جامعة بابل – كلية هندسة المواد –قسم هندسة البوليمرات والصناعات البتروكيمياوية

مبادئ الهندسة الكيمياوية

Principles of Chemical Engineering

المرحلة الثانية

Lec. 4

“Material Balance”

The objectives from studying of this

1. Understand the features of open, closed, steady-state, and unsteady-state systems, and given a process in words or pictures, select the appropriate categories for the process.
2. Express in words what the material balance is for a process involving single or multiple components.
3. Determine whether positive or negative accumulation occurs in a process.
4. Understand the manner in which a chemical reaction affects the material balance.
5. Recognize a batch or semi-batch process and write the material balance for it.

What are material balances?
A material balance is nothing more than the application of the law of the **conservation of mass "** Matter is neither created nor destroyed**"**

What is the difference between the law of the conservation of mass and the concept of the material balance?

The conservation of mass focuses on the invariance of material in a system, whereas a material balance focuses on ensuring that the flows in and out of the system along with the material in the system can be equated.

As a generic term, material balance can refer to a balance on a system for the:

1- total mass
2- total moles
3- mass of a chemical compound
4- mass of an atomic species
5- moles of a chemical compound
6- moles of an atomic spices
7- Volume (possible)

The general equation for the principles of the material balance applicable to processes both with and without chemical reaction :

In put - output + generation - consumption = accumulation

1- Balance on the <u>total moles</u>,

- In the absence of chemical reaction, the generation and consumption terms do not apply to a single chemical compounds

In put – output = accumulation

- with a chemical reaction present in the system, the generation and consumption terms do apply.

In put - output + generation - consumption = accumulation

2- Balance on the <u>total mass,</u>

The generation and consumption terms are ***zero*** whether a chemical reaction occurs in the system or not.

Input – output = accumulation

Notes:

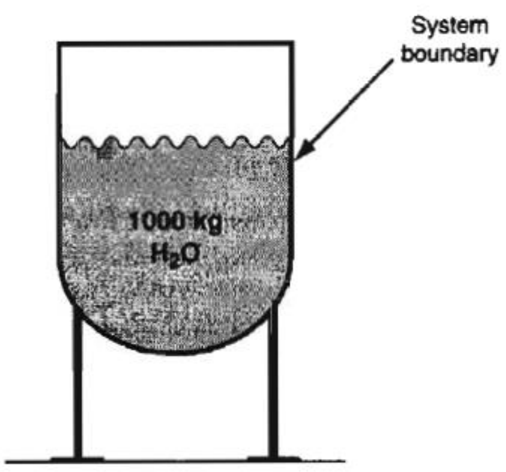
(a) both mass and mole balance for elements such as C, H, or O, the generation and consumption are not involve in material balance (i.e. equal zero).

(b) We can apply a balance on a volume when we have ideal mixing occurs and the densities of the streams are the same.

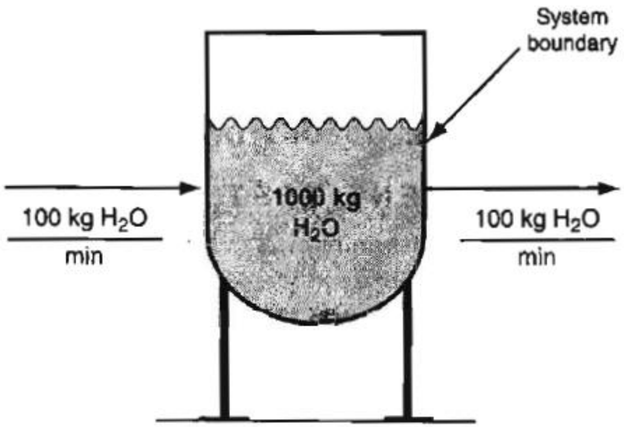
(c) We can inferred the generation and consumption terms from the stoichiometric equations

(d) The accumulation term refers to a change in mass or moles (plus or minus) within the system with respect to time.

(e) Closed system, material neither enters nor leaves the vessel, that is, no material crosses the system boundary.



(f) Open (flow) system, the material cross the system boundary (i.e. add and withdraw a material at certain rate)



(g) In ***Steady state*** problems the values of the variables in the system do not change with time, hence the accumulation term is ***zero***.

In put - output + generation - consumption = 0

The rate of addition is equal to the rate of removal as shown in Figure above.

(h) ***Unsteady state*** (or transient), problems formulated as differential equations with respect to time. The rate of addition (input) not equal to the rate of withdraw (output)

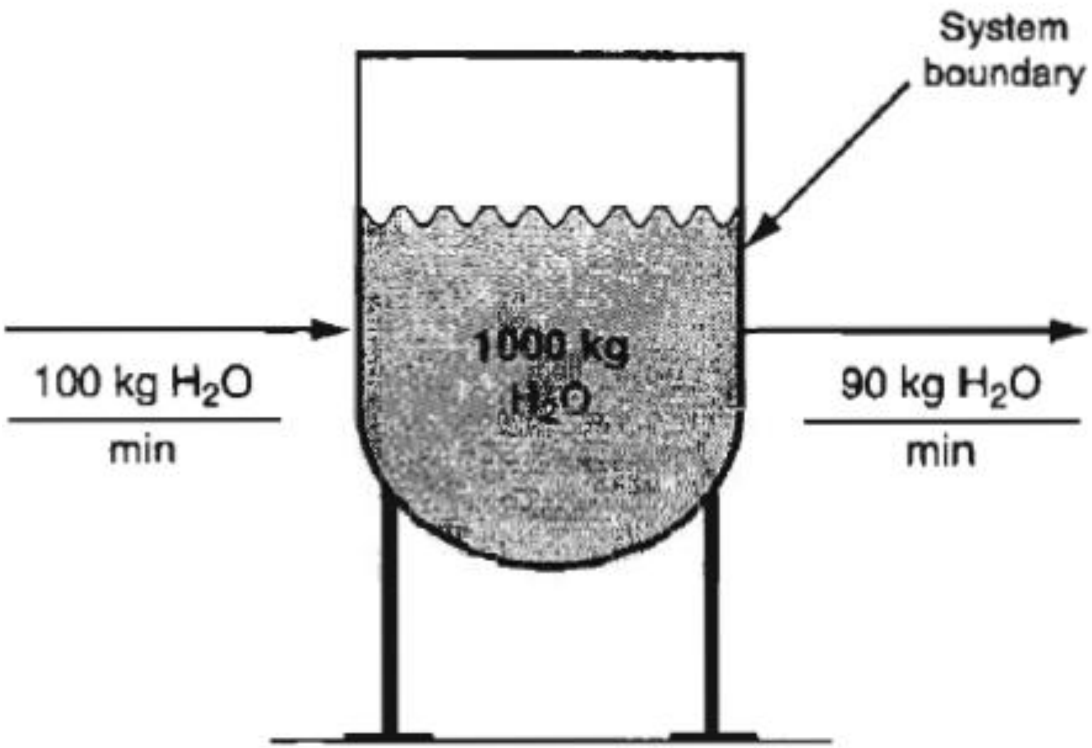


Figure 6.3 Initial conditions for an open unsteady-state system with accumulation.

(I) Semi-batch process, materials enters the process its operation, but does not leave. Instead mass is allowed to accumulate in the process vessel. Product is with draw only after the process is over.

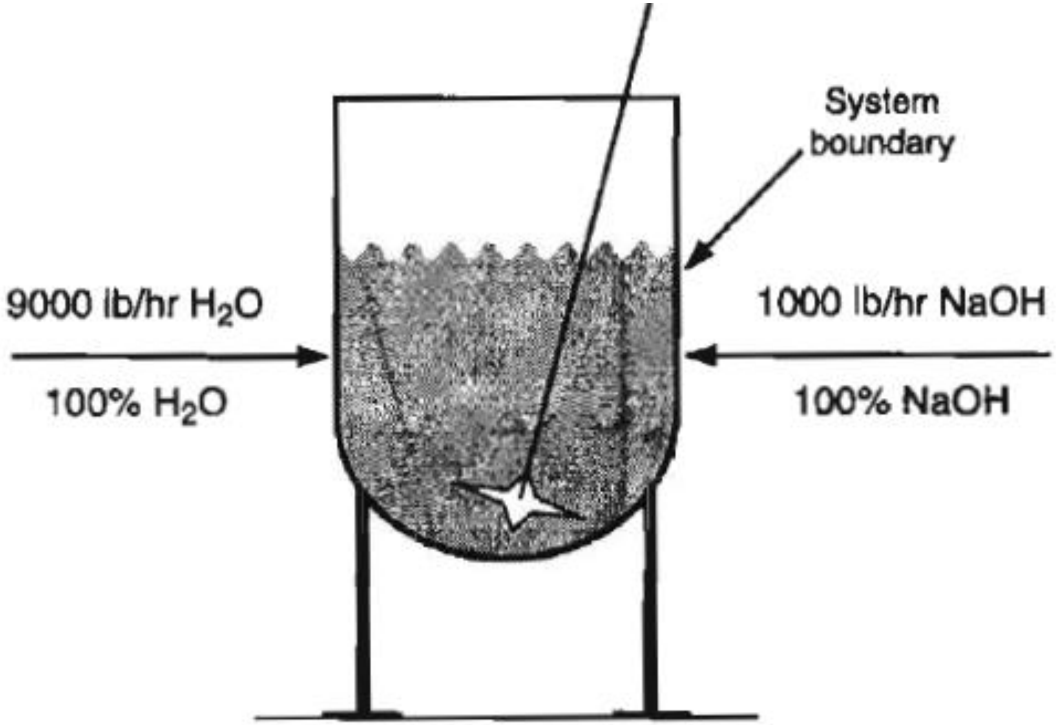


Figure 6.13a Initial condition for the semi-batch mixing process. Vessel is empty.

Accumulation An increase or decrease in the material (e.g., mass or moles) in the system.

Batch process A process in which material is neither added to nor removed from the process during its operation.

Closed system A system that does not have material crossing the system boundary.

Component balance A material balance on a single chemical component in a system.

Conservation of mass Matter is neither created nor destroyed overall.

Consumption The depletion of a component in a system due to chemical reaction.

Continuous process A process in which material enters and/or exits continuously.

Final condition The amount of material (e.g., mass or moles) in the process at the end of the processing interval.

Flow system An open system with material entering and/or leaving.

Generation The appearance of a component in a system because of chemical reaction.

Initial condition The amount of a material (e.g., mass or moles) in the process at the beginning of the processing interval.

Input Material (e.g., mass, moles) that enters the system.

Material balance The balance equation that corresponds to the conservation of mass.

Negative accumulation A depletion of material (usually mass or moles) in the system.

Open system A system in which material crosses the system boundary.

Output Material (e.g., mass, moles) that leaves the system.

Rate Flow per unit time

Semi-batch process A process in which material enters the system but product is not removed during operation.

Steady-state system A system for which all the conditions (e.g., temperature, pressure, amount of material) remain constant with time.

System Any arbitrary portion of or whole process that is considered for analysis.

System boundary The closed line that encloses the portion of the process that is to be analyzed.

Transient system A system for which one or more of the conditions (e.g., temperature, pressure, amount of material) of the system vary with time. Also known as an unsteady-state system.

Unsteady-state system A system for which one or more of the conditions (e.g., temperature, pressure, amount of material) of the system vary with time. Also known as a transient system.

Q / *Material for a distillation column*

A novice manufacturer of ethyl alcohol (denoted as EtOH) for gasohol is having a bit of difficulty with a distillation column. The process is shown in Figure E8.3. It appears that too much alcohol is lost in the bottoms (waste). Calculate the composition of the bottoms and the mass of the alcohol lost in the bottoms based on the data shown in Figure E8.3 that was collected during 1 hour of operation.

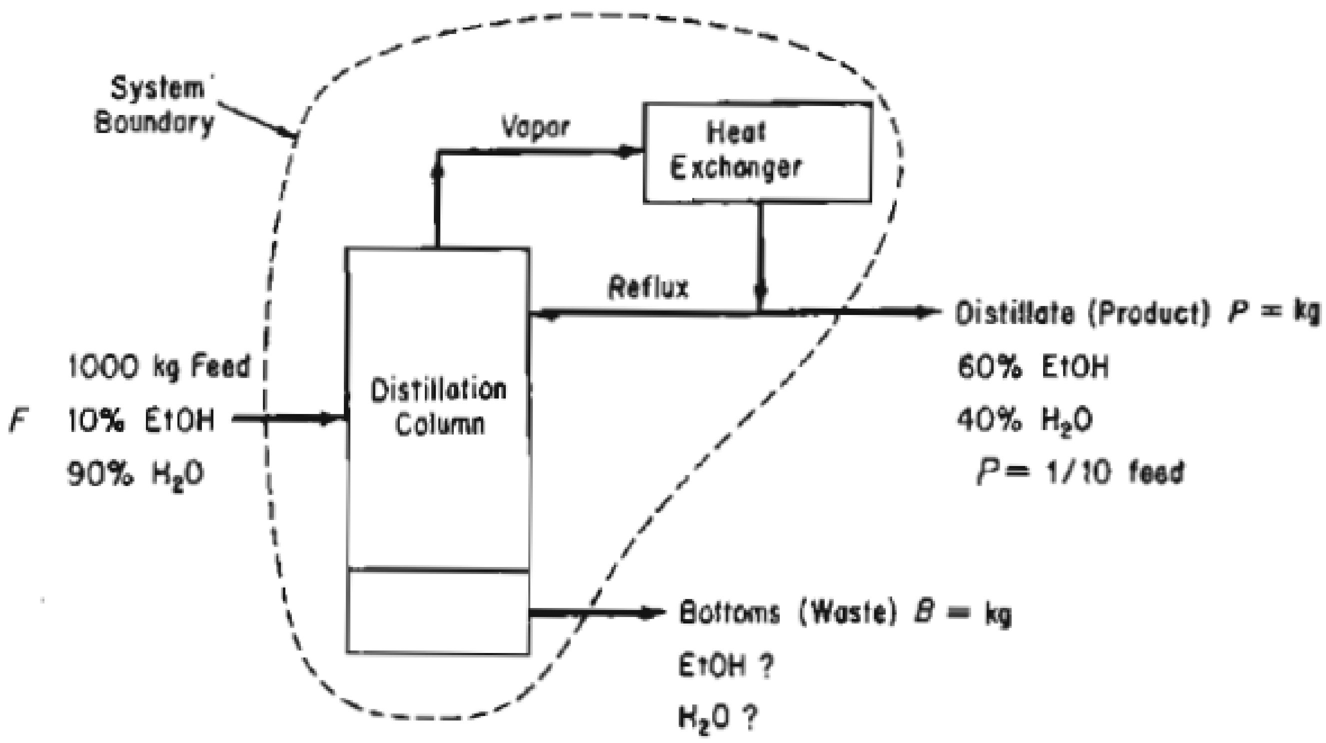


Figure E8.3

Steps 1, 2, and 3 See Fig. E2.11.
Step 4 Select as the basis the given feed

$$\text{Basis: 1000 kg of feed}$$

Step 3 (Continued) We are given that P is $\frac{1}{10}$ of F, so that

$$P = 0.1(1000) = 100 \text{ kg}$$

Steps 7, 8, and 9 Calculate B by direct subtraction using the total mass balance

$$B = 1000 - 100 = 900 \text{ kg}$$

Steps 5, 6, 7, 8, and 9 The unknown quantities are the bottoms compositions. We can make two component mass balances, or one sum of masses or mass fractions of the components in B plus one component mass balance, so that the problem has a unique solution.

The solution can be computed directly by subtraction.

	kg feed in	−	*kg distillate out*	=	*kg bottoms out*	*percent*
EtOH balance:	0.10(1000)	−	0.60(100)	=	40	4.4
H_2O balance:	0.90(1000)	−	0.40(100)	=	860	95.6
					900	100.0

If we use the total balance to calculate B, all we need to do is make one component balance because

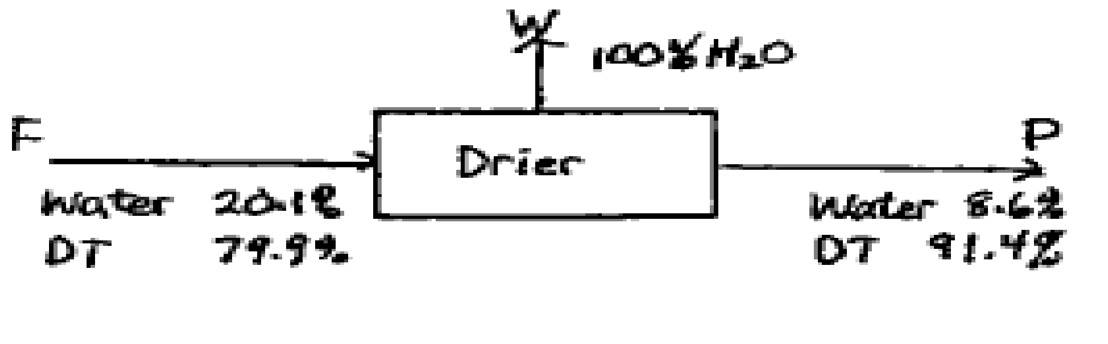
$$\text{mass } H_2O \text{ in } B = 900 - 40 = 860 \text{ kg}$$

Step 10 *Check:* 900 kg B + 100 kg P = 1000 kg F.

Q3 H.W/

A drier takes in wet timber (20.1% water) and reduces the water content to 8.6%. You want to determine the kg of water removed per kg of timber that enters the process.

a.



DT = dry timber

b. The DT is the balance of each stream.

c. Basis: F = 100 kg

d. Unknowns: F, W, P

Equations:
Basis: F = 100 kg
Material Balances: Water, DT
(total); 2 independent

e.&f. Introducing the specifications and basis into the material balances:

Water:	$(0.201)100 = (1)W$	$+ (0.086)P$	
DT:	$(0.80)\ 100 = 0$	$+ (0.914)P$	a tie element
Total:	$100 = W$	$+ P$	

g. $W = 12.5$ kg $\qquad P = 87.5$ kg

$$\frac{W}{F} = \frac{12.5\ \text{kg}}{100\ \text{kg}} = \boxed{0.125\text{kg/kg}}$$

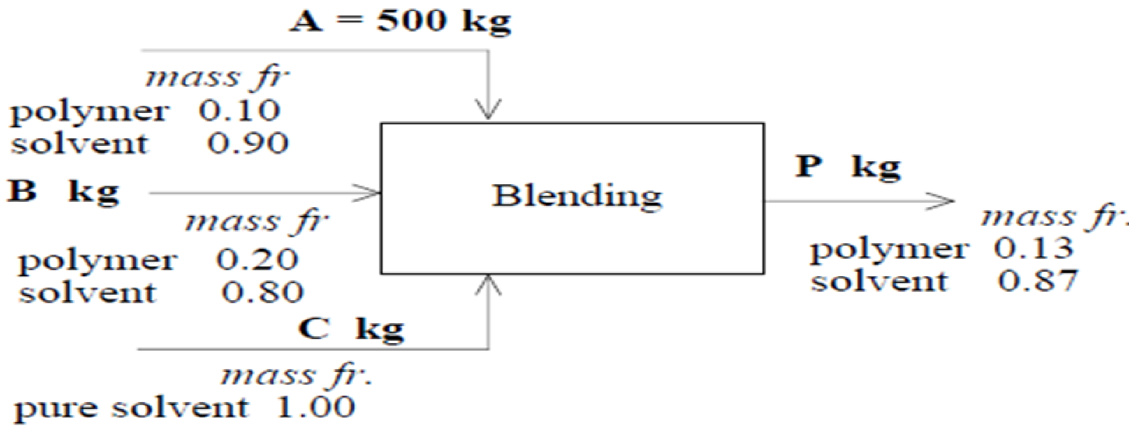
Q

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

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

B = 1700 kg

C = 800 kg

Step 10

Equation (3) can be used as a check,

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

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

Problem

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.

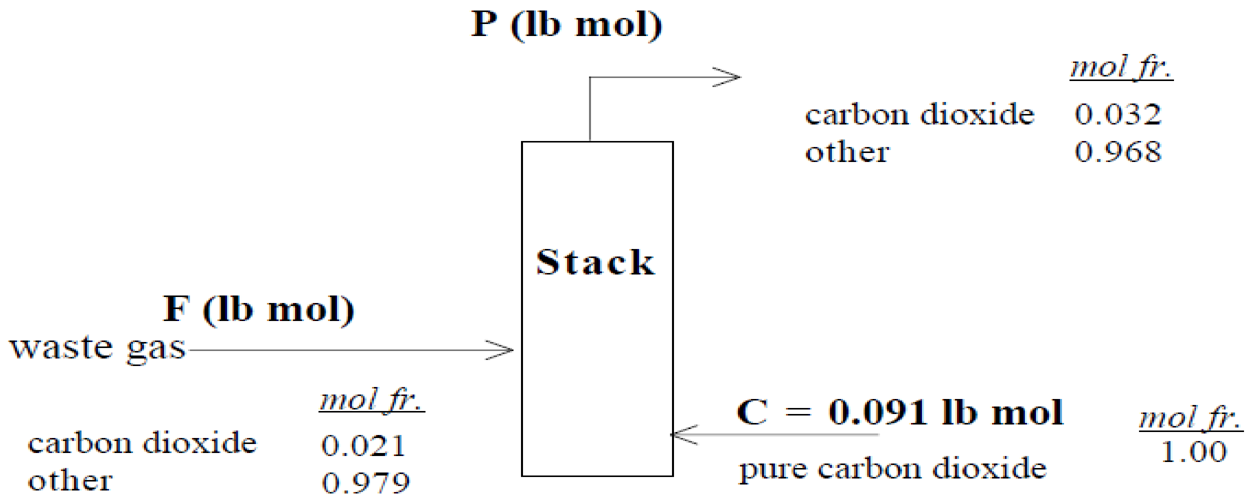
Solution

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.

$$\frac{4 \text{ lb } CO_2 \;\Big|\; 1 \text{ lb mol } CO_2}{\phantom{4 \text{ lb } CO_2} \;\Big|\; 44 \text{ lb } CO_2} = 0.091 \text{ lb mol } CO_2$$



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

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

Q5/ *Material balance with chemical reaction (combustion)*

(a) If 300 lb of air and 24.0 lb of carbon are fed to a reactor (see Fig. E2.3) at 600°F and after complete combustion no material remains in the reactor, how many pounds of carbon will have been removed? How many pounds of oxygen? How many pounds total?

(b) How many moles of carbon and oxygen enter? How many leave the reactor?

(c) How many total moles enter the reactor and how many leave the reactor?

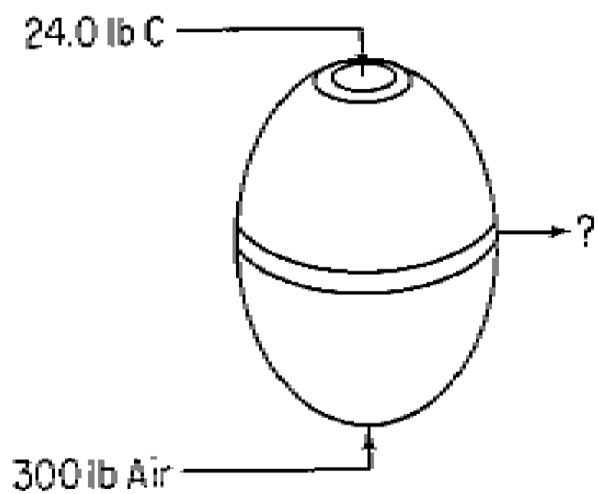


Figure E2.3

Solution

This is a problem without any accumulation. The system is the reactor and will be treated as an open system as shown in Fig. E2.3. We want to make a total mass balance and CO_2 and O_2 mole balances.

Basis: 300 lb air

First we calculate the lb mol of oxygen, nitrogen, and carbon entering:

$$\frac{300 \text{ lb air}}{} \bigg| \frac{1 \text{ lb mol air}}{29.0 \text{ lb air}} \bigg| \frac{21.0 \text{ lb mol } O_2}{100 \text{ lb mol air}} = 2.17 \text{ lb mol } O_2$$

$$\frac{2.17 \text{ lb mol } O_2}{} \bigg| \frac{79.0 \text{ lb mol } N_2}{21.0 \text{ lb mol } O_2} = 8.17 \text{ lb mol } N_2$$

$$\frac{24.0 \text{ lb C}}{} \bigg| \frac{1 \text{ lb mol C}}{12.0 \text{ lb C}} = 2.00 \text{ lb mol C}$$

The chemical reaction is

$$C + O_2 \longrightarrow CO_2$$

From the stoichiometry, 2.00 lb mol C requires 2.00 lb mol O_2 for complete combustion, so that a mole balance for O_2 leads to the conclusion that oxygen is the excess reactant, and that

$$\underset{\text{out}}{\underline{O_2 \text{ out}}} = \underset{\text{in}}{\underline{2.17}} - \underset{\text{consumption}}{\underline{2.00}} = 0.17 \text{ lb mol}$$

The carbon as C that exits is zero because all the C as such is consumed; from the stoichiometry we conclude for the CO_2 that

$$\underset{\text{out}}{\underline{CO_2}} = \underset{\text{in}}{\underline{0}} + \underset{\text{generation}}{\underline{2.00}} = 2.00 \text{ lb mol}$$

Summing up all the calculations in the form of a table, we have (mol. wt. atmospheric N_2 = 28.2)

	In		Out	
	lb	lb mol	lb	lb mol
C	24.0	2.00	0	0
O_2	69.5	2.17	5.5	0.17
N_2	230.5	8.17	230.5	8.17
CO_2	0	0	88.0	2.00
Total	324	12.34	324	10.34

We can now answer the questions posed in the problem.

(a) No carbon will be removed as the element C, but 88 lb of CO_2 will be removed, which contains 24 lb of C. Only 0.17 lb mol of O_2 will be removed as O_2; the remainder of the O_2 is in the CO_2. The total pounds removed will be that placed initially in the reactor, namely 324 lb.

(b) 2.00 lb mol C and 2.17 lb mol of O_2 enter the reactor, and 0 lb mol of C and 0.17 lb mol of O_2 as elemental species leave the reactor.

(c) 12.34 lb mol enters the reactor and 10.34 lb mol leaves the reactor.

Material balance with chemical reaction

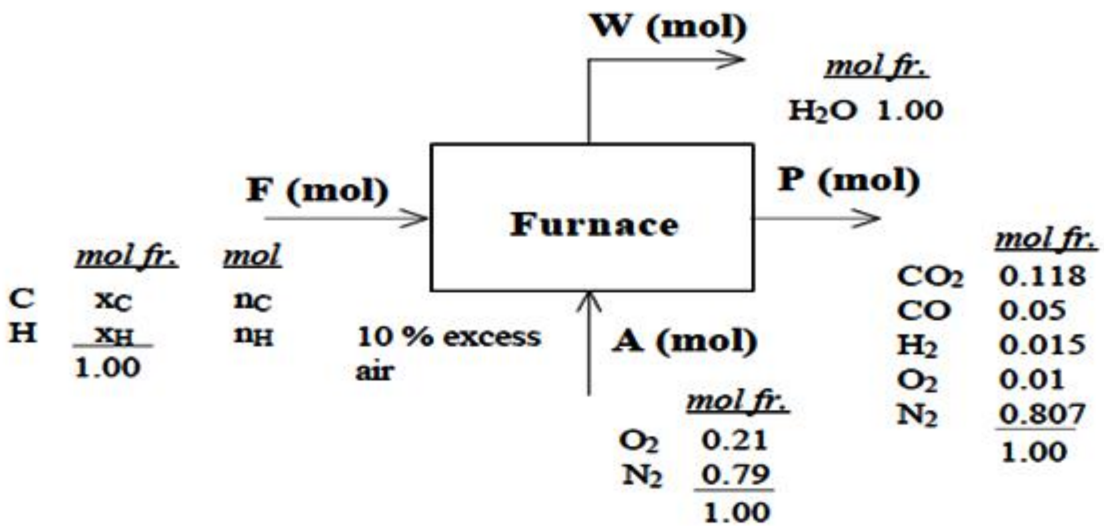
Problem

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 ca 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:

$C + O_2 \longrightarrow CO_2$ $\qquad \frac{16.8 \text{ mol C}}{} \Big| \frac{1 \text{mol } O_2}{1 \text{ mol C}} = 16.8$

$H_2 + 1/2\, O_2 \longrightarrow H_2O$ $\qquad \frac{13.7 \text{ mol } H_2}{} \Big| \frac{1 \text{mol } O_2}{2 \text{ mol } H_2} = 6.85$

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.