Overall mass balances:

$$V: \quad 0.20(98) = 0 \quad + 0.96P \qquad \text{(a)}$$

$$H_2O: \quad 0.80(98) = (1.0)W + 0.04P \qquad \text{(b)}$$

$$\text{Total:} \quad 98 = W + P \qquad \text{(c)}$$

Observe that V is a tie component so that P can be calculated directly in Eq. (a): P = 20.4 lb, and W can be calculated from Eq. (c).

$$W = 98 - 20.4 = 77.6 \text{ lb}$$

Steps 7, 8, and 9 (Continued) To determine the recycle stream R, we need to make a balance that involves the stream R. Either (a) balances around the centrifuge or (b) balances around the filter will do. The latter are easier to formulate since the mixing of R and F does not have to be calculated.

Total balance on filter:

$$\begin{aligned} C &= R + P \\ C &= R + 20.4 \end{aligned} \qquad \text{(d)}$$

Component V balance on filter:

$$\begin{aligned} C\omega_C &= R\omega_R + P\omega_P \\ 0.6C &= 0.286R + 0.96(20.4) \end{aligned} \qquad \text{(e)}$$

Solving Eqs. (d) and (e), we obtain R = 23.4 lb/hr.

Step 10 Check the value of R using a material balance around the centrifuge.

2.6-2 Recycle in Processes with Chemical Reaction

Now let us turn to recycle problems in which a chemical reaction occurs. Recall from Sec. 1.9 that not all of the limiting reactant necessarily reacts in a process. Do you remember the concept of conversion as discussed in Sec. 1.9? Two bases for conversion are used in describing a process; examine Fig. 2.18.

(a) ***Overall fraction conversion:***

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

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

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

When the fresh feed consists of more than one material, the conversion must be stated for a single component, usually the limiting reactant, the most expensive reactant, or some similar compound.

Note the distinction between *fresh feed* and *feed to the process*. The feed to the process itself is made up of two streams, the fresh feed and the recycled material.

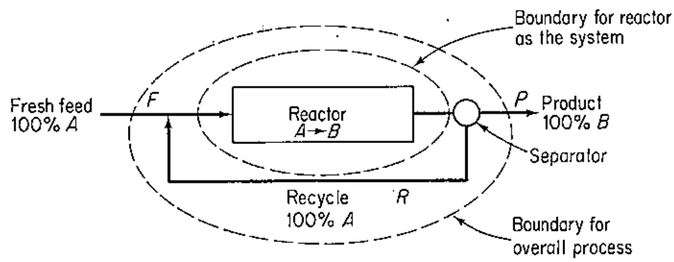

Figure 2.18 Recycle problem.

The gross product leaving the process is separated into two streams, the net product and the material to be recycled. In some cases the recycle stream may have the same composition as the gross product stream, while in other instances the composition may be entirely different depending on how the separation takes place and what happens in the process. Suppose that you are given the data that 30% of the A is converted to B on a single pass through the reactor, as illustrated in Fig. 2.18, and are asked to calculate the value of R, the recycle on the basis of 100 moles of fresh feed, F. We will make a balance for A with the reactor as the system.

Recall from Eq. (2.1) that for a specific chemical compound the steady-state material balance for a reactor is (the accumulation term in zero)

$$\left\{\begin{matrix}\textbf{input}\\ \textbf{through}\\ \textbf{system}\\ \textbf{boundary}\end{matrix}\right\} - \left\{\begin{matrix}\textbf{output}\\ \textbf{through}\\ \textbf{system}\\ \textbf{boundary}\end{matrix}\right\} + \left\{\begin{matrix}\textbf{generation}\\ \textbf{within the}\\ \textbf{system}\end{matrix}\right\} - \left\{\begin{matrix}\textbf{consumption}\\ \textbf{within the}\\ \textbf{system}\end{matrix}\right\} = 0 \qquad (2.12)$$

Reactants are consumed and products are generated. If a reaction takes place within the system, you must be given (or look up) information about the reaction stoichiometry and extent of reaction. Or, perhaps the question is to calculate the extent of conversion given some of the process data. In any case, the fraction of feed converted to products is always an essential additional piece of information that helps determine values of the terms in Eq. (2.12).

Let us examine how to apply Eq. (2.12) for a recycle reactor such as shown in Fig. 2.18, in which A is converted to B. How much A exits the reactor itself? The unconverted A is 70% of the A that enters the reactor. No A occurs in the P stream. The system is the reactor and the basis is 100 moles of fresh feed. The A balance is

$$\underbrace{[(1.0)(100) + (1.0)R]}_{\textit{Input of A}} - \underbrace{[(1.0)R + 0(P)]}_{\textit{Output of A}} - \underbrace{[0.30(100 + R)]}_{\textit{Consumption of A}} = 0$$

or

$$\underset{\textit{moles of A unconverted}}{0.70(100 + R)} = \underset{\textit{moles of A leaving the reactor}}{R}$$

$$R = 233 \text{ moles}$$

Note that in Fig. 2.18 all the A was recycled for simplicity of illustration of the principle, but such may not be the case in general. Nevertheless, Eq. (2.12) still applies.

The single-pass (mole) balance on A provides the crucial information to evaluate R. Will an A balance, or total balance, for the overall process enable you to solve for R? Try one and see why not. What is the overall fraction conversion of A for the entire process? Does that information help you solve for R?

EXAMPLE 2.26 Recycle with a Reaction Occurring

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 Fig. E2.26a, what percent conversion of glucose results on one pass through the reactor when the exit stream/recycle ratio in moles is equal to 8.33? The reaction is

$$\underset{\text{d-glucose}}{C_6H_{12}O_6} \longrightarrow \underset{\text{d-fructose}}{C_6H_{12}O_6}$$

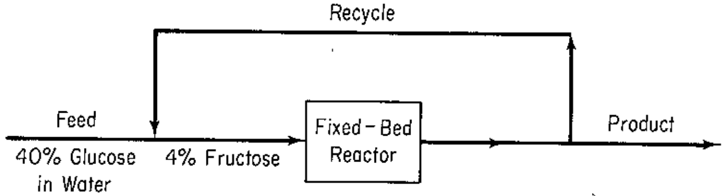

Figure E2.26a

Solution

We have a steady-state process with a reaction occurring.

Steps 1, 2, and 3 Figure E2.26b includes all the known and unknown values of the variables using appropriate notation (W stands for water, G for glucose, and F for fructose in the second position of the mass fraction subscripts). Note that the recycle stream and product stream have the same composition and consequently the same mass fraction symbols are used in the diagram for each stream.

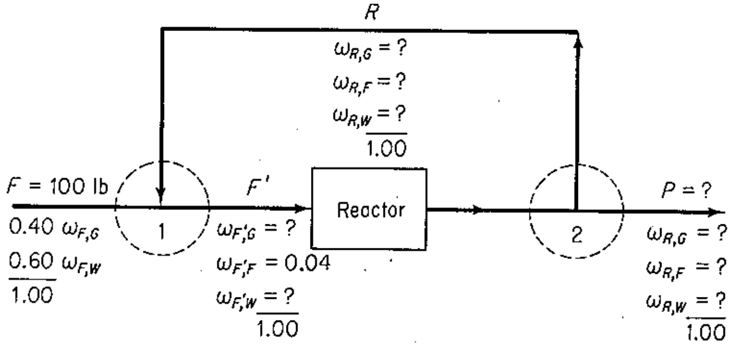

Figure E2.26b

Step 4 Pick as a basis F = 100 lb.

Steps 5 and 6 The sum of the mass fractions is one in each stream so that the unknown compositions can be picked to be $\omega_{F',G}$, $\omega_{R,G}$, $\omega_{R,W}$, and the unknown stream values are F' and P ($R = P/8.33$). Let f be the fraction conversion in the reactor. Three balances each can be make about the mixing point 1, the reactor, and the separation point 2. Not all the balances will be independent, but sufficient independent balances should exist to solve this problem. We can check as we proceed with the calculations rather than going through an extensive analysis at the beginning.

Steps 7, 8, and 9 We will start with overall balances, as they are the easiest to write.

Overall:

$$\textit{Total}:\quad 100 = P$$

Consequently,

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

No water is generated or consumed, hence

$$\textit{Water}:\quad 100\,(0.60) = P\,(\omega_{R,W}) = 100\omega_{R,W}$$

$$\omega_{R,W} = 0.60$$

We now have left three unknown values of the variables plus f.

Mixing Point 1:

$$\textit{Total}:\quad 100 + 12 = F' = 112$$

$$\textit{Glucose}:\quad 100(0.40) + 12(\omega_{R,G}) = 112(\omega_{F',G})$$

$$\textit{Fructose}:\quad 0 + 12(\omega_{R,F}) = 112(0.04)$$

or

$$\omega_{R,F} = 0.373$$

Also, because $\omega_{R,F} + \omega_{R,G} + \omega_{R,W} = 1$,

$$\omega_{R,G} = 1 - 0.373 - 0.600 = 0.027$$

and then from the glucose balance,

$$\omega_{F',G} = 0.360$$

Reactor Plus Separator 2:

$$\textit{Total}:\quad F' = 12 + 100 = 112 \qquad \text{(redundant equation)}$$

Glucose:

$$\underbrace{F'\omega_{F',G}}_{\textit{In}} - \underbrace{(R + P)\omega_{R,G}}_{\textit{Out}} - \underbrace{fF'\omega_{F',G}}_{\textit{Consumed}} = 0$$

$$112(0.360) - 112(0.027) - f(112)(0.360) = 0$$

$$f = 0.93$$

EXAMPLE 2.27 Recycle with a Reaction Occurring

Refined sugar (sucrose) can be converted to glucose and fructose by the inversion process.

$$\underset{\text{Sucrose}}{C_{12}H_{22}O_{11}} + H_2O \longrightarrow \underset{d\text{-Glucose}}{C_6H_{12}O_6} + \underset{d\text{-Fructose}}{C_6H_{12}O_6}$$

The combined quantity glucose/fructose is called inversion sugar. If 90% conversion of sucrose occurs on one pass through the reactor, what would be the recycle stream flow per 100 lb of sucrose solution entering the process shown in Fig. E2.27a? What is the concentration of inversion sugar (I) in the recycle stream and in the product stream? The concentrations of components in of the recycle stream and product stream are the same.

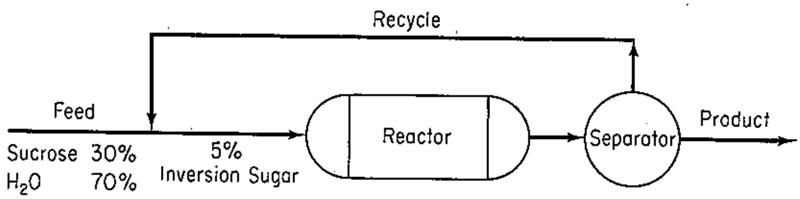

Figure E2.27a

Solution

Steps 1, 2, and 3 First we need to enter the concentrations and stream flows on the diagram. See Fig. E2.27b. (W stands for water, S for sucrose, and I for inversion sugar in the mass fraction subscripts.)

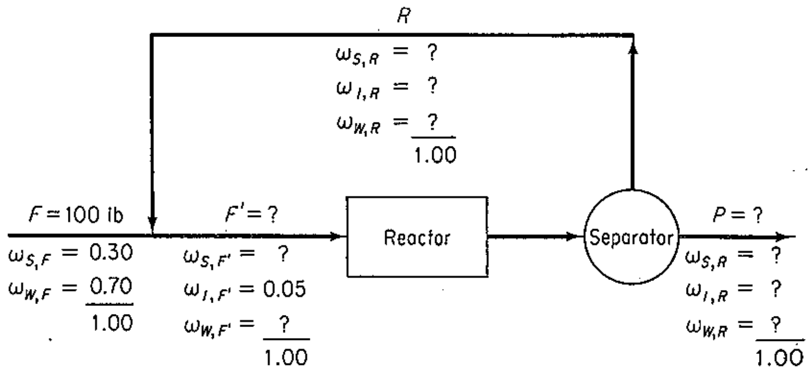

Figure E2.27b

Step 4

Basis: $F = 100$ lb

Steps 5 and 6 Keeping in mind that the sum of the mass fractions in each stream is unity, we have six unknown values of the variables, say $\omega_{S,F'}$, $\omega_{S,R}$, $\omega_{I,R}$, R, F', and P.

Steps 7, 8, and 9 Let us start with the necessary balances. Only the total balance in the overall balance is directly useful because the S and I balances involve the generation and consumption terms in Eq. (2.12).

Overall:

$$\text{Total: } 100 = P$$

Mixing Point:

Total:	$100 + R = F'$	(a)
Sucrose:	$100(0.30) + R\omega_{S,R} = F'\omega_{S,F'}$	(b)
Inversion:	$0 + R\omega_{I,R} = F'(0.05)$	(c)

Reactor plus Separator To avoid calculating the reactor output stream properties, we will make the system the reactor plus the separator. First we need to calculate the pounds of water consumed in the reaction per pound of sucrose consumed in the reaction.

1 mole sucrose uses 1 mole water

$$\frac{1 \text{ mol } W}{1 \text{ mol } S} \left| \frac{1 \text{ mol } S}{342.35 \text{ lb } S} \right| \frac{18 \text{ lb } W}{1 \text{ mol } W} = 0.0526 \frac{\text{lb } W}{\text{lb } S}$$

Total: $F' = R + P = R + 100$ [redundant equation to (a)]

Water: *In* — *Out* — *Consumed* (d)

$$F'(1 - 0.05 - \omega_{S,F'}) - (R + 100)(1 - \omega_{S,R} - \omega_{I,R}) - (F'\omega_{S,F'})(0.90)(0.0526) = 0$$

Sucrose: *In* — *Out* — *Consumed* (e)

$$F'\omega_{S,F'} - (R + 100)\omega_{S,R} - (F'\omega_{S,F'})(0.90) = 0$$

We have five independent equations (a)–(e) that can be solved for the five unknown values of the variables listed in steps 5 and 6; the value of P is given by the overall total materials balance. Either by successive substitution of Eqs. (a)–(e) into each other or by use of a computer program (see Sec. 2.7), you can find

$$R = 20.9 \text{ lb}$$

$$\omega_{I,R} = \omega_{I,P} = 0.279$$

2.6-3 Bypass and Purge

Two additional commonly encountered types of process streams are shown in Fig. 2.19.

- **(a)** A **bypass** stream—one that skips one or more stages of the process and goes directly to another stage
- **(b)** A **purge** stream—a stream bled off to remove an accumulation of inerts or unwanted material that might otherwise build up in the recycle stream

A bypass stream is 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.

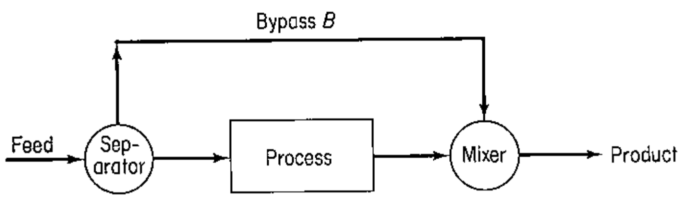

Figure 2.19a