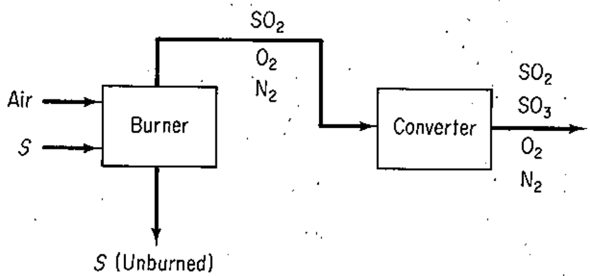
2. A simplified process for the production of SO_3 to be used in the manufacture of sulfuric acid is illustrated in the figure. Sulfur is burned with 100% excess air in the burner, but for the reaction $S + O_2 \rightarrow SO_2$, only 90% conversion of the S to SO_2 is achieved. In the converter, the conversion of SO_2 to SO_3 is 95% complete. Calculate the lb of air required per 100 lb of sulfur burned, and the concentration in mole fraction or percent of the exit gas from the burner and from the converter.



2.6 RECYCLE, BYPASS, AND PURGE CALCULATIONS

Your objectives in studying this section are to be able to:

1. Draw a flow diagram for problems involving recycle, bypass, and purge.
2. Apply the 10-step strategy to solve steady-state problems (with and without chemical reaction) involving recycle, and/or bypass, and/or purge streams.
3. Solve problems in which a modest number of interconnected units are involved by making appropriate balances.
4. Use the overall conversion and single-pass (once-through) conversion concepts to solve recycle problems involving reactors.
5. Explain the purpose of a recycle stream, a bypass stream, and a purge stream.

Recycle stream is a term denoting a process stream that conducts material exiting or downstream from a unit back to the inlet or upstream of the same unit. For example, in a reactor, unreacted material is separated from the reactor products and *fed back* and joins with a stream of reactants that enter the reactor. Examine Figure 2.16. In Figure 2.4 you can observe the recycle of C_6H_6 from the settler back to the evaporator. As another example, in planning long space missions, all the food and water will have to be provided from stores on board the spacecraft. Figure 2.17 shows the recycle of O_2 and water.

Many industrial processes employ recycle streams. In some drying operations, the humidity in the air is controlled by recirculating part of the wet air that leaves

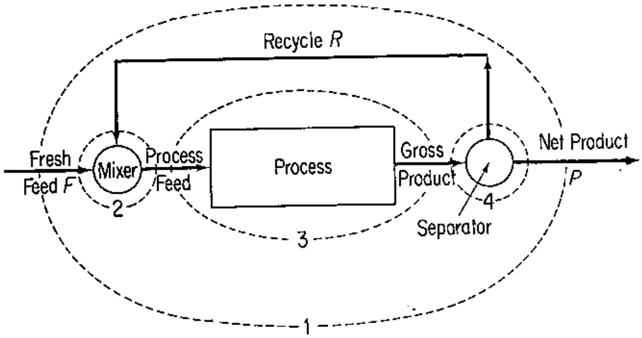


Figure 2.16 Process with recycle (the numbers designate possible system boundaries for the material balances—see the text).

the dryer. In chemical reactions, exit catalyst is returned to the reactor for reuse. Another example of the use of recycling is in fractionating columns where part of the distillate is refluxed through the column to maintain the quantity of liquid within the column.

Do not let recycle streams confuse you. The steps in the analysis and solution of material balance problems involving recycle are the same as described in Table 2.4. With a little practice in solving problems involving recycle, you should experience little difficulty in solving recycle problems in general. The essential point you should grasp with respect to recycle calculations in this chapter is that the processes such as shown in Fig. 2.4 or 2.16 are in the *steady state*.

No buildup or depletion of material takes place inside the process or in the recycle stream.

The values of F, P, and R in Fig. 2.16 are *constant*. Unsteady-state processes such as startup and shutdown are discussed in Chapter 6.

2.6-1 Recycle in Processes without Chemical Reaction

The strategy listed in Table 2.4 is the strategy to be used in solving recycle problems. You can make component and total material balances for each subsystem as discussed in Sec. 2.5, as well as component and total balances for the overall process. Not all of the equations so formulated will be independent, of course. Depending on the information available concerning the amount and composition of each stream, you can determine the amount and composition of the unknowns. If tie components are available, they often simplify the calculations.

Examine Fig. 2.16. Material balances can be written for several different systems, four of which are shown by dashed lines in Fig. 2.16:

(a) About the entire process including the recycle stream, as indicated by the dashed lines (marked 1 in Fig. 2.16)

(b) About the junction point at which the fresh feed is combined with the recycle stream (marked 2 in Fig. 2.16)

(c) About the process only (marked 3 in Fig. 2.16)

(d) About the junction point at which the gross product is separated into recycle and net product (marked 4 in Fig. 2.16)

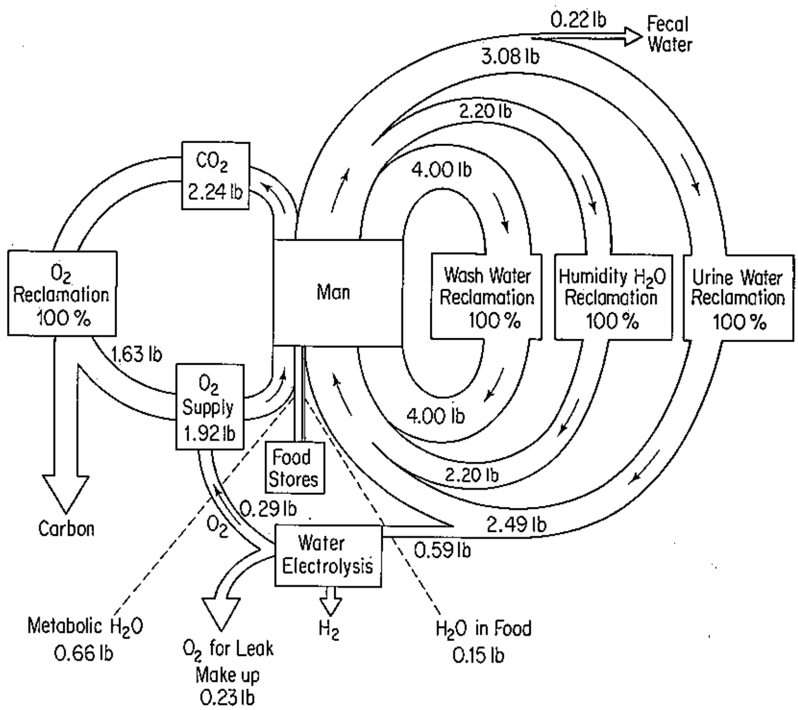


Figure 2.17 Water and oxygen recycle in a space vehicle.

In addition, balances can be made about combinations of subsystems, such as the process plus the separator (3 + 4). Only three of the four balances (a)–(d) are independent for one component. However, balance 1 will not include the recycle stream, so that the balance will not be directly useful in calculating a value for the recycle R. Balances 2 and 4 do include R. You could write a material balance for the combination of subsystems 2 and 3 or 3 and 4 and include the recycle stream.

EXAMPLE 2.23 Recycle

Examine the flow sheet in Fig. E2.23, a flowsheet that contains recycle streams. What is the maximum number of independent material balances that can be written for the system if each stream contains three components, ethanol, acetone, and methanol?

Solution

Three material balances (corresponding to three components) can be written each for units A, B, and C, for a total of 9. Any other material balance, such as one for the combined subsystem A and B or A and C, can be obtained by appropriate combination of the nine component material balances. However, all nine of the material balances may not be independent. How many would be independent would depend on the specific values of the flow streams and concentrations that are known and unknown.

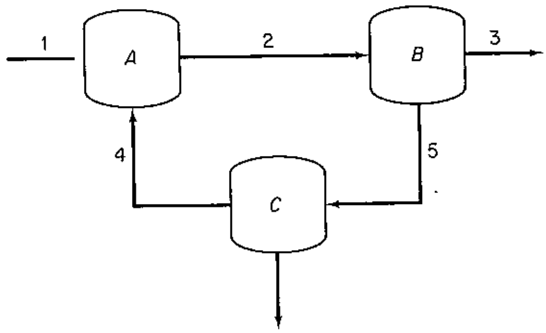


Figure E2.23

EXAMPLE 2.24 Recycle without Chemical Reaction

A distillation column separates 10,000 kg/hr of a 50% benzene–50% toluene mixture. The product D recovered from the condenser at the top of the column contains 95% benzene, and the bottoms W from the column contain 96% toluene. The vapor stream V entering the condenser from the top of the column is 8000 kg/hr. A portion of the product from the condenser is returned to the column as reflux, and the rest is withdrawn for use elsewhere. Assume that the compositions of the streams at the top of the column (V), the product withdrawn (D), and the reflux (R) are identical because the V stream is condensed completely. Find the ratio of the amount refluxed to the product withdrawn (D).

Solution

This is a steady-state problem without reaction occurring.

Steps 1, 2, and 3 See Fig. E2.24 for the known data, symbols, and other information.

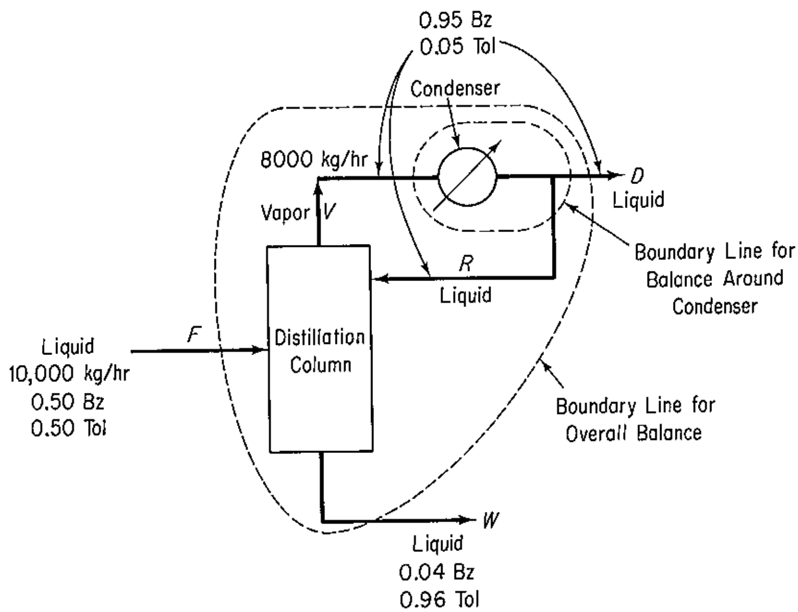


Figure E2.24

Step 4 Select a basis of 1 hr (equal to $F = 10{,}000$ kg).

Steps 5 and 6 All the compositions are known and three stream flows, D, W, and R, are unknown. No tie components are evident in this problem. Two component material balances can be made for the still and two for the condenser. Presumably three of these are independent; hence the problem has a unique solution. We can check as we proceed. A balance around either the distillation column or the condenser would involve the stream R. An overall balance would involve D and W but not R.

Steps 7, 8, and 9 What balances to select to solve for R is somewhat arbitrary. We will choose to use overall balances first to get D (and W), and then use a balance on the condenser to get R. Once D is obtained, R can be obtained by subtraction.

Overall Material balances:

Total material:

$$F = D + W$$

$$10{,}000 = D + W \tag{a}$$

Component (benzene):

$$F\omega_F = D\omega_D + W\omega_w$$

$$10{,}000(0.50) = D(0.95) + W(0.04) \tag{b}$$

Solving (a) and (b) together, we obtain

$$5000 = (0.95)(10{,}000 - W) + 0.04W$$

$$W = 4950 \text{ kg/hr}$$

$$D = 5050 \text{ kg/hr}$$

Balance around the condenser:

Total material:

$$V = R + D$$

$$8000 = R + 5050$$

$$R = 2950 \text{ kg/hr} \tag{c}$$

$$\frac{R}{D} = \frac{2950}{5050} = 0.58$$

Would the benzene or toluene balances on the condenser yield additional information to that obtained from the total balance, Eq. (c)? Write the balances down and check to see if they are redundant with Eq. (c).

EXAMPLE 2.25 Recycle without Chemical Reaction

The manufacture of such products as penicillin, tetracycline, vitamins, and other pharmaceuticals, as well as photographic chemicals, dyes, and other fine organic compounds, usually requires separating the suspended solids from their mother liquor by centrifuging, and then drying the wet cake. A closed-loop system (see Fig. E2.25a) for centrifuge unloading, drying, conveying, and solvent recovery is comprised of equipment especially designed for handling materials requiring sterile and contamination-free conditions.

Given the experimental measurements on the pilot plant equipment outlined in Fig. E2.25a, what is the lb/hr of the recycle stream R?

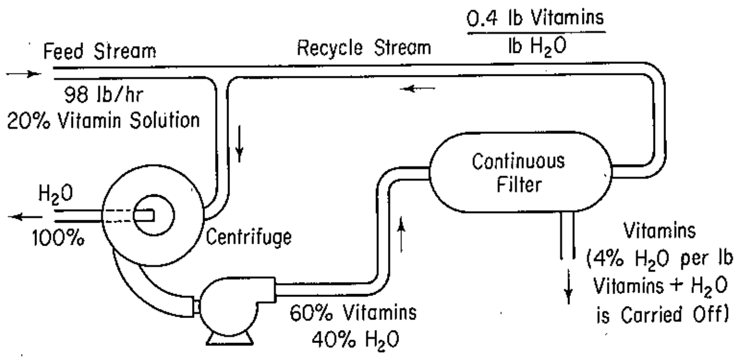


Figure E2.25a

Solution

Steps 1, 2, and 3 Figure E2.25a should be simplified with all the flows and compositions placed on it. Examine Fig. E2.25b. We computed the weight fraction of V in R from the data given in Fig. E2.25a. On the basis of 1 lb of water, the recycle stream contains (1.0 lb of H_2O + 0.4 lb of V) = 1.4 lb total. The recycle stream composition is

$$\frac{0.4 \text{ lb } V}{1 \text{ lb } H_2O} \left| \frac{1 \text{ lb } H_2O}{1.4 \text{ lb solution}} \right. = 0.286 \text{ lb } V/\text{lb solution}$$

so that there is 0.714 lb H_2O/lb solution.

Step 4 Pick as a basis 1 hr so that F = 98 lb.

Steps 5 and 6 We have four unknown values of variables, W, C, P, and R, and can make two component material balances on each of two units of equipment; hence the problem has a unique solution.

Steps 7, 8, and 9 Probably the most efficient procedure in solving this problem is to make overall mass balances to calculate W and P, and then write mass balances about one of the units to calculate R.

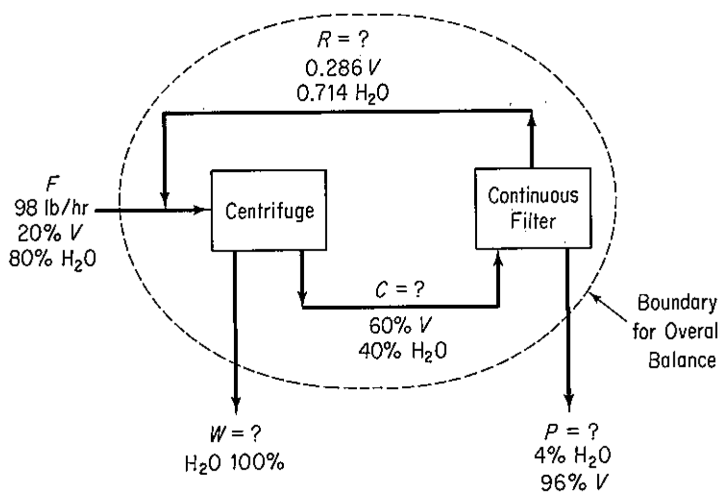


Figure E2.25b

Overall mass balances:

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

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

$$\text{Total:} \quad 98 = W + P \tag{c}$$

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:

$$\begin{aligned} C &= R + P \\ C &= R + 20.4 \end{aligned} \tag{d}$$

Component V balance on filter:

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

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.