18 Heat Exchanger Networks IV – Network Design

Having explored the targets for the heat exchanger network, it now remains to develop the design of the heat exchanger network.

18.1 THE PINCH DESIGN METHOD

The capital-energy trade-off in the heat exchanger networks was discussed in Chapter 16. Varying ΔT_{min}, as shown in Figure 16.6, changed the relative position of the process composite curves. As ΔT_{min} is changed from a small to a large value, the capital cost decreases but the energy cost increases. When the two costs are combined to obtain a total cost, the optimum point in the capital-energy trade-off is identified, corresponding with an optimum value of ΔT_{min} (Figure 16.6). As pointed out in Chapter 16, the trade-off between energy and capital suggests that individual exchangers should have a temperature difference no smaller than the ΔT_{min} between the composite curves.

It was suggested in Chapter 16 that a good initialization would be to assume that no individual exchanger should have a temperature difference smaller than ΔT_{min}. Having made this assumption, two rules were deduced in Chapter 16. If the energy target set by the composite curves (or the problem table algorithm) is to be achieved, the design must not transfer heat across the pinch by:

- Process-to-process heat transfer
- Inappropriate use of utilities

These rules are necessary for the design to achieve the energy target, given that no individual exchanger should have a temperature difference smaller than ΔT_{min}. To comply with these two rules, the process should be divided at the pinch. As pointed out in Chapter 16, this is most clearly done by representing the stream data in the grid diagram. Figure 18.1 shows the stream data from Table 16.2 in grid form with the pinch marked. Above the pinch, steam can be used (up to Q_{Hmin}), and below the pinch cooling water can be used (up to Q_{Cmin}). But what strategy should be adopted for the design? A number of simple criteria can be developed to help[1].

1. *Start at the pinch.* The pinch is the most constrained region of the problem. At the pinch, ΔT_{min} exists between all hot and cold streams. As a result, the number of feasible matches in this region is severely restricted. Quite often there are essential matches to be made. If such matches are not made, the result will be either use of temperature differences smaller than ΔT_{min} or excessive use of utilities resulting from heat transfer across the pinch. If the design was started away from the pinch at the hot end or cold end of the problem, then initial matches are likely to need follow-up matches that violate the pinch or the ΔT_{min} criterion as the pinch is approached. Putting the argument the other way around, if the design is started at the pinch, then initial decisions are made in the most constrained part of the problem. This is much less likely to lead to difficulties later.

2. *The CP inequality for individual matches.* Figure 18.2a shows the temperature profiles for an individual exchanger at the pinch, above the pinch[1,2]. Moving away from the pinch, temperature differences must increase. Figure 18.2a shows a match between a hot stream and a cold stream that has a *CP* smaller than the hot stream. At the pinch, the match starts with a temperature difference equal to ΔT_{min}. The relative slopes of the temperature–enthalpy profiles of the two streams mean that the temperature differences become smaller moving away from the pinch, which is infeasible. On the other hand, Figure 18.2b shows a match involving the same hot stream but with a cold stream that has a larger *CP*. The relative slopes of the temperature–enthalpy profiles now cause the temperature differences to become larger moving away from the pinch, which is feasible. Thus, starting with ΔT_{min} at the pinch, for temperature differences to increase moving away from the pinch[1,2]:

$$CP_H \le CP_C \text{ (above pinch)} \tag{18.1}$$

Figure 18.3 shows the situation below the pinch at the pinch. If a cold stream is matched with a hot stream with smaller *CP*, as shown in Figure 18.3a (i.e. a steeper slope), then the temperature differences become smaller (which is infeasible). If the same cold stream is matched with a hot stream with a larger *CP* (i.e. a less steep slope), as shown in Figure 18.3b, then temperature differences become larger, which is feasible. Thus, starting with ΔT_{min} at the pinch, for temperature differences to increase moving away from the pinch[1,2]:

$$CP_H \ge CP_C \text{ (below pinch)} \tag{18.2}$$

Note that the *CP* inequalities given by Equations 18.1 and 18.2 only apply at the pinch and when both ends of the match are at pinch conditions.

3. *The CP-table.* Identification of the essential matches in the region of the pinch is clarified by use of the *CP-table*[1,2].

Chemical Process Design and Integration R. Smith
 ISBNs: 0-471-48680-9 (HB); 0-471-48681-7 (PB)

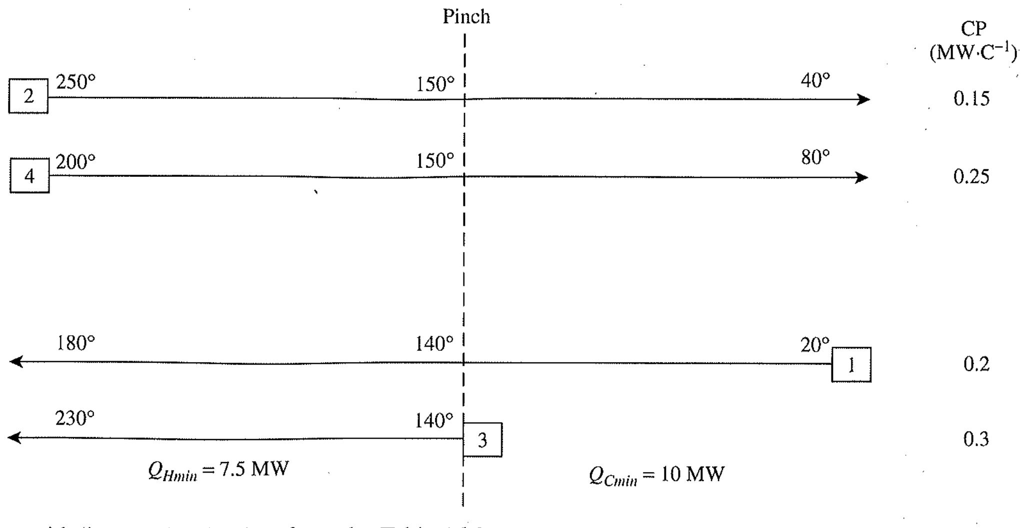


Figure 18.1 The grid diagram for the data from the Table 16.2.

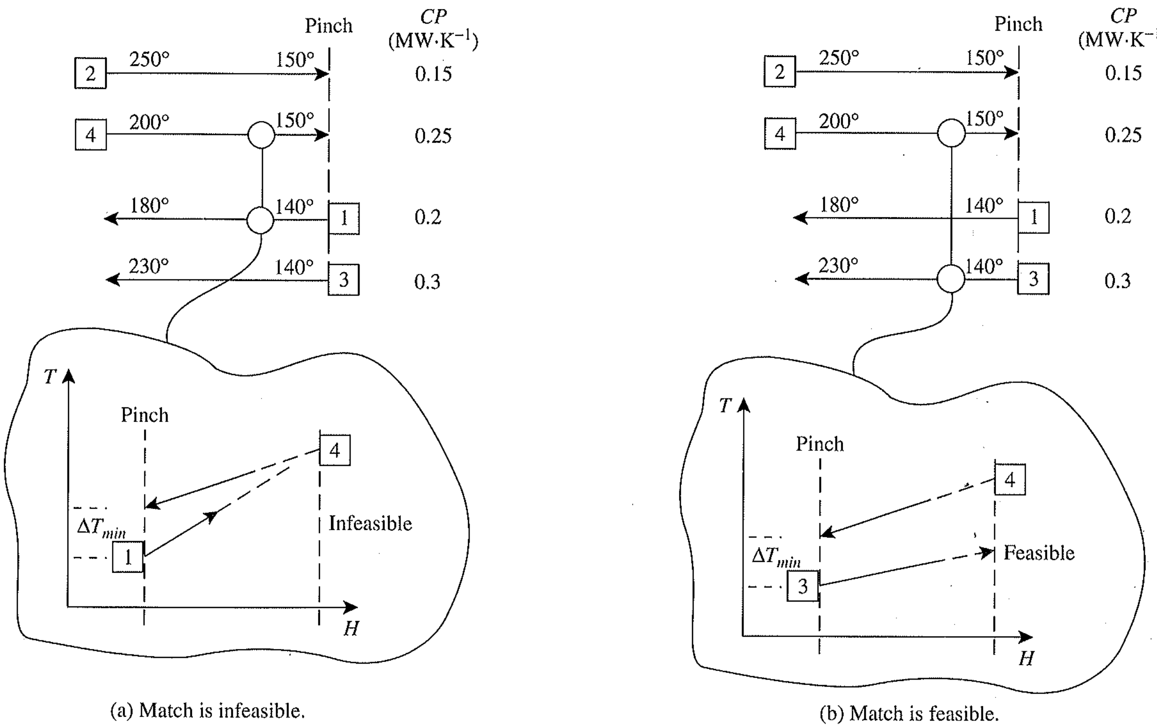
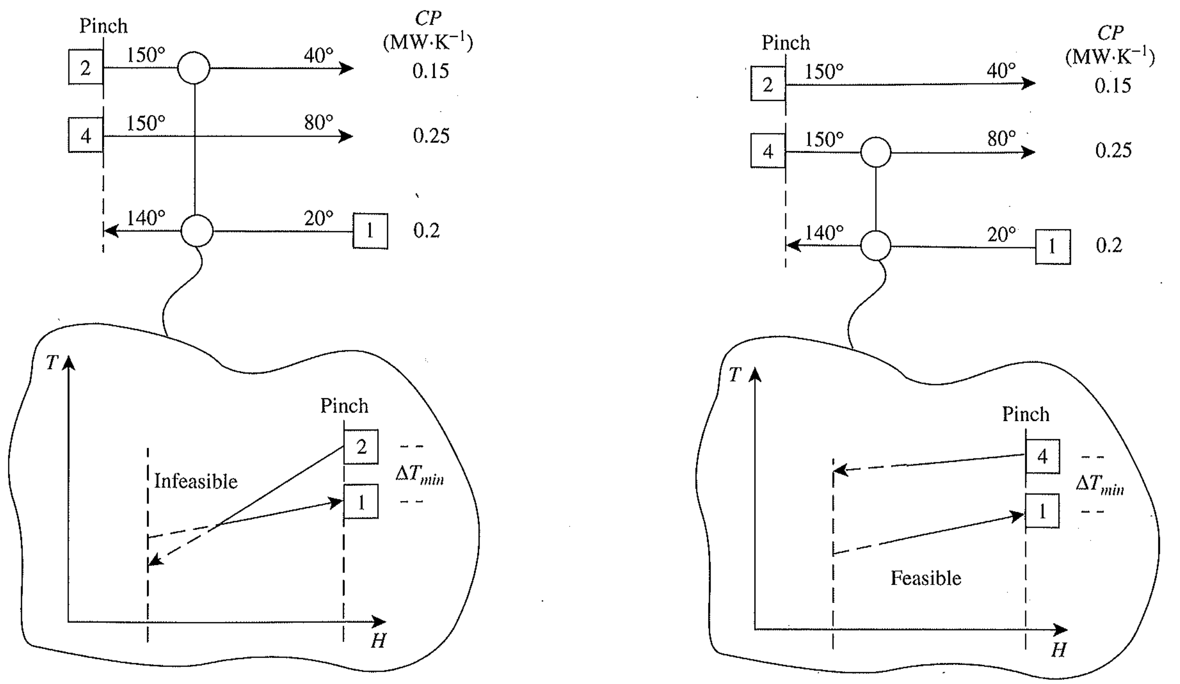


Figure 18.2 Criteria for the pinch matches above the pinch.

In the CP-table, the *CP* values of the hot and cold streams for the streams at the pinch are listed in descending order.

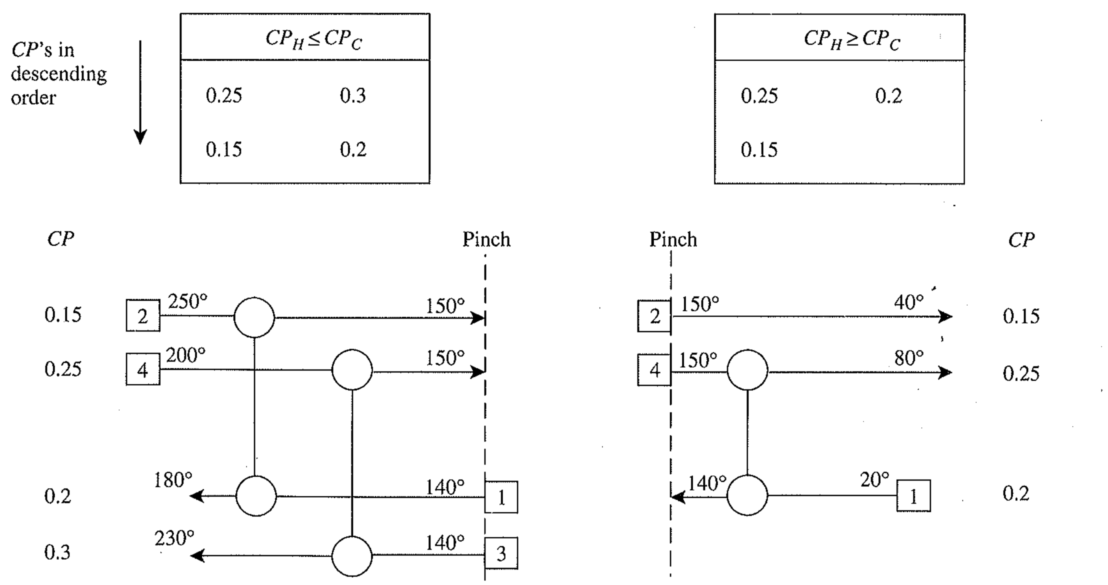
Figure 18.4a shows the grid diagram with CP-table for the design above the pinch. Cold utility must not be used above the pinch, which means that hot streams must be cooled to pinch temperature by heat recovery. Hot utility can be used, if necessary, on the cold streams above the pinch. Thus, it is essential to match hot streams above the pinch with a cold partner. In addition, if the hot stream is at pinch conditions, the cold stream it is to be matched with must also be at pinch conditions, otherwise the ΔT_{min} constraint will be violated. Figure 18.4a shows a feasible design arrangement above the pinch that does not use temperature differences smaller than ΔT_{min}. Note again that the *CP* inequality only applies when a match is made between two streams that are both at the pinch. Away from the pinch, temperature differences increase, and it is no longer essential to obey the *CP* inequalities.

Figure 18.4b shows the grid diagram with CP-table for the design below the pinch. Hot utility must not be used below the pinch, which means that cold streams must be heated to pinch temperature by heat recovery. Cold utility



(a) Match is infeasible. (b) Match is feasible.

Figure 18.3 Criteria for pinch matches below the pinch.



(a) Above pinch. (b) Below pinch.

Figure 18.4 The CP table for the designs above and below the pinch for the problem from Table 16.2.

can be used, if necessary, on the hot streams below the pinch. Thus, it is essential to match cold streams below the pinch with a hot partner. In addition, if the cold stream is at pinch conditions, the hot stream it is to be matched with must also be at pinch conditions, otherwise the ΔT_{min} constraint will be violated. Figure 18.4b shows a design arrangement below the pinch that does not use temperature differences smaller than ΔT_{min}.

Having decided that some essential matches need to be made around the pinch, the next question is how big should the matches be?

4. *The "tick-off" heuristic.* Once the matches around the pinch have been chosen to satisfy the criteria for minimum energy, the design should be continued in such a manner as to keep capital costs to a minimum. One important criterion

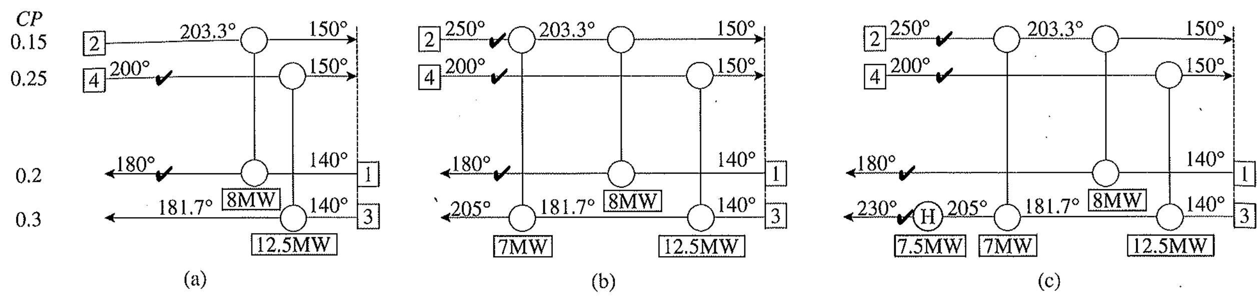


Figure 18.5 Sizing the units above the pinch using the tick-off heuristic.

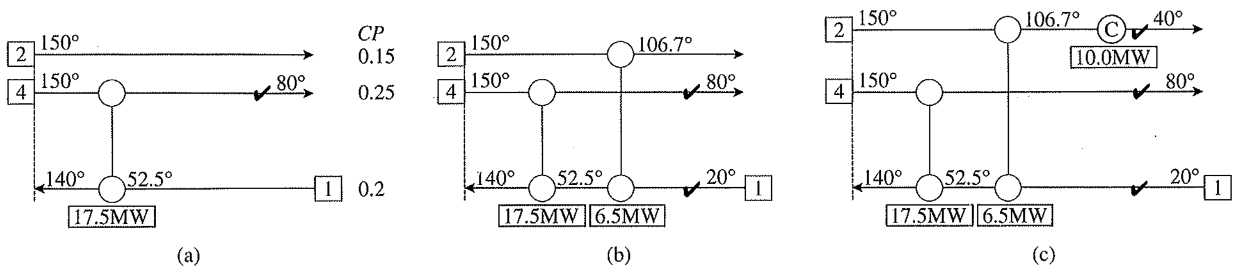


Figure 18.6 Sizing the units below the pinch using the tick-off heuristic.

in the capital cost is the number of units (there are others, of course, which shall be addressed later). Keeping the number of units to a minimum can be achieved using the *tick-off heuristic*. To tick off a stream, individual units are made as large as possible, that is, the smaller of the two heat duties on the streams being matched.

Figure 18.5a shows the matches around the pinch from Figure 18.4a with their duties maximized to tick off streams. It should be emphasized that the tick-off heuristic is only a heuristic and can occasionally penalize the design. Methods will be developed later, which allow such penalties to be identified as the design proceeds.

The design in Figure 18.5a can now be completed by satisfying the heating and cooling duties away from the pinch. Cooling water must not be used above the pinch. Therefore, if there are hot streams above the pinch for which the pinch matches do not satisfy the duties, additional process-to-process heat recovery is required. Figure 18.5b shows an additional match to satisfy the residual cooling of the hot streams above the pinch. Again, the duty on the unit is maximized. Finally, above the pinch, the residual heating duty on the cold streams must be satisfied. Since there are no hot streams left above the pinch, hot utility must be used as shown in Figure 18.5c.

Turning now to the cold end design, Figure 18.6a shows the pinch design with the streams ticked off. If there are any cold streams below the pinch for which the pinch matches do not satisfy the duties, then additional process-to-process heat recovery is required, since hot utility must not be used. Figure 18.6b shows an additional match to satisfy the residual heating of the cold streams below the pinch. Again, the duty on the unit is maximized. Finally, below the pinch, the residual cooling duty on the hot streams must be satisfied. Since there are no cold streams left below the pinch, cold utility must be used (Figure 18.6c).

The final design shown in Figure 18.7 amalgamates the hot end design from Figure 18.5c and cold end design from Figure 18.6c. The duty on hot utility of 7.5 MW agrees with Q_{Hmin} and the duty on cold utility of 10.0 MW agrees with Q_{Cmin} predicted by the composite curves and the problem table algorithm.

Note one further point from Figure 18.7. The number of units is 7 in total (including the heater and cooler). Referring back to Example 17.1, the target for the minimum number of units was predicted to be 7. It therefore appears that there was something in the procedure that naturally steered the design to achieve the target for the minimum number of units.

It is in fact the tick-off heuristic that steered the design toward the minimum number of units[1,2]. The target for the minimum number of units was given by Equation 17.2:

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

Before any matches are placed, the target indicates that the number of units required is equal to the number of streams (including utilities) minus one. The tick-off heuristic satisfied the heat duty on one stream every time one of the units was used. The stream that has been ticked off is no longer part of the remaining design problem. The tick-off heuristic ensures that having placed a unit (and used up one of the available units), a stream is removed from the problem. Thus, Equation 17.2 is satisfied if every match satisfies the heat duty on a stream or a utility.

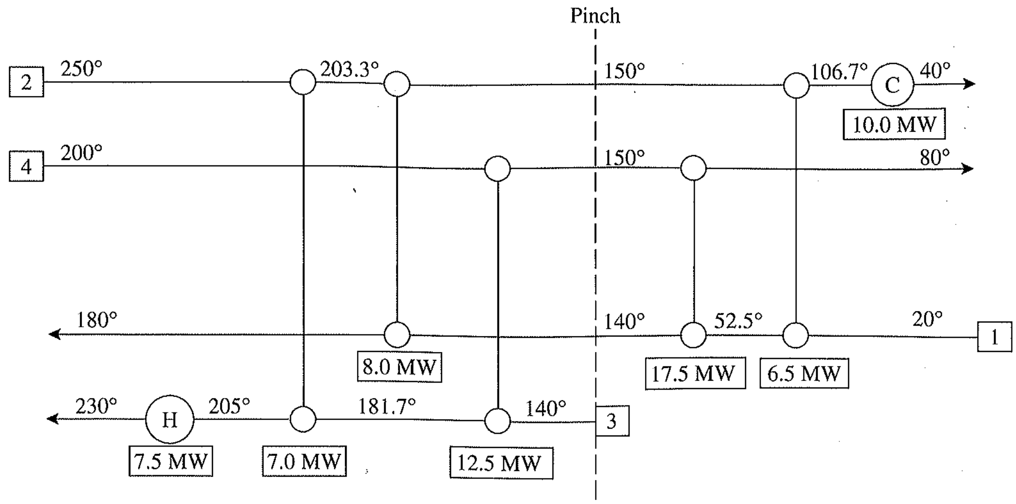


Figure 18.7 The completed design for the data from Table 16.2.

This design procedure is known as the *pinch design method* and can be summarized in five steps[1].

- Divide the problem at the pinch into separate problems.
- The design for the separate problems is started at the pinch, moving away.
- Temperature feasibility requires constraints on the *CP* values to be satisfied for matches between the streams at the pinch.
- The loads on individual units are determined using the tick-off heuristic to minimize the number of units. Occasionally, the heuristic causes problems.
- Away from the pinch, there is usually more freedom in the choice of matches. In this case, the designer can discriminate on the basis of operability, plant layout and so on.

Example 18.1 The process stream data for a heat recovery network problem are given in Table 18.1.

Table 18.1 Stream data for Example 18.1.

Stream No.	Stream Type	Supply temperature (°C)	Target temperature (°C)	Heat capacity flowrate ($MW \cdot K^{-1}$)
1	Hot	400	60	0.3
2	Hot	210	40	0.5
3	Cold	20	160	0.4
4	Cold	100	300	0.6

A problem table analysis on this data reveals that the minimum hot utility requirement for the process is 15 MW and the minimum cold utility requirement is 26 MW for a minimum allowable temperature difference of 20°C. The analysis also reveals that the pinch is located at a temperature of 120°C for hot streams and 100°C for cold streams. Design a heat exchanger network for maximum energy recovery featuring the minimum number of units.

Solution Figure 18.8a shows the hot end design with the CP-table. Above the pinch, adjacent to the pinch, $CP_H \le CP_C$. The duty on the units has been maximized according to the tick-off heuristic.

Figure 18.8b shows the cold end design with the CP-table. Below the pinch, adjacent to the pinch, $CP_H \ge CP_C$. Again the duty on units has been maximized according to the tick-off heuristic.

The completed design is shown in Figure 18.8c. The minimum number of units for this problem is given by

$$\begin{aligned} N_{UNITS} &= (S-1)_{ABOVE\ PINCH} + (S-1)_{BELOW\ PINCH} \\ &= (5-1) + (4-1) \\ &= 7 \end{aligned}$$

The design in Figure 18.8 is seen to achieve the minimum number of units target.

The pinch design method, as discussed so far, has assumed the same ΔT_{min} applied between all stream matches. In Chapter 16, it was discussed how the basic targeting methods for the composite curves and the problem table algorithm can be modified to allow stream-specific values of ΔT_{min}. The example was quoted in which liquid streams were required to have a ΔT_{min} contribution of 5°C and gas streams a ΔT_{min} contribution of 10°C. For liquid–liquid matches, this would lead to a $\Delta T_{min} = 10$°C. For gas–gas matches, this would lead to a $\Delta T_{min} = 20$°C. For liquid–gas matches, it will lead to a $\Delta T_{min} = 15$°C [2]. Modifying the problem table and the composite curves to account for these stream-specific values of ΔT_{min} is straightforward. But how is the pinch design method modified to take account of such ΔT_{min} contributions? Figure 18.9 illustrates the approach. Suppose the interval pinch temperature from the problem table is 120°C. This would correspond with hot stream pinch temperatures of 125°C and 130°C for hot streams with ΔT_{min} contributions of 5°C and 10°C respectively. For

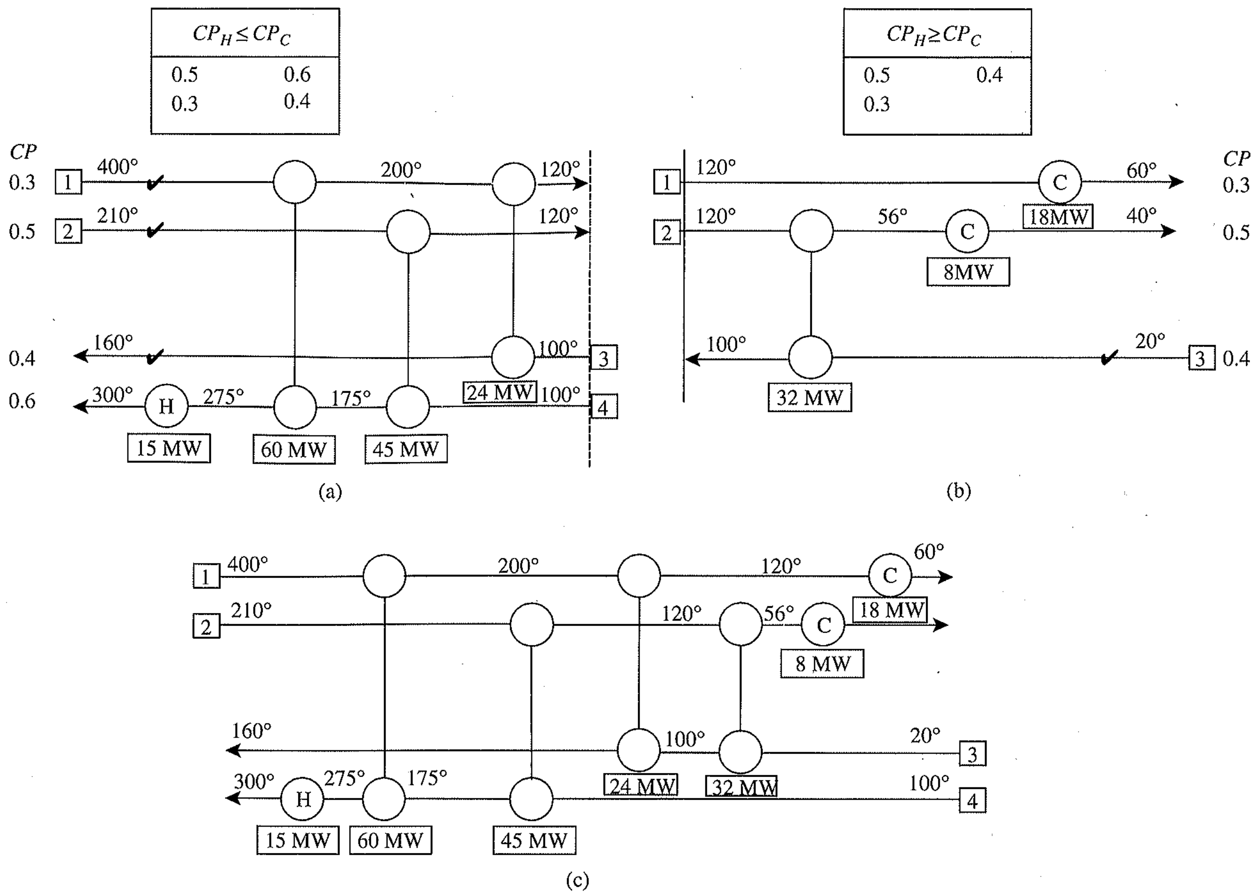


Figure 18.8 Maximum energy recovery design for Example 18.1.

an interval pinch temperature of 120°C, the corresponding cold stream pinch temperatures would be 115°C and 110°C for cold streams with ΔT_{min} contributions of 5°C and 10°C respectively. The stream grid is set up as shown in Figure 18.9 with the pinch matches being made and given their appropriate value of ΔT_{min} depending on the streams being matched. The constraints regarding the CP inequalities apply in this case, just as the case with a global value of ΔT_{min}.

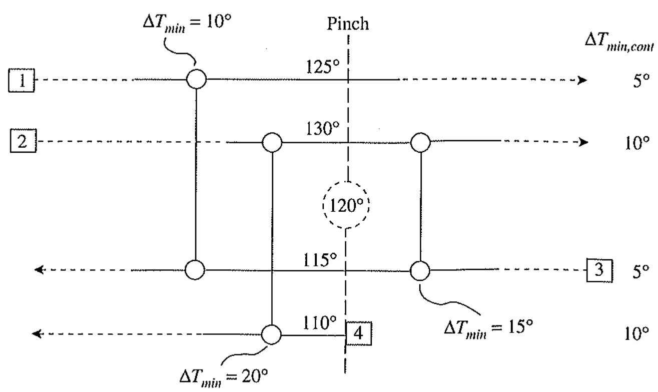


Figure 18.9 The design grid for a problem stream-specific with ΔT_{min} contributions.

18.2 DESIGN FOR THRESHOLD PROBLEMS

In Section 16.3, it was discussed that some problems, known as threshold problems, do not have a pinch. They need either hot utility or cold utility but not both. How should the approach be modified to deal with the design of threshold problems?

The philosophy in the pinch design method was to start the design where it was most constrained. If the design is pinched, the problem is most constrained at the pinch. If there is no pinch, where is the design most constrained? Figure 18.10a shows one typical threshold problem that requires no hot utility, just cold utility. The most constrained part of this problem is the no-utility end[2]. This is where temperature differences are smallest and there may be constraints, as shown in Figure 18.10b, where the target temperatures on some of the hot streams can only be satisfied by specific matches. Also, if individual matches are required to have a temperature difference no smaller than the threshold ΔT_{min}, the CP inequalities described in the pinch design method must be applied. For the most part, problems similar to those in Figure 18.10a are treated as one half of a pinched problem.

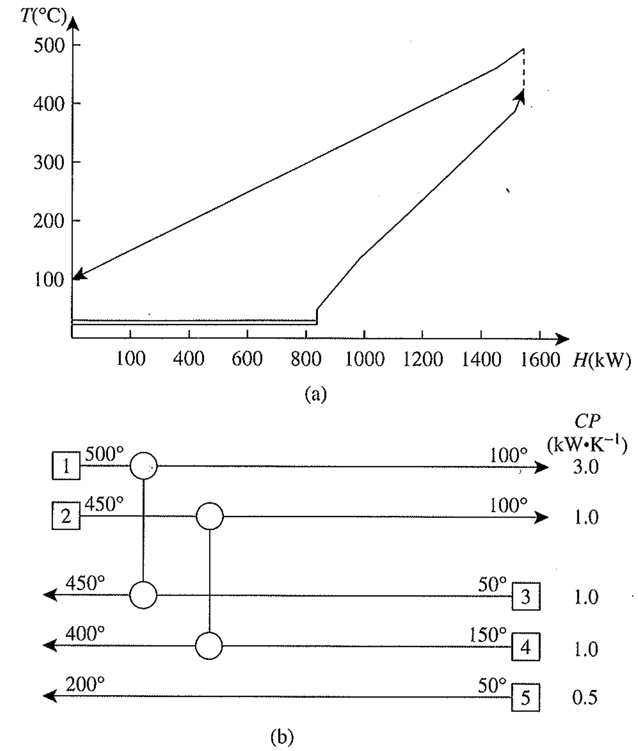


Figure 18.10 Even though threshold problems have large driving forces, there are still often essential matches to be made, especially at the no-utility end.

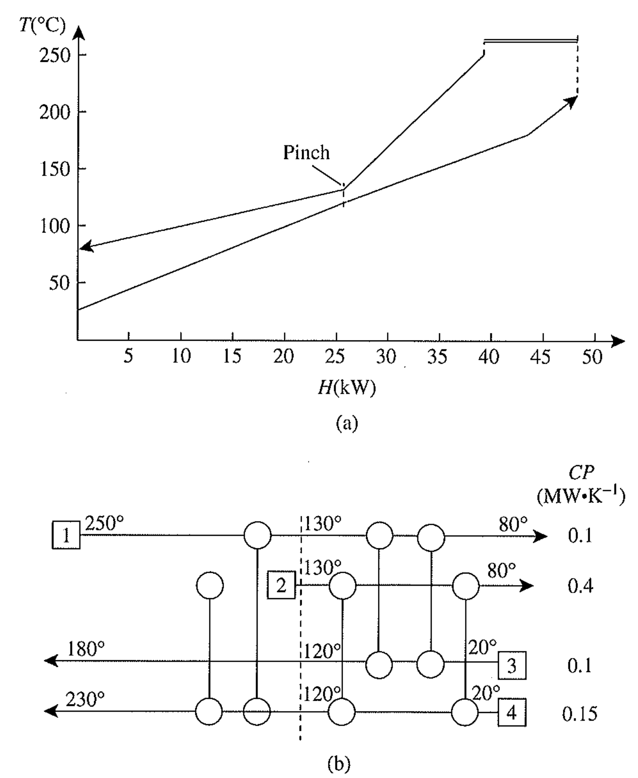


Figure 18.11 Some threshold problems must be treated as pinched problems requiring essential matches at both the no utility end and the pinch.

Figure 18.11 shows another threshold problem that requires only hot utility. This problem is different in characteristic from the one in Figure 18.10. Now the minimum temperature difference is in the middle of the problem causing a pseudo-pinch. The best strategy to deal with this type of threshold problem is to treat it as a pinched problem. In Figure 18.11, the problem is divided into two parts at the pseudo-pinch, and the pinch design method followed. The only complication in applying the pinch design method for such problems is that one half of the problem (the cold end in Figure 18.11) will not feature the flexibility offered by matching against utility.

18.3 STREAM SPLITTING

The pinch design method developed earlier followed several rules and guidelines to allow design for minimum utility (or maximum energy recovery) in the minimum number of units. Occasionally, it appears not to be possible to create the appropriate matches because one or other of the design criteria cannot be satisfied.

Consider Figure 18.12a that shows the above-pinch part of a design. Cold utility must not be used above the pinch, which means that all hot streams must be cooled to pinch temperature by heat recovery. There are three hot streams

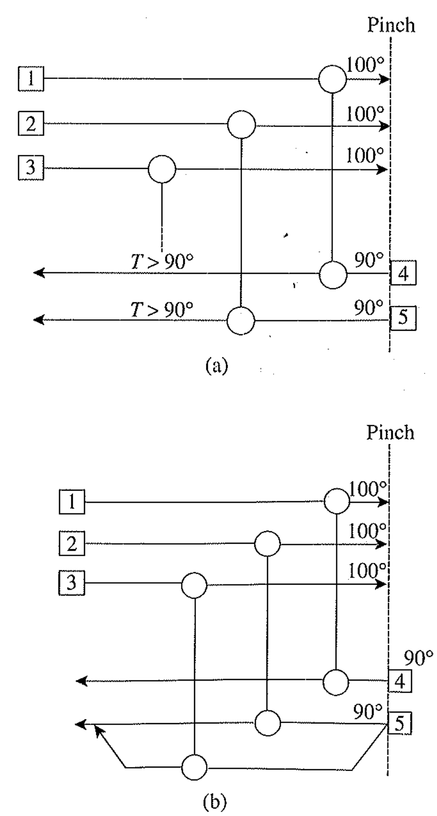


Figure 18.12 If the number of hot streams at the pinch, above the pinch, is greater than the number of cold streams, then stream splitting of the cold streams is required.

and two cold streams in Figure 18.12a. Thus, regardless of the *CP* values of the streams, one of the hot streams cannot be cooled to pinch temperature without some violation of the ΔT_{min} constraint. The problem can only be resolved by splitting a cold stream into two parallel branches as shown in Figure 18.12b. Now each hot stream has a cold partner with which to match, capable of cooling it to pinch temperature. Thus, in addition to the *CP* inequality criteria introduced earlier, there is a stream number criterion above the pinch such that[1,2]:

$$S_H \leq S_C \text{ (above pinch)} \tag{18.3}$$

where S_H = number of hot streams at the pinch (including branches)

S_C = number of cold streams at the pinch (including branches)

If there had been a greater number of cold streams than hot streams in the design above the pinch, this would not have created a problem, since hot utility can be used above the pinch.

By contrast, now consider part of a design below the pinch, as shown in Figure 18.13a. Here hot utility must not be used, which means that all cold streams must be heated to pinch temperature by heat recovery. There are now three cold streams and two hot streams in Figure 18.13a. Again, regardless of *CP* values, one of the cold streams cannot be heated to pinch temperature without some violation of the ΔT_{min} constraint. The problem can only be resolved by splitting a hot stream into two parallel branches, as shown in Figure 18.13b. Now each cold stream has a hot partner with which to match and capable of heating it to pinch temperature. Thus there is a stream number criterion below the pinch, such that[1,2]:

$$S_H \geq S_C \text{ (below pinch)} \tag{18.4}$$

Had there been more hot streams than cold below the pinch, this would not have created a problem since cold utility can be used below the pinch.

It is not only the number of streams that creates the need to split streams at the pinch. Sometimes the *CP* inequality criteria, Equations 18.1 and 18.2, cannot be met at the pinch without a stream split. Consider the above-pinch part of a problem in Figure 18.14a. The number of hot streams is less than the number of cold streams, and hence Equation 18.3 is satisfied. However, the *CP* inequality, Equation 18.1, must be satisfied. Neither of the two cold streams has a large enough *CP*. The hot stream can be made smaller by splitting it into two parallel branches (Figure 18.14b).

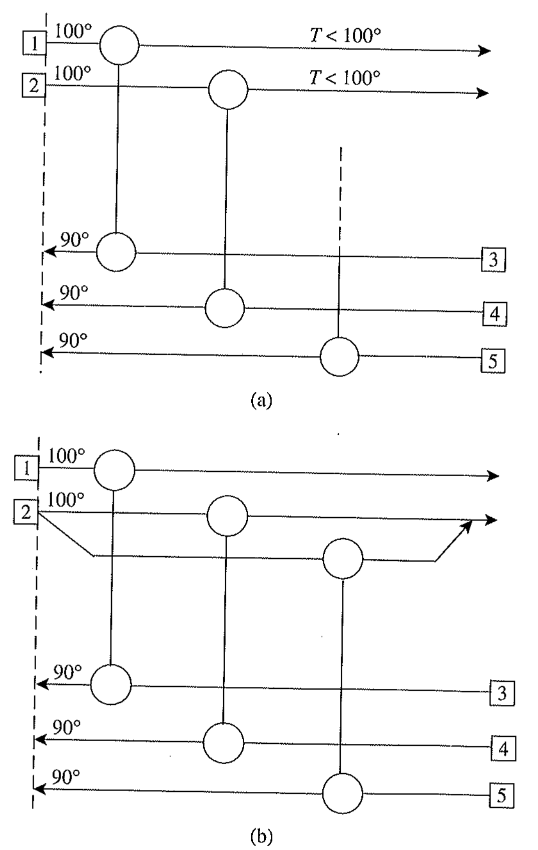


Figure 18.13 If the number of cold streams below the pinch, at the pinch, is greater than the pinch number of hot streams, then stream splitting of the hot steam is required.

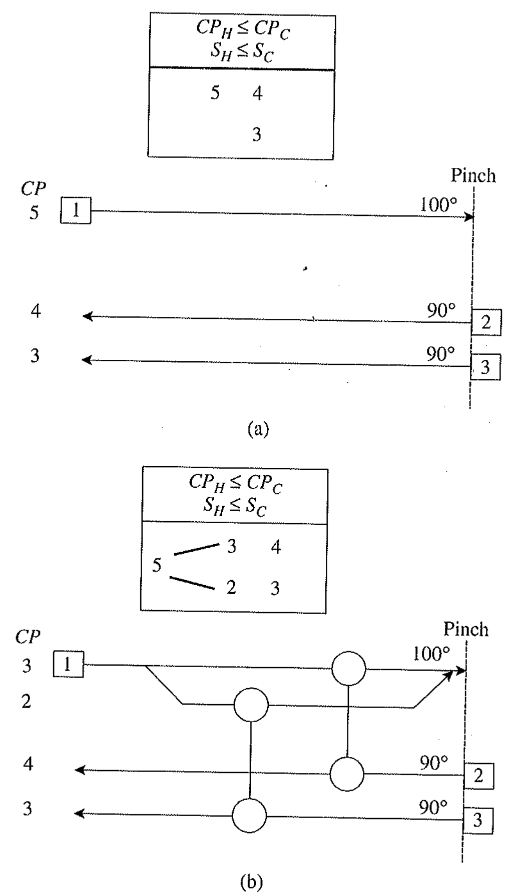


Figure 18.14 The CP in equality rules can necessitate stream splitting above the pinch.

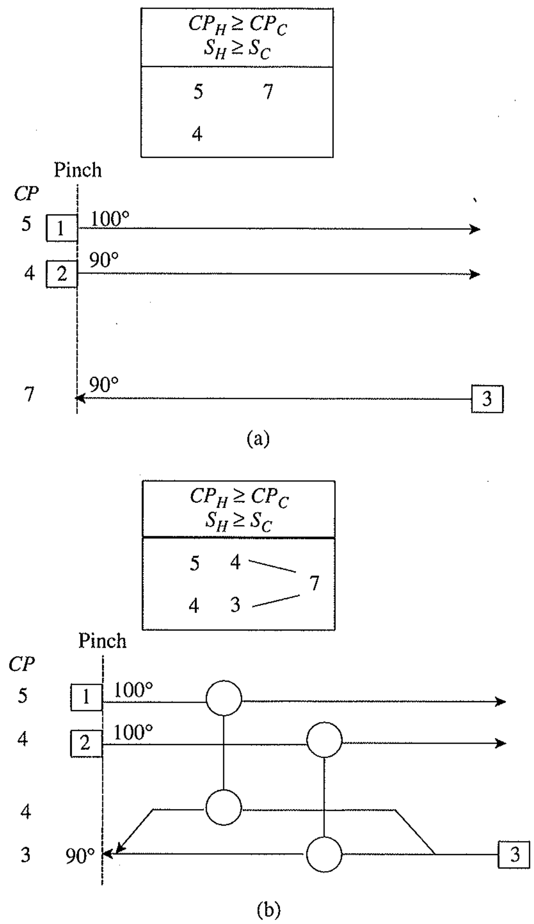


Figure 18.15 The CP in equality rules can necessitate stream splitting below the pinch.

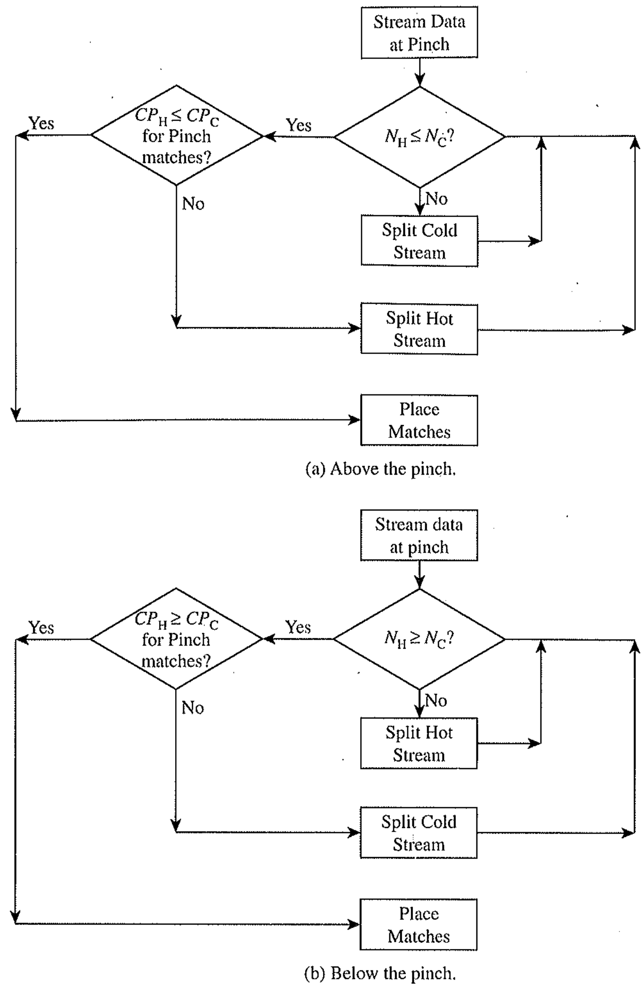


Figure 18.16 Stream splitting algorithms.

Figure 18.15a shows the below-pinch part of a problem. The number of hot streams is greater than the number of cold streams, and hence Equation 18.4 is satisfied. However, neither of the two hot streams has a large enough *CP* to satisfy the *CP* inequality, Equation 18.2. The cold stream can be made smaller by splitting it into two parallel branches (Figure 18.14b).

Clearly, in designs different from those in Figures 18.14 and 18.15, when streams are split to satisfy the *CP* inequality, this might create a problem with the number of streams at the pinch such that Equations 18.3 and 18.4 are no longer satisfied. This would then require further stream splits to satisfy the stream number criterion. Figures 18.16a and 18.16b present algorithms for the overall approach[1,2].

One further important point needs to be made regarding stream splitting. In Figure 18.14, the hot stream is split into two branches with *CP* values of 3 and 2 to satisfy the *CP* inequality criteria. However, a different split could have been chosen. For example, the split could have been into branch *CP* values of 4 and 1, or 2.5 and 2.5, or 2 and 3 (or any setting between 4 and 1, and 2 and 3). Each of these would also have satisfied the *CP* inequalities. Thus, there is a degree of freedom in the design to choose the branch flowrates. By fixing the heat duties on the two units in Figure 18.14b and changing the branch flowrates, the temperature differences across each unit are changed. The best choice can only be made by sizing and costing the various units in the completed network for different branch flowrates. This is an important degree of freedom when the network is optimized. Similar arguments could be made regarding the cold end design in Figure 18.15b.

Example 18.2 A problem table analysis for part of a high-temperature process reveals that for $\Delta T_{min} = 20°C$ the process requires 9.2 MW of hot utility, 6.4 MW of cold utility and the pinch is located at 520°C for hot streams and 500°C for cold streams. The process stream data are given in Table 18.2. Design a heat exchanger network for maximum energy recovery that features the minimum number of units.

Solution Figure 18.17a shows the stream grid with the CP-tables for the above- and below-pinch designs. Following the algorithms in Figure 18.16, a hot stream must be split above the pinch to satisfy the *CP* inequality, as shown in Figure 18.17b.

Table 18.2 Stream data.

Stream		Supply Temp. (°C)	Target Temp. (°C)	Heat Capacity Flowrate (MW·K^{-1})
No.	Type			
1	Hot	720	320	0.045
2	Hot	520	220	0.04
3	Cold	300	900	0.043
4	Cold	200	550	0.02

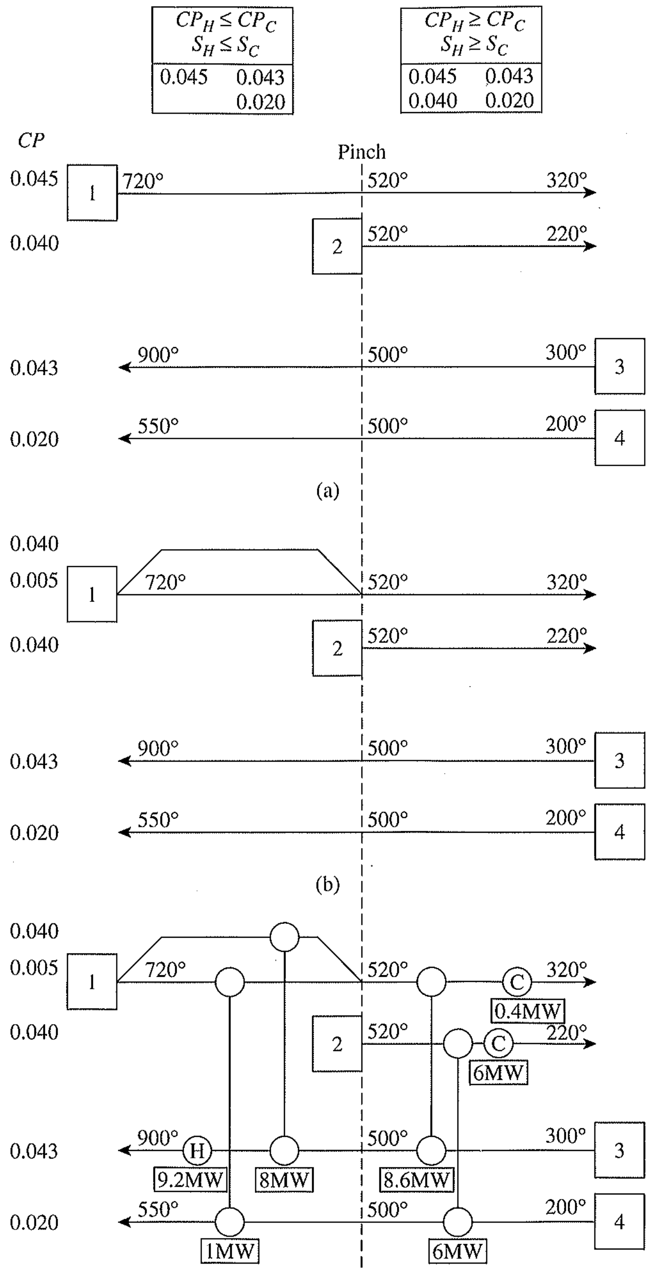


Figure 18.17 Maximum energy recovery design for Example 18.2.

Thereafter the design is straightforward, and the final design is shown in Figure 18.17c.

The target for the minimum number of units is given by:

$$N_{UNITS} = (S - 1)_{ABOVE\ PINCH} + (S - 1)_{BELOW\ PINCH}$$
$$= (4 - 1) + (5 - 1)$$
$$= 7$$

The design in Figure 18.17c is seen to achieve the minimum units target.

18.4 DESIGN FOR MULTIPLE PINCHES

In Chapter 16, it was discussed as to how the use of multiple utilities could give rise to multiple pinches. For example, the design for the process in Figure 16.2 could have used either a single level of hot utility or two steam levels (Figure 16.26a). The targeting indicated that instead of using 7.5 MW of high-pressure steam at 240°C, 3 MW of this could be substituted with low-pressure steam at 180°C. Where the low-pressure steam touches the grand composite curve in Figure 16.26a results in a utility pinch. Figure 18.18a shows the grid diagram when two steam levels are used with the utility pinch dividing the process into three parts.

Following the pinch rules, heat should not be transferred across either the process pinch or the utility pinch by process-to-process heat exchange. Also, there must be no inappropriate use of utilities. This means that above the utility pinch shown in Figure 18.18a, high-pressure steam should be used and no low-pressure steam or cooling water. Between the utility pinch, and the process pinch low-pressure steam should be used and no high-pressure steam or cooling water. Below the process pinch in Figure 18.18 only cooling water should be used. The appropriate utility streams have been included with the process streams in Figure 18.18.

The network can now be designed using the pinch design method[1,2]. The philosophy of the pinch design method is to start at the pinch, and move away. At the pinch, the rules for the *CP* inequality and the number of streams must be obeyed. Above the utility pinch in Figure 18.18, and below the process pinch in Figure 18.18 there is clearly no problem in applying this philosophy. However, between the two pinches there is a problem, since designing away from both pinches could lead to a clash.

More careful examination of Figure 18.18a reveals that, between the two pinches, one is more constrained than the other. Below the utility pinch, $CP_H \geq CP_C$ is required and low-pressure steam is available as a hot stream with an extremely large *CP*. In fact, if steam is assumed to condense or vaporize isothermally, it will have a *CP* that is infinite. Thus, following the philosophy of starting the design in the most constrained region, the design between the pinches in Figure 18.18a should be started at the most constrained pinch, which is the process pinch.

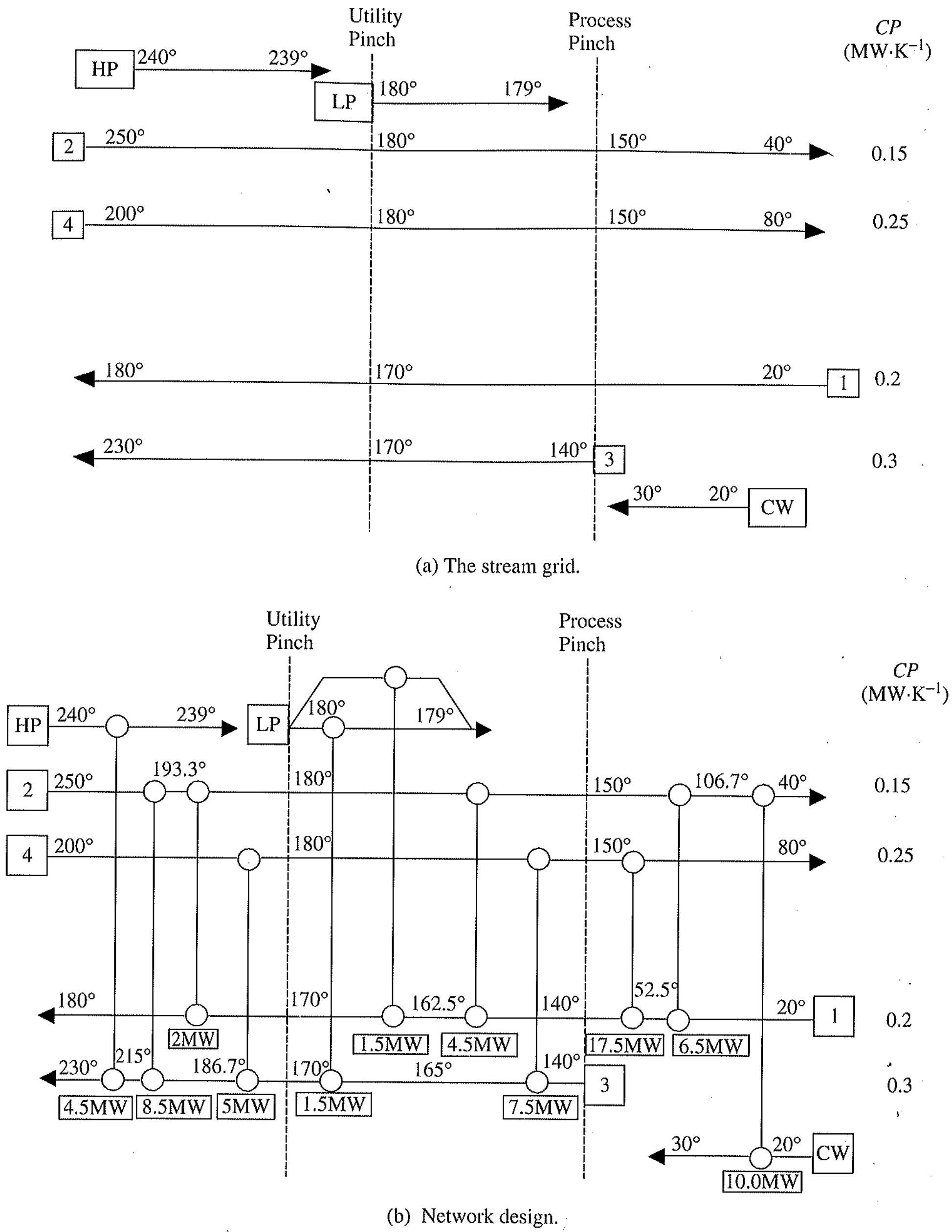


Figure 18.18 Network design for the process from Figure 16.2 using two steam levels.

Following this approach, the design is straightforward and the final design is shown in Figure 18.18b. It achieves the target set in Example 16.3 and in the minimum number of units. Remember that, in this case, to calculate the minimum number of units, the stream count must be performed separately in the three parts of the problem. Note that the stream split on the low-pressure steam in Figure 18.18b is not strictly necessary, but is made for practical reasons. Without the stream split, steam would have to partially condense in one unit and the steam-condensate mixture transferred to the next unit. The stream split allows two conventional steam heaters on low-pressure steam to be used. It is clear from Figure 18.18b that the use of two steam levels has increased the complexity of the design considerably. However, the complexity of the design can be reduced later when the structure is subjected to optimization. The optimization can remove units that are uneconomic.

It is rare for there to be two process pinches in a problem. Multiple pinches usually arise from the introduction of additional utilities causing utility pinches. However, cases such as that shown in Figure 18.19 are not uncommon, where there is strictly speaking, only one pinch (one place where ΔT_{min} occurs), but there is a near-pinch. This near-pinch is a point in the process where the temperature difference becomes small enough to be effectively another pinch, even

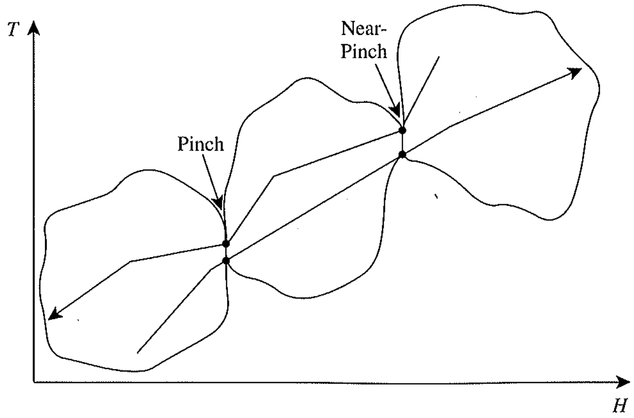


Figure 18.19 A near-pinch might require the design to be treated as if it had multiple pinches.

though the temperature difference is slightly larger than ΔT_{min}. Because the region around the near-pinch will be almost as constrained as the pinch, the best strategy is often to treat the near-pinch as if it was another pinch and divide the problem into three parts as shown in Figure 18.19. The initial design would therefore avoid heat transfer across the near-pinch and the process pinch and use hot utility only above the near-pinch and cold utility only below the pinch. The designer can then exploit the small amount of freedom around the near-pinch. Some heat transfer across the near-pinch is possible without causing an energy penalty. Exploiting this freedom allows the design to be simplified slightly.

Example 18.3 The stream data for a process are given in Table 18.3:

Table 18.3 Stream data.

Stream		Supply temperature	Target temperature	Heat capacity flowrate
No.	Type	(°C)	(°C)	($MW \cdot K^{-1}$)
1	Hot	635	155	0.044
2	Cold	10	615	0.023
3	Cold	85	250	0.020
4	Cold	250	615	0.020

It has been decided to integrate a gas turbine (GT) exhaust with the process. The exhaust temperature of the GT is 400°C with $CP = 0.05\ MW \cdot K^{-1}$. Ambient temperature is 10°C.

a. Calculate the problem table cascade for $\Delta T_{min} = 20°C$.
b. Saturated steam is to be generated by the process at a high-pressure level of 250°C and low-pressure level of 140°C, each from saturated boiler feedwater. The generation of the higher-pressure steam is to be maximized. How much steam can be generated at the two levels assuming boiler feedwater and final steam condition are both saturated?
c. Design a network for maximum energy recovery for $\Delta T_{min} = 20°C$ that generates steam at these two levels.
d. What is the residual cooling demand?

Solution

a. The problem table cascade is shown in Table 18.4 for $\Delta T_{min} = 20°C$.

Table 18.4 Problem table cascade.

Interval temperature (°C)	Cascade heat flow (MW)
625	0
390	0.235
260	6.865
145	12.73
95	13.08
20	15.105
0	16.105

b. For high-pressure steam, $T^* = 260°C$, for low-pressure steam, $T^* = 150°C$. Figure 18.20 shows the grand composite curve plotted from the problem table cascade. The two levels of steam generation are shown.

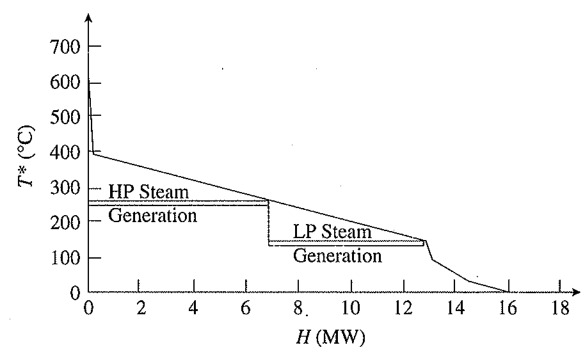


Figure 18.20 Grand composite curve for Example 18.3 showing two levels of steam generation.

Duty on high-pressure steam generation

$$= 6.865\ MW$$

By interpolation from the problem table cascade, heat flow at $T^* = 150°C$

$$= 6.865 + \frac{(260 - 150)}{(260 - 145)} \times (12.73 - 6.865)$$

$$= 12.475\ MW$$

Duty on low-pressure steam generation

$$= 12.475 - 6.865$$

$$= 5.61\ MW$$

c. The use of two levels of steam generation in Figure 18.20 creates two utility pinches. Thus, the stream grid needs to be divided into three parts. Figure 18.21 shows the final design, which achieves the targets set for both high-pressure (HP) and low-pressure (LP) steam generation. In Figure 18.21 above the HP pinch, the CP of Stream 1 and the GT stream are too large

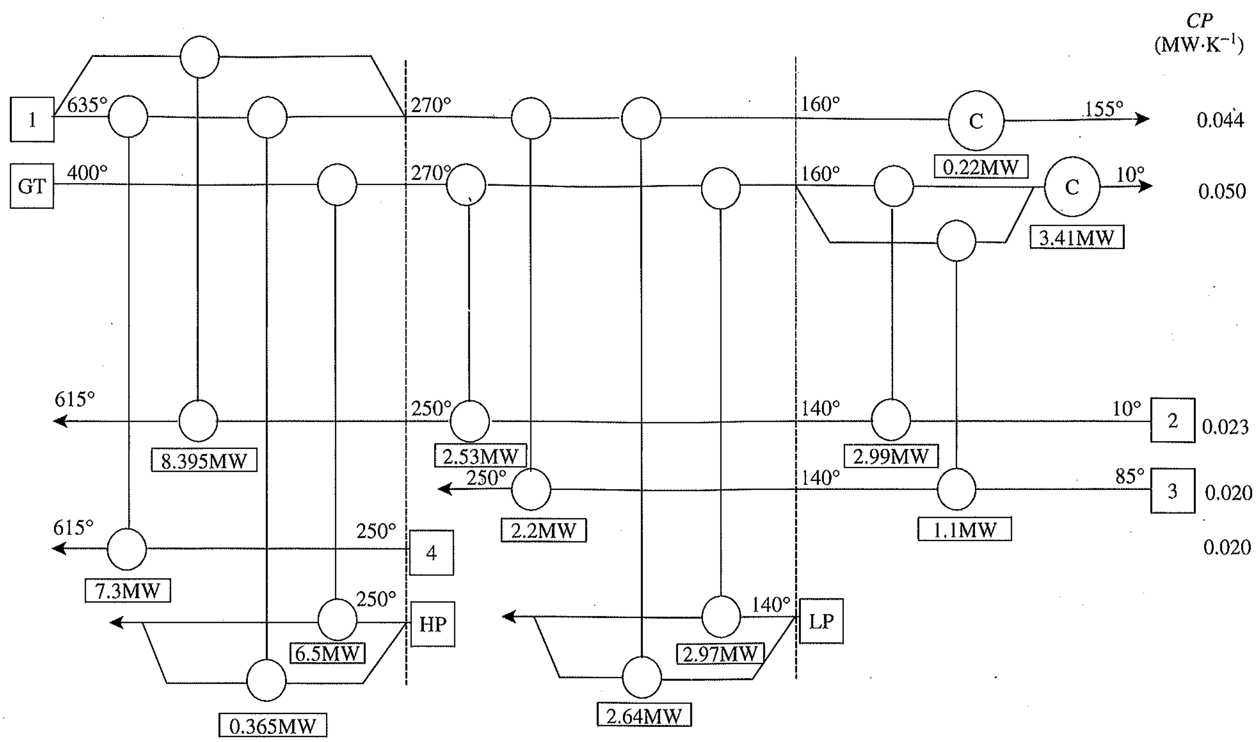


Figure 18.21 Network design for Example 18.3.

to match directly against Streams 3 and 4. This is overcome in Figure 18.21 by splitting Stream 1 and exploiting the infinite *CP* of the HP steam generation. Between the pinches, the design is started below the HP pinch and developed toward the LP pinch, where the infinite *CP* of the LP steam generation can be exploited to satisfy the *CP* inequalities. Below the LP pinch, although the *CP* inequalities can be satisfied by direct matches, the heat duty on Stream 1 is small compared with the other streams. If Stream 1 did not exist below the LP pinch, then this would call for the GT stream to be split. This has been done in Figure 18.21 because of the small duty on Stream 1. Although the steam generation for both high-pressure and low-pressure steam are shown with steam splits in Figure 18.21, in practice these units would be individual steam generators, each fed with boiler feedwater. Also, the stream split for the GT exhaust could be accommodated by splitting the gas turbine flow into two ducts, or by placing two sets of tubes in the same GT exhaust located in parallel. The design in Figure 18.21 has significant scope for simplification, but at the penalty of reduced energy efficiency. Such trade-offs are at the discretion of the designer.

d. There is a cooling demand of 0.22 MW on Stream 1 that needs to be satisfied by cold utility and cooling demand of 3.41 MW required by the GT exhaust. The cooling of the GT exhaust is satisfied by simply venting it to atmosphere after heat recovery has been completed.

18.5 REMAINING PROBLEM ANALYSIS

The considerations addressed so far in network design have been restricted to those of energy performance and number of units. In addition, the problems have all been straightforward to design for maximum energy recovery in the minimum number of units by ticking-off streams. Not all problems are so straightforward. Also, heat transfer area, number of shells when using 1–2 shells, capital cost and so on should be considered when placing matches. Here, a more sophisticated approach is needed[3].

When a match is placed, the duty needs to be chosen with some quantitative assessment of the match in the context of the whole network, without having to complete the network. This can be done by exploiting the powers of targeting using a technique known as *remaining problem analysis*.

Consider first design for minimum energy in a more complex problem than has so far been addressed. If a problem table analysis is performed on the stream data, Q_{Hmin} and Q_{Cmin} can be calculated. When the network is designed and a match placed, it would be useful to assess whether there will be any energy penalty caused by some feature of the match without having to complete the design. Whether there will be a penalty can be determined by performing a problem table analysis on the *remaining problem*. The problem table analysis is simply repeated on the stream data, leaving out those parts of the hot and cold stream satisfied by the match. One of the two results would then occur:

1. The algorithm may calculate Q_{Hmin} and Q_{Cmin} to be unchanged. In this case, the designer knows that the match will not penalize the design in terms of increased utility usage.

2. The algorithm may calculate an increase in Q_{Hmin} and Q_{Cmin}. This means that the match is transferring heat across the pinch or that there is some feature of the design that will cause cross-pinch heat transfer if the design was completed. If the match is not transferring heat across the pinch directly, then the increase in utility will result from the match being too big as a result of the tick-off heuristic.

The remaining problem analysis technique can be applied to any feature of the network that can be targeted, such as a minimum area. In Chapter 17, the approach to targeting for heat transfer area (Equation 17.6) was based on vertical heat transfer from the hot composite curve to the cold composite curve. If heat transfer coefficients do not vary significantly, this model predicts the minimum area requirements adequately for most purposes[3]. Thus, if heat transfer coefficients do not vary significantly, then the matches created in the design should come as close as possible to the conditions that would correspond with vertical transfer between the composite curves. Remaining problem analysis can be used to approach the area target, as closely as a practical design permits, using a minimum (or near-minimum) number of units. Suppose a match is placed, then its area requirement can be calculated. A remaining problem analysis can be carried out by calculating the area target for the stream data, leaving out those parts of the data satisfied by the match. The area of the match is now added to the area target for the remaining problem. Subtraction of the original area target for the whole-stream data $A_{NETWORK}$ gives the area penalty incurred.

If heat transfer coefficients vary significantly, then the vertical heat transfer model adopted in Equation 17.6 predicts a network area that is higher than the true minimum, as illustrated in Figure 17.4. Under these circumstances, a careful pattern of nonvertical matching is required to approach the minimum network area. However, the remaining problem analysis approach can still be used to steer the design toward a minimum area under these circumstances. When heat transfer coefficients vary significantly, the minimum network area can be predicted using linear programming.[4,5] The remaining problem analysis approach can then be applied using these more sophisticated area targeting methods. Under such circumstances, the design is likely to be difficult to steer toward the minimum area, and an automated design method based on the optimization of a superstructure can be used, as will be discussed later.

Targets for number of shells, capital cost and total cost also can be set. Thus, remaining problem analysis can be used on these design parameters also.

Example 18.4 The stream data for a process are given in Table 18.5 below:

Steam is available condensing between 180 and 179°C and cooling water between 20 and 30°C. All film transfer coefficients are 200 $W \cdot m^{-2} \cdot K^{-1}$. For $\Delta T_{min} = 10°C$, the minimum hot and cold utility duties are 7 MW and 4 MW respectively, corresponding with a pinch at 90°C on the hot streams and 80°C on the cold streams.

Table 18.5 Stream data.

Stream		Supply temp. (°C)	Target temp. (°C)	Heat capacity flowrate ($MW \cdot K^{-1}$)
No.	Type			
1	Hot	150	50	0.2
2	Hot	170	40	0.1
3	Cold	50	120	0.3
4	Cold	80	110	0.5

a. Develop a maximum energy recovery design above the pinch that comes close to the area target in the minimum number of units.
b. Develop a maximum energy recovery design below the pinch that comes as close as possible to the minimum number of units.

Solution

a. The area target for the above-pinch problem shown in Figure 18.22 is 8859 m^2. If the design is started at the pinch

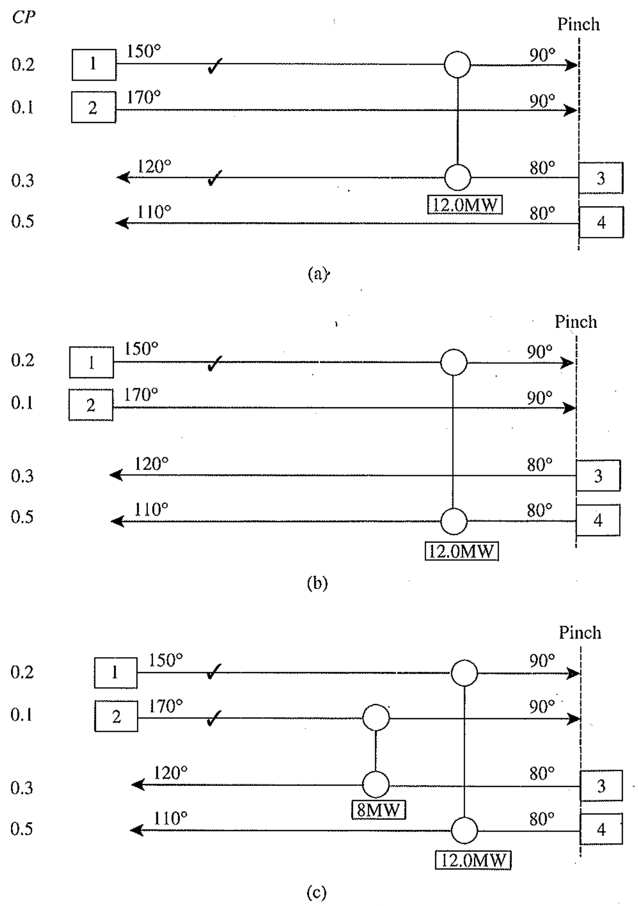


Figure 18.22 Above the pinch design for Example 18.4.

with Stream 1, then Figure 18.22a shows a feasible match that obeys the *CP* inequality. Maximizing its duty to 12 MW allows two streams to be ticked off simultaneously. This results from a coincidence in the stream data, the duties for Streams 1 and 3 being equal above the pinch. The area of the match is 6592 m^2 and the target for the remaining problem above the pinch is 3419 m^2, giving a total of 10,011 m^2. Thus, the match in Figure 18.22a causes the overall target to be exceeded by 1152 m^2 (13%). This does not seem to be a good match.

Figure 18.22b shows an alternative match for Stream 1 that also obeys the *CP* inequality. The tick-off heuristic also fixes its duty to be 12 MW. The area for this match is 5087 m^2, and the target for the remaining problem above the pinch is 3788 m^2, giving a total of 8,875 m^2. Thus, the match in Figure 18.22b causes the overall target to be exceeded by 16 m^2 (0.2%). This seems to be a better match and therefore is accepted.

Placing the next match above the pinch as shown in Figure 18.22c also allows the *CP* inequality to be obeyed. The area for both matches in Figure 18.22c is 7856 m^2 and the target for the remaining problem is 1020 m^2, giving a total of 8876 m^2. Accepting both matches causes the overall area target to be exceeded by 17 m^2 (0.2%). This seems to be reasonable, and both matches are accepted. No further process-to-process matches are possible, and it remains to place hot utility.

b. The cold utility target for the problem shown in Figure 18.23 is 4 MW. If the design is started at the pinch with Stream 3, then Stream 3 must be split to satisfy the CP inequality (Figure. 18.23a). Matching one of the branches against Stream 1 and ticking off Stream 1 results in a duty of 8 MW. This is a case in which the tick-off heuristic has caused problems. The match is infeasible, because the temperature difference between the streams at the cold end of the match is infeasible. Its duty must be reduced to 6 MW to be feasible without either stream being ticked off (Figure 18.23b).

Figure 18.23c shows an additional match placed on the other branch for Stream 3 with its duty maximized to 3 MW to tick off Stream 3. No further process-to-process matches are possible, and it remains to place cold utility.

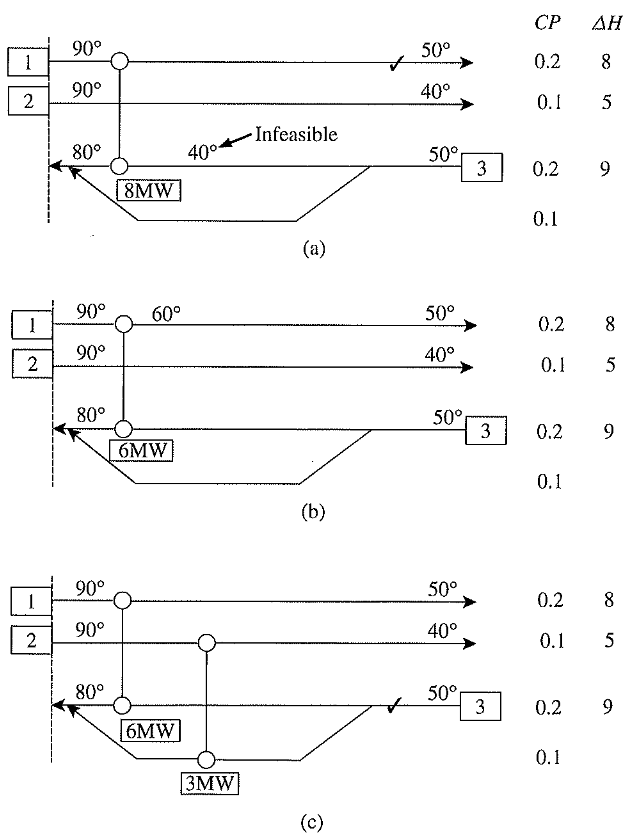


Figure 18.23 Below the pinch design for Example 18.4.

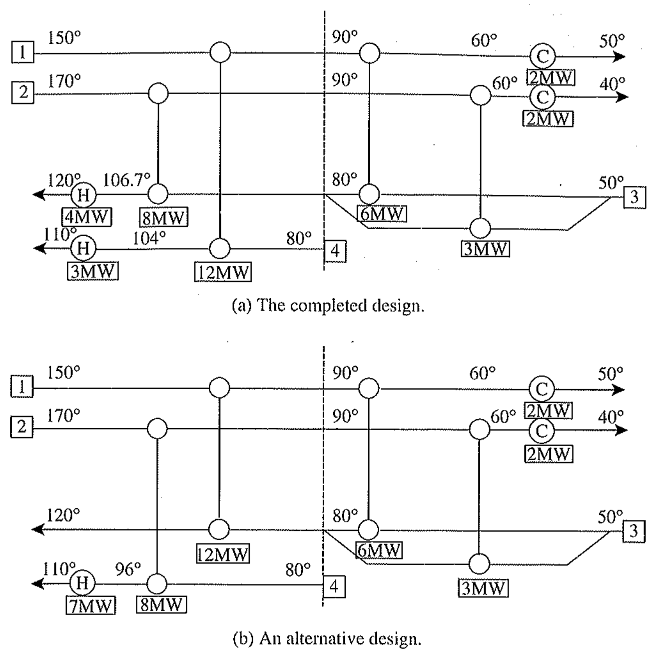


Figure 18.24 Alternative designs for Example18.4.

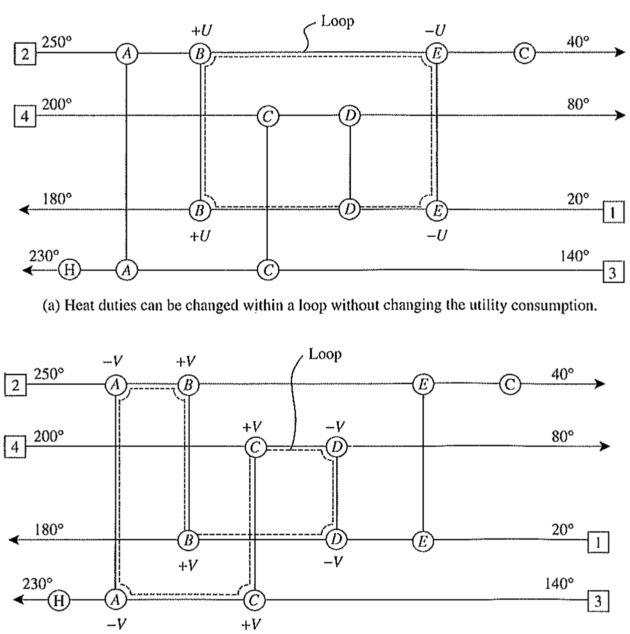
Figure 18.24a shows the complete design, achieving maximum energy recovery in one more unit than the target minimum, due to the inability to tick off streams below the pinch. If the match in Figure 18.22a had been accepted and the design completed, then the design in Figure 18.24b would have been obtained. This achieves the target for the minimum number of units of 7 (at the expense of excessive area). This results from the coincidence of data mentioned earlier in Figure 18.22a, which allowed two streams to be ticked off simultaneously. The result is that the design above the pinch uses one fewer unit than target, owing to the formation of two components above the pinch (see Section 17.1). The design below the pinch uses one more than target, and the net result is that the overall design achieves the target for the minimum number of units.

18.6 NETWORK OPTIMIZATION

The pinch design method creates a network structure based on the assumption that no heat exchanger should have a temperature difference smaller than ΔT_{min}. Having now created a structure for the heat exchanger network, the structure can now be subjected to continuous optimization. The constraint that no exchanger should have a temperature difference smaller than ΔT_{min} can now be relaxed. The continuous optimization of heat exchanger networks is based on the redistribution of the exchanger duties. Some exchangers should perhaps be larger, some smaller and some perhaps removed from the design altogether. Exchangers are removed from the design if the optimization sets their duty to zero.

Given a network structure, it is possible to identify loops and paths for it, as in Section 17.1. Within the context of optimization, only those paths that connect two different utilities need to be considered. This could be a path from steam to cooling water or a path from high-pressure steam used as hot utility to low-pressure steam also used as hot utility. These paths between two different utilities will be termed to be *utility paths*. Loops and utility paths both provide degrees of freedom in the optimization[1,2].

Consider Figure 18.25a that shows the network design from Figure 18.7, but with a loop highlighted. Heat can be shifted around loops. Figure 18.25a shows the effect of shifting heat duty U around the loop. In this loop, heat duty U is simply moved from Unit E to Unit B. The change in heat duties around the loop maintains the network heat balance and the supply and target temperatures of the streams. However, the temperatures around the loop change and hence the temperature differences of the exchangers in the loop change in addition to their duties. The magnitude of U could be changed to different values and the network costed at each value to find the optimum setting for U. If the optimum setting for U turns out to be 6.5 MW (the original duty on E), then the duty on one of the exchangers is zero and should be removed from the design.



(a) Heat duties can be changed within a loop without changing the utility consumption.

(b) Another loop allowing heat duties to be changed without changing the utility consumption.

Figure 18.25 The loops that can be exploited for the optimization of the design for Figure 16.7.

Figure 18.25b shows the network with another loop marked. Figure 18.25b shows the effect of shifting heat duty V around the loop. Again the heat balance is maintained, but the temperatures as well as the duties around the loop change. As before, the value of V can be optimized by costing the network at different settings of V. If V is optimized to 7.0 MW (the original duty on A), then the duty on A becomes zero and this unit is removed from the design. Note again that once optimization is started, there is no longer a constraint to maintain temperature differences to be larger than ΔT_{min}.

Figure 18.26a shows the network with a utility path highlighted. Heat duty can be shifted along utility paths in a similar way to that for loops. Figure 18.26a shows the effect of shifting heat duty W along the path. This time the heat balance changes because the loads imported from hot utility and exported to cold utility both change by W. The supply and target temperatures are maintained. If W is optimized to 7.0 MW, this will result in Unit A being removed from the design. Different values of W can be taken and the network sized and costed at each value to find the optimal setting for W. Figure 18.26b shows other utility paths that can be exploited for optimization.

In fact, the optimization of the network requires that U, V, W, X, Y and Z in Figures 18.25 and 18.26 must be optimized simultaneously. Furthermore, stream splits may exist in the design, and variations of their branch flowrates can be superimposed on the exploitation of loops and paths in the optimization. During this optimization, the design is no longer constrained to have temperature differences larger than ΔT_{min} (although very small values in individual heat exchangers should be avoided for practical reasons). Also, pinches no longer divide the design into independent thermodynamic regions, and there is no longer any concern about cross-pinch heat transfer. The objective now is simply to minimize cost.

Thus, loops, utility paths and stream splits offer the degrees of freedom for manipulating the network cost. The objective function in new design is usually to minimize total cost, that is, combined operating and annualized capital cost. The annualization period chosen for the capital cost will have a direct influence on the optimization. A longer annualization period will lead to more energy-efficient designs.

In practice, rather than manipulate loops and paths explicitly, the optimization is normally formulated such that the individual duties on each match are varied in the multivariable optimization, subject to:

- the total enthalpy change on each stream being within a specified tolerance of the original stream data,
- nonnegative heat duty for each match,
- positive temperature difference for each exchanger to be greater than a practical minimum value for a given type of heat exchanger,

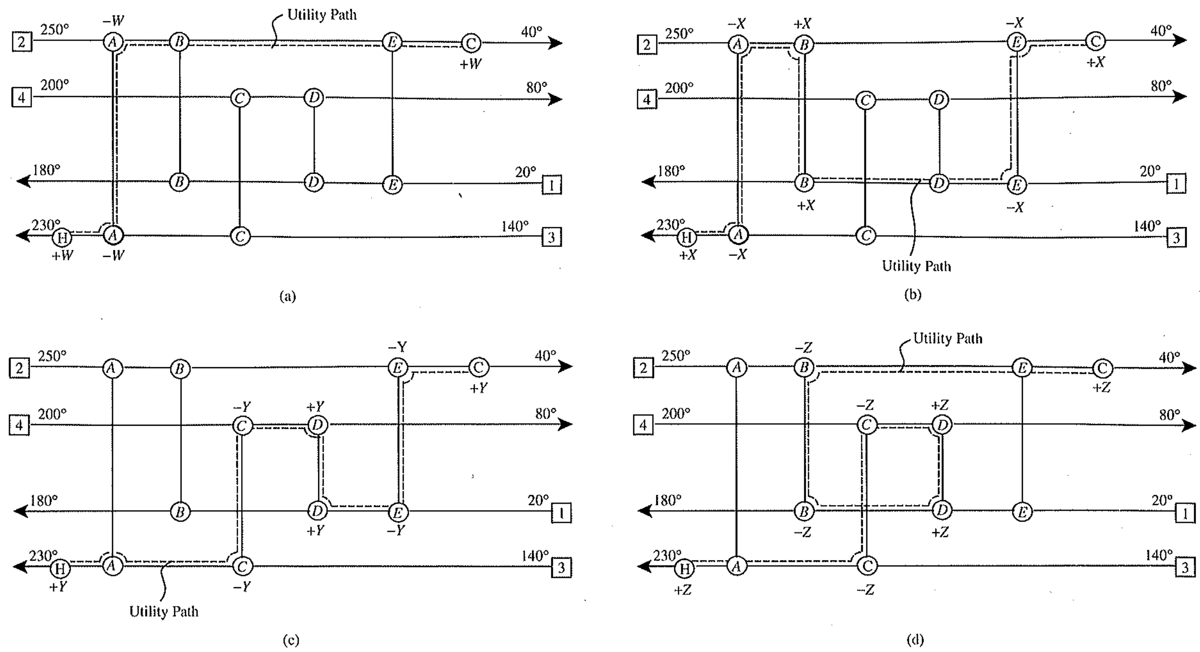


Figure 18.26 The utility paths that can be exploited for the optimization of the design from Figure 18.7.

- for stream splits, branch flowrates must be positive and above a practical minimum flowrate.

In a network, some of the duties on the matches will not be able to be varied because they are not in a loop or a utility path. This simplifies the optimization. The problem is one of multivariable nonlinear continuous optimization[6].

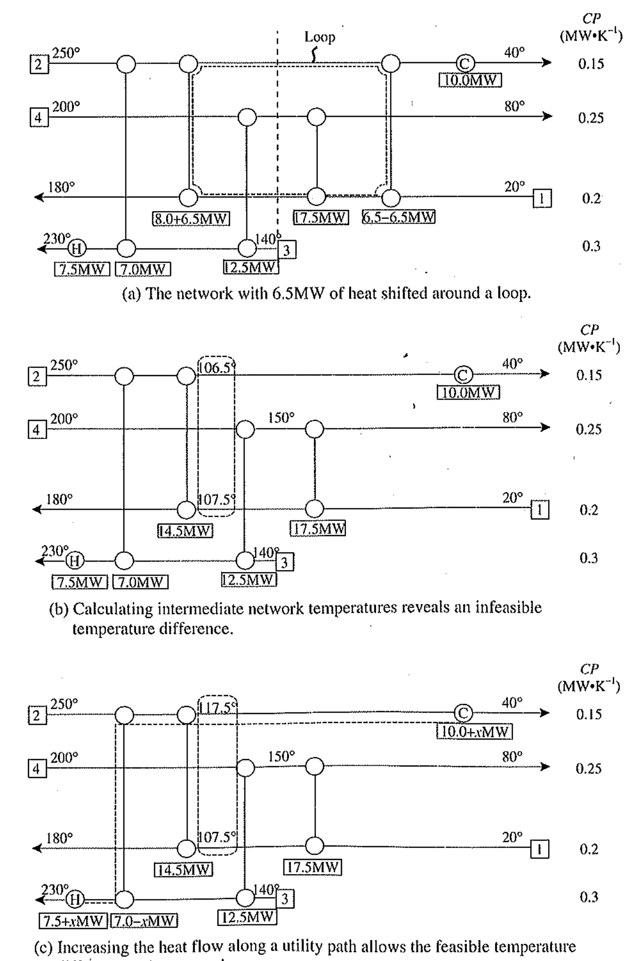
If the network is optimized at fixed energy consumption, then only loops and stream splits are exploited. When energy consumption is allowed to vary, utility paths must also be included. As the network energy consumption increases, the overall capital cost tends to decrease and vice versa.

Example 18.5 Evolve the heat exchanger network in Figure 18.7 to simplify its structure.

a. Remove the smallest heat recovery unit from the network by exploiting the degree of freedom in a loop.
b. Recalculate the network temperatures and identify any violations of the $\Delta T_{min} = 10°C$ constraint.
c. Restore the original $\Delta T_{min} = 10°C$ throughout the network by exploiting a utility path.

Solution

a. Figure 18.27a shows the network from Figure 18.7 with a loop highlighted involving the unit with the smallest heat duty (6.5 MW). A heat duty of 6.5 MW has been shifted around the loop to adjust the smallest unit to a duty of zero. This will change the temperatures around the loop.
b. Heat balances around the units for the new heat duties allow the new temperatures in the network to be calculated, as shown in Figure 18.27b. Also highlighted in Figure 18.27b, is a unit with an infeasible temperature difference. Not only is it less than



(a) The network with 6.5MW of heat shifted around a loop.

(b) Calculating intermediate network temperatures reveals an infeasible temperature difference.

(c) Increasing the heat flow along a utility path allows the feasible temperature difference to be restored.

Figure 18.27 Evolution of a network to remove a unit.

the original ΔT_{min} of 10°C, it is actually negative. Removing a unit in this way will always create a temperature difference smaller than the original ΔT_{min}, if the hot and cold utility remain fixed. There is a minimum number of units to satisfy the problem to hot utility consumption of Q_{Hmin} and a cold utility consumption of Q_{Cmin}, subject to the ΔT_{min} constraint. If a unit is then removed, something must be violated. By its nature, shifting heat load around a loop does not change the energy consumption, but does change internal temperatures.

c. Given the infeasible temperature difference in Figure 18.27b, this can be corrected by exploiting a utility path to change the temperatures in the network at the expense of increased energy consumption. Figure 18.27c shows the network with a utility path highlighted. The utility path allows one of the infeasible temperatures to be adjusted (Stream 2 in this case). If the original ΔT_{min} of 10°C is to be restored, then the intermediate temperature of Stream 2 needs to be adjusted to 117.5°C as shown in Figure 18.27c. The unknown is how much additional heat duty (x MW) needs to be shifted along the utility path to restore the temperature to 117.5°C. This can be determined by a simple heat balance around the cooler.

$$10.0 + x = 0.15\ (117.5 - 40)$$

$$x = 1.6 \text{ MW}$$

Thus the hot and cold utility consumption both need to be increased by 1.6 MW to restore the ΔT_{min} to the original 10°C. In fact there is no justification to restore the ΔT_{min} back to the original 10°C. The amount of additional energy shifted along the utility path is a degree of freedom that should be set by cost optimization. However, the example illustrates how the degrees of freedom can be manipulated in network optimization.

18.7 THE SUPERSTRUCTURE APPROACH TO HEAT EXCHANGER NETWORK DESIGN

The approach to heat exchanger network design discussed so far was based on the creation of an irreducible structure. No redundant features were included. However, after the structure was created, when the network was optimized, some of the features might be removed by the optimization. The scope for the optimization to remove features is a consequence of the assumptions made during the creation of the initial structure. However, no attempt was made to deliberately include redundant features.

An alternative approach is to create a superstructure that deliberately includes redundant features and then subject this to optimization. Redundant features are then removed by the optimization. Floudas, Ciric and Grossman[7] showed how a heat exchanger network superstructure could be set up with all structural features included. Figure 18.28a shows such a superstructure for part of a heat exchanger network problem involving two hot streams, two cold streams and steam. All possibilities have been included within this superstructure. The basic idea is then to optimize the superstructure in order to remove the unnecessary features and minimize the cost, possibly leading to the design as shown in Figure 18.28b. While this looks simple in principle, the optimization required is a mixed integer nonlinear programming problem (MINLP, see Chapter 3)[8]. This is a difficult optimization problem with all of the issues associated with local optima.

One of the ways to avoid this problem is to simplify the superstructure to remove some of the structural options in Figure 18.28a[9]. This is done in Figure 18.29. This structure is created by splitting each hot stream into a number of branches equal to the number of cold streams and splitting each cold stream into a number of branches equal to the number of hot streams. In this way, a structure is created that allows each hot stream to be matched with each cold stream[9].

One significant advantage of the simplified superstructure in Figure 18.29 is that each exchanger can be modeled by a linear equation if the supply and target temperatures of the streams are fixed. The area for each heat exchanger is

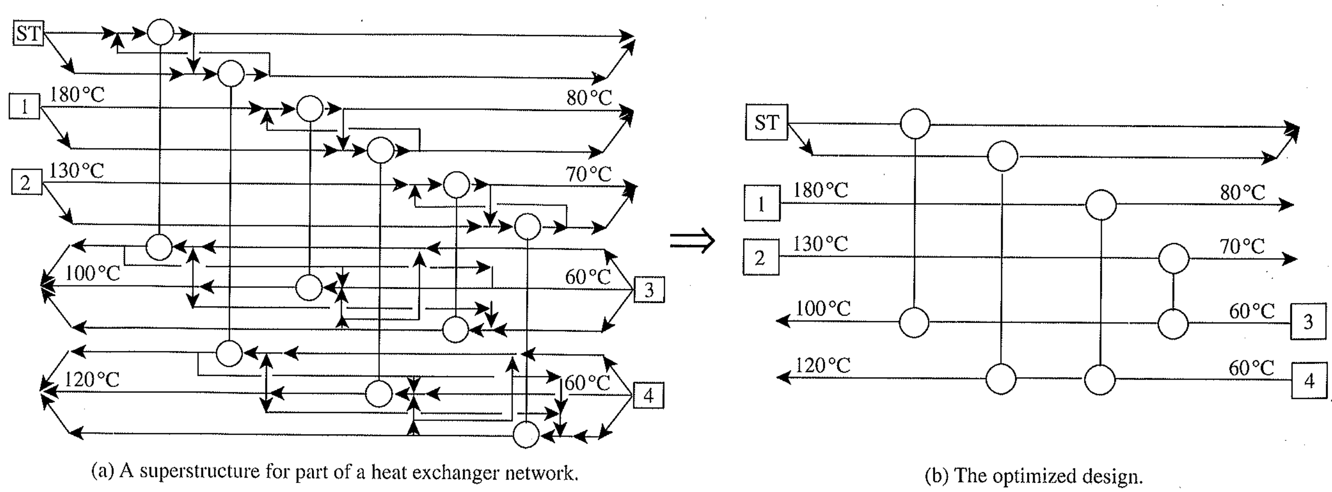


Figure 18.28 Heat exchanger network design from the optimization of a superstructure.

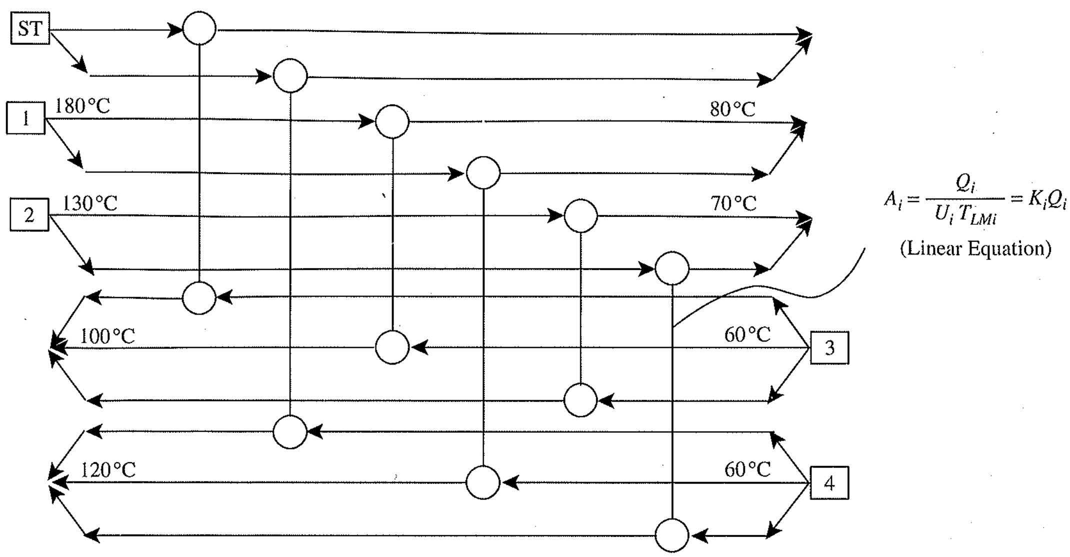


Figure 18.29 Starting with a simpler superstructure removes many structural options (some of which might be desirable, but makes the optimization linear.

given by:

$$A = \frac{Q}{U\Delta T_{LM}} \tag{18.5}$$

where A = heat transfer area
Q = heat exchanger duty
U = overall heat transfer coefficient
ΔT_{LM} = logarithmic mean temperature difference

If U is assumed to be constant, despite changing conditions during the optimization, then because ΔT_{LM} is fixed for each match in Figure 18.29, Equation 18.5 becomes a linear equation in Q. If the capital cost of the heat exchangers is taken to be a linear function, then the optimization simplifies to be mixed integer linear programming (MILP) rather than MINLP. The problem with this is that the initial superstructure shown in Figure 18.29 features parallel configurations, as shown in 18.30a. If the linear optimization needs to retain all three matches on the stream, as shown in Figure 18.30a, then this cannot evolve to all of the series configurations, 1×2 parallel configurations, series-parallel configurations and parallel-series configurations as shown in Figure 18.30b.

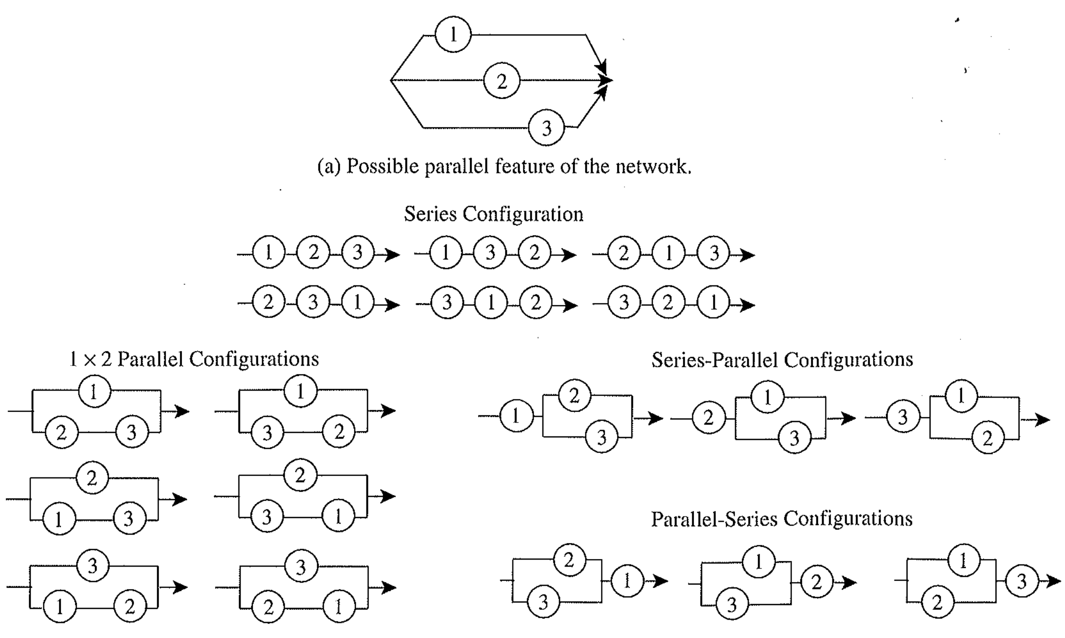


Figure 18.30 The simplified superstructure cannot be evolved to all structural options.

Another issue is how to divide the overall problem in order to set up the initial superstructure. The problem could be divided at the pinch, as done in the pinch design method, and a superstructure set up on each side of the pinch like the one in Figure 18.29. However, for large complex problems, this would not be comprehensive enough in terms of the number of structural options. The overall problem could therefore be divided into enthalpy intervals as shown in Figure 18.31 and a simplified superstructure created within each enthalpy interval[10]. Rather than dividing the composite curves into enthalpy intervals, as shown in Figure 18.31, with a superstructure within each enthalpy interval, enthalpy intervals can be merged into *blocks*[11]. A superstructure is then created within each block rather than each enthalpy interval. This simplifies the complete superstructure for the whole network. This network superstructure could then be subjected to optimization using MILP.

Note that the ΔT_{min} for the problem must be fixed in order to remain an MILP problem. Fixing ΔT_{min} fixes the composite curves and the temperatures across each enthalpy interval or block. Unfortunately, this would not necessarily lead to the best network, as the initial superstructure was already simplified with many structural options missing. But this can be allowed for by first carrying out the optimization on the basis of the simplified superstructure in Figure 18.29. If then the optimized superstructure featured structural options like the one in Figure 18.32a, then additional structural features could be added to give the structure in Figure 18.32b, which then can be subjected to MINLP optimization. This has the potential then to optimize to any parallel, series-parallel or parallel-series arrangement. This breaks the overall optimization down into two steps.

1. A simplified superstructure is first optimized using MILP.
2. If the solution from the simplified superstructure features parallel arrangements, such as that in Figure 18.32a, then additional features are added to the network, as shown in Figure 18.32b. This is then subjected to MINLP optimization to allow all the structural options in Figure 18.30 to be accessed.

This approach is one way to avoid the difficulties inherent with applying MINLP to a large complex superstructure. Another way might be to apply stochastic optimization[12]. However, this has the disadvantage of being computationally very demanding for a reasonable size of heat exchanger network.

The major advantage of the superstructure approach to heat exchanger network design is that, in principle, it is capable

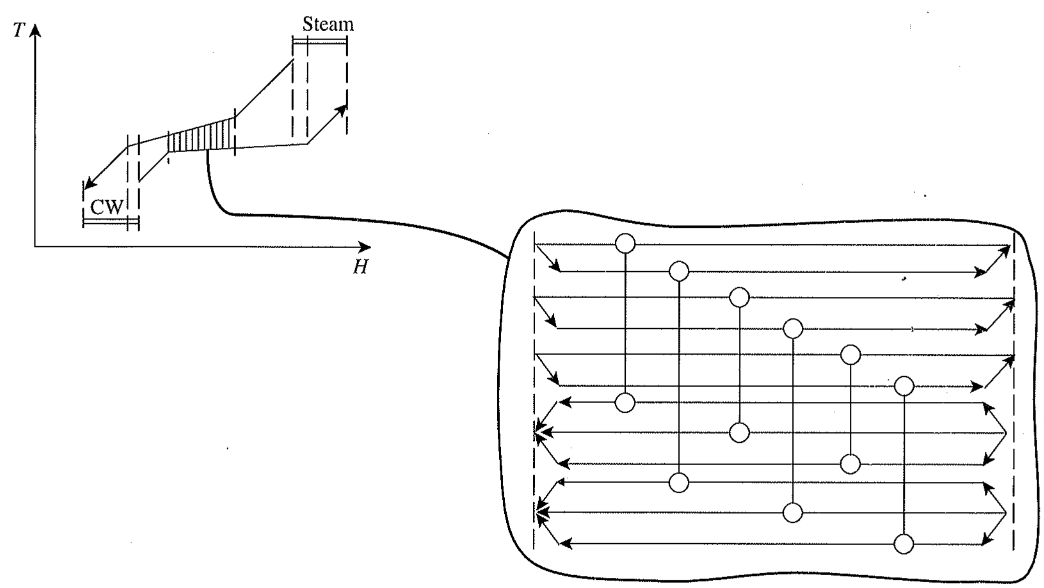


Figure 18.31 Create a simplified superstructure for each enthalpy interval.

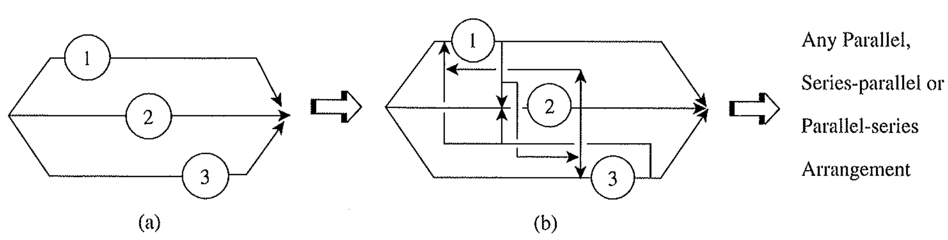
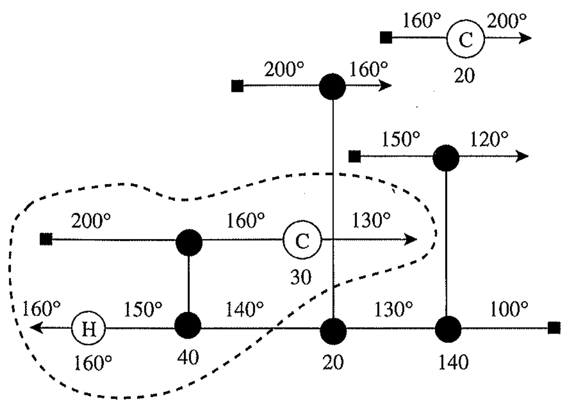
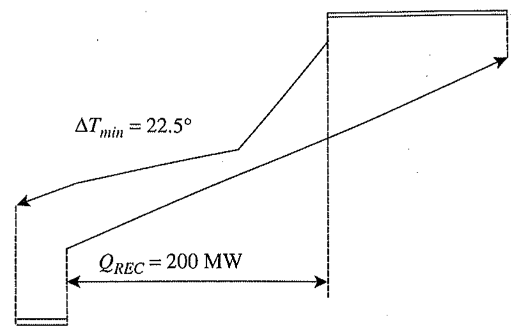


Figure 18.32 If the solution from the optimization of a simplified superstructure features parallel branches, then add additional structural features and re-optimize.



(a) Existing network with Q_{REC} = 200MW.



(b) Composite curves with Q_{REC} = 200MW.

Figure 18.33 An existing heat exchanger network. (From Asante NDK and Zhu XX, 1997, *Trans IChemE*, **75A**: 349, reproduced by permission of the Institution of Chemical Engineers.)

of designing large networks with complex constraints, mixed materials of construction, equipment types and so on. One major disadvantage of the approach is that the optimization is a difficult MINLP. Another significant disadvantage is that, because a computer carries out the optimization, the designer is removed from the decision-making.

18.8 RETROFIT OF HEAT EXCHANGER NETWORKS

So far, all considerations regarding the targeting and design of heat exchanger networks have related to new, or grassroot, design. It is often necessary to retrofit an existing heat exchanger network. The need to retrofit might arise from a desire to reduce the utility consumption of the existing network, need to increase the throughput, modification of the feed to the process or a modification to the product specification. All of these objectives might require heat duties within the network to be changed.

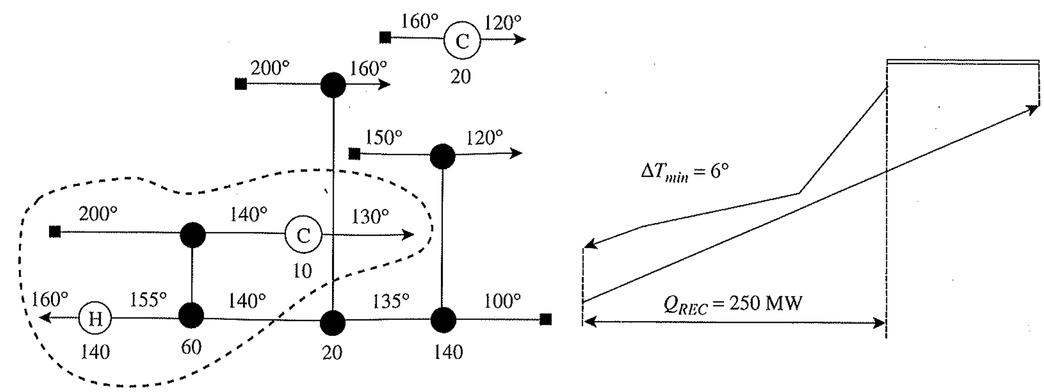
One approach to retrofit would be to try and evolve the network toward an ideal grassroot design. Following this approach, stream data would be targeted using the composite curves or the problem table to determine the location of the pinch for an assumed ΔT_{min}. Knowing the location of the pinch, the existing units in the network could then be located relative to the pinch. Any cross-pinch heat transfer could then be eliminated by disconnecting the units that are transferring heat across the pinch. These could be process-to-process, or the inappropriate use of utilities (e.g. use of steam below the pinch). The network could then be reconnected, with as many features of the existing network retained as possible[13]. This would no doubt improve the energy performance of an existing heat exchanger network, but it has a number of fundamental problems:

- Which ΔT_{min} should be used? As the value of ΔT_{min} changes, the location of the pinch changes and therefore the assessment of which unit to transfer heat across the pinch also changes.
- Existing equipment is only reused in an ad hoc way.
- The retrofit is likely to involve a large number of modifications to the existing network.
- Constraints associated with the existing network are not readily included.

The problem with this approach is that it is attempting to change the network to a grassroot design rather than accepting the features that already exist. A better approach is to evolve the network from the existing structure in order to identify only the most critical, and therefore cost-effective, changes to the network structure[14].

Suppose that it is desired to reduce the energy consumption of the existing heat exchanger network shown in Figure 18.33a. Figure 18.33b shows the composite curves for the basic stream data. The composite curves have been adjusted such that the overlap between the composite curves corresponds with the actual existing heat recovery duty of 200 MW. For the composite curves, this corresponds with a ΔT_{min} of 22.5°C. On the other hand, it can be seen that the existing heat exchanger network has minimum temperature differences of 20°C. First consider how the energy consumption of the existing network might be decreased without changing the network structure. As discussed previously, this is only possible by the exploitation of a utility path. The existing network in Figure 18.33a has only one degree of freedom that can be exploited for network optimization. This is highlighted within the bubble superimposed on the network. It involves a utility path between the heater and the cooler. The matches in the network outside of this bubble are all constrained by the heat duties on individual streams. The only way, therefore, that the utility consumption of the existing network can be decreased is by shifting heat load along the path between the heater and the cooler.

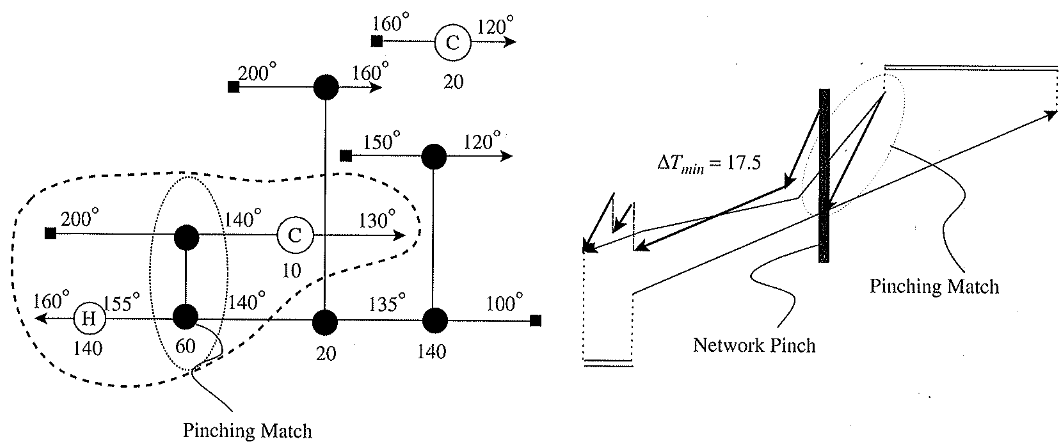
Figure 18.34a shows the network evolved to reduce the utility consumption to the point where the temperature



(a) Existing network with Q_{REC} increased to 220MW.

(b) Composite curves for maximum energy recovery indicates $Q_{REC} = 250$MW.

Figure 18.34 Maximizing the energy recovery of the existing heat exchanger network even down to $\Delta T = 0°C$ gives an energy performance worse than the energy target. (From Asante NDK and Zhu XX, 1997, *Trans IChemE*, **75A**: 349, reproduced by permission of the Institution of Chemical Engineers.)



(a) Maximum heat recovery condition with $Q_{REC} = 220$ MW.

(b) Composite curves with $Q_{REC} = 220$ MW.

Figure 18.35 The network pinch limits the energy recovery in the existing heat exchanger network. (From Asante NDK and Zhu XX, 1997, *Trans IChemE*, **75A**: 349, reproduced by permission of the Institution of Chemical Engineers.)

difference in the existing network is now 0°C[14]. This is not a limit that could be achieved in practice, but is taken here for the sake of illustration. For a minimum temperature difference of 0°C in the existing network, the energy recovery must increase to 220 MW. Compare the composite curves for increased heat recovery. These are shown in Figure 18.34b for their maximum overlap, which is 250 MW. At this setting, the composite curves still have a ΔT_{min} of 6°C. This reveals that the maximum heat recovery within the existing heat exchanger network structure is different from that theoretically possible from the composite curves. The difference is caused by the fact that the existing heat exchanger network structure is not appropriate for maximum energy recovery. How can the existing network structure be modified to improve its performance?

The existing heat exchanger network is shown again in Figure 18.35 with its recovery increased to an absolute maximum. Figure 18.35a highlights what is limiting the existing heat exchanger network in terms of its heat recovery. One of the existing units features minimum temperature difference (0°C in this case for the sake of illustration). The composite curves are also shown in Figure 18.35b, but set to the same overall heat recovery load as that featuring the existing heat exchanger network at its limit (220 MW). Superimposed on the composite curves are the temperature profiles for the hot streams in each of the existing units. One of the matches limits the heat recovery, in this case the one featuring a temperature difference of 0°C. This match that limits the heat recovery is known as the *pinching match*[14]. The point at which this occurs is known as the *network pinch*[14]. The network pinch limits the heat recovery for the existing heat exchanger network.

In practice, if the network pinch is being identified in a design study, then a practical minimum temperature difference of say 10°C or 20°C would be taken rather than the 0°C used here for the sake of illustration. The principle is exactly the same. One or more matches in the existing network feature ΔT_{min} when the network is pinched.

Consider now how the network pinch might be overcome. There are four ways in which the network pinch can be overcome and the performance of the existing heat exchanger network improved beyond that for the pinched condition[14].

a. *Resequencing*. Figure 18.36 illustrates how *resequencing* can be used to overcome the network pinch. Resequencing moves the unit to a new location in the network, but between the same streams as the original match. Figure 18.36 shows a cold stream being heated by two hot streams. One of the hot stream profiles indicates that it is a pinching match and features a minimum temperature difference of 0°C (again for the sake of illustration). In Figure 18.36, the pinching match is adjacent to another hot stream that has a finite temperature difference for the heat exchange. If the position of the two hot streams is swapped by a simple resequence, as shown in Figure 18.36, then the pinching match no longer limits. This means that there is now new scope to reduce the energy consumption of the network by exploiting a utility path, as shown in Figure 18.36. If the utility path is exploited to its limit, then a new network pinch is created, but now at a lower utility consumption for the network.

b. *Repiping*. *Repiping* is very similar to resequencing. Like resequencing, repiping moves the unit to a new location in the network. However, in repiping, the unit can be moved to a location involving streams other than in the original location, rather than be restricted to operate between the same streams. Repiping is a more general case than resequencing, but might not be practical for a variety of reasons, for example, materials of construction being unsuitable for other streams. The basic principle of repiping is the same as that for resequencing, but a distinction needs to be made for practical reasons.

c. *Inserting a new match*. Figure 18.37 shows how the network pinch can be overcome by inserting a new match. Again the principle is illustrated by two hot streams providing heat to a cold stream. One of the matches is pinched. If a new match is inserted such that the heat duty on the hot stream adjacent to the pinching match is decreased and replaced by the new match, then the position of the pinching match can be changed such that it is no longer pinching. This introduces scope to exploit the utility path to reduce the utility consumption of the network, until it is again pinched. The network is now pinched again, but at a lower utility consumption.

d. *Introduce additional stream splitting*. The fourth way to overcome the network pinch is by introducing additional stream splitting to the existing network, as illustrated in Figure 18.38. In this case, it can be seen that two matches are pinched simultaneously. By introducing a stream split, the cold stream profiles in the two pinched units are now such that one of the pinching matches is no longer pinched. This means that there is scope to exploit a utility path and reduce the energy consumption. This is being carried out to its limit in Figure 18.38 such that the network is again pinched, but at a lower utility consumption.

Again, it should be emphasized that in practice a finite practical ΔT_{min} should be used rather than 0°C. However, any assumption of ΔT_{min} to identify, and then overcome, the network pinch does not guarantee

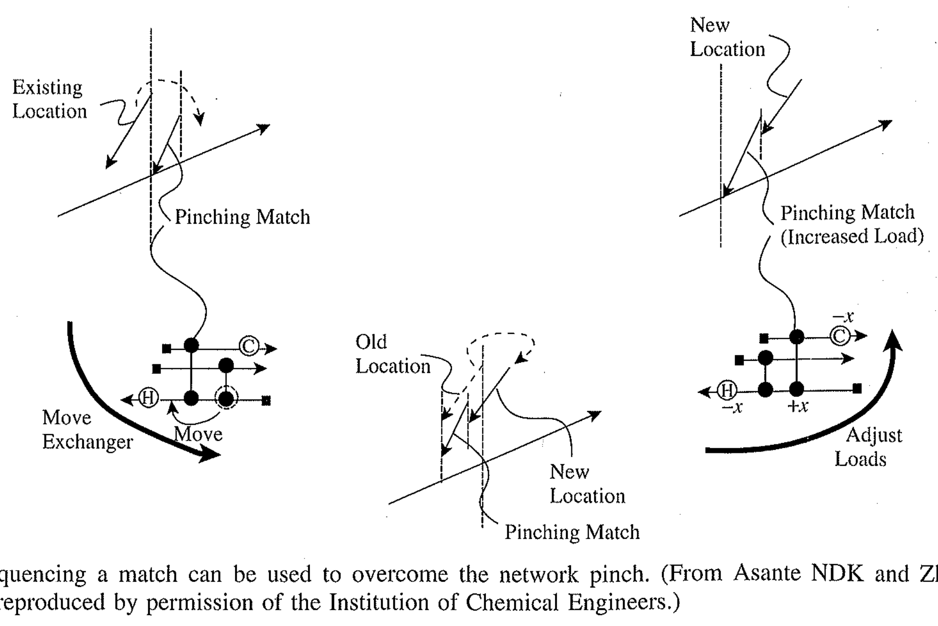


Figure 18.36 Resequencing a match can be used to overcome the network pinch. (From Asante NDK and Zhu XX, 1997, *Trans IChemE*, **75A**: 349, reproduced by permission of the Institution of Chemical Engineers.)

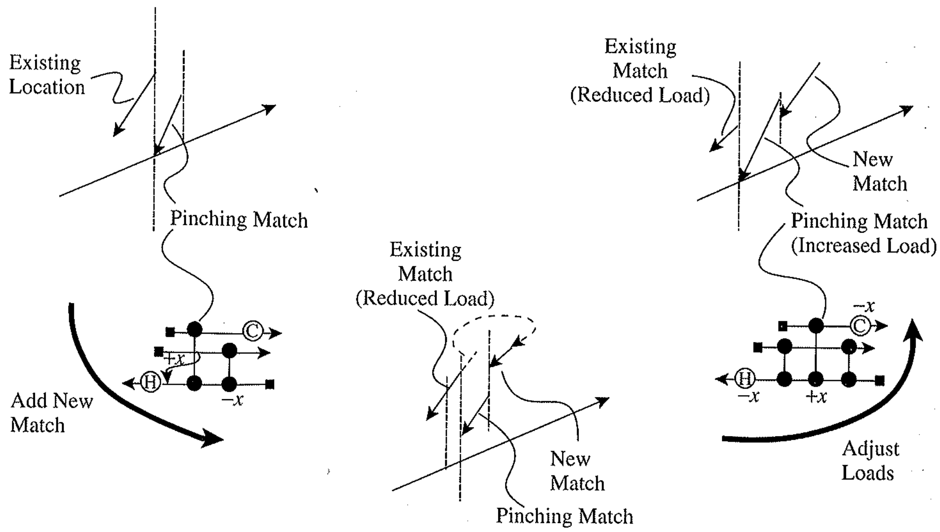


Figure 18.37 Adding a new heat exchanger can be used to overcome the heat network pinch. (From Asante NDK and Zhu XX, 1997, *Trans IChemE*, **75A**: 349, reproduced by permission of the Institution of Chemical Engineers.)

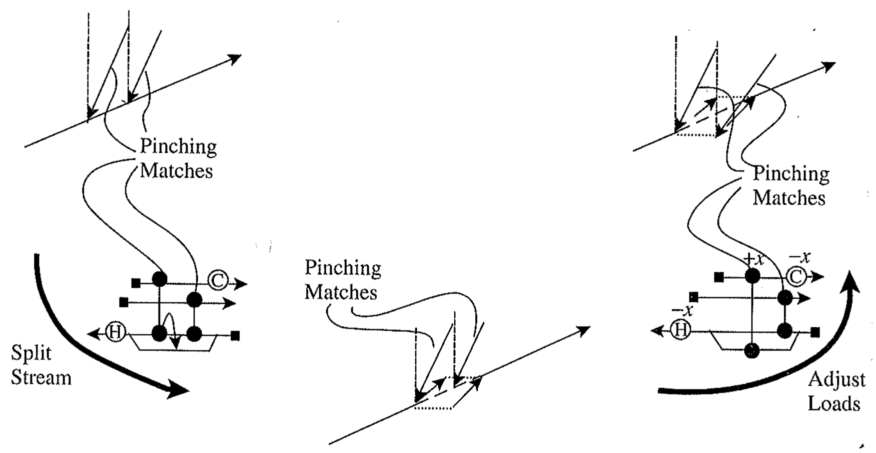


Figure 18.38 Changing the stream splitting arrangement can be used to overcome the network pinch. (From Asante NDK and Zhu XX, 1997, *Trans IChemE*, **75A**: 349, reproduced by permission of the Institution of Chemical Engineers.)

an optimum retrofit. The modified network should be subjected to cost optimization in order to obtain the correct setting for the capital-energy trade-off. The optimization of a heat exchanger network with a fixed structure is a Nonlinear Programming (NLP) optimization, as discussed previously. When dealing with the optimization of existing heat exchanger networks, it needs to be recognized that there is existing heat transfer area in place, but new area (or enhanced heat transfer) needs to be installed in some parts of the network to improve the network performance. The existing heat transfer area has zero capital cost and only the new heat transfer area and pipework modifications need to be included in the capital costs for the optimization. Care is required when specifying the form of the capital cost correlation in retrofit. Designers often like to use a cost per unit area, such as:

$$Capital\ Cost = bA \tag{18.6}$$

where A = heat transfer area
b = cost coefficient

If the capital cost of new heat transfer area is expressed in the form of Equation 18.6, then this will lead to poor retrofit projects. The problem with Equation 18.6 is that the optimization is likely to spread the new heat transfer area in the network in many locations, without incurring a cost penalty associated with the many modifications that would result. To ensure that new heat transfer area is not spread around throughout the existing heat exchanger network, a capital cost correlation should be used that is of the form:

$$Capital\ Cost = a + bA^c \tag{18.7}$$

where a, b, c = cost coefficients

In Equation 18.7, the coefficient a is a threshold cost that is incurred even if a small amount of heat transfer area

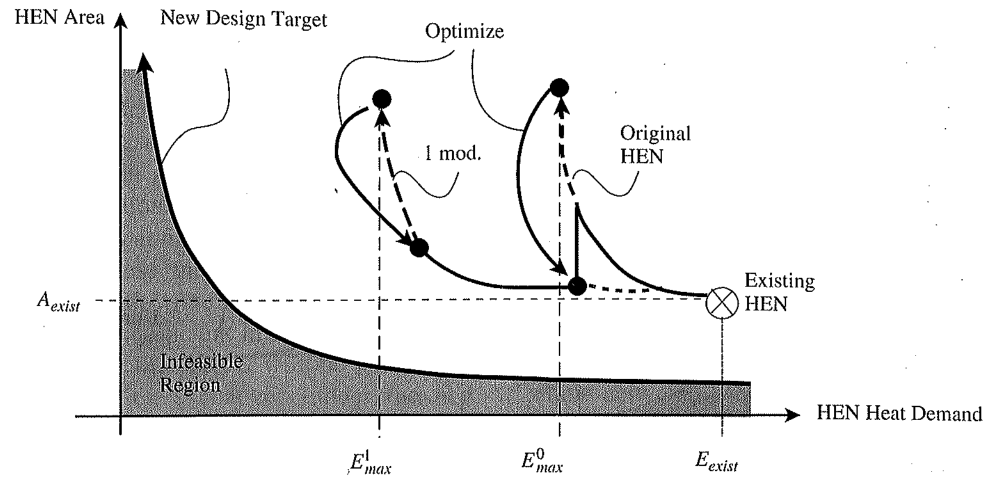


Figure 18.39 The heat exchanger network can be optimized after each modification. (From Asante NDK and Zhu XX, 1997, *Trans IChemE*, **75A**: 349, reproduced by permission of the Institution of Chemical Engineers.)

is installed. If a large threshold cost is used in the cost correlation, then this would lead an optimizer to attempt to concentrate any new heat transfer area required in as few locations as possible in the network. This, in turn, will lead to fewer modifications in the retrofit project to accommodate the new heat transfer area requirements.

It should be noted that a resequence or repipe does not involve zero capital cost, even though no new heat exchanger equipment might be purchased. The pipework modifications for a resequence or repipe might be very expensive. Also, equipment might need to be relocated. Methods for capital cost estimation for retrofit were discussed in Chapter 2.

Figure 18.39 shows the capital-energy trade-off on a plot of heat exchanger network area versus energy consumption. The new (grassroot) design target marks the infeasible region in Figure 18.39. Targeting methods for energy were discussed in Chapter 16 and targeting methods for network area were discussed in Chapter 17. The existing network performance cannot be better than the target, but it can be worse, as illustrated in Figure 18.39. If the existing network structure is retained, then there is a limit beyond which the network cannot be improved in terms of its energy performance. This is when the existing network structure is pinched at a practical minimum temperature difference for the heat exchangers. In order to approach this condition, it will require an additional heat transfer area. The more the energy consumption is decreased, the additional heat transfer area required will increase per unit energy reduction, as the network pinch is approached. For the existing heat exchanger network structure, the capital-energy trade-off can be optimized, as shown in Figure 18.39. Alternatively, the structure of the network could be modified, in which case, the limit for heat recovery for the modified network is now at a lower energy consumption, Figure 18.39. Again, the network has been modified on the basis of an assumed practical minimum temperature difference that is not necessarily providing the correct setting for the capital-energy trade-off. Therefore, the modified network can be optimized to provide the optimized network for one structural modification. This procedure could be repeated for a second and third modification, and so on. In practice, retrofits are usually only economic for a small number of network modifications.

This approach to heat exchanger network retrofit based on the concept of the network pinch can be automated[15]. A superstructure can be created for network resequencing (or repiping) and the best resequence (or repipe) identified by optimizing the superstructure of resequences (or repipes) for an assumed practical ΔT_{min}[15]. This can be formulated as an MILP optimization if the network is optimized for minimum energy consumption with a fixed ΔT_{min}. Inclusion of area calculations to estimate heat exchanger capital costs would make the optimization nonlinear. Similarly, a superstructure can be created for positioning new matches or stream split modifications in the existing network and the superstructure optimized for minimum energy cost for an assumed practical ΔT_{min}. The problem can again be formulated as an MILP problem[15].

After each suggested modification has been identified, the network can be subjected to a detailed capital-energy trade-off requiring NLP optimization. Optimization of the capital-energy trade-off is illustrated in Figure 18.40. Structural modifications are first explored using MILP and then the correct setting of the capital-energy trade-off corrected using NLP. By decomposing the problem in this way, what is overall an MINLP problem, is carried out by MILP followed by NLP, which is a more robust approach to the optimization.

This approach to heat exchanger network retrofit allows modifications to be introduced one at a time. In this way, the designer has control over the complexity of the network retrofit. At each stage, a suggested modification can be

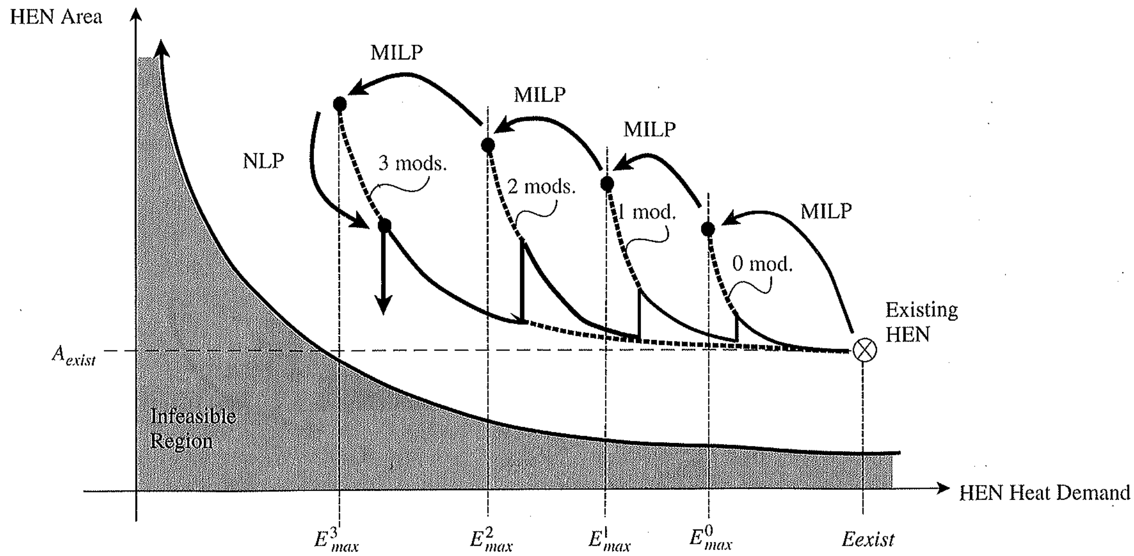


Figure 18.40 The retrofit can be proceed in a stepwise approach. (From Asante NDK and Zhu XX, 1997, *Trans IChemE*, **75A**: 349, reproduced by permission of the Institution of Chemical Engineers.)

evaluated in terms of its practicality and true costs. If the best structural option identified is considered to be impractical (e.g. the plant is too congested), then another modification can be suggested instead. For example, the optimization could be carried out to identify the best resequence, only to find that this is impractical. If this is the case, then the second best resequence could be taken, or the option of a new match chosen and so on. The designer has control and can assess each modification as is suggested by the optimization. Having identified an acceptable number of modifications, the modifications are subjected to a detailed capital-energy trade-off to assess their true economic performance.

The approach leads to simple and practical retrofit designs and has the major advantage that it allows the designer to assess modifications one at a time and to keep control over the complexity of the retrofit. Its disadvantage is that different combinations of modifications can be taken and there is no guarantee that this will lead to an optimum network retrofit. However, it is almost impossible to say that any retrofit is optimal or nonoptimal. The features of each retrofit are unique and it is difficult to formulate all the constraints for a retrofit in order to guarantee the very best retrofit.

18.9 ADDITION OF NEW HEAT TRANSFER AREA IN RETROFIT

Retrofit of heat exchanger networks requires resequencing and repiping of existing heat exchangers, installation of new heat exchange matches and changes to stream splitting arrangements. However, existing matches that have not been moved might require additional heat transfer area as a result of changes in the operation. This might result from increased heat duty, operation under reduced temperature differences or operation under reduced heat transfer coefficients. Methods for the retrofit of heat exchangers have been discussed in Chapter 15. If shell-and-tube heat exchangers are being used and additional heat transfer area is required, it might be possible to install a new tube bundle into existing shells if the additional area requirement is small. If this is not feasible, then the existing area can be supplemented by adding a new shell (or more than one shell if there is a large area requirement) in:

a. *Series*. The addition of new exchangers in series to the existing match will lead to an increase in the overall pressure drop across the match. This might be important if the pump (or compressor) is close to its maximum capacity.

b. *Parallel*. The addition of new exchangers in parallel will leave the pressure difference largely unchanged. The pressure drop across the match will be the largest between that of the existing exchangers under the new conditions and new exchangers installed in parallel.

Also, as discussed in Chapter 15, rather than install additional heat transfer area to cater for the new operational requirements, heat transfer enhancement can be considered. Changes to the number of tube passes or the baffle arrangement might allow the heat transfer coefficient to be enhanced. Alternatively, tube inserts could be used. This was discussed in Chapter 15. The major disadvantage in using heat transfer enhancement is that it increases the pressure drop. In retrofit this can be important, as the pumps driving the flow might be limited in their capacity to meet the required increase in pressure drop.

Rather than shell-and-tube heat exchangers, the network might involve plate heat exchangers. Adding additional area to plate heat exchangers is generally more straightforward than shell-and-tube exchangers. Plate heat exchangers can often have their area increased by adding additional plates to the existing frame. If an additional frame needs to be added to provide the additional area, then the new frame can be added in series or parallel with the existing frame. Series arrangements increase the pressure drop. Parallel arrangements decrease the flowrate through each frame but decrease the heat transfer coefficient in the existing frame. The pressure drop across the match will be the largest between that of the existing exchangers under the new conditions and new exchangers installed in parallel.

18.10 HEAT EXCHANGER NETWORK DESIGN – SUMMARY

A good initialization for heat exchanger network design is to assume that no individual exchanger should have a temperature difference smaller than ΔT_{min}. Having decided that no exchanger should have a temperature difference smaller than ΔT_{min} two rules were deduced in Chapter 16. If the energy target set by the composite curves (or the problem table algorithm) is to be achieved, there must be no transfer heat across the pinch by:

- Process-to-process heat transfer
- Inappropriate use of utilities.

These rules are both necessary and sufficient for the design to achieve the energy target given that no individual exchanger should have a temperature difference smaller than ΔT_{min}.

The design of heat exchanger networks can be summarized in five steps.

1. Divide the problem at the pinch into separate problems.
2. The design for the separate problems is started at the pinch, moving away.
3. Temperature feasibility requires constraints on the CP's to be satisfied for matches between the streams at the pinch.
4. The loads on individual units are determined using the tick-off heuristic to minimize the number of units. Occasionally, the heuristic causes problems.
5. Away from the pinch, there is usually more freedom in the choice of matches. In this case, the designer can discriminate on the basis of operability, plant layout and so on.

If the number of hot streams at the pinch above the pinch is greater than the number of cold streams, then the cold streams must be split to satisfy the ΔT_{min} constraint. If the number of cold streams at the pinch below the pinch is greater than the number of hot streams, then the hot streams must be split to satisfy the ΔT_{min} constraints. If the CP inequalities for all streams at the pinch cannot be satisfied, this also can necessitate stream splitting.

If the problem involves more than one pinch, then between pinches the design should be started from the most constrained pinch.

Remaining problem analysis can be used to make a quantitative assessment of matches in the context of the whole network without having to complete the network.

Once the initial network structure has been defined, then loops, utility paths and stream splits offer the degrees of freedom for manipulating network cost in multivariable continuous optimization. When the design is optimized, any constraint that temperature differences should be larger than ΔT_{min} or that there should not be heat transfer across the pinch no longer applies. The objective is simply to design for minimum total cost.

For more complex network designs, especially those involving many constraints, mixed equipment specifications and so on, design methods based on the optimization of a superstructure can be used.

Network retrofit can be performed on the basis of the concept of the network pinch. Resequencing and repiping of heat exchangers, the introduction of new exchangers and additional stream splitting can all be used to overcome the network pinch. The identification of structural modifications to the network can be done on the basis of minimizing the energy consumption for a ΔT_{min} using MILP. Once structural modifications have been identified, these should be subjected to a detailed capital-energy trade-off using NLP optimization. New heat transfer area to existing matches can be added through the addition of new heat exchanger shells in series or parallel or through heat transfer enhancement to existing exchangers.

18.11 EXERCISES

1. The stream data for a process are given in the Table 18.6:

Table 18.6 Stream data for Exercise 1.

Stream No.	Stream Type	Supply temperature (°C)	Target temperature (°C)	Heat capacity flowrate ($MW\cdot K^{-1}$)
1	Hot	200	100	0.4
2	Hot	200	100	0.2
3	Hot	150	60	1.2
4	Cold	50	140	1.1
5	Cold	80	120	2.4

a. For a ΔT_{min} of 10°C, the pinch is at 90°C for hot streams and 80°C for cold streams. Design a heat exchanger network for maximum energy recovery that features the minimum number of units.
b. By relaxing the constraint of ΔT_{min} = 10°C, shift heat load through a utility path such that the network uses only hot utility and no cold utility at all.

2. The process stream data for a heat recovery network problem are given in Table 18.7

Table 18.7 Stream data for Exercise 2.

Stream	T_S (°C)	T_T (°C)	CP (MW·K^{-1})
1. Hot	300	80	0.15
2. Hot	200	40	0.225
3. Cold	40	180	0.2
4. Cold	140	280	0.3

a. Determine the energy targets for hot and cold utility for ΔT_{min} = 20°C.
b. Design a heat exchanger network to achieve the energy targets in the minimum number of units.
c. Identify the scope to reduce the number of units by manipulating loops and utility paths by sacrificing energy consumption.
d. Design a network to realize this scope and restore ΔT_{min} = 20°C.

3. The heat recovery stream data for a process are given in Table 18.8.

Table 18.8 Stream data for Exercise 3.

Stream	T_S (°C)	T_T (°C)	CP (kW·K^{-1})
1. Hot	180	40	200
2. Hot	150	40	400
3. Cold	60	180	300
4. Cold	30	130	220

A problem table analysis for ΔT_{min} = 10°C results in the heat recovery cascade given in Table 18.9.

Table 18.9 Heat recovery cascade for Exercise 3.

Interval temperature (°C)	Heat flow (MW)
185	6.0
175	3.0
145	0
135	3.0
65	8.6
35	20.0

a. Design a heat recovery network in the minimum number of units. The number of units is below what might have been expected from the target for the number of units; why?
b. Low-pressure saturated steam can be generated from saturated boiler feedwater at an interval temperature of 115°C. Determine how much low-pressure steam can be generated and design a network to achieve this duty.
c. The network design from Part *b* results in two steam generators. Evolve the network to remove one of these by suffering a penalty in steam generation, but maintain ΔT_{min} = 10°C.

4. The process stream data for a heat recover problem are given in Table 18.10.

Table 18.10 Stream data for Exercise 4.

Stream	T_S (°C)	T_T (°C)	CP (MW·K^{-1})
1. Cold	18	123	0.0933
2. Cold	118	193	0.1961
3. Cold	189	286	0.1796
4. Hot	159	77	0.2285
5. Hot	267	80	0.0204
6. Hot	343	90	0.0538

A problem table analysis reveals that Q_{Hmin} = 13.95 MW, Q_{Cmin} = 8.18 MW, hot stream pinch temperature is 159°C and cold stream pinch temperature is 149°C for ΔT_{min} = 10°C.

a. Design a heat recovery network with the minimum number of units. (Hint: below the pinch it may be necessary to split a stream away from the pinch to achieve the minimum number of units).
b. Evolve the design to eliminate stream splits below the pinch, while maintaining the same number of units, by allowing a temperature difference slightly smaller than 10°C.

5. The data for a heat recovery problem are given in the Table 18.11.

Table 18.11 Stream data for Exercise 5.

Stream No.	Stream Type	T_S (°C)	T_T (°C)	Heat capacity flowrate (MW·K^{-1})
1	Hot	120	65	0.5
2	Hot	80	50	0.3
3	Hot	135	110	0.29
4	Hot	220	95	0.02
5	Hot	135	105	0.26
6	Cold	65	90	0.15
7	Cold	75	200	0.14
8	Cold	30	210	0.1
9	Cold	60	140	0.05
Steam		250	–	–
Cooling water		15	–	–

The problem table cascade is given in Table 18.12 for ΔT_{min} = 20°C.

Given this data:

a. Set out the stream grid.
b. Design a maximum energy recovery network.

Table 18.12 Problem table cascade for Exercise 5.

Interval temperature (°C)	Heat flow (MW)
220	20.95
210	19.95
150	6.75
125	0
110	4.2
100	12
95	13.7
85	14.5
75	16.5
70	18.25
55	28.75
40	31.75

Table 18.13 Stream data for Exercise 6.

Stream No.	Stream Type	T_s (°C)	T_T (°C)	Stream heat duty (MW)
1	Hot	150	50	−20
2	Hot	170	40	−13
3	Cold	50	120	21
4	Cold	80	110	15

6. The stream data for a process are given in the Table 18.13. Steam is available between 180 and 179°C and cooling water between 20 and 40°C. For $\Delta T_{min} = 10$°C, the minimum hot and cold utility duties are 7 MW and 4 MW respectively. The pinch is at 90°C on the hot streams and 80°C on the cold streams.
   a. Calculate the target for the minimum number of units for maximum energy recovery.
   b. Develop two alternative maximum energy recovery designs, keeping units to a minimum.
   c. Explain why the design below the pinch cannot achieve the target for the minimum number of units.
   d. How many degrees of freedom are available for network optimization?
7. The stream data for a process are given in the Table 18.14:

Table 18.14 Stream data for Exercise 7.

Stream No.	Stream Type	T_s (°C)	T_T (°C)	CP ($kW \cdot K^{-1}$)
1	Hot	170	88	23
2	Hot	278	90	2
3	Hot	354	100	5
4	Cold	30	135	9
5	Cold	130	205	20
6	Cold	200	298	18

Table 18.15 Heat flow cascade for Exercise 7.

Interval temperature (°C)	Heat flow (kW)
349	1528
303	1758
273	1368
210	675
205	520
165	0
140	250
135	255
95	1095
85	1255
83	1283
35	851

A problem table heat cascade for $\Delta T_{min} = 10$°C is given the Table 18.15. Hot utility is to be provided by a hot oil circuit with a supply temperature of 400°C. Cooling water is available at 20°C.

   a. Calculate the minimum flowrate of hot oil if C_P for the hot oil is 2.1 $kJ \cdot kg^{-1} \cdot K^{-1}$, assuming ΔT_{min} process-to-process heat recovery is 10°C and process to hot oil to be 20°C.
   b. Design a heat exchanger network for maximum energy recovery in the minimum number of units ensuring $\Delta T_{min} = 10$°C for all process-to-process heat exchangers throughout the network.
   c. Suggest an alternative network design below the pinch to eliminate stream splits by accepting a violation of ΔT_{min}.
   d. What tools could have been used to develop the design below the pinch more systematically?
8. The stream data for a process are given in Table 18.16

Table 18.16 Stream data for Exercise 8.

Stream No.	Stream Type	T_S (°C)	T_T (°C)	Heat duty (MW)
1	Hot	150	30	7.2
2	Hot	40	40	10
3	Hot	130	100	3
4	Cold	150	150	10
5	Cold	50	140	3.6

   a. Sketch the composite curves for $\Delta T_{min} = 10$°C.
   b. Determine the target for hot and cold utility for $\Delta T_{min} = 10$°C.
   c. Design a maximum energy recovery network in the minimum number of units for $\Delta T_{min} = 10$°C.
   d. Can the number of units be reduced by evolution of the network?
9. The stream data for a process are given in Table 18.17. $\Delta T_{THRESHOLD}$ for the problem is 50°C and ΔT_{min} is 20°C. A problem table analysis on this data produces the cascade given in Table 18.18 for $\Delta T_{min} = 20$°C.

Table 18.17 Stream data for exercise 9.

Stream No.	Stream Type	T_S (°C)	T_T (°C)	Heat capacity flowrate (MW·K^{-1})
1	Hot	500	100	4
2	Cold	50	450	1
3	Cold	60	400	1
4	Cold	40	420	0.75

Table 18.18 Heat flow cascade for exercise 9.

Interval temperature (°C)	Heat flow (MW)
490	0
460	120
430	210
410	255
90	655
70	600
60	582
50	575

a. Design a heat exchanger network for this problem that achieves maximum energy recovery in the minimum number of units.
b. Determine how much steam at a condensing temperature of 180°C can be generated by this process
c. Sketch the composite curves for the process showing maximum steam generation at 180°C.
d. Design a network that achieves maximum energy recovery in the minimum number of units and which generates the maximum possible steam at 180°C.

REFERENCES

1. Linnhoff B and Hindmarsh E (1983) The Pinch Design Method of Heat Exchanger Networks, *Chem Eng Sci*, **38**: 745.
2. Linnhoff B, Townsend DW and Boland D, Hewitt GF, Thomas BEA, Guy AR and Marsland RH (1982) *A User Guide on Process Integration for the Efficient Use of Energy*, IChemE, Rugby, UK.
3. Linnhoff B and Ahmad S (1990) Cost Optimum Heat Exchanger Networks: I. Minimum Energy and Capital Using Simple Models for Capital Cost, *Comp Chem Eng*, **14**: 729.
4. Saboo AK, Morari M and Colberg RD (1986) RESHEX: An Interactive Software Package for the Synthesis and Analysis of Resilient Heat Exchanger Networks: II. Discussion of area Targeting and Network Synthesis Algorithms, *Comp Chem Eng*, **10**: 591.
5. Ahmad S, Linnhoff B and Smith R (1990) Cost Optimum Heat Exchanger Networks: II. Targets and Design for Detailed Capital Cost Models, *Comp Chem Eng*, **14**: 751.
6. Gunderson T and Naess L (1988) The Synthesis of Cost Optimal Heat Exchanger Networks: An Industrial Review of the State of the Art, *Comp Chem Eng*, **12**: 503.
7. Floudas CA, Ciric AR and Grossmann IE (1986) Automatic Synthesis of Optimum Heat Exchanger Network Configurations, *AIChE J*, **32**: 276.
8. Grossmann IE (1990) Mixed-Integer Non-Linear Programming Techniques for the Synthesis of Engineering Systems, *Res Eng Des*, **1**: 205.
9. Grossmann IE and Sargent RWH (1978) Optimum Design of Heat Exchanger Networks, *Comp Chem Eng*, **2**: 1.
10. Yee TF, Grossmann IE and Kravanja Z (1990) Simultaneous Optimization Models for Heat Integration – I. Area and Energy Targeting of Modeling of Multi-stream Exchangers, *Comp Chem Eng*, **14**: 1151.
11. Zhu XX, O'Neill BK, Roach JR and Wood RM (1995) New Method for Heat Exchanger Network Synthesis Using Area Targeting Procedures, *Comp Chem Eng*, **19**: 197.
12. Dolan WB, Cummings PT and Le Van MD (1990) Algorithm Efficiency of Simulated Annealing for Heat Exchanger Network Design, *Comp Chem Eng*, **14**: 1039.
13. Tjoe TN and Linnhoff B (1986) Using Pinch Technology for Process Retrofit, *Chem Eng*, **April**: 47.
14. Asante NDK and Zhu XX (1997) An Automated and Interactive Approach for Heat Exchanger Network Retrofit, *Trans IChemE*, **75**: 349.
15. Zhu XX and Asante NDK (1999) Diagnosis and Optimization Approach for Heat Exchanger Network Retrofit, *AIChE J*, **45**: 1488.