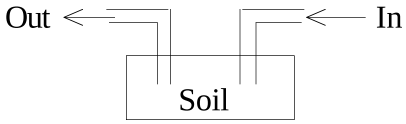
Problem 3.1A

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.

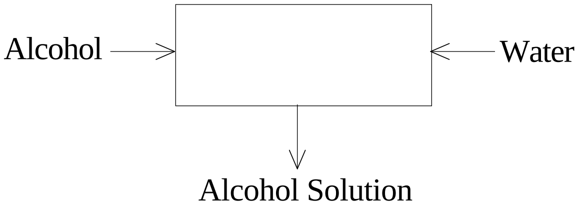
e. Assume unsteady state. If not, the accumulation would be zero and perhaps some leak from the closed system occurred (as would likely occur in the field).

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

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

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.

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

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

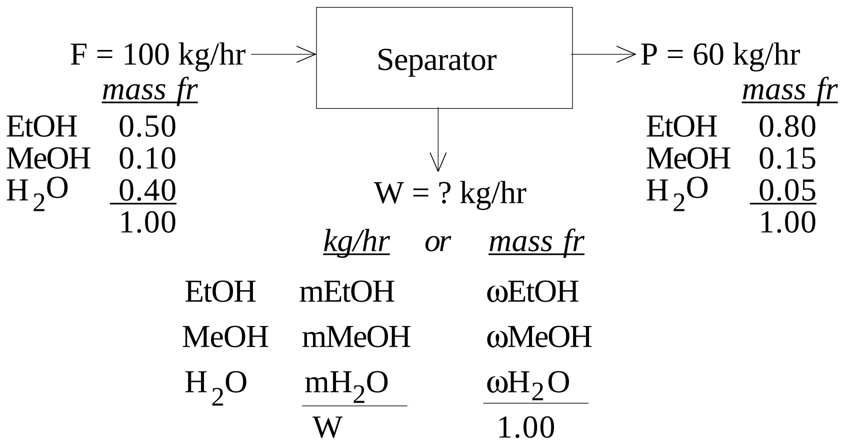
We will follow the steps in Table 3.1 in the analysis and solution of this problem.

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

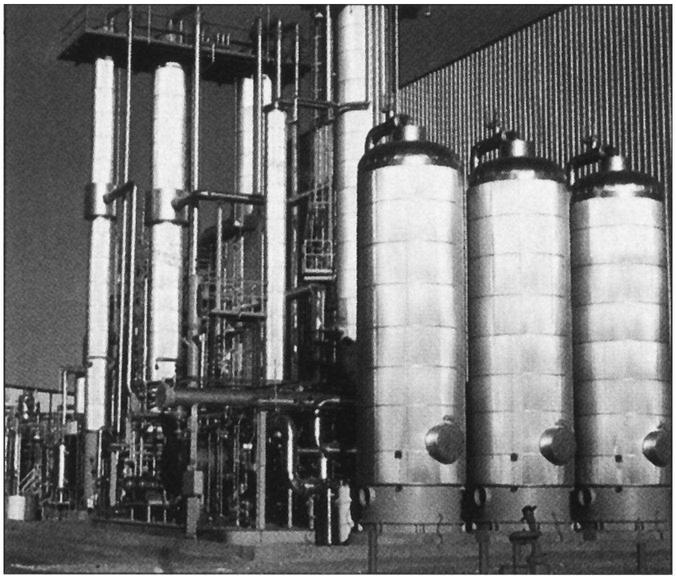


Fig. 5a. Pressure swing absorption beds for the dehydration of alcohols (*courtesy of Howe-Baker Engineers*)

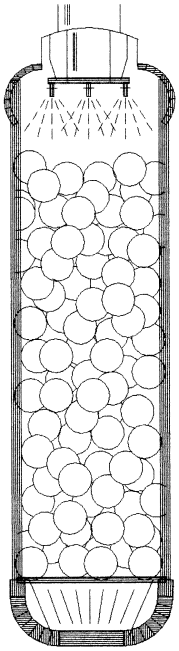


Fig. 5b. Packed bed used in adsorber.

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.

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

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	<u>37</u>	<u>0.925</u>
	40	1.00

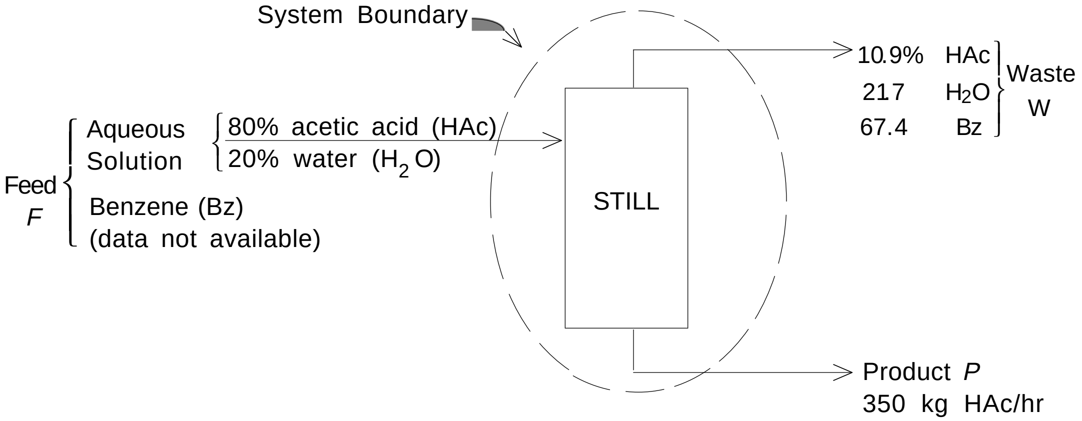
Step 10

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

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

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

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

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.*)

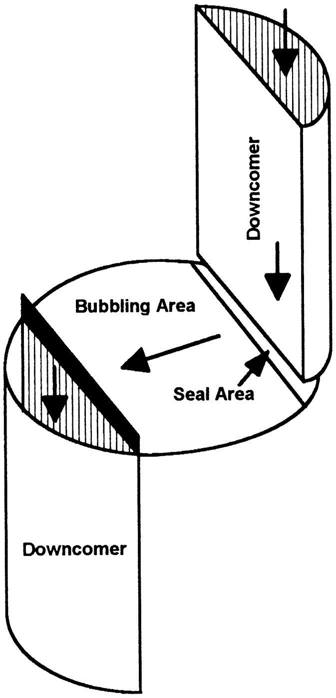


Fig. 6b. Flow of liquid down the column and across a tray through which vapor bubbles upward

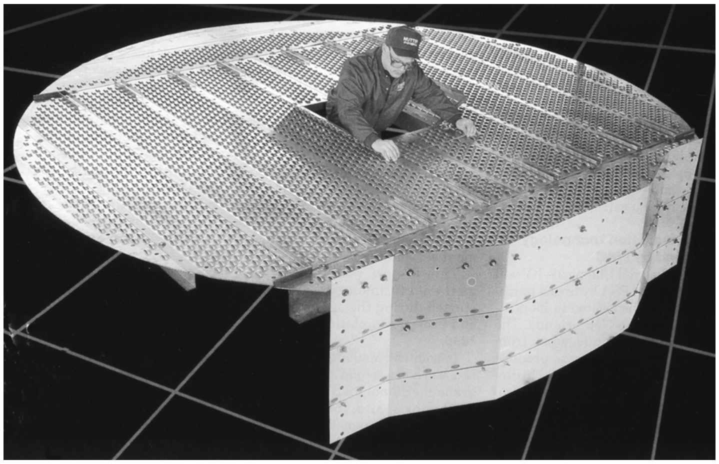


Fig. 6c. One distillation tray in the column (*courtesy of Nutter Engineering*)

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.

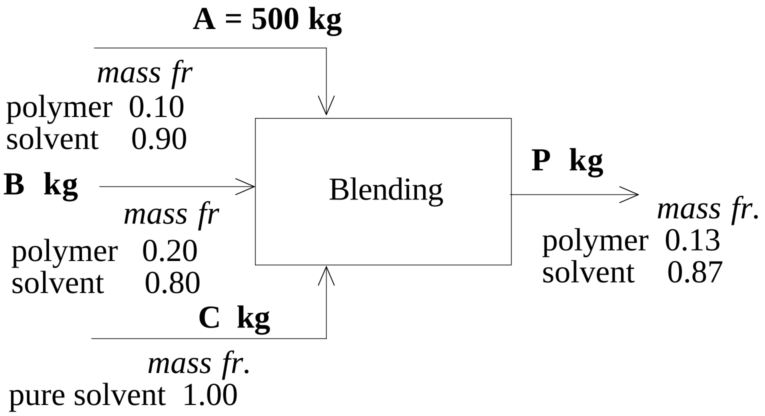
Problem 3.3 A

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)

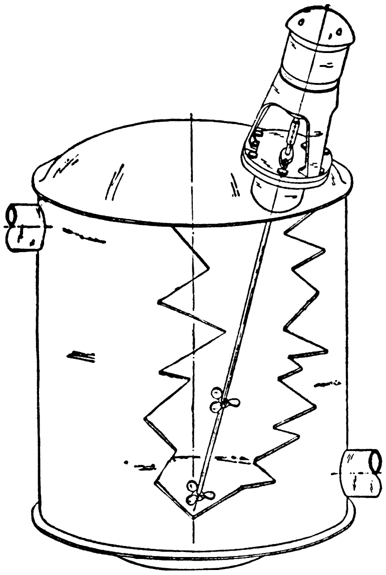


Fig. 7a. Mixing tank and agitator (*courtesy of Mixing Equipment Co.*)

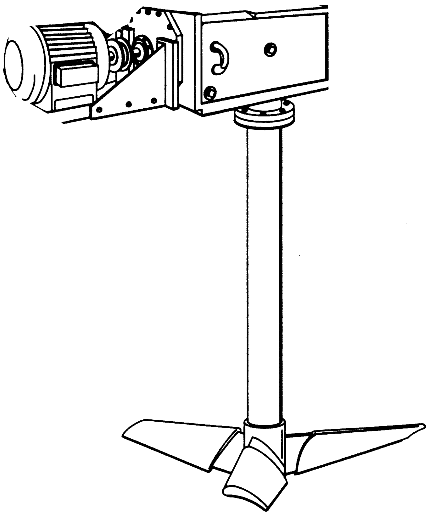


Fig. 7b. Impeller and motor for a mixing tank

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.

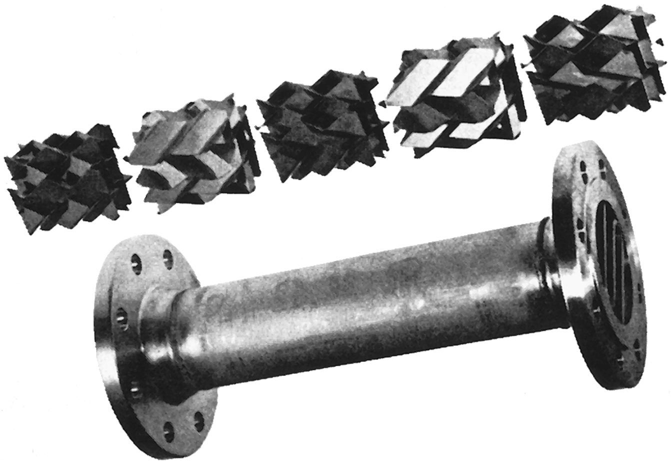


Fig. 7c. Corrugated plate type elements alongside the flanged static mixer body

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.

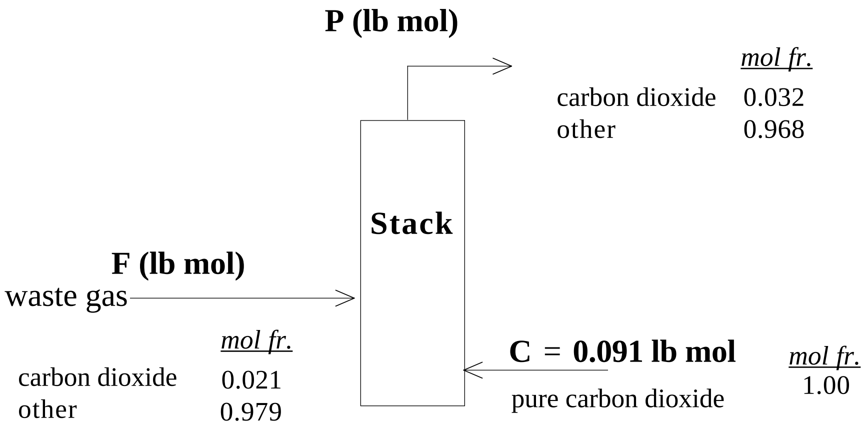
Solution

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

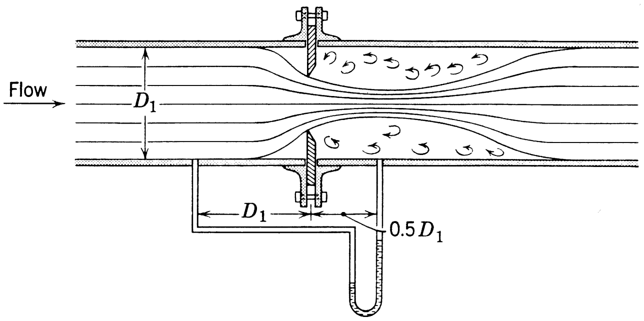
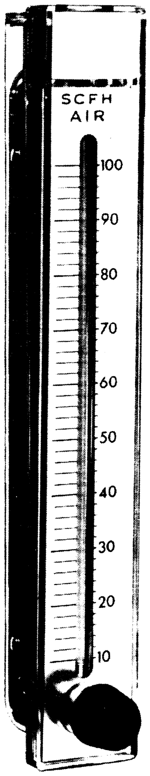


Fig. 8a. Sharp-edged orifice meter. The pressure loss in the converging-diverging flow can be related to the mass flow rate through the pipe.



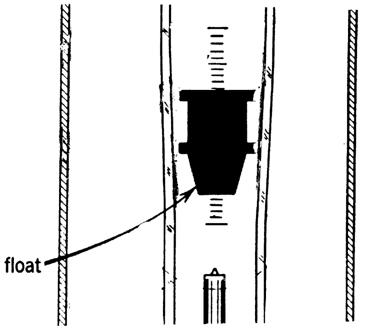


Fig. 8b. A rotameter consists of a tapered tube, glass or plastic, enclosing a small float. The fluid flow (adjusted by a valve at the bottom) causes the float to rise. Calibration may be necessary for different fluids.

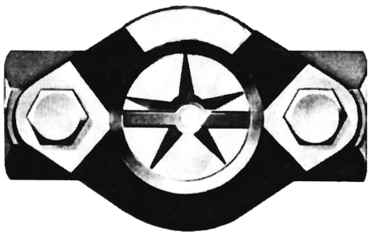


Fig. 8c. Positive displacement meter. The rotating wheel counts the volume passing through the pipe.

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

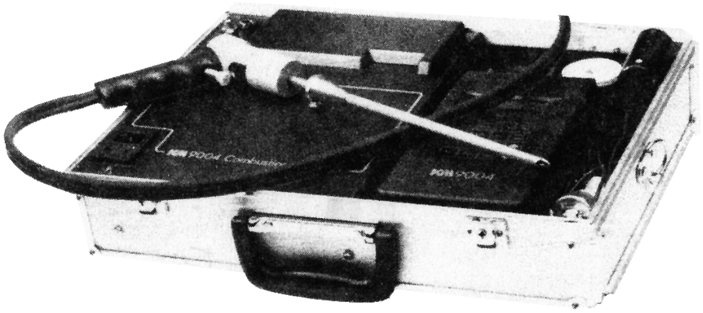


Fig. 9a. Portable combustion gas analyzer uses fuel cell technology to measure oxygen, carbon monoxide and carbon dioxide with 0.2% accuracy for O_2 and CO_2, and 1% for CO.

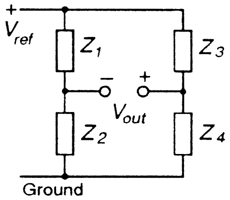


Fig. 9b. A Wheatstone bridge circuit as used in power plants for CO_2. It operates by balancing the output voltage of two circuits, one in a reference gas concentration, and the other in the gas to be measured.

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.

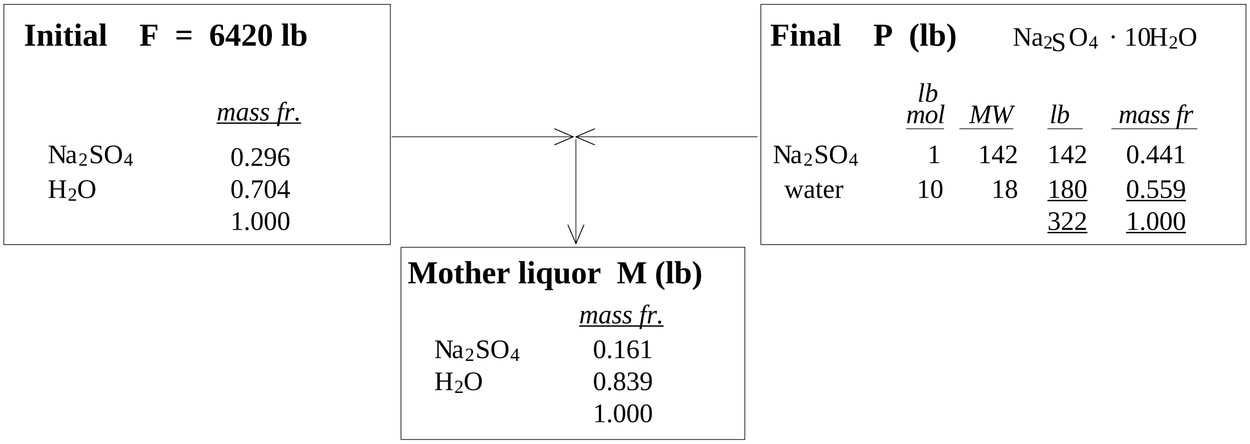
Problem 3.3 D

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 $Na_2SO_4 \cdot 10\ H_2O$. 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.

$$\begin{array}{lcccccc} & \text{Accumulation} & = & \text{In} & - & \text{out} & \\ \text{Total:} & P - F & = & 0 & - & M & (1) \\ Na_2SO_4\text{:} & 0.441P - 0.296\ F & = & 0 & - & 0.161\ M & (2) \end{array}$$

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 : $0.704\ F = 0.551\ P + 0.839\ M$

$0.704\ (6420) = 4520\ \text{lb} \qquad 0.551\ (3100) + 0.839\ (3330) = 4500\ \text{lb}$

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

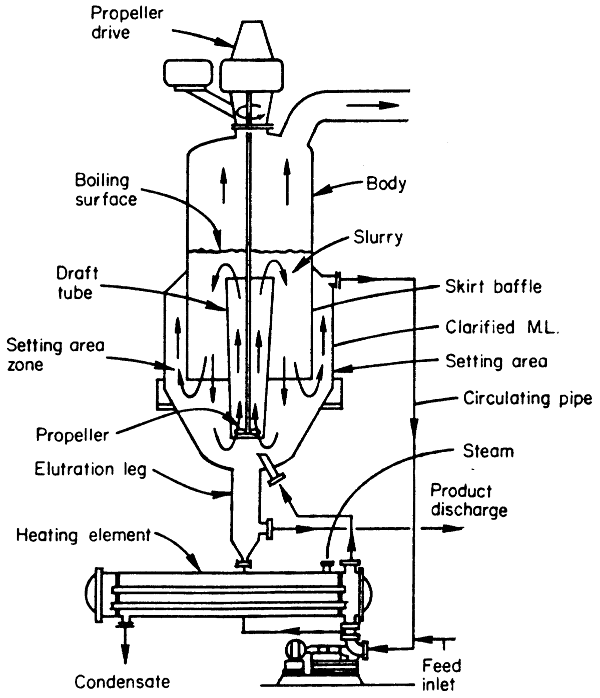


Fig. 10a. Continuous crystallizer (*courtesy of Swenson Process Equipment*). Fine crystals are brought from the bottom to the surface where the rate is higher.

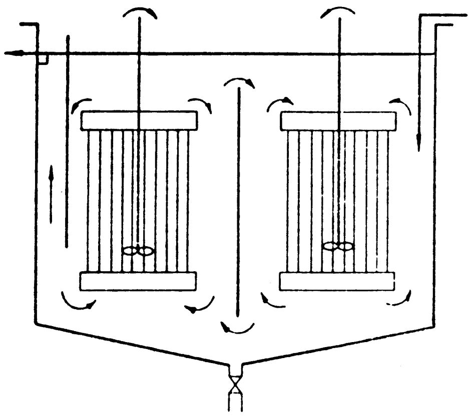


Fig. 10b. Batch crystallizer

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

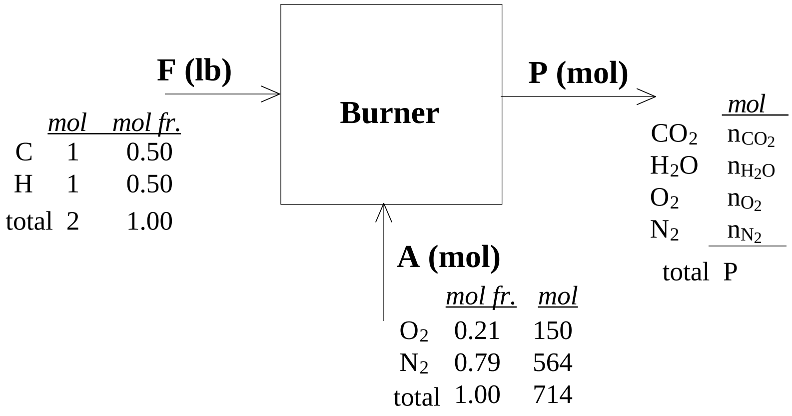
A furnace used to provide heat to anneal steel burns a fuel oil whose composition can be represented as $(CH_2)_n$. It is planned to burn this fuel with stoichiometric air.

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

$$\frac{100 \text{ mol oil}}{} \bigg| \frac{1.5 \text{ mol } O_2}{1 \text{ mol oil}} = 150 \text{ mol } O_2$$

Nitrogen entering

$$\frac{150 \text{ mol } O_2}{} \bigg| \frac{79 \text{ mol } N_2}{21 \text{ mol } O_2} = 564 \text{ mol } N_2$$

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

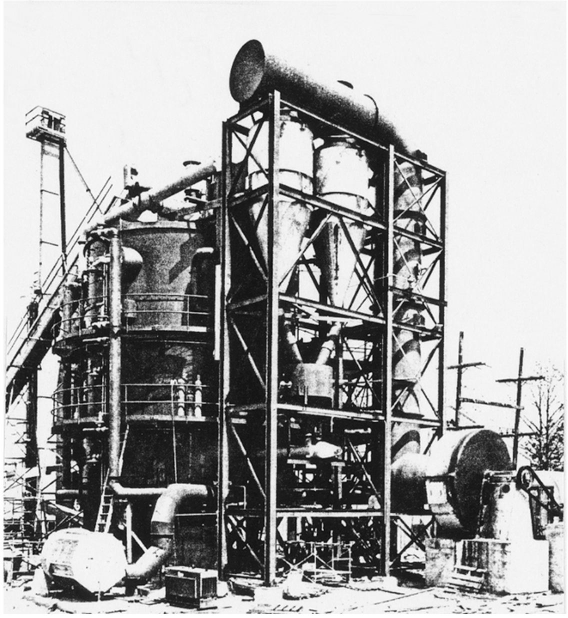
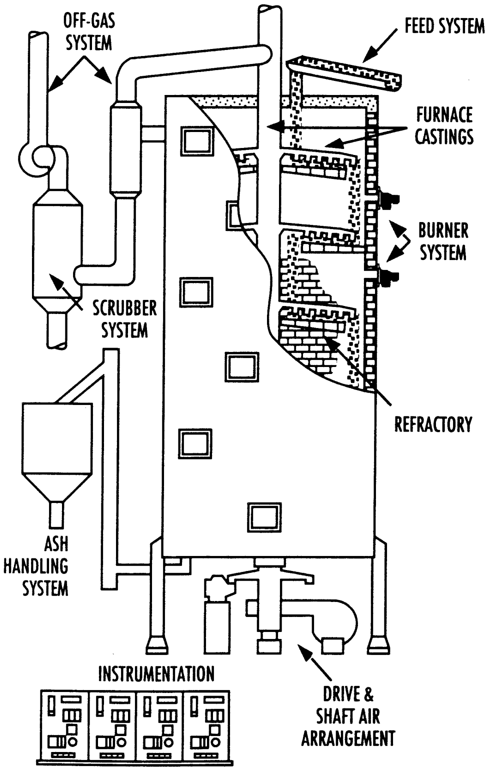


Fig. 11. Multiple hearth furnace (*courtesy of BSP Thermal Systems*)

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

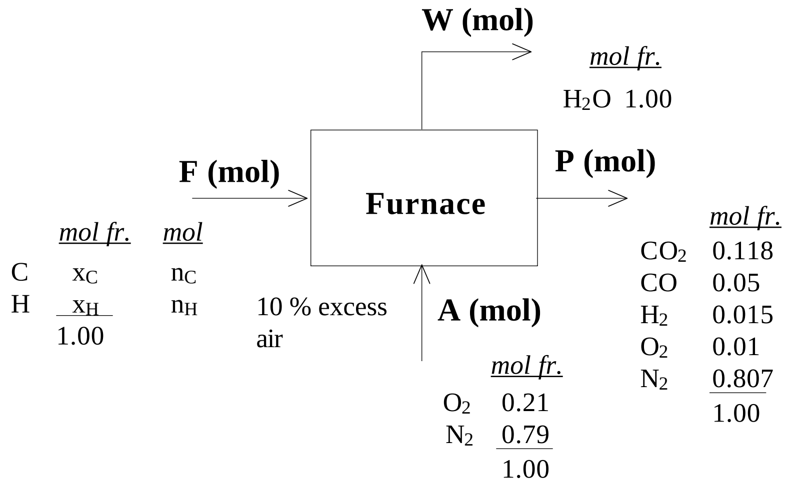
Problem 3.4 B

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:

$C + O_2 \longrightarrow CO_2$

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

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

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

Total required O_2	=	23.65
10% excess	=	2.37
Total O_2	=	26.00

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.

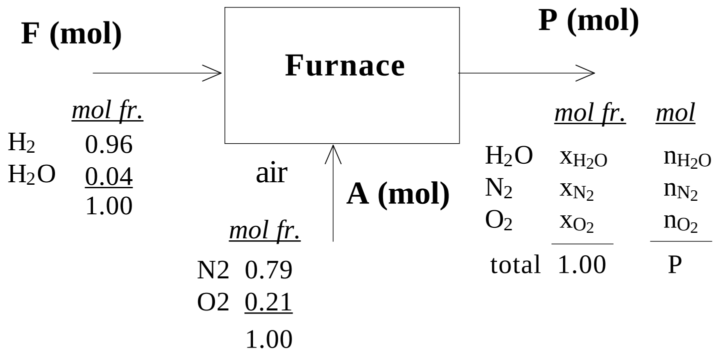
Problem 3.4 C

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:

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

Excess O_2

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

Total oxygen in 63 mol

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

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.

In - Out + Generation - Consumption = 0 (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.*)

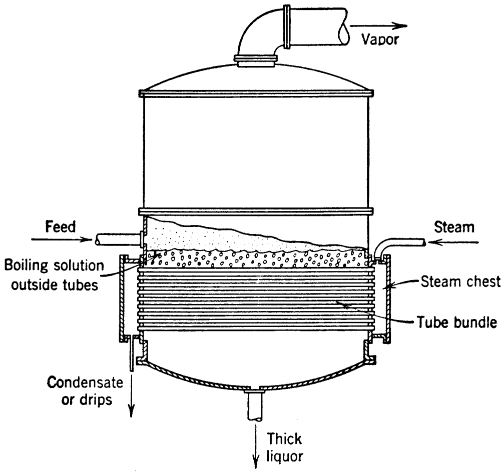
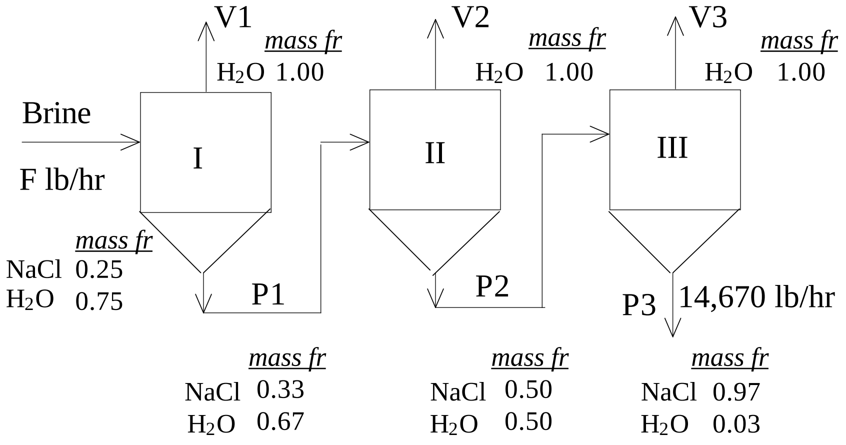


Fig. 12b. Crossection of a single effect evaporator (*courtesy of Swenson Process Equipment Co.*)

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.

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) $\mathbf{V_1 = 13{,}800}$ **lb/hr**

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

From equation (1) $56{,}900 = 13{,}800 + 14{,}700 + V_3 + 14{,}670$

$\mathbf{V_3 = 13{,}800}$ **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)

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

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 %.

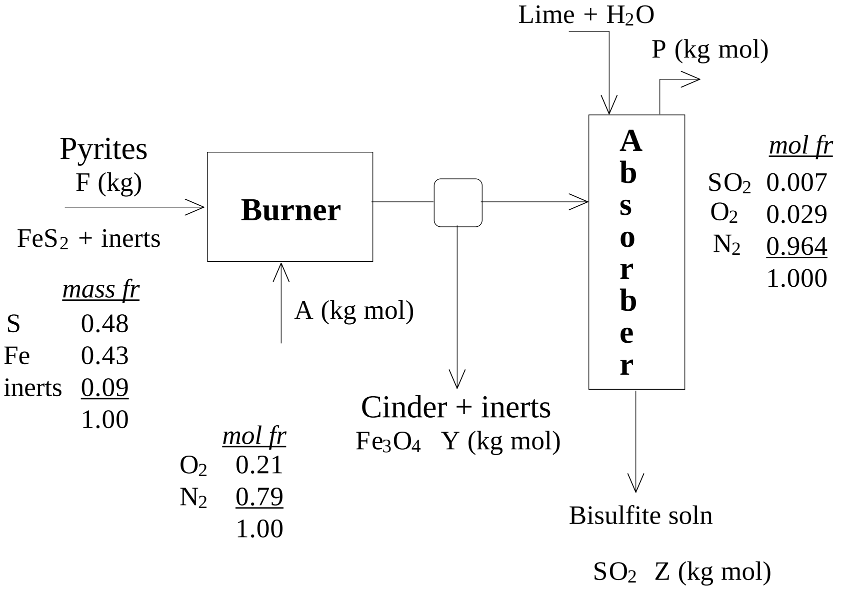
Calculate the kg of air supplied to the burner per kg of the pyrites burned.

(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.

$$3\ FeS_2 + 8\ O_2 \text{ -----> } Fe_3O_4 + 6\ SO_2$$



FLASH COMBUSTION

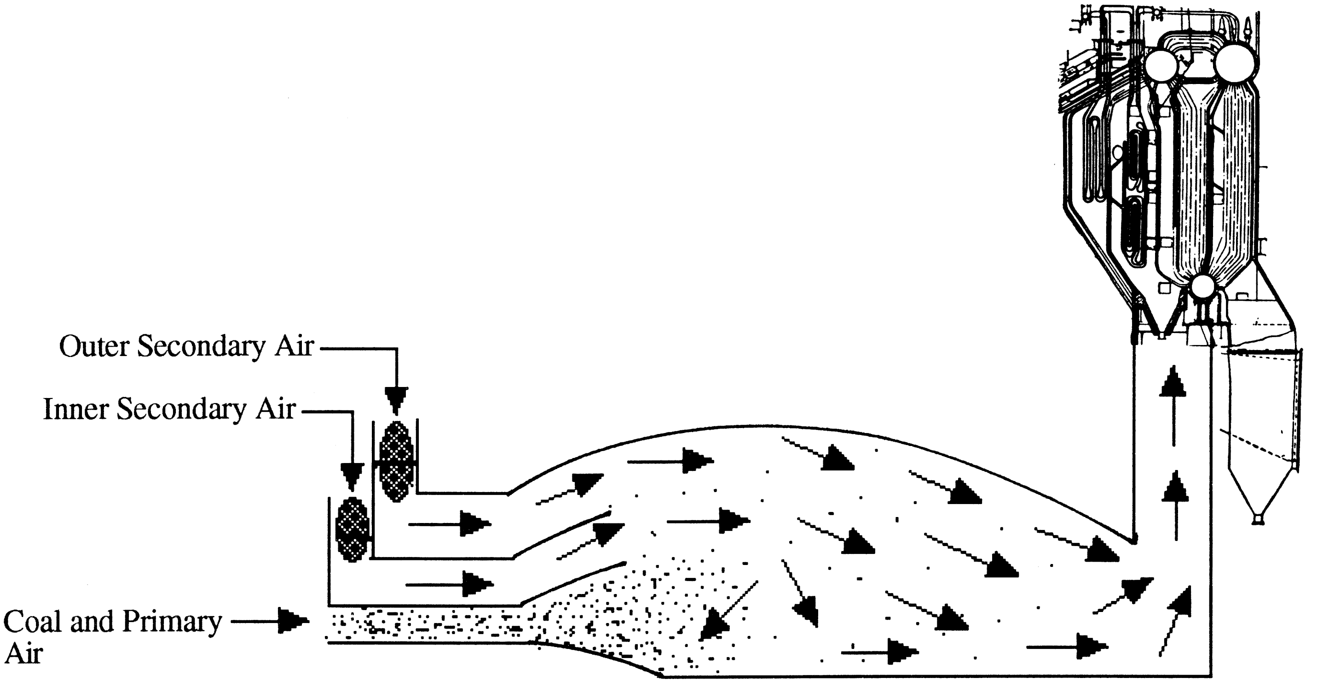


Fig. 13.

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)

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

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

$$O2\quad 0.21\ A = Z + 100(0.007 + 0.029) + \frac{Y\ \text{mol}\ Fe_3O_4 \;\Big|\; 2\ \text{mol}\ O_2}{\Big|\; 1\ \text{mol}\ Fe_3O_4} \qquad (3)$$

$$Fe\quad (0.43/56)\ F = \frac{Y\ \text{mol}\ Fe_3O_4 \;\Big|\; 3\ \text{mol Fe}}{\Big|\; 1\ \text{mol}\ Fe_3O_4} \qquad (4)$$

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

$$\frac{\text{kg air}}{\text{kg pyrites}} = \frac{122\ \text{kg mol air} \;\Big|\; 29\ \text{kg air}}{1130\ \text{kg pyrites} \;\Big|\; \text{kg mol air}} = \mathbf{3.1}\ \frac{\textbf{kg air}}{\textbf{kg pyrites}}$$

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*		*Accum-ulation*
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

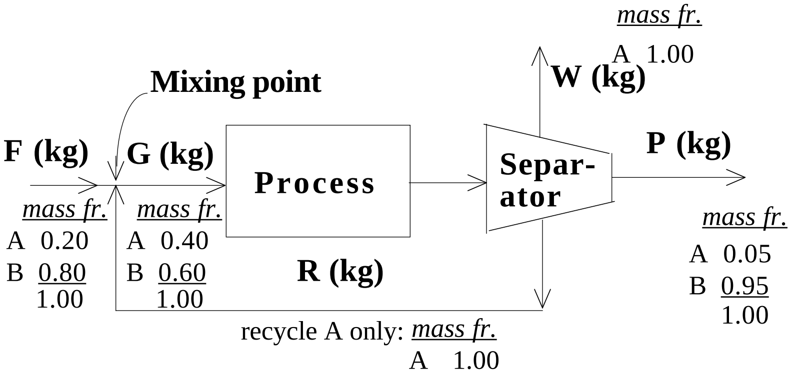
Problem 3.6 A

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

Total $F = P + 100$ (1)
A $0.20\ F = 0.05\ P + 1.00\ (100)$ (2)
B $0.80\ F = 0.95\ P$ (3)

Mixing point

Total $F + R = G$ (4)
A $0.20\ F + (1.00)\ R = 0.40\ G$ (5)
B $0.80\ F = 0.60\ G$ (6)

Process + Separator

Total $G = P + W + R$ (7)
A $0.40\ G = 0.05\ P + (1.00)100 + (1.00)R$ (8)
B $0.60\ G = 0.95\ P$ (9)

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) $633 + R = 844$ $\quad R = 211 \text{ kg}$ $\qquad \dfrac{R}{F} = \dfrac{211 \text{ kg}}{633 \text{ kg}} = \mathbf{0.33} \; \dfrac{\textbf{kg R}}{\textbf{kg F}}$

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)

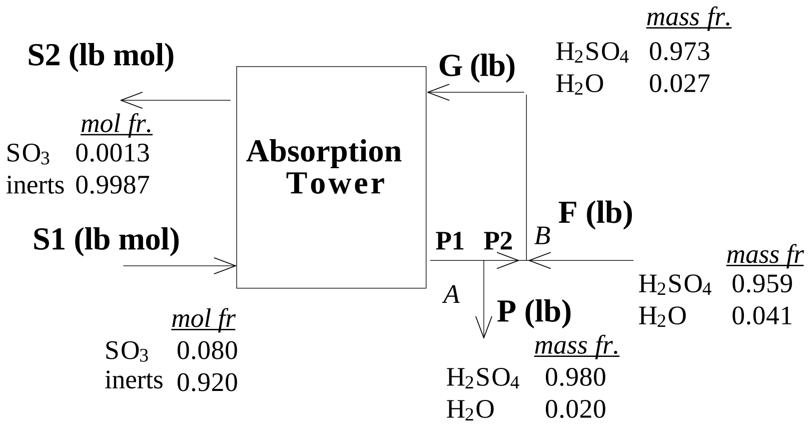
$$0.40\, G = 0.05\, P + W + R$$
$$0.40\,(844) = 0.05\,(533) + 100 + 211$$
$$338 \text{ kg} = 338 \text{ kg}$$

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

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

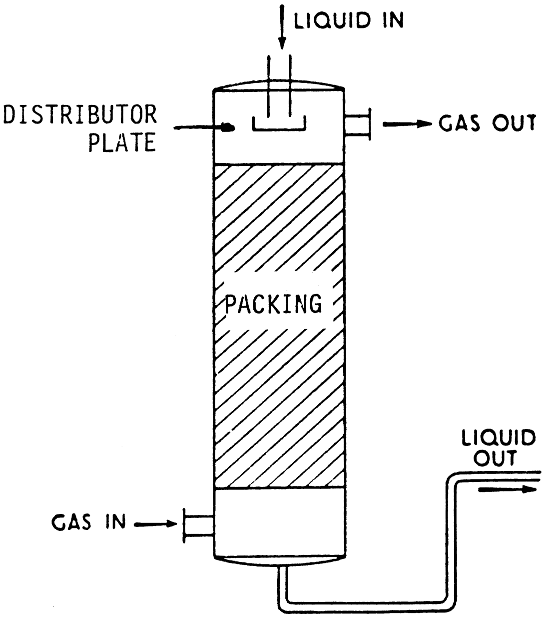
Calculate the SO_3 absorbed in the tower and the composition of S2.

Step 5 Basis : 100 mol S1

Step 4

$$\frac{0.08 \text{ mol } SO_3 \;\Big|\; 100 \text{ mol S1}}{1 \text{ mol S1} \;\Big|\;} = 8 \text{ mol } SO_3$$

ABSORPTION



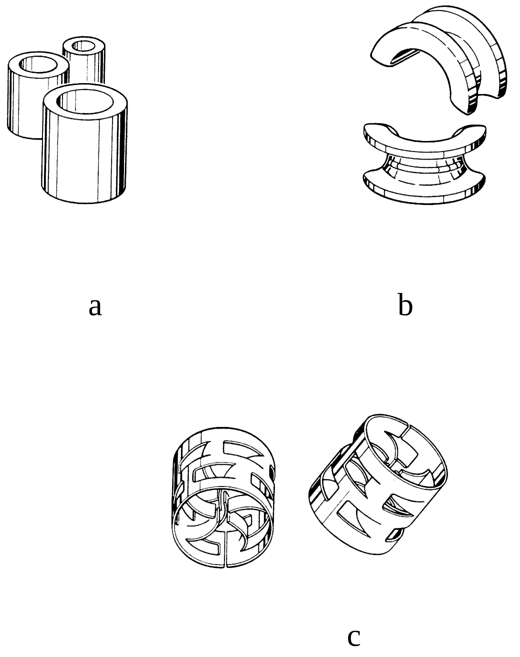


Fig. 14a. Packed column

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

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

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

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

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: $0.041\ (2060) + 0.020\ (4410) \overset{?}{=} 0.027\ (6470)$
$84.4 + 88.2 \cong 175$ 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.

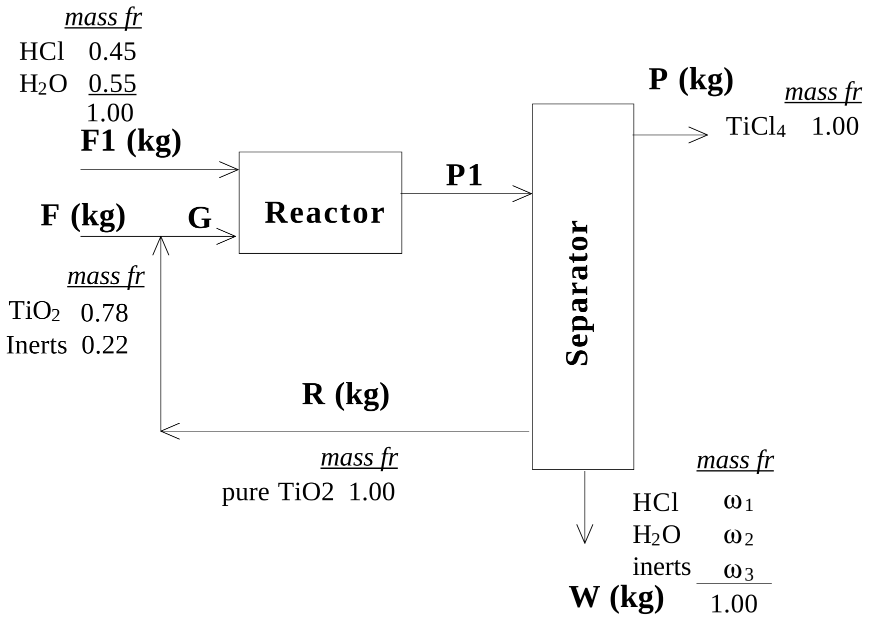
$$TiO_2 + 4\,HCl \text{ -----> } TiCl_4 + 2H_2O$$

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

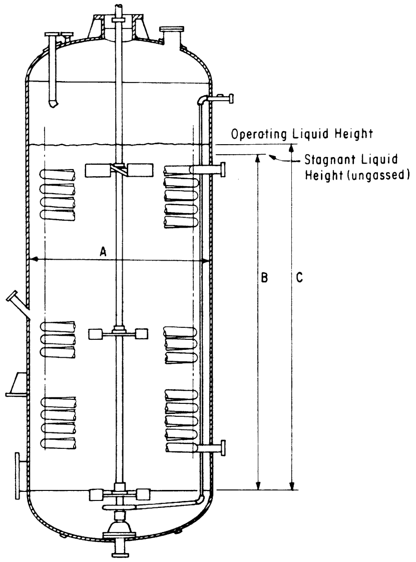


Fig. 15. Slurry reactor (*courtesy of Howard Rase*)

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

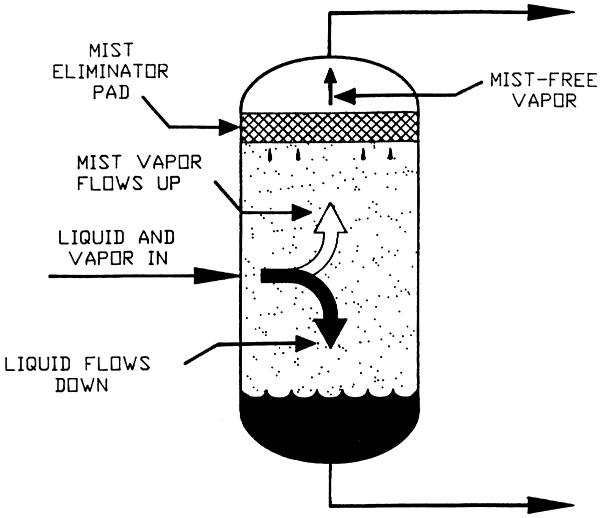


Fig. 16a. A typical vapor-liquid separator

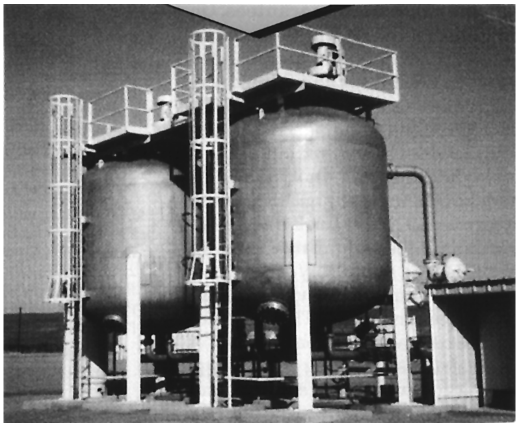


Fig. 16b. Flotation separators remove emulsified oil and suspended solids (*courtesy of EIMCO Process Equipment Co.*)

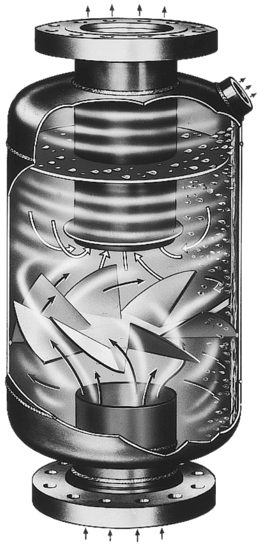


Fig. 16c. Liquid-vapor separator via centrifugal flow (*courtesy of Wright Austin Co.*)

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

$$\text{Total:}\quad 100 + R = G$$

$$TiO_2\text{:}\quad 100\,(0.78) + R\,(1.00) = m^{G}_{TiO_2}$$

$$\text{Inerts:}\quad 100\,(0.22) = m^{G}_{\text{inerts}}$$

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:

$$TiO_2\text{:}\quad \overset{\textit{In}}{\overline{100(0.78) + R(1.00)}} - \overset{\textit{Out}}{\overline{R(1.00)}} + \overset{\textit{Generation}}{\overline{0}} - \overset{\textit{Consumption}}{\overline{0.75[100(0.78) + R] = 0}}$$

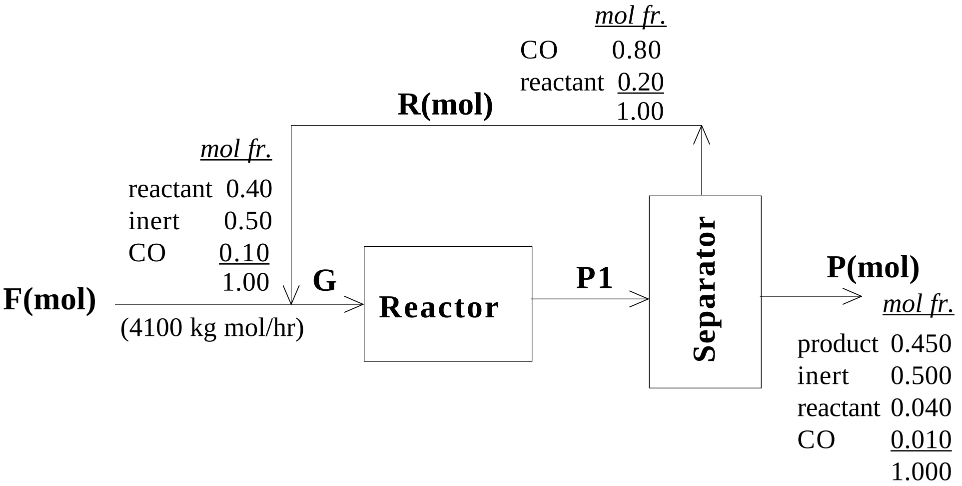
$$R = 26\text{ kg}$$

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

$$\begin{array}{c|c|c|c} 4100 \text{ kg mol F} & 40 \text{ mol reactant} & 90 \text{ mol react} & 2.5 \text{ mol product} \\ \hline & 100 \text{ mol F} & 100 \text{ mol reactant} & 2 \text{ mol reactant} \end{array}$$

$$= 1845 \text{ kg mol product}$$

Inert

$$\begin{array}{c|c} 4100 \text{ kg mol F} & 50 \text{ mol inert} \\ \hline & 100 \text{ mol F} \end{array} = 2050 \text{ kg mol inert}$$

Reactant

$$\begin{array}{c|c|c} 4100 \text{ kg mol F} & 40 \text{ mol reactant} & 0.10 \text{ mol unreacted} \\ \hline & 100 \text{ mol F} & 1.0 \text{ mol reactant} \end{array} = 164 \text{ kg mol reactant}$$

CO

$$\begin{array}{c|c|c} 4100 \text{ kg mol F} & 10 \text{ mol CO} & 0.10 \text{ mol unreacted CO} \\ \hline & 100 \text{ mol F} & 1.0 \text{ mol CO} \end{array} = 41 \text{ kg mol CO}$$

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

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:

$$\begin{array}{ccccccccc} \textit{In} & & \textit{Out} & & \textit{Gen.} & & \textit{Consumption} & & \textit{Accum.} \\ \hline 0.40(4100) + 0.20R & - & (0.20R + 0.040(4100)) & + & 0 & - & 0.73[0.40(4100) + 0.20R] & = & 0 \end{array}$$

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

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

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

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 $Ba(ClO_4)_2$.

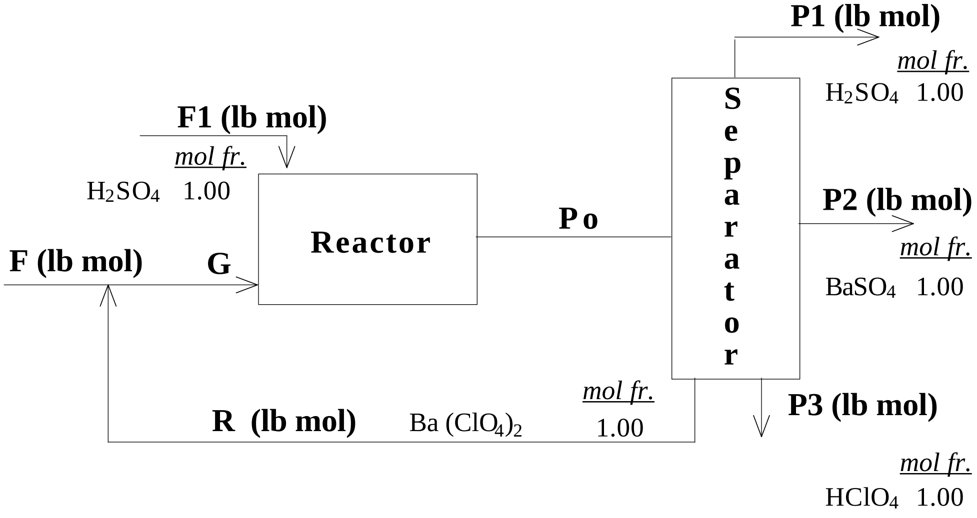
Note : 20 % H_2SO_4 is based on the total $Ba(ClO_4)_2$ entering the reactor.

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

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)

$$\text{Cl:}\quad \begin{array}{c|c|c} \text{F lb mol} & 0.729\text{ lb mol Ba(ClO}_4)_2 & 2\text{ lb mol Cl} \\ \hline & 1\text{ lb mol F} & 1\text{ lb mol Ba(ClO}_4)_2 \end{array}$$

$$+\ \begin{array}{c|c|c} \text{F lb mol} & 0.271\text{ lb mol HClO}_4 & 1\text{ lb mol Cl} \\ \hline & 1\text{ lb mol F} & 1\text{ lb mol HClO}_4 \end{array}$$

$$=\ \begin{array}{c|c|c} 173.13\text{ lb mol P3} & 1\text{ lb mol HClO}_4 & 1\text{ lb mol Cl} \\ \hline & 1\text{ lb mol P3} & 1\text{ lb mol HClO}_4 \end{array}$$

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

$$\text{Ba:}\quad \begin{array}{c|c|c} (100.1)\text{ lb mol} & 0.\ 729\text{ lb mol Ba(ClO}_4)_2 & 1\text{ lb mol Ba} \\ \hline & 1\text{ lb mol F} & 1\text{ lb mol Ba(ClO}_4)_2 \end{array}$$

$$=\ \begin{array}{c|c} \text{P2 lb mol} & 1\text{ lb mol Ba} \\ \hline & 1\text{ lb mol P2} \end{array}$$

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

$$\text{S:}\quad \begin{array}{c|c|c} \text{F1 lb mol} & 1\text{ lb mol H}_2\text{SO}_4 & 1\text{ lb mol S} \\ \hline & 1\text{ lb mol F1} & 1\text{ lb mol H}_2\text{SO}_4 \end{array}$$

$$=\ \begin{array}{c|c} \text{P1 lb mol} & 1\text{ lb mol S} \\ \hline & 1\text{ lb mol P1} \end{array}\ +\ \begin{array}{c|c} 73.0\text{ lb mol BaSO}_4 & 1\text{ lb mol S} \\ \hline & 1\text{ lb mol BaSO}_4 \end{array}$$

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

c. F1 = 109 lb mol or **10,700 lb 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.

$$\begin{array}{ccccccccc} \textit{Accum.} & & \textit{In} & & \textit{Out} & & \textit{Generation} & & \textit{Consumption} \\ 0 & = & 91.2 & - & \dfrac{6125}{336} & + & 0 & & -f(91.2) \end{array}$$

$$\mathbf{f = 0.80}$$

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

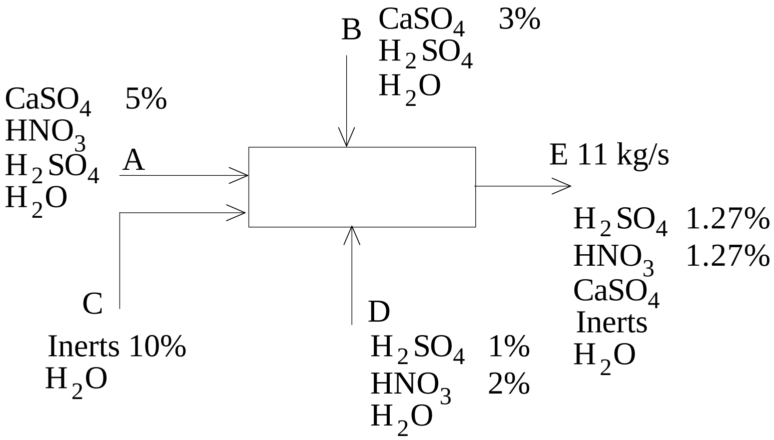
3.2A Determine the rank of the following matrix .

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

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?

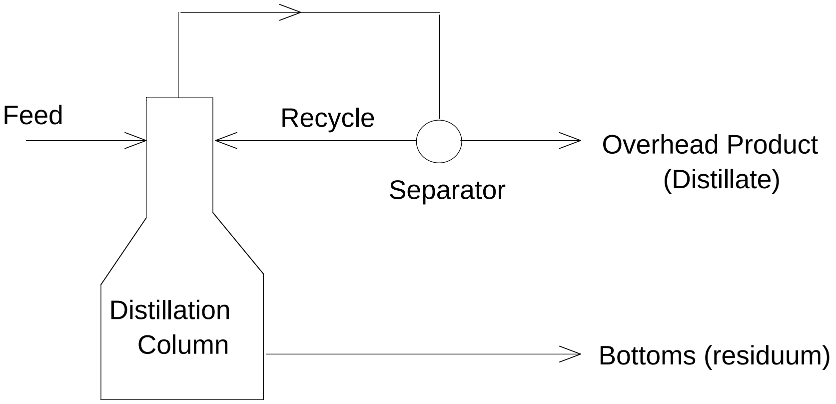
3.3B If 100g of Na_2SO_4 is dissolved in 200g of H_2O and the solution is cooled until 100 g of $Na_2SO_4 \cdot 10H_2O$ crystallizes out, find

(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).

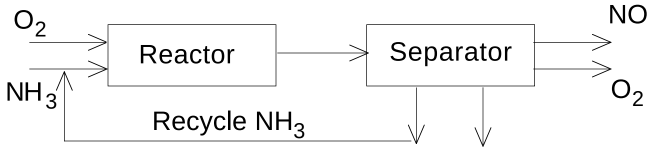
Section 3.6

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:

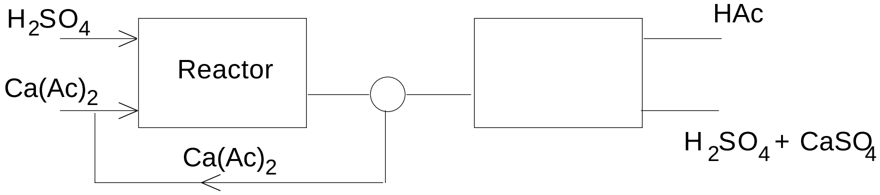
$$4NH_3 + 5O_2 \longrightarrow 4NO + 6H_2O$$

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.

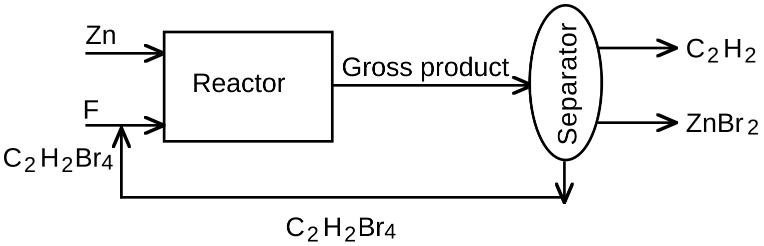


3.6B Acetic acid is to be generated by the addition of 10 percent excess sulfuric acid to calcium acetate. The reaction $Ca(AC)_2 + H_2SO_4 \longrightarrow CaSO_4 + 2HAc$ goes on with 90 percent completion. The unused $Ca(Ac)_2$ and the H_2SO_4 are separated from the products of the reaction, and the 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.