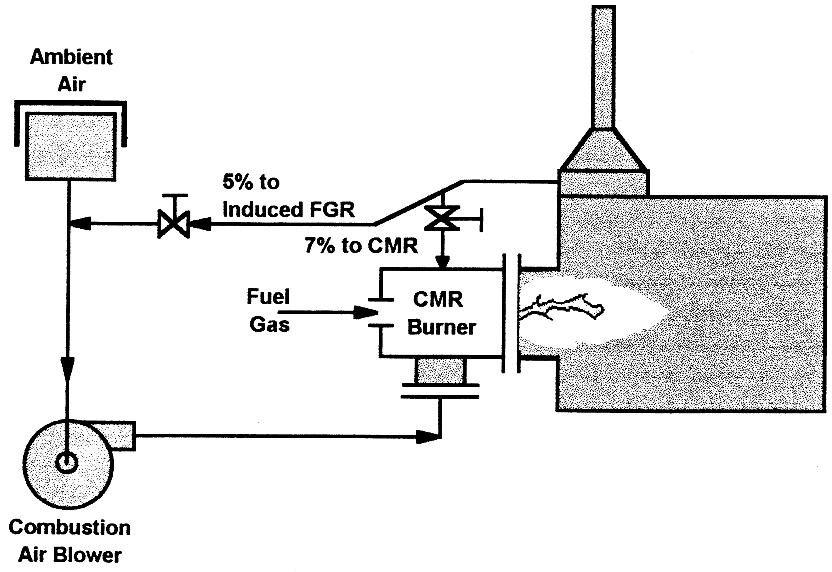


Fig 23 Furnace (with recirculated combustion products)

Combustion of fuel focuses on the production of CO_2 and H_2O, but a small amount of N_2 also oxidizes to form various nitrogen oxides, NO_x, that are pollutants. Increasingly stringent federal and local regulations for the permitted NO_x emmissions in flue gas discharge have led to various technologies for NO_x reduction. A combination of combustion staging, premix combustion, and recirculation make it possible to achieve low NO_x levels.

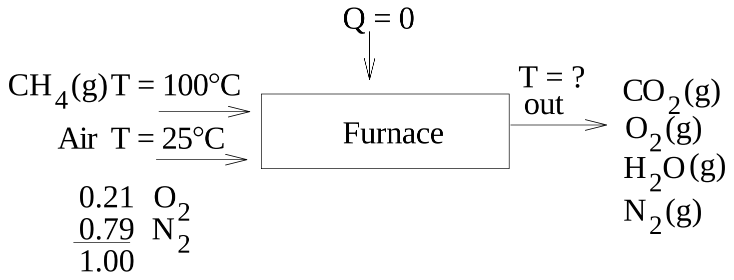
Problem 5.4F

Methane at 100°C is burned with 100% excess air which is at 25°C in an insulated furnace. From the data given, calculate the adiabatic flame temperature.

Solution

Steps 1, 2, 3 and 4

The system is the reactor.



This is a steady state process with reaction

	$CH_4(g)$ +	$2O_2(g) \rightarrow$	$CO_2(g)$ +	$2H_2O(g)$
$\Delta\hat{H}_f^\circ$(kJ/g mol):	–74.84	0	–393.51	–241.826

Step 5 Basis: 1 g mol CH_4 entering

Steps 6, 7, 8 and 9

Material Balance Summary

Component	*g mol in*	*g mol out*
$CH_4(g)$	1.0	0
$O_2(g)$	2 reqd + 2xs = 4	2.0
$N_2(g)$	15.05	15.05
$CO_2(g)$	0	1.0
$H_2O(g)$	0	2.0

The energy balance reduces to $\Delta H = 0$. Let T = 25°C be the reference temperature. The sensible heats will be taken from the tables of enthalpies of gases so that a trial and error solution procedure will be needed. (If heat capacity equations are used to calculate the "sensible heats," i.e., $\Delta\hat{H}_{298}^{T}$, then the energy balance reduces to a cubic or quadratic equation in T_{out} that must be solved for T_{out}.

Components In	T(K)	g mol	$\Delta\hat{H}_f^\circ$(kJ/g mol)	$\Delta\hat{H}_{298}^{T}$(kJ/g mol)	ΔH(kJ)
$CH_4(g)$	373	1.0	–74.84	(3.717 – 0.879)	–72.00
$O_2(g)$	298	4.0	0	(0.732 – 0.732)	0
$N_2(g)$	298	15.05	0	(0.728 – 0.728)	0
				Total	–72.00

Components Out	g mol	$\Delta\hat{H}^\circ_f$(kJ/g mol)	$\Delta\hat{H}^T_{298}$(kJ/g mol)	ΔH(kJ)
CO_2(g)	1.0	–393.51	$\left(\Delta\hat{H}^T_{CO_2} - 0.912\right)$	$\Delta\hat{H}^T_{CO_2} - 394.422$
H_2O(g)	2.0	–241.826	$\left(\Delta\hat{H}^T_{H_2O} - 0.837\right)$	$2\Delta\hat{H}^T_{H_2O} - 485.326$
O_2(g)	2.0	0	$\left(\Delta\hat{H}^T_{O_2} - 0.732\right)$	$2\Delta\hat{H}^T_{O_2} - 1.464$
N_2(g)	15.05	0	$\left(\Delta\hat{H}^T_{N_2} - 0.728\right)$	$15.05\Delta\hat{H}^T_{N_2} - 10.956$
			Total	$\Sigma\Delta\hat{H}^T_i - 892.168$

Substitution of the above quantities into the energy balance ($\Delta H = 0$) gives ($\Delta H_{out} - \Delta H_{in}$) = 0 or

$$\left[\Delta\hat{H}^T_{CO_2} + 2\Delta\hat{H}^T_{H_2O} + 2\Delta\hat{H}^T_{O_2} + 15.05\ \Delta\hat{H}^T_{N_2} - 892.168\right] - [-72.00] = 0$$

We assume a series of temperatures to bracket the solution, and introduce the corresponding $\Delta\hat{H}^T_i$ values from the enthalpy tables into the equation.

Let T = 1500 K

$$62.676 + 2\ (48.848) + 2\ (41.337) + 15.05\ (39.145) - 820.168 = 12.010$$

Let T = 1400K

$$56.860 + 2(44.237) + 2(37.693) + 15.05\ (35.639) - 820.168 = -63.081$$

$$T = 1500 - \frac{(12.010 - 0)}{(12.010 - (-63.081))}(100) = \mathbf{1484\ K}$$

Problem 5.5A

Nitrogen at 500K and 200kPa absolute is enclosed in a cylinder fitted with a frictionless piston. The weight of the piston exerts a force of 50.1 kPa on the gas, and the barometer reads 99.0 kPa. The gas moves the piston up expanding the gas volume from 0.50m^3 to 0.63m^3. Calculate the work done by nitrogen for two cases:

(a) The expansion is isobaric (constant pressure)
(b) The expansion is isothermal (constant temperature)

Assume the N_2 behaves as an ideal gas.

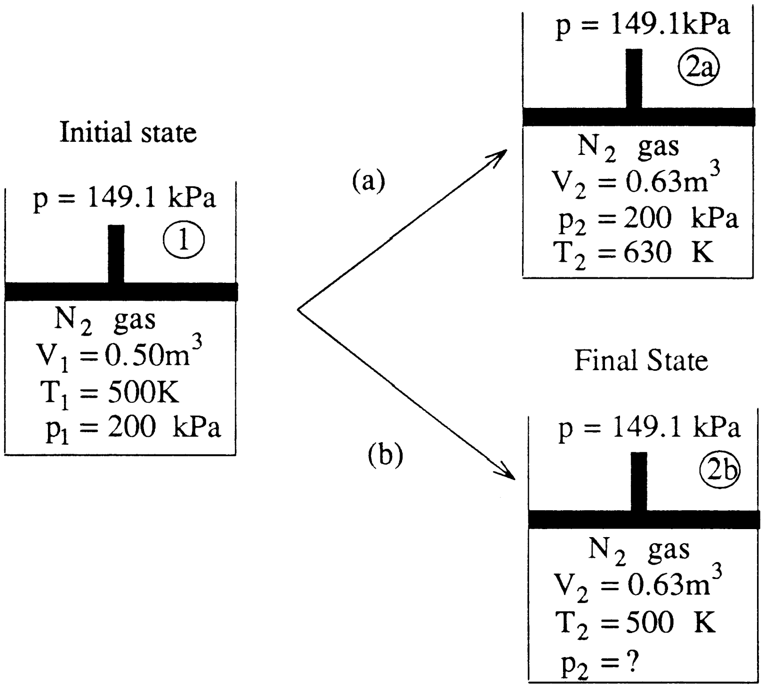
Solution

Note that the piston has to be frictionless because otherwise work will be done in an unknown amount against the cylinder wall. The force of the gas in the bottom of the piston is 200 kPa, and the force on the top exerted by the atmosphere and the weight of the piston is 149.1 kPa so that the system is not at equilibrium and the piston must be held in place initially by a lock. If the piston is released, the gas will expand until the gas pressure reaches some new value at a new volume (the piston has to be stopped by a lock), but the expansion will not be a reversible process -- quite the contrary. The system is the gas.

What we will calculate is the upper limit obtainable for the work if the gas expanded reversibly. The idea of maintaining reversibility during expansion is itself contradicted by the need for a pressure difference (absence of equilibrium) for expansion to take place! Heat has to be added to the cylinder to maintain a constant pressure or temperature in the gas.

Steps 1, 2, 3 and 4

The figure shows the two cases, a and b, and the calculated data has been placed on the figure.



Step 5 Basis: 0.50m^3 of N_2 at 500K and 200 kPa

Steps 6, 7, 8 and 9

The unknown is the work done by the gas, W. Assume that N_2 is an ideal gas so that pV = nRT.

$$n_{N_2} = \frac{pV}{RT} = \frac{200\text{kPa}}{\dfrac{8.314(\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})}}\left|\frac{0.5\text{m}^3}{500\text{K}}\right. = 0.024 \text{ kg mol}$$

Isobaric Process

$$\frac{p_2V_2}{p_1V_1} = \frac{n_2RT_2}{n_1RT_1} \text{ or } T_2 = 500\left(\frac{0.63}{0.50}\right) = 630\text{K}$$

$$\lim W = -\int_{0.50}^{0.63} p\,dV = \frac{200 \text{ kPa}}{}\left|\frac{(0.63-0.50)\text{m}^3}{}\right|\frac{1000 \text{ Pa}}{1 \text{ kPa}}\Bigg|$$

$$\frac{1\dfrac{\text{N}}{\text{m}^2}}{1 \text{ Pa}}\left|\frac{1\dfrac{\text{J}}{\text{m}}}{1 \text{ N}}\right|\frac{1 \text{ kJ}}{1000 \text{ J}} = -26 \text{ kJ}$$

Isothermal Process

$$p_2 = p_1\frac{V_1}{V_2} = 200\left(\frac{0.50}{0.63}\right) = 159 \text{ kPa}$$

$$\lim W = -\int_{0.50}^{0.63} p\,dV = \int_{0.50}^{0.63}\frac{nRT}{V}\,Vd = nRT\,ln\left(\frac{0.63}{0.50}\right)$$

$$= \frac{0.024 \text{ kg mol}}{}\left|\frac{8.314(\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})}\right|\frac{500 \text{ K}}{}\left|\frac{ln(1.26)}{}\right|$$

$$\times\frac{1 \text{ kJ}}{1(\text{kPa})(\text{m}^3)} = -23 \text{ kJ}$$

Note that the work done by the gas is the sum of the work done is pushing back the atmosphere by 0.13 m^3 plus the gain in the potential energy of the piston relative to a reference plane.

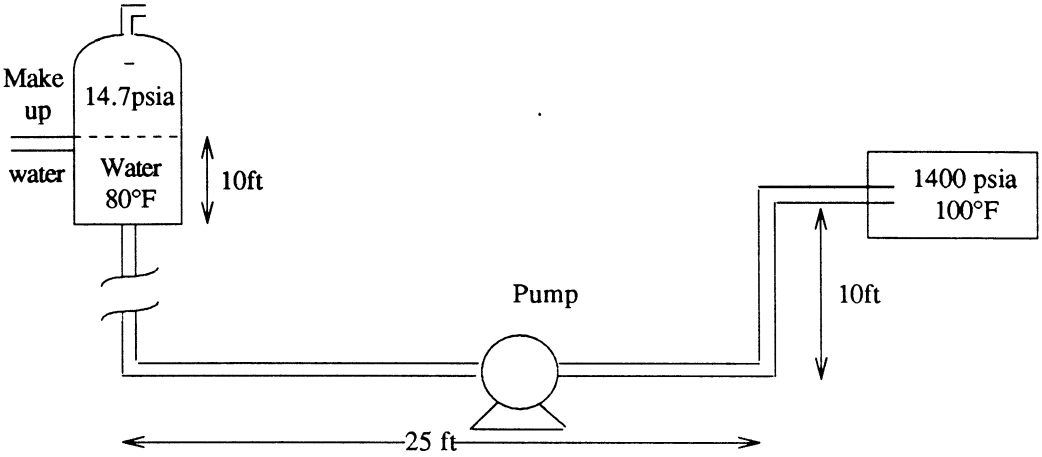
Problem 5.5B

A pump delivers water from the bottom of a storage tank (open to the atmosphere) containing water at 80°F. The bottom of the tank is 100 ft from the ground, and the water is maintained at a level 10 ft deep in the tank. The pump delivers 100°F water at 1400 psia to a chamber at a level 10ft off the ground and 25ft away from the storage tank. From a handbook you can find that the losses of energy in the transit of the fluid because of friction, etc. are estimated to be 320(ft)(lb_f)/lb_m, and for the normal flow rate of 10,000 lb/hr the pump efficiency is 76.2 percent. What horsepower pump is required to deliver 10,000 lb of water per hour to the chamber?

Solution

Steps 1, 2, 3, and 4

All the data have been placed on the figure. This is a steady state flow process. The system is the water.



From the steam tables for saturated liquid

$$\hat{V}(80°F) = 0.01607 \text{ ft}^3/\text{lb}_m \qquad \hat{V}(100°F) = 0.01613 \text{ ft}^3/\text{lb}_m$$

so that we can assume water is incompressible at 0.0161 ft^3/lb_m

Step 5 Basis: 1 hr (10,000 lb water)

Step 6 The unknown is the work, W, done by the pump.

Steps 7, 8, and 9

Since we know the frictional losses, E_v, we can use the steady state mechanical energy balance to solve for W.

$$\Delta\left(\hat{K} + \hat{P}\right) + \int_{p_1}^{p_2} \hat{V}dp - \hat{W} + \hat{E}_v = 0$$

$$E_V = \frac{10{,}000\ \text{lb}_\text{m}}{} \bigg| \frac{320(\text{ft})(\text{lb}_\text{f})}{\text{lb}_\text{m}} = 3.20\times 10^6(\text{ft})(\text{lb}_\text{f})$$

$\Delta K =$ 0 (no information on the water velocity, but the value will be very small)

$$\Delta P = \frac{10{,}000\ \text{lb}_\text{m}}{} \bigg| \frac{(10\ \text{ft} - 110\ \text{ft})}{} \bigg| \frac{32.2\ \text{ft}}{\text{s}^2} \bigg| \frac{(\text{s}^2)(\text{lb}_\text{f})}{32.2(\text{ft})(\text{lb}_\text{m})}$$

$$= -1.00\times 10^6(\text{ft})(\text{lb}_\text{f})$$

$$m\int_{14.7}^{1400} \hat{V}dp = \frac{10{,}000\ \text{lb}_\text{m}}{} \bigg| \frac{0.0161\ \text{ft}^3}{\text{lb}_\text{m}} \bigg| \frac{(1400-14.7)}{\text{in.}^2} \bigg| \frac{(12\text{in.})^2}{(1\ \text{ft}^2)} = 32.1\times 10^6(\text{ft})(\text{lb}_\text{f})$$

$W = 3.20\times 10^6 + 32.1\times 10^6 - 1.00\times 10^6 = 34.3\times 10^6(\text{ft})(\text{lb}_\text{f})$ or

$$W = \frac{34.3\times 10^6(\text{ft})(\text{lb}_\text{f})}{\text{hr}} \bigg| \frac{1(\text{hp})(\text{hr})}{1.98\times 10^6(\text{ft})(\text{lb}_\text{f})} = 17.3\ \text{hp (work done on the water)}$$

If the motor and pump is 75% efficient, the size needed is $\boldsymbol{\frac{17.3}{0.75} = 23\ \textbf{hp}}$

Problem 5.6A

Ammonium dihydrogen phosphate ($NH_4H_2PO_4$) is used in both the chemical and fertilizer industries. Given the experimental data below for the integral heat of formation of $NH_4H_2PO_4$ in water

a. Plot the standard integral heat of solution curve for $NH_4H_2PO_4$ in water;

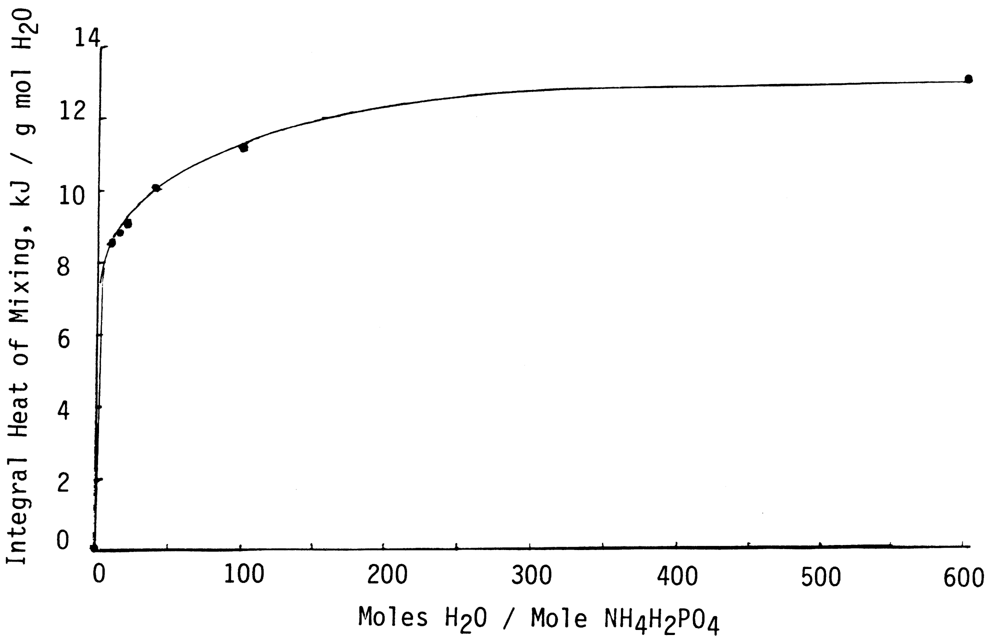
b. What would be the approximate final temperature of the solution if you mix $NH_4H_2PO_4$ and H_2O each at 25°C to form a 15% solution of $NH_4H_2PO_4$? The C_p^o of $NH_4H_2PO_4$ (crystal) is 182 J/g mol.

Heat of formation$\left(\Delta\hat{H}_f^o, \text{kJ / g mol } H_2O \text{ in solution}\right)$

Mole H_2O:	0	11	13	15
$\Delta\hat{H}^o$:	−1573.7	−1565.1	−1565.0	−1564.9
Mole H_2O:	20	40	100	600
$\Delta\hat{H}^o$:	−1564.6	−1563.6	−1562.3	−1560.6

Solution

a. The plot is as follows



b. To get the final temperature of the solution, make an energy balance. Assume a flow process for the mixing, or assume $\Delta H = \Delta U$ for a batch process ($\Delta pV \cong 0$). Then $\Delta H_{in} = \Delta H_{out}$, and on the basis of 100 g of a 15% solution of $NH_4H_2PO_4$ (MW = 115)

$$\frac{\text{mol } H_2O}{\text{mol } NH_4H_2PO_4} = \frac{\dfrac{(100)(0.85)}{18}}{\dfrac{(100)(0.15)}{115}} = 36.2$$

From the graph, $\Delta\hat{H}_{\text{soln}} \cong 9.8$. At 25°C

$$\Delta\hat{H}_f^\circ(\text{soln}) = 9.8 + (-1573.7) = -1563.9 \text{ kJ / g mol } NH_4H_2PO_4$$

To make the energy balance, we have to know the enthalpy of the 15% solution as a function of temperature. What value should be used for C_p? Usually, for not too concentrated solutions, we can assume the C_p of the solution is the C_p of water multiplied by the mass fraction of water in the solution.

ΔH_{in}			ΔH_{out}
$NH_4H_2PO_4$	H_2O		Solution
$\left(\frac{(100)(0.15)}{115}\right)(-1573.7\times10^3)+$	$\left(\frac{0.85}{18}\right)(0)$	$=$	$\left(\frac{(100)(0.15)}{115}\right)(-1563.9\times10^3) + \int_{25}^{T}(0.85)(100)(4.184)dT$

$T - 25 = -3.6$ so that **T = 21.4°C**

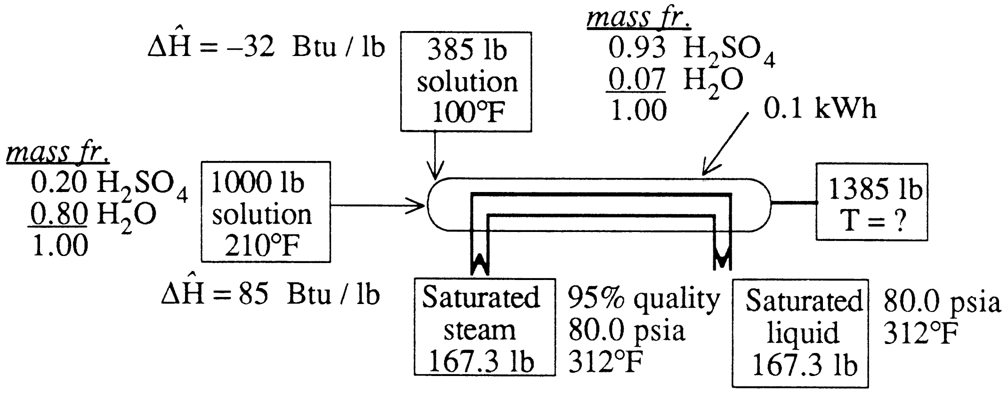
Problem 5.6B

A stainless steel mixing tank contains a steam coil and agitator. One thousand lb of 20% H_2SO_4 solution at 210°F is initially in the tank, and steam at 65.3 psig, 95% quality, is turned on into the coil. The agitator starts and 385 lb of 93% H_2SO_4 solution at 100°F added to the tank. Measurements from the steam trap attached to the coil should that 167.3 lb condensate at 312°F was removed from the coil. It is estimated that the agitator transmitted 0.10 kWh of energy to the liquid. What is the final temperature, weight, and composition of the solution in the tank?

Solution

Steps 1, 2, 3, and 4

Data required for the solution of this problem are the enthalpies of the steam and the H_2SO_4 solutions (see Appendices C and I in the textbook). The reference states are identical. The data have been entered on the figure below. Treat the process as a flow process.



Step 5 Basis: Data in diagram

Steps 6, 7, 8, and 9

The *material balance* is simple:

Total balance: 1000 + 385 = **1385 lb H_2SO_4 solution leave**
H_2SO_4 balance: 1000 (.20) + 385(.93) = 558 lb H_2SO_4

$$\frac{558}{1385}(100) = 40.3\%\ \ H_2SO_4\ \ \text{overall}$$

However, some of the water vaporizes (40% is in the two phase region of the enthalpy concentration chart).

The *energy balance* is $\Delta H_{in} + 0.1\ \text{kWh}\left(\frac{3.413\times 10^3\ \ \text{Btu}}{1\ \ \text{kWh}}\right) = \Delta H_{out}$ if $Q = 0$.

Flow	%H_2SO_4	T(°F)	$\Delta\hat{H}$ (Btu/lb)	ΔH(Btu)
1000 lb and	20	210	85	85,000
385 lb and	93	100	-32	-12,320
(0.95) 167.3 lb steam	0	312	1183	188,020
167.3 lb water	0	312	282	41,179
1385 lb and	40.3	?	?	?

$$(1385)\Delta\hat{H}_{out} + 41{,}179 = 341 + 85{,}000 - 12{,}320 + 188{,}020 + (0.05)167.3(282)$$
$$\Delta\hat{H}_{out} = 159\ \ \text{Btu / lb}$$

From the enthalpy concentration chart at 40.3% H_2SO_4 solution and $\Delta\hat{H} = 159\ \ \text{Btu / lb}$, we find the solution is in the two phase region at ~249°F. The liquid concentration is ~46% H_2SO_4 solution $\left(\Delta\hat{H} = 17\ \ \text{Btu / lb}\right)$, the vapor is steam at 249°F $\left(\Delta\hat{H} = 1163.2\right)$, and the weight of the solution (x) is

$$1385(159) \cong 220{,}000 = x(17) + (1385 - x)1163.8$$

x = 1213 lb of 46% H_2SO_4 solution

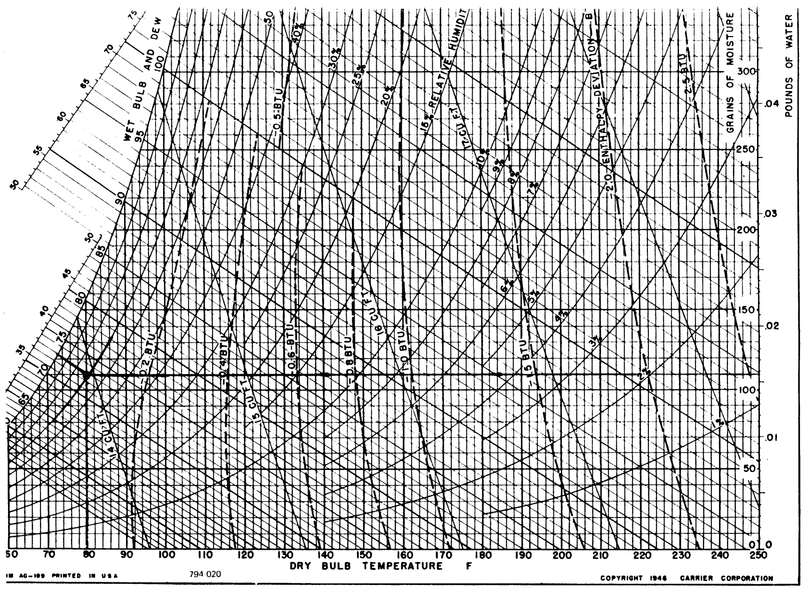
Problem 5.7A

Given t_{DB} = 80°F and t_{WB} = 73°F, from the psychrometric chart find the

a. percentage relative humidity
b. dewpoint
c. specific enthalpy
d. specific volume
e. humidity

Solution

The two given conditions completely specify the state of the air-water vapor mixture on the chart, and consequently the other conditions may be read directly from the chart.

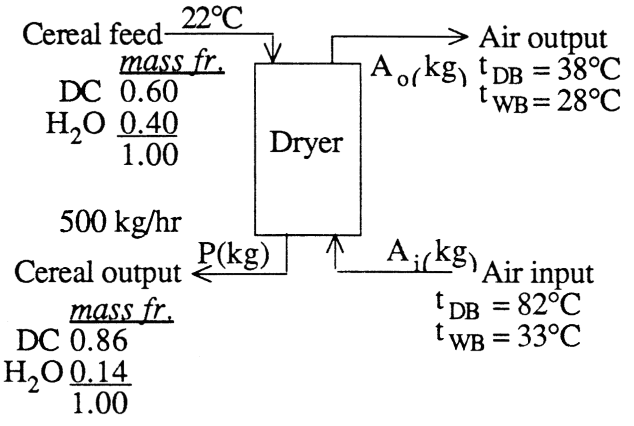


They are

a. **70% relative humidity** read from the curve sloping at 45°.
b. **70°F** (read left at constant humidity).
c. $\Delta\hat{H}$(saturated) = 36.8 Btu/lb. Subtract about 0.1 Btu/lb for less than saturated (interpolating between the dashed curves) to get **36.7 Btu/lb.**
d. Interpolating between the solid line, $\hat{V} \cong \mathbf{13.95\ ft^3 / lb}$.
e. Read the value of the humidity from the far right hand axis as about **0.0158 lb H_2O/lb air.**

Problem 5.7B

Breakfast cereal is being dried in a fluidized bed dryer in which the cereal moves roughly countercurrent to the air flow. The figure below shows the process with the data placed on the respective stream flows. Determine the required inlet moist air flowrate in m^3/hr if the cereal must have a water content of no more than 14.0 percent. (DC = dry cereal).



$\frac{\text{kg } H_2O}{\text{kg dry air}}$	*mass fr.*
0.020	H_2O 0.0196 Air 0.9804 1.00
0.012	H_2O 0.0119 Air 0.9881 1.00

Solution

Steps 1, 2, 3, and 4 All the data is in the figure above. The data on concentrations comes from the SI psychometric chart. Assume p = 1 atm.

Step 5 Basis: 1 hr

Steps 6, 7, 8, and 9

Dry cereal balance

$$500\ (0.60) = P\ (0.86) \qquad P = 348.8 \text{ kg}$$

Dry air balance

$$A_i(0.9881) = A_o(0.9804)$$

Water balance

$$500\ (0.40) + A_i\ (0.019) = 348.8\ (0.14) + A_o\ (0.0196) \qquad A_i = 193 \times 10^4 \text{ kg}$$

From the psychrometric chart the specific volume is approximately 1.025 m^3/kg dry air

$$\frac{1.025 \text{ m}^3}{\text{kg dry air}}\left|\frac{1.93\times10^4 \text{ kg wet air}}{\text{hr}}\right|\frac{0.9881 \text{ kg dry air}}{1 \text{ kg wet air}} = \mathbf{1.96\times10^4\ m^3\ /\ hr\ at\ 82°C\ and\ 1\ atm}$$

DRYERS

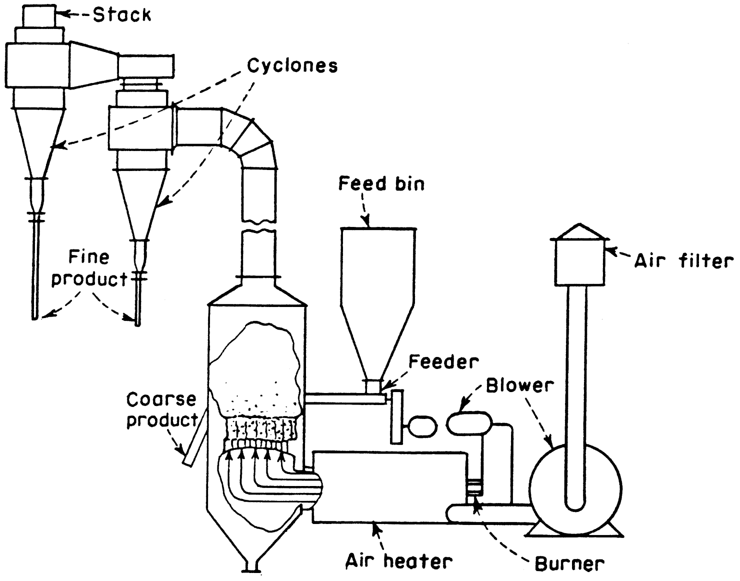


Fig. 24a. Fluidized bed dryer used for materials with high moisture content

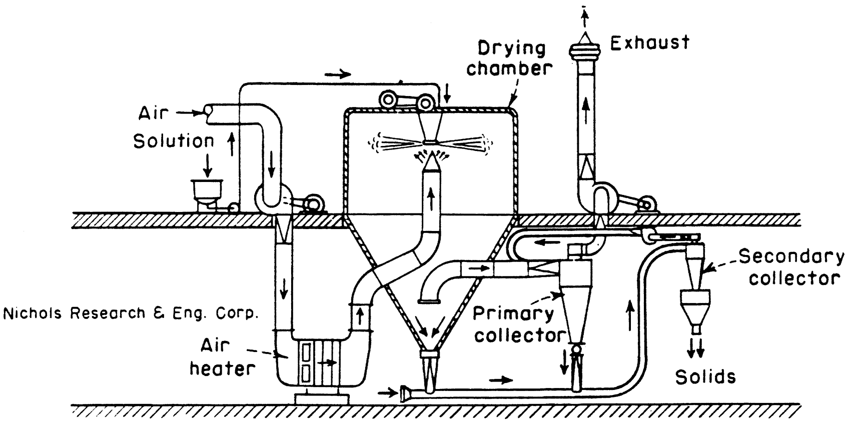


Fig. 24b. Spray dryer used for solutions

Drying is understood as a technology for removing a liquid from a solid by vaporization of the liquid. The solid product does not have to be entirely dry because any material will reach equilibrium with the water in the surrounding atmosphere. Two basic types of dryers are (1) directly heated and (2) indirectly heated. In the former the heat is applied to the wet solid by the heating medium, usually a hot gas which carries away the vaporized liquid. In freeze drying the liquid sublimates. In indirect dryers, heat is applied by conduction from the heat source through an intermediate wall. If a gas is used, its purpose is just to carry away the vapor produced in the process. Other types of dryers uses infrared heat or microwave heating.

Problem 5.7C

Air enters a drier at 200°F with a dew point of 80°F. The total pressure is 1 atm.

a. What is the humidity?

b. What is the wet bulb temperature?

c. What is the relative humidity?

The drier operates adiabatically and the air is cooled to 110°F. At 110°F

d. What is the humidity?

e. What is the dew point?

Finally the air is heated at constant humidity to 180°F. At 180°F

f. What is the adiabatic saturation temperature?

g. What is the dew point?

h. What is the relative humidity?

i. How much energy is used per lb of dry air?

Solution

Steps 1, 2, 3, and 4 Refer to the psychrometric chart.

Step 5 Basis: a fixed amount of air at 200°F, 1 atm, and a dew point of 80°F

Steps 6, 7, 8, and 9

a. Read on the right hand axis **0.022 lb H_2O/lb BDA.**

b. Read up along the adiabatic cooling line to **102°F.**

c. Read along the curved line **4.3% relative humidity.**

d. Read along the adiabatic cooling line **to 110°F and then to the right axis to get 0.044 lb H_2O/lb BDA.**

e. Read back along the constant humidity line to get **100.7°F.**

f. The adiabatic saturation temperature is the wet bulb temperature or **111°F.**

g. Dew point is **100.7°F.**

h. Relative humidity is **13%.**

i. $\Delta\hat{H}$ before = 75 – 0.15 = 74.85 Btu/lb BDA

$\Delta\hat{H}$ after = 95 – 1.35 = 93.65 Btu/lb BDA

Heat added = $\Delta\hat{H}$ = 93.65 – 74.85 = **18.8 Btu/lb BDA.**

CHAPTER 5 – ADDITIONAL PROBLEMS
(Answers will be found in Appendix A)

Section 5.1

5.1A Explain specifically what the system is for each of the following processes; also indicate which of the two modes of energy transfer, heat and work (Q and W), are involved.

(a) A liquid inside a well insulated metal can is shaken very rapidly in a vibrating shaker.
(b) Hydrogen is exploded in a calometric bomb, and the water layer outside the bomb rises in temperature by 1°C.
(c) A motor boat is driven by an outboard-motor propeller.
(d) Water flows through a pipe at 10 ft/min, and the temperature of the water and the air surrounding the pipe are the same.

5.1B Are the following variables intensive or extensive variables? Explain for each.

(a) Pressure.
(b) Volume.
(c) Specific volume.
(d) Refractive index.
(e) Surface tension.

5.1C Suppose that a constant force of 40.0 N is exerted to move an object for 6.00 m. What is the work accomplished (on an ideal system) expressed in the following:

(a) joules
(b) (ft)(lb_f)
(c) Btu

5.1D If a pail weighting 1/2 lb is dropped into a well 50 ft deep, what is the kinetic and potential energy of the pail (a) just before it hits the water, and (b) after it hits the water surface (at 50 ft)?

5.1E A chart for carbon dioxide (see Appendix) shows that the enthalpy of saturated CO_2 liquid is zero at —40°F. Can this be true? Explain your answer.

Section 5.2

5.2A Experimental values of the heat capacity C_p have been determined in the laboratory as follows; fit a second-order polynomial in temperature (determine values for a, b, and c in the relation $C_p = 1 + bT + CT^2$):

T,°C	C_p cal/(g mol)(°C)
100	9.69
200	10.47
300	11.23
400	11.79
500	12.25
600	12.63
700	12.94

(The data are for carbon dioxide; if a computer is used in the data-fitting process, also calculate the confidence limits for the predicted value of C_p.)

5.2B Your assistant has developed the following equation, to represent the heat capacity of air (with C_p in J/(g mol) (K) and T in K):

$$C_p = 26.7 + 7.36 \times 10^{-3}T - 1.09 \times 10^{-6}T^2$$

Derive an equation giving C_p but with the temperature expressed in °C.

5.2C Given that the heat capacity C_p for mercury at —20°C is 0.140 J/g, while at 100°C the value of C_p is 0.137, compute the change of enthalpy of 10 g of mercury from —20°C to 100°C. Given that the heat capacity at constant volume, C_v, is 0.123 at —20°C and 0.116 J/g at 100°C, compute the change in internal energy for the same temperature range. Then compute ΔpV for mercury for the same temperature range. Assume C_p and C_v change linearly with T.

5.2D Calculate the enthalpy change in raising 1 g mole of CO_2 from 50° to 100°C at 1 atm. Do this problem by three different methods.

(a) Use the heat capacity equation from the Appendix;
(b) Use the CO_2 chart in the Appendix;
(c) Use the data in the Table of Enthalpies of the Combustion Gases.

5.2E Use the chart for n-butane to calculate the enthalpy change for 10 lb of butane from a volume of 2.5 ft^3 at 360F to saturated liquid at 10 psia.

5.2F The vapor pressure of n-pentane is given by the equation.

$$\ln p^* = A - \frac{B}{(C+T)}$$

where p^* = vapor pressure in mm Hg and T is in K. The values of the coefficients are

A = 15.8333
B = 2477.07
C = –39.94

Calculate the heat of vaporization of n-pentane at the normal boiling point in J/g. Compare with experimental value.

5.2G Use the steam tables to answer the following questions.

(a) What is the enthalpy change needed to change 1 lb of a water-steam mixture of 60 percent quality to one of 80 percent quality if the mixture is at 300°F?
(b) Calculate the ΔH value for an isobaric (constant pressure) change of steam from 120 psia and 500°F to saturated liquid.
(c) Do the same for an isothermal change to saturated liquid.
(d) Does an enthalpy change from saturated vapor at 450°C to 210°F and 7 psia represent an enthalpy increase or decrease? A volume increase or decrease?
(e) In what state is water at 40 psia and 267.24°F? At 70 psia and 302°F? At 70 psia and 304°F?

Section 5.3

5.3A One pound mole of an *ideal* gas whose C_p is 7 Btu/(lb mole)(°R) is confined in a reservoir with a floating top such that the pressure on the gas is 60 psig no matter what its volume is. In the morning the gas is at 50°F, but late in the afternoon its temperature rises to 90°F.

(a) Determine how much heat has been transferred into the tank, the work done by the gas, and the internal energy change for the gas from the morning to afternoon.
(b) If the system returns to its original state in the evening, again find Q, W, and the internal energy and enthalpy changes for the cooling process.
(c) What are Q, W, and the internal energy and enthalpy changes for the overall process of heating and cooling?

5.3B Write the simplified energy balance for the following processes. List and number each assumption or decision made in the simplification.

(a) A fluid flows steadily through a poorly designed coil in which it is heated from 170° to 250°F. The pressure at the coil inlet is 120 psia, and at the coil outlet is 70 psia. The coil is of uniform cross section, and the fluid enters with a velocity of 2 ft/sec.

(b) A fluid is allowed to flow through a cracked (slightly opened) valve from a region where its pressure is 200 psia and 670°F to a region where its pressure is 40 psia, the whole operation being adiabatic.

5.3C In one stage of a process for the manufacture of liquid air, air as a gas at 4 atm abs and 250K is passed through a long, insulated 3-in. ID pipe in which the pressure drops 3 psi because of frictional resistance to flow. Near the end of the line, the air is expanded through a valve to 2 atm abs. State all assumptions.

(a) Compute the temperature of the air just downstream of the valve.
(b) If the air enters the pipe at the rate of 100 lb/hr, compute the velocity just downstream of the valve.

5.3D Your company produces small power plants that generate electricity by expanding a waste process steam in a turbine. You are asked to study the turbine to determine if it is operating as efficiently as possible. One way to ensure good efficiency is to have the turbine operate adiabatically. Measurements show that for steam at 500°F and 250 psia.

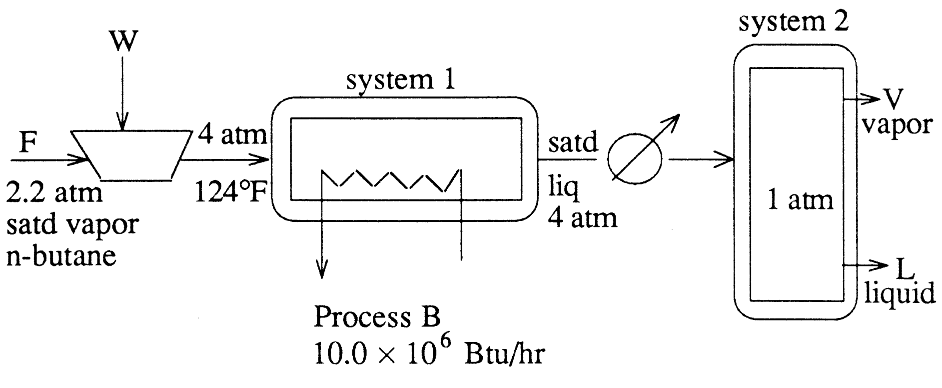
(a) The work output of the turbine is 86.5 hp.
(b) The rate of steam usage is 1000 lb/hr.
(c) The steam leaves the turbine at 14.7 psia and consists of 15 percent moisture (i.e., liquid H_2O).

Is the turbine operating adiabatically? Support your answer with calculations.

5.3E In a waste treatment plant, wet sludge containing 50 wt% moisture is fed into a rotary, countercurrent (sludge and air flow in opposite directions through the vessel) dryer at the rate of 300 lb/minute. The air enters at 220°F and has an absolute humidity of 0.007 lb H_2O/lb BDA, and leaves at 100°F and a RH of 100%. The sludge enters the dryer at 70°F and leaves at 97°F with 3 wt% moisture. Assuming adiabatic operation of the dryer so that the heat loss from dryer to the surroundings can be neglected, calculate:

(a) Pounds per hour of dry air passing through the dryer.
(b) Humidity of the air leaving the dryer in lb H_2O/lb BDA.

5.3F A saturated vapor stream of n-butane is available at 2.2 atm for a heat pump application. The vapor is compressed to 4 atm and 124°F. The heat released when it is condensed to a saturated liquid at 4 atm is used to heat process B, which requires 10.0×10^6 Btu/hr. The butane pressure is then reduced to 1 atm where the vapor and liquid streams are sent separately to another area in the plant. Calculate:
(a) The n-butane flow rate (lb/hr) required to provide heat to process B.
(b) The vapor flowrate lb/hr.
(c) The liquid flow rate lb/hr.
(d) If the n-butane flow rate and all the pressures are maintained constant, but the process B heat load drops to 7.5×10^6 Btu/hr, what are the new vapor and liquid flow rates?



Section 5.4

5.4A Calculate the heat of reaction of the following reaction at 25°C.

$$\underset{\text{methyl alcohol}}{CH_3OH(g)} + \tfrac{1}{2}O_2 \rightarrow \underset{\text{formaldehyde}}{H_2CO(g)} + H_2O(g)$$

5.4B When water is formed from $H_2(g)$ and $O_2(g)$, the reaction is exothermic. How much steam at 100°C has to be condensed per mole of $H_2(g)$ to maintain the vessel in which the reaction takes place at 25°C?

5.4C Calculate the heat of reaction for the synthesis of methanol

$$CO(g) + 2H_2(g) \rightarrow CH_3OH(g)$$

when the gases enter and leaves the reaction at 400°C and 200 atm.

5.4D In a heat treating plant, 10 tons of steel plate are being processed per hour by being heated from 80°F to 1500°F before quenching. The furnace atmosphere is required to be a reducing atmosphere to prevent excessive oxidation of the steel surface. Therefore it is necessary to burn the fuel oil (whose composition is approximately $C_{16}H_{34}$ incompletely with dry air to produce a stack gas containing a ratio of CO_2 to CO of 2 to 1. Assume that all of the hydrogen in the oil is burned to water and there is no O_2 in the stack gas and that 60% of the heat generated from the combustion is lost by radiation and stack losses. What quantities of oil (in lb) and air in standard cubic feet (32°F, 760 mm Hg) are needed per hour?

5.4E The reaction $SO_2 + \frac{1}{2}O_2 \rightarrow SO_3$ would seem to offer a simple method of making sulfur trioxide. However, both the reaction rate and equilibrium considerations are unfavorable for this reaction; the reaction is only about 70 percent complete. If the products leave the reactor at 900K and the reactants enter at 25°C, what is the heat evolved or absorbed from the system under these conditions (per mol of SO_2)?

5.4F Propane, butane, or liquefied petroleum gas (LPG) has seen practical service in passenger automobiles for 30 years or more. Because LPG is used in the vapor phase, it pollutes less than gasoline but more than natural gas. A number of cars in the Clean Air Car Race ran on LPG. The table below lists the results and those for natural gas. It must be kept in mind that these vehicles were generally equipped with platinum catalyst reactors and with exhaust-gas recycle. Therefore the gains in emission control did not come entirely from the fuels.

	Natural gas, avg 6 cars	*LPC, avg 13 cars*	*Fed. Std.*
HC (g/mile)	1.3	0.49	0.22
CO (g/mile)	3.7	4.55	2.3
NO_x (g/mile)	0.55	1.26	0.6

Suppose that in a test butane gas at 100°F is burned completely with the stoichiometric amount of air which is at 400°F and a dew point of 77°F in an engine. To cool the engine, 12.5 lb of steam at 100 psia and 95 percent quality were generated from water at 77°F per pound of butane burned. It may be assumed that 7 percent of the gross heating value of the butane is lost as radiation from the engine. Will the exhaust gases leaving the engine exceed the temperature limit of the catalyst of 1500°F?

5.4G A power plant burns natural gas (90 percent CH_4, 10 percent C_2H_6) at 25°C and 100kPa with 70 percent excess air at the same conditions. Calculate the theoretical maximum temperature (in K) in the boiler if all the products are in the gaseous state.

5.4H If CO at constant pressure is burned with excess air and the theoretical flame temperature is 981°C, what was the percentage of excess air used ? The reactants enter at 93°C.

Section 5.5

5.5A Water is being pumped from a pond through a long fire hose. A 50-hp motor drives the pump, and the overall efficiency of the motor pump is 75 percent i.e. 75 percent of the energy supplied by the motor is transferred to the water. The nozzle of the hose is 25 ft above and 250 ft from the pond; 100 gpm are being pumped, and the water velocity at the nozzle exit is 50 ft/sec. Estimate the temperature change in the water between the pond and the nozzle exit.

5.5B A system consists of 5 kg of water vapor at the dew point. The system is compressed isothermally at 400K, and 400kJ of work are done on the system by the surroundings. What volume of liquid was present in the system before and after compression?

5.5C Solid carbon dioxide (dry ice) has innumerable uses in industry and in research. Because it is easy to manufacture, the competition is severe, and it is necessary to make dry ice very cheaply to be successful in selling it. In a proposed plant to make dry ice, the gaseous CO_2 is compressed isothermally and essentially reversibly from 6 psia and 40°F to a specific volume of 0.05 ft^3/lb_m.

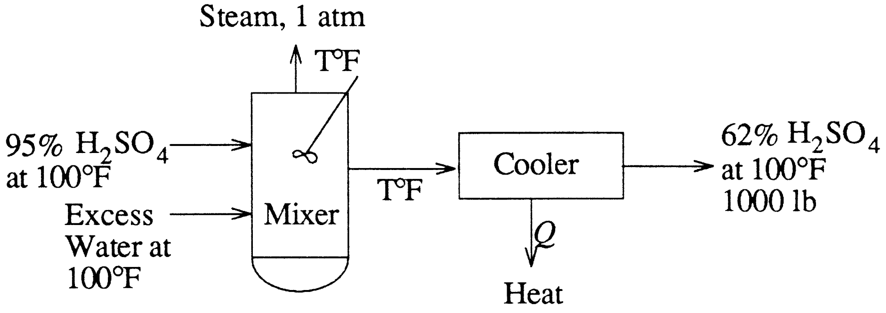
(a) What is the final state of the compressed CO_2?
(b) Compute the work of compression.
(c) What is the heat removed ?
(d) If the actual efficiency of the compressor (relative to a reversible compressor) is 85 percent and the electricity to run the compressor motor costs $0.02/kWh, what is the cost of compression of the solid CO_2 in dollars per pound of dry ice?

Section 5.6

5.6A A 10 percent (by weight) sulfuric acid solution at 70°F is placed in an open kettle evaporator and evaporated at atmospheric pressure to a 60 percent solution. If the steam leaving the kettle contains no sulfuric acid and is considered as leaving at the average temperature of the boiling range (arithmetic mean temperature)

(a) What are the initial and final boiling temperatures?
(b) How much heat must be supplied per pound of 60 percent acid produced?

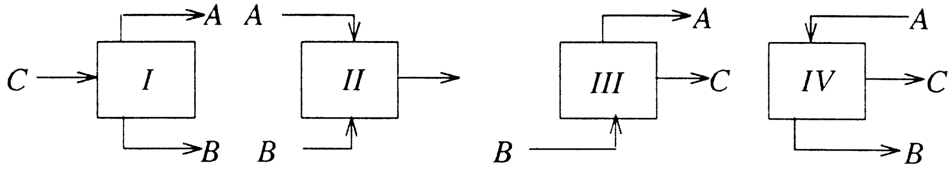
5.6B A dilute sulfuric acid (62 percent by weight) is to be made by diluting concentrated acid (95 percent) with water; however, due to the highly exothermic nature of the mixing, some provision is necessary to hold down the temperature of the fluid during mixing. The scheme shown in Fig. P5.6B is to be used. The concentrated acid is mixed with an excess of water and the mixture boils, driving off steam (no H_2SO_4 evaporates). Hot acid of the desired concentration leaves the mixer (both the steam and hot acid leave at the same temperature) and is finally cooled to 100°F. Determine the following:



(a) The amount of concentrated acid required per 1000 Ib of dilute acid produced.
(b) The amount of steam that leaves.
(c) The amount of water added to mixer.
(d) The temperature of the contents of the mixer.
(e) The amount of heat removed from the acid by the cooler.

5.6C In each of the four cases diagrammed in the figure below, the following data apply:

stream	*wt % EtOH*	*condition*	*amount*
A	80	Unknown	Unknown
B	10	70°F	Unknown
C	60	Superheated vapor at 800 Btu/lb	100 lb



Making the necessary material and energy balances for each diagram, and find the mass flows, compositions, and specific enthalpies of each stream.

Section 5.7

5.7A Moist air at 1 atm, a dry-bulb temperature of 195°F, and a wet-bulb temperature of 115°F is enclosed in a rigid container. The container and its contents are cooled to 110°F.

(a) What is the molar humidity of the cooled moist air?
(b) What is the final total pressure in atm in the container?
(c) What is the dew point in °F of the cooled moist air?
(d) What is the final wet-bulb temperature in °F?

5.7B A humidifier is conditioning air to 120°F dry-bulb and 90°F wet-bulb by heating outside air and then passing it through a spray chamber in which it reaches 90 percent humidity, and then reheating it to the desired temperature. The outside air is foggy at 40°F, carrying as liquid water 0.0004 lb water/ft^3 wet air. What temperature (of the air) must be reached in each heating operation, and how many Btu are required in each heating stage per 100 lb of dry air entering from the outside ?

5.7C In one of the hotter regions of the country a home owner decides to keep her home at an average temperature of 80°F and 40 percent humidity. On a typical day the outside conditions are as follows: dry-bulb temperature = 95°F and wet-bulb = 85°F. The city water supply is at 70°F and scarce. She therefore decides to use an electric refrigeration unit to cool the air entering the ventilating ducts. Summary of conditions:

Size of home: 50,000 ft^3.
Recirculation rate: one complete change every 3 min.
Average outlet temperature of the air: 82°F.
The increase in humidity in the house may be considered as zero.
Makeup air may be considered at 15 percent of the inlet air.

Give a complete flow sheet of the process and determine the amount of refrigeration and reheating necessary to maintain the above conditions.

Appendix A
Answers to Unsolved Problems

Chapter 1

1.1A (a) 26.82 m/s; (b) 0.626 lb_f/ft^2, (c) 1.548×10^{-2} Btu, (d) 4.21×10^3 J/s

1.1B (a) 0.518 lb, (b) 21.5 ft^3, (c) 1.87 lb/ft^3, (d) 1.034 kg/cm^2

1.1C 2.40×10^5 (ft) (lb_f)

1.1D 1.4×10^3 (ft) (lb_f)

1.1E Btu/(hr) (ft^2) (°F)

1.1F cm/s or cm^2/(s) (cm of height)

1.1G (a) A is g/cm^3, B is g (cm^3)(°C), C is atm^{-1}; (b) A is 68.4 lb_m/ft^3, B is 0.055 $lb_m/(ft^3)$(°R), C is 0.0000648/(lb_f/in^2)

1.2A (a) 2.27 g mol, (b) 0.22 lb N_2

1.2 B (a) 3.18×10^6 g, (b) 15.4 lb, (c) 932 g mol, (d) 4.54×10^{-3} lb mol

1.3A (a) 0.0311 lb mol/gal, (b) 22.9 lb/ft^3, (c) 366 g/L, (d) 0.428 lb H_2SO_4/lb H_2O, (e) 0.927 lb mol H_2O/lb mol total solution

1.3B (a) 0.659, (b) 15 gal

1.3C 18.2 ppm

1.3D (a) 17.5° API, (b) 7.94 lb/gal, (c) 59.3 lb/ft^3

1.4A 72.2 lb

1.4B 21.8 lb/ lb mol

1.4C CO_2:21.7, CO:10.9, CH_4:49.5, H_2:17.9

1.5A (a) –30°C, (b) 243.2K

1.5B (a) 356.8°C, (b) 675°F, (c) 1135°R

1.6A 1.07×10^4 lb_f/in^2

1.6B 2.06 psia

1.6C 4.49 psia

1.6D (a) $h_3 = 7.15$ in., (b) $h_2 = 20.65$ in.

1.7A 0.945 g Cr_2S_3

1.7B (a) $BaSO_4$ is limiting reactant, C is excess reactant, (b) % xs = 50.6%, (c) degree of completion = 0.901

Chapter 2

2.1A At 100°C (because phenol freezes at 42.5°C!)

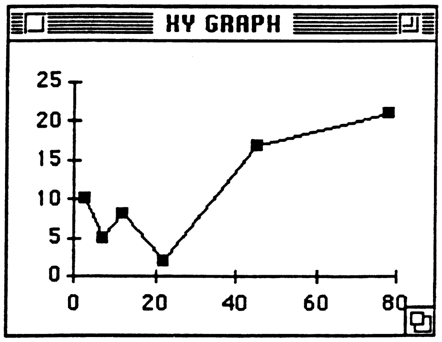
2.1B Pick up the second beaker from the left, pour all the ethanol into the fifth beaker from the left, and replace the second beaker in its original location.

2.1C The other team's catcher and the umpire.

2.2A x = 1, y = 2, z = 3

2.2B x = 4, y = 32

2.2C



Chapter 3

3.1A (a) closed, (b) open, (c) open, (d) open if it leaks, closed otherwise

3.2A rank = 3

3.2B No; you have 3 unknown variables and two independent equations

3.2C No.

3.3A $51.90/ton

3.3B (a) Na_2SO_4 28%, H_2O 72%, (b) 33.3 g crystals/100 g solution

3.3C Overhead: C_2H_4 (7.8%), C_2H_6 (11.7%), C_3H_6 (19.4%), C_3H_8 (56.0%), iC_4H_{10} (5.1%). Bottoms: C_3H_8 (0.8%), iC_4H_6 (31.9%), nC_4H_{10} (47.1%), nC_5H_{12} (20.2%)

3.4C CO_2:17.82%, O_2:1.18%, N_2:81.0%

3.4B 686%

3.4C 8.98%

3.5A (a) 87.6%, (b) 25.0%

3.5B (a) 17,650 bbl, (b) 1:52.45%, 2:40.20%, 3:6.67%, 4:0.68%; (c) 1:49.90%, 2:44.05%, 3:6.05%; (d) 22.14 bbl

3.6A (a) 1 mol NO/1 mol NH_3 in, (b) R = 42.9 mol NH_3/mol NH_3 fed

3.6B (a) R = 111 lb Ca $(Ac)_2$ /hr, (b) 760 lb HAc/hr

3.6C (a) 75.1 kg C_2H_2, (b) 250 kg, (c) 454 kg (d) 2.00

Chapter 4

4.1A 248 gal/hr

4.1B A leak occurred. The CO_2 balance indicates the analysis is correct.

4.1C (a) C_6H_6:1.13 mol/min, C_6H_{12}:11.5 mol/min, H_2:11.5 mol/min; (b) C_6H_6:44.5 L/min, C_6H_{12}:452.5L/min, H_2:452L/min; (c) C_6H_6:6.4 mol/min (200L/min), H_2:25.8 mol/min (799L/min)

4.1D (a) all kN/m^2:CH_4 (80), C_2H_4 (10), N_2 (10); (b) No.

4.2A (a) RK:1193.1 cm^3/g mol, (b) PR:1168.9 cm^3/g mol

4.2B (a) van der Waals: 18.3lb, (b) 23.4 lb

4.2C (a) Eq. of State: 0.862 ft^3, (b) compressibility factor: 0.877 ft^3

4.3A (a) 20 atm

4.3B 50 psia (340 kPa)

4.4A 70.7L

4.4B O_2:296 ft^3 at 745 mm Hg and 25°C; C_2H_2: 54 ft^3 at 745 mm Hg and 25°C

4.4C 7.2L at SC

4.4D 44°C (111°F)

4.5A L/V = 1.59

4.5B Hexane 0.545, heptane 0.280, octane 0.180

4.5C (a) 75.2 lb H_2O/100 lb feed, (b) 48.4 wt% nonvolatile

4.5D Yes

4.6A (a) 43.6%, (b) 0.0136 mol Tol/mol H_2, (c) 0.043, (d) 42.9%, (e) 1.34%

4.6B (a) 219 psia, (b) 0.00435 lb mol H_2O/lb mol N_2, (c) 0.999

4.6C (a) 20.5°C, (b) 0.024, (c) 0.805

4.7A The solution is wrong. The problem is underspecified. No unique solution is possible.

4.7B (a) 50.5%, (b) 200 kPa, (c) 11°C, (d) 7%, (e) No

4.7C (a) 103.6°F, (b) 80.3 in. Hg, (c) 84%

4.7D (a) 89 ft^3/min, (b) 1180 mm Hg

Chapter 5

5.1A (a) system: can plus water, $Q = 0$, $W \neq 0$; (b) system: H_2 plus bomb, $W = 0$, $Q \neq 0$; (c) system: motor, $Q \neq 0$, $W \neq 0$; (d) system: pipe plus water, $Q = 0$, $W \neq 0$.

5.1B All are intensive except the volume

5.1C (a) 240 J, (b) 177 (ft)(lb_f), (c) 0.226 Btu

5.1D (a) KE = 25 (ft)(lb_f), for reference of the ground level, PE = –25 (ft)(lb_f); (b) KE = 0, PE = 0

5.1E Yes. The reference for enthalpy changes is arbitrary.

5.2A $C_p = 8.78 + 0.00963T - 0.00000529T^2$

5.2B $C_p = 6.852 + 1.62 \times 10^{-3}\, T_{^\circ C} - 0.26 \times 10^{-6}\, T^2_{^\circ C}$

5.2B $C_p = 27.5 + 6.78 \times 10^{-3}\, T_{^\circ C} - 1.09 \times 10^{-6}\, T^2_{^\circ C}$, J/(g mol) (°C)

5.2C (a) 39.8 cal, (b) 34.2 cal, (c) 5.6 cal

5.2D (a) 1955 J/g mol, (b) 1640 J/g mol, (c) 1937 J/g mol

5.2E –2020 Btu

5.2F 376 J/g vs. 357 J/g by experiment

5.3A (a) W_{rev} = –79.5 Btu/lb mol, Q = 280 Btu/lb mol, ΔU = 200.5 Btu/lb mol; (b) ΔH = Q = –280 Btu/lb mol, W = +79.5 Btu/lb mol, ΔU = –200.5 Btu/lb mol; (c) Q and W are zero, and ΔH = ΔU = O

5.3B (a) ΔH = Q, (b) ΔH = 0

5.3C (a) T_2 = 250K, (b) v_2 = 3.2 ft/s

5.3D No

5.3E (a) air = 3915 lb/min (b) humidity = 0.0425 lb H_2O/lb BDA

5.3F (a) 6.37×10^4 lb/hr, (b) 1.72×10^4 lb/hr, (c) 4.65×10^4 lb/hr, (d) L = 3.16×10^4 lb/hr, V = 3.21×10^4 lb/hr

5.4A –156.47 kJ

5.4B 57.5 kg

5.4C –122.2 kJ

5.4D (a) 488 lb/hr, (b) 31,240 ft^3 at SC

5.4E –28,240 J (heat evolved)

5.4F T = 1278°F < 1500°F

5.4G T = 982K

5.4H 276%

5.5A About –1.8°F

5.5B (a) Before = 0, (b) After = 0.0024 m^3

5.5C (a) 0.37 gas and 0.63 liquid, (b) 98 Btu/lb, (c) –173 Btu/lb, (d) \$6.76 × 10^{-4}/lb

5.6A (a) T_o = 210°F, T_f = 295°F

5.6B (a) 653 lb, (b) 8.85 lb, (c) 355.9 lb, (d) 300°F, (e) 10^5 Btu

5.6C Masses in lb: A = 71.5, B = 28.5, ΔH = Btu/lb; III and IV are impossible to exist

5.7A (a) 0.078, (b) 0.871 atm, (c) 99°F, (d) 100°F

5.7B (a) T_B = 166°F, T_c = 85.2 °F; (b) ΔH_I = 3080 Btu, ΔH_{II} = 860 Btu

5.7C Refrigeration = 4830 Btu/min; Reheating = 124.5 Btu/min

Appendix B
Data

TABLE B1 Typical Dry Gas Analyses

	Analysis (vol. %—excluding water vapor)									
Type	CO_2	O_2	N_2	CO	H_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	$C_5H_{12}+$
Natural gas	6.5					77.5	16.0			
Natural gas, dry*	0.2		0.6			99.2				
Natural gas, wet*	1.1					87.0	4.1	2.6	2.0	3.4
Natural gas, sour†	(H_2S 6.4)					58.7	16.5	9.9	5.0	3.5
Butane							2.0	3.5	75.4 *n*-butane 18.1 isobutane	
									Illuminants	
Reformed refinery oil	2.3	0.7	4.9	20.8	49.8	12.3	5.5	5.5	3.7	
Coal gas, by-product	2.1	0.4	4.4	13.5	51.9	24.3			3.4	
Producer gas	4.5	0.6	50.9	27.0	14.0	3.0				
Blast furnace gas	5.4	0.7	8.3	37.0	47.3	1.3				
Sewage gas	22.0		6.0		2.0	68.0				

*Dry gas contains much less propane (C_3H_8) and higher hydrocarbons than wet gas does.

†*Sour* implies that the gas contains significant amounts of hydrogen sulfide.

SOURCE: *Fuel Flue Gases*, American Gas Association, New York, 1941, p. 20.

TABLE B2 Ultimate Analysis of Petroleum Crude

			Weight %				
Type	Sp Gr	At °C	C	H	N	O	S
Pennsylvania	0.862	15	85.5	14.2			
Humbolt, Kan.	0.921		85.6	12.4			0.37
Beaumont, Tex.	0.91		85.7	11.0	2.61		0.70
Mexico	0.97	15	83.0	11.0	1.7		
Baku USSR	0.897		86.5	12.0		1.5	

SOURCE: Data from W.L. Nelson, *Petroleum Refinery Engineering*, 4th ed., McGraw-Hill, New York, 1958.

TABLE B3 Chemical Analyses of Various Wastes

Material	Raw paper	Charred paper	Tire rubber	Dry sewage sludge	Charred sewage sludge	Charred animal manure	Garbage composite *A*	Garbage composite *B*
Moisture	3.8	0.8	0.5	13.6	1.2	0.0	3.4	12.3
Hydrogen*	6.9	3.1	4.3	6.7	1.4	5.4	6.6	7.0
Carbon	45.8	84.9	86.5	28.7	48.6	41.2	57.3	44.4
Nitrogen	—	0.1	—	2.6	3.7	1.5	0.5	0.4
Oxygen*	46.8	8.5	4.6	26.5	—	26.0	22.1	42.1
Sulfur	0.1	0.1	1.2	0.6	—	0.4	0.4	0.2
Ash	0.4	2.5	3.4	34.9	45.7	25.5	10.2	5.9

* The hydrogen and oxygen values reflect that due to both the presence of water and that contained within the moisture-free material.

TABLE B4 Refinery Biological Treatment

	Ranges reported*
Chlorides (mg/L)	200–960
COD (mg/L)	140–640
BOD_5 (mg/L)	97–280
Suspended solids (mg/L)	80–450
Alkalinity (mg/L as $CaCO_3$)	77–210
Temperature, (°F)	69–100
Ammonia, nitrogen (mg/L)	56–120
Oil (mg/L)	23–130
Phosphate (mg/L)	20–97
Phenolics (mg/L)	7.6–61
pH	7.1–9.5
Sulfides (mg/L)	1.3–38
Chromium (mg/L)	0.3–0.7

*Values are the averages of the minima and maxima reported by 12 refineries treating total effluent. Individual plants have reported data well outside many of these ranges.

SOURCE: *Manual on Disposal of Refinery Wastes*, American Petroleum Institute, New York, 1969, pp. 2–4.

TABLE B5 Higher Heating Value of Municipal Refuse (kJ/kg)

Refuse component	As delivered	Dry basis	Refuse component	As delivered	Dry basis
Lawn grass	4,780	19,320	Average	—	20,050
Meat scraps, cooked	32,260	32,260	Mail	14,150	14,820
Newspaper	18,530	19,710	Cardboard	16,370	17,260
Shrub cuttings	6,290	20,300	Ripe tree leaves	18,550	20,610
Vegetable food waste	4,170	19,220	Magazine	12,210	12,730

TABLE B6 Calorie Counts in Various Foods

Food	Portion	Kilo-calories	Food	Portion	Kilo-calories
Beer	12 oz	165	Orange juice	$\frac{1}{2}$ glass	56
Chicken, broiled	$\frac{1}{2}$	308	Soft drink	1 can	73
Coffee	1 cup	0	Toast	2 pieces	120
Martini	1 oz	168	Trout	1 lb	224

TABLE B7 Higher Heating

Class	kJ/kg	Btu/lb
Meta-anthracite	26,680	11,480
Anthracite	33,110	14,250
Low-volatile bituminous	35,370	15,220
High-volatile bituminous	27,790	11,960
Subituminous	23,330	10,040
Lignite	17,290	7,440

TABLE B8 Heating Values of Fuels

Class	Btu/gal
Kerosene	134,000
No. 2 burner fuel oil	140,000
No. 4 heavy fuel oil	144,000
No. 5 heavy fuel oil	150,000
No. 6 heavy fuel oil, 2.7% sulfur	152,000
No. 6 heavy fuel oil, 0.3% sulfur	143,800
natural gas	*1,000
liquefied butane	103,300
liquefied propane	91,6000

*10^3 Btu/ft^3 at SCNGI

TABLE B9 Elemental Compositions and Heating Values of Raw and Hydrotreated Coal Liquids

	Boiling range (C)	Specific gravity	Heating value, (kJ/kg)	H	C	O	S	N
liquid organic liquid	65-205	0.847	42212	11.33	83.77	4.0	0.60	0.30
liquid organic liquid	110-230	0.918	40068	9.93	84.44	5.0	0.40	0.23
SRC-Illinois No. 6 coal	340+	1.184	37090	5.72	88.50	3.5	0.57	1.71
distillate≅syncrude mode	190-350	0.968	42056	9.14	88.87	1.5	0.10	0.39
fuel oil≅Illinois No. 6 coal	260+		40498	7.94	88.77	2.1	0.42	0.77
distillate syncrude	180-330	0.942	43326	10.46	89.12	0.3	<0.01	0.12

Source: R. H. Heck and M. J. Dabkowski, "Heating Value Correlation for Coal," *Ind. Eng. Chem. Res*, **27**, 1922 (1988).

TABLE B10 Thermodynamic Charts Showing Enthalpy Data for Pure Compounds*

Compound	Reference†
Acetone	2
Acetylene	1
Air	V.C. Williams, *AIChE Trans.*, v. 39, p. 93 (1943); *AIChE J.*, v. 1, p. 302 (1955).
Benzene	1
1,3-Butadiene	C.H. Meyers, *J. Res. Natl. Bur. Stand.*, v. A39, p. 507 (1947).
i-Butane	1, 3
n-Butane	1, 3, 4
n-Butanol	L.W. Shemilt, in *Proceedings of the Conference on Thermodynamic Transport Properties of Fluids*, London, 1957, Institute of Mechanical Engineers, London, 1958.
t-Butanol	F. Maslan, *AIChE J.*, v. 7, p. 172 (1961).
n-Butene	1
Chlorine	R.E. Hulme and A.B. Tilman, *Chem. Eng.* (January 1949).
Ethane	1, 3, 4
Ethanol	R.C. Reid and J.M. Smith, *Chem. Eng. Prog.*, v. 47, p. 415 (1951).
Ethyl ether	2
Ethylene	1, 3
Ethylene oxide	J.E. Mock and J.M. Smith, *Ind. Eng. Chem.*, v. 42, p. 2125 (1950).
Fatty acids	J.D. Chase, *Chem. Eng.*, p. 107 (March 24, 1980).
n-Heptane	E.B. Stuart et al., *Chem Eng. Prog.*, v. 46, p. 311 (1950).
n-Hexane	1
Hydrogen sulfide	J.R. West, *Chem. Eng. Prog.*, v. 44, p. 287 (1948).
Isopropyl ether	2
Mercury	General Electric Company Report GET-1879A, 1949.
Methane	1, 3, 4
Methanol	J.M. Smith, *Chem. Eng. Prog.*, v. 44, p. 52 (1948).
Methyl ethyl ketone	2
Monomethyl hydrazine	F. Bizjak and D.F. Stai, *AIAA J.*, v. 2, p. 954 (1964).
Neon	Cryogenic Data Center, National Bureau of Standards, Boulder, Colo.
Nitrogen	G.S. Lin, *Chem. Eng. Prog.*, v. 59, no. 11, p. 69 (1963).

*For mixtures, see V.F. Lesavage et al., *Ind. Eng. Chem.*, v. 59, no. 11, p. 35 (1967).

†1. L.N. Cajar et al., *Thermodynamic Properties and Reduced Correlations for Gases*, Gulf Publishing Company, Houston, 1967. (Series of articles which appeared in the magazine *Hydrocarbon Processing* from 1962 to 1965.)

2. P.T. Eubank and J.M. Smith, *J. Chem. Eng. Data*, v. 7, p. 75 (1962).

3. W.C. Edmister, *Applied Hydrocarbon Thermodynamics*, Gulf Publishing Company, Houston, 1987.

4. K.E. Starling et al., *Hydrocarbon Processing*, 1971 and following. *Note:* Charts available separately from Gulf Publishing Company, Houston.

Heat capacity of hydrogen vapor[1]

$$C_p = (0.0450K - 0.233) + (0.440 + 0.0177K)(10^{-3}t) - 0.1520(10^{-6}t^2)$$

where C_p = specific heat of vapor, Btu/(lb$_m$)(°F)
t = temperature, °F
K = characterization factor

Heat capacity of hydrocarbon liquids[1]

$$C_p = [(0.355 + 0.128 \times 10^{-2}\mathrm{API}) + (0.503 + 0.117 \times 10^{-2}\mathrm{API})(10^{-3}t)] \times (0.05K + 0.41)$$

where API = gravity degrees API and the other units are the same as for vapor heat capacity.

Specific gravity

$$\text{sp gr} = \frac{141.5}{131.5 + {}^\circ\mathrm{API}}$$

where sp gr = specific gravity, 60/60°F
°API = degrees API

Pseudo critical temperature [2]

$$t_c' = a_0 + a_1T + a_2T^2 + a_3AT + a_4T^3 + a_5T^2 + a_6A^2T^2$$

where t_c' = pseudo-critical temperature, °R
T = molal average boiling point, °F
A = degrees API
a_i = constants in the correlation (see Table K.3)

Pseudo critical pressure [2]

$$p_c' = b_0 + b_1T + b_2T^2 + b_3AT + b_4T^3 + b_5AT^2 + b_6A^2T + b_7A^2T^2$$

where p_c' = pseudo-critical pressure psia
T = mean average boiling point, °F
A = degrees API
b_i = constants in the correlation

Constants for Cavett Correlations

i	a_i	b_i
0	768.07121	2.8290406
1	(0.17133693) (10)	(0.94120109) (10^{-3})
2	(−0.10834003) (10^{-2})	(−0.30474749) (10^{-5})
3	(−0.89212579) (10^{-2})	(−0.20876110) (10^{-4})
4	(0.38890584) (10^{-6})	(0.15184103) (10^{-8})
5	(0.53094920) (10^{-5})	(0.11047899) (10^{-7})
6	(0.32711600) (10^{-7})	(−0.48271599) (10^{-7})
7		(0.13949619) (10^{-9})

Enthalpy. Calculated as

$$\Delta H = \int_{T_{\text{ref}}}^{\bar{T}_1} C_{p_{\text{liq}}}\,dt + \Delta H_{\text{vaporization at }\bar{T}_1} + \int_{\bar{T}_1}^{T} C_{p_{\text{vap}}}\,dt$$

where $\overline{T_1}$ is the mean average boiling point.

Heat of vaporization[1]

$$\Delta H_{vap} = 2.303\,\{(z_g - z_l)R(T_c)[A + 40T_r^2(T_r - b)e^{-20}(T_r - b)^2]\}$$

where H_{vap} = latent heat of vaporization, Btu/lb_{m}
$z_g - z_l$ = pressure correction (see Fallon and Watson for table of values)
R = universal gas constant
T_c = critical temperature, °R

T_r = reduced temperature
A, b = constants (see Fallon and Watson for ways to calculate values)

or (a somewhat less accurate equation)[3]

$$\Delta H_{\text{vap}} = 0.95RT_B\left(\frac{T_B}{T_B - 43}\right)^2\left(\frac{1 - T_r}{1 - T_{rB}}\right)^{0.38}$$

where T_B = molal average boiling point, °R
T_r = reduced temperature
T_{rB} = reduced T_B

Boiling-point relations

(a)
$$\bar{t}_v = \sum_{i=1}^{n} X_{vi} t_{bi}$$

where X_{vi} = volume fraction of the ith component of the petroleum fraction
t_{bi} = normal boiling point of the midpoint of the ith volume fraction, °F or °R
n = number of volume fractions in the distillation curve to characterize the petroleum product

(b)
$$\bar{t} = (V_1 t_1^{1/3} + V_2 t_2^{1/3} + \cdots + V_n t_n^{1/3})^3$$

where $\bar{t}$ = cubic average boiling point, °F
V_i = volume fraction i of a petroleum product having a normal boiling point of t_i
t_i = temperature, °F

(c)
$$\bar{t}_x = x_1 t_1 + x_2 t_2 + \cdots + x_n t_n$$

where $\bar{t}_x$ = molar average boiling point, °F
x_i = the mole fractions of the narrow boiling range with normal boiling points t_i
t_i = temperature, °F

(d)
$$\bar{t}_M = \frac{\bar{t}_x + \bar{t}}{2}$$

where $\bar{t}_M$ is the mean average boiling point, °F.

Sources of Equations

1. J. F. Fallon and K. M. Watson, "Thermal Properties of Hydrocarbons," *Nat. Pet. News (Tech. Sec.)*, p. R-372 (June 7,1944).
2. R. H. Cavett. "Physical Data for Distillation Calculations-Vapor-Liquid Equilibria," *Proc. Am. Pet. Inst. Div. Refining*. v. 42, p. 351 (1962).
3. K. M. Watson, "Thermodynamics of the Liquid State," *Ind. Eng. Chem.*, v. 35, p. 398 (1943).

Index