3
Pinch Technology

In recent years a new technology for minimising the energy requirements of process plants has been developed: this has been named *Pinch Technology* or *Process Integration* by its major proponent, Linnhoff (Linnhoff and Senior, 1983; Linnhoff and Turner 1981). Process plants, such as oil refineries or major chemical manufacturing plants, require that heating and cooling of the feed stock take place as the processes occur. Obviously it would be beneficial to use the energy from a stream which requires cooling to heat another which requires heating; in this way the energy that has to be supplied from a high temperature source (or utility) is reduced, and the energy that has to be rejected to a low temperature sink (or utility) is also minimised. Both of these external transfers incur a cost in running the plant. Pinch technology is an approach which provides a mechanism for automating the design process, and *minimising the external heat transfers*.

Pinch situations also occur in power generation plant; for example, in a combined cycle gas turbine (CCGT) plant (see Fig 3.1) energy has to be transferred from the gas turbine exhaust to the working fluid in the steam turbine. A $T-s$ diagram of a CCGT plant is

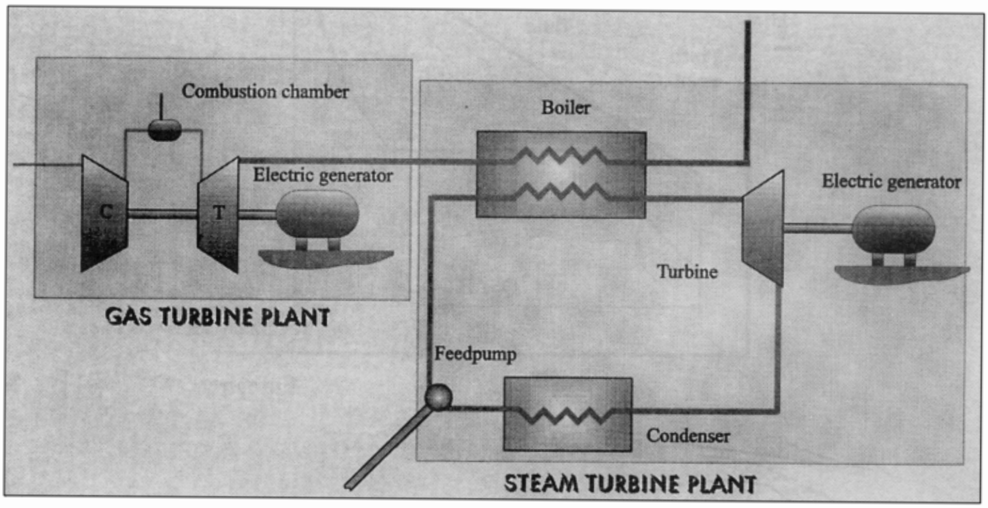

Fig. 3.1 Schematic of CCGT

shown in Fig 3.2, where the heat transfer region is shown: the pinch is the closest approach in temperature between the two lines. It is defined as the minimum temperature difference between the two streams for effective heat transfer, and is due to the difference in the properties of the working fluids during the heat transfer process (namely, the exhaust gas from the gas turbine cools down as a single phase but the water changes phase when it is heated) – this limits the amount of energy that can be taken from the hot fluid. The heat transfer processes are shown on a temperature–enthalpy transfer diagram in Fig 3.3, where the pinch is obvious.

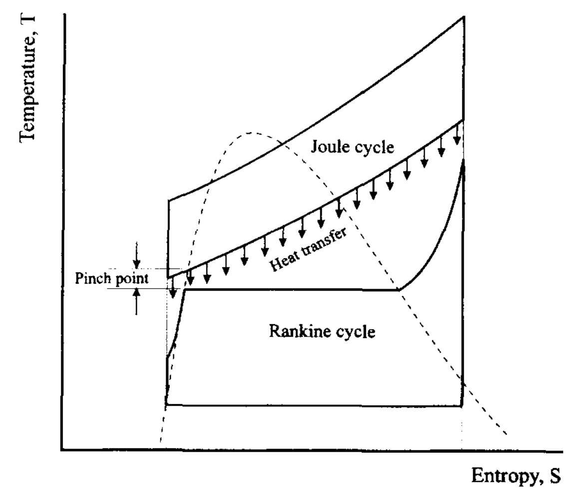

Fig. 3.2 $T-s$ diagram of CCGT

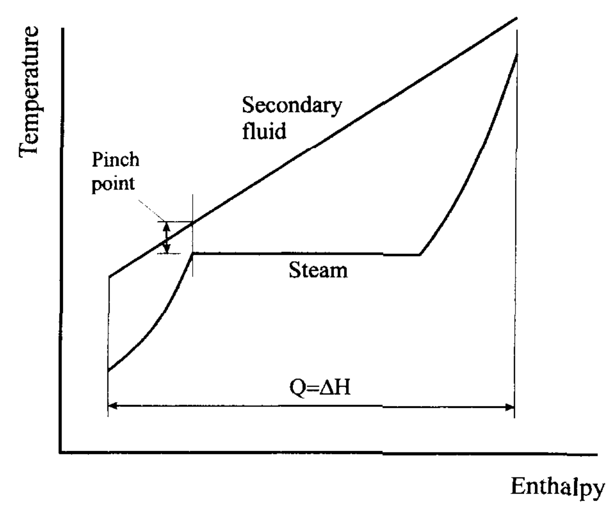

Fig. 3.3 $H-T$ diagram of CCGT

Perhaps the easiest way of gaining an understanding of pinch techniques is to consider some simple examples.

3.1 A heat transfer network without a pinch problem

This example has a total of seven streams, three hot and four cold, and it is required to use the heating and cooling potential of the streams to minimise the heat transfer from high temperature utilities, and the heat transfer to low temperature utilities. The parameters for the streams involved in the processes are given in Table 3.1. The supply temperature, T_S, is the initial temperature of the stream, and the target temperature, T_T, is the target final temperature that must be achieved by heat transfer. The heat flow capacity, mC, is the product of the mass flow and the specific heat of the particular stream, and the heat load is the amount of energy that is transferred to or from the streams.

Table 3.1 Specification of hot and cold streams

Stream no	Stream type	Supply temperature $T_S/(°C)$	Target temperature $T_T/(°C)$	Heat flow capacity $mC/(MJ/hK)$	Heat load $Q/(MJ/h)$
1	Cold	95	205	2.88	316.8
2	Cold	40	220	2.88	518.4
3	Hot	310	205	4.28	−449.4
4	Cold	150	205	7.43	408.7
5	Hot	245	95	2.84	−426.0
6	Cold	65	140	4.72	354.0
7	Hot	280	65	2.38	−511.7

In this case there are three streams of fluid which require cooling (the hot streams) and four streams of fluid which require heating (the cold streams). The simplest way of achieving this is to cool the hot streams by transferring heat directly to a cold water supply, and to heat the cold streams by means of a steam supply; this approach is shown in Fig 3.4. This means that the hot utility (the steam supply) has to supply 1597.9 MJ of energy, while the cold utility (a cold water supply) has to remove 1387.1 MJ of energy. Both of these utilities are a cost on the process plant. The steam has to be produced by burning a fuel, and use of the cold water will be charged by the water authority. In reality a *minimum net heat supply* of 1597.9−1387.1 = 210.8 MJ/h could achieve the same result, if it were possible to transfer all the energy available in the hot streams to the cold streams. This problem will now be analysed.

If heat is going to be transferred between the hot and cold streams there must be a temperature difference between the streams: assume in this case that the minimum temperature difference (δT_{min}) is 10°C.

The method of tackling this problem proposed by Linnhoff and Turner (1981) is as follows.

Step 1: Temperature intervals

Evaluate the temperature intervals defined by the 'interval boundary temperatures'. These can be defined in the following way: the unadjusted temperatures of the cold streams can be used, and the hot stream temperatures can be adjusted by subtracting δT_{min} from the actual values. In this way the effect of the minimum temperature difference has been included in the calculation. This results in Table 3.2.

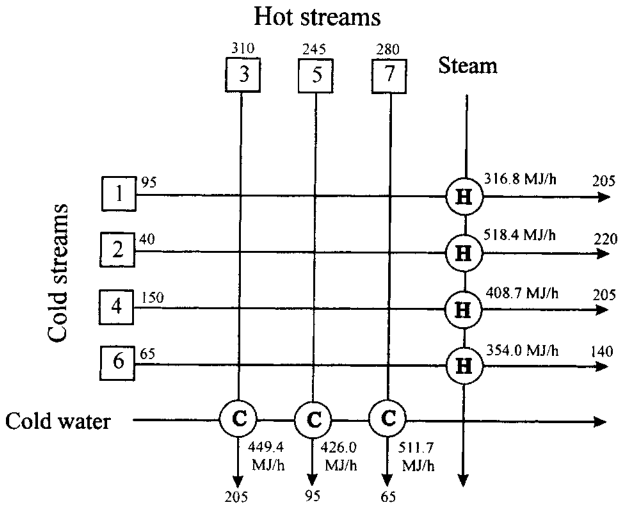

Fig. 3.4 Direct heat transfer between the fluid streams and the hot and cold utilities

Table 3.2 Ordering of hot and cold streams

Stream no	Stream type	Supply temperature T_S/(°C)	Target temperature T_T/(°C)	Adjusted temperatures		Order
1	Cold	95		95		T_9
			205		205	T_5
2	Cold	40		40		T_{13}
			220		220	T_4
3	Hot	310		300		T_1
			205		195	T_6
4	Cold	150		150		T_7
			205		205	Duplicate
5	Hot	245		235		T_3
			95		85	T_{10}
6	Cold	65		65		T_{11}
			140		140	T_8
7	Hot	280		270		T_2
			65		55	T_{12}

The parameters defining the streams can also be shown on a diagram of temperature against heat load (enthalpy transfer; see Fig 3.5). This diagram has been evaluated using the data in Table 3.2, and is based on the unadjusted temperatures. The hot stream line is based on the *composite* temperature–heat load data for the hot streams, and is evaluated using eqn (3.2); the cold stream line is evaluated by applying the same equation to the cold streams. It can readily be seen that the two lines are closest at the temperature axis, when they are still 25°C apart: this means that there is no 'pinch' in this example because the temperature difference at the pinch point is greater than the minimum value allowable.

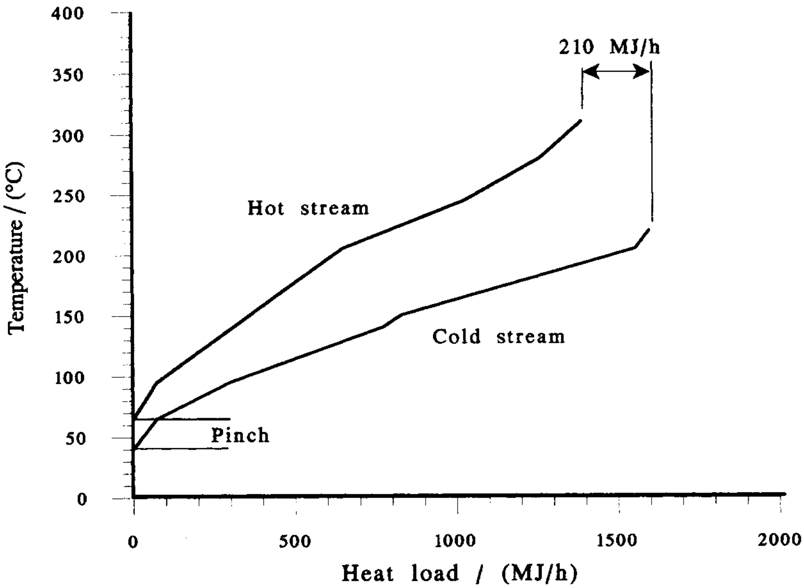

Fig. 3.5 Temperature–heat load diagram

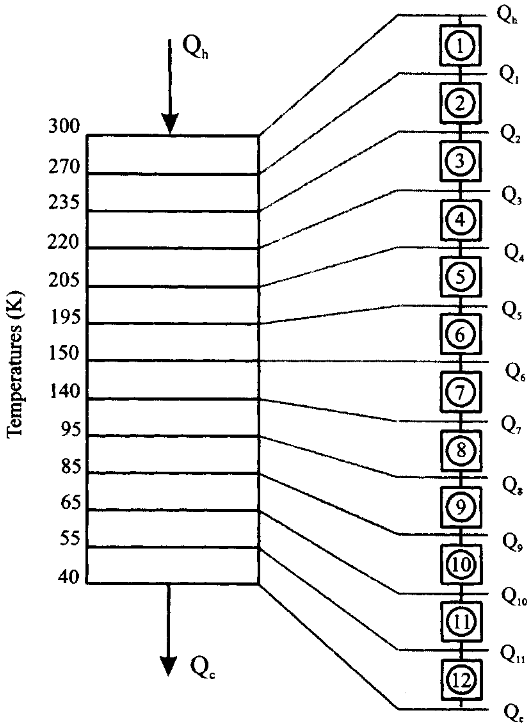

Fig. 3.6 Temperature intervals for heat transfer network

Hence, the problem reduces to transferring energy from the hot streams to the cold streams, and finally adding 210.8 MJ/h from a hot utility. The mechanism for allocating the energy transfers will now be introduced.

Having defined the temperature intervals it is possible to consider the problem as shown in Fig 3.6. The energies flowing into and out of the combined systems, Q_h and Q_c, are those which have to be supplied by and lost to the external reservoirs respectively. It is also apparent that the difference between these values is the difference between the enthalpies of the hot and cold streams, i.e.

$$Q_c - Q_h = \delta H \tag{3.1}$$

Consideration will show that δH is constant, because the difference between the enthalpies of the hot and cold streams is constant, and this means that any additional energy added from the high temperature supplies must be compensated by an equal amount of energy being rejected to the low temperature sinks: hence energy will have just flowed wastefully through the overall system. The heat transfer network can be shown schematically as in Fig 3.7. The heat flows through each of the temperature intervals can be evaluated as shown in the next step.

Step 2: Interval heat balances

Table 3.2 includes the effect of the minimum temperature difference between the streams, δT_{min}, and hence the intervals have been established so that full heat transfer is possible between the hot and cold streams. It is now necessary to apply the First Law to examine the enthalpy balance between the streams, when

$$\delta H_i = \left(\sum_{\substack{\text{Hot} \\ i,\, i+1}} (mC)_h - \sum_{\substack{\text{Cold} \\ i,\, i+1}} (mC)_c \right)(T_i - T_{i+1})$$

where i = initial temperature of the interval
$i + 1$ = final temperature of the interval (3.2)

Applying this equation to this example results in the heat flows shown by the $\delta H = mC\delta T$ values in Fig 3.8.

It can be seen from Fig 3.8 that the individual heat transfers are positive (i.e. from the hot streams to the cold streams) in the first four intervals. In the fifth interval the amount of energy required by the cold streams exceeds that available from the hot streams in that temperature interval, but the energy can be supplied from that available in the higher temperature intervals. However, by the eighth interval the demands of the cold streams exceed the total energy available from the hot streams, and it is at this point that the energy should be added from the hot utility, because this will limit the temperature required in the hot utility. In reality, the 210.8 MJ could be provided from the hot utility at any temperature above 140°C, but the higher the temperature of the energy the more will be the irreversibility of the heat transfer process. It is now useful to look at the way in which the heat can be transferred between the hot and cold streams.

The streams available for the heat transfer processes are shown in Fig 3.9. First, it should be recognised that there is no heat transfer to the cold utility, and thus all the heat transfers from the hot streams must be to cold streams This constrains the problem to ensure that there is always a stream cold enough to receive heat from the hot sources. This means that the temperature of Stream 7 must be cooled to its target temperature of 65°C by transferring heat to a colder stream: the only one available is Stream 2. Hence, the total heat transfer from Stream 7 is passed to Stream 2: an energy balance shows that the

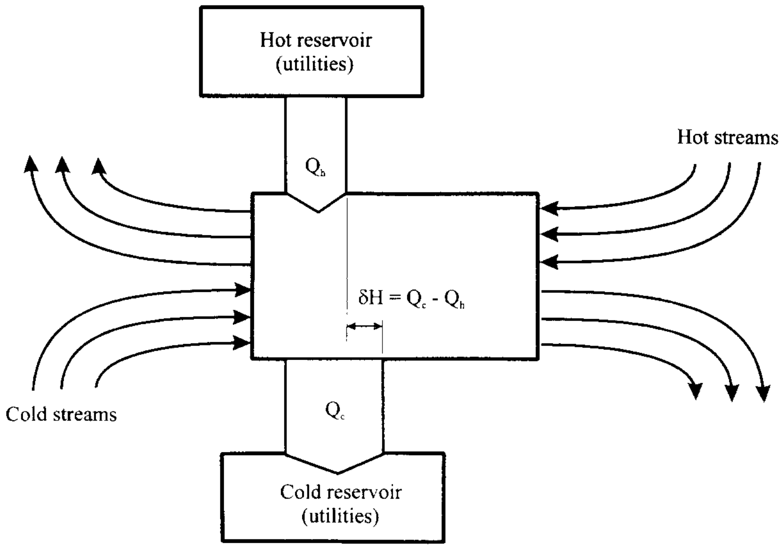

Fig. 3.7 Overall energy for heat transfer network

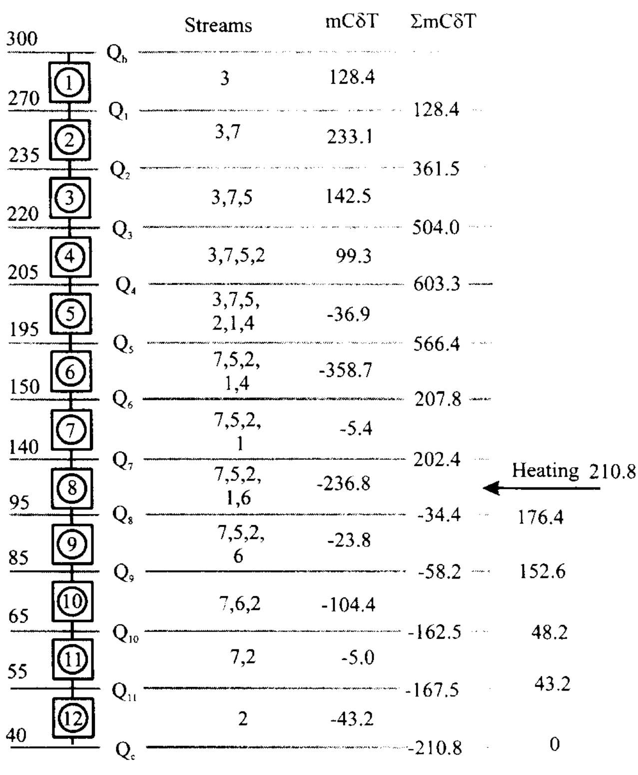

Fig. 3.8 Heat flows

temperature of Stream 2 is raised to 218°C, and there is a residual heat capacity of 6.7 MJ/h before the stream reaches its target temperature In a similar manner it is necessary for Stream 5 to be matched to Stream 6 because this is the only stream cold enough to bring its temperature down to 95°C. In this way it is possible to remove Streams 6 and 7 from further consideration because they have achieved their target temperatures; Streams 2 and 5 must be left in the network because they still have residual energy before they achieve their targets. Figure 3.9 can be modified to Fig 3.10.

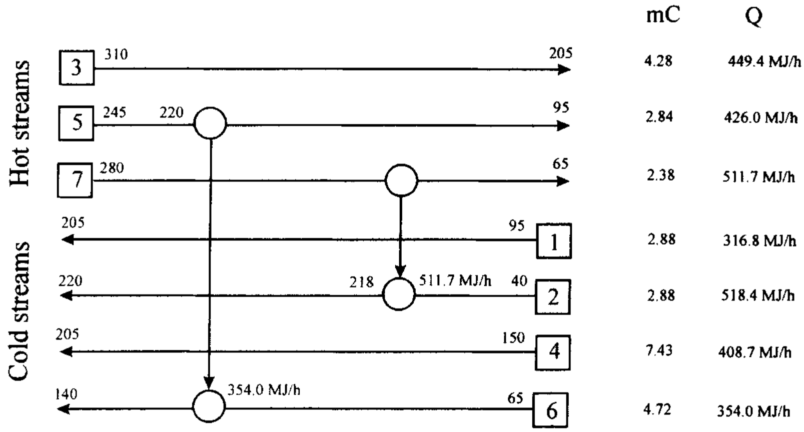

Fig. 3.9 Initial heat transfer: heat transfer from Streams 5 to 6, and 7 to 2

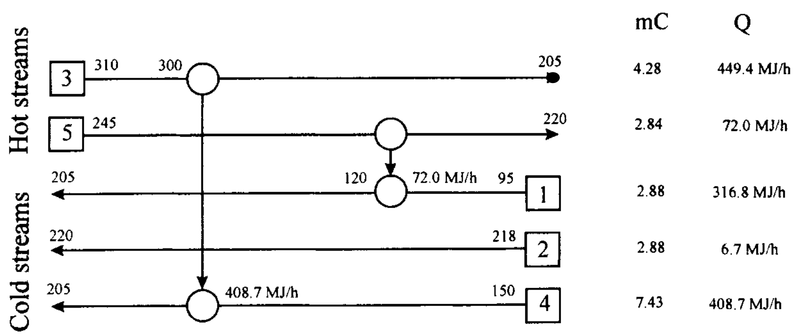

Fig. 3.10 Removing the residuals from Streams 2 and 5

Streams 2 and 5 are represented in this diagram by their residual energies, and by the temperatures that were achieved in the previous processes. It is possible to cool Streams 3 and 5 by transferring energy with either of cold Streams 1 or 4. The decision in this case is arbitrary, and for this case Stream 3 will be matched with Stream 4, and Stream 5 will be matched with Stream 1. This results in the heat transfers shown in Fig 3.10, and by this stage Streams 5 and 4 can be removed from further consideration. This results in another modified diagram, Fig 3.11.

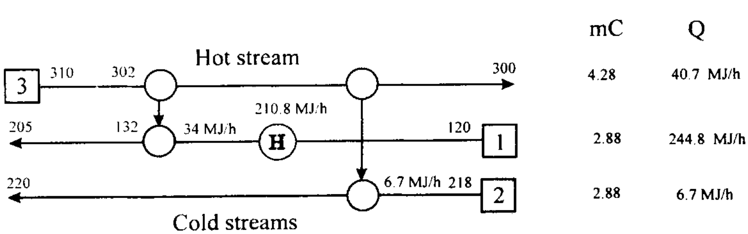

Fig. 3.11 Completing the heat transfer network

By this stage it is necessary to consider adding the heat from the hot utility. In this case, the temperature at which this energy is added is relatively arbitrary, and the heat should be transferred at as low a temperature as possible. This is indicated by the 210.8 MJ/h heat transfer in Fig 3.11.

The previous analysis has considered the problem in discrete parts, but it is now possible to combine all these sub-sections into a composite diagram, and this is shown in Fig 3.12.

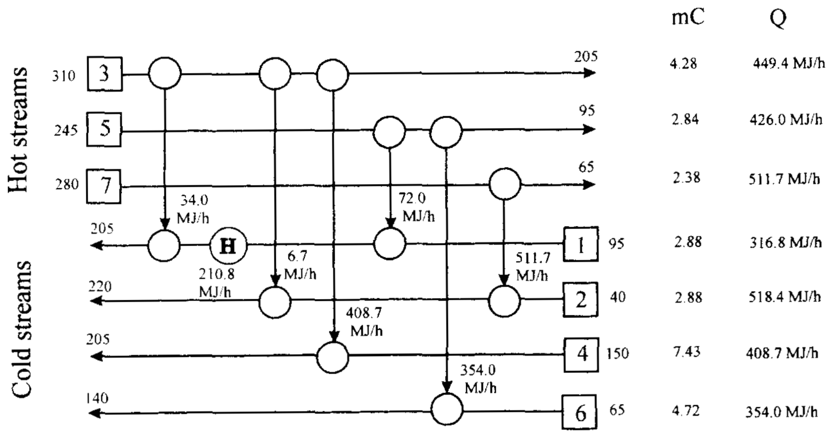

Fig. 3.12 Composite diagram for heat exchanger network

The diagram given in Fig 3.12 suggests that seven heat exchangers are required, but the diagram is not the most succinct representation of the network problem, which is better illustrated as shown in Fig 3.13, which grows directly out of the original arrangement shown in Fig 3.4.

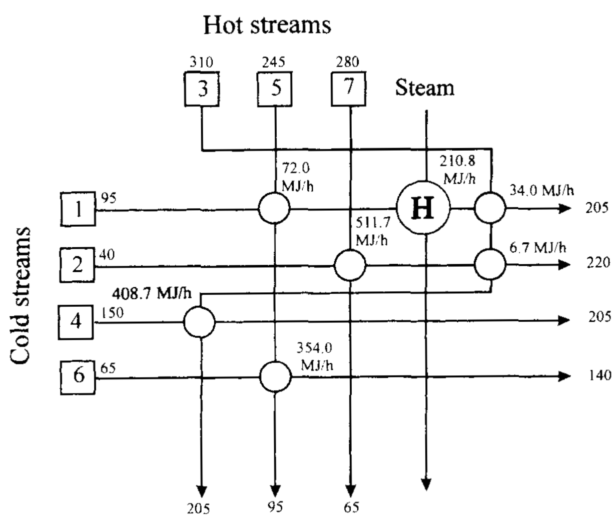

Fig. 3.13 Diagram showing the minimum number of heat exchangers to achieve heat transfer

This case was a relatively straightforward example of a heat exchanger network in which it was always relatively easy to match the streams, because there was always a sufficient temperature difference to drive the heat transfer processes. The next example shows what happens when there is not sufficient temperature difference to drive the heat transfer processes.

3.2 A heat transfer network with a pinch point

Consider there are four streams of fluid with the characteristics given in Table 3.3. Assume that the minimum temperature difference between any streams to obtain acceptable heat transfer is 5°C, i.e. $\delta T_{min} = 5$°C. This value of δT_{min} is referred to as the *pinch point* because it is the closest that the temperatures of the streams are allowed to come. The temperatures of the streams can be ordered in a manner similar to the first case and the results of this are shown in Table 3.4.

Table 3.3 Characteristics of streams

Process stream		Supply temperature	Target temperature	Heat capacity flowrate, mC	Heat load $mC(T_S - T_T)$
Number	Type	T_S/(°C)	T_T/(°C)	/(MJ/hK)	/(MJ/h)
1	Cold	50	110	2.0	120
2	Hot	130	70	3.0	180
3	Cold	80	115	4.0	140
4	Hot	120	55	1.5	97.5

Table 3.4 Definition of temperature intervals

Stream no	Stream type	T_S/(°C)	T_T/(°C)	Adjusted temperatures		Order
1	Cold	50		50		T_6
			110		110	T_3
2	Hot	130		125		T_1
			70		65	T_5
3	Cold	80		80		T_4
			115		115	T_2
4	Hot	120		115		Duplicate
			55		50	Duplicate

These temperature intervals can be depicted graphically as shown in Fig 3.14. It can be seen that there are five intervals in this case, as opposed to the 12 in the first case.

It is now possible to draw the temperature–heat load diagram for this problem, and this is shown in Fig 3.15. It can be seen that the basic cold stream is too close to the hot stream and there will not be a sufficient temperature difference to drive the heat transfer processes. The modified cold stream line has been drawn after undertaking the following analysis, and does produce sufficient temperature difference at the pinch.

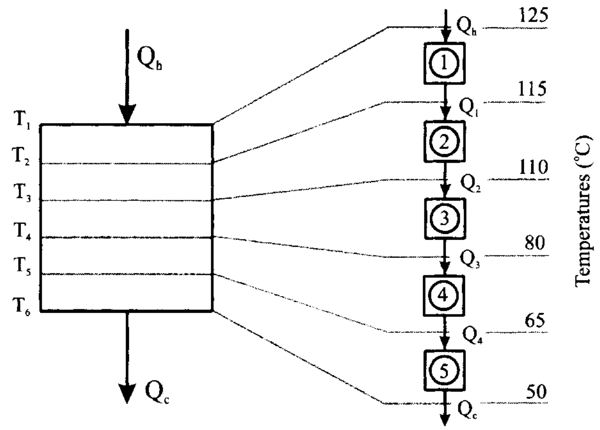

Fig. 3.14 Temperature intervals for heat transfer network

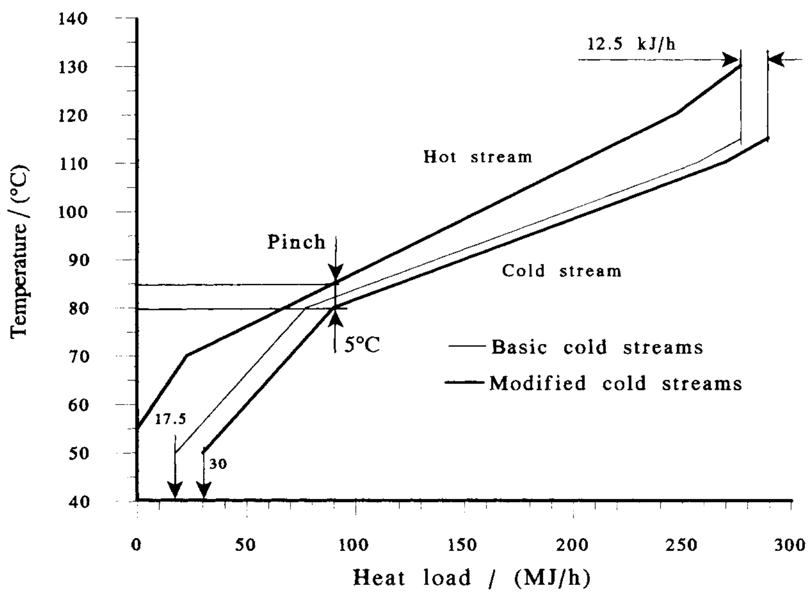

Fig. 3.15 Temperature–heat load diagram, indicating pinch point

Step 3: Heat cascading

This step is an additional one to those introduced previously, and consideration will show why it comes about. Figure 3.16 indicates the heat flows in the various intervals and, in the left-hand column of figures, shows that if the heat flow from the hot utility (or heat source) is zero then there will be a negative heat flow of −12.5 units in temperature interval 3 between 110°C and 80°C. Consideration will show that *this is impossible because it means that the heat will have been transferred against the temperature gradient.* Such a situation can be avoided if sufficient energy is added to the system to make the largest negative heat flow zero in this interval. The result of this is shown in the right-hand column of figures in Fig 3.16, which has been achieved by adding 12.5 units of energy to the system. It can be seen that in both cases the difference between Q_h and Q_c is 17.5 units of energy. If an energy balance is applied to the streams defined in Table 3.3 then

$$\sum \delta H_i = 3 \times (130-70) + 1.5 \times (120-55) - 2 \times (110-50) - 4 \times (115-80)$$
$$= 17.5 \qquad (3.3)$$

Hence, as stated previously, the energies obey the steady-flow energy equation for the system shown in Fig 3.16.

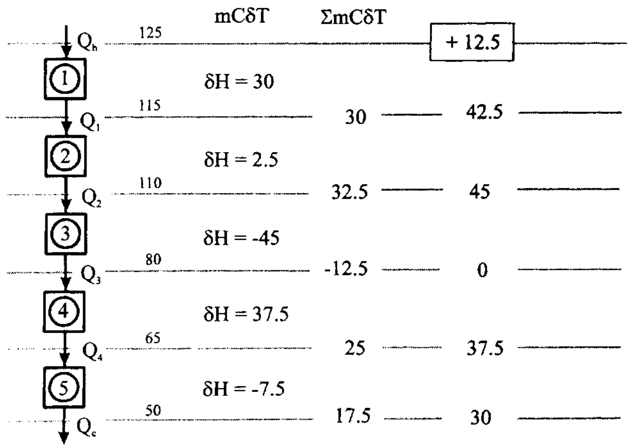

Fig. 3.16 Temperature intervals and heat loading

There is now a point in the temperature range where the heat flow is zero: this point is called *the pinch*. In this example it is at 80°C, which means that the pinch occurs at a cold stream temperature of 80°C and a hot stream temperature of 85°C. There are three important constraints regarding the pinch:

1. Do not transfer heat across the pinch. Any heat flow across the pinch results in the same amount of heat being added to every heat flow throughout the system, and hence increases Q_h and Q_c.
2. Do not use the cold sink above the pinch. If the system has been designed for minimised heat flow it does not reject any heat above the pinch (see Fig 3.16, where the heat rejection has been made zero at the pinch).
3. Do not use the hot source below the pinch. If the system has been designed for minimised heat flow it does not absorb any heat below the pinch.

It is hence possible to reduce the problem into two parts: above the pinch and below the pinch, as shown in Fig 3.17, which is a modification of Fig 3.7.

It is now necessary to break the problem at the pinch, and this results in Fig 3.18, which is the equivalent of Fig 3.9 for the first example.

Now the problem can be analysed, bearing in mind the restrictions imposed by the pinch point. This means that cooling to the utility stream is not allowable above the pinch, and hence the only transfer can be with the hot utility above the pinch. It is now necessary, as far as possible, to match the hot and cold streams above the pinch.

1. Consider Stream 2 is matched with Stream 1, and Stream 4 is matched with Stream 3. Then Stream 2 can transfer 70 MJ/h to Stream 1, and enable Stream 1 to achieve its

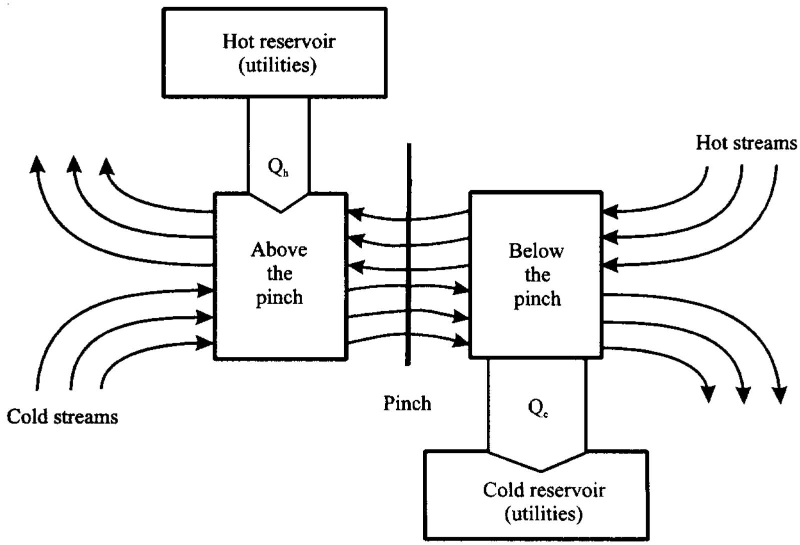

Fig. 3.17 Breaking the problem at the pinch point

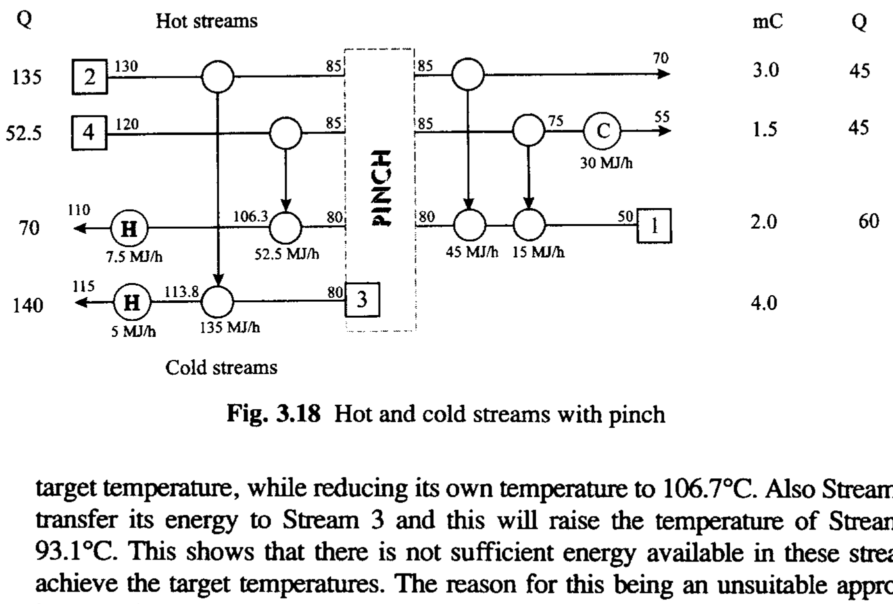

Fig. 3.18 Hot and cold streams with pinch

target temperature, while reducing its own temperature to 106.7°C. Also Stream 4 can transfer its energy to Stream 3 and this will raise the temperature of Stream 3 to 93.1°C. This shows that there is not sufficient energy available in these streams to achieve the target temperatures. The reason for this being an unsuitable approach is because the heat capacity flowrate for Stream 1 above the pinch is greater than that of the cold stream above the pinch. Since both streams have the same temperature at the pinch point, then the higher temperature of the cold stream would have to be higher than that of the hot stream to achieve an energy balance: this would result in an impossible heat transfer situation. Hence, for a satisfactory result to be possible

$$mC_{\text{cold}} \geqslant mC_{\text{hot}} \tag{3.4}$$

above the pinch point.

2. If the alternative match is used, namely, Stream 2 matched to Stream 3, and Stream 4 matched to Stream 1, then the answer shown in Fig 3.19 is obtained.

The heat transfers are shown on the diagram. It can be seen that it is not possible to match the hot and cold streams either above or below the pinch. This means that utility heat transfers are required from the hot utility above the pinch, and heat transfers to the cold utility are required below the pinch. This proposal does obey inequality (3.4), and is hence acceptable.

3. It can be seen that, above the pinch point, energy has to be added to the system from the hot utility. This obeys the rules proposed above, and the total energy added is 12.5 MJ/h, which is in agreement with the value calculated in Fig 3.16.
4. Considering the heat transfers below the pinch, it can be seen that Stream 1 can be heated by energy interchange with Streams 2 and 4: neither Stream has sufficient capacity alone to bring Stream 1 to its target temperature. However, it is feasible to bring about the heating because

$$mC_{\text{hot}} \geqslant mC_{\text{cold}} \tag{3.5}$$

which is the equivalent of inequality (3.4) for the transfers below the pinch. In this case it was chosen to transfer all the energy in Stream 4 because this results in a lower temperature for heat transfer to the cold utility. The 30 MJ/h transferred to the cold utility is in line with that calculated in Fig 3.16.

These diagrams can now be joined together to give the composite diagram in Fig 3.19.

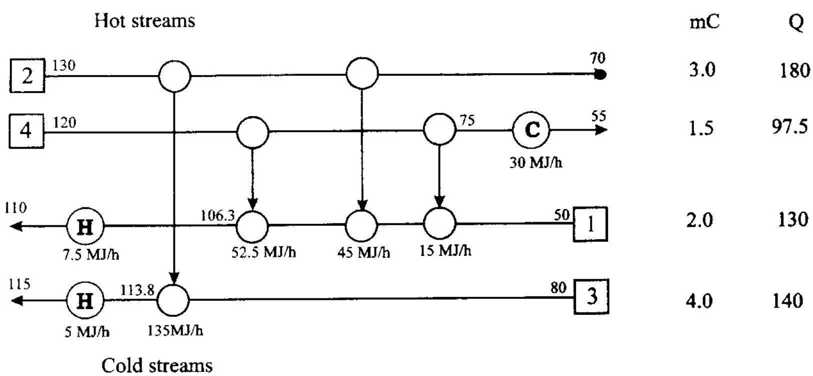

Fig. 3.19 Composite diagram for heat transfer network in Example 2

The heat load against temperature diagram for this problem, before heat transfer from the utilities has been supplied, is shown in Fig 3.15, and was discussed previously. It is now possible to consider the modified diagram, when it can be seen that the energy transfers have produced a sufficient temperature difference to satisfy the constraints of the problem.

3.3 Concluding remarks

A method has been introduced for improving the efficiency of energy transfers in complex plant. It has been shown that in some plants there is a *pinch point* which restricts the freedom to transfer energy between process streams. To ensure that the plant attains its maximum efficiency of energy utilisation, energy should be added to the system only above the pinch, and extracted from it only below the pinch.

PROBLEMS

1 A process plant has two streams of hot fluid and two streams of cold fluid, as defined in Table P3.1. It is required to minimise the energy which must be transferred to hot and cold utilities by transferring energy between the streams. If the minimum temperature difference for effective heat transfer is 20°C, design a network which achieves the requirement, and minimises the transfers to the utilities. Is there a pinch point in this problem, and at what temperature does it occur? Calculate the minimum heat transfers to and from the cold and hot utilities.

Table P3.1 Data related to Q.1

Stream no	Stream type	Supply temperature T_S/(°C)	Target temperature T_T/(°C)	Heat flow capacity mC/(MJ/hK)
1	Hot	205	65	2.0
2	Hot	175	75	4.0
3	Cold	45	180	3.0
4	Cold	105	155	4.5

[105°C (cold stream); $Q_{H_{min}} = 90$ MJ/h; $Q_{C_{min}} = 140$ MJ/h]

2 Some stream data have been collected from a process plant, and these are listed in Table P3.2. Assuming the minimum temperature difference between streams, $\Delta T_{min} = 10°C$,

(a) calculate the data missing from Table P3.2;

(b) analyse this data to determine the minimum heat supplied from the hot utility, the minimum heat transferred to the cold utility, and the pinch temperatures;

(c) draw a schematic diagram of the heat transfer network.

Table P3.2 Data related to Q.2

Stream no	Stream type	Supply temperature T_S/(°C)	Target temperature T_t/(°C)	Enthalpy change ΔH/(kW)	Heat flow capacity mC/(kW/K)
1	Cold	60	180	?	3
2	Hot	180	40	?	2
3	Cold	30	130	220	?
4	Hot	150	40	400	?
5	Cold	60	80	40	?

[360 kW; 280 kW; 2.2 kW/K; 4.0 kW/K; 2.0 kW/K; $Q_{H_{min}} = 60$ kW; $Q_{C_{min}} = 160$ kW; $T_{C_{pinch}} = 140°C$]

3 Figure P3.3 shows a network design using steam, cooling water and some heat recovery.

(a) Does this design achieve the minimum energy target for $\Delta T_{min} = 20°C$?

(b) If the current network does not achieve the targets, show a network design that does.

[(a) $T_{C_{pinch}} = 150°C$; $T_{H_{pinch}} = 170°C$; $Q_C = 480$ kW; $Q_H = 380$ kW; (b) $Q_{C_{min}} = 360$ kW; $Q_{H_{min}} = 260$ kW]

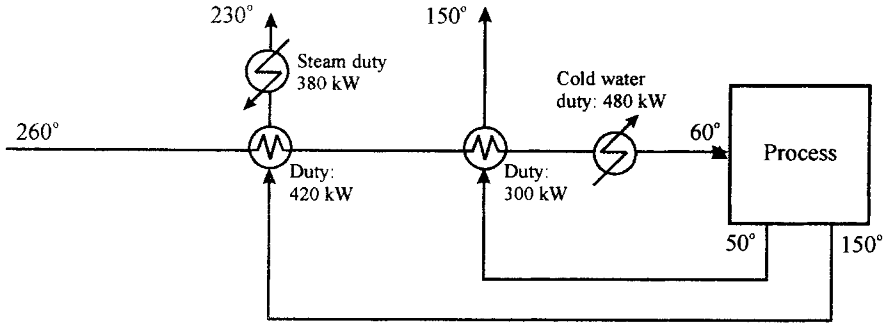

Fig. P3.3 Network for Q.3

4 Figure P3.4 shows two hot streams and two cold streams for heat integration (subject to $\Delta T_{min} = 20°C$).

(i) What are the energy targets?
(ii) Show a network design achieving these targets.

[$Q_{H_{min}} = 0$; $Q_{C_{min}} = 0$]

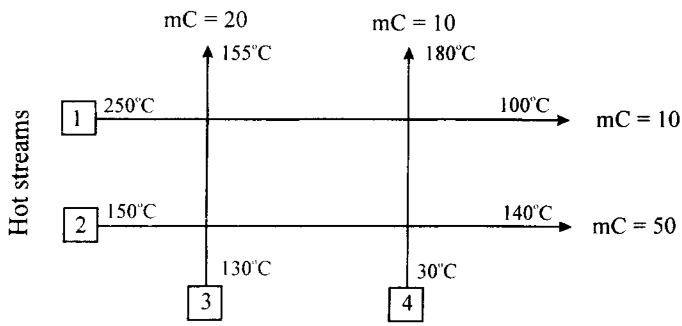

Fig. P3.4 Network for Q.4

5 Figure P3.5 shows an existing design of a process plant, containing two exothermic processes. These require streams of reactants as shown in the diagram, and produce products at the temperatures shown. The plant achieves the necessary conditions by providing 480 kW of heat from a steam source, and rejects a total of 560 kW of energy to cold water utilities; only 460 kW is transferred between the streams.

(a) Show that there is a pinch point, and evaluate the temperature.
(b) Show that the existing plant is inefficient in its use of the energy available.
(c) Calculate the energy targets for $\Delta T_{min} = 20°C$ and show a design that achieves these targets.

[(a) $T_{C_{pinch}} = 110°C$; $T_{H_{pinch}} = 130°C$; (b) $Q_C = 560$ kW; $Q_H = 480$ kW; (c) $Q_{C_{min}} = 210$ kW; $Q_{H_{min}} = 130$ kW]

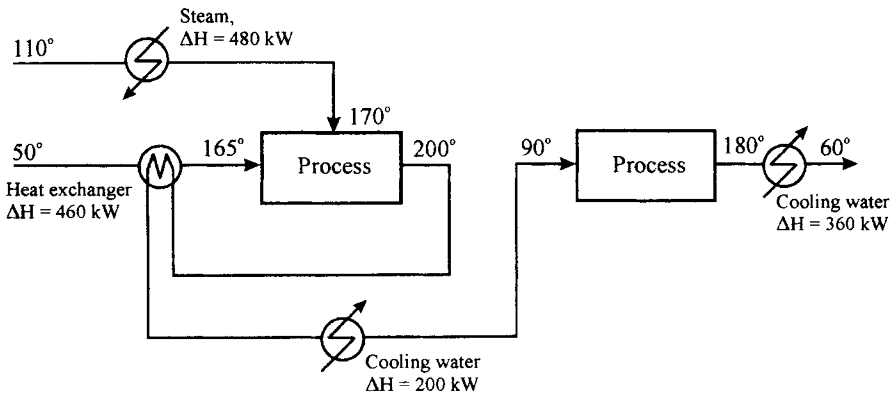

Fig. P3.5 Network for Q.5

6 Recalculate the problem in Q.5 using a $\Delta T_{min} = 10°C$. Comment on the effect of reducing the minimum temperature difference.

[(a) $T_{C_{pinch}} = 110°C$; $T_{H_{pinch}} = 120°C$; (b) $Q_C = 560$ kW; $Q_H = 480$ kW; (c) $Q_{C_{min}} = 120$ kW; $Q_{H_{min}} = 40$ kW]

7 A network for a process plant is shown in Fig P3.7.

(a) Calculate the energy targets for $\Delta T_{min} = 10°C$ and show a design that achieves these targets.

(b) Explain why the existing network does not achieve the energy targets.

[(a) $Q_{C_{min}} = 190$ kW; $Q_{H_{min}}$T = 90 kW; (b) there is transfer across the pinch]

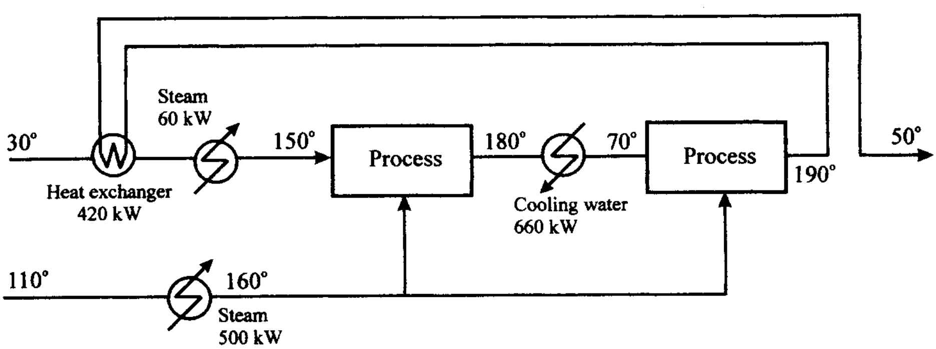

Fig. P3.7 Network for Q.7