Excerpted from chapter 9 "Optimum Design and Design Strategy"

Optimization Application: Pinch Technology Analysis

Pinch Technology Concept Based on thermodynamic principles, pinch technology offers a systematic approach to optimum energy integration in a process. The improvements in the process associated with this technique are not due to the use of advanced unit operations, but to the generation of a heat integration scheme. One of the key advantages of pinch technology over conventional design methods is the ability to set an *energy target* for the design. The energy target is the minimum theoretical energy demand for the overall process.

The principal objective of this technology is to match cold and hot process streams with a network of exchangers so that demands for externally supplied utilities are minimized. Pinch technology establishes a temperature difference, designated as the pinch point, that separates the overall operating temperature region observed in the process into two temperature regions. Once a pinch point has been established, heat from external sources must be supplied to the process only at temperatures above the pinch and removed from the process by cooling media only at temperatures below the pinch. Such a methodology will maximize the heat recovery in the process with the establishment of a heat exchanger network based on pinch analysis principles. The best design for an energy-efficient heat exchanger network will result in a tradeoff between the energy recovered and the capital costs involved in this energy recovery.

The success of pinch technology has led to more inclusive ideas of *process integration* in which chemical processes are examined for both mass and energy efficiency. Even though process integration is a relatively new technology, its importance in process design is continuing to grow as processes become more complex.[†]

[†] N. Hallale, *Chem. Eng. Prog.*, **97**(7): 30 (2001).

As noted above, one concept of pinch analysis is to set energy targets prior to the design of the heat exchanger network. Targets can be set for the heat exchanger network without actually having to complete the design.[†] Energy targets can also be set for the utility heat duties at different temperature levels such as refrigeration and steam heat supply levels. Pinch analysis provides the thermodynamic rules to ensure that the energy targets are achieved during the heat exchanger network design.

Pinch Technology Analysis The starting point for a pinch technology analysis is to identify in the process of interest all the process streams that need to be heated and all those that need to be cooled. This means identifying the streams, their flow rates and thermal properties, phase changes, and the temperature ranges through which they must be heated or cooled. This can be accomplished after mass balances have been performed and temperatures and pressures have been established for the process streams. Energy quantities can be calculated conveniently by using a simulation program or by traditional thermodynamic calculations. Some heat duties may not be included in the network analysis because they are handled independently of the integration. For example, distillation column reboiler heating and condenser cooling may be treated independently of the rest of the heat duties. However, such independent duties should always be considered for inclusion in the network.

All the process streams that are to be heated, their temperatures, and enthalpy change rates corresponding to their respective temperature changes or phase changes are then tabulated. The enthalpy change rate for *each* stream is obtained from

$$\Delta \dot{H} = \dot{m} C_p \, \Delta T = CP \, \Delta T \qquad (9\text{-}88)$$

where $\Delta \dot{H}$ is the enthalpy change rate, $\dot{m}$ the mass flow rate, C_p the heat capacity, ΔT the temperature change in the stream, and CP the heat capacity rate defined as the $\dot{m} C_p$ product. The enthalpy change rates are then added over each temperature interval that includes one or more of the streams to be heated. The resulting values allow plotting of the temperature versus enthalpy rate to provide a composite curve of all the streams that require a heat source. The same information and procedures are followed to develop a composite curve of the streams to be cooled. The resulting diagram, shown in Fig. 9-13, is designated as a *composite diagram* for the heat integration problem. The actual steps involved in preparing such a diagram are presented in Example 9-7.

It must be recognized that while each temperature is a fixed value on the vertical axis, enthalpy change rates are relative quantities. Enthalpy changes rather than absolute enthalpies are calculated via thermodynamic methods. Thus, the horizontal location of a composite line on the diagram is arbitrarily fixed. For the purposes of pinch technology analysis, the composite curve for streams to be cooled is located so as to be to the left, at every temperature, of the composite curve for those streams to be heated. Fixing the location of the composite curves with respect to one another with the use of a preselected value of $\Delta T_{\min}$ completes the composite diagram. The location

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[†] R. Smith, *Chemical Process Design,* McGraw-Hill, New York, 1995.

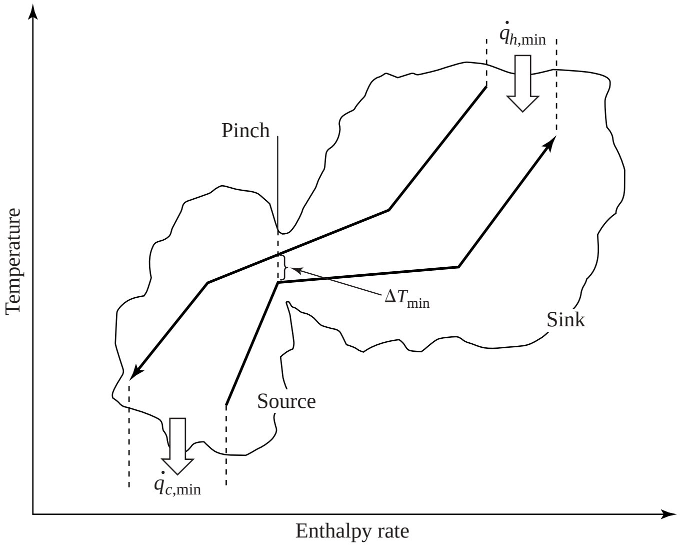

Figure 9-13
Composite diagram prepared for pinch technology analysis

of $\Delta T_{\min}$ on the composite diagram is where the two curves most closely approach each other in temperature, when measured in a vertical direction. On the first plotting of these curves, the vertical distance will rarely equal the preselected $\Delta T_{\min}$. This deficiency is remedied by moving one of the two curves *horizontally* until the distance of closest vertical approach matches the preselected $\Delta T_{\min}$. This can be done graphically or by calculation. All these steps can be accomplished readily with a spreadsheet, provided adequate thermodynamic property values are available.

The optimum value for $\Delta T_{\min}$ is generally in the range of 3 to 40°C for heat exchange networks, but is unique for each network and needs to be established before the pinch technology analysis is completed. If no cooling media are required below about 10°C, the optimum $\Delta T_{\min}$ is often in the range of 10 to 40°C. For a given $\Delta T_{\min}$, the composite curves define the utility heating and cooling duties.

The composite curves show the overall profiles of heat availability and heat demand in the process over the entire temperature range. These curves represent the cumulative heat sources and heat sinks in the process. The overlap between the two composite curves indicates the maximum quantity of heat recovery that is possible within the process.[†] The overshoot of the hot composite curve represents the minimum quantity of external cooling $\dot{q}_{c,\min}$ required, and the overshoot of the cold composite curve represents the minimum quantity of external heating $\dot{q}_{h,\min}$ required for the process.

Note that the composite curves can be used to evaluate the overall tradeoff between energy and capital costs. An increase in $\Delta T_{\min}$ causes the energy costs to

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[†] B. Linnhof and D. R. Vredevelt, *Chem. Eng. Prog.*, **80**(7): 33 (1984).

increase, but also provides larger driving forces for heat transfer and accompanying reduced capital costs.

Construction of a Composite Diagram EXAMPLE 9-7

Figure 9-14 shows a process flowsheet in which two reactant streams, each at 20°C, are to be heated to 160°C and fed to a reactor. It has been decided to mix the two streams before heating them, since both reactants need to be heated to the same temperature and will be mixed in the reactor anyway. Mixing these feed streams before they enter the reactor reduces the number of heat exchangers required from two to one. Since the reaction is slightly endothermic, the product stream leaves the reactor at 120°C. After further heating the reactant stream to 260°C, it is sent to a distillation column to recover the product. The liquid distillate product from the column is at 180°C and must be cooled to 20°C for storage. The bottom product from the column is cooled from 280 to 60°C. Although hot and cold utilities could be used for all the heating and cooling requirements, there clearly is an opportunity for savings in heat exchange since it is apparent from Fig. 9-14 that the process streams are, for the most part, within overlapping temperature ranges.

Since the reboiler temperature is too high for heat exchange with any of the process streams, it becomes an independent heat exchange problem. A hot oil utility stream available at 320°C and cooled to 310°C is to be used for heating the reboiler, as well as any process heating loads not met by process-process exchange. The cost of the hot oil is \$2.25/GJ. The condenser temperature is in a range that could be used to heat some of the process streams; however, for brevity purposes it will not be included in the present analysis. The cooling utility is cooling water available at 10°C with an allowable temperature rise of 10°C and a cost of \$0.25/GJ.

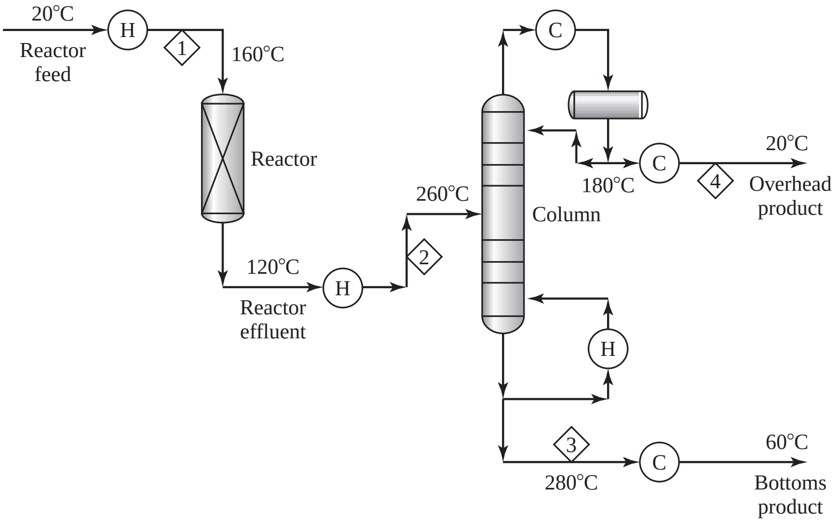

Figure 9-14
Process flowsheet diagram applicable for Example 9-7
(Reprinted with permission from *Handbook of Energy Efficiency*, F. Krieth and R. E. West, eds., Fig. 15.6, p. 597. Copyright © 1997 CRC Press, Boca Raton, Florida.)

Data for the process streams are provided in the following table.[†‡]

Stream Number	Stream description	Temperature interval, °C		Heat capacity rate, kJ/(s·°C) $CP = \dot{m}C_p$		Enthalpy change rate, kJ/s $CP(T_{out} - T_{in})$
Streams to be heated		**In**	**Out**			
1	Reactor feed	20	160	50		7,000
2	Reactor effluent	120	260	55		7,700
					Total	14,700
Streams to be cooled						
3	Bottom product	280	60	30		−6,600
4	Overhead product	180	20	40		−6,400
					Total	−13,000

a. Find the annual cost if only hot and cold utilities are used to supply all the heating and cooling for the process streams. Construct a composite diagram for this process.

b. Reconstruct the composite diagram to achieve a $\Delta T_{\min}$ of 20°C.

c. Construct the balanced composite diagram for the process with a $\Delta T_{\min}$ of 20°C, and find the minimum utility duties and the annual cost for the utilities after the heat integration.

■ Solution

a. The total enthalpy change rate provided in the table can be used directly to obtain the cost of providing all the heating and cooling requirements with only the hot and cold utilities.

$$\text{Hot utility cost} = \left(\frac{2.25}{10^6}\right)(14{,}700) = \$0.0331/\text{s}$$

$$\text{Cold utility cost} = \left(\frac{0.25}{10^6}\right)(13{,}000) = \$0.00325/\text{s}$$

$$\text{Total utility cost} = \$0.0363/\text{s}, \text{ or } \$1.03 \times 10^6/\text{yr (at 90\% operating factor)}$$

A review of the stream information in the table shows that only stream 1 is to be heated over the temperature interval from 20 to 120°C; between 120 and 160°C, streams 1 and 2 are to be heated; and from 160 to 260°C, only stream 2 is to be heated. These four temperatures and the corresponding stream numbers and values for the heat capacity rates are entered into the temperature interval table in the next page. Where there is more than one stream in an interval, the sum of the heat capacity rate values for all the streams is entered. The same procedure is followed for the streams to be cooled. The enthalpy change rate is obtained for each interval by multiplying the total heat capacity value by the temperature interval, and this product is entered into the sixth column of the table.

[†] See Fig. 9-14 to identify these streams.

[‡] In these tabulations, it is assumed that the heat capacity is independent of temperature. A consequence of this assumption is that the temperature versus enthalpy change rate curves are linear. In reality, the heat capacity generally tends to increase with temperature, resulting in some curvature in the curves. Determination of these curves using temperature-dependent heat capacity relationships would provide better results. However, the use of temperature-dependent properties does not change the heat integration method; only the details of the computations are changed.

Enthalpy change rates are fixed by selecting a baseline value for the enthalpy change rate at one stream temperature. A starting enthalpy change rate of 5000 kJ/s at 20°C is selected for the streams to be heated, while a value of 15,000 kJ/s at 280°C is chosen for the streams to be cooled. These values are arbitrary, selected only for graphical convenience since there is no unique composite diagram until a $\Delta T_{\min}$ has been implemented. The enthalpy change rates in the table are added to the initial enthalpy change rate values to yield the enthalpy rate values tabulated with the corresponding temperatures.

Initial temperature interval table

Stream number[†]	**Required temperature interval, °C**		**Heat capacity rate *CP*, kJ/(s·°C)**	**Enthalpy change rate, kJ/s**	**Initial enthalpy selection**	
					X	***Y***
Streams to be heated	**In**	**Out**			5,000	20
1	20	120	50	5,000	10,000	120
1 & 2	120	160	105	4,200	14,200	160
2	160	260	55	5,500	19,700	260
				Total 14,700		
Streams to be cooled					15,000	280
3	280	180	30	−3,000	12,000	180
3 & 4	180	60	70	−8,400	3,600	60
4	60	20	40	−1,600	2,000	20
				Total −13,000		
Utilities						
Hot oil	320	310		−3,900		
Cooling water	10	20		2,200		

[†] See Fig. 9-14 to identify these streams.

The sets of temperature versus enthalpy rate values that have been established for the streams that are to be cooled and those that are to be heated are plotted in Fig. 9-15. This is a composite diagram for the heat integration problem. It is apparent from the figure that the closest vertical approach of the two curves occurs at an enthalpy change rate of 10,000 kJ/s. This is the pinch point for the two composite curves and occurs where the temperature of the streams that are to be heated is 120°C and the temperature of the streams that are to be cooled is about 153°C. This $\Delta T_{\min}$ of 33°C is simply a consequence of the starting enthalpy rates that were initially chosen.

b. To achieve a $\Delta T_{\min}$ of 20°C, one of the curves must be moved horizontally to bring the two curves closer together. One way to do this is to move the curve representing the streams that are to be cooled to the right, so that a temperature of 140°C is intercepted at an enthalpy rate of 10,000 kJ/s. In Fig. 9-15, the slope of that portion of the curve at the pinch point is obtained from

$$\frac{180-60}{12{,}000-3600} = 0.01428$$

and the intercept is

$$180-(0.01428)(12{,}000) = 8.57$$

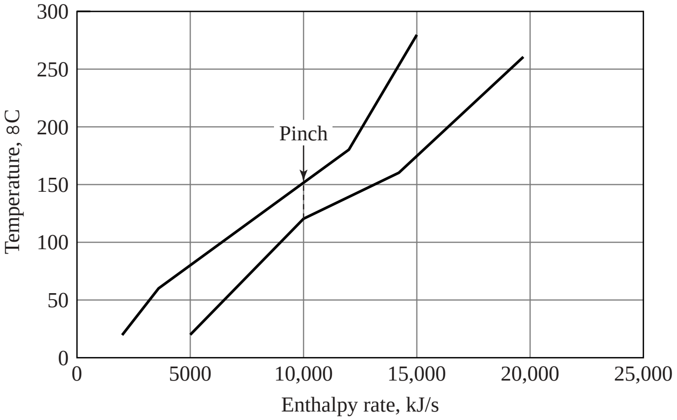

Figure 9-15
Composite diagram with 33°C approach temperature

At 140°C, the enthalpy rate now is

$$\frac{140 - 8.57}{0.01428} = 9204 \text{ kJ/s}, \quad \text{or} \quad \sim 9200 \text{ kJ/s}$$

This value of 9200 must be increased to 10,000 kJ/s to make the ΔT at the pinch point equal to 20°C. Therefore, 800 kJ/s must be added to every enthalpy change rate value associated with the streams to be heated. This action changes the enthalpy rate to 15,800 kJ/s. The revised temperature interval table is shown below.

Revised temperature interval table

Stream number†	Required temperature interval, °C		Heat capacity rate, kJ/(s·°C)	Enthalpy change rate, kJ/s		Revised enthalpy selection	
						X	*Y*
Streams to be heated	**In**	**Out**				5,000	20
1	20	120	50		5,000	10,000	120
1 & 2	120	160	105		4,200	14,200	160
2	160	260	55		5,500	19,700	260
				Total	14,700		
Streams to be cooled						15,800	280
3	280	180	30		−3,000	12,800	180
3 & 4	180	60	70		−8,400	4,400	60
4	60	20	40		−1,600	2,800	20
				Total	−13,000		
Utilities							
Hot oil	320	310			−3,900	15,800	310
						19,700	320
Cooling water	10	20			2,200	2,800	10
						5,000	20

[†] See Fig. 9-14 to identify these streams.

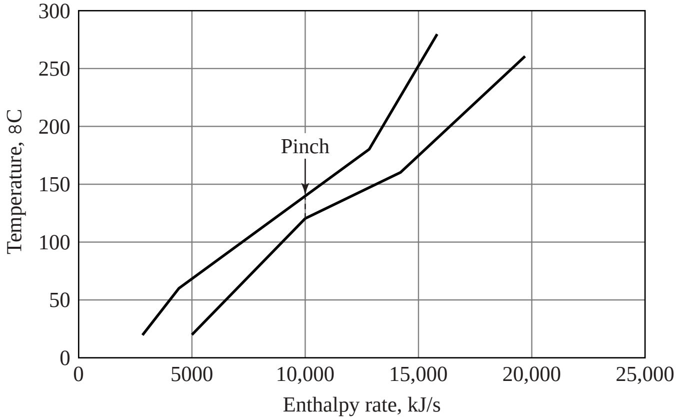

Figure 9-16
Composite diagram with 20°C approach temperature

These values are plotted in Fig. 9-16, the composite diagram for this problem for a $\Delta T_{\min}$ of 20°C.

c. It is clear from the composite diagram of Fig. 9-16 that above the cold stream temperature of about 190°C there is no hot stream curve above the cold stream curve. Since all heat transfer is vertical on a composite diagram, there is no process stream available to heat the cold stream from 190 to 260°C with an enthalpy change rate of about 3900 kJ/s. Therefore, a hot utility must be used to provide this heat. In fact, this quantity of heat needed is the *minimum hot utility requirement* for the problem as defined in Fig. 9-16, with its temperatures, heat duties, and specified $\Delta T_{\min}$ of 20°C. Similarly, below a hot stream temperature of about 70°C there is no cold process stream available to cool the hot process streams. Thus, a cold utility must be used to remove this heat. The corresponding $\Delta \dot{H}$ of about 2200 kJ/s is the *minimum cold utility requirement* for the problem as defined. For this process with a $\Delta T_{\min}$ of 20°C, various heat exchanger networks can be devised which require more hot and cold utilities, but no network that will require less utilities. Only by decreasing $\Delta T_{\min}$ can these heat duties be reduced, and then not reduced beyond the values corresponding to a $\Delta T_{\min}$ of zero. If the curves for the required heating and cooling utilities are included in the composite diagram and all heating and cooling loads are satisfied, the diagram is called a *balanced composite diagram,* as shown in Fig. 9-17.

Examination of Fig. 9-17 shows that at the cold end of the network, the process stream temperature is 20°C and the cooling water enters at 10°C, for an approach temperature difference of only 10°C. This is a consequence of the available water inlet temperature and the required outlet temperature for the warm stream. While this temperature difference appears to violate the $\Delta T_{\min}$ specification of 20°C, it actually does not because $\Delta T_{\min}$ applies only to process stream heat exchanges and not to utility process heat exchanges. Nonetheless, it might be useful to determine whether the 20°C outlet temperature for the warm stream is necessary. If that temperature can be increased, the area of the cooler can be reduced.

The minimum hot utility requirement is 3900 kJ/s—the difference between the highest enthalpy rate of 19,700 kJ/s for the streams that are to be heated and the highest enthalpy rate of

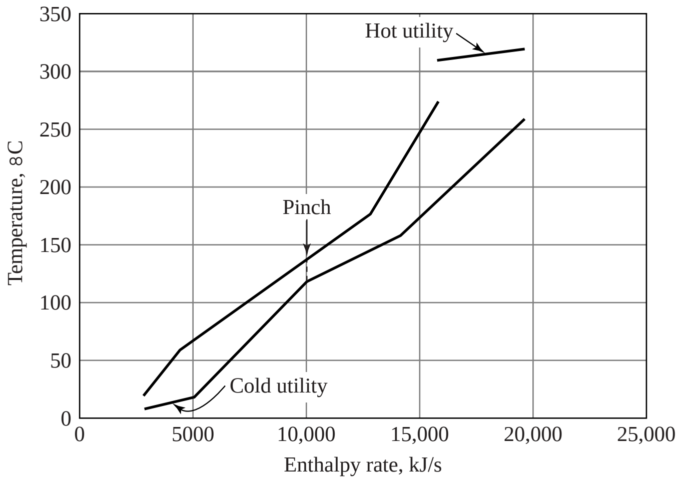

Figure 9-17
Balanced composite diagram

15,800 kJ/s for the streams that are to be cooled. The minimum cold utility requirement is 2200 kJ/s—the difference between the lowest enthalpy rate of 5000 kJ/s for the streams that are to be heated and the lowest enthalpy rate of 2800 kJ/s for the streams that are to be cooled. The total utility cost for these duties is

$$\left(\frac{2.25}{10^6}\right)(3900) + \left(\frac{0.25}{10^6}\right)(2200) = \$0.00933/\text{s}$$

providing a utility savings of \$0.0270/s or $\$7.66 \times 10^5$/yr (at 90 percent operating factor) compared to using utilities for all the heating and cooling duties. This savings does not come without a cost, however, since it requires purchasing, installing, operating, and maintaining the heat exchangers needed for the process-process heat exchange. Whether this is worthwhile depends upon an economic analysis of the savings and costs.

■

Pinch Technology Guidelines Pinch technology includes several principles that offer guidance in constructing a feasible and near optimal heat exchanger network:

1. Do not transfer heat across the pinch point; the pinch point divides the heat exchanger network into two distinct regions.
2. Do not use a hot utility below the pinch point.
3. Do not use a cold utility above the pinch point.
4. Heat transfer always takes place from a higher to a lower temperature.
5. No process-process heat exchanger should have an approach temperature less than the specified $\Delta T_{\min}$.
6. Minimize the number of heat exchangers that are needed.
7. Avoid loops in the heat integration system.

A few comments on these guidelines may be helpful. For example, any process-stream heat that is transferred from one side of the pinch point to the other side of the pinch point only increases the requirements for both utilities. This generally results in a nonoptimal network design and should be recommended only if it can be economically justified. Also, using a hot utility below the pinch point or a cold utility above the pinch point only increases the requirement for each utility and thereby nearly always leads to a nonoptimal design. Violation of the ΔT_{min} guideline will change the structure of the heat integration system and will probably move the solution away from optimal conditions. Note also that the optimal network is usually the one that uses the least number of heat exchangers to meet the problem needs. Using more than the minimum number is usually not optimal. The *loop* referred to in the guidelines infers that there is an energy route that could be followed that leads back to the starting point. This can happen, for example, when the same two streams exchange heat in more than one heat exchanger or when a utility is used where it is not needed. Each loop adds an unnecessary heat exchanger to the network.

The minimum number of heat exchangers required for a given composite diagram can be obtained from the diagram. The number of exchangers required is given by[†]

$$N_E = N_s - 1 \tag{9-89}$$

where N_E is the number of heat exchangers and N_s the total number of streams exchanging heat. This rule must be applied to each separate section of heat transfer, generally four in most network problems. These are identified from a balanced composite diagram by drawing a vertical line at the pinch point, another vertical line where the hot utility is initially required, and a third vertical line where the cold utility initially is required. This divides the diagram into four distinct sections which are, moving from left to right on the diagram, the cold utility section, the process exchange section below the pinch (also designated as the *source section*), the process exchange section above the pinch (also designated as the *sink section*), and the hot utility section. In each section, the sum of the enthalpy change rate values for all the streams in the section that are to be heated will match the sum obtained for all the streams in that same section that are to be cooled, except the latter will have a minus sign. Moreover, because the two curves are developed to have only one pinch point, there will be process stream matches that are consistent with the specified ΔT_{min}.

In each of the four sections, the number of streams participating in the heat exchange, including any utility streams, is counted. Labeling line segments on the diagram with stream names or numbers expedites this counting. Within any one section, each stream is counted only once; but each stream is counted in every section in which it appears. The minimum number of heat exchangers needed in a section is then obtained directly with Eq. (9-89). The resulting four values, when added, give the minimum total number of heat exchangers needed for the overall network. By emphasizing the goal of minimizing the number of heat exchangers used, the design engineer should be able to develop a heat integration network by using the minimum number of heat

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[†] E. C. Hohmann, Ph.D. thesis, University of Southern California, Los Angeles, 1971.

exchangers. Such a network should be at least near optimal for the problem posed. It is virtually certain that a network using more than the minimum number of exchangers will not be optimal.

Identifying an Optimal Heat Exchange Network There is not a unique network for any but a two-stream heat exchange problem. So the design engineer needs both insight and creativity, in addition to described procedures that identify an appropriate network among the many possibilities. A network is developed one section at a time. Since the minimum number of heat exchangers already has been established, the task now becomes one of identifying which streams go to which exchangers. For each heat exchanger, a heat balance must be satisfied. If it is assumed that there are negligible heat gains or losses from the exchanger, the heat balance equation is

$$\Delta \dot{H} = 0 = [CP(T_{\text{out}} - T_{\text{in}})]_{\text{hot stream}} + [CP(T_{\text{out}} - T_{\text{in}})]_{\text{cold stream}} \qquad (9\text{-}90)$$

Some specific guidelines useful in finding good heat exchange matches are given below:

1. At the pinch point, each stream that is to be heated must enter or leave an exchanger at the pinch point, cold composite temperature; and each stream that is to be cooled must enter or leave an exchanger at the pinch point, hot composite temperature.
2. Start the analysis of exchangers in the sink and source sections at the pinch point where all temperatures are fixed.
3. A point of discontinuity in a composite curve indicates the addition or removal of a stream, or the onset of a phase change. The stream that is being added or removed must enter or leave an exchanger at the temperature where the discontinuity occurs.
4. If there are only two streams in a section, they both go to the one exchanger that is reserved for the section.
5. If there are three streams in a section, the stream with the largest change in enthalpy should be split across two exchangers to satisfy the heat duties for each of the other two streams.
6. If there are four streams in a section, three heat exchangers will be required. If three streams are either heated or cooled, then the fourth stream is split into three flows to satisfy the heat duties from the other three streams. If there are two streams that are to be heated and two streams that are to be cooled, a convenient way to allocate the streams to exchangers is to prepare a new composite diagram and use this to make the allocations. (This is demonstrated in Example 9-8.)
7. If there are more than four streams in a section, attempt to follow guideline 6. The use of a computer-based algorithm is recommended for these more complicated cases.[†]

[†] Two examples of this type of software are ASPEN PLUS-PINCH and PRO/II-LNGHY.

8. If the matches between heat exchange duties result in more than the minimum number of exchangers being required, try other matches. Look for loops and eliminate them.
9. If a discontinuity occurs in a process stream curve within a utility section, it may be possible by means of the adjacent process section to meet the duty of the stream by leaving the curve at the discontinuity and still not violate the $\Delta T_{\min}$. Doing so reduces the required number of exchangers by 1 without changing the utility requirements and many times is an economical choice.

Establishing Minimum Number of Heat Exchangers and Recommended Heat Exchange Network

EXAMPLE 9-8

Refer to the process heating and cooling problem presented in Example 9-7. In this problem,

a. Determine the minimum number of heat exchangers required for a $\Delta T_{\min}$ of 20°C.
b. Establish a heat exchanger network meeting the process requirements with the minimum required number of exchangers, as evaluated in part (a).
c. Reevaluate the number of exchangers required in the cold utility section.
d. Recommend a heat exchanger network for this process.

■ Solution

a. The minimum number of heat exchangers required for the problem is determined with the aid of Fig. 9-18 and Eq. (9-89). On the graph, vertical lines are drawn to divide the curves into four independent exchange sections: the cold utility section, the process exchange section below the pinch point, the process exchange section above the pinch point, and the hot utility section.

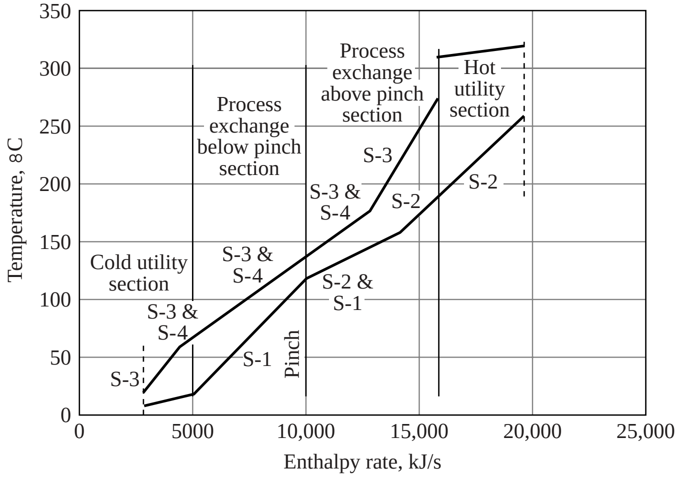


Figure 9-18
Balanced composite diagram with 20°C approach temperature

The lines on the diagram are labeled with the streams that are represented. The total number of hot and cold streams in each section is then counted and decreased by 1 to provide the number of heat exchangers required in those sections. Doing this in the cold utility section shows that three streams and two exchangers are required. In the process section below the pinch, there are three streams; thus, two exchangers are required. In the process section above the pinch, there are four streams and three exchangers. Since there are two streams in the hot utility section, one exchanger is needed. The minimum total number of exchangers required therefore is eight.

b. Starting with the cold utility section, and referring to Fig. 9-18, streams are matched to obtain the desired heat exchange. In this section, two exchangers are needed; one is for stream 4 and the cooling water, and the other is for stream 3 and the cooling water. These exchangers are designated as C-1 and C-2.

The inlet temperatures of the process streams to the cold utility section in C-1 and C-2 are determined by energy balances made in the process section below the pinch. Consideration should be given to cooling stream 3 to the required 60°C by using a process stream, and this will be done in part (c).

Now proceed to the process section below the pinch point shown in Fig. 9-18. In this section two heat exchangers are required. Stream 1 with an inlet temperature of 20°C and an exit temperature of 120°C, will be split between two exchangers, E-1 and E-2. Both stream 3 and stream 4 will be cooled from 140°C to an exit temperature T_{out}, given by an energy balance over the two exchangers

$$50(120-20)+(30+40)(T_{\text{out}}-140)=0$$

$$T_{\text{out}}=\frac{-5000+9800}{70}=68.6^\circ\text{C}$$

This is the temperature of streams 3 and 4 leaving E-1 and E-2 and the inlet temperature to coolers C-1 and C-2.

An energy balance for exchanger E-1, between streams 1 and 3, gives the fraction of stream 1 that must be used in this exchanger:

$$50x(120-20)+30(68.6-140)=0$$

$$x=\frac{2142}{5000}=0.428$$

where x is the fraction of stream 1 sent to exchanger E-1 resulting in a heat duty of 2142 kJ/s for E-1. The fraction of stream 1 sent to exchanger E-2 is 0.572. The heat duty for E-2 is $0.572(50)(120-20)$, or 2860 kJ/s.

The section above the pinch point requires three exchangers. The problem here is to match up the four streams by using only three exchangers. At the pinch point, both of the streams that are to be cooled must exit from the heat exchanger at their pinch point temperature of 140°C while both of the streams that are to be heated must enter the heat exchanger at their pinch point temperature of 120°C. A simple way to illustrate the problem is to plot all four streams on a temperature versus enthalpy graph. Begin by setting up an energy balance table for all the individual streams in the section above the pinch point, as shown here.

Streams in the section above the pinch	**Temperature interval, °C**		**Heat capacity rate, kJ/(s·°C)**	**Enthalpy change rate, kJ/s**	**Enthalpy rate, kJ/s**	
Streams to be heated	**In**	**Out**			**In**	**Out**
S-1	120	160	50	2000	10,000	12,000
S-2	120	189.1	55	3800	10,000	13,800
				Total 5800		
Streams to be cooled						
S-3	280	140	30	−4200	14,200	10,000
S-4	180	140	40	−1600	11,600	10,000
				Total −5800		

All the values in the first four columns of the table are directly available from the given data, except the exit temperature for stream 2. This value may be estimated from Fig. 9-18 or calculated from an energy balance. The total enthalpy change per second of 5800 kJ/s for streams 1 and 2 must equal that of streams 3 and 4. Since the enthalpy change rate of stream 2 is known to be 2000 kJ/s, that for stream 1 must be the difference between 5800 kJ/s and 2000 kJ/s, or 3800 kJ/s. The exit temperature of stream 2 can be calculated from

$$55(T_{\text{out}} - 120) = 3800$$

$$T_{\text{out}} = 189.1^\circ\text{C}$$

The values in the preceding table are then used to plot the individual stream values, as shown in Fig. 9-19. The latter can now be used to match streams to form a heat exchange network, for this section. Three different matches will be developed.

Match 1

In Fig. 9-20, a vertical line is drawn from the upper end of line S-4 to line S-1. All the 1600 kJ/s heat duty of stream S-4 will be transferred to stream S-1 in heat exchanger E-3. The exit temperature of stream S-1 can be obtained from the graph or calculated by an energy balance as

$$1600 = 50(T_{\text{out}} - 120)$$

$$T_{\text{out}} = \frac{1600}{50} + 120 = 152^\circ\text{C}$$

Next, a vertical line is drawn from the upper end of line S-2 to line S-3. All the 3800 kg/s heat duty of stream 2 will be supplied by stream 3 in heat exchanger E-4. The exit temperature of stream 3 leaving exchanger E-4 can be obtained from the graph or calculated by another energy balance as

$$3800 = 30(T_{\text{out}} - 140)$$

$$T_{\text{out}} = \frac{3800}{30} + 140 = 266.7^\circ\text{C}$$

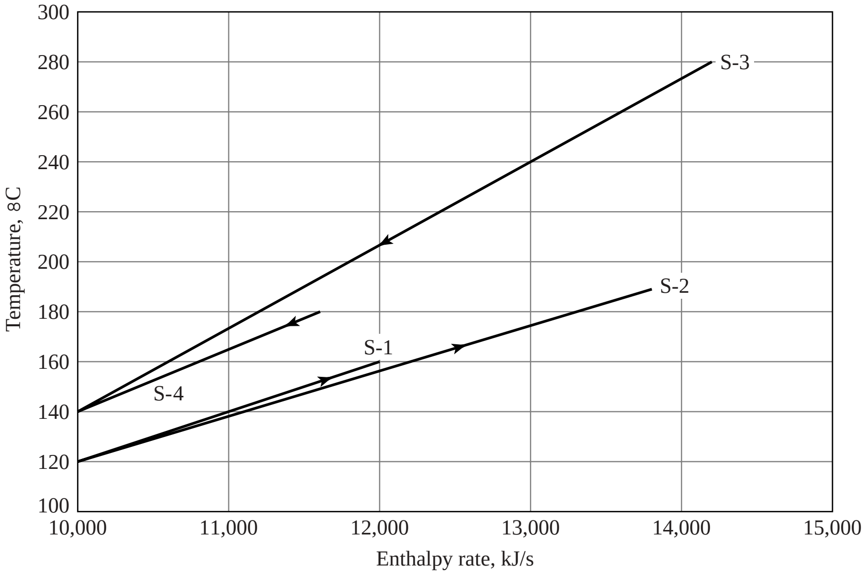


Figure 9-19
Enthalpy rates for the four streams in section above pinch

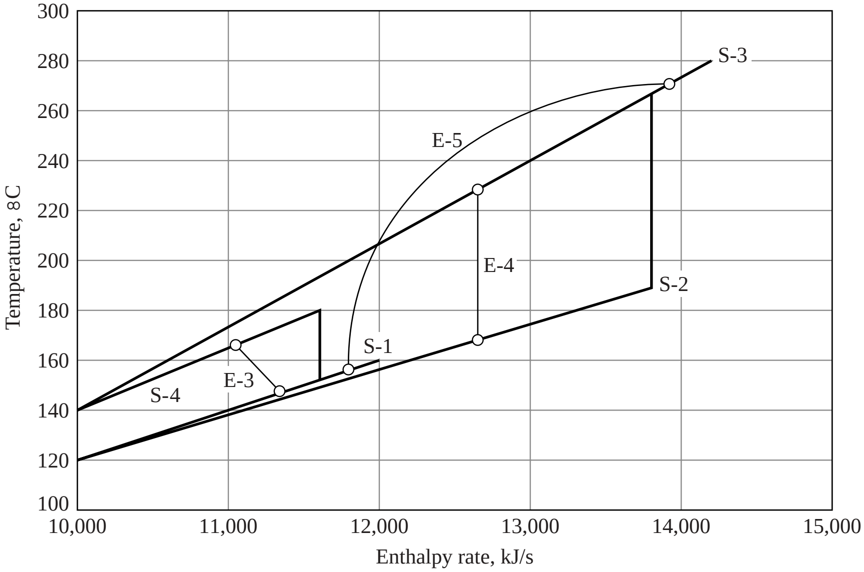


Figure 9-20
Possible heat exchange for match 1

The remaining 400 kJ/s heat duty of stream 3 not removed in exchanger 4 is removed in exchanger E-5 by the 400 kJ/s heat duty that is available from stream 1. This arrangement of the three heat exchangers is shown in Fig. 9-23c.

The minimum number of heat exchangers for this section has been met. Since all temperature differences are 20°C or greater, an acceptable network has been developed. Note, however, that E-5 has a much smaller heat duty than in the other two heat exchangers. As a consequence, consideration should be given to the elimination of E-5 in this match. This can be accomplished with a small increase in heating and cooling utilities, provided the savings in heat exchanger and associated costs are sufficient to justify such a change. This choice can only be made by an economic analysis.

Match 2

Note that in match 1 the higher-temperature end of stream S-3 is used to heat a much cooler portion of stream S-1. To alleviate this heat exchange inefficiency, some modification to match 1 is suggested. Begin by leaving exchanger E-3 as provided in match 1, but providing the remaining duty for the upper end of stream S-1 by heat duty from the section of stream S-3 immediately above that of stream S-1 in heat exchanger E-4, as shown in Fig. 9-21. This provides a much closer temperature match between the two streams.

Now use the two remaining sections of stream S-3 to meet the heat duties of stream S-2; but this requires two exchangers, E-5 and E-6. Even though the heat loads all balance and the temperature differences are above the $\Delta T_{\min}$, this match is not a good choice because an extra heat exchanger is required. In fact, this match has created a loop that can be verified by starting at E-6 in Fig. 9-21, moving down line S-2 to E-5, and following the E-5 curve to line S-3 and then back to E-6. This path

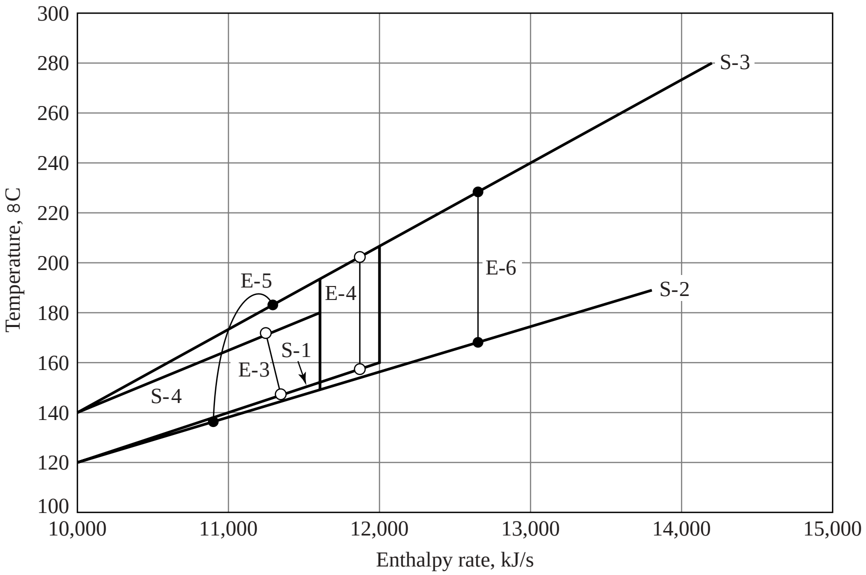


Figure 9-21
Possible heat exchange match 2

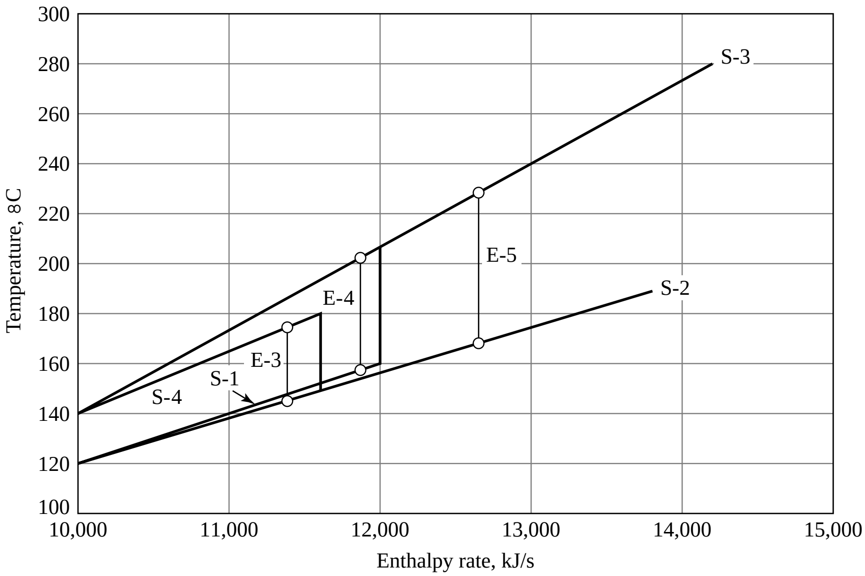


Figure 9-22
Possible heat exchange match 3

is marked with the darkened circles in Fig. 9-21. Since this violates one of the heat integration guidelines, this match should be rejected.

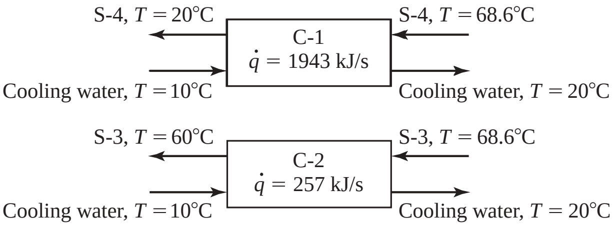
Match 3

With reference to Fig. 9-22, match streams S-4 and S-2 in heat exchanger E-3. This match removes the total heat duty of 1600 kJ/s from stream S-4. The exit temperature of stream S-2 in heat exchanger E-3 can be obtained from the graph or calculated by an energy balance as 149.1°C. Now match all of stream S-1 with the low-temperature end of stream S-3 in heat exchanger E-4. This heat exchange utilizes all the 2000 kJ/s heat duty of stream S-1. An energy balance provides an inlet temperature into E-4 of 206.7°C. The remaining heat duty of stream S-3 supplies the 2200 kJ/s required by stream S-2 in exchanger E-5. As in match 1, all the heat loads and temperature constraints are met, and the minimum number of heat exchangers is used. An economic advantage may occur with this match since the heat duties in the three heat exchangers are more equally distributed than in match 1.

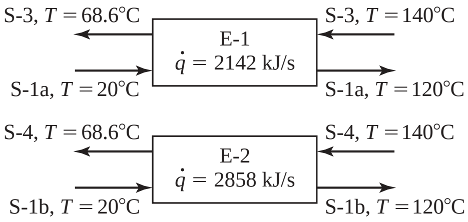
Finally, the unmet heat load of 3900 kJ/s on the upper end of stream S-2 in Fig. 9-18 is met by the use of the hot oil utility in heater H-1, as shown in Fig. 9-23e. Combining the exchangers shown in Fig. 9-23, using either match 1 or match 3, yields an acceptable network.

c. Streams S-3 and S-4 in part (b) were both cooled to 68.6°C in the section located below the pinch. Since stream S-3 only needs to be cooled to 60°C, it might be advantageous to use stream S-1 to cool stream S-3 to 60°C rather than to use a separate cooler. The remaining heat duty in stream S-1 could be used to partially cool stream S-4. Further cooling of stream S-4 to 20°C would be accomplished with cooling water. No additional cooling water would be required, but one less cooler would be needed. For this option, exchanger E-3 needs to be reevaluated with

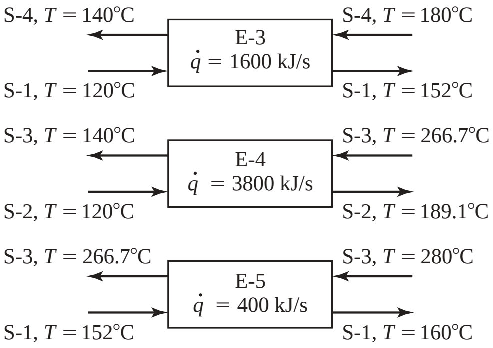
(a) Cold utility section



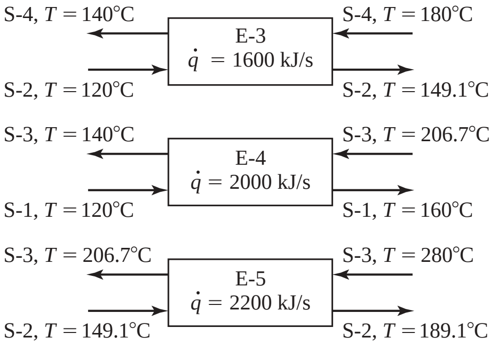
(b) Section below the pinch



(c) Section above the pinch for match 1



(d) Section above the pinch for match 3



(e) Hot utility section

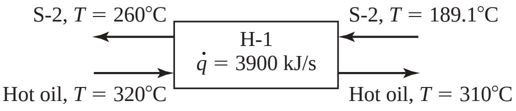


Figure 9-23
Development of heat exchanger network

stream S-3 leaving at 60°C. By an energy balance

$$50x(120 - 20) + 30(60 - 140) = 0$$

$$x = \frac{2400}{5000} = 0.48$$

Thus, 48 percent of stream S-1 will be used in heat exchanger E-1 with a heat duty of 2400 kJ/s. In turn, 52 percent of stream S-1 goes to heat exchanger E-2. An energy balance around exchanger E-2 determines the exit temperature of stream S-1 as

$$50(0.52)(120 - 20) = -40(T_{\text{out}} - 140)$$

$$T_{\text{out}} = \frac{2600}{-40} + 140 = 75^\circ\text{C}$$

This flow arrangement results in the same cooling utility duties as before, but with only one cooler rather than two as in match 1. One cooler is more economical than two and should be selected for the proposed flowsheet.

d. A recommended network for this problem could include the single cooler C-1, exchangers E-1 and E-2 corresponding to the single-cooler case, match 1 or match 3 for the section above the pinch point, and heater H-1 for the hot utility section. The final network that uses one cooler and the results from match 3, as shown in Fig. 9-24, is probably preferable, but the final network selection depends upon an economic analysis.

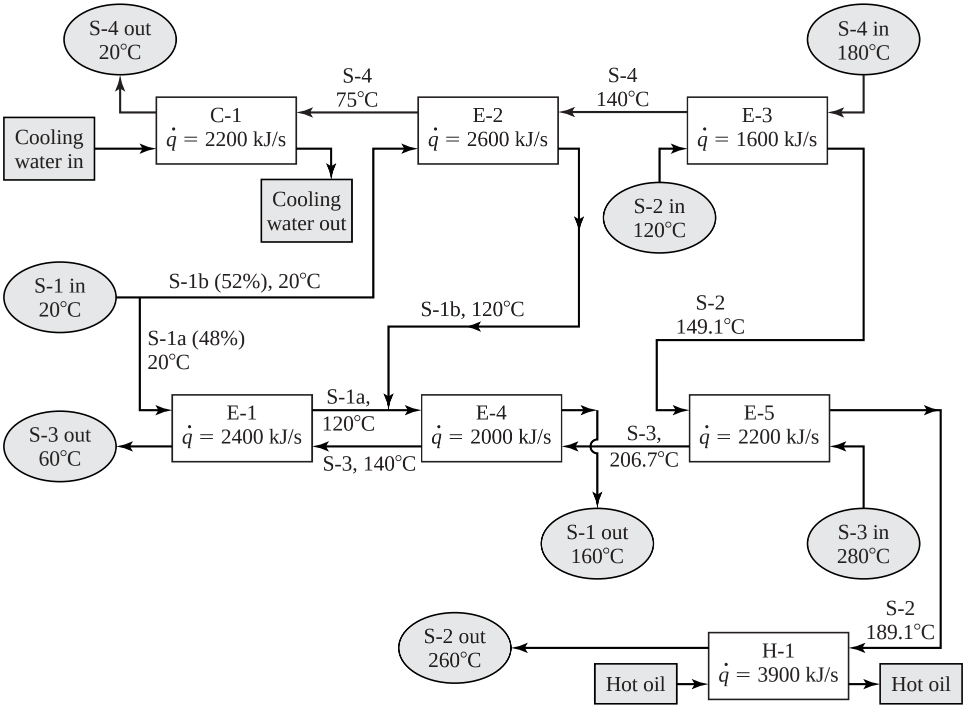


Figure 9-24
Recommended heat exchanger network

Optimization of Heat Exchange Networks In Example 9-8, a heat exchange network was recommended that appeared to be close to optimal based on qualitative observations. However, finding the feasible networks and then finding that network which maximizes the net present worth, or minimizes the present worth of all variable costs, for the application would make a preferable selection. This could be done with a computer-based, heat exchanger network synthesis tool, or with a good optimization program. The optimal network in Example 9-8 has not yet been determined, however, because the example was prepared with a predetermined value of $\Delta T_{\min}$. The particular value selected may not yield a global optimum. Therefore, it is necessary to repeat the process for other values of $\Delta T_{\min}$ until a global optimum is obtained. Once again, this can be done with a computer-based, heat exchanger-network synthesis tool; or it can be done with a single-variable directed search such as a five-point or Golden section search. It should be clear from the foregoing simple example why a good computer-based method is desirable for such an optimization.