الجامعة التكنولوجية

قسم الهندسة الكيمياوية

المرحلة الاولى

مبادئ الهندسة الكمياوية

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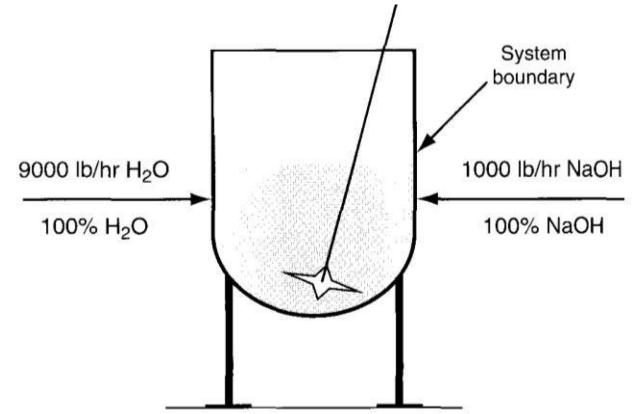


Figure 6.13a Initial condition for thesemi-batch mixing process. Vessel isempty.

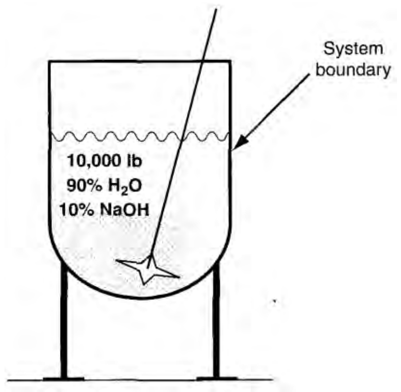


Figure 6.13b Condition of asemi-batch mixing process after 1 hour ofoperation.

Example6.3

Ameasurementforwaterflushingofasteeltankoriginallycontainingmotoroilshowedthat0.15 percentbyweightoftheoriginalcontentsremainedontheinteriortanksurface.Whatisthe fractionallossofoilbeforeflushingwithwater,andthepoundsofdischargeofmotoroilintothe environmentduringofa10,000galtanktruckthatcarriedmotoroil?(Thedensityofmotoroilis a bout $0.80 g/cm^3$).

Solution

Basis: 10,000 gal motor oil at an assumed77°F

The initial mass of the motor oil in the tankwas

(10000 gal)(3.785 lit/1 gal)(1000 cm^3/1 lit)(0.8 g/cm^3)(1 lb/454 g) = 66700lb

The mass fractional loss is **0.0015**. The oil material balanceis

Initial		unloaded		residualdischarged oncleaning
66,700	=	66,700(0.9985)	+	66,700(0.0015)

Thus, the discharge on flushing is **66,700 (0.00 15) = 100lb**.

Questions

1. Is it true that if no material crosses the boundary of a system, the system is a closed system?
2. Is mass conserved within an openprocess?
3. Can an accumulation be negative? What does a negative accumulationmean?
4. Underwhatcircumstancescantheaccumulationterminthematerialbalancebezerofora process?
5. Distinguish between a steady-state and an unsteady-stateprocess.
6. What is a transient process? Is it different than an unsteady-stateprocess?

7. Does Equation 6.4 apply to a system involving more than onecomponent?
8. Whenachemicalplantorrefineryusesvariousfeedsandproducesvariousproducts,does Equation 6.4 apply to each component in the plant?
9. What terms of the general material balance, Equation (6.5), can be deletedif
    a. The process is known to be a steady-stateprocess.
    b. The process is carried out inside a closed vessel.
    c. The process does not involve a chemicalreaction.
10. What is the difference between a batch process and a closedprocess?
11. What is the difference between a semi-batch process and a closedprocess?
12. What is the difference between a semi-batch process and an openprocess?

Answers:

1. Yes
2. Not necessarily – accumulation canoccur
3. Yes; depletion
4. No reaction (a) closed system, or (b) flow of a component in and out areequal.
5. Inanunsteady-statesystem,thestateofthesystemchangeswithtime,whereaswitha steady-state system, it doesnot.
6. A transient process is an unsteady-stateprocess.
7. Yes
8. Yes
9. (a) Accumulation; (b) flow in and out; (c) generation andconsumption
10. None
11. A flow inoccurs
12. None, except in a flow process, usually flows occur both in andout

Problems

1. Here is a report from a catalytic polymerizationunit:

Charge:	**Poundsperhour**
Propanes andbutanes	15,500
Production:	
Propane andlighter	5,680
Butane	2,080
Polymer	missing

What is the production in pounds per hour of thepolymer?

2. Aplantdischarges4,000gal/minoftreatedwastewaterthatcontains0.25mg/LofPCB, (polychloronated biphenyls) into a river that contains no measurable PCBs upstream ofthe discharge. If the river flow rate is 1,500 cubic feet per second, after the discharged waterhas thoroughlymixedwiththeriverwater,whatistheconcentrationofPCBsintheriverin mg/L?

Answers:

1. 7740lb/hr
2. $1.49 * 10^{-3}$mg/L

Supplementary Problems (ChapterSix):

Problem1

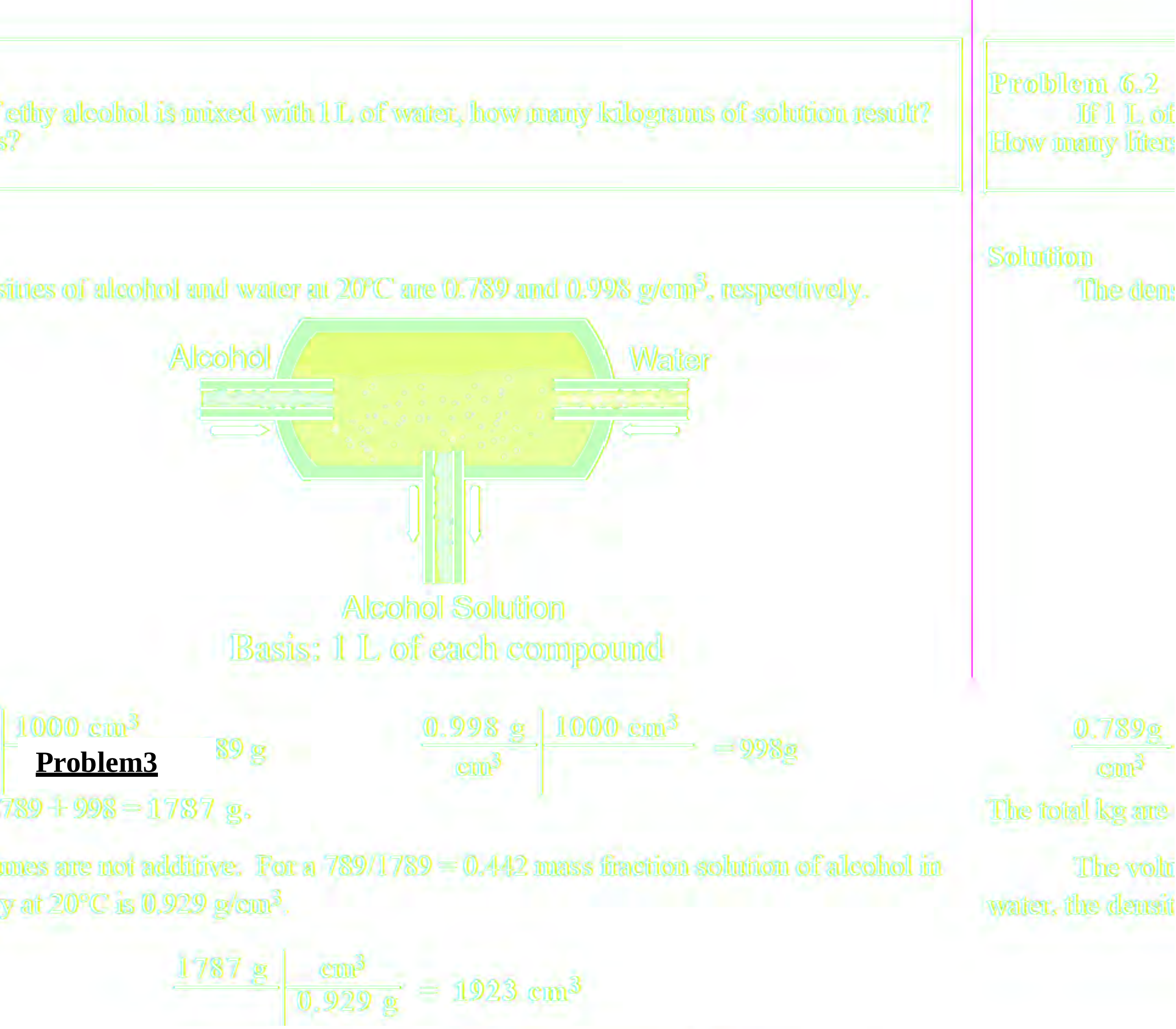
b. The input is 1.5 kg in one hour.

c. The output is 1.2 kg in one hour.

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

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

Problem2



Problem 6.2
If 1 L of
How many liters

ethy alcohol is mixed with 1 L of water, how many kilograms of solution result?
s?

Solution
The dens

sities of alcohol and water at 20°C are 0.789 and 0.998 g/cm³, respectively.

Basis: 1 L of each compound

$$\frac{0.789\text{g}}{\text{cm}^3}\left|\frac{1000\ \text{cm}^3}{}\right. \quad 89\ \text{g}$$

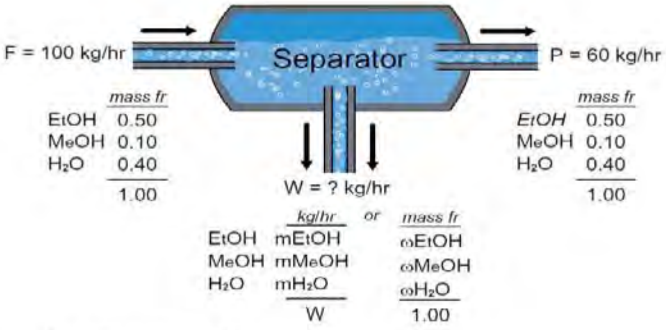
$$\frac{0.998\ \text{g}}{\text{cm}^3}\left|\frac{1000\ \text{cm}^3}{}\right. = 998\text{g}$$

The total kg are
789 + 998 = 1787 g.

The volu
mes are not additive. For a 789/1789 = 0.442 mass fraction solution of alcohol in
water, the densit
y at 20°C is 0.929 g/cm³.

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

Problem3



An obvious basis is one hour.

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

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

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

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

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

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

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

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

Chapter7

A General Strategy for Solving Material BalanceProblems

7.1 ProblemSolving

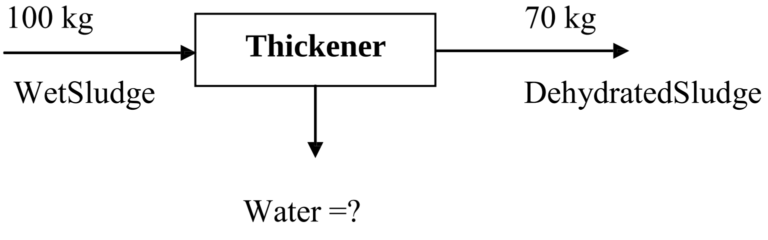
An orderly method of analyzing problems and presenting their solutions representstraining inlogicalthinkingthatisofconsiderablygreatervaluethanmereknowledgeofhowtosolvea particular type ofproblem.

7.2 The Strategy for SolvingProblems

1. Read and understand the problemstatement.
2. Draw a sketch of the process and specify the systemboundary.
3. Place labels for unknown variables and values for known variables on the sketch.
4. Obtain any missing neededdata.
5. Choose abasis.
6. Determine the number of unknowns.
7. Determine the number of independent equations, and carry out a degree of freedomanalysis.
8. Write down the equations to besolved.
9. Solve the equations and calculate the quantities askedfor.
10. Check youranswer.

Example7.1

Athickenerinawastedisposalunitofaplantremoveswaterfromwetsewagesludgeasshownin FigureE7.1.Howmanykilogramsofwaterleavethethickenerper100kgofwetsludgethatenter the thickener? The process is in the steadystate.



FigureE7.1

Solution

Basis: 100 kg wetsludge

The system is the thickener (an open system). No accumulation, generation, or consumptionoccurs. The total mass balanceis

$$\underline{\text{In}} \quad = \quad \underline{\text{Out}}$$

$$100\ \text{kg} = 70\ \text{kg} + \text{kg of water}$$

Consequently, the water amounts to 30kg.

Example7.2

AcontinuousmixermixesNaOHwithH_2OtoproduceanaqueoussolutionofNaOH.Determine the composition and flow rate of the product if the flow rate of NaOH is 1000 kg/hr, and the ratioof the flow rate of the H_2O to the product solution is 0.9. For thisprocess,

1. Sketch of the process isrequired.
2. Place the known information on the diagram of theprocess.
3. What basis would you choose for theproblem?
4. How many unknowns exist?
5. Determine the number of independentequations.
6. Write the equations to besolved.
7. Solve theequations.
8. Check youranswer.

Solution

1. The process is an open one, and we assume it to be steadystate.

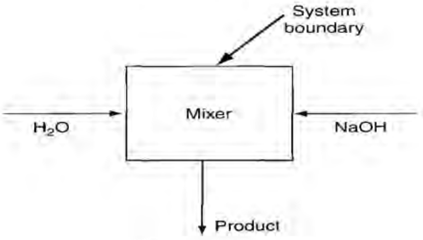
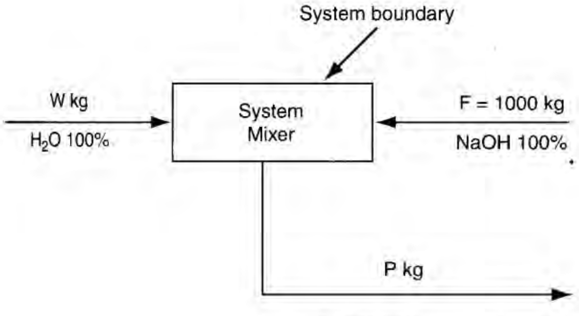


Figure E7.2

2. Because no contrary information is provided about the composition of the H_2O andNaOH streams, we will assume that they are 100% H_2O and NaOH,respectively.



Component	kg	ω (add if useful)
NaOH	P_{NaOH}	$\omega^P_{NaOH} = \frac{P_{NaOH}}{P}$
H_2O	P_{H_2O}	$\omega^P_{H_2O} = \frac{P_{H_2O}}{P}$
Total	P	1.00

3. Basis (1000 kg or 1 hour or 1000 kg/hr) (all areequivalent)

4. We do not know the values of four variables: W, P, P_{NaOH}andP_{H2O}.

5. You can write three materialbalances:

- one for theNaOH
- one for the H_2O
- one total balance (the sum of the two componentbalances)

Only two areindependent.

<u>Note:</u>Youcanwriteasmanyindependentmaterialbalancesastherearespeciesinvolvedin thesystem.

6. Material balance: in =out or in – out =0

$$\begin{array}{llcll}
\text{NaOH balance:} & 1000 = P_{\text{NaOH}} & \text{or} & 1000 - P_{\text{NaOH}} = 0 & (1)\\
\text{H}_2\text{O balance:} & W = P_{\text{H}_2\text{O}} & \text{or} & W - P_{\text{H}_2\text{O}} = 0 & (2)\\
\text{Given ratio:} & W = 0.9P & \text{or} & W - 0.9P = 0 & (3)\\
\text{Sum of components in } P\text{:} & P_{\text{NaOH}} + P_{\text{H}_2\text{O}} = P & \text{or} & P_{\text{NaOH}} + P_{\text{H}_2\text{O}} - P = 0 & (4)
\end{array}$$

Couldyousubstitutethetotalmassbalance1000+W=Pforoneofthetwocomponentmass balances? Of courseIn fact, you could calculate P by solving just twoequations:

$$\begin{array}{ll}
\text{Total balance:} & 1000 + W = P\\
\text{Given ratio:} & W = 0.9P
\end{array}$$

7. Solveequations:

W = 0.9 P substitute in total balance 1000 + 0.9 P =P

∴ P = 10000 kg & W = 0.9 * 10000 = 9000kg (The basis is still 1 hr (F_{NaOH}= 1000kg))

From these two values you can calculate the amount of H_2O and NaOH in the product

$$\text{From the } \left\{\begin{array}{l}\text{NaOH balance:}\\ \\ \text{H}_2\text{O balance:}\end{array}\right. \quad \text{you get } \left\{\begin{array}{l}P_{\text{NaOH}} = 1000\text{ kg}\\ \\ P_{\text{H}_2\text{O}} = 9000\text{ kg}\end{array}\right.$$

Then

$$\omega^{P}_{\text{NaOH}} = \frac{1000\text{ kg NaOH}}{10{,}000\text{ kg Total}} = 0.1$$

$$\omega^{P}_{\text{H}_2\text{O}} = \frac{9{,}000\text{ kg H}_2\text{O}}{10{,}000\text{ kg Total}} = 0.9$$

Note

$$\boxed{\omega^{P}_{\text{NaOH}} + \omega^{P}_{\text{H}_2\text{O}} = 1}$$

8. The total balance would have been a redundant balance, and could be used to check theanswers

$$P_{\text{NaOH}} + P_{\text{H2O}} = P$$

$$1{,}000 + 9{,}000 = 10{,}000$$

<u>Note:</u> After solving a problem, use a <u>redundant equation</u> to check yourvalues.

Degree of FreedomAnalysis

The phrase degrees of freedom have evolved from the design of plants in which fewerindependent equations than unknowns exist. The difference is called the degrees of freedom available tothe designertospecifyflowrates,equipmentsizes,andsoon.Youcalculatethenumberofdegreesof freedom (N_D) asfollows:

Degrees of freedom = number of unknowns — number of independentequations

$$N_D = N_U - N_E$$

✶ Whenyoucalculatethenumberofdegreesoffreedomyouascertainthesolveabilityofa problem. **Three** outcomesexist:

Case	N_D	Possibility ofSolution
$N_U = N_E$	0	Exactly specified (determined); a solutionexists
$N_U > N_E$	>0	Under specified (determined); more independent equationsrequired
$N_U < N_E$	<0	Over specified(determined)

For the problem in **Example7.2**,

$N_U = 4$

$N_E = 4$

So that

$N_D = N_U - N_E = 4 - 4 = 0$

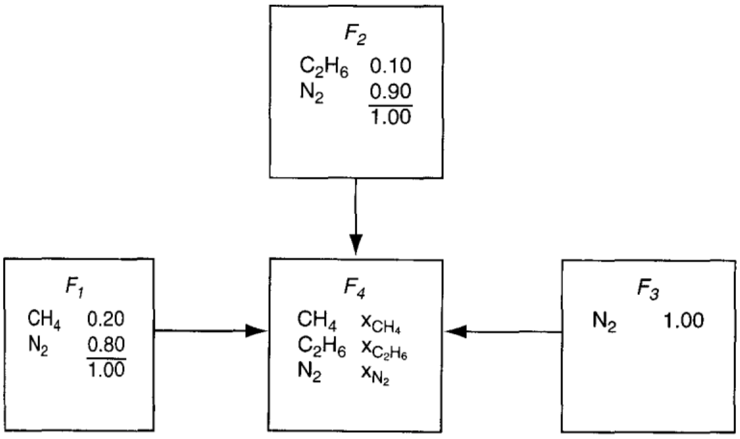
And a **unique** solution exists for theproblem.

Example7.3

A cylinder containing CH_4, C_2H_6, and N_2 has to be prepared containing a CH_4 to C_2H_6 mole ratioof 1.5 to 1. Available to prepare the mixture is (l) a cylinder containing a mixture of 80% N_2 and20% CH_4,(2)acylindercontainingamixtureof90%N_2and10%C_2H_6,and(3)acylindercontaining pureN_2.Whatisthenumberofdegreesoffreedom,i.e.,thenumberofindependentspecifications that must be made, so that you can determine the respective contributions from each cylinder toget the desired composition in the cylinder with the threecomponents?

Solution

A sketch of the process greatly helps in the analysis of the degrees of freedom. Look at FigureE7.3.



FigureE7.3

Do you count **seven unknowns** — **three** values of $x_i$and **four** values of F_i?Howmany independent equations can bewritten?

- Three material balances: CH_4, C_2H_6, andN_2
- One specified ratio: moles of CH_4 to C_2H_6 equal 1.5 or $(X_{CH4}/X_{C2H6}) = 1.5$
- One summation of mole fractions: $\sum x_i^{F_4} = 1$

Thus,thereare**sevenminusfiveequalstwodegreesoffreedom**($N_D=N_U–N_E=7–5=2$).Ifyou pick a basis, such as $F_4 = 1$, one other value has to be specified to solve the problem tocalculate composition ofF_4.

Questions

1. What does the concept–solution of amaterialbalanceproblem‖mean?
2. (a) How many values of unknown variables can you compute from one independentmaterial balance?

   (b) From three independent material balanceequations?

   (c) From four material balances, three of which areindependent?
3. Ifyouwanttosolveasetofindependentequationsthatcontainfewerunknownvariables than equations (the over specified problem), how should you proceed with thesolution?
4. What is the major category of implicit constraints (equations) you encounter inmaterialbalance problems?
5. If you want to solve a set of independent equations that contain more unknown variablethan equations (the underspecified problem), what must you do to proceed with thesolution?

Answers:

1. A solution means a (possibly unique) set of values for the unknowns in a problemthat satisfies the equations formulated in theproblem.
2. (a) one; (b) three; (c)three.
3. Delete nonpertinent equations, or find additional variables not included in theanalysis.
4. The sum of the mass or mole fraction in a stream or inside a system isunity.
5. Obtain more equations or specifications, or delete variables of negligibleimportance.

Problems

1. Awatersolutioncontaining10%aceticacidisaddedtoawatersolutioncontaining30% acetic acid flowing at the rate of 20 kg/min. The product P of the combination leaves therate of 100 kg/min. What is the composition of P? For thisprocess,
   a. Determine how many independent balances can bewritten.
   b. List the names of thebalances.
   c. Determine how many unknown variables can be solvedfor.
   d. List their names andsymbols.
   e. Determine the composition of P.
2. Can you solve these three material balances for F, D, and P? Explain whynot.

$$\begin{aligned} 0.1F + 0.3D &= 0.2P \\ 0.9F + 0.7D &= 0.8P \\ F + D &= P \end{aligned}$$

3. HowmanyvaluesoftheconcentrationsandflowratesintheprocessshowninFigure SAT7.2P3 are unknown? List them. The streams contain two components, 1 and2.

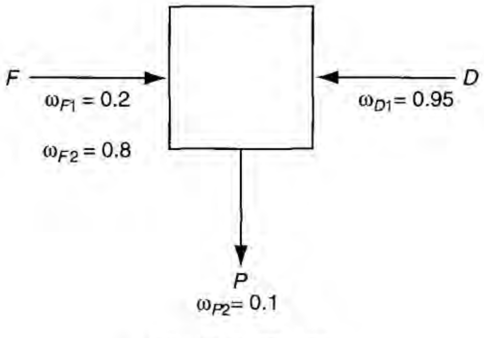


Figure SAT7.2P3

4. How many material balances are needed to solve problem 3? Is the number the same asthe number of unknown variables?Explain.

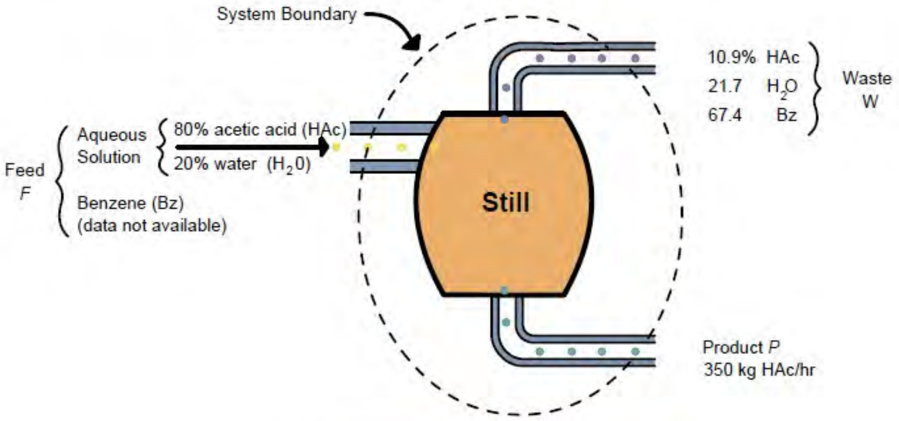
Answers:

1. (a)Two;(b)twoofthesethree:aceticacid,water,total;(c)two;(d)feedofthe10% solution(sayF)andmassfractionωoftheaceticacidinP;(e)14%aceticacidand86% water
2. Not for a unique solution because only two of the equations areindependent.
3. F, D, P, ω_{D2}, ω_{P1}
4. Threeunknownsexist.Becauseonlytwoindependentmaterialbalancescanbewrittenfor theproblem,onevalueofF,D,orPmustbespecifiedtoobtainasolution.Notethat specifying values of ω_{D2} or ω_{P1} will nothelp.

Supplementary Problems (ChapterSeven):

Problem1

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



Solution

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

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

The total balance would be: $F = W + 350$ (in kg).

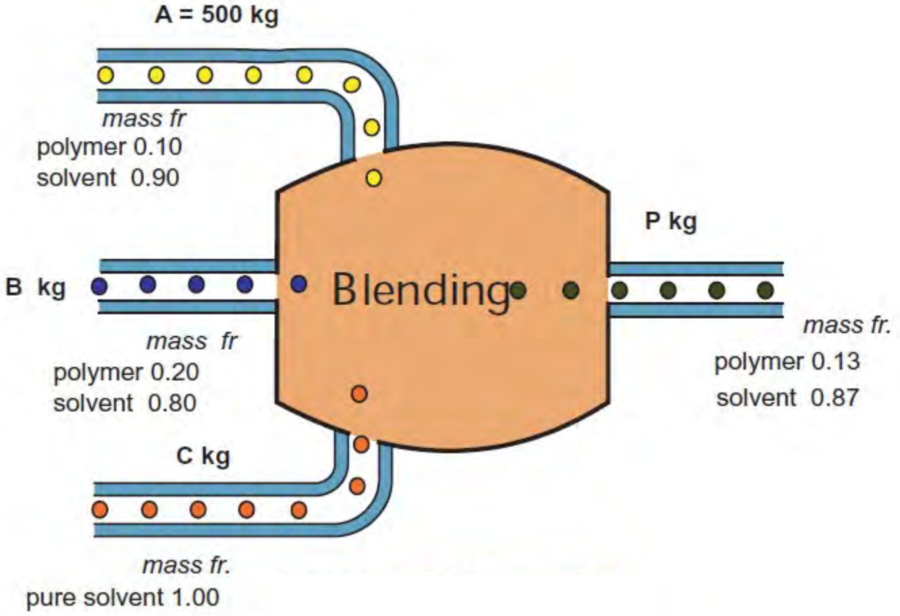
Problem2

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

This is a steady state process without reaction.



Basis: 3000 kg 13 wt % polymer solution

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

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).

from (2) $0.1\,(500) + 0.20\,B = 0.13\,(3000)$ **B = 1700 kg**

from (1) $500 + 1700 + C = 3000$ **C = Ê800 kg**

Equation (3) can be used as a check,

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

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

Chapter8

Solving Material Balance Problems for Single Units withoutReaction

Theuseofmaterialbalancesinaprocessallowsyou**(a)**tocalculatethevaluesofthetotal flows and flows of species in the streams that enter and leave the plant equipment, and **(b)**to calculate the change of conditions inside theequipment.

Example8.1

DeterminethemassfractionofStreptomycinintheexitorganicsolventassumingthatno water exits with the solvent and no solvent exits with the aqueous solution. Assume that thedensity of the aqueous solution is 1 g/cm^3 and the density of the organic solvent is 0.6 g/cm^3. Figure E8.1 shows the overallprocess.

Solution

This is an **open** (flow), **steady-state** process without reaction. Assume because of the low concentrationofStrep.intheaqueousandorganicfluidsthatthe**flowrates**ofthe**entering**fluids **equal** the flow rates of the **exit**fluids.

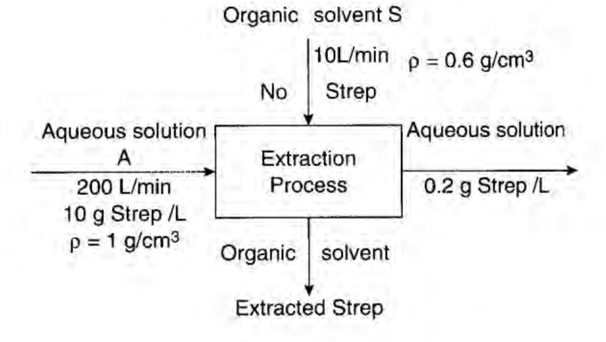


Figure E8.1

Basis: 1min

Basis: Feed = 200 L (flow of aqueous entering aqueoussolution)

- Flow of exiting aqueous solution (same as existingflow)
- Flow of exiting organic solution (same as existingflow)

The material balances are **in = out** in **grams**. Let **x** be the **g** of Strep per **L** of solvent **S**

Strep.balance:

$$\frac{200\ \text{L of A}}{}\bigg|\frac{10\ \text{g Strep}}{1\ \text{L of A}} + \frac{10\ \text{L of S}}{}\bigg|\frac{0\ \text{g Strep}}{1\ \text{L of S}} = \frac{200\ \text{L of A}}{}\bigg|\frac{0.2\ \text{g Strep}}{1\ \text{L of A}} + \frac{10\ \text{L of S}}{}\bigg|\frac{x\ \text{g Strep}}{1\ \text{L of S}}$$

x = 196 g Strep/L ofsolvent

To get the g Strep/g solvent, use the density of thesolvent:

$$\frac{196 \text{ g Strep}}{1 \text{ L of S}}\bigg|\frac{1 \text{ L of S}}{1000 \text{ cm}^3 \text{ of S}}\bigg|\frac{1 \text{ cm}^3 \text{ of S}}{0.6 \text{ g of S}} = 0.3267 \text{ g Strep/g of S}$$

$$\text{The mass fraction Strep} = \frac{0.3267}{1 + 0.3267} = 0.246$$

Example8.2

Membranesrepresentarelativelynewtechnologyfortheseparationofgases.Oneusethathas attractedattentionistheseparationofnitrogenandoxygenfromair.FigureE8.2aillustratesa nanoporousmembranethatismadebycoatingaverythinlayerofpolymeronaporousgraphite supportinglayer.Whatisthecompositionofthewastestreamifthewastestreamamountsto80% of the inputstream?

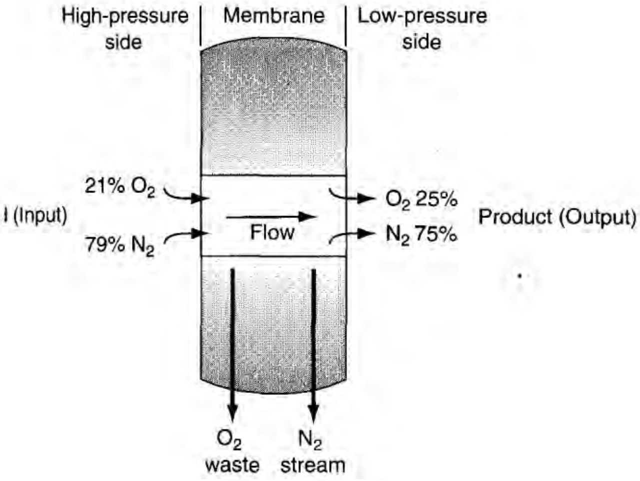
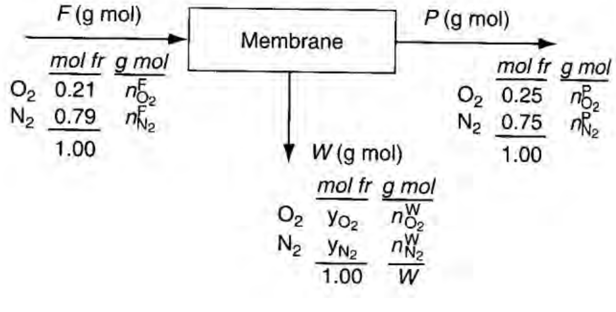


Figure E8.2a

Solution

This is an **open**, **steady-state process** without chemicalreaction.



Basis: 100 g mol =F

Basis: F =100

$$\text{Specifications:} \quad n^F_{O_2} = 0.21(100) = 21$$

$$n^F_{N_2} = 0.79(100) = 79$$

$$y_{O_2}^P = n_{O_2}^P/P = 0.25 \qquad n_{O_2}^P = 0.25P$$
$$y_{N_2}^P = n_{N_2}^P/P = 0.75 \qquad n_{N_2}^P = 0.75P$$
$$W = 0.80(100) = 80$$

Material balances: O_2 andN_2

Implicit equations: $\Sigma n_i^W = W$ or $\Sigma y_i^W = 1$

	In	Out		In	Out
O_2:	$0.21\,(100)$	$= 0.25P + y_{O_2}^W\,(80)$	or	$0.21\,(100)$	$= 0.25P + n_{O_2}^W$
N_2:	$0.79\,(100)$	$= 0.75P + y_{N_2}^W\,(80)$	or	$0.79\,(100)$	$= 0.75P + n_{N_2}^W$
	1.00	$= y_{O_2}^W + y_{N_2}^W$	or	80	$= n_{O_2}^W + n_{N_2}^W$

The solution of these equationsis

$n_{O_2}^W = 16$ and $n_{N_2}^W = 64$, or $y_{O_2}^W = 0.20$ and $y_{N_2}^W = 0.80$, and $P = 20$ g mol

Check: total balance 100 = 20 + 80 OK

- **Another method forsolution**

The overall balance is easy to solvebecause

F = P +W or 100=P+80

Gives P = 20 straight off. Then, the oxygen balance wouldbe

$$0.21(100) = 0.25(20) + n_{O_2}^W$$

$n_{O_2}^W = 16$ g mol, and $n_{O_2}^W = 80 - 16 = 64$ g mol.

Note (Example8.2)

$n_{O_2}^F + n_{N_2}^F = F$ is a redundant equation because it repeats some of thespecifications.

Also, $n_{O_2}^P + n_{N_2}^P = P$ is redundant. Divide the equation by P to get $y_{O_2}^P + y_{N_2}^P = 1$, a relation thatis equivalent to the sum of two of thespecifications.

Example8.3

Anovicemanufacturerofethylalcohol(denotedasEtOH)forgasoholishavingabitofdifficulty with a distillation column. The process is shown in Figure E 8.3. It appears that too much alcoholis lostinthebottoms(waste).Calculatethecompositionofthebottomsandthemassofthealcohol lostinthebottomsbasedonthedatashowninFigureE8.3thatwascollectedduring1hourof operation.

Solution

The process is an **open system**, and we assume it is in the **steady state**. No **reaction**occurs.

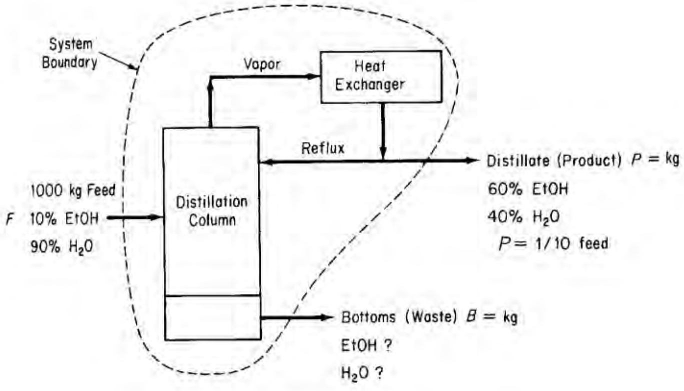


Figure E8.3

Basis: 1 hour so that **F = 1000 kg** offeed

We are given that P is (1/10) of F, so that P = 0.1(1000) = 100kg

Basis: F= 1000kg

Specifications: $m^F_{\text{EtOH}} = 1000(0.10) = 100$

P = (0.1) (F) = 100kg

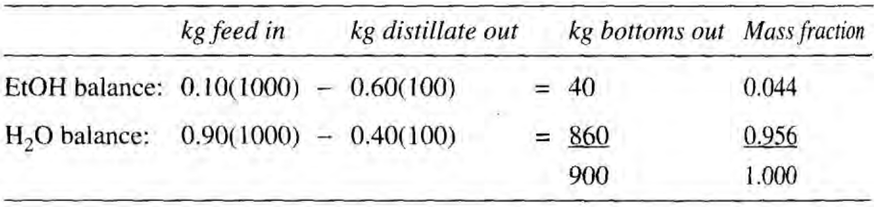
Material balances: EtOH andH_2O

Implicit equations: $\Sigma m_i^B = B$ or $\Sigma \omega_i^B = 1$

The total massbalance: F = P +B

B = 1000 – 100 = 900kg

Thesolutionforthecompositionofthe**bottoms**canthenbecomputeddirectlyfromthematerial balances:



	kg feed in		kg distillate out		kg bottoms out	Mass fraction
EtOH balance:	0.10(1000)	–	0.60(100)	=	40	0.044
H_2O balance:	0.90(1000)	–	0.40(100)	=	860	0.956
					900	1.000

As a **check** let's use the redundantequation

$$m^B_{\text{EtOH}} + m^B_{\text{H}_2\text{O}} = B \quad \text{or} \quad \omega^B_{\text{EtOH}} + \omega^B_{\text{H}_2\text{O}} = 1$$

40 + 860 = 900 =B

Example8.4

You are asked to prepare a batch of 18.63% battery acid as follows. A tank of old weak batteryacid (H_2SO_4) solution contains 12.43% H_2SO_4 (the remainder is pure water). If 200 kg of 77.7% H_2SO_4 isaddedtothetank,andthefinalsolutionistobe18.63%H_2SO_4,howmanykilogramsofbattery acid have been made? See FigureE8.4.

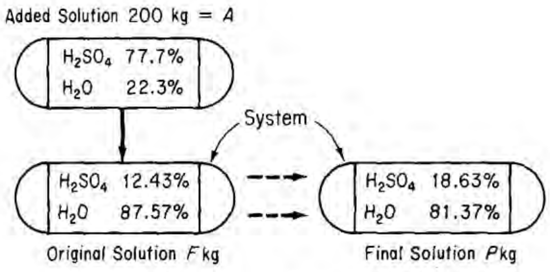


Figure E8.4

Solution

1. An unsteady-state process (the tank initially contains sulfuric acidsolution).

Accumulation = In –Out

2. Steady-state process (the tank as initially beingempty)

In = Out (Because no **accumulation** occurs in thetank)

1) Solve the problem with the mixing treated as an **unsteady-stateprocess**.

Basis = 200 kg ofA

Material balances: H_2SO_4 andH_2O The balances will be in**kilograms**.

Type of Balance	*Accumulation in Tank*				*In*		*Out*
	Final		Initial				
H_2SO_4	$P(0.1863)$	−	$F(0.1243)$	=	200(0.777)	−	0
H_2O	$P(0.8137)$	−	$F(0.8757)$	=	200(0.223)	−	0
Total	P	−	F	=	200	−	0

Note that any **pair** of the three equations is**independent**.

P = 2110 kg acid & F = 1910 kgacid

2) The problem could also be solved by considering the mixing to be a **steady- stateprocess**.

	A in		*F in*		*P out*
H_2SO_4	200(0.777)	+	F(0.1243)	=	P(0.1863)
H_2O	200(0.223)	+	F(0.8757)	=	P(0.8137)
Total	A	+	F	=	P

Note: You can see by inspection that these equations are no different than the first set of mass balances except for the arrangement and labels.

Example 8.5

In a given batch of fish cake that contains 80% water (the remainder is dry cake), 100 kg of water is removed, and it is found that the fish cake is then 40% water. Calculate the weight of the fish cake originally put into the dryer. Figure E8.5 is a diagram of the process.

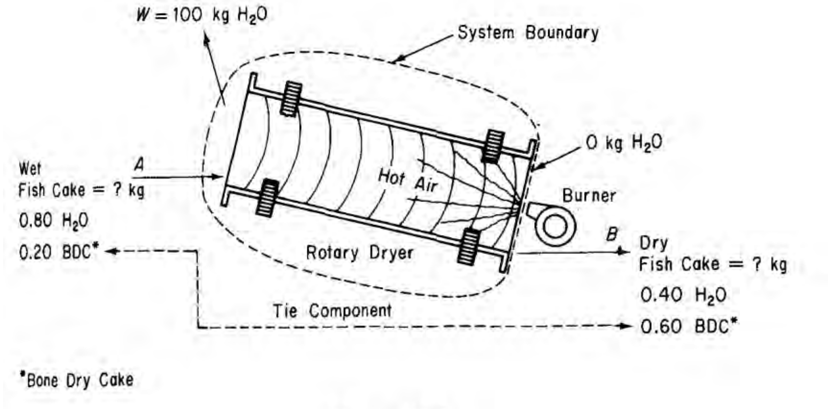


Figure E8.5

Solution

This is a steady-state process without reaction.

Basis: 100 kg of water evaporated = W

$$\left.\begin{array}{lll} & \underline{\text{In}} & \underline{\text{Out}} \\ \text{Total balance:} & A & = B + W = B + 100 \\ \text{BDC balance:} & 0.20A & = 0.60B \end{array}\right\} \text{mass balances}$$

A = 150 kg initial cake and B = (150)(0.20/0.60) = 50 kg

Check via the water balance: 0.80 A = 0.40 B + 100

$$0.80(150) \approx 0.40(50) + 100$$

$$120 = 120$$

Note

In Example 8.5 the BDC in the wet and dry fish cake is known as a **tie component** because the BDC goes from a single stream in the process to another single stream **without loss, addition, or splitting**.

Example8.6

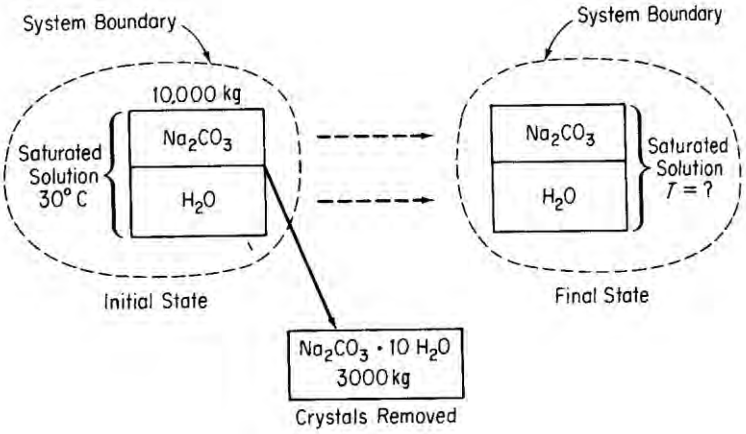
A tank holds 10,000 kg of a saturated solution of Na_2CO_3 at 30°C. You want to crystallize fromthis solution3000kgof$Na_2CO_3.10H_2O$withoutanyaccompanyingwater.Towhattemperaturemust the solution becooled?

You definitely need solubility data for Na_2CO_3 as a function of thetemperature:

Temp.(°C)	Solubility (g Na_2CO_3/100 g H_2O)
0	7
10	12.5
20	21.5
30	38.8

Solution

No **reaction** occurs. Although the problem could be set up as a **steady-state problem** with flowsin andoutofthesystem(thetank),itisequallyjustifiedtotreattheprocessasan-**unsteady-stateprocess**.



Becausetheinitialsolutionissaturatedat30°C,youcancalculatethecompositionoftheinitial solution:

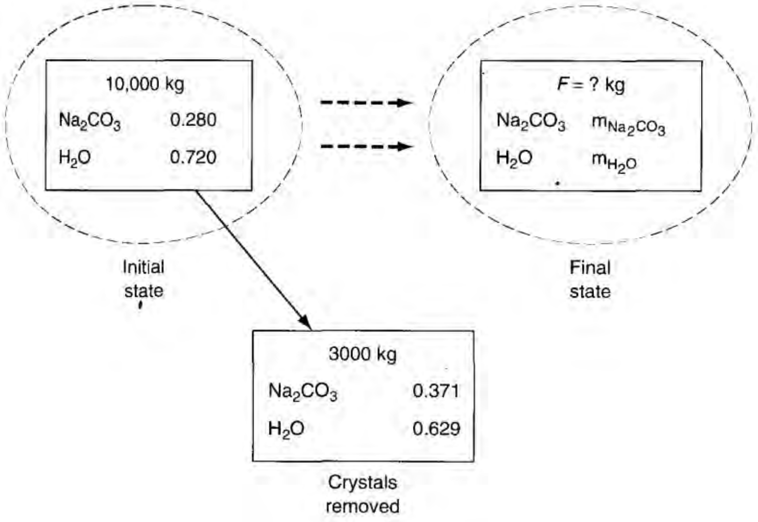
$$\frac{38.8\text{ g }Na_2CO_3}{38.8\text{ g }Na_2CO_3 + 100\text{ g }H_2O} = 0.280\text{ mass fraction }Na_2CO_3$$

Next, you should calculate the composition of thecrystals.

Basis: 1 g mol $Na_2CO_3.10H_2O$

Comp.	*Mol*	*Mol wt.*	*Mass*	*Mass fr*
Na_2CO_3	1	106	106	0.371
H_2O	10	18	180	0.629
Total			286	1.00

Basis: 10,000 kg of saturated solution at30°C



An **unsteady-state** problem, the mass balance reduces to (the flow in =0)

Accumulation = In –Out

Basis: I = 10,000kg

Material balances: Na_2CO_3,H_2O

Note that $\omega_i{}^I I = m_i^I, \omega_i{}^F F = m_i^F$, and $\omega_i{}^C C = m_i^C$ are redundantequations. C =Crystals

Also redundant are equations suchas $\Sigma\omega_i = 1$ and $\Sigma m_i = m_{total}$.

M.B.:

	Accumulation in Tank				
	Final		*Initial*		*Transport out*
Na_2CO_3	$m^F_{Na_2CO_3}$	−	10,000(0.280)	=	−3000(0.371)
H_2O	$m^F_{H_2O}$	−	10,000(0.720)	=	−3000(0.629)
Total	F	−	10,000	=	−3000

The solution for the composition and amount of the final solutionis

Component	*kg*
$m^F_{Na_2CO_3}$	1687
$m^F_{H_2O}$	5313
F (total)	7000

Check using the totalbalance: 7,000 + 3,000 = 10,000

To find the temperature of the finalsolution, $\frac{1{,}687 \text{ kg } Na_2CO_3}{5{,}313 \text{ kg } H_2O} = \frac{31.8 \text{ g } Na_2CO_3}{100 \text{ g } H_2O}$

Thus, the temperature to which the solution must be cooled lies between **20°C** and **30°C**. By **linear interpolation**

$$30°\text{C} - \frac{38.8-31.8}{38.8-21.5}(10.0°\text{C}) = 26°\text{C}$$

Example8.7

Thisexamplefocusesontheplasmacomponentsofthestreams:water,uricacid(UR), creatinine (CR), urea (U), P, K, and Na. You can ignore the initial filling of the dialyzer becausethe treatmentlastsforanintervaloftwoorthreehours.Giventhemeasurementsobtainedfromone treatmentshowninFigureE8.7b,calculatethegramsperliterofeachcomponentoftheplasmain the outlet solution.

Solution

This is an open steady-statesystem.

Basis: 1minute

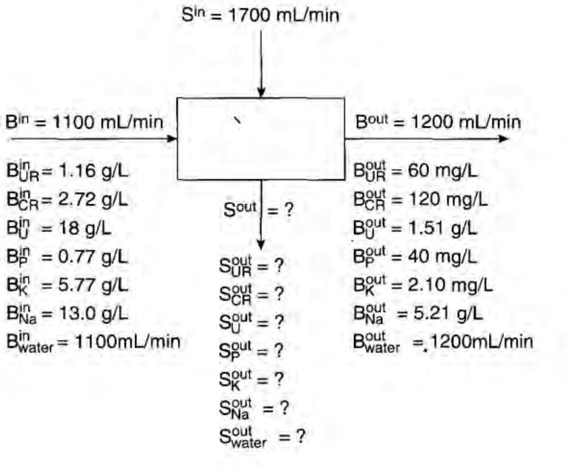


Figure E8.7b

- The **entering solution** is assumed to be essentially**water**.

The water balance in grams, assuming that 1 mL is equivalent to 1 gram,is:

$$1100 + 1700 = 1200 + S^{out}_{water} \quad \text{hence:} \qquad S^{out}_{water} = 1600 \text{ mL}$$

The component balances in gramsare:

$$\begin{array}{ll} & \underline{g/L} \\ \text{UR:}\ \ 1.1(1.16) + 0 = 1.2(0.060) + 1.6\,S^{out}_{UR} & S^{out}_{UR} = 0.75 \\ \text{CR:}\ \ 1.1(2.72) + 0 = 1.2(0.120) + 1.6\,S^{out}_{CR} & S^{out}_{CR} = 1.78 \\ & \\ \text{U:}\ \ 1.1(18) + 0 = 1.2(1.51) + 1.6\,S^{out}_{U} & S^{out}_{U} = 11.2 \\ \text{P:}\ \ 1.1(0.77) + 0 = 1.2(0.040) + 1.6\,S^{out}_{P} & S^{out}_{P} = 0.50 \\ \text{K:}\ \ 1.1(5.77) + 0 = 1.2(0.120) + 16\,S^{out}_{K} & S^{out}_{K} = 3.8 \\ \text{Na:}\ \ 1.1(13.0) + 0 = 1.2(3.21) + 1.6\,S^{out}_{Na} & S^{out}_{Na} = 6.53 \end{array}$$

Questions

1. Answer the following questions true or false:
    a. The most difficult part of solving material balance problems is the collection and formulation of the data specifying the compositions of the streams into and out of the system, and of the material inside the system.
    b. All open processes involving two components with three streams involve zero degrees of freedom.
    c. An unsteady-state process problem can be analyzed and solved as a steady-state process problem.
    d. If a flow rate is given in kg/min, you should convert it to kgmol/min.
2. Under what circumstances do equations or specifications become redundant?

Answers:

1. (a) T; (b) F; (c) T; (d)F
2. When they are not independent.

Problems

1. A cellulose solution contains 5.2% cellulose by weight in water. How many kilograms of 1.2% solution are required to dilute 100 kg of the 5.2% solution to 4.2%?
2. A cereal product containing 55% water is made at the rate of 500 kg/hr. You need to dry the product so that it contains only 30% water. How much water has to be evaporated per hour?
3. If 100 g of Na_2SO_4 is dissolved in 200 g of H_2O and the solution is cooled until 100 g of $Na_2SO_4.10H_2O$ crystallizes out; find (a) the composition of the remaining solution (the mother liquor) and (b) the grams of crystals recovered per 100 g of initial solution.
4. Salt in crude oil must be removed before the oil undergoes processing in a refinery. The crude oil is fed to a washing unit where fresh water fed to the unit mixes with the oil and dissolves a portion of the salt contained in the oil. The oil (containing some salt but no water), being less dense than the water, can be removed at the top of the washer. If the “spent” wash water contains 15% salt and the crude oil contains 5% salt, determine the concentration of salt in the “washed” oil product if the ratio of crud oil (with salt) to water used is 4:1.

Answers:

1. 33.3 kg
2. 178kg/hr
3. (a) 28% Na_2SO_4 ; (b)33.3
4. Salt: 0.00617; Oil:0.99393

Supplementary Problems (ChapterEight):

Problem1

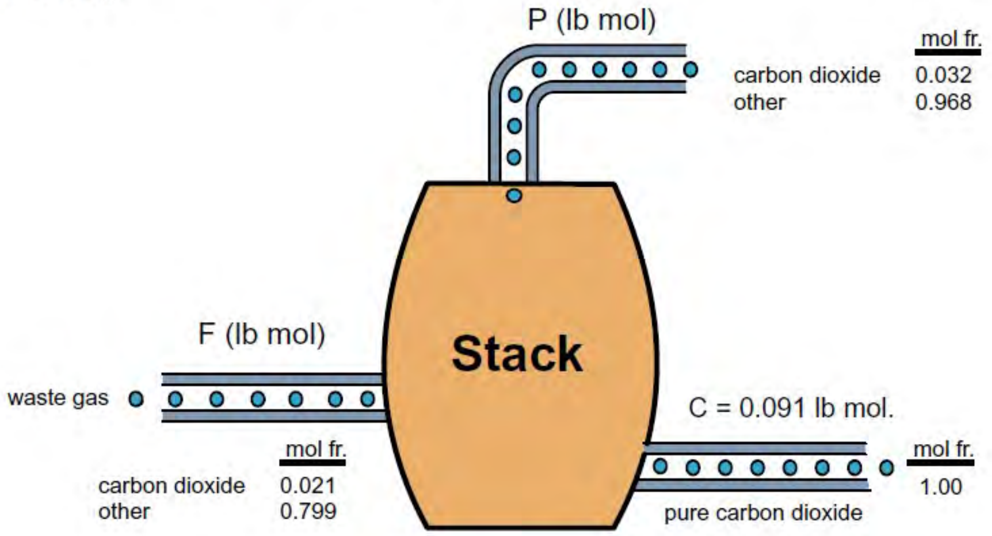
You are asked to measure the rate at which waste gases are being discharged from a stack. The gases entering contain 2.1 % carbon dioxide. Pure carbon dioxide is introduced into the bottom of the stack at a measured rate of 4.0 lb per minute. You measure the discharge of gases leaving the stack, and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

Solution

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

This is a steady state problem without reaction.

$$\begin{array}{l|l} 4\ \text{lb}\ CO_2 & 1\ \text{lb mol}\ CO_2 \\ \hline & 44\ \text{lb}\ CO_2 \end{array} = 0.091\ \text{lb mol}\ CO_2$$



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

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

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

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

To check above values, substitute them in the total balance

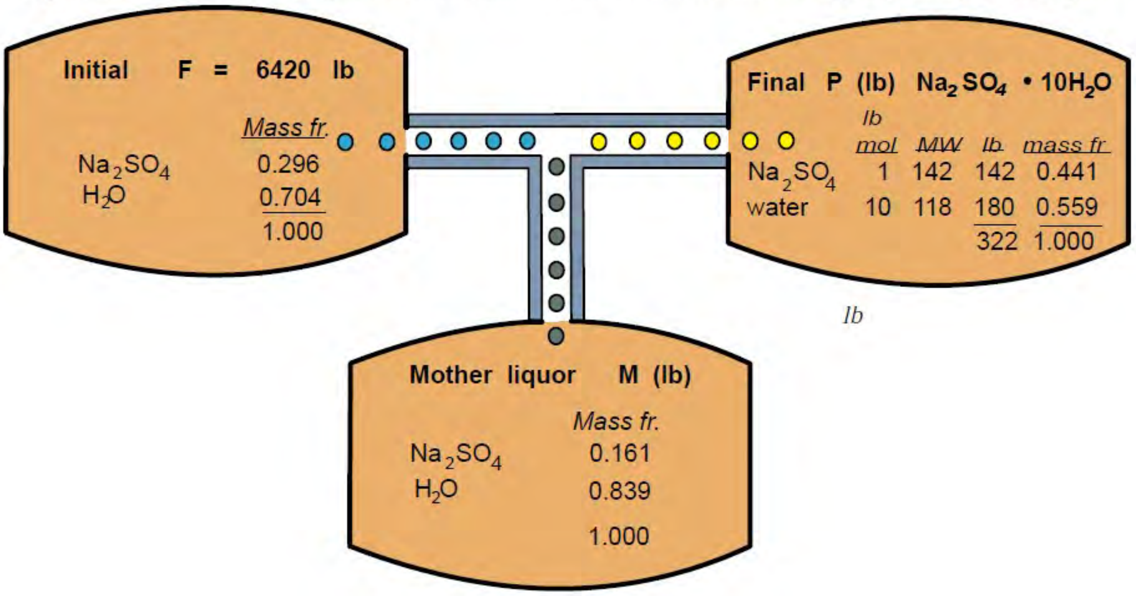
$$F + 0.091 = 8.00 = P = 8.00$$

Problem2

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

Solution

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



Basis : 6420 lb of 29.6 wt% Na_2SO_4 solution

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

Accumulation = In - out

Total: $P - F = 0 - M$ (1)

Na_2SO_4: $0.441P - 0.296\ F = 0 - 0.161\ M$ (2)

from (1) $P = 6240 - M$

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

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

Use H_2O balance as a check

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

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

Chapter 11

Material Balance Problems Involving MultipleUnits

- A **process flowsheet (flowchart)** is a graphical representation of a process. Aflowsheet describesthe**actualprocess**insufficientdetailthatyoucanuseittoformulatematerial (and energy)balances.

Figure 11.1a illustrates a serial combination of mixing and splitting stages. In a **mixer**, two ormore enteringstreamsofdifferent**compositionsarecombined**.Ina**splitter**,twoormorestreamsexit, all of which have the **same composition**. In a **separator**, the exit streams can be of **different compositions**.

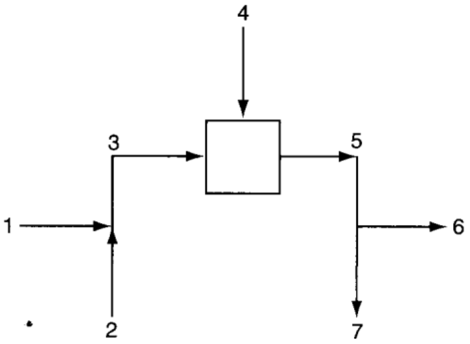


Figure 11.1a serial mixing and splitting in a system without reaction. Streams 1 plus 2 mixto form Stream 3, and Stream 5 is split into Streams 6 and7.

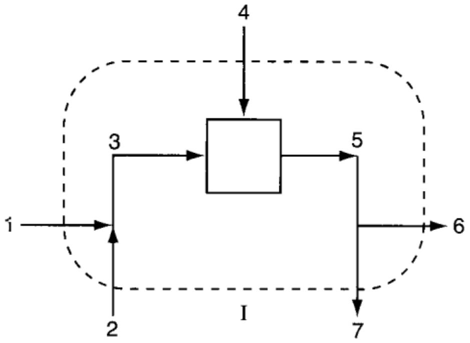


Figure 11.1b the dashed line I designates the boundary for overall material balances madeon the process in Figurel1.1a.

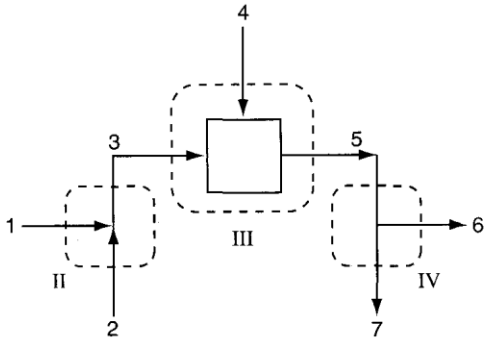


Figure 11.1c Dashed lines II, III and IV designate the boundaries for materialbalances around each of the individual units comprising the overallprocess.

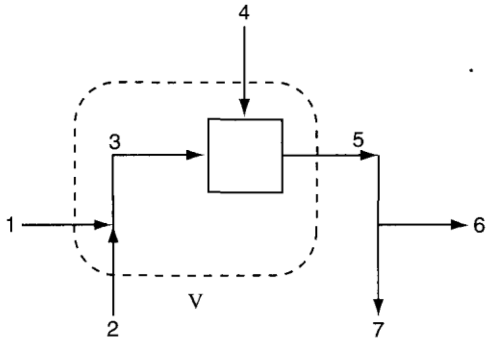


Figure 11.1d the dashed line V designates the boundary for material balances arounda system comprised of the mixing point plus the unit portrayed by thebox.

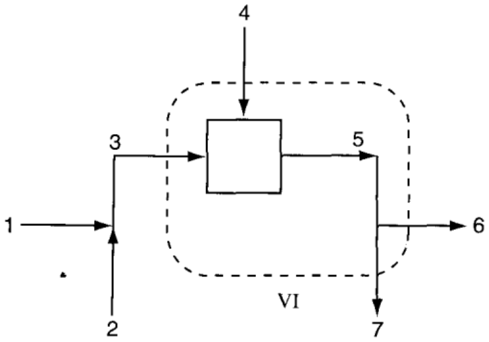


Figure 11.1e the dashed line VI designates the boundary for material balances about asystem comprised of the unit portrayed by the box plus thesplitter.

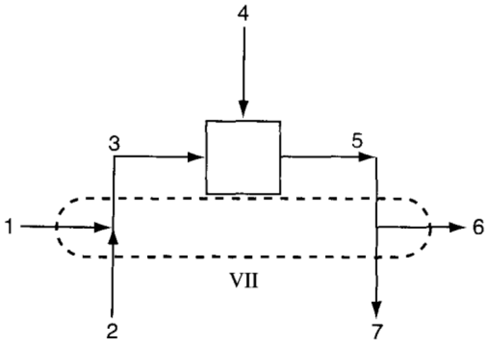


Figure 11.1f the dashed line VII designates the boundary for material balances about asystem comprised of the mixer plus thesplitter.

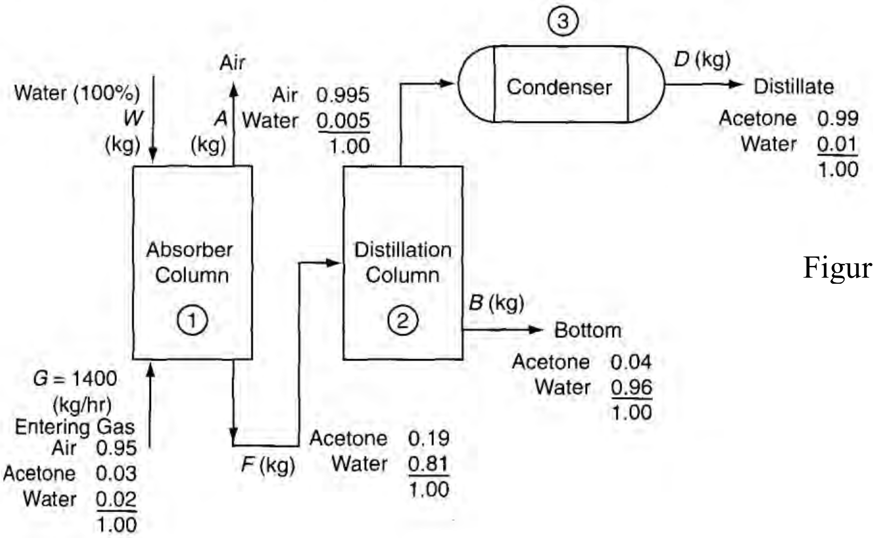
Example11.1

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 todesign an acetone recovery system having the flow sheet illustrated in Figure El1.1. All theconcentrations shownin El1.1of boththe 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 = 1400kg/hr.

Solution

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

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



FigureE11.1

The mass balances for **Unit 1 (AbsorberColumn)**

	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 = 157.7kg/hr

(**Check**) Use the total balance (AbsorberColumn).

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

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 = 186.1kg/hr

(**Check**) Use the total balance (Distillation &Condenser)

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

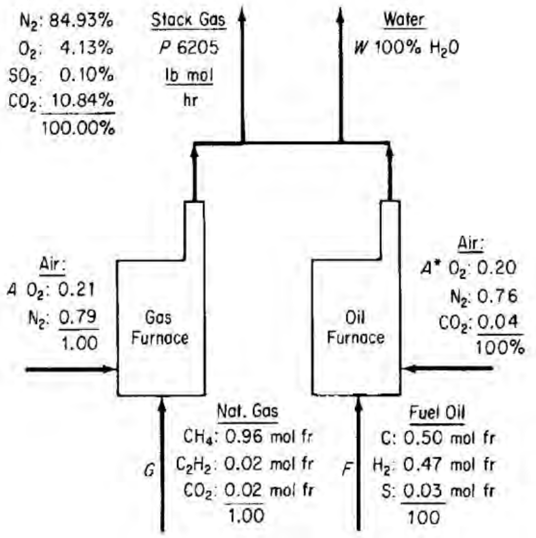
Note

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

	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)

Example11.2

In the face of higher fuel costs and the uncertainty of the supply of a particular fuel,many companiesoperatetwofurnaces,onefiredwithnaturalgasandtheotherwithfueloil.Thegas 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 FigureEl1.2.



FigureE11.2

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 lbmol/hr of natural gas were being consumed? The minimum heating load for the company when translated into the stack gas output was 6205 lbmol/hr of dry stack gas. The molecular weight of the fuel oil was 7.91 lb/lbmol, and its density was 7.578lb/gal.

Solution

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

Basis: 1 hr, so that P = 6205 lbmol

The **overall balances** for the **elements** are (in poundmoles)

	In		*Out*
2H:	$G(1.94) + F(0.47)$	=	$W(1)$
2N:	$A(0.79) + A^*(0.76)$	=	$6205(0.8493)$
2O:	$A(0.21) + A^*(0.20 + 0.04) + G(0.02)$	=	$6205(0.0413 + 0.001 + 0.1084) + W(\frac{1}{2})$
S:	$F(0.03)$	=	$6205(0.0010)$
C:	$G(0.96) + (2)(0.02) + 0.02 + F(0.50) + 0.04A^*$	=	$6205(0.1084)$

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 lbmol/hr and G = 499 lbmol/hr

Finally, the fuel oil consumption is

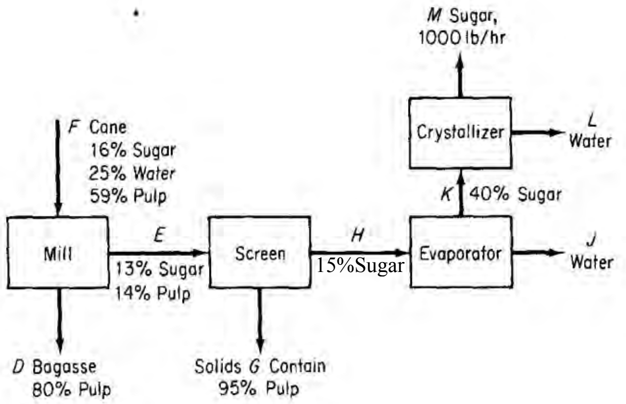
$$\frac{207\text{ lb mol}}{\text{hr}}\left|\frac{7.91\text{ lb}}{\text{lb mol}}\right|\frac{\text{gal}}{7.578\text{ lb}}\left|\frac{\text{bbl}}{42\text{ gal}}\right. = 5.14\text{ bbl/hr}$$

If the fuel oil reserves were only 560bbl,

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

Example11.3

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



FigureE11.3

(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 equationsare (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 = 1500lb.

Check using the totalflows: 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 variablesare:

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 Flis 1000 lb/hr, calculate the value of F2 and the composition ofF2.

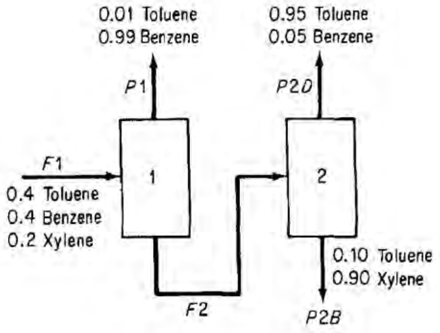


Figure SAT11P1

2. A simplified process for the production of SO_3 to be used in the manufacture of sulfuricacid isillustratedinFigureSAT11P2.Sulfurisburnedwith100%excessairintheburner,but for the reaction $S + O_2 \longrightarrow SO_2$, only 90% conversion of the S to SO_2 is achieved inthe burner. In the converter, the conversion of SO_2 to SO_3 is 95% complete. Calculate the kgof airrequiredper100kgofsulfurburned,andtheconcentrationsofthecomponentsinthe exit gas from the burner and from the converter in molefractions.

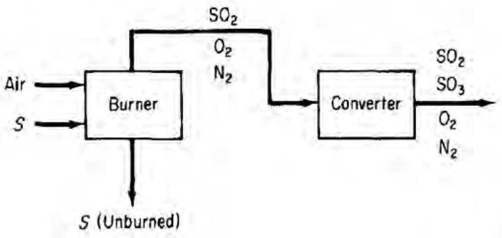


Figure SAT11P2

3. Intheprocessfortheproductionofpureacetylene,C_2H_2(seeFigureSAT11P3),pure methane (CH_4), and pure oxygen are combined in the burner, where the followingreactions occur:

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

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

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

   a. Calculate the ratio of the moles of O_2 to moles of CH_4 fed to theburner.
   b. Onthebasisof100lbmolofgasesleavingthecondenser,calculatehowmany pounds of water are removed by thecondenser.
   c. Whatistheoverallpercentageyieldofproduct(pure)C_2H_2,basedonthecarbonin the natural gas entering theburner?

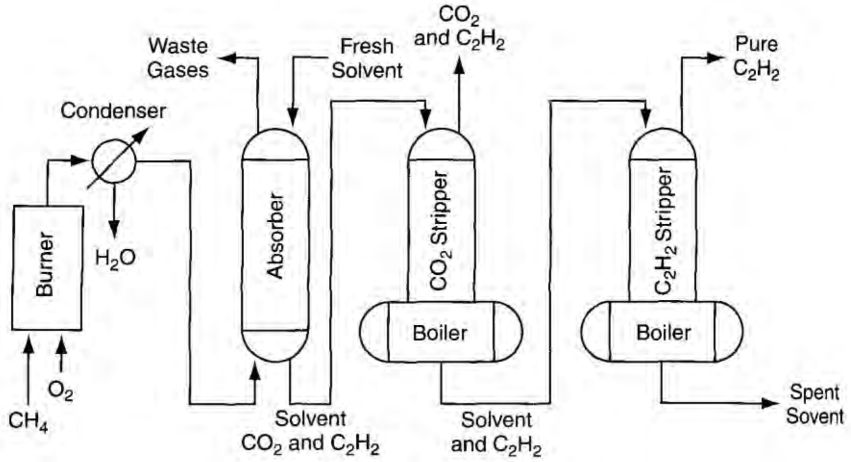


Figure SAT11P3

The gases from the burner are cooled in the condenser that removes all of the water. The analysisof the gases leaving the condenser is asfollows:

	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 areremoved withthesolvent.ThesolventfromtheabsorberissenttotheCO2stripper,wherealltheCO2is removed. The analysis of the gas stream leaving the top of the CO_2 stripper is asfollows:

	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 asa pureproduct.

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/lbS

	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 (ChapterEleven):

Problem1

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.

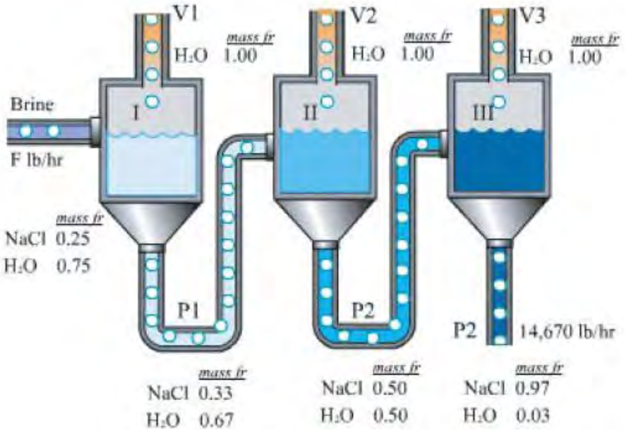
The data are shown in the accompanying figure.

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

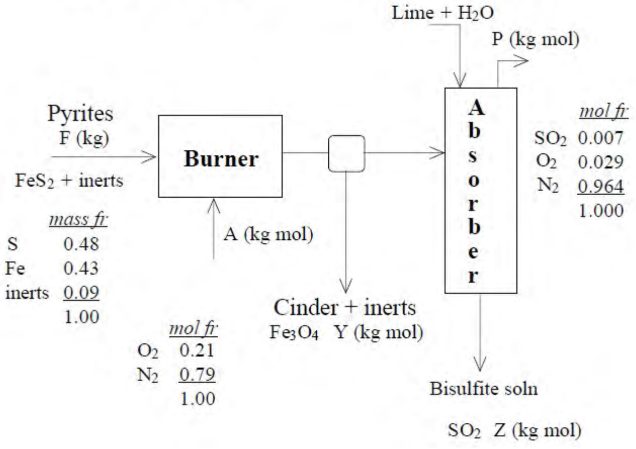
Problem2

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

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



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)

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

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

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

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

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

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

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

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

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

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

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

Accumulation = In - out + generation - consumption = 0

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

Chapter 12

Recycle, Bypass, Purge, and the Industrial Application of MaterialBalances

12.1 Introduction

- **Recycle** is fed back from a **downstream** unit to an **upstream** unit, as shown in Figure12.lc. The stream containing the recycled material is known as a **recyclestream**.
- Recycle system is a system that includes one or more recyclestreams.
- Becauseoftherelatively**highcost**ofindustrialfeedstocks,when**chemicalreactions**are involved in a process, **recycle** of **unused reactants** to the reactor can offersignificant **economic** savings for high-volume processing systems. **Heat recovery** within aprocessing unit (**energy recycle**) reduces the overall energy consumption of theprocess.

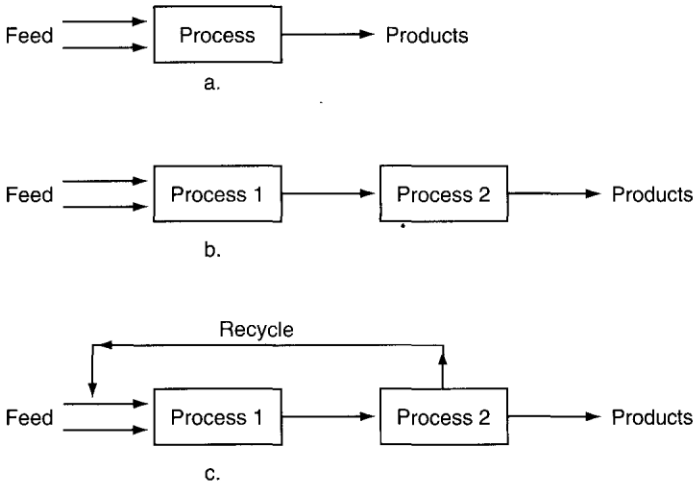


Figure 12.1: Figure 12.la shows a single unit with serial flows. Figure 12.b showsmultiple units but still with serial flows. Figure 12.lc shows the addition ofrecycle.

12.2 Recycle without ChemicalReaction

- ❖ **Recycle**ofmaterialoccursinavarietyofprocessesthatdo**not**involvechemicalreaction, including **distillation**, **crystallization**, and **heating and refrigeration**systems.
- ❖ Examine Figure 12.2. You can write material balances for several different systems, **four**of whichareshownbydashedlinesinFigure12.2**(Overallbalance1,Mixerbalance2, Process balance 3 & Separator balance4)**.
- ❖ The **fresh feed** enters the overall system and the **overall or net product** isremoved.
- ❖ The **total (gross) feed** enters the process and the **gross product** isremoved.

- Inaddition,youcanmakebalances(notshowninFigure12.2)about**combinationsof subsystems**,suchasthe**processplustheseparator**(**3plus4**),orthe**mixingpointplus the process** (**2 plus3**).

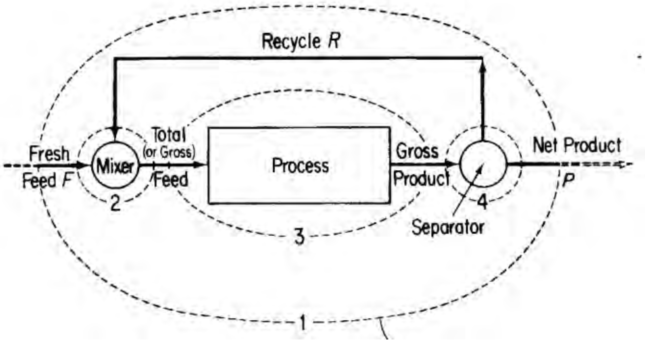


Figure 12.2 Process with recycle (the numbers designate possible system boundaries forthe materialbalances).

Example12.1

FigureE12.laisaschematicofaprocessfortheproductionofflakeNaOH,whichisusedin hous eholds t o clear plugged drains in the plumbing (e.g.,Drano).

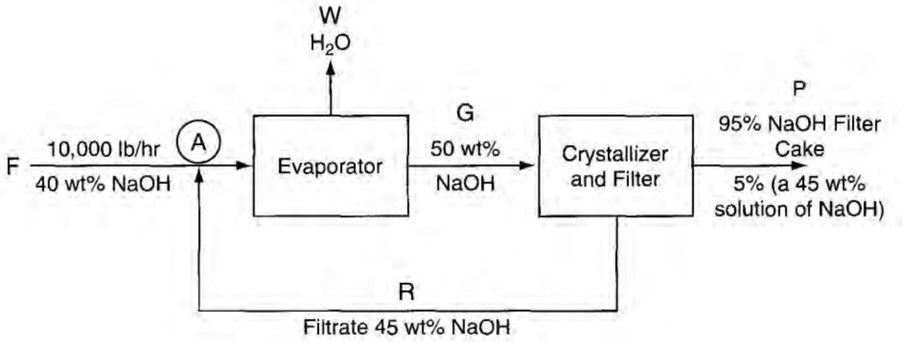


Figure E12.1a

Thefreshfeedtotheprocessis10,000lb/hrofa40%aqueousNaOHsolution.Thefreshfeedis combinedwiththerecycledfiltratefromthecrystallizer,andfedtotheevaporatorwherewateris removedtoproducea50%NaOHsolution,whichinturnisfedtothecrystallizer.Thecrystallizer produces a filter cake that is 95% NaOH crystals and 5% solution that itself consists of 45%NaOH. The filtrate contains 45%NaOH.

a. Youareaskedtodeterminetheflowrateofwaterremovedbytheevaporator,andthe recycle rate for thisprocess.
b. Assume that the same production rate of NaOH flakes occurs, but the filtrate is notrecycled. Whatwouldbethetotalfeedrateof40%NaOHhavetobethen?Assumethattheproduct solution from the evaporator still contains 50%NaOH.

Solution

Open, steady-stateprocess.

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

The unknowns are W, G, P, andR.

Overall NaOHbalance

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

Overall H_2Obalance

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

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

The total amount of NaOH exiting with Pis [(0.95) + (0.45)(0.05)](4113) =

4000lbNaOH balance on the**crystallizer** $0.5\,G = 4000 + 0.45R$

H_2O balance on the**crystallizer** $0.5\,G = 113 + 0.55R$

(or use the total balance G = R +4113)

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

b. FigureE12.lb.

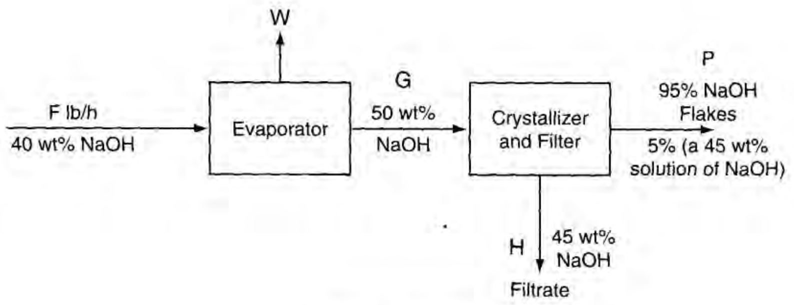


Figure E12.1b

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

The unknowns are now F, W, G, andH.

NaOH balance on the**crystallizer**

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

H_2O balance on the**crystallizer**

$$0.5G = [(0.05)\,(0.55)\,(4113)] + 0.55H$$
$$H = 38{,}870\text{lb}$$

Overall NaOHbalance

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

☒ Notethat**withoutrecycle**,thefeedratemustbe**5.37timeslarger**than**withrecycle**to produce the same amount ofproduct.

12.3 Recycle with ChemicalReaction

☒ Themostcommonapplicationofrecycleforsystemsinvolvingchemicalreactionisthe recycleofreactants,anapplicationthatisusedtoincreasetheoverallconversionina r eactor. Figure 12.3 shows a simple example for thereaction

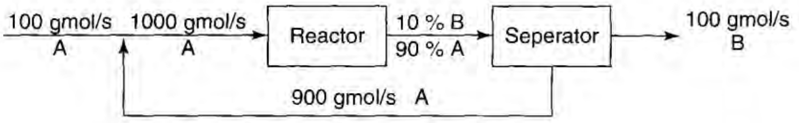


Figure 12.3 A simple recycle system with chemicalreaction.

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

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

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

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

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

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

- Two types of **conversion** when reactionsoccur:

1. **Overall fractionconversion:**

mass(moles)ofreactantinthefreshfeed-mass(moles)ofreactantintheoutputoftheoverallprocessmass (moles) of

reactant in the freshfeed

2. **Single - pass (“once - through”) fractionconversion:**

mass(moles)ofreactantfedintothereactor-

mass(moles)ofreactantexitingthereactormass(moles)ofreactantfedint othereactor

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