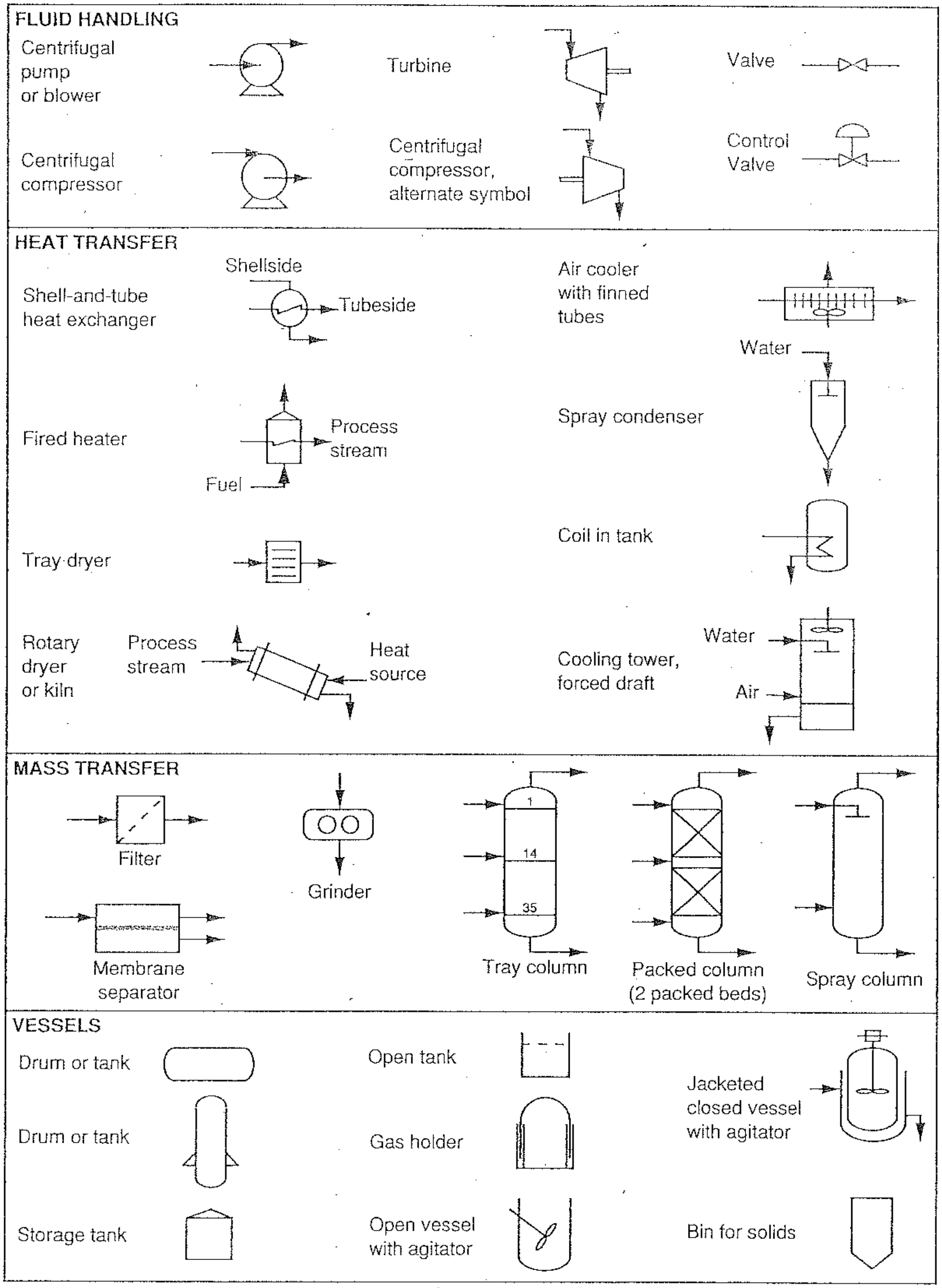

Figure 2.5 Typical symbols used in process flow diagrams and piping and instrumentation diagrams

Since a few homework problems in this book include the construction of some simple process flow diagrams, the following procedure is suggested for that construction:

IMPORTANT SUMMARY!

Steps for Constructing a Process Flow Diagram

1. **Identify streams** entering the process ("feed streams") and exiting the process ("product streams").
2. **Identify key process steps and major equipment items** needed for the process.
3. **Determine the symbol** to be used for each major piece of equipment.
4. **Draw the symbols on the flow diagram** and connect them with appropriate stream lines. The general flow of the diagram should be from left to right.
5. **Label major pieces of equipment,** usually using abbreviations of a few letters and numbers (e.g., P-2 for pump #2 and HX-15 for heat exchanger #15). For this introductory course, full names can also be used (as in Figure 2.6).
6. **Label streams** with a number and/or letter (e.g., 10, A, or 10A).
7. **Include a stream table,** if desired, that contains information about each stream (described below).

EXAMPLE 2.2

A common practice when performing open-heart surgery is to divert the patient's blood through a "cardiopulmonary bypass" system or "heart-lung machine." The following configuration is an example:

A. The blood from the main veins (called "venous blood") is caused to leave the body through plastic tubing.

B. An intravenous (IV) line adds anticoagulant drugs to the tubing.

C. The blood passes through a centrifugal pump, which provides the flow of the blood through the system.

D. The blood passes through the coil side of a coil-in-tank-type cooler to cool the patient's blood (to reduce oxygen requirements). Ice water enters and leaves the tank to supply the cooling.

E. The cooled blood passes through the tube side of a shell-and-tube mass exchanger (called an oxygenator and is very similar to a shell-and-tube heat exchanger). A gas stream passes through the shell side of the oxygenator. In the oxygenator, oxygen passes through the walls of the tubes and enters the blood, where the following reactions occur:

$$Hb + 4O_2 \rightarrow Hb(O_2)_4$$
$$H_2CO_3 \rightarrow H_2O + CO_2$$

Hb represents "hemoglobin," the protein inside red blood cells that carries the oxygen. The carbon dioxide passes from the blood through the walls of the tubes and into the gas stream. Thus, when the gas stream enters the oxygenator, it consists mainly of oxygen, and when it leaves, it contains much more carbon dioxide than when it entered.

F. The blood leaving the oxygenator passes through a filter, which traps air bubbles and removes them from the blood to form an air stream output from the filter.

G. The blood (now called "arterial blood") returns to the patient and enters the main artery.

Construct a pictorial process flow diagram using the symbols in Figure 2.5 (without a stream table).

SOLUTION

The solution is shown as an example of biomedical engineering in Figure 2.6c (also see Figure 2.7c).

READING QUESTIONS

1. In the definition of a chemical process, what is the purpose of the equipment and conditions used in the process?

2. How does a continuous process differ from a batch process?

3. What distinguishes a process as being steady-state?

4. How does a PFD differ from a block diagram?

5. In our example of making chemical C from A and B, we formulated an automated process (Fig. 2.2) to replace a laboratory scheme (Fig. 2.1). What equipment in the automated process replaced each of the following laboratory equipment items?

test tubes
laboratory burner
reaction vessel
distillation apparatus

HOMEWORK PROBLEMS

1. Classify the following as either *batch* or *continuous* processes, and indicate whether each is a *steady-state* or an *unsteady-state* process:

   a. A "surge tank" is used when a liquid is coming from one part of a process at a variable rate and we want to provide a reservoir of that liquid to feed another part of the process. Thus, a surge tank continuously (but at varying flow rates) receives liquid from an incoming stream and also loses that same liquid continuously (also possibly at changing flow rates) in an outgoing stream. The volume in the tank also changes with time.

   b. We bake a cake by mixing together the ingredients in a cake pan, placing the pan and mixture in an oven for a prescribed amount of time, and then removing the cake to cool down.

   c. A company produces latex paint base by mixing together the ingredients for the paint. All flow rates are held constant to maintain the proper ratio of ingredients. Working around the clock, the company makes approximately 800 *gallons* of paint every 24 *hours*.

2. The procedure for treating patients with insufficient kidney function is called "hemodialysis." This procedure typically takes place for approximately 4 hours, three times per week. The following configuration is representative:

   A. The "impure" blood (containing waste products that need to be removed) is caused to leave the body from a blood vessel through plastic tubing.

   B. An anticoagulant called "heparin" is added continuously to the tubing carrying the "impure" blood to prevent clotting in the hemodialysis system.

   C. The blood passes through a centrifugal pump, which provides the flow of the blood through the system.

   D. The blood passes through the "tube" side of a shell-and-tube "mass exchanger' (which is called a "hemodialyzer" and is very similar to a shell-and-tube heat exchanger). A liquid stream of "warm dialysate" passes through the "shell" side of the hemodialyzer. In the hemodialyzer, the waste products in the blood pass through the walls of the tubes and enter the dialysate.

   E. The blood leaving the hemodialyzer passes through a filter, which traps particulates (typically, clusters of cells) and removes them from the blood.

   F. The "cleansed" blood returns to the patient.

   G. The dialysate is prepared from a dialysate concentrate, which is purchased and diluted during the procedure to the desired concentration. To accomplish this dilution, the concentrate is pumped through tubing to a junction in the tubing where it joins another tubing stream carrying ultrapure water. The ultrapure water is prepared by pumping it from a distilled water source through tubing and through an ultrapure filter before joining the dialysate concentrate. After the dialysate concentrate and ultrapure water streams join, the dialysate is at its proper diluted concentration, as determined by the relative pumping flow rates of the water and concentrate pumps.

   H. The diluted dialysate flows through a heater (coil-in-tank type, with a stream of hot water flowing through the heater to provide the heat) to produce "warm dialysate."

   I. The "warm dialysate" stream passes through the hemodialyzer as described in part D and then flows to the drain.

Construct a pictorial Process Flow Diagram (without the stream table) using the symbols given in Figure 2.5.

3. In 2007, a group of students and faculty from Brigham Young University developed and took to Tonga a process for using coconuts (available in plentiful supply) to produce biodiesel fuel and soap (both products of high value to the Tongan people). The process consists of the following:

A. The coconuts are preprocessed (the preprocessing method doesn't need to be represented on the diagram) to produce coconut milk and "dry" coconut oil.

B. The coconut oil passes through an "Oil Heater" (fuel-type) before entering a reactor (open-tank, stirred).

C. Methanol and a small amount of sodium hydroxide (NaOH, acting as a catalyst) are mixed together in a mixer (open-tank, stirred), and the resulting mixture also enters the reactor described in B.

D. In the reactor (described in B), the methanol and coconut oil react to form biodiesel and glycerol. Two streams leave the reactor: crude biodiesel (also containing some water and residuals) and glycerol (also containing unreacted methanol).

E. The crude biodiesel passes through a "washer" where water is sprayed into the stream (like a spray condenser), and a stream of water and residuals leaves the bottom of the washer. Meanwhile, the washed (wet) biodiesel leaves the washer and passes through a water filter, which removes most of the water.

F. The biodiesel finally enters a 2-stage evaporator. Stage 1 is a "Diesel Heater" (fuel-type) that warms the biodiesel, which then enters Stage 2, a "Water Evaporator" tank (horizontal tank) where the water vapor evaporates and exits from the top, while the dry diesel exits the bottom.

G. The glycerol stream from the reactor (described in D) enters a 2-stage evaporator. Stage 1 is a "Glycerol Heater" (fuel-type) that warms the glycerol stream, which then enters Stage 2, a "Methanol Evaporator" tank (horizontal tank) where the methanol vapor evaporates and exits from the top, while the purified glycerol exits the bottom.

H. The purified glycerol from G enters a Solidifier (open tank, mixed). Also entering the Solidifier is some salt (NaCl) solution (a solidifying agent) and some of the coconut milk (described in A). From the Solidifier comes the solid soap.

I. The methanol vapor leaving the Methanol Evaporator (described in G) passes through a "Methanol Condenser" (coil-in-tank), with a cold-water stream providing the cooling. The condensed methanol leaving the condenser is returned to make up part of the methanol stream entering the mixer described in C.

Construct a pictorial Process Flow Diagram (without the stream table) using the symbols given in Figure 2.5.

4. Hydrogen gas is a valuable product, because it is used as a feedstock (starting material) for many chemical processes. A common way to produce high-purity hydrogen gas is by reaction of propane gas with steam using the following scheme:

A. The propane gas is first sent to a Desulfurizer to remove any sulfur present in the propane gas, because the sulfur would poison catalysts in later process steps.

B. Steam is added to the desulfurized propane, and the combined gas is sent to a Reforming Furnace (a fired heater) (1500°*F*) to produce the *reforming* reaction:

$$C_3H_8 + 3H_2O \rightarrow 3CO + 7H_2$$

C. More steam is added to the gas mixture leaving the Reforming Furnace, and the combined gas goes to a CO Converter, where the carbon monoxide in the mixture is converted:

$$CO + H_2O \rightarrow CO_2 + H_2$$

D. The gas mixture from the CO Converter enters the CO_2 Absorber, where most of the CO_2 in the mixture is absorbed into an amine solution.

E. The gas mixture from the CO_2 Absorber now contains H_2 with traces of CO and CO_2. The last traces of CO and CO_2 are converted to methane in a Methanator:

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

a. Construct a block diagram for the process described above.

b. Construct a pictorial process flow diagram (without the stream table) using the symbols given in Figure 2.5. The following additional information will be helpful:

- Liquid propane will be fed from a Propane Tank.
- The propane leaving the Propane Tank is vaporized via a shell-and-tube heat exchanger in which steam is used on the tube side (see the next bullet).
- A shell-and-tube heat exchanger (as you will learn later) is a cylinder (shell) through which a number of tubes pass. One fluid flows inside the tubes (*tube side*), and the other fluid flows outside the tubes but inside the outer cylinder (*shell side*), and the streams don't mix. In the symbol for a shell-and-tube heat exchanger, a line representing the tube side passes through the circle (which represents the shell or outer cylinder). Other lines stop at the boundary of the circle to represent the shell-side fluid entering and leaving the shell. The orientations and directions of the lines and arrows are not critical.
- The Reforming Furnace is a fired heater.

(Continued on the next page.)

- The Desulfurizer, CO Converter, CO_2 Absorber, and Methanator are packed columns with one bed of packing each, and the process gas enters the bottom and exits the top. In the case of the CO_2 Absorber, amine solution enters the top (Amine Solution In) and exits the bottom (Amine Solution Out), where the source and destination of the amine solution streams will not be indicated.
- For the CO_2 Absorber, the Absorber inlet stream is cooled by two shell-and-tube heat exchangers in series. In the first exchanger, the Absorber inlet stream flows through the shell side, while cool outlet gas is looped back from the Absorber to flow through the tube side before continuing on its way to the Methanator. In the second exchanger, the Absorber inlet stream again flows through the shell side, while water is used as the tube-side coolant.
- The gas leaving the Methanator is cooled again by water in a shell-and-tube exchanger (the gas on the shell side), and the diagram should label the cooled stream as "Purified hydrogen to storage."

5. A common and important process is the manufacture of gelatin for food, pharmaceuticals, photographic film, and various technical applications. The chemistry is the simple hydration of collagen from animal bones or skins:

$$\underset{\text{collagen}}{C_{102}H_{149}N_{31}O_{38}} + \underset{\text{water}}{H_2O} \rightarrow \underset{\text{gelatin}}{C_{102}H_{151}N_{31}O_{39}}$$

Bones must be pretreated with steam to remove the grease, crushed into small particles, and then sent to a series of acid-wash steps to remove calcium phosphate and other mineral matter. The remaining collagen then goes to long storage (1 month or more) in lime to remove soluble proteins before finally going to the reactor and purification processes. An abbreviated process flow diagram appears below (Fig. P2.5).

For your interest, to produce 1 *ton* of gelatin requires approximately 3 *tons* of bones, 1 *ton* of hydrochloric acid, 3/4 *tons* of lime, and 400 lb_m of steam.

For each of the following operations in this process, which of the first four chemical engineering phenomena (fluid mechanics, heat transfer, mass transfer, and reaction engineering) do you think are important parts of the operation?

a. Cooker: Steam is used to heat the bones and cause the grease to flow more easily. The stream of grease is caused to flow away from the bones.

b. Acid Wash: A stream of acid is brought in and mixed with the bone particles. The acid reacts with the solid material of the bones to break down that material and release the calcium phosphate and other minerals. The acid stream also carries away the minerals as it leaves the process.

c. Dryer: Steam is brought into the compartment where strips of gelatin are laying on trays. The steam heats the compartment until the gelatin is completely dry.

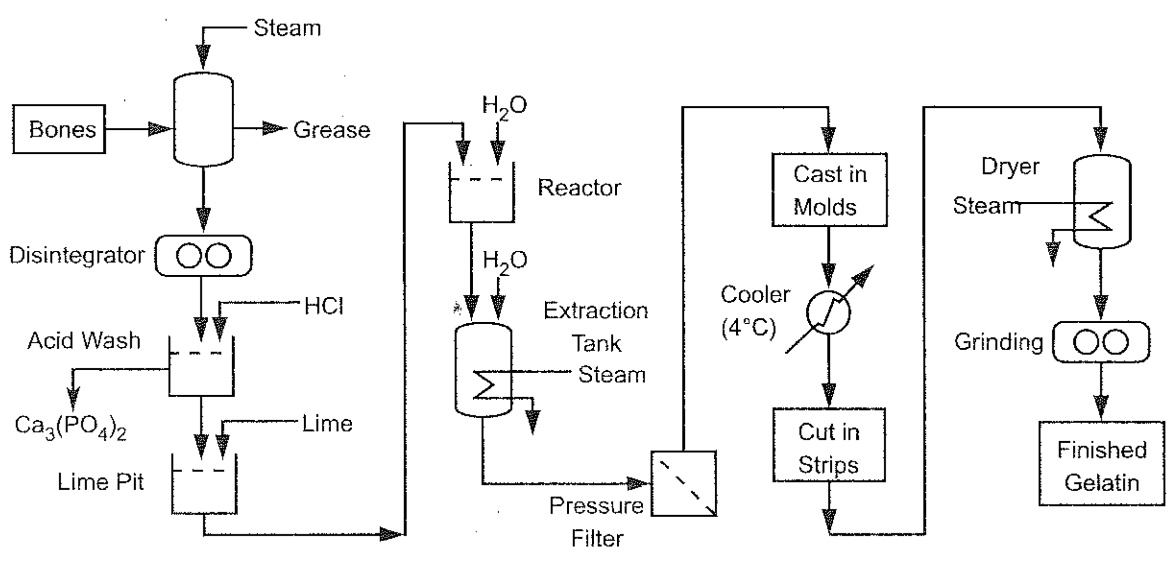

Figure P2.5 Process for Gelatin Manufacture (adapted from ref. 4)