CHAPTER II

PINCH TECHNOLOGY AND HEAT-EXCHANGER NETWORK DESIGN

The starting point for an energy integration analysis is the calculation of the minimum heating and cooling requirements for a heat exchanger network. These calculations can be performed without having to specify any heat-exchanger network. Then the minimum number of exchangers and stream-matching alternatives can be followed up by the subsequent design of a heat-exchanger network.

2.1 Mimimum Heating and Cooling Requirements

2.1.1 First-Law Analysis

Suppose we consider a very simple problem where we have two streams that need to be heated and two streams that need to be cooled (see the data in Table 2.1). If we simply calculate the heat available in the hot streams and heat required for the cold streams, the difference between these two values is the net amount of heat that we would have to remove or supply to satisfy the first law. The results are also shown in the Table 2.1, and the first two entries are determined as follows:

Table 2.1 : First-law calculation

STREAM No.	FCp, kw/^{o}C	Tin, ^{o}C	Tout, ^{o}C	Q available, kW
1,COLD	2.0	20	135	-230
2,HOT	3.0	170	60	330
3,COLD	4.0	80	140	-240
4,HOT	1.5	150	30	180
				40

$$Q1 = F1Cp1\triangle T1 = (2kW/^{o}C)(20-135^{o}C) = -230 \quad kW.$$

$$Q2 = F2Cp2\triangle T2 = 3(170-60) = 330 \quad kW.$$

Thus, 40 kW must be rejected to cold utilities if there are no restrictions on temperature-driving forces.

2.1.2 Composite Curve

In any process flowsheet, a number of streams must be heated and other streams must be cooled. The interchangers are occured if hot stream temperatures are higher than cold stream temperatures. The hot and cold streams in a process can be represented on a temperature - heat content (enthalpy) graph once their input and output temperatures (or "supply" and "target" temperatures), their flowrates and physical properties are known. Starting from the individual streams it is possible to construct one "composite curve" of all hot streams in the process and another of all cold streams, by simple addition of heat contents over the temperature ranges in the problem.

The method is illustrated in Figure 2.1 (a), in which three hot streams are plotted separately, with their supply and target temperatures defining a series of "interval" temperatures T1 to T5. Between T1 and T2, only stream B exists, and so the heat available in this interval is given by CpB(T1-T2). However between T2 and T3, all three streams exist and so the heat available in this interval is (CpA + CpB + CpC)(T2-T3). A series of values of $\triangle$ H for each interval can be obtained in this way and the result is re-plotted against the interval temperatures as in Figure 2.2 (b). The resulting T/H plot is a single curve representing all the hot streams. A similar procedure gives a composite of all cold streams in a problem.

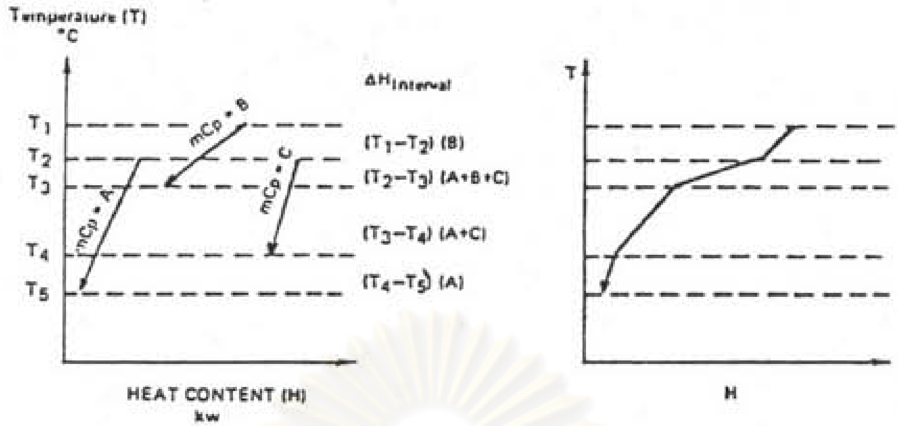


Figure 2.1 Construction of "Composite Curve"

The result for a set of hot and cold streams is a plot of two composite curves as shown in Figure 2.2. Note that the hot stream is represented by the line with the arrow head pointing to the left, and the cold stream is represented conversely. For feasible heat exchange between the two,i.e., to transfer heat from a hot composite to a cold composite, the hot stream must at all corresponding points be hotter than the cold stream. The "over-shoot" of the hot composite represents the minimum amount of external cooling required and the "over-shoot" of the cold composite represents the minimum amount of external heating. Because of the "bottleneck" nature of the curves, they approach most closely at only one point, termed "the pinch point".

In Figure 2.2 the cold stream is shown shifted far away from the hot stream on the H-axis. Then the higher distance between the curves and the larger value of $\triangle$ Tmin are obtained. The effect of this shifting is to increase the driving force of the system and leads to an increase in the utility heating and cooling by equal amount and also to a reduction in reduce the load on the exchanger by the same amount.

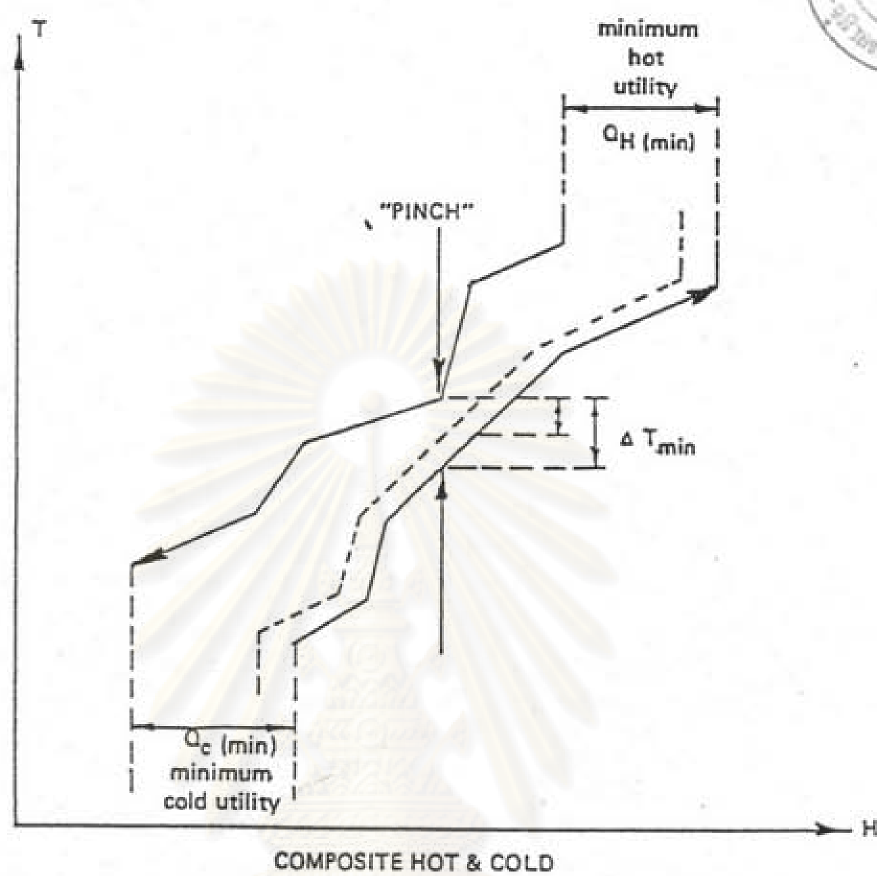


Figure 2.2 Energy targets and "the Pinch" with composite curves

This means it is possible to design a network which uses the mimimum utility requirements, where only the heat exchangers at the pinch need to be operated at $\triangle$ T values down to $\triangle$ Tmin.

2.1.3 A Targeting Procedure - Cascade Diagram

In principle, the "composite curves" described in the previous sub-section could be used to obtain energy targets at the given values of $\triangle$ Tmin. However, another simple way of incorporating second-law considerations into the energy analysis was presented by Hohmann, Umeda et al., and Linnhoff and Flower. Refering to the data given in Table 2.1, if we choose a mimimum driving force of 10 ^{o}C between the hot and cold streams, we can establish two temperature scales on a graph, one for the hot streams and the other for the cold streams, which are shifted by 10 ^{O}C. Next we establish a series of temperature intervals that correspond to the heads and tails of the arrows on the graph,i.e., the inlet and outlet temperatures of the hot and cold streams given in Table 2.1 (see Figure 2.3).

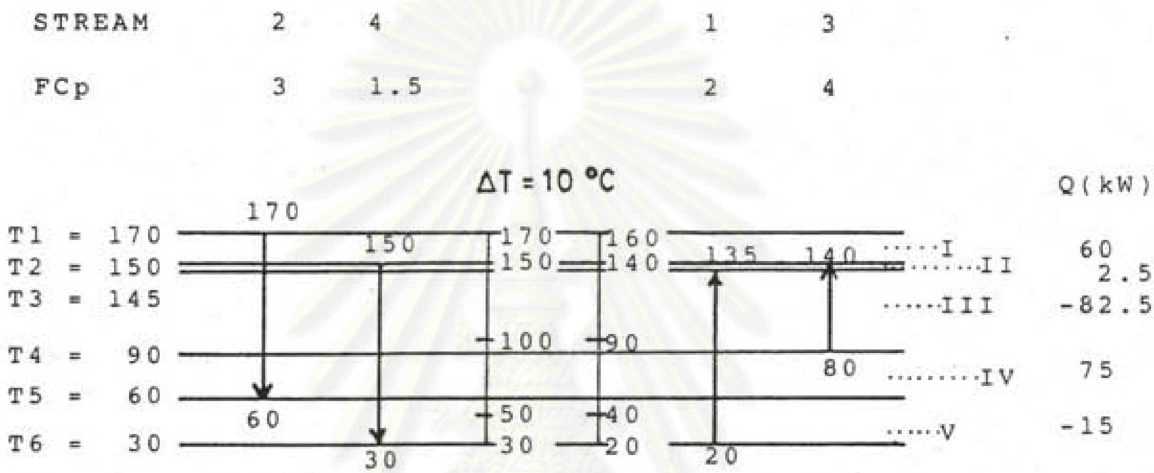


FIgure 2.3 Shifted temperature scales & temperature intervals

In each temperature interval we can transfer heat from the hot streams to the cold streams because we are guaranteed that the temperature driving force is adequate. Of course, we can also transfer heat from any of the hot streams in the high-temperature intervals to any of the cold streams at lower - temperature intervals. Knowing the stream population in each interval (from Figure 2.3), enthalpy balance can easily be calculated according to

$$Qi = [\sum (FCp)hot,i - \sum (FCp)cold,i)] \triangle Ti$$

for each interval. The results are shown in the right-hand-side column of Figure 2.3. We also note that the summation of the heat available in all the intervals is 40 kW, which is identical to the result obtained for the first law calculation,i.e., the net difference between the heat available in the hot streams and in the cold streams.

2.1.3.1 <u>Cascade Diagram</u>

As a key feature of the temperaure intervals, any heat available in interval i is hot enough to supply any duty in interval i+1. This is shown in Figure 2.4, where heat cascading of each interval are illustrated. Instead of sending the 60 kW of surplus heat from interval 1 into cold utility, it can be sent down into interval 2. There it joins the 2.5 kW surplus from interval 2, making 62.5 kW to cascade into interval 3. Interval 3 has a 82.5 kW deficit, hence after accepting the 62.5 kW we must supply other 20 kW

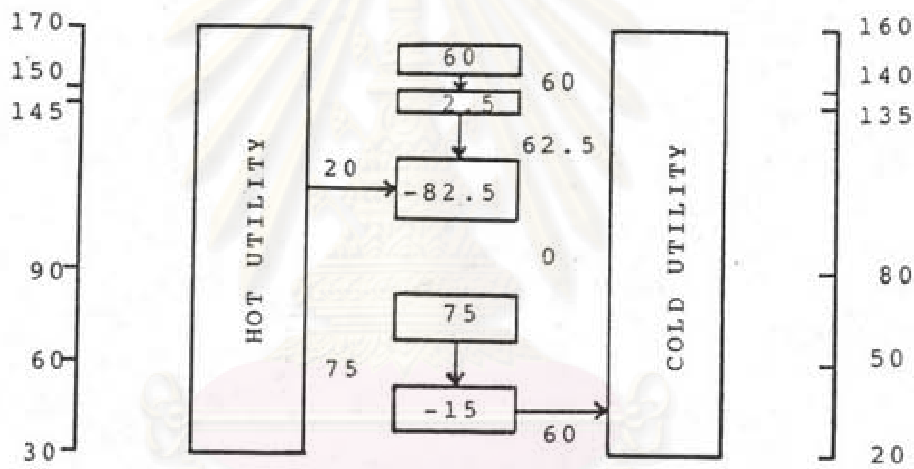


Figure 2.4 Cascade diagram

from a hot utility to satisfy the heat requirement. Then, there would be no transfer of heat between the third and fourth temperature intervals. Interval 4 has a 75 kW surplus passing to interval 5. Finally, the 15 kW deficit in interval 5 means that 60 kW is the final cascade energy to cold utility.

2.1.3.2 <u>Minimim Utility Loads</u>

The net result of the operation is that the minimum utility requirements have been predicted, i.e., 20 kW of hot and 60 kW of cold utilities.

2.1.3.3 Pinch Temperature

At the third and fourth temperature intervals, there is no energy transfer. Thus, the position of the pinch is located ,i.e., 90 $^{\circ}$C for the hot streams or 80 $^{\circ}$C for the cold streams.

By using the principle of heat cascading demonstrated here we can also set up a computer program to evaluate the energy targets and point out the pinch location for each value of $\triangle$ Tmin. The computer program developed in the present thesis gives us much faster results comparing to the cascade procedure. More details concerning on the program and its applications will be described in the Chapter IV.

2.2 Simple Design of Minimum-Energy Heat-Exchanger Networks

2.2.1 The Significance of the "Pinch"

Figure 2.5 (a) shows the composite curves for a multi-stream problem dissected at the pinch. "Above" the pinch (i.e. in the region to the right), the composite hot transfers all its heat into the composite cold, leaving only utility heating required. The region above the pinch is therefore a heat sink, with heat flowing into it but no heat flowing out. Conversely below the pinch, only cooling is required and the region is therefore a heat source. The problem therefore falls into two thermodynamically distinct regions, as indicated by the enthalpy balance envelopes in Figure 2.5 (b). Heat Qh,min flows into the problem above the pinch and Qc,min out of the problem below the pinch but the heat flow across the pinch is zero. This result was observed in the description of the Heat Cascading algorithm in the previous sub-section. It follows that any network design that transfers heat α across the pinch must, by overall enthalpy balance, require α more than minimum from hot and cold utilities, as shown in Figure 2.5 (c). As a corollary, any utility

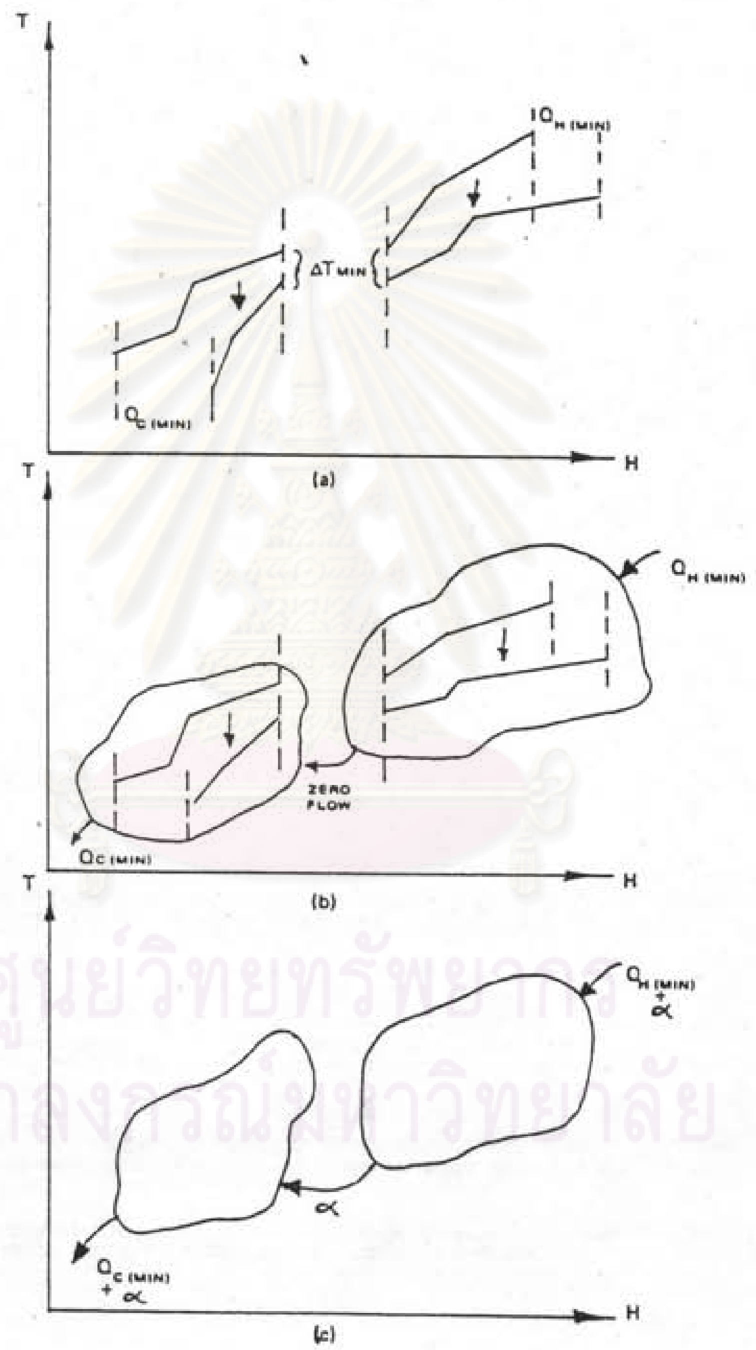


Figure 2.5 The pinch decomposition

cooling above the pinch must incur extra hot utility , and conversely below the pinch. So for the designer wishing to produce a minimum utility design, the firm message is :

- Don't transfer heat across the pinch.
- Don't use cold utility above.
- Don't use hot utility below.

2.2.2 Network Representation

The heat exchanger network from the flowsheet in Figure 2.6 (a) can be represented in the "grid" form as shown in Figure 2.6 (b). The advantage of this representation is that the heat exchanger matches 1 and 2 (each represented by two circles joined by a vertical line in the grid) can be placed in either order without redrawing the stream system. Furthermore, it is easier to check exchanger temperature feasibility.

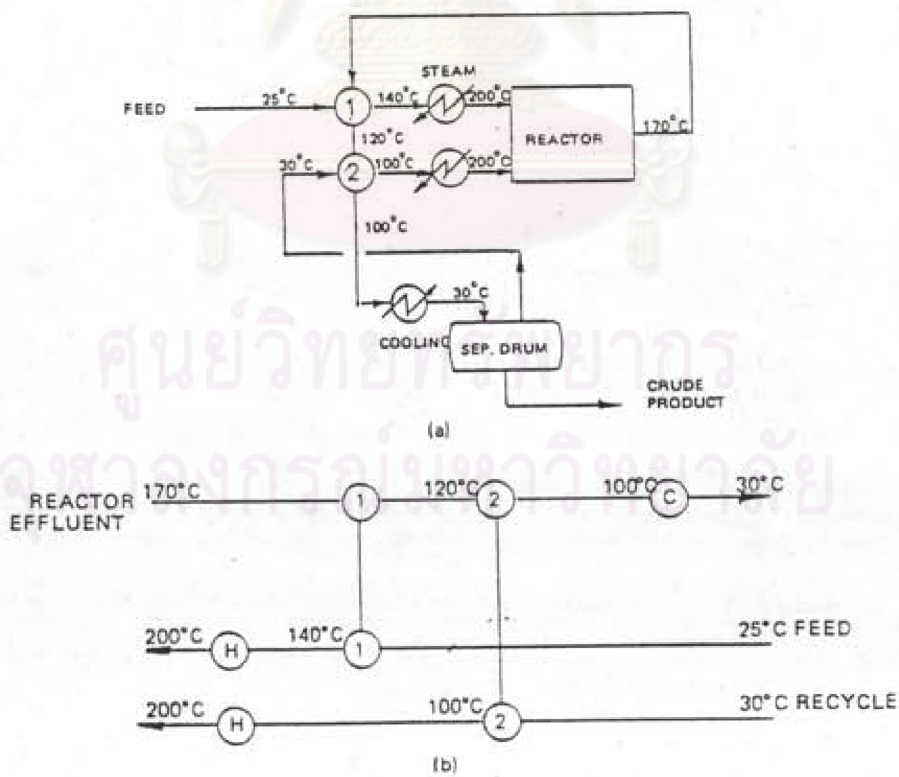


Figure 2.6 Heat exchanger network representation

2.2.3 Design for Minimum Energy Recovery

The data in Table 2.1 were analysed by the cascade diagram with the result that the minimum utility requirements are 20 kW hot and 60 kW cold. The pinch occurs where the hot streams are at 90 ^{o}C and the cold at 80 ^{o}C. To the further design for Minimum - Energy Recovery, we consider the problem in two parts : First we design a network for above the pinch and then another for below the pinch.

2.2.3.1 Design Above the Pinch

As the first step in the design procedure, we calculate the heat loads between either the inlet or the outlet temperature and the pinch temperature for each stream by the expression of $Q = FCp\triangle T$. The results are shown in Figure 2.7.

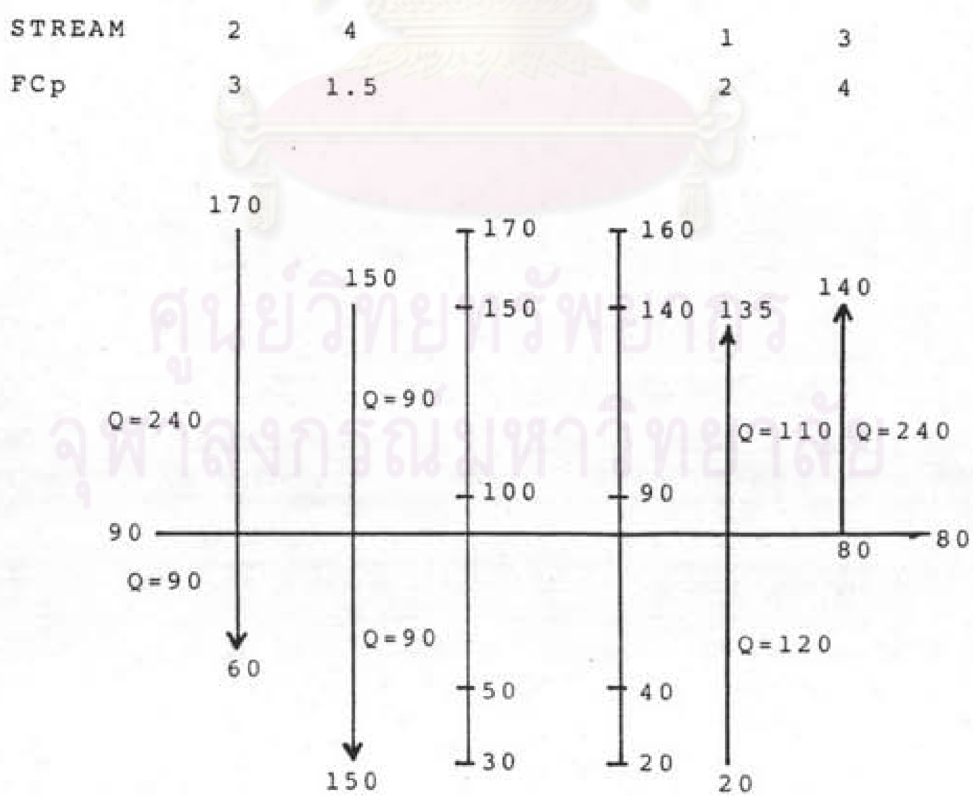


Figure 2.7 Heat load for streams

Feasible Matches : We remember that above the pinch, if best performance is to be obtained, no utility cooling should be used. This means, all hot streams must be brought to pinch temperature by interchange against cold streams. We must therefore start the design at the pinch, finding matches that fulfil this condition. In this example, above the pinch there are two hot streams at the pinch temperature, therefore requiring two "pinch matches". In Figure 2.8 (a) a match between streams 2 and 1 is shown, with a T/H plot of the match shown in inset. Because the Cp of stream 2 is greater than that of stream 1, as soon as any load is placed on the match, the $\triangle$ T in the interchange becomes less than $\triangle$ Tmin at its hot end. The exchanger is clearly infeasible and therefore we must look for another match. In Figure 2.8 (b), stream 2 and 3 are matched, and now the relative gradient of the T/H plots mean that the putting of load on the exchanger opens up the $\triangle$ T. This match is therefore acceptable. Then another match is provided for matching between stream 4 and stream 1. Looking at the relative sizes of the CPs for stream 4 and 1, the match is feasible ($Cp4 < Cp1$). Summarising, in the design immediately above the pinch, it is required to meet the criterion :

$$Cp,hot \leq Cp,cold$$

Having found a feasible pinch design it is necessary to decide on the match heat loads. The strategy of matching design is "maximise the heat load so as to completely satisfy one of the streams". So, since stream 2 above the pinch requires 240 kW of cooling and stream 3 above the pinch requires 240 kW of heating, co-incidentally the 2/3 match is capable of satisfying both streams. However, the 4/1 match can only satisfy stream 4 , having a load of 90 kW and therefore heating up stream 1 only as far as 125 ^{o}C. Since both hot streams have now been completely exhausted by these two design steps, stream 1 must be heated from 125 ^{o}C to its target temperature of 135 ^{o}C by external hot utility as shown in figure 2.8 (c). The amount of 20 kW are as predicted by the cascade diagram. The complete design above the pinch shows the number of exchangers, its minimum heating utilities requirement, and the temperature driving force at the end of every heat exchanger is 10 ^{o}C or greater.

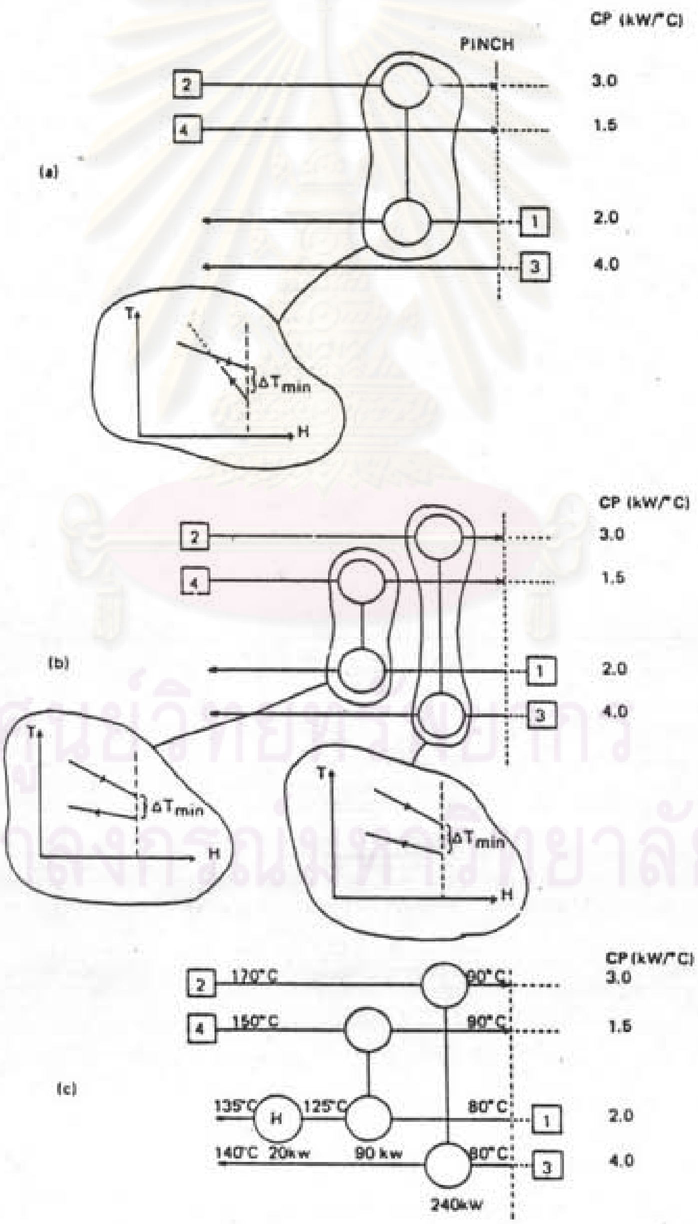


Figure 2.8 Matches above the pinch

2.2.3.2 Design Below the Pinch

Below the pinch, the design steps follow the same concept, only with the design criteria that mirror those for the "above the pinch" design. In Figure 2.9 (a) the stream system below the pinch is shown. Now, it is required to bring cold streams to

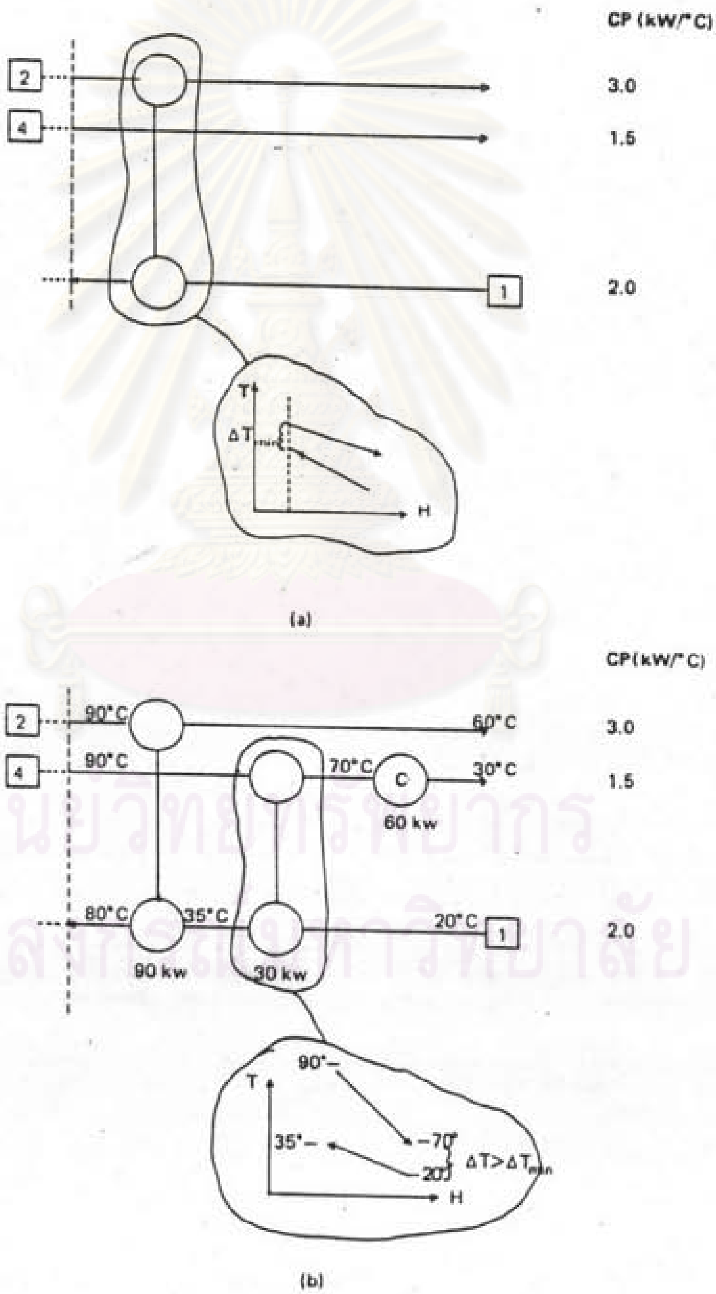


Figure 2.9 Matches below the pinch

the pinch temperature by interchange with hot streams, since we do not want to use utility heating below the pinch. In this example, only one cold stream exists below the pinch which must be matcheed against one of the two available hot streams. The match between stream 1 and 2 is feasible, as shown by the inset diagram in Figure 2.9 (a) because the Cp of the hot stream is greater than that of the cold. The other possible match 1/4 is not feasible. Immediately below the pinch, the neccessary criterion is :

$$Cp,hot \geq Cp,cold$$

which is the inverse of the criterion for design above the pinch.

Maximising the load on this match satisfies stream 2, the load being 90 kW. The heating required by stream 1 is 120 kW and therefore 30 kW of residual heating, to take stream 1 from its supply temperature of 20 ^{o}C to 35 ^{o}C, is required. Again this must come from interchange with a hot stream, the only one now available being stream 4. Although the Cp inequality dose not hold for this match, it is feasible because it is away form the pinch. That is to say, it is not a match that has to bring the cold stream up to the pinch temperature. So, as shown inset in figure 2.9 (b), the match does not become infeasible. Putting a load of 30 kW on this match leaves residual cooling of 60 kW on stream 4 which must be taken up by cold utility as we predicted.

2.2.3.3 <u>Minimum - Energy : Complete Design</u>

By putting the above and below pinch designs together gives the complete design shown in Figure 2.10. It achieves best possible energy performance for a $\triangle$ Tmin of 10 ^{o}C incorporating four exchangers, one heater and one cooler. In other words, six units of heat transfer equipment in all.

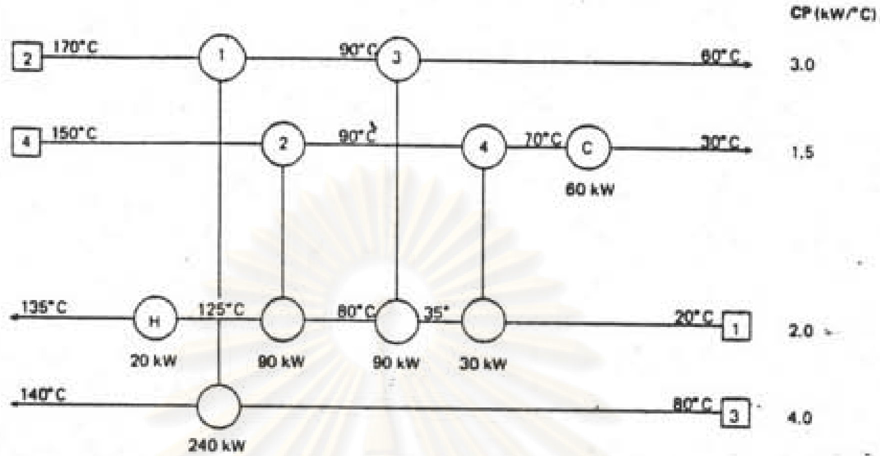


Figure 2.10 Complete minimum energy design

Summarising, the design was produced by :

- Dividing the problem at the pinch, and designing each part separately.
- Starting the design at the pinch and moving away.
- At the adjacent to the pinch, obeying the constraints :

$$\text{Above the pinch} : Cp,hot \leq Cp,cold$$

$$\text{Below the pinch} : Cp,hot \geq Cp,cold$$

- Maximising exchanger loads.
- Supplying external heating only above the pinch, and external cooling only below the pinch.

2.3 Trading off - Reducing the Number of Heat-Exchanger

The capital cost of chemical processes tends to be dominated by the number of items on the flowsheet. This is certainly true of heat exchanger networks and there is a strong incentive to reduce the number of matches between hot and cold streams.

2.3.1 Trading off Units and Energy

As the design in Figure 2.10 has six units, we consider that there is a loop existing traced out with a dotted line as shown in Figure 2.11. Hence, it should be possible to remove an exchanger from the network by supplying more energy to the process.

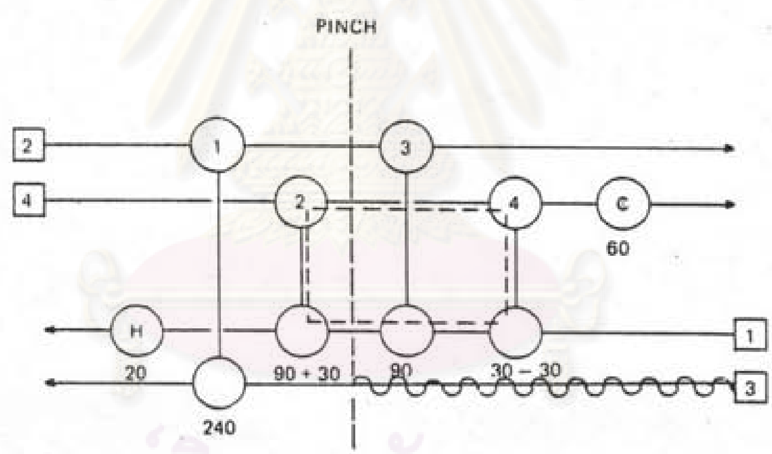


Figure 2.11 Example loop existence

2.3.2 Loop - Breaking : Since there is a loop in the system, the smallest load on one of the match in the loop is to be chosen. If we choose the smallest load on match 4 to be zero,i.e., we substract 30 kW of load from the design value, then match 4 is eliminated and the 30 kW must be carried by match 2. This is shown in Figure 2.11. Having shifted loads in this way, temperatures in the network can be recomputed as shown in Figure 2.12. Now, the value of $\triangle$ Tmin at the cold end of match 1 is less than the allowed value ($\triangle$

Tmin = 10 ^{o}C). So changing this design by loop-breaking, if the utility usages are not changed, must inevitably lead to a $\triangle$ Tmin violation.

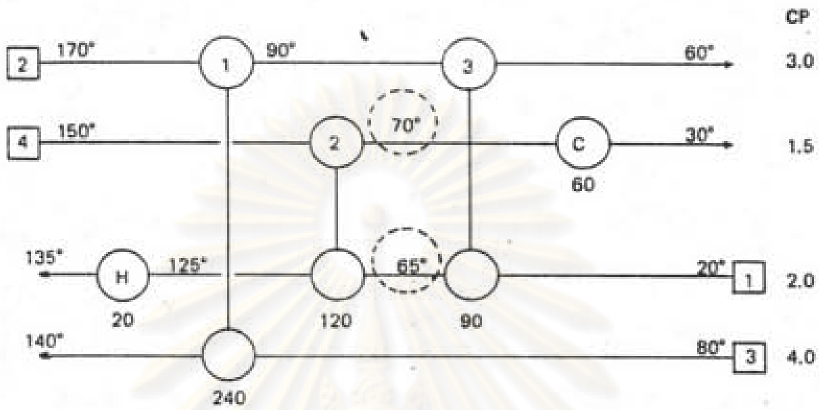


Figure 2.12 Break a loop in minimum energy design

2.3.3 <u>Restoring $\triangle$ Tmin</u> : The path through the network in Figure 2.13 is shown dotted, going from the heater, along stream 1 to match 2, and along stream 4 to the cooler. We want the new outlet temperature of stream 4 at match 2 (T2) to be 75 ^{o}C. To reduce the load (Q) on match 2 must increase the T2, thus opening out the $\triangle$ T at

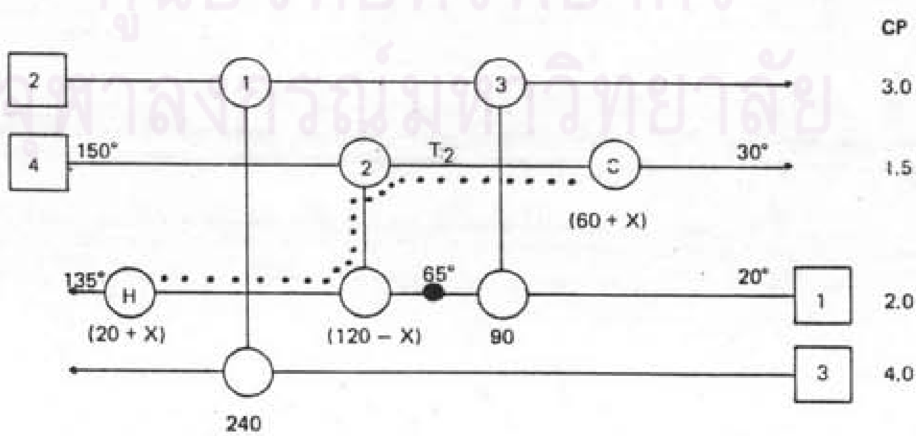


Figure 2.13 Shift heat along a path

its cold end. Solving the load on match 2 to restore T2 to 75 °C yields Q = 7.5 kW. The "relaxed" solution is shown in Figure 2.14 with the temperature between the heater and match 2 on stream 1 computed.

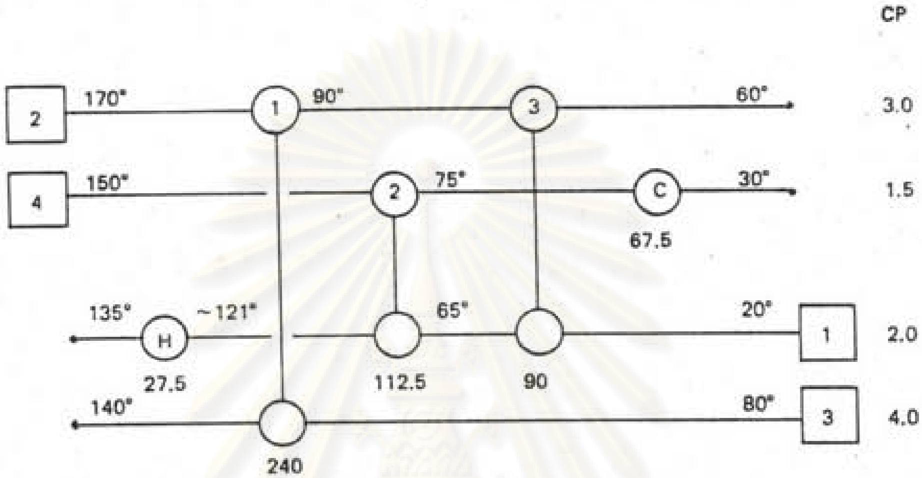


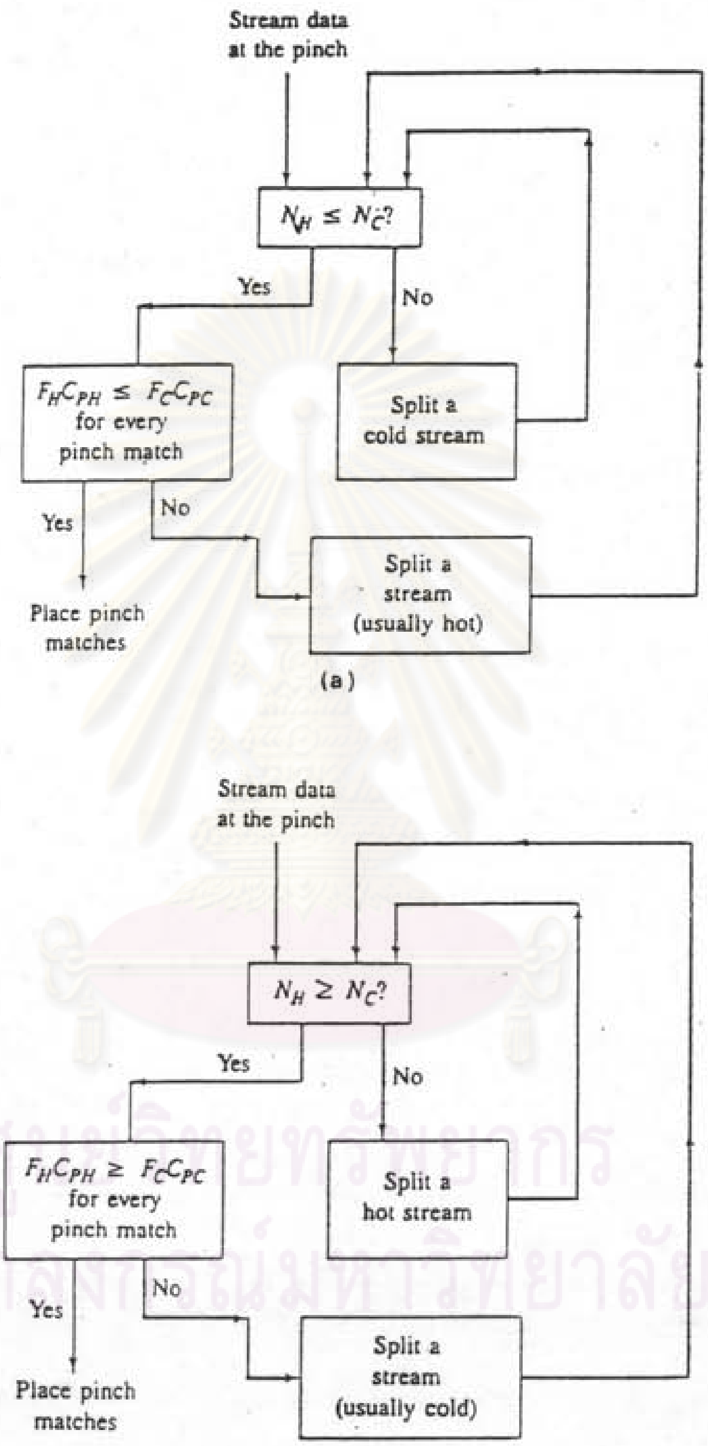
Figure 2.14 Final design - minimum exchangers

In summary : On the subject of "energy relaxation", the procedure for reducing units at minimum energy sacrifice is :

- Identify a loop (across the pinch).
- Break it by substracting and adding loads.
- Recalculate network temperatures and identify the $\triangle$ Tmin violations.
- Find a relaxation path and restore $\triangle$ Tmin.

2.4 A More Complete Design Algorithm

The principle of the pinch design has been illustrated earlier by a simple example. Anyway, there are some situations where our design procedure does not mention. However, a general design algorithm for conditions above and below the pinch is shown in Figure 2.15 (a) and (b).



(b)

Figure 2.15 Design procedure algorithm (From B.Linnhoff et.al., 1982)

(a) above the pinch (b) below the pinch