Chapter 19. Process Input/Output Models

What You Will Learn

- All chemical processes have an input-output structure.

Imagine you are in charge of operations for a portion of a chemical plant when you are informed that the pressure of a distillation column has begun to rise slowly. You know that if the pressure continues to rise, the structural integrity of the column may be in jeopardy, or that a relief valve will open and release valuable product to the stack. Both of these scenarios have serious negative consequences. In order to solve the problem without shutting down the plant, which might be very costly, it is necessary to understand how the distillation column performs in order to diagnose the problem and determine a remedy.

Dealing with the day-to-day performance of a chemical process differs from design of a new process. When designing a new process, there is freedom to choose equipment specifications as long as it produces the desired performance. However, once a piece of equipment has been designed and constructed, it performs in a unique manner. The specific performance of a piece of equipment must be considered when operating such equipment.

When designing equipment, alternative specifications can yield the same operating results. When dealing with existing equipment, day-to-day operation is constrained by the fixed equipment characteristics.

Although it may be tempting to proceed immediately to the analysis of performance of individual pieces of equipment, it is important to develop an intuitive understanding of how equipment performs. This chapter introduces a framework by which individual equipment and complete process performance may be understood. The following chapters develop and use tools for analysis of system performance. Having an intuitive understanding of process and equipment performance is a necessary complement to the ability to do numerous, repetitive, high-speed calculations.

To determine the outputs of a unit operation or chemical process, the process inputs must be known and the performance for each unit of equipment involved in the process must be understood. The relationship between input and output can be described as

$$\text{Output} = f(\text{Input, Unit Performance}) \qquad (19.1)$$

Input changes are the driving force for change.

Unit performance defines the characteristics of fixed equipment by which inputs are changed to outputs.

To change process output, the process input and/or equipment performance must be altered. Conversely, the cause of a process output disturbance is a change in process input, equipment performance, or both.

Changes in process output result from changes in process inputs and/or equipment performance.

19.1. Representation of Process Inputs and Outputs

Figure 19.1 illustrates how outputs are connected to inputs through the process system. The process system may consist of a single piece of equipment or several unit operations, with the output from one unit becoming the input to another unit. As a result, a change of input to one unit operation affects all of the downstream units. For systems containing recycle streams, the output from a unit operation returns to affect its input.

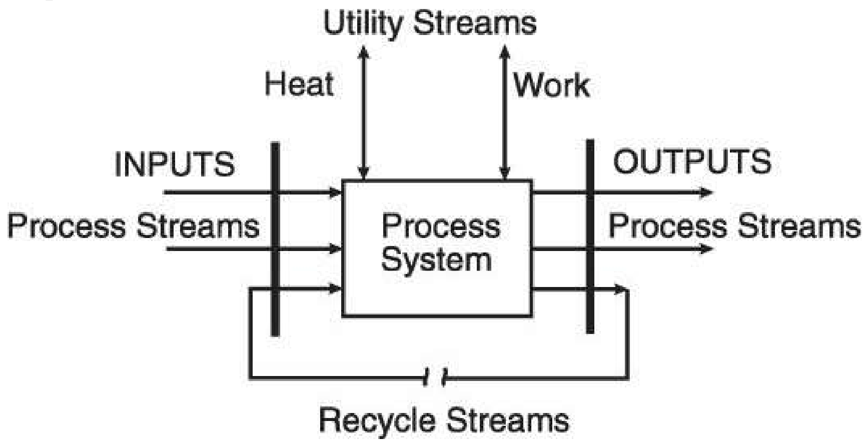


Figure 19.1. Input/Output Diagram for Chemical Process

Figure 19.1 provides the input/output representation of a chemical process. It shows

- **a. Process System** (shown in the center box): This may consist of a single process unit, or a collection of process units (such as a distillation system), that, taken together, performs a specific function or a complete chemical process.
- **b. Process Flow Streams:** These are divided into two types:
  - **i. Input Streams** (shown on the left): They consist of process flow streams entering a unit operation or process.
  - **ii. Output Streams** (shown on the right): They consist of process flow streams exiting a unit operation or process.
- **c. Utility Streams:** Utility streams provide for the transfer of energy to or from process streams or process units. They are used to regulate temperatures and pressures required in the process. Utility stream inputs and outputs are shown at the top of Figure 19.1.
  - **i. Heat:** Heat is most often provided by the flow of a heating or cooling medium but can be provided by other sources such as electrical energy.
  - **ii. Work:** This represents shaft work for a pump or compressor doing work on the fluid.
- **d. Recycle Streams:** These streams are internal to the process. They are critical to the operation of the process system. Recycle streams must be identified and their impact on the process understood. A recycle stream is illustrated by **cutting** or **tearing** the recycle stream (see Chapter 13). The **cut ends** create a set of pseudo-input and pseudo-output streams. They are shown along the bottom of the process system block, connected by a broken line. The pseudo-output stream is fed back to the process as a pseudo-input stream.

  Recycle streams fall into two categories:
  - i. Process recycle streams recover raw materials and/or energy to reduce the cost of raw materials, waste disposal, and energy.
  - ii. Equipment recycle streams affect equipment performance. As an example, increasing reflux to a distillation tower improves separations.

Example 19.1 illustrates how to represent process inputs and outputs for individual pieces of equipment.

Example 19.1.

Draw an input/output model for

a. A pump

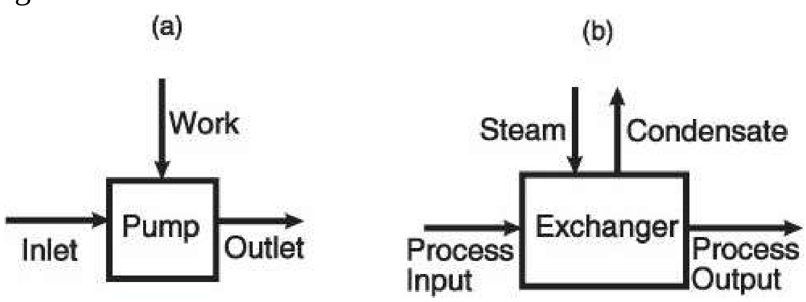
b. A heat exchanger in which a process stream is heated using condensing steam

c. A distillation column

Solution

a. The result is shown in Figure E19.1(a). The mass balance on a pump has one input and one output, as shown. The energy balance on a pump (or one's intuitive understanding of how a pump works) indicates that there is energy input to the process stream, as shown.

b. The result is shown in Figure E19.1(b). A heat exchanger using a utility has one process stream input and one process stream output. The utility also flows in (steam) and out (condensate) of the heat exchanger.



Figures E19.1(a) and (b). Solutions to Example 19.1

c. The result is shown in Figure E19.1(c). The process streams are the feed, bottoms, and distillate. The utility streams are steam for the reboiler and cooling water for the condenser. Finally, the reflux from the condenser and the boil-up from the reboiler are represented as recycle streams, which both leave and enter across system boundaries.

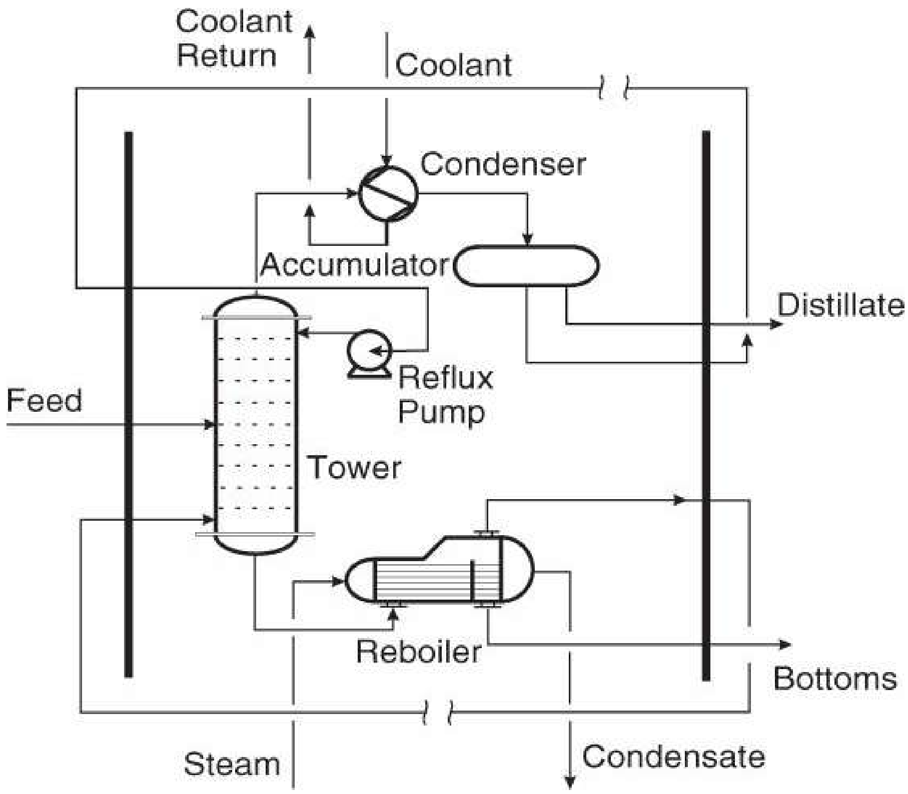


Figure E19.1(c). Solution to Example 19.1(c)

Using the input/output diagram in Figure 19.1, two classifications are identified for process analysis problems encountered in this text:

1. **Process Design Analysis:** Input and output streams are fixed. A process system is designed to transform the input into the output.
2. **Process Performance Analysis:** Input and equipment are fixed. The outputs are determined by the process system.

19.2. Analysis of the Effect of Process Inputs on Process Outputs

An intuitive understanding of the effect of process inputs on process outputs can be obtained by categorizing the relationships used to analyze equipment. These relationships are broken down into two groups:

1. **Equipment-Independent Relationships:** These relationships are independent of equipment specifications. Material balance, energy balance, kinetics, and equilibrium relationships are examples of equipment-independent relationships.
2. **Equipment-Dependent Relationships:** These are often called **design equations** and involve equipment specifications. The heat transfer equation (contains area, A) and the frictional pressure relationship (contains pipe size, D_p, and the equivalent length, L_{eq}) are examples of equipment-dependent relationships.

Unless equipment-dependent relationships are known and used, the impact of a change of process input on the output cannot be determined correctly.

Example 19.2. illustrates equipment-independent and equipment-dependent relationships.

Example 19.2.

What relationships are used to analyze the following pieces of equipment? Classify these as equipment independent and equipment dependent.

a. Heat exchanger

b. Adiabatic reactor

c. Multistage extraction

Solution

a. The energy balance—which for a temperature change without phase change is $Q = \dot{m} C_p \Delta T$, and for a phase change is $Q = \dot{m} \lambda$—is an equipment-independent relationship. The design (or performance) equation for a heat exchanger is $Q = UA\Delta T_{lm}F$. It is observed that only the equipment-dependent relationship contains equipment specifications—in this case, the area for heat transfer, A.

b. In a reactor, equipment-independent relationships may include kinetics and/or the definition of equilibrium. If there are no equilibrium limitations, the kinetics may take the form $r = kC_AC_B$, where A and B are the reactants. All kinetic expressions are equipment independent and are only functions of temperature, pressure, and concentration. The energy balance, which is necessary to determine the outlet temperature of the adiabatic reactor, is another relevant equipment-independent relationship. One equipment-dependent relationship is the design equation for the reactor, and it depends upon the type of reactor. For example, for a CSTR, this relationship is $V/F_{Ao} = X/(-r_A)$. It is observed that this relationship contains an equipment specification—in this case, the reactor volume, V. Another equipment-dependent relationship is for the pressure drop through the reactor, which is important in analyzing changes in flowrates.

c. In any multistage separation involving a mass separating agent, the mass balance is the key equipment-independent relationship. For example, it is understood that increasing the solvent rate results in a better separation. Another equipment-independent relationship is the statement of phase equilibrium. An equipment-dependent relationship does not exist as a simple, closed-form equation, except in certain limiting cases. However, an intuitive understanding of the equipmentdependent relationship is possible. For example, it is understood that increasing the number of stages will (usually) improve the separation. For the limiting case of dilute solutions, all the above relationships can be expressed as a single, closed-form equation, the Kremser equation. This will be discussed in Chapter 21. Another equipmentdependent relationship is the efficiency of the equipment, which is dependent on the liquid and vapor flowrates.

19.3. A Process Example

It is assumed that both the equipment-independent and equipment-dependent relationships are understood, and attention is focused on integrating these relationships to analyze a complete processes. In a chemical process, a change in input to one piece of equipment or a change in performance of that piece of equipment affects more than just the output from that piece of equipment. Because the output from the piece of equipment in question usually becomes the input to another piece of equipment, the disturbance caused by the change in the original piece of equipment can propagate through the process.

This is important in two types of problems that are discussed in later chapters. In one type of problem, the effect of a planned disturbance, such as a 10% scale-up in production, can be quantified only by considering the effect of a changed output from one unit on the subsequent unit. Similarly, in a second type of problem, an observed disturbance in the output of a particular unit may trace back to a disturbance in a unit far removed from the observed disturbance.

In order to analyze these problems, the input/output model for an entire process must be understood, as must the equipment-independent and equipment-dependent relationships for each piece of equipment in the process. This is illustrated in Example 19.3.

Example 19.3.

Consider the toluene hydrodealkylation process illustrated in Figure 1.5. Draw and label an input/output diagram, similar to Figure 19.1, for this process. Label all process inputs and outputs, all utility streams, and all recycles. Then pick any two adjacent units and draw their input/output diagrams together, showing how the output from one unit affects the adjacent unit.

Figure E19.3(a) is the input/output diagram for the entire process. It is observed that there are two recycles: one for hydrogen and one for toluene, both unreacted reactants. This is a particularly useful representation because all of the inputs and outputs also represent cash flows. By showing all of the utilities, it is less likely that one could be omitted from a cash flow analysis.

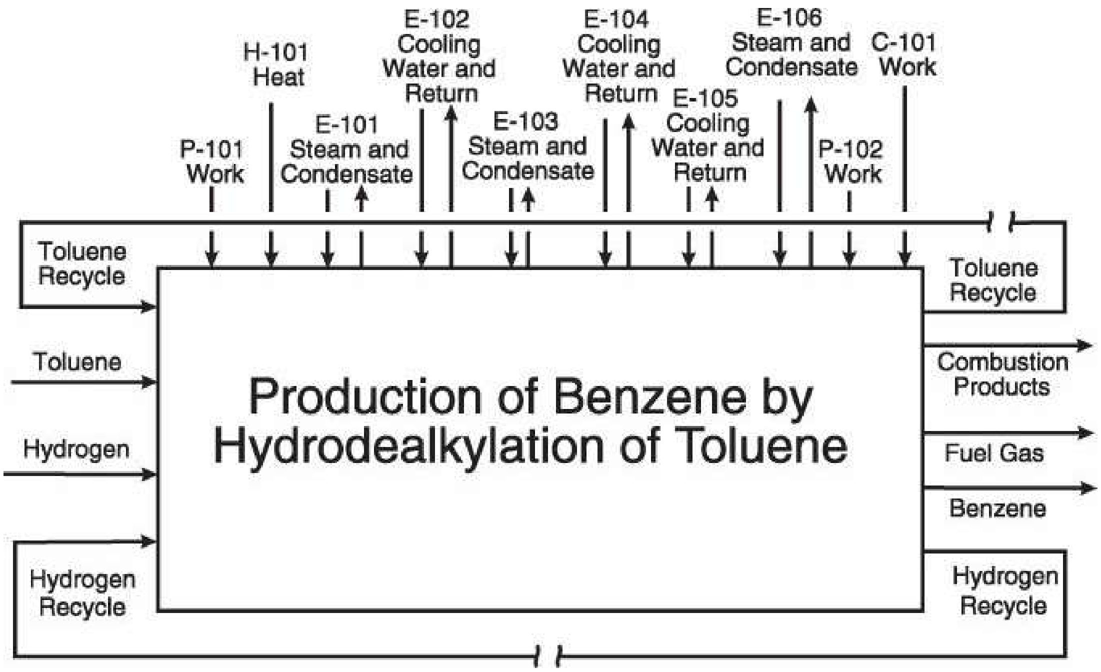


Figure E19.3(a). Solution to Example 19.3

Figure E19.3(b) is an input/output diagram for the toluene feed pump (P-101) and the heat exchanger (E-101). This diagram makes it evident that any disturbance in the feed to or the operation of the pump not only affects the pump output but also affects the heat-exchanger output. Clearly, this disturbance would also propagate to other downstream equipment.

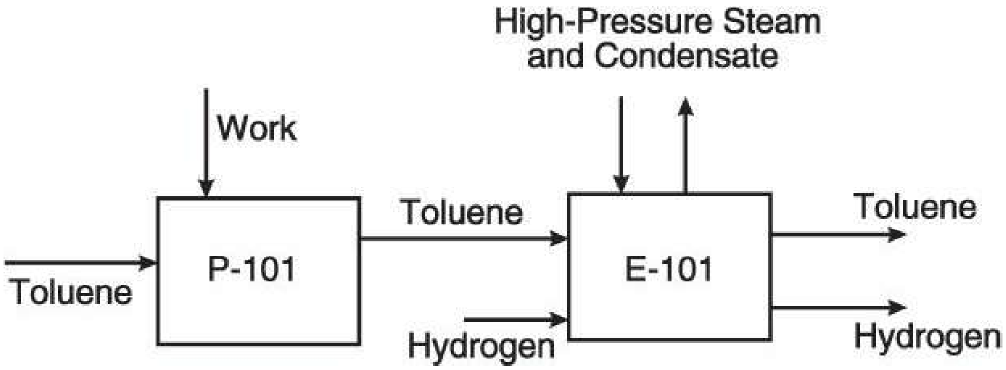


Figure E19.3(b). One Possible Solution to Example 19.3

19.4. Summary

This chapter introduced and demonstrated the importance of the input/output characteristics of chemical processes. In the input/output structure, process inputs are the driving force for change and the unit operations are the mechanism for change.

Recycle streams are of special importance and create pseudo-input/output streams that are critical to analysis of process changes. Utility streams act as "servants" of the process units and streams and provide the desired temperature and pressure for the process units. They exchange energy with the process stream and process units.

As a consequence of the linkage between process units, a change in a single input or unit affects the total system. The impact on the process cannot be evaluated solely from analysis of isolated units.

What You Should Have Learned

- How to represent and understand the input-output structure of a chemical process

Problems

1. Draw input/output diagrams for the following pieces of equipment:
   a. A fluidized bed
   b. A turbine
   c. A pump
   d. A stripper
   e. An adiabatic batch reactor
   f. A semibatch reactor with heat removal
   g. A heat exchanger between two process streams (no utilities)
2. Write down the equipment-independent and equipment-dependent relationships for each piece of equipment listed in Problem 19.1.
3. Write down the equipment-independent and equipment-dependent relationships for a distillation column.
4. Draw input/output diagrams for the following processes. Pick any two adjacent pieces of equipment, and draw input/output diagrams for these, clearly showing how the output from one affects the input to the other.

a. Ethylbenzene, described in Appendix B, Project B.2
b. Styrene, described in Appendix B, Project B.3
c. Drying oil, described in Appendix B, Project B.4
d. Maleic anhydride, described in Appendix B, Project B.5
e. Ethylene oxide, described in Appendix B, Project B.6
f. Formalin, described in Appendix B, Project B.7