

Chapter 28

Open-Ended Problems

INTRODUCTION

The education literature provides frequent references to individuals, particularly engineers and scientists, that have different learning styles. And, in order to successfully draw on these different styles, a variety of approaches can be employed. One such approach involves the use of open-ended problems.

The term “open-ended problem” has come to mean different things to different people. It basically describes an approach to the solution of a problem and/or situation for which there is usually not a unique solution. The author of this text has applied this somewhat unique approach by including numerous open-ended problems in several course offerings at Manhattan College. Student comments for the graduate course “Accident and Emergency Management” were recently tabulated. Student responses (unedited) to the question, “What aspects of this course were most beneficial to you?” are listed below:

1. “The open-ended questions gave engineers a creative license. We don’t come across many of these opportunities.”
2. “Open-ended questions allowed for candid discussions and viewpoints the class may not have been otherwise exposed to.”
3. “The open-ended questions gave us an opportunity to apply what we were learning in class with subjects we have already learned which gave us a better understanding of the course.”
4. “Much of the knowledge that was learned in this course can be applied to everyday situations and in our professional lives.”
5. “Open-ended problems made me sit down and research the problem to come up with ways to solve them.”
6. “I thought the open-ended problems were inventive and got me to think about problems in a better way.”
7. “I felt that the open-ended problems were challenging. I, like most engineers, am more comfortable with quantitative problems vs qualitative.”

There is a tale⁽¹⁾ that appeared in print many years ago that dissected the value of an open-ended approach to a particular problem. The story (adapted for purposes of this text) is presented below. This is a tale that occurred late in 1960 that may or may not serve to justify the value of an open-ended approach to a particular engineering/science problem. That story, as recounted by an engineering educator, follows.

Some time ago, I received a call from a colleague named Lou Theodore who asked if I would be willing to serve as the referee on the grading of an examination question. He was about to give a student a zero for his answer to a heat transfer question, while the student claimed he should receive a perfect score and would if the system were not rigged against the student. During discussions with my colleague, it became apparent that he felt the student was a “loser and a liability, and would ultimately serve as an embarrassment to the department in later years.” He also complained that the student “was Irish, often showed up late for class, was occasionally inebriated, and used many of my lectures as a sleeping pill.”

I went to my colleague’s office and read the examination question: “As part of a QA/QC (quality assurance/quality control) test, outline how one can ascertain the readings on this long stem mercury thermometer employed in the department’s lab is correct.” My colleague felt that the student should have provided an answer that reflected the lecture material. For example, the mercury in the narrow tube expands as it gets hotter due to its coefficient of expansion. In effect, the mercury expands by an amount that linearly depends on the temperature so that a rise of 10 degrees produces twice the expansion than a 5 degree increase. In any event, my colleague (Dr. Theodore) and the student agreed to submit this to an impartial arbiter, and I had been selected.

The student had answered the exam as follows: “Place several other thermometers along the one of concern and check the readings. If all the readings are in close agreement with one another, one can conclude that the lab thermometer reading is correct.”

I pointed out to Dr. Theodore that the student really had a strong case for full credit since he had answered the question completely and correctly. On the other hand, if full credit was given, it could well contribute to a high grade for the student in his heat transfer course. A high grade is supposed to certify competence in the subject of concern, but the answer did not confirm this. I suggested that the student have another try at answering the question. I was not surprised that Dr. Theodore agreed, but I was surprised that the student did.

I gave the student ten minutes to answer the question with the warning that the answer should show some knowledge of heat transfer. At the end of five minutes, he had not written anything. I asked if he wished to give up, but he said no. He had many answers to this problem; he was just thinking of the best one. I excused myself for interrupting him and asked him to please go on. In the next minute, he dashed off his answer which read:

Call the local airport and weather bureau and inquire about the ambient temperature. Then take the thermometer outside. If the reading is in close proximity to that reported by the two agencies, one can conclude that the reading is correct.

At this point, I asked my colleague if he would give up. He conceded and I gave the student almost full credit.

In leaving Dr. Theodore's office, I recalled that the student had said he had many other answers to the problem, so I asked him what they were. "Oh yes" said the student. "There are a great many ways of checking the validity of the thermometer readings. For example, you could mail the thermometer back to the vendor and request that it be recalibrated to reassure the reading is valid."

"Fine" I asked, "And the others?"

"Yes," said the student. "There is a very basic measurement method that you will like. In this method you take the thermometer and place it in running tap water. Since the tap water in the lab is in the 62–64°F range, a temperature reading of the lab thermometer in that range would signify validity."

"Of course, if you want an even simpler method, you can take the thermometer to the lab technician. Speak to him as follows: 'Mr. Technician, here I have a fine thermometer. If you tell me if the thermometer is properly calibrated, I will give you this thermometer.'"

Finally, he concluded there are many other ways of solving the problem. "Probably the best but perhaps a somewhat unorthodox way is to use the traditional method to take Dr. Theodore's temperature. If the thermometer registers something in the 98.6°F area, it must be in working order."

At this point I asked the student if he really did know the conventional answer to this question. He admitted that he did, but said that he was fed up with traditional education and college professors trying to teach him how to think using the "scientific method", i.e., to explore the deep inner logic of the subject in a pedantic way, as is often done in the new mathematics, rather than teaching him the structure of the subject.

Interestingly, the student did manage to graduate despite the efforts of my dear colleague. The student married soon after graduation, and his two children—Michelle and Mark—later served as babysitters for the children of my colleague who had married a beautiful woman of Irish decent later in life. The student? John D. McKenna, who went on to earn a law degree and a PhD. He is currently President and CEO of ETS International in Roanoke, VA.

So much for the decision-making capabilities of some of our educators. Need more be said?

The remainder of this chapter addresses a host of topics involved with open-ended problems. The remaining sections are entitled:

Developing Students' Power of Critical Thinking

Creativity

Brainstorming

Inquiring Minds

The chapter concludes with open-ended applications primarily in the heat transfer field. Applications in other areas can be found in the literature.^(2,3)

DEVELOPING STUDENTS' POWER OF CRITICAL THINKING⁽⁴⁾

It has often been noted that today's society is living in the middle of an information revolution. That revolution has had an effect on teaching and learning for nearly two decades. Teachers are hard-pressed to keep up with the advances in their fields. Often their attempts to keep the students informed are limited by the difficulty of making new material available.

The basic need of both teacher and student is to have useful information readily accessible. Then comes the problem of how to use this information properly. The objectives of both teaching and studying such information are: to assure comprehension of the material and to integrate it with the basic tenets of the field it represents; and, to use comprehension of the material as a vehicle for critical thinking, reasoning, and effective argument.

Information is valueless unless it is put to use; otherwise it becomes mere data. To use information most effectively, it should be taken as an instrument for understanding. The process of this utilization works on a number of incremental levels. Information can be: absorbed, comprehended, discussed, argued in reasoned fashion, written about, and integrated with similar and contrasting information.

The development of critical and analytical thinking is the key to the understanding and use of information. It is what allows the student to discuss and argue points of opinion and points of fact. It is the basis for the student's formation of independent ideas. Once formed, these ideas can be written about and integrated with both similar and contrasting information.

CREATIVITY

Engineers bring mathematics and science to bear on practical problems, molding materials and harnessing technology for human benefit. Creativity is often a key component in this synthesis; it is the spark that motivates efforts to devise solutions to novel problems, design new products, and improve existing practices. In the competitive marketplace, it is a crucial asset in the bid to win the race to build better machines, create new materials, decrease product delivery times, and anticipate the needs of future generations.⁽⁵⁾

Although one of the keys to success for an engineer or a scientist is the ability to generate fresh approaches, processes, and products, they need to be creative. Gibney⁽⁵⁾ has detailed how some schools and institutions are attempting to use certain methods that essentially share the same objective: to open students' minds to their own creative potential.

Gibney⁽⁵⁾ provides information on "The Art of Problem Definition" developed by Rensselaer Polytechnic Institute. To stress critical thinking, they teach a seven step methodology for creative problem development. These steps are:

1. Define the problem
2. State the objective⁽²⁾

3. Establish functions
4. Develop specifications
5. Generate multiple alternatives
6. Evaluate alternatives
7. Build

In addition, Gibney⁽⁵⁾ identified the phases of the creative process set forth by psychologists. They essentially break the process down into five basic stages:

1. Immersion
2. Incubation
3. Insight
4. Evaluation
5. Elaboration

Psychologists have ultimately described the creative process as recursive. At any one of these stages, a person can double back, revise ideas, or gain new knowledge that reshapes his or her understanding. For this reason, being creative requires patience, discipline, and hard work.

Finally, Delle Femina⁽⁶⁾ recently outlined five secrets regarding the creative process:

1. Creativity is ageless
2. You don't have to be Einstein
3. Creativity is not an eight hour job
4. Failure is the mother of all creativity
5. Dead men don't create

The reader is left with a thought from Theodore:⁽⁷⁾ Creativity usually experiences a quick and quiet death in rooms that house large conference tables.

BRAINSTORMING

Panitz⁽⁸⁾ has demonstrated how brainstorming strategies can help engineering students generate an outpouring of ideas. Brainstorming guidelines include:

1. Carefully define the problem upfront
2. Allow individuals to consider the problem before the group tackles it
3. Create a comfortable environment
4. Record all suggestions
5. Appoint a group member to serve as a facilitator
6. Keep brainstorming groups small

A checklist for change was also provided:

1. Adapt
2. Modify
3. Magnify
4. Minify
5. Put to other uses
6. Substitute
7. Rearrange
8. Reverse
9. Combine

INQUIRING MINDS

In an exceptional and well-written article by Lih⁽⁹⁾ titled *Inquiring Minds*, Lih commented on *Inquiring Minds* saying “You can’t transfer knowledge without them.” His thoughts (which have been edited) on the inquiring or questioning process follow.

1. Inquiry is an attitude—a very important one when it comes to learning. It has a great deal to do with curiosity, dissatisfaction with the status quo, a desire to dig deeper, and having doubts about what one has been told.
2. Questioning often leads to believing. There is a saying that has been attributed to Confucius: “Tell me, I forget. Show me, I remember. Involve me, I understand.” It might also be fair to add: “Answer me, I believe.”
3. Effective inquiry requires determination to get to the bottom of things.
4. Effective inquiry requires wisdom and judgment. This is especially true for a long-range intellectual pursuit that is at the forefront of knowledge.
5. Inquiry is the key to successful life-long learning. If one masters the art of questioning, independent learning is a breeze.
6. Questioning is good for the questionee as well. It can help clarify issues, uncover holes in an argument, correct factual and/or conceptual errors, and eventually lead to a more thoughtful outcome.
7. Teachers and leaders should model the importance of inquiry. The teacher/leader must allow and encourage questions and demonstrate a personal thirst for knowledge.

APPLICATIONS

Twelve open-ended illustrative examples follow.

ILLUSTRATIVE EXAMPLE 28.1

Using terms a liberal arts major could understand, briefly explain the concept of:

1. Unit conversion(s) or conversion factors
2. Dimensional analysis
3. Dimensionless numbers
4. Kinetic energy
5. Potential energy
6. Energy conservation

SOLUTION: Qualitative questions like these are often difficult to answer. Perhaps (1) is the easiest of the six. For this case, one might draw an analogy between 5 pennies and 1 nickel, or 2 nickels and 1 dime, or 12 inches and 1 foot, etc. ■

ILLUSTRATIVE EXAMPLE 28.2

The Alaska Department of Environmental Protection (DEP) has requested your consulting firm to provide “the best estimate” of the oil requirements to sustain a proposed remote outpost in the middle of a pristine region. If both the heating and electrical requirements for the site are known, *outline* how to calculate the average daily oil needs. Assume the energy value of the oil is given. Indicate if any additional information is required. Note that no calculations are required.⁽¹⁰⁾

SOLUTION: When calculating the average daily oil needs for the outpost, several factors come into play. The most important is knowing the heating and electrical requirements for the site and the heating value of the oil. It is also important to take into account how the oil will be transported to the outpost. It is one thing to purchase the oil and another entirely different thing to transport and store the oil at the outpost. As this nation knows, oil prices are governed by international and national events as well as the demand for the oil. Thus, the fluctuations in the oil prices also need to be accounted for. The thermal conversion efficiencies are also required to be known. The following four-step approach is suggested.

Step 1: Break down the given heating and electrical requirements into a per month basis and from this the average daily oil needs can be obtained. (Take the total monthly requirements and divided it by the number of days in a month to get the average daily requirements.) One reason for this is that winter months tend to use more electricity, heating and oil than summer months. Also, one must know when the “peak hours are.” This is what is referred to as “demand.”

Step 2: Use conversion factors to convert the heating and electrical units into oil units. Oil is usually sold by the barrel. Once all the units are converted into Btu units, the heating value of oil can be used (such as one barrel = 6.287 million Btu) as a way to see how many barrels of oil are required.

Step 3: Find out the cost of oil after calculating how much the daily and monthly consumption will be.

Step 4: Decide how the oil will be transported to the outpost and how/where it will be stored.

Include all these factors in the analysis. ■

Table 28.1 P, V, T Data

P , atm	V , m ³	T , K	z
1.0	10.0	200	1.0
5.0	4.0	400	1.0
20.0	2.3	800	1.15
40.0	1.3	800	1.3
100.0	1.6	1,000	3.2

ILLUSTRATIVE EXAMPLE 28.3

The P, V, T (plus the compressibility coefficient, z) data for a recently synthesized gas is given in Table 28.1 ($MW = 609$ gmol). Based on either statistical or theoretical principles (or both), develop an equation describing the P, V, T behavior of this gas. State the limitations of the approach and/or final equations.

SOLUTION: The sky is the limit regarding what approach to employ. See Illustrative Example 28.4 for suggestions. ■

ILLUSTRATIVE EXAMPLE 28.4

The heat capacity variation with temperature of a fluid are given in Table 28.2. As part of a simulation project, your immediate supervisor has requested that you develop an algebraic equation describing the c_p variation with T . Outline how to solve the problem and justify your approach.

SOLUTION: As noted in Chapter 26, regression analysis is a useful statistical technique for developing a quantitative relationship between a dependent variable and one or more independent variables. It usually utilizes experimental data on the pertinent variable to develop a numerical equation showing the influence of the independent variable(s) on the dependent variable of the system.

As noted in Chapter 26, a simple correlation problem can arise when one asks whether there is any relationship between smoking and heart ailments, between beauty and brains, between kinetic energy and velocity, between drag force and pressure, etc. For example, in a thermal combustion unit involving a complex chemical reaction, regression methods have been used to develop an equation relating the conversion to entering concentrations, temperature, pressure, and residence time.^(11,12) One of the problems of fitting a curve to a set of points in some efficient manner is essentially that of estimating the parameters of a proposed equation. Although there

Table 28.2 Heat Capacity Variation with Temperature

C_p , cal/gmol · K	T , K
0.203	200
0.238	300
0.258	400
0.274	500

are numerous methods for performing the estimation of such parameters, the best known and most popular method is referred to as the method of least squares.⁽¹²⁾

The least-squares regression development can be applied to several types of polynomials. Four of these functions are:

$$\text{0th degree polynomial: } y = a_0 \quad (28.1)$$

$$\text{1st degree polynomial: } y = a_0 + a_1x_1 \quad (28.2)$$

$$\text{2nd degree polynomial: } y = a_0 + a_1x_1 + a_2x_2^2 \quad (28.3)$$

$$\text{nth degree polynomial: } y = a_0 + a_1x_1 + \cdots + a_nx_n^n \quad (28.4)$$

Applying these equations to the four data points is left as an exercise for the reader. However, some information is provided in the Numerical Methods chapter (see Chapter 26).

Finally, to obtain information on the “best” model, one must resort to a statistical technique referred to as ANOVA, an acronym referring to ANalysis Of VAriance. This topic is beyond the scope of this text; however, information is available in the literature.⁽¹²⁾ ■

ILLUSTRATIVE EXAMPLE 28.5

It has been proposed to use the sensible heat from the flue gas of a boiler to reduce the energy need of the combustion process. A young engineer, recently graduated from Manhattan College’s prestigious #2 ranked Chemical Engineering Department has proposed to recover the heat in a heat exchanger and use the recovered heat to preheat the air required for combustion. Comment on the advantages and disadvantages of the young engineer’s proposal.

SOLUTION: The total energy content of the gas should be taken into consideration before implementing the proposal since the mass involved is (relatively speaking) small (i.e., the density of the gas is low). ■

ILLUSTRATIVE EXAMPLE 28.6

Over time, the heat required to keep a catalytic cracker in an oil refinery at its operating temperature of 1200°F has increased by a factor of 2. Rather than purchasing a new reactor, you are asked to recommend other possible ways to decrease the amount of energy required to heat the reactor to 1200°F.

SOLUTION:

1. Schedule a routine maintenance during a plant shutdown to clear any possible carbon buildup in the reactor.
2. Preheat the crude oil to a higher temperature before entering the reactor so less heat is required for heating to 1200°F.
3. Paint the reactor black to absorb heat to assist the heating of the reactor contents. ■

ILLUSTRATIVE EXAMPLE 28.7

Provide reasons for choosing a batch heat-transfer operation rather than a continuous one.⁽⁴⁾

SOLUTION:

1. The liquid being processed for the product is not continuously available.
2. The heating or cooling medium to the equipment is not continuously available.
3. Reaction-time or treating-time requirements necessitate holdup.
4. The economics of intermittently processing a large batch is often justified.
5. Cleaning or regeneration procedures take up a significant part of the total operating period.
6. Simplified operation of most batch processes. ■

ILLUSTRATIVE EXAMPLE 28.8

As a plant manager and as part of a project concerned with energy conservation, you have asked your plant personnel to examine and provide recommendations in order to reduce the use of utilities, i.e., fuel, steam, water, etc. A young upstart on your staff has requested that you detail exactly what she should be looking for. List recommendations for this individual.

SOLUTION:⁽¹³⁾**Fouling**

An expression for the overall heat transfer coefficient of a heat exchanger is:

$$\frac{1}{UA} = \frac{1}{(\eta hA)_c} + \left(\frac{R_f}{\eta A}\right)_c + \frac{1}{(\eta hA)_h} + \left(\frac{R_f}{\eta A}\right)_h + R_w$$

The assumption is made that the heat exchangers in the plant have been in service and have set operating conditions and surface areas. It is clear from this equation that fouling of a heat exchanger's surfaces will increase the resistance for heat transfer between fluids. Fouling in a heat exchanger may be reduced as follows:

1. Periodically draining and cleaning the heat exchanger (especially fuel oil heaters)
2. Reducing the temperature increase when using an impure coolant (i.e., fouling factors are significantly increased with sea and river waters raised above 50°C).
3. When using oils, use high-grade oil that will not suffer thermal breakdown.
4. Oil purifiers can be incorporated into the closed loop oil cooling systems.

Fluid Combinations

Use different fluid combinations to improve heat transfer. For example, an average heat transfer coefficient between oil and water is 230 W/m² · K. If temperatures allow using water on both sides of the heat exchanger, the efficiency will improve because the heat transfer coefficient between water and water is approximately 1275 W/m² · K.

Performance Analysis

The performance of a concentric tube or shell and tube heat exchanger can be improved by simply changing the flow characteristics of the fluids. The equation used for heat exchanger

analysis is (see Chapter 14):

$$Q = UA\Delta T_{\text{lm}}$$

One of the most important observations that can be made using this equation is that the log mean temperature difference for a counterflow heat exchanger will be greater than that for a parallel flow heat exchanger. This means that for similar inlet and outlet conditions, and the same surface area, a counterflow exchanger will provide greater heat transfer. On the design end, the surface area requirements to affect a prescribed transfer rate would be smaller for a counterflow exchanger than for a parallel flow exchanger. Thus, simply changing the flow of fluids will make a difference in the heat transfer rate of an exchanger.

Insulation

Loss of heat from heat exchangers, tanks and piping can be reduced by properly insulating equipment. Heat loss or gain to the atmosphere may counteract the work of a heat exchanger and reduce the net heat transfer.

If heat transfer rates are increased, then less utilities, steam and other forms of energy are needed to achieve desired heat transfer rates. ■

ILLUSTRATIVE EXAMPLE 28.9

List a key factor that should be included in the design of a heat exchanger.

SOLUTION: There are a number of factors that should be included in the design of a heat exchanger.

One of the more important is that the exchanger should be designed for appropriate film temperatures and high turbulence. This reduces the inefficiencies of heat transfer by the exchanger. This reduction takes place since there is a decrease in cling (which appears on the process side) or scale (which appears on the utility side). In addition, the exchanger is able to operate more efficiently with less cling or scale and therefore, transfers more energy. ■

ILLUSTRATIVE EXAMPLE 28.10

A heat exchanger is designed to cool a discharging water stream to a required 105°F. However, the unit is currently only cooling the stream to the 110 to 115°F range. Rather than replace the heat exchanger you have been asked to list or briefly describe what steps can be taken to get the heat exchanger back to design specifications.

SOLUTION: Depending on the type of heat exchanger, the approaches to bring the heat exchanger back to design specification are different. However, most of them include the following:

1. Cleaning of heat exchanger
2. Installation or removal of insulation
3. Correction of leakage

4. Upgrading or replacing of gaskets
5. Increasing the mass flow rate of the cooling fluid
6. Change the cooling medium (e.g., have colder water pass through the heat exchanger)

ILLUSTRATIVE EXAMPLE 28.11⁽¹⁴⁾

A plant has three streams to be heated (see Table 28.3) and three streams to be cooled (see Table 28.4). Cooling water (90°F supply, 155°F return) and steam (saturated at 250 psia) are available. Note that the saturated steam at 250 psia has a temperature of 401°F. Calculate the heating and cooling duties and indicate what utility (or utilities) should be employed.

SOLUTION: The sensible heating duties for all streams are first calculated. The results are shown in Table 28.5.

The total heating and cooling duties can now be computed and compared.

$$\text{Heating: } 7,475,000 + 6,612,000 + 9,984,000 = 24,071,000 \text{ Btu/h}$$

$$\text{Cooling: } 12,600,000 + 4,160,000 + 3,150,000 = 19,910,000 \text{ Btu/h}$$

$$\text{Heating} - \text{Cooling} = 24,071,000 - 19,910,000 = 4,161,000 \text{ Btu/h}$$

As a minimum, 4,431,000 Btu/h will have to be supplied by steam or another hot medium.

Table 28.3 Streams to be Heated in Illustrative Example 28.11

Stream	Flowrate, lb/h	c_p , Btu/lb · °F	T_{in} , °F	T_{out} , °F
1	50,000	0.65	70	300
2	60,000	0.58	120	310
3	80,000	0.78	90	250

Table 28.4 Streams to be Cooled in Illustrative Example 28.12

Stream	Flowrate, lb/h	c_p , Btu/lb · °F	T_{in} , °F	T_{out} , °F
4	60,000	0.70	420	120
5	40,000	0.52	300	100
6	35,000	0.60	240	90

Table 28.5 Duty Requirements in Illustrative Example 28.11

Stream	Duty, Btu/h
1	7,475,000
2	6,612,000
3	9,984,000
4	12,600,000
5	4,160,000
6	3,150,000

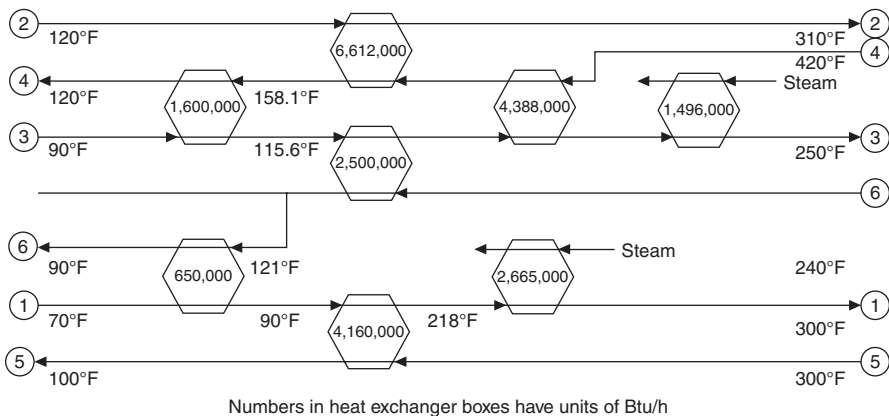
ILLUSTRATIVE EXAMPLE 28.12

Refer to the previous Illustrative Example. Devise a network of heat exchangers that will make full use of heating and cooling streams against each other, using utilities only if necessary.

SOLUTION: Figure 28.1 represents a system of heat exchangers that will transfer heat from the hot streams to the cold ones in the amounts desired. It is important to note that this is but one of many possible schemes. The optimum system would require a trial-and-error procedure that would examine a host of different schemes. Obviously, the economics would come into play.

It should also be noted that in many chemical and petrochemical plants there are cold streams that must be heated and hot streams that must be cooled. Rather than use steam to do all the heating and cooling water to do all the cooling, it is often advantageous, as demonstrated in this problem, to have some of the hot streams heat the cold ones. The problem of optimum heat exchanger networks to accomplish this has been extensively studied and is available in the literature. This example provides one simple illustration.

Finally, highly interconnected networks of exchangers can save a great deal of “quality” energy (referred to in Chapter 21) in a chemical plant. An economic analysis should be included

**Figure 28.1** Flow diagram for Illustrative Example 28.12.

in any study.⁽¹⁵⁾ The more interconnected they are, however, the harder the plant is to control, start-up, and shut down. Often auxiliary heat sources and cooling sources must be included in the plant design in order to ensure that the plant can operate smoothly. ■

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