17 Heat Exchanger Networks III – Capital and Total Cost Targets

In addition to being able to predict the energy costs of the heat exchanger network directly from the material and energy balance, it would be useful to be able to calculate the capital cost of the network.

The principal components that contribute to the capital cost of the heat exchanger network are:

- number of units (matches between hot and cold streams)
- heat exchange area
- number of shells
- materials of construction
- heat exchanger type
- pressure rating.

Now consider each of these components in turn and explore whether they can be estimated from the material and energy balance without having to perform heat exchanger network design.

17.1 NUMBER OF HEAT EXCHANGE UNITS

To understand the minimum number of matches or units in a heat exchanger network, some basic results of *graph theory* can be used[1,2]. A *graph* is any collection of points in which some pairs of points are connected by lines. Figures 17.1a and 17.1b give two examples of graphs. Note that the lines such as *BG* and *CE* and *CF* in Figure 17.1a are not supposed to cross, that is, the diagram should be drawn in three dimensions. This is true for the other lines in Figure 17.1 that appear to cross.

In this context, the points correspond to process and utility streams, and the lines to heat exchange matches between the heat sources and heat sinks.

A *path* is a sequence of distinct lines that are connected to each other. For example, in Figure 17.1a *AECGD* is a path. A graph forms a single *component* (sometimes called a *separate system*) if any two points are joined by a path. Thus, Figure 17.1b has two components (or two separate systems), and Figure 17.1a has only one.

A *loop* is a path that begins and ends at the same point, like *CGDHC* in Figure 17.1a. If two loops have a line in common, they can be linked to form a third loop by deleting the common line. In Figure 17.1a, for example, *BGCEB* and *CGDHC* can be linked to give *BGDHCEB*. In this case, this last loop is said to be *dependent* on the other two.

From graph theory, the main result needed in the present context is that the number of independent loops for a graph is given by[1]:

$$N_{UNITS} = S + L - C \tag{17.1}$$

where N_{UNITS} = number of matches or units (lines in graph theory)
S = number of streams including utilities (points in graph theory)
L = number of independent loops
C = number of components

In general, the final network design should be achieved in the minimum number of units to keep down the capital cost (although this is not the only consideration to keep down the capital cost). To minimize the number of units in Equation 17.1, L should be zero and C should be a maximum. Assuming L to be zero in the final design is a reasonable assumption. However, what should be assumed about C? Consider the network in Figure 17.1b that has two components. For there to be two components, the heat duties for streams A and B must exactly balance the duties for streams E and F. Also, the heat duties for streams C and D must exactly balance the duties for streams G and H. Such balances are likely to be unusual and not easy to predict. The safest assumption for C thus appears to be that there will be one component only, that is, $C = 1$. This leads to an important special case when the network has a single component and is loop-free. In this case[1,2]:

$$N_{UNITS} = S - 1 \tag{17.2}$$

Equation 17.2 put in words states that the minimum number of units required is one less than the number of streams (including utility streams).

This is a useful result since, if the network is assumed to be loop-free and has a single component, the minimum number of units can be predicted simply by knowing the number of streams. If the problem does not have a pinch, then Equation 17.2 predicts the minimum number of units. If the problem has a pinch, then Equation 17.2 is applied on each side of the pinch separately[2]:

$$N_{UNITS} = [S_{ABOVE\ PINCH} - 1] + [S_{BELOW\ PINCH} - 1] \tag{17.3}$$

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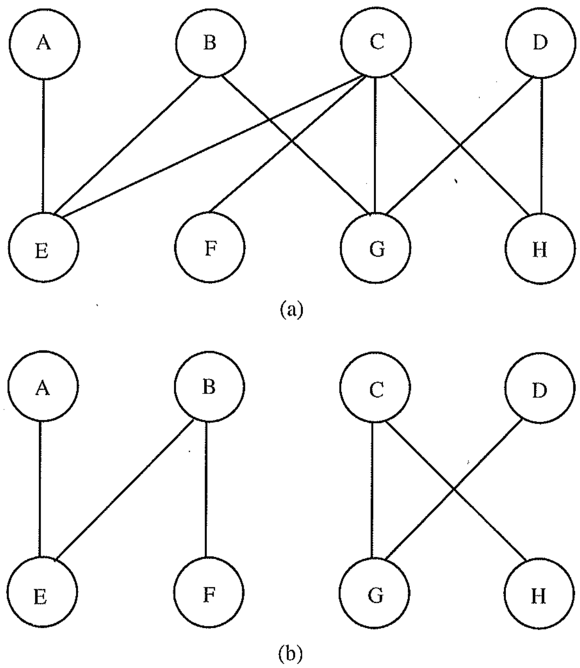

Figure 17.1 Two alternative graphs. (From Linnhoff B, Mason D and Wardle I, 1979, *Comp and Chem Engg*, **3**: 279, reproduced by permission of Elsevier Ltd.)

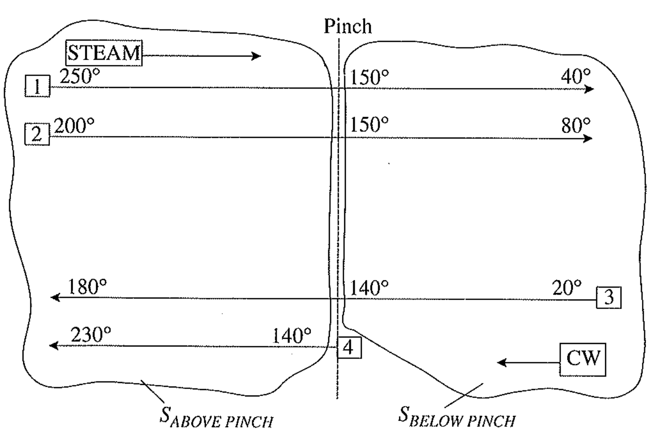

Figure 17.2 To target the number of units for pinched problems the streams above and below the pinch must be counted separately with the appropriate utilities included.

Example 17.1 For the process in Figure 17.2, calculate the minimum number of units given that the pinch is at 150°C for the hot streams and 140°C for the cold streams.

Solution Figure 17.2 shows the stream grid with the pinch in place dividing the process into two parts. Above the pinch, there are five streams, including the steam. Below the pinch, there are four streams, including the cooling water. Applying Equation 17.3:

$$N_{UNITS} = (5 - 1) + (4 - 1)$$
$$= 7$$

Looking back at the design presented for this problem in Figure 16.9, it does in fact use the minimum number of units of 7. In the next chapter, design for the minimum number of units will be addressed.

17.2 HEAT EXCHANGE AREA TARGETS

In addition to giving the necessary information to predict energy targets, the composite curves also contain the necessary information to predict network heat transfer area. To calculate the network area from the composite curves, utility streams must be included with the process streams in the composite curves to obtain the *balanced composite curves*[3], going through the same procedure as illustrated in Figures 16.3 and 16.4 but including the utility streams. The resulting balanced composite curves should have no residual demand for utilities. The balanced composite curves are divided into vertical *enthalpy intervals* as shown in Figure 17.3. Assume initially that the overall heat transfer coefficient U is constant throughout the process. Assuming true countercurrent heat transfer, the area requirement for enthalpy interval k for this *vertical heat transfer* is given by[1,3]:

$$A_{NETWORKk} = \frac{\Delta H_k}{U \Delta T_{LMk}} \tag{17.4}$$

where $A_{NETWORKk}$ = heat exchange area for vertical heat transfer required by interval k
ΔH_k = enthalpy change over interval k
ΔT_{LMk} = log mean temperature difference for interval k
U = overall heat transfer coefficient

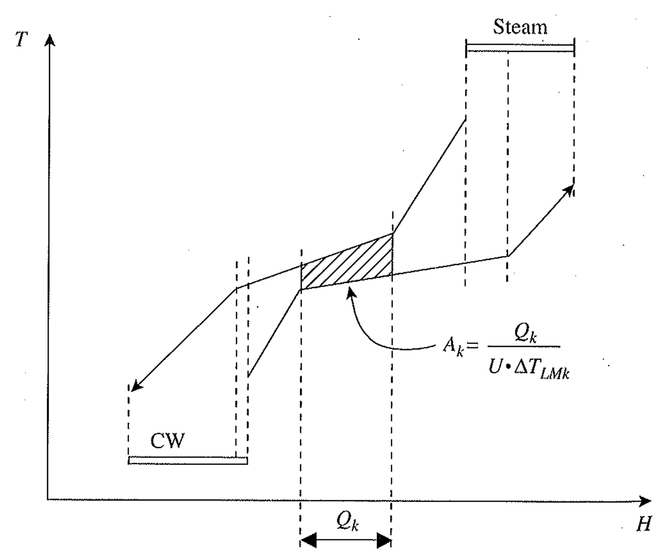

Figure 17.3 To determine the network area the balanced composite curves are divided into enthalpy intervals.

To obtain the network area, Equation 17.4 is applied to all enthalpy intervals[1,3]:

$$A_{NETWORK} = \frac{1}{U} \sum_{k}^{INTERVALS\ K} \frac{\Delta H_k}{\Delta T_{LMk}} \quad (17.5)$$

where $A_{NETWORK}$ = heat exchange area for vertical heat transfer for the whole network
K = total number of enthalpy intervals

The problem with Equation 17.5 is that the overall heat transfer coefficient is not constant throughout the process. Is there some way to extend this model to deal with the individual heat transfer coefficients?

The effect of individual stream film transfer coefficients can be included using the following expression, which is derived in Appendix F[3,4]:

$$A_{NETWORK} = \sum_{k}^{INTERVALS\ K} \frac{1}{\Delta T_{LMk}} \left[\sum_{i}^{HOT\ STREAMS\ I} \frac{q_{i,k}}{h_i} + \sum_{j}^{COLD\ STREAMS\ J} \frac{q_{j,k}}{h_j} \right] \quad (17.6)$$

where $q_{i,k}$ = stream duty on hot stream i in enthalpy interval k
$q_{j,k}$ = stream duty on cold stream j in enthalpy interval k
h_i, h_j = film transfer coefficients for hot stream i and cold stream j (including wall and fouling resistances)
I = total number of hot streams in enthalpy interval k
J = total number of cold streams in enthalpy interval k
K = total number of enthalpy intervals

This simple formula allows the network area to be targeted, on the basis of a vertical heat exchange model if film transfer coefficients vary from stream to stream. However, if there are large variations in film transfer coefficients, Equation 17.6 does not predict the true minimum network area. If film transfer coefficients vary significantly, then deliberate nonvertical matching is required to achieve minimum area. Consider Figure 17.4a. Hot stream A with a low heat transfer coefficient is matched against cold stream C with a high coefficient. Hot stream B with a high heat transfer coefficient is matched with cold stream D with a low coefficient. In both matches, the temperature difference is taken to be the vertical separation between the curves. This arrangement requires 1616 m^2 area overall.

By contrast, Figure 17.4b shows a different arrangement. Hot stream A with a low heat transfer coefficient is matched with cold stream D, which also has a low coefficient but uses temperature differences greater than vertical separation. Hot stream B is matched with cold stream C, both with high heat transfer coefficients, but with temperature differences less than vertical. This arrangement requires 1250 m^2 area overall, less than the vertical arrangement.

If film transfer coefficients vary significantly from stream to stream, the true minimum area must be predicted using linear programming[5,6]. However, Equation 17.6 is still a

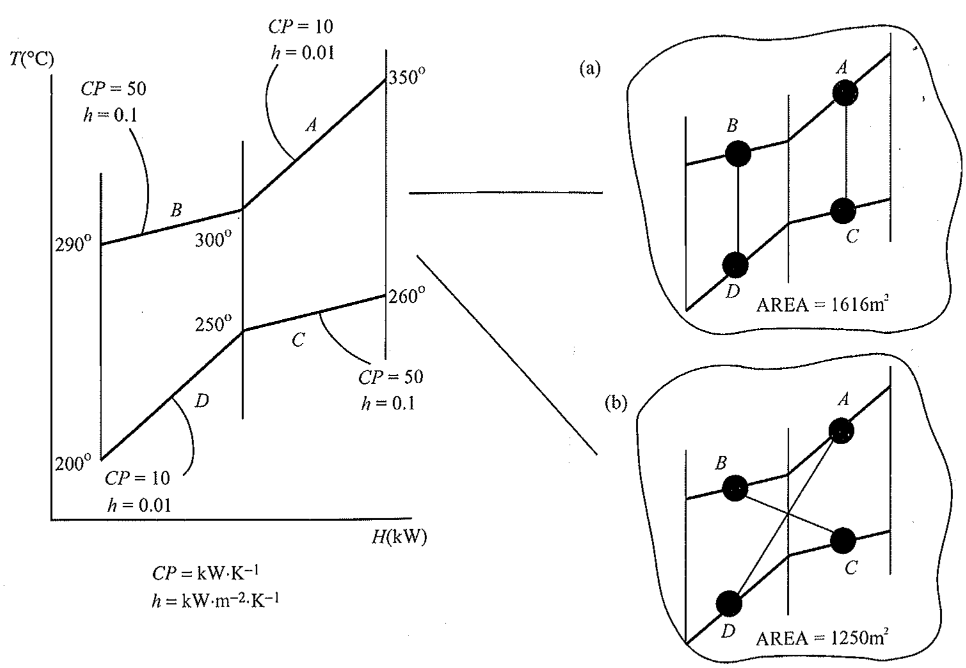

Figure 17.4 If film transfer coefficients differ significantly then nonvertical heat transfer is necessary to achieve the minimum area. (From Linnhoff B and Ahman S, 1990, *Comp and Chem Engg*, **7**: 729 with permission of Elsevier Science Ltd.)

useful basis to calculate the network area for the purposes of capital cost estimation, for the following reasons.

1. Providing film coefficients vary by less than one order of magnitude, then Equation 17.6 has been found to predict network area to within 10% of the actual minimum[6].
2. Network designs tend *not* to approach the true minimum in practice, since a minimum area design is usually too complex to be practical. Putting the argument the other way around, starting with the complex design required to achieve minimum area, then a significant reduction in complexity usually only requires a small penalty in area.
3. The area target being predicted here is used for predesign optimization of the capital–energy trade-off and the evaluation of alternative flowsheet options, such as different reaction and separation configurations. Thus, the area prediction is used in conjunction with capital cost data for heat exchangers that often have a considerable degree of uncertainty. The capital cost predictions obtained later from Equation 17.6 are likely to be more reliable than the capital cost predictions for the major items of equipment, such as reactors and distillation columns.

One significant problem remains; where to get the film transfer coefficients h_i and h_j from. There are the following three possibilities.

1. Tabulated experience values (see Chapter 15).
2. By assuming a reasonable fluid velocity, together with fluid physical properties, heat transfer correlations can be used (see Chapter 15).
3. If the pressure drop available for the stream is known, the expressions from Chapter 15, derived in Appendix C can be used.

The detailed allocation of fluids to tube-side or shell-side can only be made later in the heat exchanger network design. Also, the area targeting formula does not recognize fluids to be allocated to the tube-side or shell-side. Area targeting only recognizes the individual film heat transfer coefficients. All that can be done in network area targeting is to make a preliminary estimate of the film heat transfer coefficient on the basis of an initial assessment as to whether the fluid is likely to be suited to tube-side or shell-side allocation in the final design. Thus, in addition to the approximations inherent within the area targeting formula, there is uncertainty regarding the preliminary assessment of the film heat transfer coefficients.

However, one other issue that needs to be included in the assessment often helps mitigate the uncertainties in the assessment of the film heat transfer coefficient. A fouling allowance needs to be added to the film transfer coefficient according to Equation 15.13.

Example 17.2 For the process in Figure 16.2, calculate the target for network heat transfer area for $\Delta T_{min} = 10°C$. Steam at 240°C and condensing to 239°C is to be used for hot utility. Cooling water at 20°C and returning to the cooling tower at 30°C is to be used for cold utility. Table 17.1 presents the stream data, together with utility data and stream heat transfer coefficients.

Calculate the heat exchange area target for the network.

Solution First, the balanced composite curves must be constructed using the complete set of data from Table 17.1. Figure 17.5 shows the balanced composite curves. Note that the steam has been incorporated within the construction of the hot composite curve to maintain the monotonic nature of composite curves. The same is true of the cooling water in the cold composite curve. Figure 17.5 also shows the curves divided into enthalpy intervals where there is a change of slope either on the hot composite curve or on the cold composite curve.

Figure 17.6 now shows the stream population for each enthalpy interval together with the hot and cold stream temperatures. Now set up a table to compute Equation 17.6. This is shown below in Table 17.2.

Thus, the network area target for this problem for $\Delta T_{min} = 10°C$ is 7410 m^2.

The network design in Figure 16.9 already achieves minimum energy consumption, and it is now possible to judge how close the area target is to design if the area for the individual units in Figure 16.9 is calculated. Using the same heat transfer coefficients as given in Table 17.1, the design in Figure 16.9 requires some 8341 m^2, which is 13% above target. Remember that no attempt was made to steer the design in Figure 16.9 towards minimum

Table 17.1 Complete stream and utility data for the process from Figure 16.2.

Stream	Supply temperature T_S (°C)	Target temperature T_T (°C)	ΔH (MW)	Heat capacity flowrate, CP ($MW \cdot K^{-1}$)	Film heat transfer coefficient, h ($MW \cdot m^{-2} \cdot K^{-1}$)
1. Reactor 1 feed	20	180	32.0	0.2	0.0006
2. Reactor 1 product	250	40	−31.5	0.15	0.0010
3. Reactor 2 feed	140	230	27.0	0.3	0.0008
4. Reactor 2 product	200	80	−30.0	0.25	0.0008
5. Steam	240	239	7.5	7.5	0.0030
6. Cooling water	20	30	10.0	1.0	0.0010

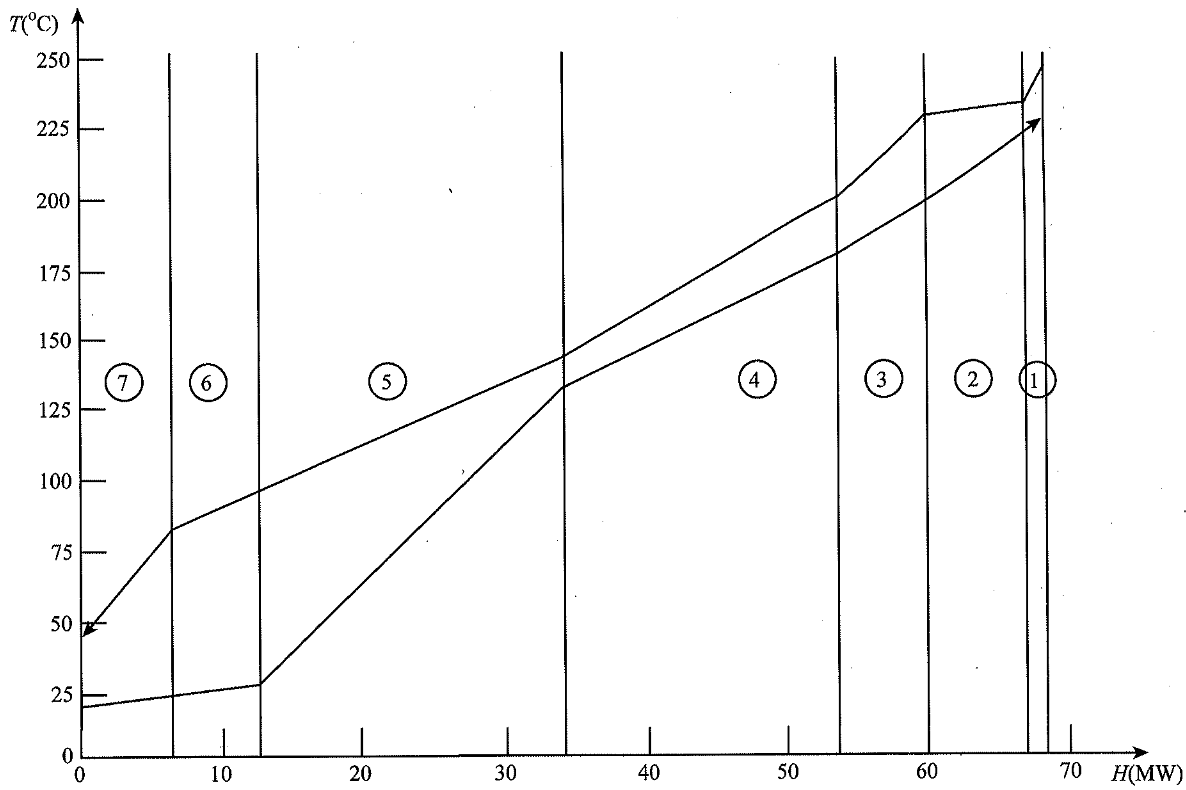

Figure 17.5 The enthalpy intervals for the balanced composite curves of Example 17.2.

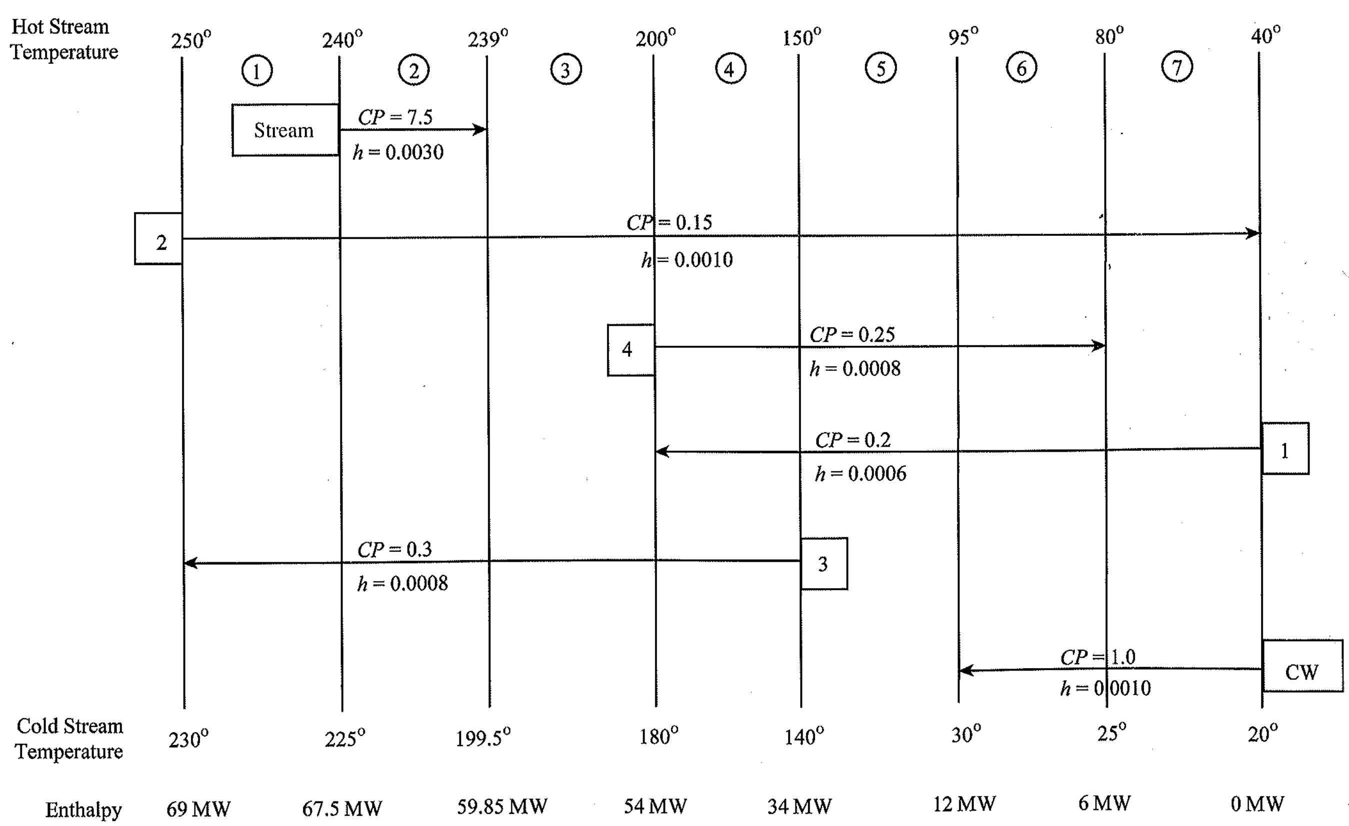

Figure 17.6 The enthalpy interval stream population for Example 17.2.

Table 17.2 Network area target for the process from Figure 17.2.

Enthalpy interval	ΔT_{LMk}	Hot streams $\Sigma(q_i/h_i)_k$	Cold streams $\Sigma(q_j/h_j)_k$	A_k
1	17.38	1500	1875	194.2
2	25.30	2650	9562.5	482.7
3	28.65	5850	7312.5	459.4
4	14.43	23,125	28,333.3	3566.1
5	29.38	25,437.5	36,666.7	2113.8
6	59.86	6937.5	6666.7	227.3
7	34.60	6000	6666.7	366.1
			ΣA_k	7409.6

area. Instead, the design achieved the energy target in the minimum number of units that tends to lead to simple designs.

17.3 NUMBER-OF-SHELLS TARGET

The shell-and-tube exchanger is the most common type of exchanger used in the chemical and process industries. The basic heat exchanger design equation was developed in Chapter 15:

$$Q = UA\Delta T_{LM} F_T \quad \text{where } 0 < F_T < 1 \tag{15.47}$$

In Chapter 15, the F_T correction factor was correlated in terms of two dimensionless ratios, the ratio of the two heat capacity flowrates (R) and the thermal effectiveness of the exchanger (P). Practical designs were limited to some fraction of P_{max}, that is[7]:

$$P = X_P P_{max}, \quad 0 < X_P < 1 \tag{15.54}$$

where X_P is a constant defined by the designer to satisfy the minimum allowable F_T (for example, for $F_{Tmin} > 0.75$, $X_P = 0.9$ is used). Equations were also developed in Chapter 15 to allow the number of shells for a unit to be determined:

$R \neq 1$[7]:

$$N_{SHELLS} = \frac{\ln\left(\dfrac{1-RP}{1-P}\right)}{\ln W} \tag{15.62}$$

$$\text{where } W = \frac{R+1+\sqrt{R^2+1}-2RX_P}{R+1+\sqrt{R^2+1}-2X_P} \tag{15.63}$$

$R = 1$[7]:

$$N_{SHELLS} = \frac{\left(\dfrac{P}{1-P}\right)\left(1+\dfrac{\sqrt{2}}{2}-X_P\right)}{X_P} \tag{15.64}$$

If exchangers are countercurrent devices, then the number of units equals the number of shells, providing individual shells do not exceed some practical upper size limit. If, however, equipment is used that is not completely countercurrent, as with the 1–2 shell and tube heat exchanger, then:

$$N_{SHELLS} \geq N_{UNITS} \tag{17.7}$$

Since the number of shells can have a significant influence on the capital cost, it would be useful to be able to predict it as a target ahead of design.

A simple algorithm can be developed (see Appendix G) to target the minimum total number of shells (as a real, i.e. noninteger, number) for a stream-set based on the temperature distribution of the composite curves. The algorithm starts by dividing the composite curves into enthalpy intervals in the same way as the area target algorithm.

The resulting number of shells is[8]:

$$N_{SHELLS} = \sum_{k}^{INTERVALS\ K} N_k(S_k - 1) \tag{17.8}$$

where N_{SHELLS} = total number of shells over K enthalpy intervals
N_k = real (or fractional) number of shells resulting from the temperatures of enthalpy interval k
S_k = number of streams in enthalpy interval k

N_k is given by the application of Equations 15.62 to 15.64 to interval k.

In practice, the integer number of shells is evaluated from Equation 17.8 for each side of the pinch. This maintains consistency between achieving maximum energy recovery and the corresponding minimum number of units target N_{UNITS}. In summary, the number-of-shells target can be calculated from the basic stream data and an assumed value of X_P (or equivalently, F_{Tmin}).

The F_T correction factor for each enthalpy interval depends both on the assumed value of X_P and the temperatures of the interval on the composite curves. It is possible to modify the simple area target formula to obtain the resulting increased overall area, $A_{NETWORK}$, for a network of 1–2 exchangers[8].

$$A_{NETWORK,1-2} = \sum_{k}^{INTERVALS\ K} \frac{1}{\Delta T_{LMk} F_{Tk}} \left[\sum_{i}^{HOT\ STREAMS\ I} \frac{q_{i,k}}{h_i} + \sum_{j}^{COLD\ STREAMS\ J} \frac{q_{j,k}}{h_j} \right] \tag{17.9}$$

Furthermore, the average area per shell ($A_{NETWORK,1-2}/N_{SHELL}$) can also be considered at the targeting stage. If this is greater than the maximum allowable area per shell, $A_{SHELL,max}$, then the shells target needs to be increased to the next largest integer above $A_{NETWORK,1-2}/A_{SHELL,max}$. Again, this can be applied each side of the pinch.

17.4 CAPITAL COST TARGETS

To predict the capital cost of a network, it must first be assumed that a single heat exchanger with surface area A can be costed according to a simple relationship such as:

$$\textit{Installed Capital Cost of Exchanger} = a + bA^c \quad (17.10)$$

where a, b, c = cost law constants that vary according to materials of construction, pressure rating and type of exchanger.

When cost targeting, the distribution of the targeted area between network exchangers is unknown. Thus, to cost a network using Equation 17.10, some area distribution must be assumed, the simplest being that all exchangers have the same area:

$$\textit{Network Capital Cost} = N[a + b(A_{NETWORK}/N)^c] \quad (17.11)$$

where N = number of units or shells, whichever is appropriate.

At first sight, the assumption of equal area exchangers used in Equation 17.11 might seem crude. However, from the point of view of predicting capital cost, the assumption turns out to be a remarkably good one[6]. At the targeting stage, no given distribution can be judged consistently better than another, since the network is not yet known. The implications of these inaccuracies, together with others, will be discussed later.

If the problem is dominated by equipment with a single specification (i.e. a single material of construction, equipment type and pressure rating), then the capital cost target can be calculated from Equation 17.11 with the appropriate cost coefficients. However, if there is a mix of specifications such as different streams requiring different materials of construction, then the approach must be modified.

Equation 17.11 uses a single cost function in conjunction with the targets for the number of units (or shells) and network area. Differences in cost can be accounted for by either introducing new cost functions or adjusting the heat exchange area to reflect the cost differences[9]. This can be done by weighting the stream heat transfer coefficients in the calculation of network area with a factor ϕ to account for these differences in cost. If, for example, a corrosive stream requires more expensive materials of construction than the other streams, it has a greater contribution to the capital cost than a similar noncorrosive stream. This can be accounted for by artificially decreasing its heat transfer coefficient to increase the contribution the stream makes to the network area. This fictitious area when turned into a capital cost using the cost function for the noncorrosive materials returns a higher capital cost, reflecting the increased cost resulting from special materials.

Heat exchanger cost data can usually be manipulated such that the fixed costs, represented by the coefficient a in Equation 17.10, do not vary with exchanger specification[9]. If this is done, then Equation 17.6 can be modified, as derived in Appendix H, to[9]:

$$A^*_{NETWORK} = \sum_k^{INTERVALS\ K} \frac{1}{\Delta T_{LMk}} \left[\sum_i^{HOT\ STREAMS\ I} \frac{q_{i,k}}{\phi_i h_i} + \sum_j^{COLD\ STREAMS\ J} \frac{q_{j,k}}{\phi_j h_j} \right] \quad (17.12)$$

where

$$\phi_j = \left(\frac{b_1}{b_2}\right)^{\frac{1}{c_1}} \left(\frac{A_{NETWORK}}{N}\right)^{1-\frac{c_2}{c_1}} \quad (17.13)$$

where ϕ_i = cost-weighting factor for hot stream i
ϕ_j = cost-weighting factor for cold stream j
a_1, b_1, c_1 = cost law coefficients for the reference cost law
a_2, b_2, c_2 = cost law coefficients for the special cost law
N = number of units or shells, whichever is applicable

Heat exchanger cost laws can often be adjusted with little loss of accuracy such that the coefficient c is constant for different specifications, that is, $c_1 = c_2 = c$. In this case, Equation 17.13 simplifies to[9]:

$$\phi = \left(\frac{b_1}{b_2}\right)^{\frac{1}{c}} \quad (17.14)$$

Thus, to calculate the capital cost target for a network comprising mixed exchanger specifications, the procedure is as follows.

1. Choose a reference cost law for the heat exchangers. Greatest accuracy is obtained if the category of streams that make the largest contribution to capital cost is chosen as reference[9].
2. Calculate ϕ-factors for those streams that require a specification different from that of the reference, using Equations 17.13 or 17.14. If Equation 17.13 is to be used, then the actual network area $A_{NETWORK}$ must first be calculated using either Equation 17.6 or 17.9 and N_{UNITS} or N_{SHELLS}, whichever is appropriate.
3. Calculate the weighted network area $A^*_{NETWORK}$ from Equation 17.12. When the weighted h-values (ϕh) vary appreciably, say by more than one order of magnitude, an improved estimate of $A^*_{NETWORK}$ can be evaluated by linear programming[5,6].

4. Calculate the capital cost target for the mixed specification heat exchanger network from Equation 17.11 using the cost law coefficients for the reference specification.

Example 17.3 For the process in Figure 16.2, the stream and utility data are given in Table 17.1. Pure countercurrent (1-1) shell and tube heat exchangers are to be used. For $\Delta T_{min} = 10°C$:

a. calculate the capital cost target if all individual heat exchangers can be costed by the relationship:

$$\textit{Heat Exchanger Capital Cost} = 40{,}000 + 500A \ (\$)$$

where A is the heat transfer area in m^2.

b. calculate the capital cost target if cold stream 3 from Table 17.1 required a more expensive material. Individual heat exchangers made entirely from this more expensive material can be costed by the relationship:

$$\textit{Heat Exchanger Capital Cost (special)} = 40{,}000 + 1{,}100A(\$)$$

where A is the heat transfer area in m^2.

Solution

a. The capital cost target of the network can be calculated from Equation 17.11. To apply this equation requires the target for both the number of units (N_{UNITS}) and the heat exchange area ($A_{NETWORK}$). In Example 17.1, $N_{UNITS} = 7$ was calculated, and in Example 17.2 $A_{NETWORK} = 7410$ m^2. Thus:

$$\textit{Network Capital Cost} = 7[40{,}000 + 500(7410/7)^1] = 3.99 \times 10^6 \ \$$$

b. To calculate the capital cost target of the network with mixed materials of construction, a reference material is first chosen. In principle, either of the materials can be chosen as reference. However, greater accuracy is obtained if the reference is taken to be that category of streams that makes the largest contribution to capital cost. In this case, the reference should be taken to be the cheaper material of construction. Now calculate ϕ-factors for those streams that require a specification different from the reference. In this problem, it only applies to stream 3. Since the c constant is the same for both cost laws, Equation 17.14 can be used.

$$\phi_3 = (500/1100)^{1/1} = 1/2.2$$

$$\phi_3 h_3 = 0.0008/2.2$$

Now recalculate the network area target substituting $\phi_3 h_3$ for h_3 in Figure 17.6. Table 17.2 is revised to the values shown in Table 17.3.

Thus, the weighted network area $A^*_{NETWORK}$ is 9547 m^2. Now calculate the network capital cost for mixed materials of construction by using $A^*_{NETWORK}$ in conjunction with the cost coefficients for the reference material in Equation 17.11.

Table 17.3 Area target per enthalpy interval.

Enthalpy interval	ΔT_{LMk}	Hot streams $\Sigma(q_i/h_i)_k$	Cold streams $\Sigma(q_j/h_j)_k$	A_k
1	17.38	1500	4125.0	323.6
2	25.30	2650	21,037.5	936.1
3	28.65	5850	16,087.5	765.6
4	14.43	23,125	46,333.4	4814.5
5	29.38	25,437.5	36,666.7	2113.8
6	59.86	6937.5	6666.7	227.3
7	34.60	6000	6666.7	366.1
			ΣA_k	9546.9

$$\textit{Network Capital Cost (mixed materials)} = 7[40{,}000 + 500(9547/7)^1] = 5.05 \times 10^6 \ \$$$

Consider now how accurate the capital cost targets are likely to be. It was discussed earlier how the basic area targeting equation (Equations 17.6 or 17.9) represents a true minimum network area if all heat transfer coefficients are equal but slightly above the true minimum if there are significant differences in heat transfer coefficients. Providing heat transfer coefficients vary by less than one order of magnitude, Equations 17.6 and 17.9 predict an area that is usually within 10% of the minimum. However, this does not turn into a 10% error in capital cost of the final design since practical designs are almost invariably slightly above the minimum. There are also the following two errors inherent in the approach to capital cost targets.

- Total heat transfer area is assumed to be divided equally between exchangers. This tends to overestimate the capital cost.
- The area target is usually slightly less than the area observed in design.

These small positive and negative errors partially cancel each other. The result is that capital cost targets predicted by the methods described in this chapter are often within 5% of the final design, providing heat transfer coefficients vary by less than one order of magnitude. If heat transfer coefficients vary by more than one order of magnitude, then a more sophisticated approach can sometimes be justified[6].

If the network comprises mixed exchanger specification, then an additional degree of uncertainty is introduced into the capital cost target. Applying the ϕ-factor approach to a single exchanger, where both streams require the same specification, there is no error. In practice, there can be different specifications on two streams being matched, and $\phi_H \neq \phi_C$ for specifications involving shell-and-tube heat exchangers with different materials of construction and pressure rating. In principle, this does not present a problem since the exchanger can be designed for different materials of construction or pressure rating on the shell-side and the tube-side of a heat exchanger. If, for example, there is a mix of streams, some requiring carbon steel and some stainless steel, then some of the matches involve a corrosive stream on one side of the exchanger and a noncorrosive stream on the other. The capital cost of such exchangers will lie somewhere between the cost based on the sole use of either material. This is what the capital cost target predicts. Thus, introducing mixed specifications for materials of construction and pressure rating does not significantly decrease the accuracy of the capital cost predictions.

By contrast, the same is not true of mixed exchanger types. For networks comprising different exchanger types (e.g. shell-and-tube, plate-and-frame, spiral, etc.), it is not possible to mix types in a single unit. Although a cost-weighting factor may be applied to one stream in targeting, this assumes that different exchanger types can be mixed. In practice, such a match is forced to be a special-type exchanger. Thus, there may be some discrepancy between cost targets and design cost when dealing with mixed exchanger types.

Overall, the accuracy of the capital cost targets is usually good enough for the purposes for which they are used:

- Screening design options from the material and energy balance. For example, changes in reactor design or separation system design can be screened effectively without performing repeated network design.
- Different utility options such as furnaces, gas turbines and different steam levels can be assessed more easily and with greater confidence, knowing the capital cost implications for the heat exchanger network.
- Preliminary process optimization is greatly simplified.
- The design of the heat exchanger network is greatly simplified if the design is initialized with an optimized value for ΔT_{min}.

17.5 TOTAL COST TARGETS

Increasing the chosen value of process energy consumption also increases all temperature differences available for heat recovery and hence decreases the necessary heat exchanger surface area, Figure 16.6. The network area can be distributed over the targeted number of units or shells to obtain a capital cost using Equation 17.11. This capital cost can be annualized as detailed in Chapter 2. The annualized capital cost can be traded off against the annual utility cost as shown in Figure 16.6. The total cost shows a minimum at the optimum energy consumption.

Example 17.4 For the process in Figure 16.2, determine the value of ΔT_{min} and the total cost of the heat exchanger network at the optimum setting of the capital–energy trade-off. The stream and utility data are given in Table 17.1. The utility costs are:

$$\text{Steam Cost} = 120{,}000\ (\$\cdot\text{MW}^{-1}\cdot\text{y}^{-1})$$

$$\text{Cooling Water Cost} = 10{,}000\ (\$\cdot\text{MW}^{-1}\cdot\text{y}^{-1})$$

The heat exchangers to be used are single-tube and shell-pass. The installed capital cost is given by:

$$\textit{Heat Exchanger Capital Cost} = 40{,}000 + 500A(\$)$$

where A is the heat transfer area in m^2. The capital cost is to be paid back over five years at 10% interest.

Solution From Equation 2.7 from Chapter 2:
Annualized Heat Exchanger Capital Cost

$$= \textit{Capital Cost} \times \frac{i(1+i)^n}{(1+i)^n - 1}$$

where i = fractional interest rate per year
n = number of years

Annualized Heat Exchanger Capital Cost

$$= [40{,}000 + 500A] \times \frac{0.1(1+0.1)^5}{(1+0.1)^5 - 1}$$
$$= [40{,}000 + 500A]0.2638$$
$$= 10{,}552 + 131.9A$$

Annualized Network Capital Cost

$$= N_{UNITS}\left[10,552 + \frac{131.9A_{NETWORK}}{N_{UNITS}}\right]$$

Now scan a range of values of ΔT_{min} and calculate the targets for energy, number of units and network area and combine these into a total cost. The results are given in Table 17.4.

The data from Table 17.4 are presented graphically in Figure 17.7. The optimum ΔT_{min} is at 10°C, confirming the initial value used for this problem in Chapter 16. The total annualized cost at the optimum setting of the capital–energy trade-off is 2.05×10^6 $\$\cdot y^{-1}$.

For more complex examples, total cost profiles return step changes shown in Figure 17.8 (due to changes in N_{UNITS} and N_{SHELLS}). These step changes are easily located, prior to design, through simple software. Most importantly, experience has shown that predicted overall costs are typically accurate within 5% or better[6].

17.6 HEAT EXCHANGER NETWORK AND UTILITIES CAPITAL AND TOTAL COSTS – SUMMARY

There are parts of the flowsheet synthesis problem that can be predicted without having to study actual designs. These are the layers of the process onion relating to the

Table 17.4 Variation of annualized costs with ΔT_{min}.

ΔT_{min}	Q_{Hmin} (MW)	Annual hot Utility Cost (10^6 \$·y^{-1})	Q_{Cmin} (MW)	Annual cold utility cost (10^6 \$·y^{-1})	$A_{NETWORK}$ (m^2)	N_{UNITS}	Annualized capital cost (10^6 \$·y^{-1})	Annualized total cost (10^6 \$·y^{-1})
2	4.3	0.516	6.8	0.068	15,519	7	2.121	2.705
4	5.1	0.612	7.6	0.076	11,677	7	1.614	2.302
6	5.9	0.708	8.4	0.084	9645	7	1.346	2.138
8	6.7	0.804	9.2	0.092	8336	7	1.173	2.069
10	7.5	0.900	10.0	0.100	7410	7	1.051	2.051
12	8.3	0.996	10.8	0.108	6716	7	0.960	2.064
14	9.1	1.092	11.6	0.116	6174	7	0.888	2.096

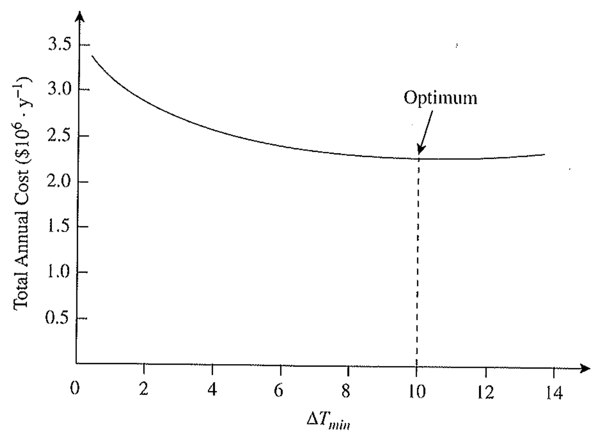

Figure 17.7 Optimization of the capital–energy trade-off for Example 17.5.

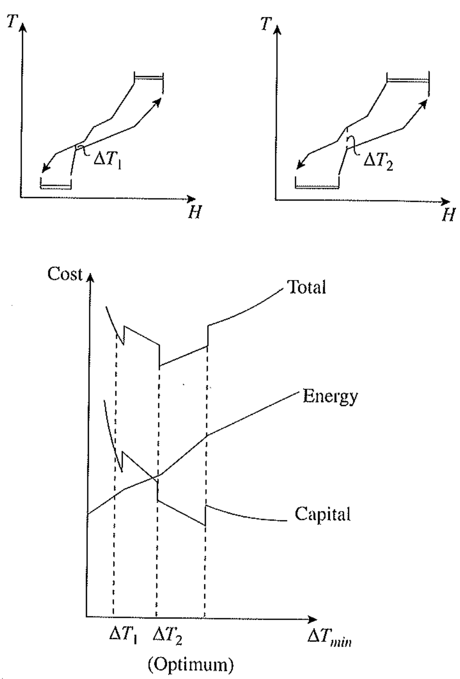

Figure 17.8 Energy and capital cost targets can be combined to optimize prior to design (From Smith R and Linnhoff B, 1988, *ChERD*,**66**: 195 reproduced by permission of the Institution of Chemical Engineers.).

heat exchanger network and utilities. For these parts of the process design, targets can be set for energy costs and capital costs directly from the material and energy balance without having to resort to heat exchanger network design for evaluation.

Once a design is known for the reaction and separation systems, the overall total cost is the total cost of all reactors and separators (evaluated explicitly) plus the total cost target for heat exchanger network.

17.7 EXERCISES

1. The problem table cascade for a process is given in Table 17.5 for $\Delta T_{min} = 10°C$. The process hot utility requirement is to be provided by a steam turbine exhaust. The exhaust steam is saturated. The performance of the turbine can be described by the equation:

$$W = 0.6 \times Q_H \frac{T_H - T_C}{T_H}$$

where W = power generated (MJ)
Q_H = heat input from high-pressure steam (MJ)
T_H = temperature of input steam (K)
T_C = temperature of exhaust steam (K)

High-pressure steam is available at 400°C. Table 17.6 below presents the relevant cost data.

a. Determine the optimum exhaust temperature for $\Delta T_{min} = 10°C$. The variation of network area (with the exhaust steam

Table 17.5 Cascade heat flow.

Interval temperature (°C)	Heat flow (MW)
435	8.160
395	12.160
116	9.928
115	1.120
35	0.480
25	0.000

Table 17.6 Cost data for Exercise 1.

Power cost	=	50 $\$\cdot MWh^{-1}$
High-pressure steam cost	=	15 $\$\cdot MWh^{-1}$
Process availability	=	8000 $h\cdot y^{-1}$
Heat exchanger cost	=	$350A$ ($)
(where A is exchanger area in m^2)		
Plant lifetime	=	5 years
Interest rate	=	8%

Table 17.7 Variation of heat exchanger network area with steam turbine exhaust temperature.

Steam turbine exhaust temperature (°C)	Network area (m^2)
120	3345
130	2415
140	2078
150	1914
160	1818

included) is given in Table 17.7 for a range of exhaust temperatures.

b. The optimization of the steam turbine exhaust temperature used a fix value of ΔT_{min}. Is this correct? If not, why, and what would have been a better way for the calculation to have been done?

2. Figure 17.9 shows a heat exchanger network designed with the minimum number of units and to satisfy the energy target at $\Delta T_{min} = 20°C$. On the basis of the following utilities and cost data, it has a total annual cost of 14.835×10^6 ($\$\cdot y^{-1}$).

$$\text{Cost of saturated steam (200°C)} = 70\ \$\cdot kW^{-1}\cdot y^{-1}$$

$$\text{Cost of cooling water (10°C to 40°C)} = 7.5\ \$\cdot kW^{-1}\cdot y^{-1}$$

$$\text{Heat exchanger installed cost (\$)} = 15{,}000 + 700A$$

where A = heat exchanger area (m^2)

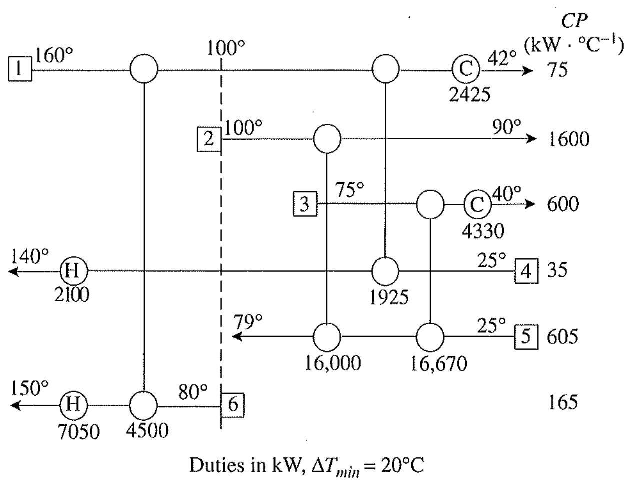

Figure 17.9 A heat exchanger network.

Table 17.8 Targets for Exercise 2.

ΔT_{min} (°C)	Hot utility (kW)	Area (m^2)	Units
10	7150	86,730	9
20	9150	75,920	8
30	14,945	62,721	9
40	21,345	56,486	9
45	24,545	54,796	9
50	27,745	53,703	9

Assume plant lifetime is 5 years and that all streams (process and utilities) have a heat transfer coefficient of 0.05 $kW\cdot m^{-2}\cdot K^{-1}$. Rather than accepting this network design, a designer proposes to examine the energy–capital trade-off for the stream data by evaluating the targets in Table 17.8.

$$\text{Cold utility (kW)} = \text{hot utility (kW)} - 2395\ \text{(kW)}$$

(a) From the targets and cost data given, construct a table to show the targets for energy cost, annualized capital cost and total annual cost for each of the values of ΔT_{min} in Table 17.8. Plot the total annual cost target against ΔT_{min}. What value of ΔT_{min} can be suggested for a network design featuring optimum total cost?

(b) Using the optimum value of ΔT_{min}, design a network with the minimum number of units and minimum energy (the pinch corresponds with the start of Hot Stream 2). Ignore ΔT_{min} violations in utility exchangers.

(c) Calculate the total annual cost of your network design. Locate this and the network in Figure 17.9 against the total annual cost profile from Part *a*.

(d) Why is the structure of your network design necessarily different from that in Figure 17.9? Could this have been known before the design? What can you conclude about ΔT_{min} initialization for obtaining optimum cost networks?

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