الجامعة التكنولوجية

قسم الهندسة الكيمياوية

المرحلة الاولى

مباديء الهندسة الكيمياوية

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The element balances:

$$C: F(8) + G(0) = 100[(0.195)(3) + (0.594)(4) + (0.211)(5)]$$

$$H: F(18) + G(2) = 100[(0.195)(8) + (0.594)(10) + (0.211)(12)]$$

And the solution is F = 50.2 g mol

G = 49.8 g mol The ratio

$$\frac{H_2 \text{ consumed}}{C_8H_{18} \text{ reacted}} = \frac{49.8 \text{ g mol}}{50.2 \text{ g mol}} = 0.992$$

10.3 Material Balances Involving Combustion

⌘ **Combustion** is the reaction of a substance with **oxygen** with the associated release of energy and generation of product gases such as H_2O, CO_2, CO, and SO_2.

⌘ Most **combustion processes** use **air** as the source of **oxygen**. For our purposes you can assume that air contains **79% N_2** and **21% O_2**.

Special terms:

1. **Flue or stack gas**: All the gases resulting from combustion process including the water vapor, sometimes known as a **wet basis**.
2. **Orsat analysis or dry basis**: All the gases resulting from combustion process **not including** the **water** vapor. **Orsat analysis** refers to a type of gas analysis apparatus in which the volumes of the respective gases are measured over and in equilibrium with water; hence each component is saturated with water vapor. The net result of the analysis is to **eliminate water** as a component being measured (show Figure 10.4).
3. **Complete combustion**: the complete reaction of the hydrocarbon fuel producing CO_2, SO_2, and H_2O.
4. **Partial combustion**: the combustion of the fuel producing at least some **CO**. Because CO itself can react with oxygen, the production of CO in a combustion process does not produce as much energy as it would if only **CO_2** were produced.
5. **Theoretical air (or theoretical oxygen)**: The minimum amount of **air (or oxygen)** required to be brought into the process **for complete combustion**. Sometimes this quantity is called the **required air** (**or oxygen**).

6. **Excess air (or excess oxygen)**: In line with the definition of excess reactant given in Chapter 9, excess air (or oxygen) would be the amount of air (or oxygen) **in excess of that required for complete combustion** as defined in (5).

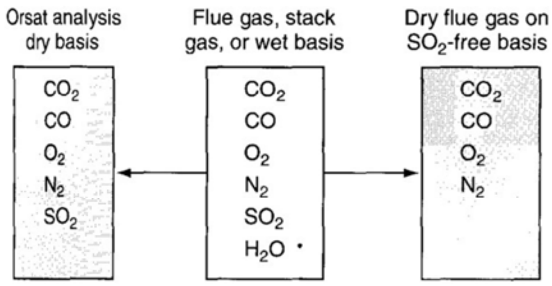


Figure 10.4 Comparison of a gas analysis on different bases.

Note: The calculated amount of excess air does not depend on how much material is **actually** burned but what is **possible** to be **burned**. Even if only **partial combustion** takes place, as, for example, **C** burning to both **CO** and **CO_2**, the excess air (or oxygen) is computed as if the process of combustion went to completion and produced only **CO_2**.

The **percent excess air** is identical to the percent **excess O_2**:

$$\%\text{ excess air} = \frac{\text{excess air}}{\text{required air}} \times 100 = \frac{\text{excess } O_2/0.21}{\text{required } O_2/0.21} \times 100 \qquad \ldots\ 10.6$$

Note that the ratio **1/0.21** of air to **O_2** cancels out in Equation 10.6. **Percent excess air** may also be computed as

$$\%\text{ excess air} = \frac{O_2\text{ entering process} - O_2\text{required}}{O_2\text{required}} \times 100 \qquad \ldots\ 10.7$$

Or

$$\%\text{ excess air} = \frac{\text{excess } O_2}{O_2\text{ entering} - \text{excess } O_2} \times 100 \qquad \ldots\ 10.8$$

Example 10.7

Fuels other than gasoline are being eyed for motor vehicles because they generate lower levels of pollutants than does gasoline. Compressed propane is one such proposed fuel.

Suppose that in a test 20 kg of C_3H_8 is burned with 400 kg of air to produce 44 kg of CO_2 and 12 kg of CO. What was the percent excess air?

Solution

This is a problem involving the following reaction $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$

Basis: 20 kg of C_3H_8

➊ Since the percentage of excess air is based on the **complete combustion** of C_3H_8 to CO_2 and H_2O, the fact that **combustion** is **not complete** has **no influence** on the **calculation** of **"excess air."**

The required O_2 is

$$\frac{20 \text{ kg } C_3H_8}{} \left| \frac{1 \text{ kg mol } C_3H_8}{44.09 \text{ kg } C_3H_8} \right| \frac{5 \text{ kg mol } O_2}{1 \text{ kg mol } C_3H_8} = 2.27 \text{ kg mol } O_2$$

The entering O_2 is

$$\frac{400 \text{ kg air}}{} \left| \frac{1 \text{ kg mol air}}{29 \text{ kg air}} \right| \frac{21 \text{ kg mol } O_2}{100 \text{ kg mol air}} = 2.90 \text{ kg mol } O_2$$

The percentage of excess air is

$$\%\text{ excess air} = \frac{O_2 \text{ entering process} - O_2 \text{required}}{O_2 \text{required}} \times 100$$

$$\%\text{ excess air} = \frac{2.90 \text{ lb mol } O_2 - 2.27 \text{ lb mol } O_2}{2.27 \text{ lb mol } O_2} \left| \frac{100}{} \right. = 28\%$$

Note:

In calculating the amount of excess air, remember that the excess is the amount of air that enters the combustion process over and above that required for complete combustion.

For example, suppose that a gas containing 80% C_2H_6 and 20% O_2 is burned in an engine with 200% excess air. Eighty percent of the ethane goes to CO_2, 10% goes to CO, and 10% remained unburned. What is the amount of the excess air per 100 moles of the gas?

Solution

First, you can ignore the **information** about the **CO** and the **unburned ethane** because the basis of the calculation of **excess air is complete combustion**. Specifically C goes to CO_2; S to SO_2, H_2 to H_2O, CO goes to CO_2 and so on.

Second, the oxygen in the fuel cannot be ignored. Based on the reaction

$$C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O$$

Basis: 100 moles of gas

- 80 moles of C_2H_6 require 3.5(80) = 280 moles of O_2 for complete combustion.

- The gas contains 20 moles of O_2, so that only 280 – 20 = 260 moles of O_2 are needed in the entering air for complete combustion.
- Thus, 260 moles of O_2 are the required O_2 and the calculation of the 200% excess O_2 (air) is based on 260, not 280, moles of O_2:

Entering with air	Moles O_2
Required O_2:	260
Excess O_2:	(2)(260) = 520
Total O_2:	780

Example 10.8

Figure El0.8 is a sketch of a fuel cell in which a continuous flow of methane (CH_4) and air (O_2 plus N_2) produce electricity plus CO_2 and H_2O. Special membranes and catalysts are needed to promote the reaction of CH_4. Based on the data given in Figure El0.8, you are asked to calculate the composition of the products in P.

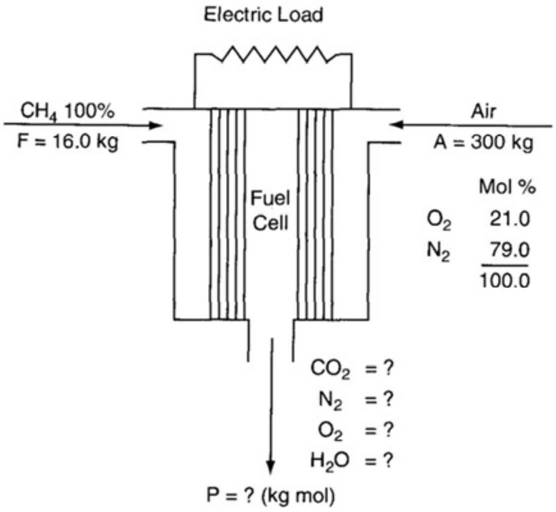


Figure E10.8

Solution

Assume a **complete reaction** occurs because no CH_4 appears in P. The system is the fuel cell (open, steady state). The necessary preliminary conversions as follows:

$$\frac{300\ \text{kg A}}{} \left| \frac{1\ \text{kg mol A}}{29.0\ \text{kg A}} \right. = 10.35\ \text{kg mol A in}$$

$$\frac{16.0\ \text{kg}\ CH_4}{} \left| \frac{1\ \text{kg mol}\ CH_4}{16.0\ \text{kg}\ CH_4} \right. = 1.00\ \text{kg mol}\ CH_4\ \text{in}$$

$$\frac{10.35\ \text{kg mol A}}{} \left| \frac{0.21\ \text{kg mol}\ O_2}{1\ \text{kg mol A}} \right. = 2.17\ \text{kg mol}\ O_2\ \text{in}$$

$$\frac{10.35\ \text{kg mol A}}{} \left| \frac{0.79\ \text{kg mol}\ N_2}{1\ \text{kg mol A}} \right. = 8.18\ \text{kg mol}\ N_2\ \text{in}$$

Basis: 16.0 kg CH_4 entering = 1 kg mol CH_4

Specifications and calculated quantitie $n_{O_2}^{A} = 2.17,\ n_{N_2}^{A} = 8.18$

Implicit equation: $\Sigma n_i^P = P$

The element material balances are (in moles):

	Out		In
C:	$n_{CO_2}^P(1)$	=	1(1)
H:	$n_{H_2O}^P(2)$	=	1(4)
O:	$n_{CO_2}^P(2) + n_{O_2}^P(2) + n_{H_2O}^P(1)$	=	2.17(2)
2N:	$n_{N_2}^P$	=	8.18

The species material balances are:

Compound	Out		In		$v_i\xi$		g mol
CH_4:	$n_{CH_4}^P$	=	1.0	−	1 × 1	=	0
O_2:	$n_{O_2}^P$	=	2.17	−	2 × 1	=	0.17
N_2:	$n_{N_2}^P$	=	8.18	−	0 × 1	=	8.18
CO_2:	$n_{CO_2}^P$	=	0	+	1 × 1	=	1.0
H_2O:	$n_{H_2O}^P$	=	0	+	2 × 1	=	2.0

The **solution** of **either** set of **equations** gives

$$n_{CH_4}^P = 0, n_{O_2}^P = 0.17, n_{N_2}^P = 8.18, n_{CO_2}^P = 1.0, n_{H_2O}^P = 2.0, P = 11.35$$

The mole percentage composition of P is

$$y_{O_2} = 1.5\%, y_{N_2} = 72.1\%, y_{CO_2} = 8.8\%, \text{and } y_{H_2O} = 17.6\%$$

Problems

1. Hydrofluoric acid (HF) can be manufactured by treating calcium fluoride (CaF_2) with sulfuric acid (H_2SO_4). A sample of fluorospar (the raw material) contains 75% by weight CaF_2 and 25% inert (nonreacting) materials. The pure sulfuric acid used in the process is in 30% excess of that theoretically required. Most of the manufactured HF leaves the reaction chamber as a gas, but a solid cake that contains 5% of all the HF formed, plus $CaSO_4$, inerts, and unreacted sulfuric acid is also removed from the reaction chamber. Assume complete conversion of the CaF_2 occurs. How many kilograms of cake are produced per 100 kg of fluorospar charged to the process?

2. Corrosion of pipes in boilers by oxygen can be alleviated through the use of sodium sulfite. Sodium sulfite removes oxygen from boiler feedwater by the following reaction:

$$2Na_2SO_3 + O_2 \rightarrow 2NaSO_4$$

How many pounds of sodium sulfite are theoretically required (for complete reaction) to remove the oxygen from 8,330,000 lb of water (10^6 gal) containing 10.0 parts per million (ppm) of dissolved oxygen and at the same time maintain a 35% excess of sodium sulfite?

3. Consider a continuous, steady-state process in which the following reactions take place:

$$C_6H_{12} + 6H_2O \rightarrow 6CO + 12H_2$$
$$C_6H_{12} + H_2 \rightarrow C_6H_{14}$$

In the process 250 moles of C_6H_{12} and 800 moles of H_2O are fed into the reactor each hour. The yield of H_2 is 40.0% and the selectivity of H_2 relative to C_6H_{14} is 12.0. Calculate the molar flow rates of all five components in the output stream.

4. Consider a system used in the manufacture of electronic materials (all gases except Si)

SiH_4, Si_2H_4, Si_2H_6, H_2, Si

How many independent element balances can you make for this system?

5. Methane burns with O_2 to produce a gaseous product that contains CH_4, O_2, CO_2, CO, H_2O, and H_2. How many independent element balances can you write for this system?
6. Solve the problems (1, 2 & 3) using element balances.
7. Pure carbon is burned in oxygen. The flue gas analysis is: CO_2 75 mo1%, CO l4 mol% & O_2 11 mol%. What was the percent excess oxygen used?
8. Toluene, C_7H_8, is burned with 30% excess air. A bad burner cause 15% of the carbon to form soot (pure C) deposited on the walls of the furnace, what is the Orsat analysis of the gases leaving the furnace?
9. A synthesis gas analyzing CO_2: 6.4%, O_2: 0.2%, CO: 40.0% and H_2: 50.8% (the balance is N_2) is burned with excess dry air. The problem is to determine the composition of the flue gas. How many degrees of freedom exist in this problem, that is, how many additional variables must be specified?
10. A hydrocarbon fuel is burnt with excess air. The Orsat analysis of the flue gas shows 10.2% CO_2, 1.0% CO, 8.4% O_2, and 80.4% N_2. What is the atomic ratio of H to C in the fuel?

Answers:

1. 186 kg
2. 887 lb
3. (a) C_6H_{12} = 139 mol/hr; (b) H_2O = 453 mol/hr; (c) CO = 347 mol/hr; (d) H_2 = 640 mol/hr;

(e) C_6H_{14} = 53.3 mol/hr.

4. Two

5. Three
6. See the answers to the problems (1, 2 &3).
7. 4.5%
8. 9.1% CO_2, 8.9% O_2, 82% N_2
9. 1
10. 0.81

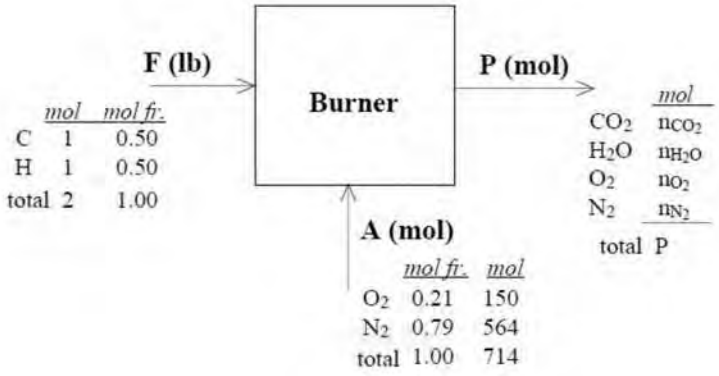
Supplementary Problems (Chapter Ten):

Problem 1

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



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 mol fuel oil

a.

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

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

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.

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

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.

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

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

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 ?

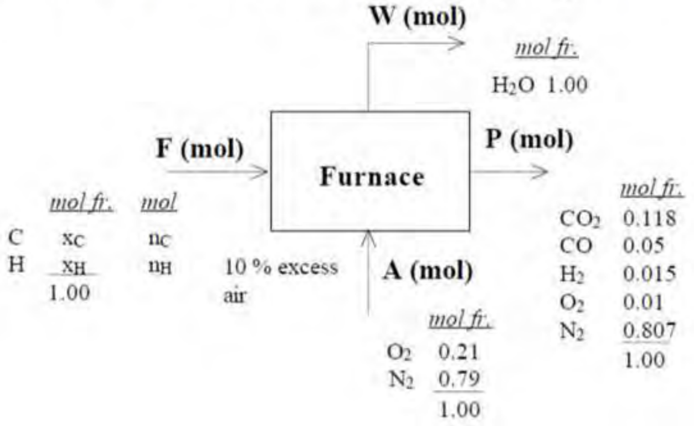
Solution

Problem 2

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

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.

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	$n_H = 27.4$

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:

$C + O_2 \text{ -----> } CO_2$ $$\frac{16.8 \text{ mol C} \mid 1 \text{mol} O_2}{\mid 1 \text{ mol C}} = 16.8$$

$H_2 + 1/2\, O_2 \text{ -----> } H_2O$ $$\frac{13.7 \text{ mol } H_2 \mid 1 \text{mol } O_2}{\mid 2 \text{ mol } H_2} = 6.85$$

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.

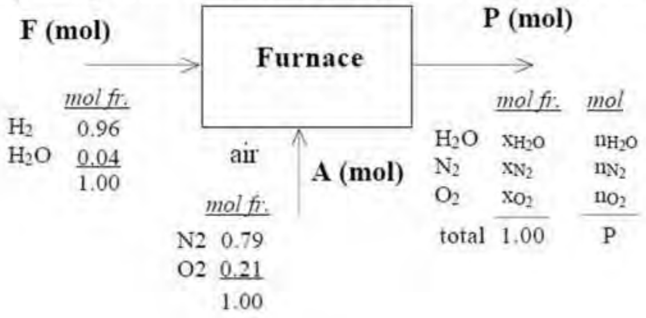
Problem 10.3

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

Problem 3

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



Basis: 100 mol F

We first calculate the amount of entering air.

$$H_2 + 0.5\,O_2 \dashrightarrow H_2O$$

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

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

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

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

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.

Chapter 11

Material Balance Problems Involving Multiple Units

- A **process flowsheet (flowchart)** is a graphical representation of a process. A flowsheet describes the **actual process** in sufficient detail that you can use it to formulate material (and energy) balances.

Figure 11.1a illustrates a serial combination of mixing and splitting stages. In a **mixer**, two or more entering streams of different **compositions are combined**. In a **splitter**, two or more streams exit, all of which have the **same composition**. In a **separator**, the exit streams can be of **different compositions**.

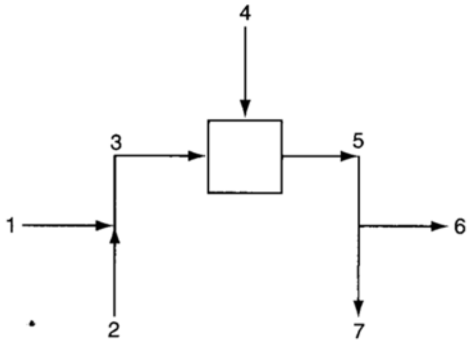


Figure 11.1a serial mixing and splitting in a system without reaction. Streams 1 plus 2 mix to form Stream 3, and Stream 5 is split into Streams 6 and 7.

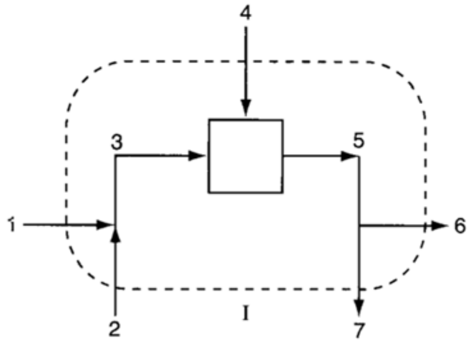


Figure 11.1b the dashed line I designates the boundary for overall material balances made on the process in Figure l1.1a.

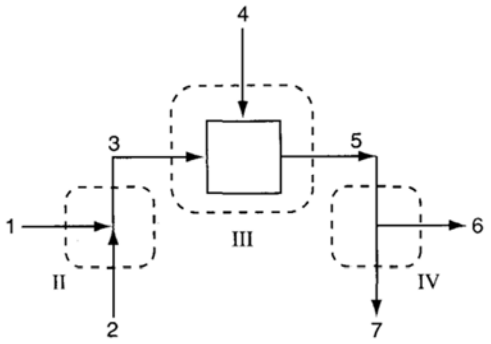


Figure 11.1c Dashed lines II, III and IV designate the boundaries for material balances around each of the individual units comprising the overall process.

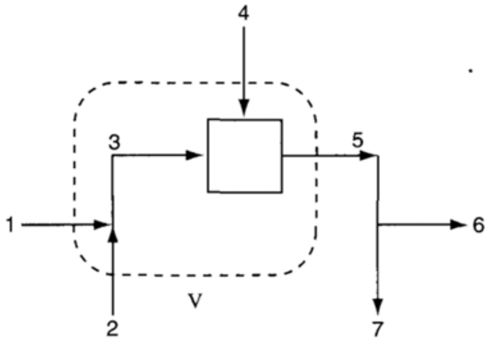


Figure 11.1d the dashed line V designates the boundary for material balances around a system comprised of the mixing point plus the unit portrayed by the box.

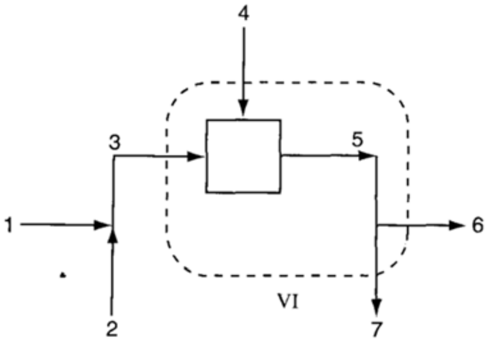


Figure 11.1e the dashed line VI designates the boundary for material balances about a system comprised of the unit portrayed by the box plus the splitter.

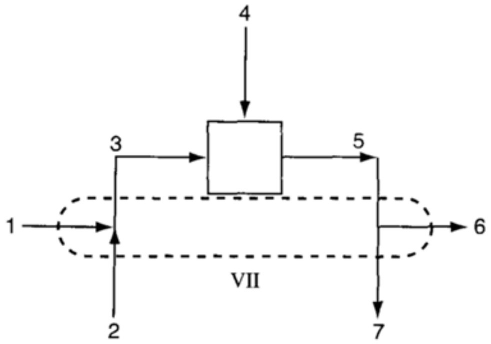


Figure 11.1f the dashed line VII designates the boundary for material balances about a system comprised of the mixer plus the splitter.

Example 11.1

Acetone is used in the manufacture of many chemicals and also as a solvent. In its latter role, many restrictions are placed on the release of acetone vapor to the environment. You are asked to design an acetone recovery system having the flow sheet illustrated in Figure El1.1. All the concentrations shown in El1.1 of both the gases and liquids are specified in weight percent in this special case to make the calculations simpler. Calculate, A, F, W, B, and D per hour. G = 1400 kg/hr.

Solution

This is an **open, steady-state process** without reaction. **Three subsystems** exist.

Pick 1 hr as a basis so that G = 1400 kg.

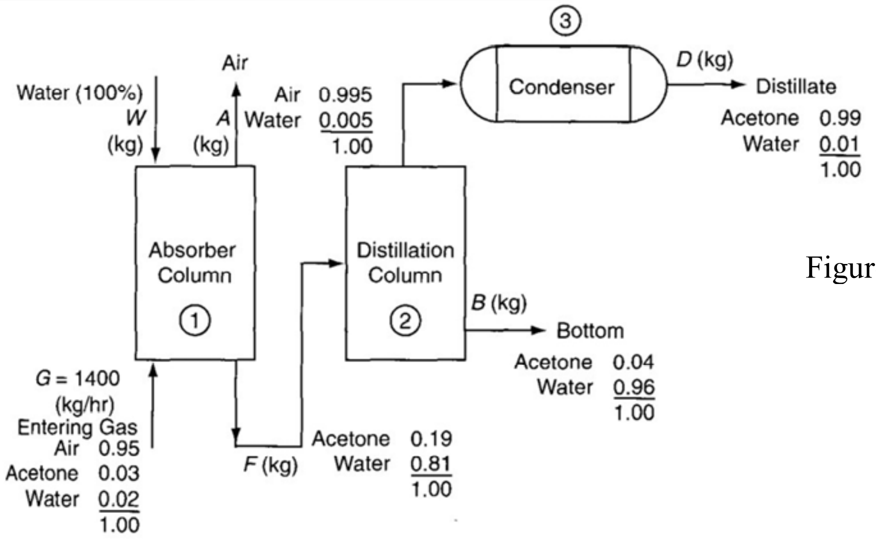

③
Condenser
D (kg)
Distillate
Acetone 0.99
Water 0.01
1.00
Air
Water (100%)
W
(kg)
A
(kg)
Air 0.995
Water 0.005
1.00
Absorber
Column
①
Distillation
Column
②
B (kg)
Bottom
Acetone 0.04
Water 0.96
1.00
G = 1400
(kg/hr)
Entering Gas
Air 0.95
Acetone 0.03
Water 0.02
1.00
F (kg)
Acetone 0.19
Water 0.81
1.00

Figure E11.1

The mass balances for **Unit 1 (Absorber Column)**

	In		*Out*			
Air:	$1400\ (0.95)$	$=$			$A(0.995)$	(a)
Acetone:	$1400\ (0.03)$	$=$	$F(0.19)$			(b)
Water:	$1400\ (0.02) + W(1.00)$	$=$	$F(0.81)$	$+$	$A(0.005)$	(c)

Solve Equations (a), (b), and (c) to get A =1336.7 kg/hr, F = 221.05 kg/hr and W = 157.7 kg/hr (**Check**) Use the total balance (Absorber Column).

$$\begin{array}{ccc} G + W & = & A + F \\ 1400 & & 1336 \\ \underline{157.7} & & \underline{221.05} \\ 1557.7 & \cong & 1557.1 \end{array}$$

The mass balances for the combined **Units 2 plus 3** (**Distillation & Condenser**) are:

$$\text{Acetone:} \quad 221.05(0.19) = D(0.99) + B(0.04) \qquad \text{(d)}$$

$$\text{Water:} \quad 221.05(0.81) = D(0.01) + B(0.96) \qquad \text{(e)}$$

Solve Equations (d) and (e) simultaneously to get D = 34.90kg/hr and B = 186.1 kg/hr (**Check**) Use the total balance (Distillation & Condenser)

$$F = D + B \text{ or } 221.05 \cong 34.90 + 186.1 = 221.0$$

Note

As a matter of interest, what other mass balances could be written for the system and substituted for any one of the Equations (a) through (e)? Typical balances would be **the overall balances**

	In		*Out*					
Air:	$G\ (0.95)$	$=$	$A(0.995)$					(f)
Acetone:	$G(0.03)$	$=$			$D(0.99)$	$+$	$B(0.04)$	(g)
Water:	$G\ (0.02) + W$	$=$	$A(0.005)$	$+$	$D(0.01)$	$+$	$B(0.96)$	(h)
Total	$G + W$	$=$	A	$+$	D	$+$	B	(i)

Example 11.2

In the face of higher fuel costs and the uncertainty of the supply of a particular fuel, many companies operate two furnaces, one fired with natural gas and the other with fuel oil. The gas furnace uses air while the oil furnace uses an oxidation stream that analyzes: O_2, 20%; N_2, 76%; and CO_2, 4%. The stack gases go up a common stack, See Figure El1.2.

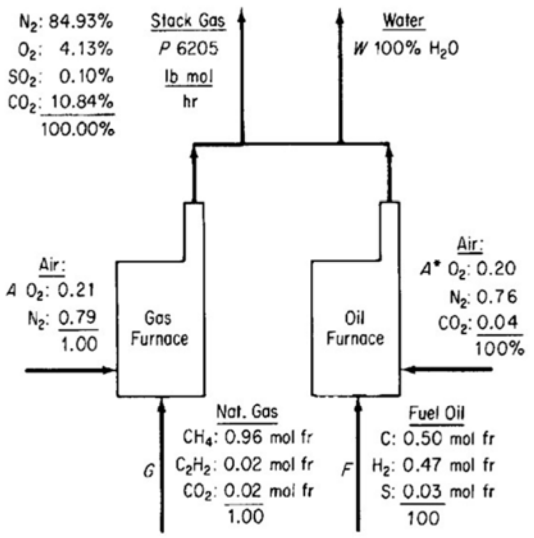


Figure E11.2

The reserve of fuel oil was only 560 bbl. How many hours could the company operate before shutting down if no additional fuel oil was attainable? How many lb mol/hr of natural gas were being consumed? The minimum heating load for the company when translated into the stack gas output was 6205 lb mol/hr of dry stack gas. The molecular weight of the fuel oil was 7.91 lb/lb mol, and its density was 7.578 lb/gal.

Solution

This is an **open**, **steady-state process** with **reaction**. Two **subsystems** exist.

Basis: 1 hr, so that P = 6205 lb mol

The **overall balances** for the **elements** are (in pound moles)

$$
\begin{array}{lllcl}
 & \multicolumn{2}{c}{\text{In}} & & \text{Out} \\
2\text{H}: & G(1.94) & +\ F(0.47) & = & W(1) \\
2\text{N}: & A(0.79) & +\ A^{*}(0.76) & = & 6205(0.8493) \\
2\text{O}: & A(0.21) & +\ A^{*}(0.20+0.04) & & 6205(0.0413+0.001+0.1084) \\
 & & \quad +\ G(0.02) & = & \qquad +W(^{1}/_{2}) \\
\text{S}: & F(0.03) & & = & 6205(0.0010) \\
\text{C}: & G(0.96) & +\ (2)(0.02)+0.02 & & \\
 & & +\ F(0.50)+0.04A^{*} & = & 6205(0.1084)
\end{array}
$$

Solve the **S** balance **for F**; the sulfur is a **tie component**. Then solve for the other four balances simultaneously for G. The results are: F = 207 lb mol/hr and G = 499 lb mol/hr

Finally, the fuel oil consumption is $\dfrac{207\ \text{lb mol}}{\text{hr}}\left|\dfrac{7.91\ \text{lb}}{\text{lb mol}}\right|\dfrac{\text{gal}}{7.578\ \text{lb}}\left|\dfrac{\text{bbl}}{42\ \text{gal}}\right. = 5.14\ \text{bbl/hr}$

If the fuel oil reserves were only 560 bbl,

$$\frac{560\ \text{bbl}}{5.14\dfrac{\text{bbl}}{\text{hr}}} = 109\ \text{hr}$$

Example 11.3

Figure E11.3 shows the process and the known data. You are asked to calculate the compositions of every flow stream, and the fraction of the sugar in the cane that is recovered.

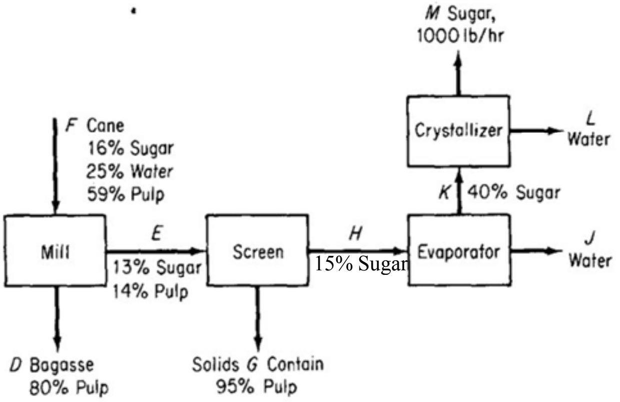


Figure E11.3

(Bagasse) dry pulpy residue left after the extraction of juice from sugar cane

Solution

Basis: l hour (M= l000lb)

Let S = sugar, P = pulp, and W = water.

For the crystallizer the equations are

$$(\text{using } \omega_W^K = 1 - 0.40 = 0.60)$$

Sugar: K (0.40) = L (0) + 1000

Water: K (0.60) = L + 0

From which you get K = 2500 lb and L = 1500 lb.

Check using the total flows: 2500 = 1500 + 1000 = 2500

Using same method for solution: **evaporator**, **screen**, and lastly solve the equations for the **mill**. The results for all of the variables are:

lb	*mass fraction*
$D = 16{,}755$	$\omega_S^D = 0.174$
$E = 7{,}819$	$\omega_W^D = 0.026$
$F = 24{,}574$	$\omega_W^E = 0.73$
$G = 1{,}152$	$\omega_S^G = 0.014$
$H = 6{,}667$	$\omega_W^G = 0.036$
$J = 4{,}167$	$\omega_W^H = 0.85$
$K = 2{,}500$	$\omega_W^K = 0.60$
$L = 1{,}500$	
$M = 1000$	

The fraction of sugar recovered = [product (sugar) / in (sugar)]

= [1000/(24,574)*(0.16)] = 0.25

Problems

1. A two-stage separations unit is shown in Figure SAT11P1. Given that the input stream Fl is 1000 lb/hr, calculate the value of F2 and the composition of F2.

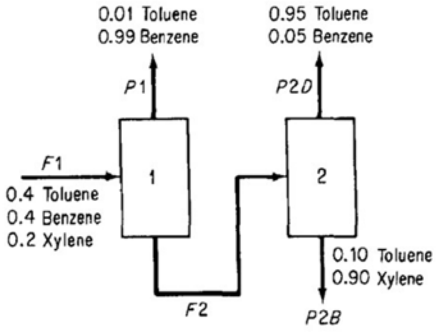


Figure SAT11P1

2. A simplified process for the production of SO_3 to be used in the manufacture of sulfuric acid is illustrated in Figure SAT11P2. Sulfur is burned with 100% excess air in the burner, but for the reaction $S + O_2 \longrightarrow SO_2$, only 90% conversion of the S to SO_2 is achieved in the burner. In the converter, the conversion of SO_2 to SO_3 is 95% complete. Calculate the kg of air required per 100 kg of sulfur burned, and the concentrations of the components in the exit gas from the burner and from the converter in mole fractions.

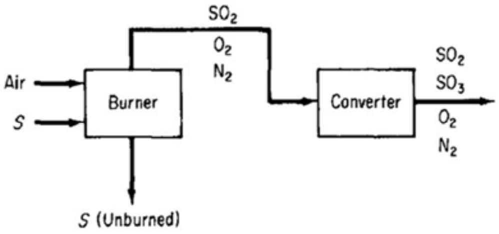


Figure SAT11P2

3. In the process for the production of pure acetylene, C_2H_2 (see Figure SAT11P3), pure methane (CH_4), and pure oxygen are combined in the burner, where the following reactions occur:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \quad (1)$$

$$CH_4 + 1\tfrac{1}{2}O_2 \rightarrow 2H_2O + CO \quad (2)$$

$$2CH_4 \rightarrow C_2H_2 + 3H_2 \quad (3)$$

   a. Calculate the ratio of the moles of O_2 to moles of CH_4 fed to the burner.
   b. On the basis of 100 lb mol of gases leaving the condenser, calculate how many pounds of water are removed by the condenser.
   c. What is the overall percentage yield of product (pure) C_2H_2, based on the carbon in the natural gas entering the burner?

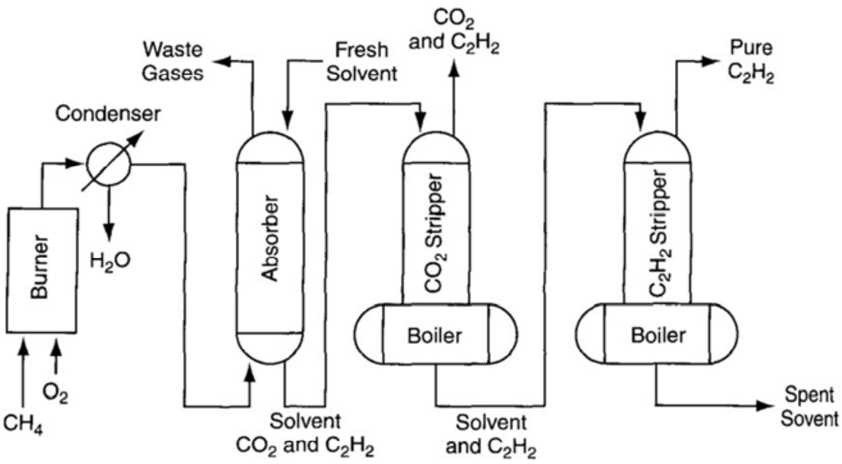


Figure SAT11P3

The gases from the burner are cooled in the condenser that removes all of the water. The analysis of the gases leaving the condenser is as follows:

	Mol %
C_2H_2	8.5
H_2	25.5
CO	58.3
CO_2	3.7
CH_4	4.0
Total	100.0

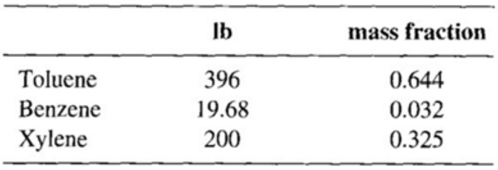
These gases are sent to an absorber where 97% of the C_2H_2 and essentially all the CO_2 are removed with the solvent. The solvent from the absorber is sent to the CO_2 stripper, where all the CO_2 is removed. The analysis of the gas stream leaving the top of the CO_2 stripper is as follows:

	Mol %
C_2H_2	7.5
CO_2	92.5
Total	100.0

The solvent from the CO_2 stripper is pumped to the C_2H_2 stripper, which removes all the C_2H_2 as a pure product.

Answers:

1. Assume that the compositions in the figure are mass fractions. Then:



	lb	mass fraction
Toluene	396	0.644
Benzene	19.68	0.032
Xylene	200	0.325

2. 863 lb air/lb S

	Converter	Burner
SO_2	0.5%	9.5%
SO_3	9.4	—
O_2	7.4	11.5
N_2	82.7	79.0

3. (a) 1.14; (b) 2240 lb; (c) 9.9%

Supplementary Problems (Chapter Eleven):

Problem 1

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.

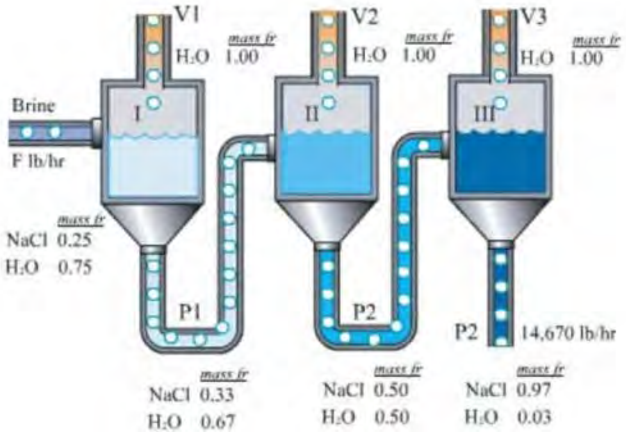
The data are shown in the accompanying figure.

Solution

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

Basis: 14,670 lb = 1 hr

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



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)

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

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

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

$\mathbf{V_3 = 13{,}800\ lb/hr}$

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 2

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

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

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.

Element balances (in moles)

S: $(0.48/32)\,F = Z + 0.007\,(100)$ (1)

N2 $0.79\,A = 0.964\,(100)$ (2)

O2 $0.21\,A = Z + 100(0.007 + 0.029) + \dfrac{Y \text{ mol } Fe_3O_4 \;\big|\; 2 \text{ mol } O_2}{\big|\; 1 \text{ mol } Fe_3O_4}$ (3)

Fe $(0.43/56)\,F = \dfrac{Y \text{ mol } Fe_3O_4 \;\big|\; 3 \text{ mol Fe}}{\big|\; 1 \text{ mol } Fe_3O_4}$ (4)

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

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

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

Recycle, Bypass, Purge, and the Industrial Application of Material Balances

12.1 Introduction

- **Recycle** is fed back from a **downstream** unit to an **upstream** unit, as shown in Figure 12.lc. The stream containing the recycled material is known as a **recycle stream**.
- Recycle system is a system that includes one or more recycle streams.
- Because of the relatively **high cost** of industrial feedstocks, when **chemical reactions** are involved in a process, **recycle** of **unused reactants** to the reactor can offer significant **economic** savings for high-volume processing systems. **Heat recovery** within a processing unit (**energy recycle**) reduces the overall energy consumption of the process.

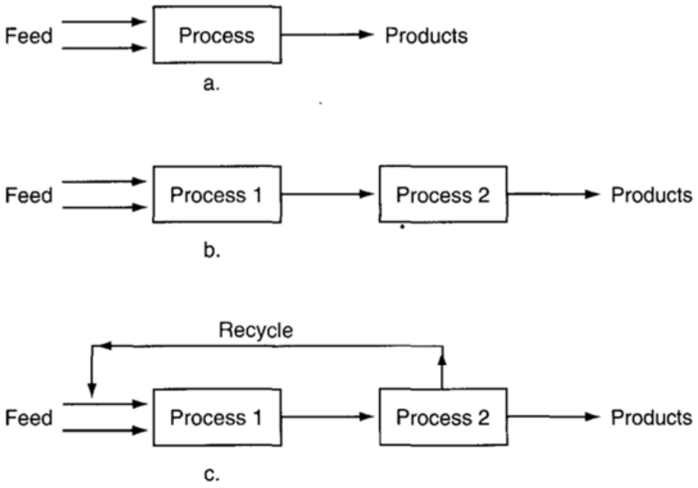


Figure 12.1: Figure 12.la shows a single unit with serial flows. Figure 12.b shows multiple units but still with serial flows. Figure 12.lc shows the addition of recycle.

12.2 Recycle without Chemical Reaction

- ❖ **Recycle** of material occurs in a variety of processes that do **not** involve chemical reaction, including **distillation**, **crystallization**, and **heating and refrigeration** systems.
- ❖ Examine Figure 12.2. You can write material balances for several different systems, **four** of which are shown by dashed lines in Figure 12.2 **(Overall balance 1, Mixer balance 2, Process balance 3 & Separator balance 4)**.
- ❖ The **fresh feed** enters the overall system and the **overall or net product** is removed.
- ❖ The **total (gross) feed** enters the process and the **gross product** is removed.

- In addition, you can make balances (not shown in Figure 12.2) about **combinations of subsystems**, such as the **process plus the separator** (**3 plus 4**), or the **mixing point plus the process** (**2 plus 3**).

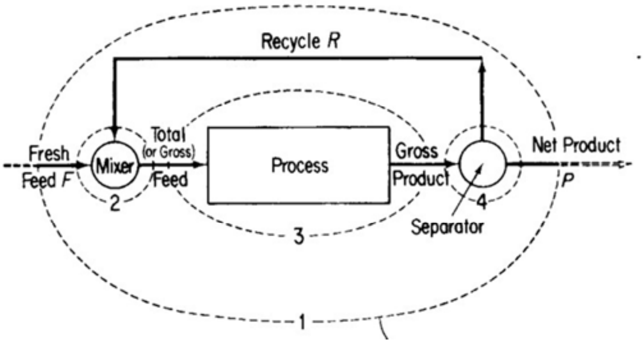


Figure 12.2 Process with recycle (the numbers designate possible system boundaries for the material balances).

Example 12.1

Figure E12.la is a schematic of a process for the production of flake NaOH, which is used in households to clear plugged drains in the plumbing (e.g., Drano).

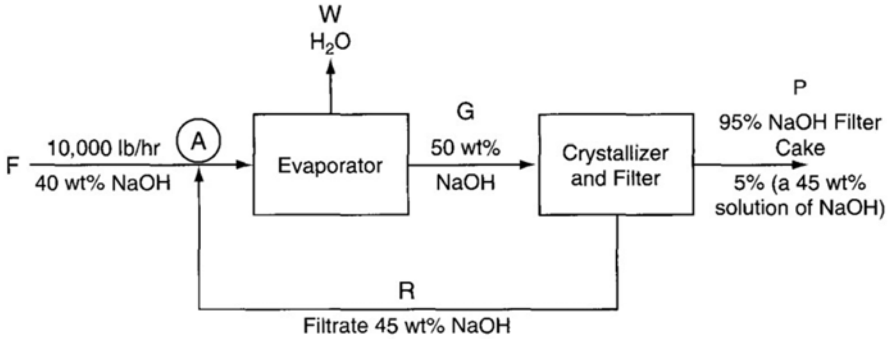


Figure E12.1a

The fresh feed to the process is 10,000 lb/hr of a 40% aqueous NaOH solution. The fresh feed is combined with the recycled filtrate from the crystallizer, and fed to the evaporator where water is removed to produce a 50% NaOH solution, which in turn is fed to the crystallizer. The crystallizer produces a filter cake that is 95% NaOH crystals and 5% solution that itself consists of 45% NaOH. The filtrate contains 45% NaOH.

a. You are asked to determine the flow rate of water removed by the evaporator, and the recycle rate for this process.
b. Assume that the same production rate of NaOH flakes occurs, but the filtrate is not recycled.

What would be the total feed rate of 40% NaOH have to be then? Assume that the product solution from the evaporator still contains 50% NaOH.

Solution

Open, steady-state process.

a. **Basis: 10,000 lb fresh feed (equivalent to 1 hour)**

The unknowns are W, G, P, and R.

Overall NaOH balance

$$(0.4)(10,000) = 0.95\ P + (0.45)\ (0.05)\ P$$
$$P = 4113\ \text{lb}$$

Overall H_2O balance

$$(0.6)\ (10,000) = W + [(0.55)(0.05)](4113)$$
$$W = 5887\ \text{lb}$$

(or use the overall total balance 10,000 = 4113 + W)

The total amount of NaOH exiting with P is [(0.95) + (0.45)(0.05)](4113) = 4000 lb NaOH balance on the **crystallizer** 0.5 G = 4000 + 0.45 R

H_2O balance on the **crystallizer** 0.5 G = 113 + 0.55 R (or use the total balance G = R + 4113)

$$R = 38,870\ \text{lb}$$

b. **Figure E12.lb.**

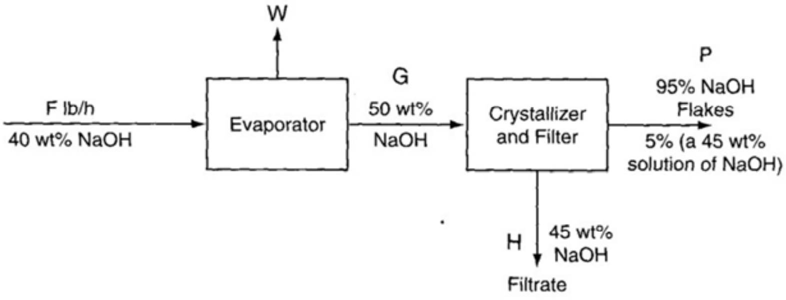


Figure E12.1b

The basis is now P = 4113 lb (the same as 1 hour)

The unknowns are now F, W, G, and H. NaOH balance on the **crystallizer**

$$0.5\ G = [(0.95) + (0.05)\ (0.45)]\ (4113) + 0.45\ H$$

H_2O balance on the **crystallizer**

$$0.5G = [(0.05)\ (0.55)\ (4113)] + 0.55\ H$$

$$H = 38,870 \text{ lb}$$

Overall NaOH balance

$$0.40\ F = 0.45(38,870) + 4000$$
$$F = 53,730 \text{ lb}$$

☒ Note that **without recycle**, the feed rate must be **5.37 times larger** than **with recycle** to produce the same amount of product.

12.3 Recycle with Chemical Reaction

☒ The most common application of recycle for systems involving chemical reaction is the recycle of reactants, an application that is used to increase the overall conversion in a reactor. Figure 12.3 shows a simple example for the reaction

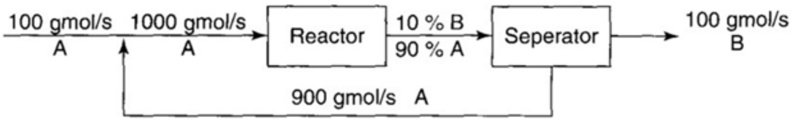


Figure 12.3 A simple recycle system with chemical reaction.

If you calculate the **extent of reaction** for the **overall process** in Figure 12.3 **based on B**

$$\xi_{\text{overall}} = \frac{100 - 0}{1} = 100 \text{ moles reacting}$$

If you use material balances to calculate the **output P** of the **reactor** (on the **basis** of **1 second**) you get A = 900 g mol B = 100 g mol

And the **extent of reaction based on B** for the **reactor** by itself as the system is

$$\xi_{\text{reactor}} = \frac{100 - 0}{1} = 100 \text{ moles reacting}$$

In general, **the extent of reaction** is the **same** regardless of whether an **overall material** balance is used or a material balance for the **reactor** is used.

- Two types of **conversion** when reactions occur:

1. **Overall fraction conversion:**

$$\frac{\text{mass (moles) of reactant in the fresh feed} - \text{mass (moles) of reactant in the output of the overall process}}{\text{mass (moles) of reactant in the fresh feed}}$$

2. **Single - pass ("once - through") fraction conversion:**

$$\frac{\text{mass (moles) of reactant fed into the reactor} - \text{mass (moles) of reactant exiting the reactor}}{\text{mass (moles) of reactant fed into the reactor}}$$

For the simple recycle reactor in Figure 12.3, **the overall conversion** is

$$\frac{100 - 0}{100} \times 100 = 100\%$$

And the **single-pass conversion** is

$$\frac{1000 - 900}{1000} \times 100 = 10\%$$

When the **fresh feed** consists of **more than one reactant**, the **conversion** can be expressed for a **single component**, usually the **limiting reactant**, or the most important (expensive) reactant.

- The **overall conversion** and the **single-pass conversion** can be expressed in terms of the **extent of reaction**, ξ.

$$\text{Overall conversion of species A} = f_{OA} = \frac{-v_A \xi}{n_A^{\text{fresh feed}}} \tag{12.1}$$

$$\text{Single-pass conversion} = f_{SP} = \frac{-v_A \xi}{n_A^{\text{reactor feed}}} \tag{12.2}$$

$$\frac{f_{SP}}{f_{OA}} = \frac{n_A^{\text{fresh feed}}}{n_A^{\text{fresh feed}} + n_A^{\text{recycle}}} \tag{12.3}$$

Example 12.2

Cyclohexane (C_6H_{12}) can be made by the reaction of benzene (Bz) (C_6H_6) with hydrogen according to the following reaction:

$$C_6H_6 + 3H_2 \rightarrow C_6H_{12}$$

For the process shown in Figure El2.2, determine the ratio of the recycle stream to the fresh feed stream if the overall conversion of benzene is 95%, and the single-pass conversion is 20%. Assume that 20% excess hydrogen is used in the fresh feed, and that the composition of the recycle stream is
22.74 mol % benzene and 77.26 mol % hydrogen.

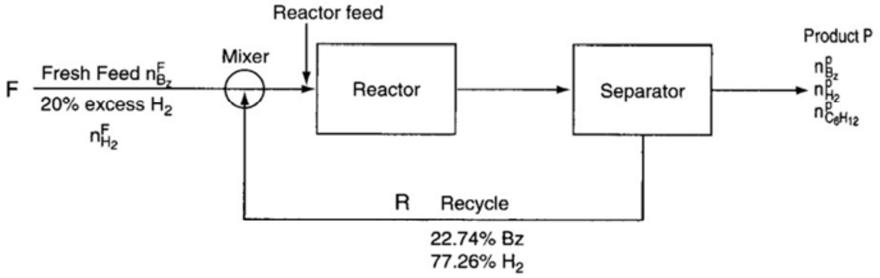


Figure E12.2 Schematic of a recycle reactor.

Solution

The process is **open** and **steady state**.

Basis = 100 mol (g mol or lb mol) of fresh benzene feed

Excess H_2 = (in – required)/ required (**for complete reaction**)

In H_2 (Feed):

$$n^{F}_{H_2} = 100(3)(1 + 0.20) = 360 \text{ mol}$$

The total fresh feed = 100 + 360 = 460 mol. From Equation (12.1) for benzene ($\nu_{Bz} = -1$)

$$0.95 = \frac{-(-1)\xi}{100}$$

$\xi = 95$ reacting moles.

The unknowns are R, n^{P}_{Bz}, $n^{P}_{H_2}$, and $n^{P}_{C_6H_{12}}$.

The species **overall balances** are

$$n_i^{out} = n_i^{in} + \nu_i \xi_{overall}$$

$$\begin{aligned} &Bz: & n^{P}_{Bz} &= 100 + (-1)(95) &&= 5 \text{ mol} \\ &H_2: & n^{P}_{H_2} &= 360 + (-3)(95) &&= 75 \text{ mol} \\ &C_6H_{12} & n^{P}_{C_6H_{12}} &= 0 + (1)(95) &&= \underline{95 \text{ mol}} \\ & & & & P &= 175 \text{ mol} \end{aligned}$$

The amount of the **Bz** feed to the **reactor** is **100 + 0.2274 R**, and **$\xi = 95$.** Thus, for benzene

$$0.20 = \frac{-(-1)95}{100 + 0.2274R}$$

and R = 1649 mol

Finally, the ratio of **recycle** to **fresh feed** is

$$\frac{R}{F} = \frac{1649 \text{ mol}}{460 \text{ mol}} = 3.58$$

Example 12.3

Immobilized glucose isomerase is used as a catalyst in producing fructose from glucose in a fixed- bed reactor (water is the solvent). For the system shown in Figure El2.3a, what percent conversion of glucose results on one pass through the reactor when the ratio of the exit stream to the recycle stream in mass units is equal to 8.33? The reaction is

$$\underset{\text{Glucose}}{C_{12}H_{22}O_{11}} \rightarrow \underset{\text{Fructose}}{C_{12}H_{22}O_{11}}$$

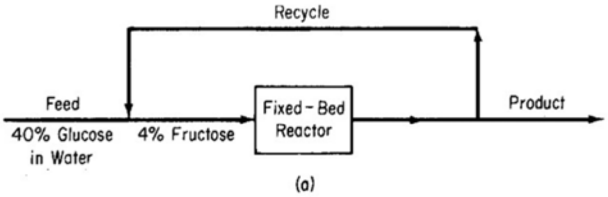


Figure E12.3a

Solution

The process is an **open**, **steady-state** process with a **reaction occurring** and a **recycle**.

☒ Figure E12.3b includes all the known and unknown values of the variables using appropriate notation (W stands for water, G for glucose, and F for fructose).

☒ **Note** that the **recycle stream** and **product stream** have the **same composition**, and consequently the same mass symbols are used in the diagram for each stream.

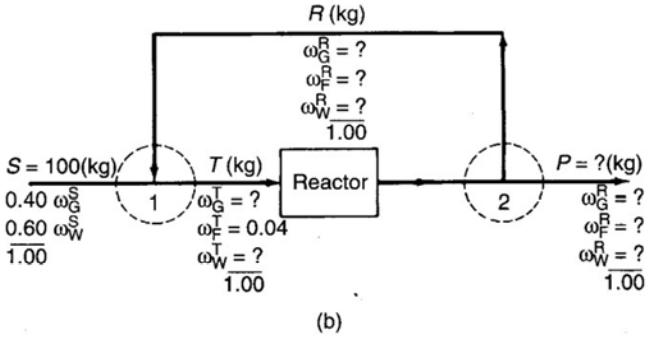


Figure E12.3b

Pick as a basis S = 100 kg

Overall balances

Total: P = S = 100 kg

Consequently,

$$R = \frac{100}{8.33} = 12.0 \text{ kg}$$

[P/R = 8.33]

Overall no **water** is **generated** or **consumed**, hence

Water:
$$100(0.60) = P\omega_W^R = 100\omega_W^R$$
$$\omega_W^R = 0.60$$

Mixing point 1

Total: $100 + 12 = T = 112$

Glucose: $100(0.40) + 12\omega_G^R = 112\omega_G^T$

Fructose: $0 + 12\omega_F^R = 112(0.04)$

Or $\omega_F^R = 0.373$

Also, because $\omega_F^R + \omega_G^R + \omega_W^R = 1$,

$\omega_G^R = 1 - 0.373 - 0.600 = 0.027$

$$\omega_G^T = 0.360$$

Next from the glucose balance

Reactor plus Separator 2

Total: T = 12 + 100 = 112 (a redundant equation)

$$\text{Glucose:}\quad \omega_G^T T - (R + P)(\omega_G^R) = (f)(\omega_G^T T)$$

$$(0.360)(112) - (112)(0.027) = f(0.360)(112)$$

$$40.3 - 3.02 = f(40.32)$$

$$f = 0.93$$

Check by using Equation 12.2 and the **extent of reaction**

$$\xi = \frac{3.02 - 40}{-1} = 37 \quad f = \frac{-(-1)(37)}{40} = 0.93$$

Example 12.4

Reactors that involve biological materials (bioreactors) use living organisms to produce a variety of products. Bioreactors are used for producing ethanol, antibiotics, and proteins for dietary supplements and medical diagnosis. Figure E12.4 shows a recycle bioreactor in which the overall conversion of the proprietary component in the fresh feed to product is 100%. The conversion of the proprietary component to product **per pass** in the reactor is 40%. Determine the amount of recycle and the mass percent of component in the recycle stream if the product stream contains 90% product, and the feed to the reactor contains 3 wt % of the component.

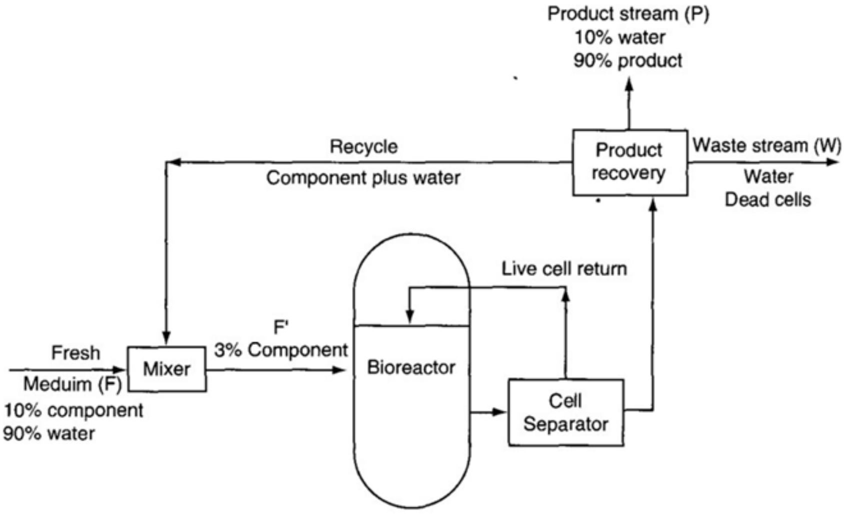


Figure E12.4

Assume that the component and the product have essentially the same molecular weight, and that the waste contains only water and dead cells.

Solution

Basis = 100 kg of fresh feed (F).

Overall balances

Total balance: 100 = P + W

Component balance: 0.10 (100)

= 0.90 P P = 11.1 kg W = 88.9

kg

The reactor plus the product recovery unit balance

$$\begin{array}{cclllll} \textit{Accumulation} & & \textit{Input} & \textit{Output} & \textit{Generation} & \textit{Consumption} \\ 0 & = & [100\,(0.10) + R\omega] & -\ R\omega\ + & 0 & -0.40\,[100\,(0.10) + R\omega] \end{array}$$

$$R\omega = 15 \text{ kg of component in the recycle stream}$$

Mixer balance

Component balance: $100\,(0.10) + 15 = 0.03\,F' \rightarrow F' = 833$ kg

Total balance: $R + 100 = F' \rightarrow R = 833 - 100 = 733$ kg

$$\omega = \frac{15}{733} = 0.0205$$

12.4 Bypass and Purge

a. A **bypass** stream—a stream that skips one or more stages of the process an **goes directly** to another downstream stage (Figure 12.4).

   A **bypass** stream can be used to control the composition of a final exit stream from a unit by mixing the bypass stream and the unit exit stream in suitable proportions to obtain the desired final composition.

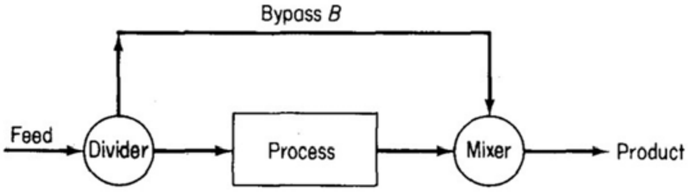


Figure 12.4 A process with a bypass stream.

b. A **purge** stream—a stream bled off from the process to remove an accumulation of inert or unwanted material that might otherwise build up in the recycle stream (Figure 12.5).

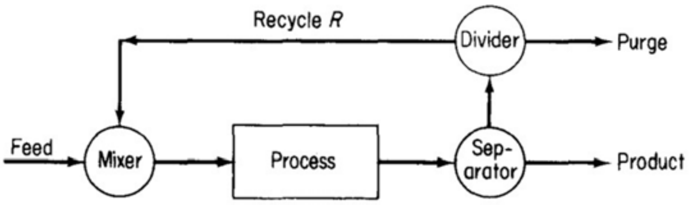


Figure 12.5 A process with a recycle stream with purge.

Example 12.5

In the feedstock preparation section of a plant manufacturing natural gasoline, isopentane is removed from butane-free gasoline. Assume for purposes of simplification that the process and components are as shown in Figure E12.5. What fraction of the butane-free gasoline is passed through the isopentane tower? The process is in the steady state and no reaction occurs.

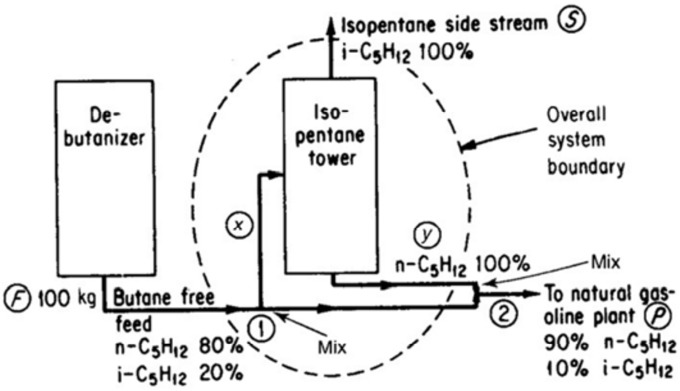


Figure E12.5

Solution

n-pentane isomer; the other two are called isopentane (methylbutane) and neopentane (dimethylpropane)

Basis: 100 kg feed

Overall balances

Total material balance:

$$\frac{In}{100} = \frac{Out}{S + P} \qquad (a)$$

Component balance for n-C_5 (tie component)

$$\frac{In}{100(0.80)} = \frac{Out}{S(0) + P(0.90)} \qquad (b)$$

Consequently,

$$P = 100\left(\frac{0.80}{0.90}\right) = 88.9 \text{ kg}$$

$$S = 100 - 88.9 = 11.1 \text{ kg}$$

Balance around isopentane tower:

Let **x** be the kg of butane-free gas going to the isopentane tower, and **y** be the kg of the n-C_5H_{12} stream leaving the isopentane tower.

Total material balance: $\frac{In}{x} = \frac{Out}{11.1 + y}$ (c)

Component balance for n-C_5 $x\,(0.80) = y$ (d)

Consequently, combining (c) and (d) yields **x = 55.5 kg**, or the desired fraction is 0.55.

Another approach to this problem is to make a balance at **mixing points 1** and **2**.

Balance around mixing point 2:

Material into junction = Material out

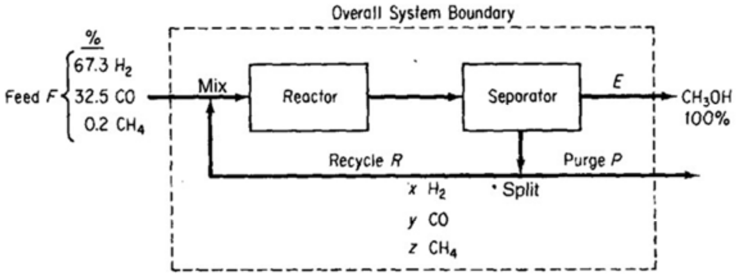
Total material: $(100 - x) + y = 88.9$ (e)

Component (iso-C_5): $(100 - x)(0.20) + 0 = 88.9(0.10)$ (f)

Solving yields **x = 55.5 kg as before**

Example 12.6

Figure E12.6 illustrates a steady-state process for the production of methanol. All of the compositions are in mole fractions or percent. The stream flows are in moles.



$$CO + 2H_2 \rightarrow CH_3OH$$

Figure E12.6

Note in Figure E12.6 that some CH_4 enters the process, but does not participate in the reaction. A purge stream is used to maintain the CH_4 concentration in the exit from the separator at no more than 3.2 mol%, and prevent hydrogen buildup as well. The **once-through conversion** of the CO in the reactor is 18%.

Compute the moles of recycle, CH_3OH, and purge per mole of feed, and also compute the purge gas composition.

Solution

The mole fraction of the components in the purge stream have been designated as x, y, and z for H_2, CO, and CH_4, respectively.

Basis: F = 100 mol

The variables whose values are unknown are x, y, z, E, P, and R.

$$z = 0.032 \qquad \text{(a)}$$

The implicit mole fraction balance in the recycle stream $x + y + z = 1$ (b)

The **overall element balances** are (in moles):

$$\begin{aligned}
&2H:\ 67.3 + 0.2(2) = E(2) + P(x + 2z) && \text{(c)}\\
&C:\ \ 32.5 + 0.2 \quad = E(1) + P(y + z) && \text{(d)}\\
&O:\ \ 32.5 \qquad\quad\ = E(1) + P(y) && \text{(e)}
\end{aligned}$$

Reactor plus the Separator

$$\text{CO:}\quad \underset{[32.5 + Ry]}{\underline{In}} - \underset{[y(R+P)]}{\underline{Out}} = \underset{(32.5 + Ry)(0.18)}{\underline{Consumed}} \qquad \text{(f)}$$

Equation (a) can be substituted into Equations (b) through (f), and the resulting five equations solved by successive substitution or by using a computer program. The resulting values obtained are (in moles)

E	CH_3OH	31.25
P	purge	6.25
R	recycle	705
x	H_2	0.768
y	CO	0.200
z	CH_4	0.032

Problems

1. How many recycle streams occur in Figure SAT12.1PI?

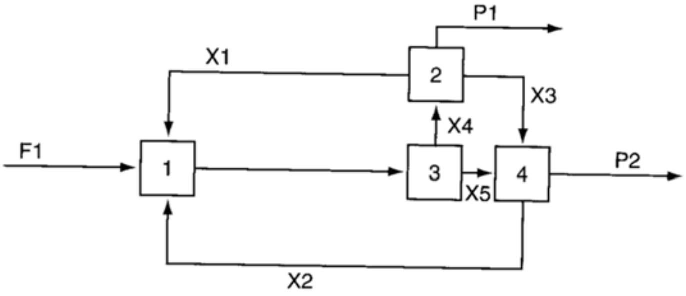


Figure SAT12.1P1

2. The Hooker Chemical Corporation operates a process in Michigan for the purification of HCl. Figure SATI2.1P2 shows the flow sheet for the Hooker process. The streams from the bottoms of the five towers are liquid. The streams from the tops of the towers are gases. HCl is insoluble in the HCB (hexachlorobutadiens). The various stream compositions are shown in Figure SAT12.1P2.

   How many recycle streams are there in the Hooker process?

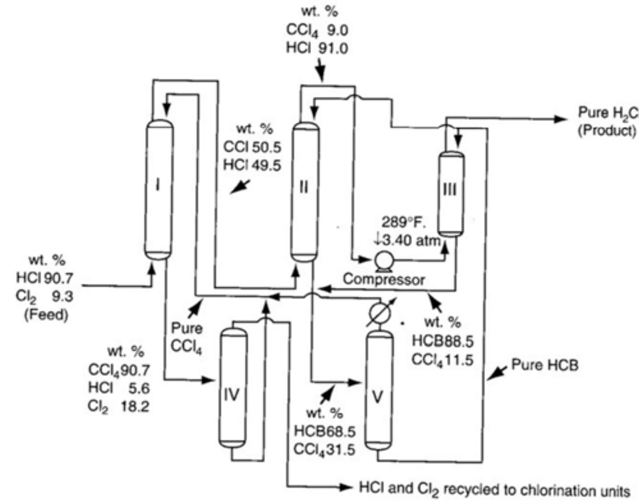


Figure SAT12.1P2

3. A ball mill grinds plastic to make a very fine powder. Look at Figure SAT12.2P1.

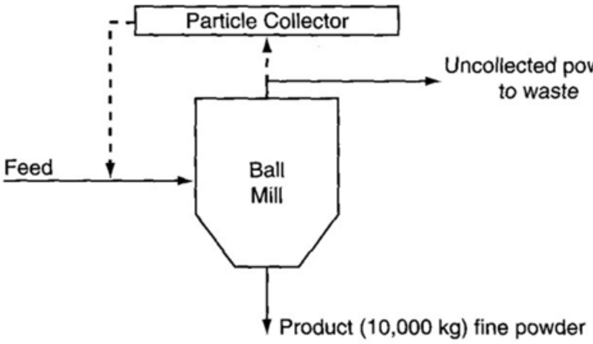


Figure SAT12.2P1

At the present time 10,000 kg of powder are produced per day. You observe that the process (shown by the solid lines) is inefficient because 20% of the feed is not recovered as powder—it goes to waste.

You make a proposal (designated by the dashed lines) to recycle the uncollected material back to the feed so that it can be remilled. You plan to recycle 75% of the 200 kg of uncollected material back to the feed stream. If the feed costs \$1.20/kg, how much money would you save per day while producing 10,000 kg of fine powder?

4. Sea water is to be desalinized by reverse osmosis using the scheme indicated in Figure SATI2.2P2. Use the data given in the figure to determine: (a) the rate of waste brine removal (B); (b) the rate of desalinized water (called potable water) production (P); (c) the fraction of the brine leaving the reverse osmosis cell (which acts in essence as a separator) that is recycled.

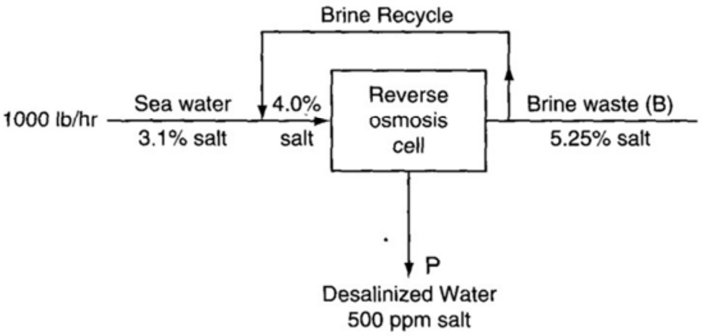


Figure SAT12.2P2

5. A material containing 75% water and 25% solid is fed to a granulator at a rate of 4000 kg/hr. The feed is premixed in the granulator with recycled product from a dryer, which follows the granulator (to reduce the water concentration of the overall material fed into the granulator to 50% water, 50% solid). The product that leaves the dryer is 16.7% water. In the dryer, air is passed over the solid being dried. The air entering the dryer contains 3% water by weight (mass), and the air leaving the dryer contains 6% water by weight (mass).
    a. What is the ratio of the recycle to the feed entering the granulator?
    b. What is the rate of air flow to the dryer on a dry basis?
6. Benzene, toluene, and other aromatic compounds can be recovered by solvent extraction with sulfur dioxide (SO_2). Figure SAT12.2P4 is the process schematic. As an example, a catalytic reformate stream containing 70% benzene and 30% nonbenzene material is passed through the countercurrent extractive recovery scheme shown in Figure SAT12.2P4. 1000 lb of reformate and 3000 lb of SO_2 are fed to the system per hour. The benzene product stream contains 0.15 lb of SO_2 per lb of benzene. The raffinate stream contains all the initially charged nonbenzene material as well as 0.25 lb of benzene per lb of nonbenzene material. The remaining component in the raffinate stream is SO_2. How many lb of benzene are extracted in the product stream on an hourly basis? How many lb of raffinate are produced per hour?

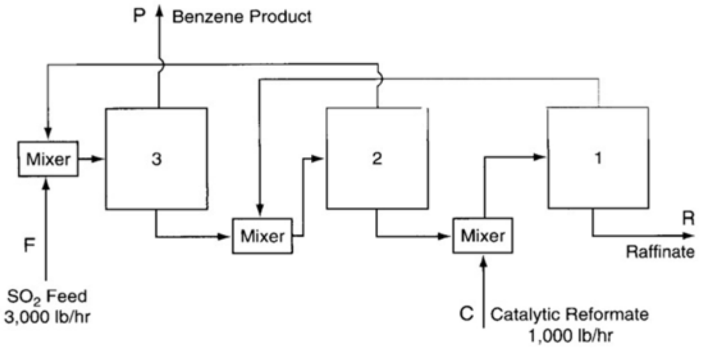


Figure SAT12.2P4

7. A catalytic dehydrogenation process shown in Figure SAT12.3Pl, produces 1, 3 butadiene (C_4H_6) from pure normal butane (C_4H_{10}). The product stream contains 75 mol/hr of H_2 and 13 mol/hr of C_4H_{10} as well as C_4H_6. The recycle stream is 30% (mol) C_4H_{10} and 70% (mol) C_4H_6, and the flow is 24 mol/hr.

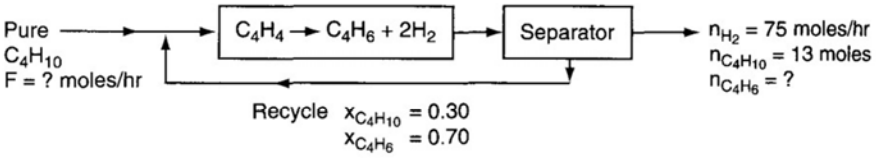


Figure SAT12.3P1

(a) What are the feed rate, F, and the product flow rate of C_4H_6 leaving the process?

(b) What is the single-pass conversion of butane in the process?

8. Pure propane (C_3H_8) from El Paso is dehydrogenated catalytically in a continuous process to obtain propylene (C_3H_6). All of the hydrogen formed is separated from the reactor exit gas with no loss of hydrocarbon. The hydrocarbon mixture is then fractionated to give a product stream containing 88 mole % propylene and 12 mole % propane. The other stream, which is 70 mole % propane and 30 mole % propylene, is recycled. The one-pass conversion in the reactor is 25%, and 1000 kg of fresh propane are fed per hour. Find (a) the kg of product stream per hour, and (b) the kg of recycle stream per hour.

9. Ethyl ether is made by the dehydration of ethyl alcohol in the presence of sulfuric acid at 140°C:

$$2C_2H_5OH \rightarrow C_2H_5OC_2H_5 + H_2O$$

Figure SAT12.3P3 is a simplified process diagram. If 87% conversion of the alcohol fed to the reactor occurs per pass in the reactor, calculate: (a) kilograms per hour of fresh feed, and (b) kilograms per hour of recycle.

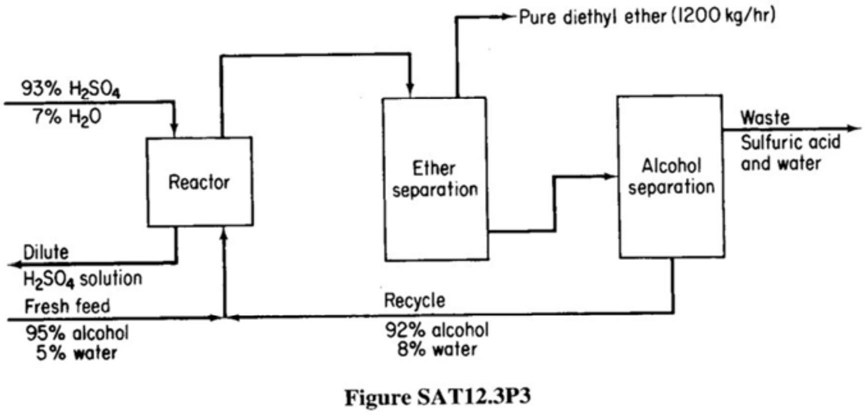


Figure SAT12.3P3

10. In the famous Haber process (Figure SAT12.4P1) to manufacture ammonia, the reaction is

carried out at pressures of 800 to 1000 atm and at 500 to 600°C using a suitable catalyst.

Only a small fraction of the material entering the reactor reacts on one pass, so recycle is needed. Also, because the nitrogen is obtained from the air, it contains almost 1% rare gases (chiefly argon) that do not react. The rare gases would continue to build up in the recycle until their effect on the reaction equilibrium would become adverse. Therefore, a small purge stream is used.

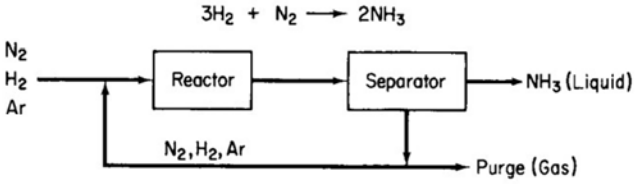


Figure SAT12.4P1

The fresh feed of gas composed of 75.16% H_2, 24.57% N_2, and 0.27% Ar is mixed with the recycled gas and enters the reactor with a composition of 79.52% H_2. The gas stream leaving the ammonia separator contains 80.0 1% H_2 and no ammonia. The product ammonia contains no dissolved gases. Per 100 moles of fresh feed:

a. How many moles are recycled and purged?
b. What is the percent conversion of hydrogen per pass?

11. Figure SAT12.4P2 shows a simplified process to make ethylene dichloride ($C_2H_4C1_2$). The feed data have been placed on the figure. Ninety percent conversion of the C_2H_4 occurs on each pass through the reactor. The overhead stream from the separator contains 98% of the Cl_2 entering the separator, 92% of the entering C_2H_4, and 0.1% of the entering $C_2H_4C1_2$. Five percent of the overhead from the separator is purged. Calculate (a) the flow rate and (b) the composition of the purge stream.

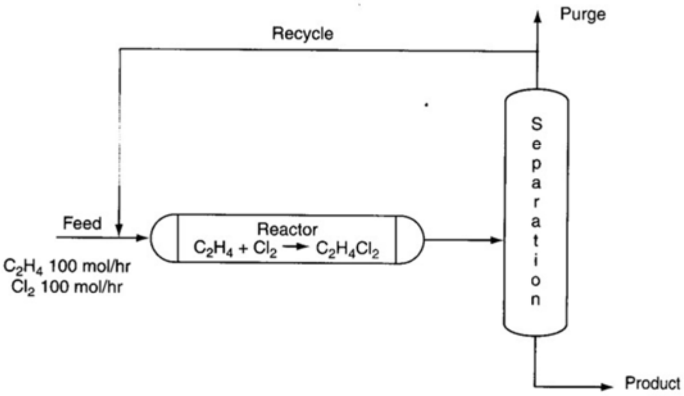


Figure SAT12.4P2

Answers:

1. 2
2. 5
3. \$2250
4. (a) 591 lb/hr; (b) 409 lb/hr; (c) 0.55
5. (a) ratio = 3000 kg of recycle/hr and feed = 7000 kg/hr; (b) air = 85,100 kg/hr
6. (a) benzene extracted: P = 625 lb/hr; (b) raffinate produced: R = 3,281 lb/hr
7. (a) mol/hr C_4H_6 = 37.5 and F = 50.5 mol/hr; (b) 0.65
8. (a) 960 kg/hr; (b) 3659 kg/hr
9. (a) 1570 kg/hr; (b) 243 kg/hr
10. (a) 890 recycled and 3.2 purged; (b) 9.2% conversion (errors can be caused by loss of significant figures)
11. (a) 1.49 mol/hr; (b) Cl_2: 0.658; C_2H_4: 0.338; $C_2H_4C1_2$: 0.0033

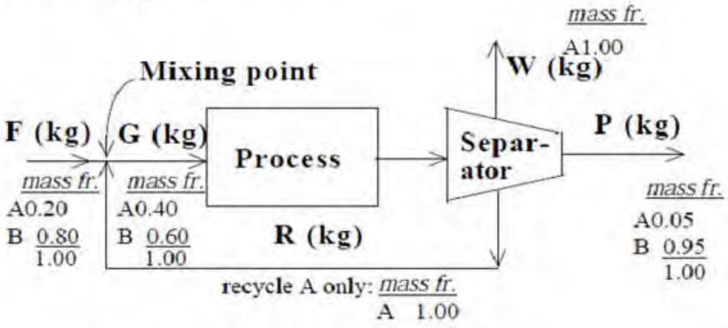
Supplementary Problems (Chapter Twelve):

Problem 1

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

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



Basis : W = 100 kg

The unknowns are F, R, P and G

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)

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) $633 + R = 844$

$R = 211$ kg $\frac{R}{F} = \frac{211\ \text{kg}}{633\ \text{kg}} = \mathbf{0.33}\ \frac{\textbf{kg R}}{\textbf{kg F}}$

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) $0.40\,G = 0.05\,P + W + R$

$0.40\,(844) = 0.05\,(533) + 100 + 211$

$338\ \text{kg} = 338\ \text{kg}$

Check

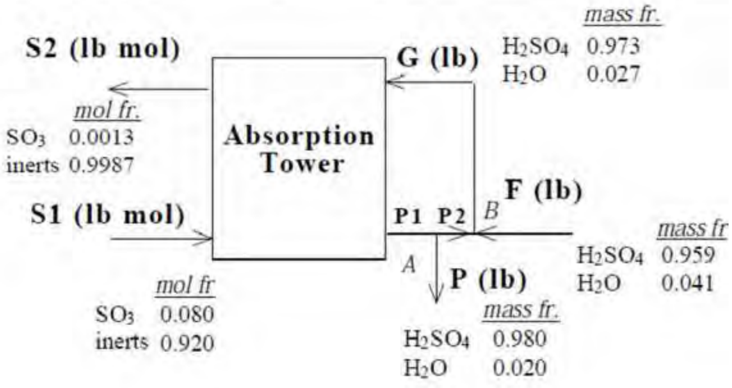
A contact sulfuric acid plant produces 98.0 % sulfuric acid, by absorbing SO_3 into a 97.3 % sulfuric acid solution. A gas containing 8.00 % SO_3 (remainder inerts) enters the SO_3 absorption tower at the rate of 28 lb mol per hour. 98.5 % of the SO_3 is absorbed in this tower. 97.3 % sulfuric acid is 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.



Problem 2

Solution

This is a steady state process.

$$H_2O + SO_3 \dashrightarrow H_2SO_4$$

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

Basis : 100 mol S1

$$\frac{0.08\ \text{mol}\ SO_3}{1\ \text{mol S1}} \left| \frac{100\ \text{mol S1}}{} \right. = 8\ \text{mol}\ SO_3$$

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):

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

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

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

H_2O : 0.041 F - 0.020 P + 0 - 28 (0.08) (0.985) | 1 mol SO_3 | 1 lb mol H_2O = 0 (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)

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**

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

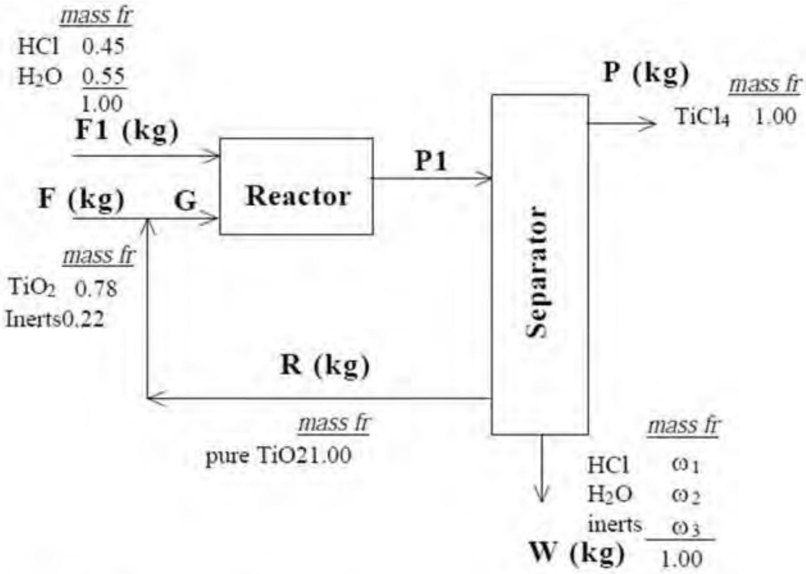
$TiCl_4$ can be formed by reacting titanium dioxide (TiO_2) with hydrochloric acid. TiO_2 is available as an ore containing 78 % TiO_2 and 22 % inerts. The HCl is available as 45 wt% solution (the balance is water). The per pass conversion of TiO_2 is 75 %. The HCl is fed into the reactor in 20 % excess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

$$TiO_2 + 4\,HCl \dashrightarrow TiCl_4 + 2H_2O$$

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



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

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.

Calculate F1

$$1.00\text{ kg F}\;\Big|\;\frac{0.78\text{ kg TiO}_2}{1\text{ kg F}}\;\Big|\;\frac{1\text{ kg mol TiO}_2}{79.9\text{ kg TiO}_2}\;\Big|\;\frac{4\text{ kg mol HCl}}{1\text{ kg mol TiO}_2}\;\Big|\;1.20\;\Big|$$

$$\times\;\frac{36.47\text{ kg HCl}}{1\text{ kg mol HCl}}\;\Big|\;\frac{1\text{ kg F1}}{0.45\text{ kg HCl}} = \text{F1} = 3.80\text{ kg}$$

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

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.

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.

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: $$\frac{(3.80)(0.55)\,\big|\,16}{\big|\,18} + (1.00)(0.78)(0.401) = \frac{(2.94)(\omega_2)\,\big|\,16}{\big|\,18}$$

$$\omega_2 = 0.83$$

Cl: $$\frac{(3.80)(0.45)\,\big|\,35.45}{\big|\,36.47} = \frac{1.85\,\big|\quad\big|\,4\,\big|\,35.45}{\big|\,189.7\,\big|\quad\big|\,1} + \frac{2.94\,(\omega_1)\,\big|\,35.45}{1\,\big|\,36.47}$$

$$\omega_1 = 0.096$$

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

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

a. $$\frac{\text{kg F}}{\text{kg P}} = \frac{1.00}{1.854} = \mathbf{0.54}\,\frac{\textbf{kg}}{\textbf{kg}}$$

b. $$\frac{\text{kg F1}}{\text{kg P}} = \frac{3.798}{1.854} = \mathbf{2.05}\,\frac{\textbf{kg}}{\textbf{kg}}$$

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.

Total: $100 + R = G$

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

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

Next use the system of reactor plus separator.

Total $G + 3.80 = 1.85 + 2.94 + R$

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:

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

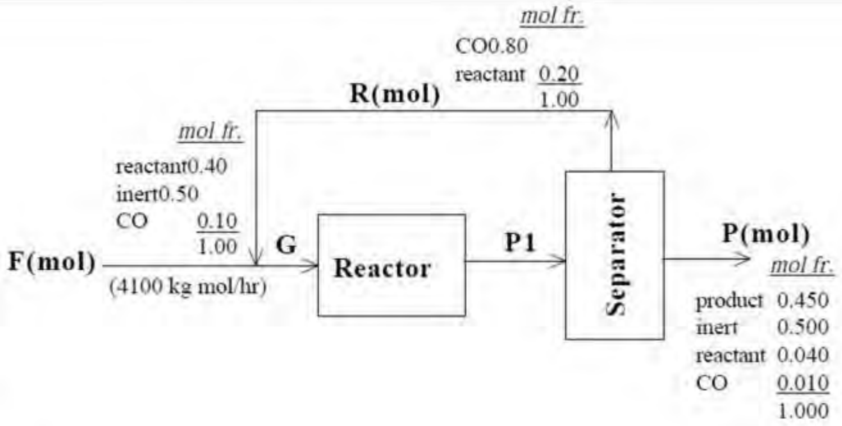
$$R = 26\text{ kg}$$

c.

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

Problem 4

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

This is a steady state process with reaction and recycle.

Basis : 4100 kg mol F

Unknowns : P and its components

Calculate the composition of stream P

Product

$$\frac{4100 \text{ kg mol F}}{} \left| \frac{40 \text{ mol reactant}}{100 \text{ mol F}} \right| \frac{90 \text{ mol react}}{100 \text{ mol reactant}} \left| \frac{2.5 \text{ mol product}}{2 \text{ mol reactant}} \right.$$

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

Inert

$$\frac{4100 \text{ kg mol F}}{} \left| \frac{50 \text{ mol inert}}{100 \text{ mol F}} \right. = 2050 \text{ kg mol inert}$$

Reactant

$$\frac{4100 \text{ kg mol F}}{} \left| \frac{40 \text{ mol reactant}}{100 \text{ mol F}} \right| \frac{0.10 \text{ mol unreacted}}{1.0 \text{ mol reactant}} = 164 \text{ kg mol reactant}$$

CO

$$\frac{4100 \text{ kg mol F}}{} \left| \frac{10 \text{ mol CO}}{100 \text{ mol F}} \right| \frac{0.10 \text{ mol unreacted CO}}{1.0 \text{ mol CO}} = 41 \text{ kg mol CO}$$

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

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.

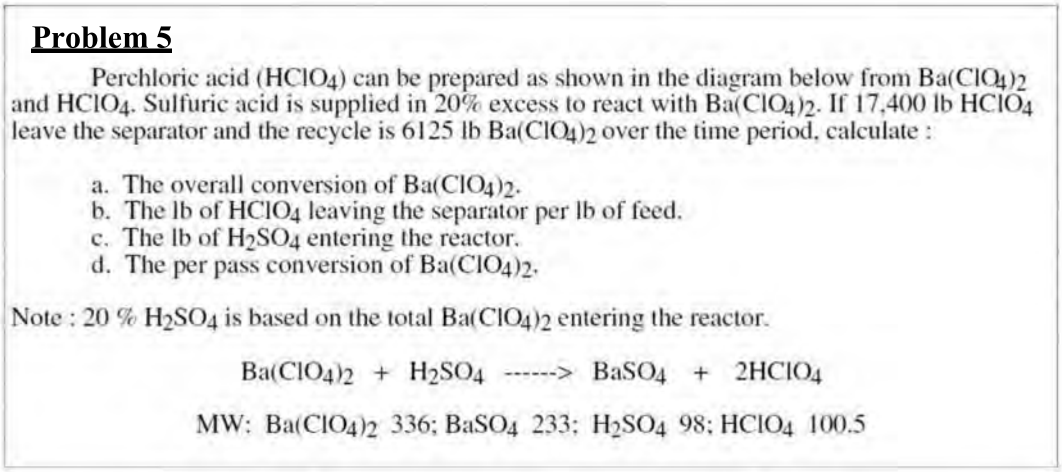
Reactant:

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

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

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

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



Problem 5

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 $Ba(ClO_4)_2$.

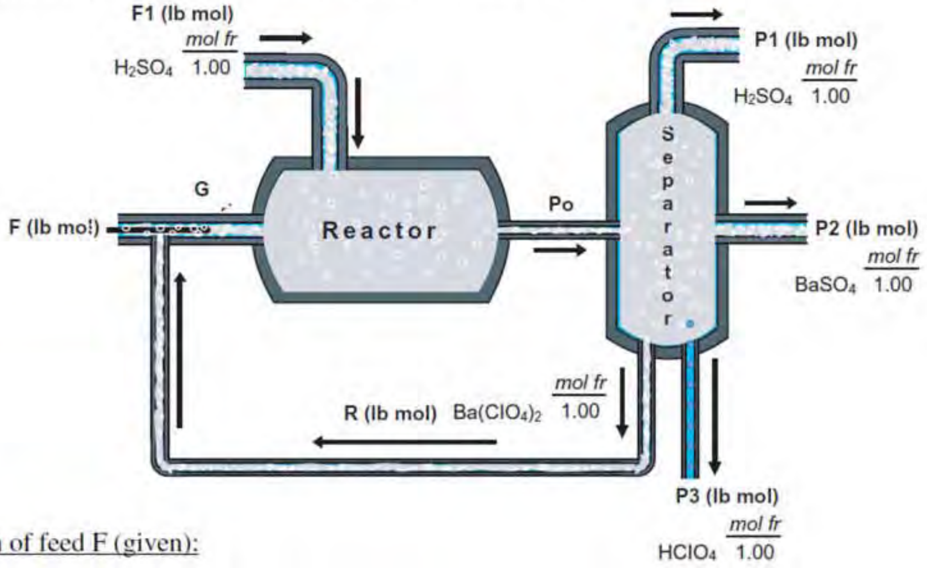
Note : 20 % H_2SO_4 is based on the total $Ba(ClO_4)_2$ entering the reactor.

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

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

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

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

This is a steady state process with reaction.

we will pick P3 = 17.400 lb as the basis equivalent to 17.400/100.5 = 173.13 lb **mol**

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

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)

$$\text{Cl:} \quad \frac{F \text{ lb mol}}{} \left| \frac{0.729 \text{ lb mol } Ba(ClO_4)_2}{1 \text{ lb mol F}} \right| \frac{2 \text{ lb mol Cl}}{1 \text{ lb mol } Ba(ClO_4)_2}$$

$$+\ \frac{F\ \text{lb mol}}{}\left|\frac{0.271\ \text{lb mol}\ HClO_4}{1\ \text{lb mol}\ F}\right|\frac{1\ \text{lb mol Cl}}{1\ \text{lb mol}\ HClO_4}$$

$$=\ \frac{173.13\ \text{lb mol P3}}{}\left|\frac{1\ \text{lb mol}\ HClO_4}{1\ \text{lb mol P3}}\right|\frac{1\ \text{lb mol Cl}}{1\ \text{lb mol}\ HClO_4}$$

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

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

$$= \frac{\text{P2 lb mol}}{}\,\Bigg|\,\frac{1\ \text{lb mol Ba}}{1\ \text{lb mol P2}}$$

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

S: $$\frac{\text{F1 lb mol}}{}\,\Bigg|\,\frac{1\ \text{lb mol H}_2\text{SO}_4}{1\ \text{lb mol F1}}\,\Bigg|\,\frac{1\ \text{lb mol S}}{1\ \text{lb mol H}_2\text{SO}_4}$$

$$= \frac{\text{P1 lb mol}}{}\,\Bigg|\,\frac{1\ \text{lb mol S}}{1\ \text{lb mol P1}} + \frac{73.0\ \text{lb mol BaSO}_4}{}\,\Bigg|\,\frac{1\ \text{lb mol S}}{1\ \text{lb mol BaSO}_4}$$

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

Mixing point

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

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

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.

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

$$\mathbf{f = 0.80}$$