Chapter 10

PINCH POINT ANALYSIS

10.1 INTRODUCTION

Energy saving is a major issue in sustainable development. Thanks to the effort of several researchers, a methodology was developed in the decade 1980-90 under the label *Pinch Point Technology*. Some key concepts have been published at the end of 1970, but Linnhoff and co-workers have the merit of the most important contributions. They published the first 'Guide for Optimal Use of Energy in Process Industries' in 1982 (republished in 1994) where the concept of *Process Integration* was introduced. Since, Process Integration evolved to a paradigm of process design, which addresses not only energy saving but other important systemic issues (see Chapter 1). Today the label *Pinch Point Analysis* designates the systematic research of innovative solutions in the area of energy saving (Linnhoff et al., 1994).

Pinch Point Analysis

Pinch Point Analysis (PPA) is an extension of the second principle of Thermodynamics to the energy management of the whole plant. PPA deals with the optimal structure of the heat exchange between the process streams, as well as the optimal use of utilities. Among benefits we mention:

1) Assess the reference basis of an energy saving project, namely:
- Minimum Energy Requirements (MER), as heating and cooling loads for utility system, for a minimum temperature approach ΔT_{min} assumed at Pinch;
- Maximum energy saving by process/process heat exchange;
- Capital and operation costs needed by MER.

2) Set optimal targets before the detailed design of the heat exchanger network:
- Design targets for the Heat Exchangers Network (HEN), as the total heat exchange area and the number of units for achieving MER;
- Nature and amount of utilities needed for satisfying the optimal loads;
- Integration on heat saving with power generation.

3) Suggest modifications in technology and process design with significant impact on saving energy, as:
- Optimisation of the operating parameters of reactors and separators;
- Heat integration of distillation columns;
- Optimal placement of heat engines and heat pumps, etc.

PPA makes use intensively of conceptual graphical tools. The concept of *Pinch* has proved a generic value, being extended to the management of other valuable resources, as water, solvents and hydrogen (Linnhoff et al., 1994).

In parallel with PPA, a different approach was developed, based on *Mathematical Programming* (MP). Grossman, Floudas and co-workers have brought significant contributions (see the references). Nowadays the two approaches are largely complementary, PPA as conceptual tool while MP as automatic design tool.

Specialised packages for implementing Pinch Point Analysis are available, as SUPERTARGET™ (Linnhoff/KBC), ASPEN Pinch™, HEXTRAN™(Simsci). The synthesis of a heat exchanger network by mathematical programming may be handled by means of packages based on the generic environment GAMS™.

10.1.1 Basic concepts

Composite and Grand composite curves

The most fundamental concepts in Pinch analysis are *Composite and Grand Composite Curves*. Composite Curves (Fig. 10.1-left) visualises the flow of heat between the hot and cold process streams selected for heat integration. A composite curve is obtained by plotting the cumulative enthalpy of streams, cold or hot, against temperature. The relative position of the composite curves depends on the minimum temperature difference ΔT_{min} between cold and hot streams. This sets also the Pinch position as the place where the heat transfer between the hot and cold streams is the most constrained.

Composite Curves enable to determine directly the Minimum Energy Requirements (MER) from stream data without ever calculate heat exchangers. These are the minimum hot Q_{h} and minimum cold Q_{c} utility required for driving the heat exchanger network, with a minimum driving force of ΔT_{min} at Pinch.

The *Pinch principle* states that any design where heat is transferred across the Pinch will require more energy than minimum requirements. Consequently, the heat recovery problem is divided into two subsystems, above and below the Pinch.

The same information can be used for drawing the diagram *Grand Composite Curve* (Figure 10.1-right). Here the difference between the enthalpy of the hot and cold streams is plotted against a conventional shifted temperature scale. This representation identifies the possibilities of heat recovery by internal process/process exchange, as well as the optimal selection and placement of utilities.

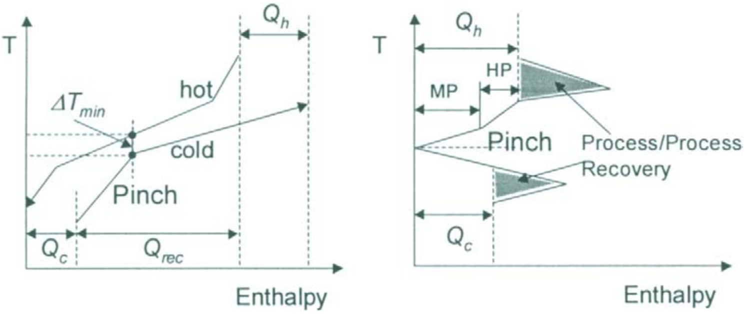

Figure 10.1 Composite Curves, Pinch Point, and Minimum Energy Requirements

Supertargeting

Energy costs increases roughly proportional with ΔT_{min}, while capital costs (heat exchangers) decrease more sharply than proportional (Fig. 10.2). S*upertargeting* consists of setting design targets for the whole process by an overall optimisation procedure well ahead the detailed sizing of heat exchangers.

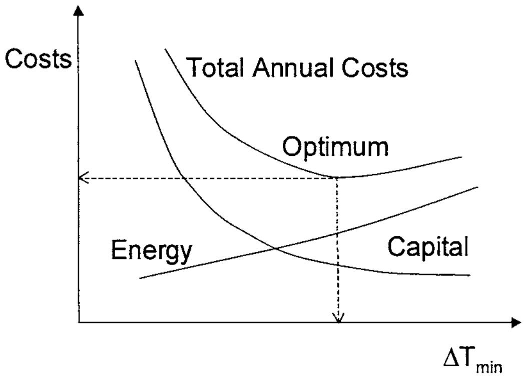

Figure 10.2 Targeting of energy and capital costs before HEN design

Grid Diagram

Grid diagram (Fig. 10.3) designates a working frame for developing the *Heat Exchanger Network* (HEN). The bubbled stick linking two streams in Fig. 10.3 symbolises a heat exchanger. The development of HEN is based on feasibility rules that form the *Pinch Design* method. HEN developed for MER is optimal when both energy and capital costs are considered. Additional reduction in capital costs may be obtained by removing small units. This operation might transfer heat across the Pinch, and as a results makes increase the total consumption of utilities.

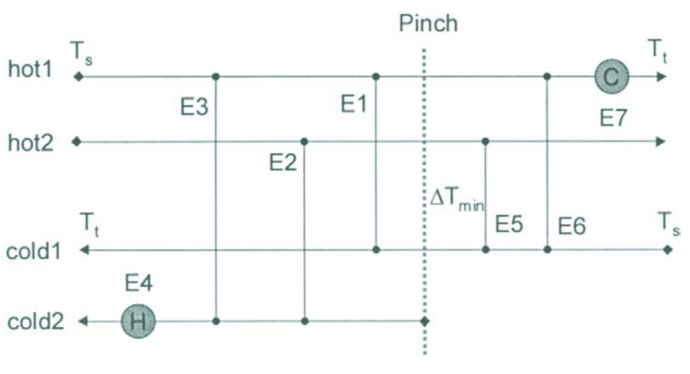

Figure 10.3 The Grid Diagram enables to develop the Heat Exchanger Network

Appropriate Placement

To ensure energy saving, the position of unit operations with respect to Pinch must respect the rules of the *Appropriate Placement*. For example, a heat engine has to be placed either above or below the Pinch, but not across it. Distillation columns should not be placed across the Pinch. Contrary, a heat pump is optimally placed across the Pinch. This subject will be discussed in more detail in the Chapter 11.

Plus/Minus Principle

The visualisation of heat exchange opportunities by the composite curves, combined with the rules of Appropriate Placement, can suggest changes in process design with significant effects on the energetic efficiency. In this way, Pinch Point Analysis becomes an empowering tool for Process Synthesis. *Plus/Minus principle* consists of some rules that can reduce the consumption of both hot and cold utilities. Figure 10.4 presents an example. Originally a distillation column is placed across the Pinch, the reboiler above, and the condenser below (dotted curves). Note that the reboiler is considered a cold stream! By lowering the pressure, the reboiler moves from above to below the Pinch. Thus, a cold stream is removed from above the Pinch (minus) and placed below (plus). Hence, a reduction in both hot and cold utilities is obtained. Consequently, the distillation column can run at zero net utility consumption, compared with the previous situation.

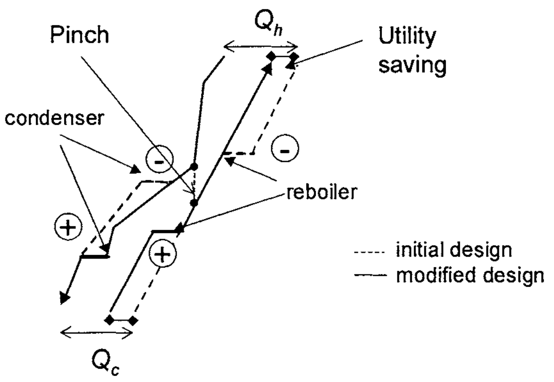

Figure 10.4 Plus/Minus principle

Balanced Composite Curves and Grid Diagram

Balanced composite curves are similar with those discussed above, with the difference that now the utilities are considered as streams. Since the utilities covers any imbalance between the streams selected for integration, the enthalpy balance is closed. Moreover, the design of the heat exchangers is done in the balanced grid diagram.

10.1.2 The overall approach

Pinch Point Analysis starts with the input of data. The first step is the extraction of *stream data* from a flowsheet simulation, which describes typically the material balance envelope (Reactors and Separators). Proper selection and treatment of streams by segmentation is a key factor for efficient heat integration. The next step is the selection of utilities. Additional information regards the partial heat transfer coefficients of the different streams and segments of streams, and of utilities, as well as the cost of utilities and the cost laws for heat exchangers.

After the input of data the next step is *targeting*, which consists of finding the optimal ΔT_{min} as a trade-off between energy and capital costs. On this basis targets for MER can be determined, as well as the overall heat exchange area and the number of units. If the economic data are not reliable, selecting a practical ΔT_{min} is recommended.

Then, the Appropriate Placement of unit operations is checked. This may suggest some design modifications by applying the Plus/Minus principle. Utility options are tested again. Capital costs are trade-off against energy costs. The procedure may imply iteration between targeting and process revision. Significant modifications could require reviewing the flowsheet simulation.

The iterative procedure is ended when no further improvement can be achieved. Note that during different steps of the above procedure the individual heat exchangers are never sized, although information about the heat transfer coefficients of participating streams are required. Only after completing the overall design targets the detailed sizing of the Heat Exchanger Network can take place. Optimisation can be used to refine the design. Then the final solution is checked by rigorous simulation.

Summing-up, Pinch Point Analysis consists of a systematic screening of maximum energy saving that can be obtained in a plant by internal process/process exchange, as well as the optimal use of the available utilities. The method is capable to assess optimal design targets for Heat Exchanger Network well ahead the detailed design of the equipment. Furthermore, PPA may suggest improvements in the original design that could enhance significantly the energetic performance of the process, from changes in the parameters of the operational units to structural modifications in the flowsheet.

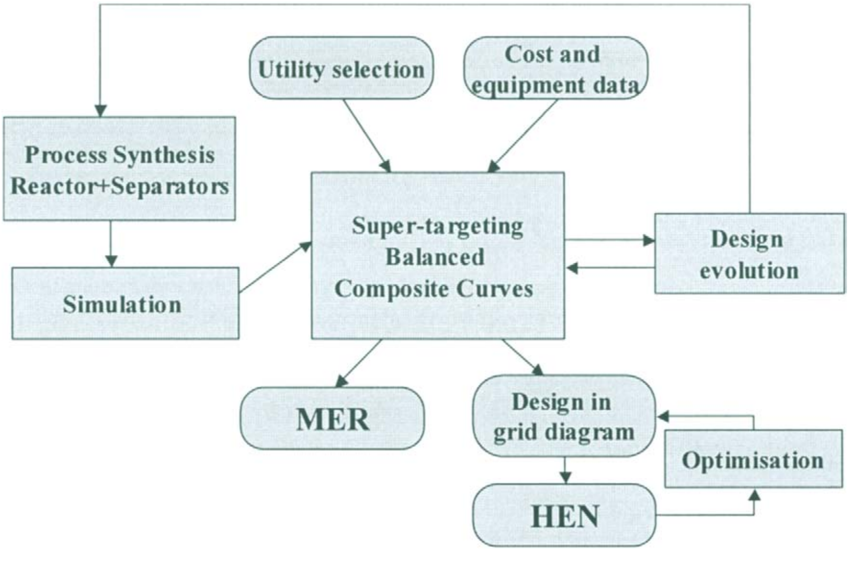

Figure 10.5 Overall approach in designing a Heat Exchanger Network by Pinch Point Analysis

10.2 TARGETS FOR ENERGY RECOVERY

10.2.1 Composite Curves

Stream data

Table 10.1 presents the stream data chosen to illustrate the construction of the Composite Curves. The following minimum elements are necessary:

- Stream or segment temperatures: supply T_s, and target T_t.
- Heat capacity of each stream or segment, defined as $CP=\Delta H/\Delta T$, where ΔH is the enthalpy variation over the temperature interval ΔT. Conversely, the enthalpy change of a stream segment is:

$$\Delta H = CP \times (T_t - T_s) \quad (10.1)$$

The hypothesis of constant *CP* is fundamental in PPA. If the enthalpy-temperature relation is not linear, then the stream must be 'segmented'. Note that in the relation (10.1) *CP* is in fact the term *F*×*CP* (mass flow rate by the mass heat capacity).

Table 10.1 Stream data for Composite Curves

Stream	Name	T_S °C	T_t °C	*CP* kW/C	ΔH kW
1	**hot1**	220	60	100	-16000
2	**hot2**	180	90	200	-18000
3	**cold1**	50	150	150	15000
4	**cold2**	130	180	400	20000
	Total				**1000**

The heat balance of the streams in the Table 10.1 shows an excess of 1000 kW. However, adding 1000 kW cold utility is not sufficient. The second law of Thermodynamics requires a minimum temperature difference between hot and cold streams. Consequently, the real energetic consumption is much higher.

Composite Curves

Composite Curve (CC) displays the cumulated enthalpy of all streams, hot or cold, available in a temperature interval between the extreme supply and targets temperatures. The formula to calculate the relation enthalpy-temperature is:

$$H = H_0 + \sum_i [\sum_j (CP_j)]_{i-1}^{i} \Delta T_i \quad (10.2)$$

CP_j's are the heat capacities of the active streams in the temperature interval ΔT_i. The value H_0 can shift the position of the composite curve. The partition in temperature intervals is based on the analysis of stream population. For the streams in Table 10.1, there are three intervals for the hot streams, and three for the cold streams (Fig. 10.6).

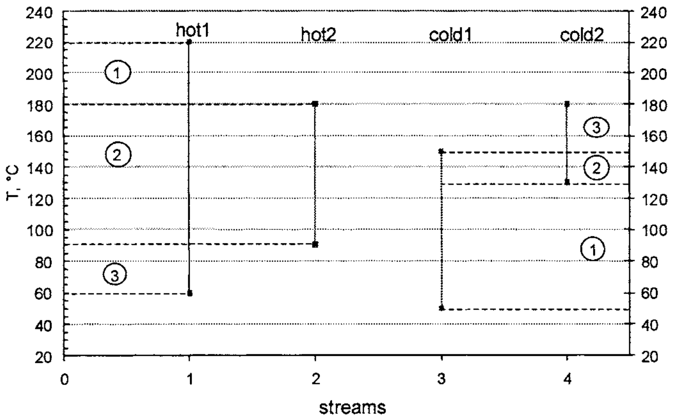

Figure 10.6 Temperature intervals of hot and cold streams

Figure 10.7 explains the graphical construction of the *hot Composite Curve*. The two streams, **hot1** and **hot2**, are represented by the segments ab and cd with CP_1=100 and CP_2=200 kW/°C, respectively. The total enthalpy variation is $\Delta H_h = \Delta H_1 + \Delta H_2 =$ 16000+18000=34000 kW. The interval between the target and supply temperatures is divided in three subintervals: 60-90, 90-180 and 180-220 °C. In each interval the overall *CP* can be obtained simply by adding the *CP*'s of the active streams. For instance, in the first and third interval there is only **hot1**, so that *CP*=100. In the second interval both **hot1** and **hot2** are active, therefore $CP = CP_1 + CP_2 = 300$. Thus, each change in the slope of the composite curve corresponds to the entry or to the exit of a stream. Slope close to zero (horizontal position) means very high *CP*, as in the case of phase transitions.

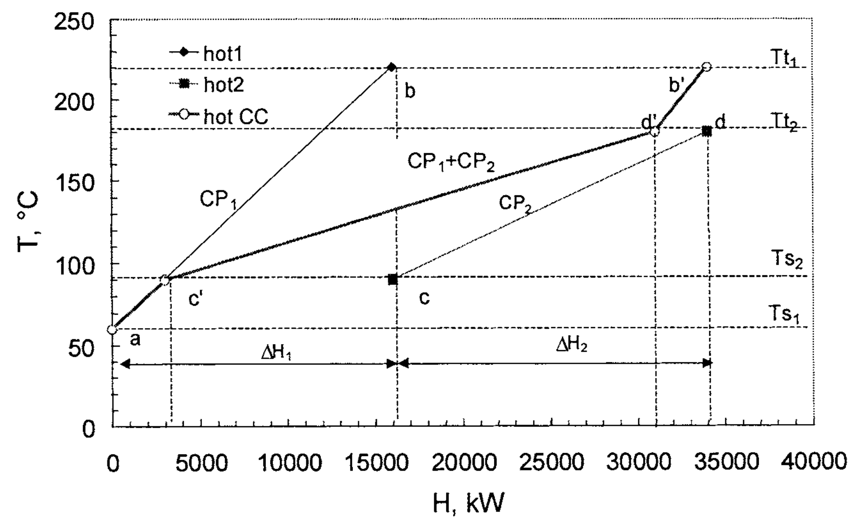

Figure 10.7 Construction of a hot Composite Curve

The same method can be applied to draw the *cold Composite Curve* (Fig. 10.8). There are three temperature intervals, 50-130, 130-150, and 150-180 °C, where CP_3=150, CP_3+CP_4=550 and CP_4=400. The enthalpy is $\Delta H_c=\Delta H_3+\Delta H_4$= 15000+20000=35000 kW.

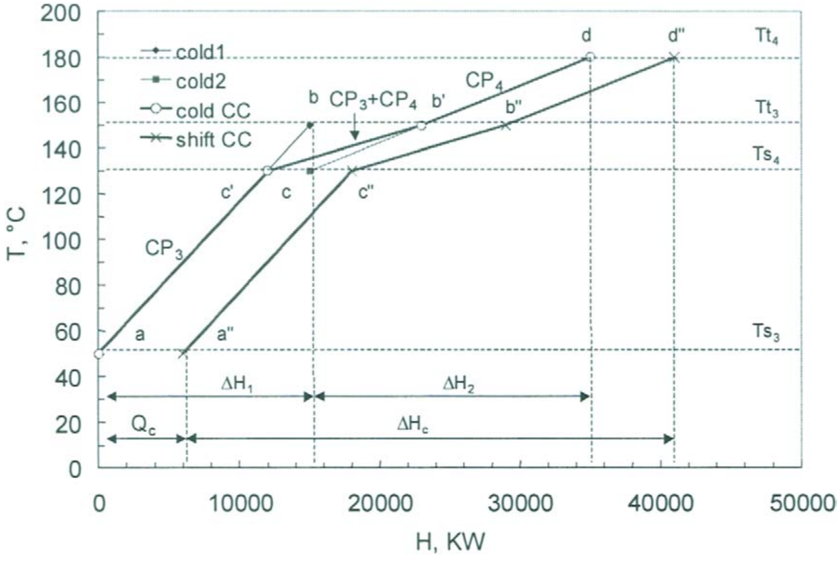

Figure 10.8 Construction of a cold Composite Curve

Both composite curves can be plot on the same diagram (Fig. 10.9). The hot CC may keep the original position. The cold CC shifts to the right by adding an amount of heat such to achieve ΔT_{min}. For ΔT_{min}= 10 °C Q_c= *6000* kW and Q_h=*7000* kW. The Pinch is situated between 130 and 140 °C.

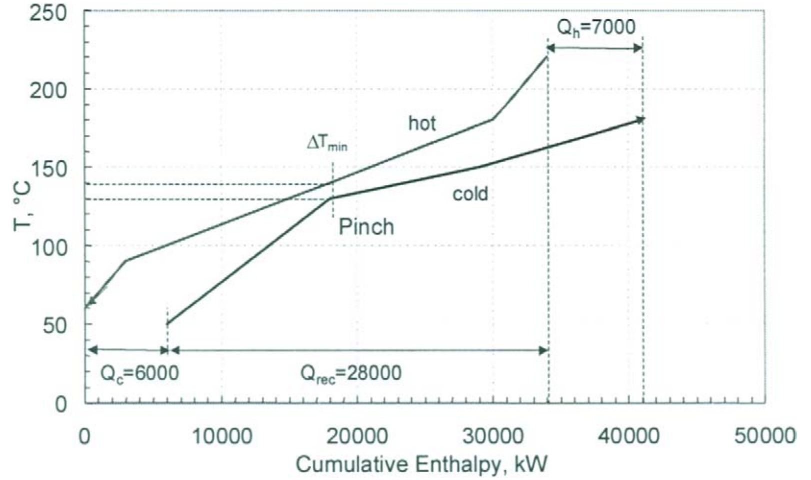

Figure 10.9 Composite Curves

In this way, the graphical representation has identified two fundamental elements of a heat integration problem:

1. Minimum temperature approach at Pinch, ΔT_{min}.
2. Minimum Energy Requirements (MER) as utility targets for heat recovery.

MER and ΔT_{min} are interdependent as illustrated in the Fig. 10.10. If ΔT_{min} is set to 15 °C, the hot CC keeps the same place, while the cold CC shifts to the right. One gets graphically Q_c=7500 and Q_h=8500 kW. The Pinch is located at 130-145 °C. Note that both utility requirements have increased with 1500 kW. In the first case the heat available for recovery was 28000 kW, while in the second case 26500 kW. Hence, increasing ΔT_{min} makes necessary more utilities and diminishes the energy saving.

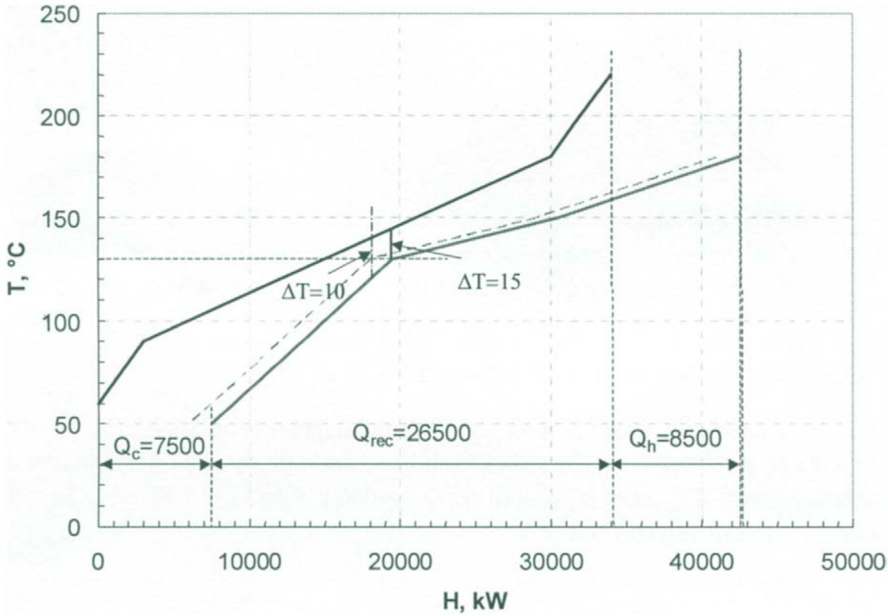

Figure 10.10 Shifting the composite curves modifies ΔT_{min} and utility targets

Problem Table algorithm

When investigating the heat integration between hot and cold streams available in a temperature interval, we must ensure that the driving force is at least equal with ΔT_{min}. Linnhoff and Flower (1978) solved elegantly this problem by means of a method designated by *Problem Table* algorithm.

Firstly, the temperature scale is modified such to accommodate a minimum driving force ΔT_{min} (Fig. 10.11). Hot streams are represented on the left scale. Cold streams are plotted on the right scale, where the temperature is shifted with ΔT_{min}, say by convenience with 10°C. Both hot and cold streams can be referred to *shifted temperature scale*, where the hot stream temperatures are moved down with $\Delta T_{min}/2$, and the cold stream temperatures shifted up with $\Delta T_{min}/2$.

Secondly, temperature intervals for heat integration are identified. In the above example, there are six temperature intervals. The first is delimited by the supply temperature of **hot1** (220 °C), as well as by the target temperature of **cold2** (180 °C). The shift temperatures are 215 °C and 185 °C, corresponding to an interval ΔT=30 °C. The next interval appears because of the entry of stream **hot2**. The shift temperature varies from 185 °C to 175 °C. The third interval corresponds to the exit of **cold1**, etc.

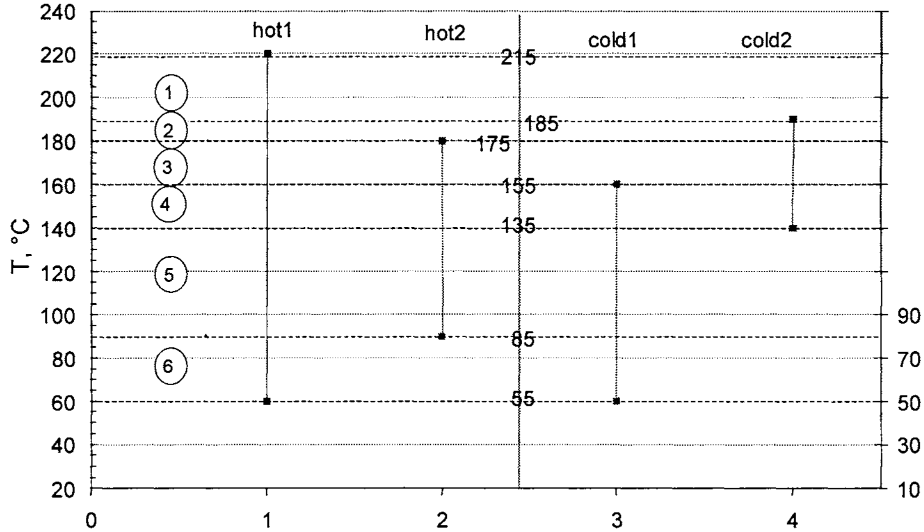

Figure 10.11 Shifted temperature scale

The next step is the set-up of the 'Problem Table'. Figure 10.12 gives a sample from an EXCEL™ workbook. The first three columns contain hot and cold stream temperatures, as well as shifted temperatures. Column four gives the temperature intervals. Column five gives the ΔT_{in}'s. Columns five to nine indicate the active streams necessary for *CP* calculation: zero for inactive streams, -1 for hot active streams, and 1 for cold active streams. This information can be related to the Table 10.1 for computing the *CP's* of each interval, as given in the column CP_{in}. Finally, the enthalpy variation of each interval is found by multiplying each *CP* by ΔT_{in}.

The last column gives a qualitative message: negative value signifies heat surplus, positive value means deficit. Excess heat can be removed by cold utility, while deficit heat can be covered by hot utility. Obviously, this approach would mean poor use of energy. Instead, we should try to combine the heat content of different temperature intervals. Thus, the deficit of cold streams can be covered with the surplus of the hot process streams, and only the unbalanced amount by hot utilities. Finally, this strategy allows the identification of the maximum recoverable energy by process-process heat exchange, and of the minimum amount of hot and cold utilities needed to cover the heat balance. It is important to note that the condition of a minimum temperature approach between coupled hot and cold streams must be fulfilled, but only in a restricted zone, of the Pinch. Far from the Pinch, the temperature difference could be larger than ΔT_{min}.

Thot	Shift T	Tcold	Interval	ΔT_{in}	CP_1	CP_2	CP_3	CP_4	CP_{int}	Delta H	Heat
220	215	210									
			1	30	-1	0	0	0	-100	-3000	surplus
190	185	180									
			2	10	-1	0	0	1	300	3000	deficit
180	175	170									
			3	20	-1	-1	0	1	100	2000	deficit
160	155	150									
			4	20	-1	-1	1	1	250	5000	deficit
140	135	130									
			5	50	-1	-1	1	0	-150	-7500	surplus
90	85	80									
			6	30	-1	0	1	0	50	1500	deficit
60	55	50									

Figure 10.12 Problem Table algorithm

The coupling of intervals can be found by organising the flow of heat in a cascade manner. In a first trial (Fig. 10.13-left) we assume that no heat is transferred from the hot utility. The first interval has an excess of 3000 kW that can be transferred to the second one, resulting in a net enthalpy flow of 0-(-3000)=3000 kW. The second interval has a deficit of 3000 kW, so that the net heat flow after this interval becomes zero. Consequently, the first and second intervals match perfectly each other. The third interval has a deficit of 2000 kW, and at its exit a net heat flow deficit of 2000 appears, which would increase at –7000 kW on the fourth interval. Clearly, a negative heat flow cannot be cascaded further. Therefore, this solution is not feasible.

In a second trial we may consider a hot utility load of 7000 kW that could compensate the deficit noted before. The result of cascading heat flow can be seen in the Figure 10.13 right. After the first interval the net heat flow is 7000-(-3000)=10000 kW. The second interval delivers 10000-3000=7000 kW. The cascade of heat flow goes on until the lowest interval is reached. As it can be seen, now all the net flows but one are positive. The location where the heat flow is zero is the *Pinch Point*! The shifted temperature is of 135 °C, or 130-140 °C expressed in real stream temperatures.

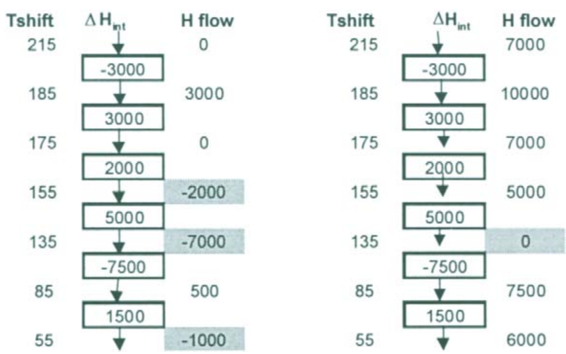

Figure 10.13 Cascade diagram

Grand Composite Curve

With the information issued from the Problem Table, we can draw the Grand Composite Curve (GCC). A composite curve is obtained by plotting the heat content of each temperature interval (*x*-axis) against shifted temperature scale (*y*-axis). As mentioned, the shifted temperature scale takes into account a difference of ΔT_{min} between hot and cold streams. Figure 10.14 presents *GCC* corresponding to the streams given in Table 10.1 for ΔT_{min}=10 °C. The following observations are of interest:

1. The Pinch Point divides the diagram in two regions, above and below the Pinch, in which the heat recovery problem can be analysed separately.
2. Above the Pinch there is need only for hot utilities. Below the Pinch only cold utilities must be used.
3. The 'pockets' of the grand composite curve designate possible heat recovery by process-process exchange.

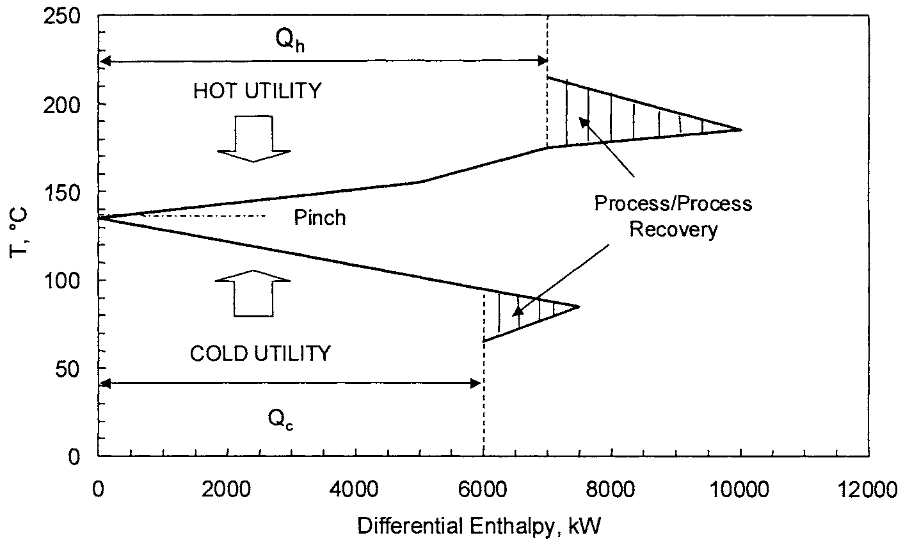

Figure 10.14 Grand Composite Curve

10.2.2 Pinch Point Principle

From the above example we learned that the Pinch separates the space of heat recovery into distinct regions, as represented in Fig. 10.15. The original problem is decomposed in two sub-problems, above and below the Pinch. Consequently, a *Pinch Point principle* can be formulated as follows (Linnhoff and Hindmarsh, 1982):

1. Do not transfer heat across the Pinch.
2. Do not use cold utility above the Pinch.
3. Do not use hot utility below the Pinch.

If there is heat flow across the Pinch, then the energy consumption is higher than minimum necessary. Both hot and cold utility consumption will increase with the same amount XP above the minimum targets. The Pinch equation is:

$$\text{Actual Energy (A)} = \text{Target (T)} + \text{Cross-Pinch Energy flow (XP)} \quad (10.3)$$

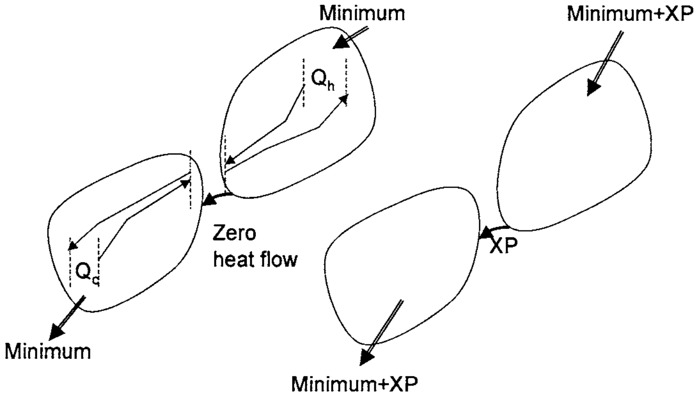

Figure 10.15 Pinch Point Principle

Thus, transferring heat across the Pinch is a double loss in energy. However, during the effective design of the heat exchanger network, the initial targets must be revised to accommodate constrains, as for example smaller number of units, or some imposed loads. The actual energy consumption could increase above the minimum targets, but the designer should try to keep the pinch violation as small as possible.

The temperature approach ΔT_{min} is a key variable in PPA. Recommended values are 10 to 20 °C in petrochemical industry, 20 °C in refining, but only 5 °C in cryogenics. More rigorously, ΔT_{min} can be determined by a *super-targeting* procedure, which performs an optimisation between the costs of utilities and of capital, as explained by the Fig. 10.2. Beside stream data, supplementary information is needed as:

- Type, temperature and costs of utilities.
- Partial heat transfer coefficients of streams (or of segments) and of utilities.
- Maximum heat transfer area of the heat exchangers.

As mentioned, because the energy targets increase linearly with ΔT_{min}, the cost of utilities follows the same trend. On the contrary, the capital cost decreases non-linearly with ΔT_{min}. Note that the cost function exhibits a jump when the number of units changes. Therefore, it is important to keep in mind that reduction in the number of units is by far more important for overall costs optimisation than the incremental reduction of heat transfer area.

10.2.3 Balanced Composite Curves

In balanced composite curves (Fig. 10.16) both utility and process streams are considered as usual streams. When more than one hot or cold utility is used, each supplementary utility introduces a new pinch. Hence, we may have a main process Pinch and several utility Pinches. The selection of utilities may be guided by some heuristics. The simplest recommendations are:

1. Add heat at the lowest temperature level relative to the process Pinch.
2. Remove heat at the highest temperature level relative to the process Pinch.

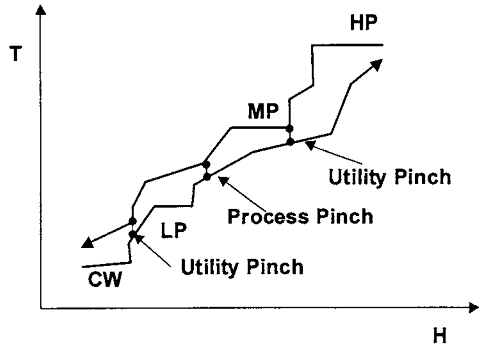

Figure 10.16 Balanced composite curves

10.2.4 Stream segmentation

The hypothesis of constant *CP* is the fundamental assumption in Pinch Point Analysis. In fact, the stream enthalpy is not strictly a linear function of temperature. This is particularly true for mixtures undergoing phase change. In this case we should decompose a *T-H* curve in segments of constant *CP*'s by an operation called *stream segmentation*. Let's examine the vaporisation/condensation of a pure component. We may define a virtual *CP* by considering a small temperature change, say 1 K (Fig. 10.17). Thus, the phase transition of a pure component stream may be represented by a (large) horizontal segment. In the case of a mixture we, can divide the stream in segments on which the *CP*'s are constant. Note that the segmentation has to be done always on the 'safe side', meaning that the segments should be placed below a hot stream, or above a cold stream (Fig. 10.18).

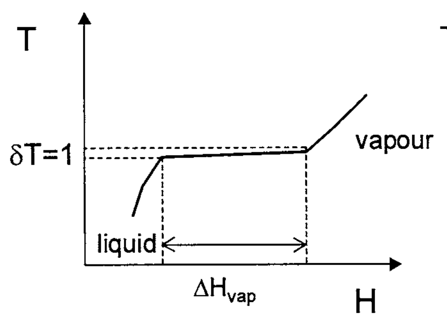

Figure 10.17 Phase transition

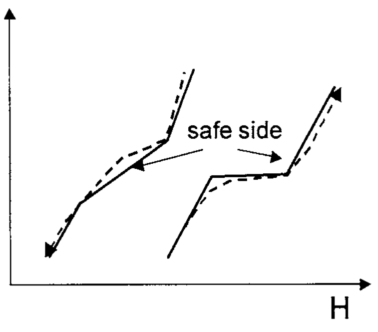

Figure 10.18 Stream segmentation

10.2.5 Data extraction

The selection of streams is determinant for efficient heat integration. Most of the studies are based on results issued from a process simulator. Automatic transfer of data to the Pinch software is a current feature of many simulation systems, commonly called 'data extraction', which sometimes is assisted by an expert system. However, the user should be aware about possible problems in heat integration caused by inappropriate stream extraction, even if it is computer-assisted. Hereafter some recommendations:

a. Check the accuracy of the thermodynamic model used for enthalpy calculation. Equations of state models often underestimate the enthalpy of phase transition.
b. Consider the plant decomposition in sections. The proximity of streams selected for integration is an important practical constraint. Furthermore, short path of the energy avoid time delays in control.
c. List carefully the process constraints. These must include controlled temperatures, as for example before reactors, separation flashes and distillation columns, for which heaters (furnaces) or coolers (refrigerant driven) are necessary. Some imposed heat exchangers may be eliminated from analysis.
d. 'Implicit' duties unimportant in simulation could become significant for heat integration, as those included in flashes.
e. Evaluate carefully the integration of chemical reactors, particularly for high exothermic reactions. Avoid the feedback of energy that might lead to multiple steady states and unstable behaviour.
f. In a first attempt do not consider the condensers and reboilers of the distillation columns, except if there is a particular incentive to save utilities by using process streams. These duties have a high energetic potential. However, the heat integration of separators with other process streams is limited by serious constraints on controllability. Use the plant or site utility system for such exchange.

10.2.6 Targets for energy and capital

As it was previously demonstrated, the Pinch Point principle enables to determine in a simple manner the load and cost of utilities for a given ΔT_{min}. These are minimum requirements that become targets in an energy saving project. The capital cost forms the other part of the targeting procedure. This is controlled by the following elements: equipment type, number of units, heat exchange area, number of shells, material of construction, pressure and pressure drop, piping and equipment layout.

Number of Heat Exchange Units

It can be demonstrated (see later in this chapter) that the number of the heat exchangers involving S streams, including utilities, is given by the simple relation:

$$N_U = S - 1 \tag{10.4}$$

If the Pinch is disregarded, then the above formula gives the total minimum number of units. For example for the streams given in the Table 10.1 we have N_U=(4+2)-1=5. If the Pinch is considered, above the Pinch N_U=(3+1)-1=3, while below the Pinch N_U=(4+1)-1=4, in total 7 units. The difference is explained by the existence of two *loops*. The subchapter 10.3 will develop this topic.

Heat Exchange Area

Heat exchange area can be estimated from the balanced composite curves. The simplest is adopting the hypothesis of counter-current, as well as vertical heat transfer driving force. The total area $A_{1\text{-}1}$ is obtained by summing the differential heat-exchange area in different temperature intervals, as expressed by the relation:

$$A_{1-1} = \sum_{k}^{intervals} \frac{1}{\Delta T_{LMk}} \left(\sum_{i}^{hot} \frac{q_i}{h_i} + \sum_{j}^{cold} \frac{q_j}{h_j} \right) \qquad (10.5)$$

In the above relation q_i or q_j are enthalpy variations over a temperature interval with a mean-logarithmic temperature difference ΔT_{LMk}. The notation h_i or h_j designates partial heat transfer coefficients, including fouling. Note that ΔT_{min} for process-utility heat exchangers may be different than for process-process heat exchangers.

Number of Shells

The number of shells can be determined simply by dividing the target of total area by the area of the selected type of heat exchanger. Shell-and-tube heat exchangers are sill the most used in process industries. The simplest is 1-1 type (1 shell pass, 1 tube pass), where the relation (10.5) is valid. There are situations when multi-pass heat exchangers are more advantageous, the most common being of type 1-2 (1 shell pass, 2 tube passes). The deviation from purely counter-current flow can be accounted for by means of the F_T factor. A practical value is F_T=0.9. Values lower than 0.75 should be avoided. The overall heat exchange area can be computed with the relation:

$$A_{1-2} = \sum_{k}^{intervals} \frac{1}{\Delta T_{LMk} F_{Tk}} \left(\sum_{i}^{hot} \frac{q_i}{h_i} + \sum_{j}^{cold} \frac{q_j}{h_j} \right) \qquad (10.6)$$

The calculated area is increased by an oversizing factor of 10-20%. Then the number of shells can be found simply by knowing the area of single shell. The manufacture of shell-and-tubes heat exchangers is regulated by standards, the most known being the TEMA standards. Chapter 16 gives some guidelines.

Capital cost law

Simple cost law can be used to estimate the capital of a heat exchanger, such as:

$$Capital = A + B(Area)^{n} \qquad (10.7)$$

The constants *A, B,* and *n* are function of the type of exchanger, pressure and material. The installed costs include insulation, piping and instrumentation. A usual assumption is that the network heat transfer area is divided evenly in a number of units, constrained by the maximum shell area. Note that the capital costs must be aligned with the energy costs on annual basis. The simplest way is the assumption of a payback time, usually three years.

The above method gives reasonable results within 10% errors providing that the variation of the heat transfer coefficients is less than an order of magnitude (Smith, 1995). The search of preliminary targets can be summarised as follows:

1. Screen design options in conceptual design reflected in alternative material and energy balances.
2. Try different utility options with implications in both energy and capital costs.
3. Start preliminary process optimisation.

Thus, the targeting procedure makes possible a rapid estimation of energy and capital targets. This idea can be extended for designing a complete heat exchanger network by decomposing the plant in subsystems, where local integration may be applied (Polley & Heggs, 1999). The reduced number of streams leads finally to simple but reliable solutions, even if these might be considered as sub-optimal.

EXAMPLE 10.1 ΔT_{min} and minimum energy targets

Determine the optimal ΔT_{min} and the targets for energy recovery with the streams listed in the Table 10.1. Consider as utilities cooling water at 20 °C and steam at 250 °C.

Solution.

1. Capital costs.

We use the values A=16000, B=3600, n=0.7 (Polley and Heggs, 1999), the cost being expressed in \$/year. The area will be estimated as 1-1 shell-and-tube heat exchangers. We assume that the process streams have h_i of 0.5 kW/m^{2}K, plus 2.0 kW/m^{2}K for cooling water and 4 kW/m^{2}K for steam, all values including fouling resistances. Thermal effectiveness is 0.9. Maximum exchanger size is 500 m^2/shell. In addition we consider a payback time of 3 years and interest rate of 7.5%.

2. Utility costs.

The prices of utilities can be expressed on annual basis, for instance in \$/(kWyear). From steam tables (Appendix F) at 250 °C the saturation pressure is 39.76 bar and the vaporisation enthalpy ΔH_v=1715.7kJ/kg. Consequently, the ton of steam has 1.716 GJ. The energy unit (kWyear) is equivalent with 1kJ/s×3600×8000= 28.8 GJ. Thus, the annual steam cost is 28.8/1.715=16.78×(cost of 1 ton steam). A price of 10 \$/t gives 167.8 \$/(kW year). This value might be compared with 0.0218 \$/kWh=174.4 \$/(kWyear) reported in reference. The price of water is 0.0015 \$/kWh=12 \$/(kWyear). However, in this example we consider the following prices: for steam 125 \$/(kWyear), and for water 12.5 \$(kWyear). Figure 10.19 presents the results of targeting obtained with SUPERTARGET™.

In this case the optimum ΔT_{min} is between 9 and 10 °C. The reader can check the values found for the energy targets, and verify that they increase linearly with $\Delta T_{min.}$ The capital costs decrease non-linearly.

This example gives the opportunity to draw some useful remarks:

- Targeting is sensitive to the cost data, particularly to the most expensive utility and to the exponent in the capital cost relation.
- In many cases when only area is variable the optimum is almost flat. Contrary, the objective function shows a sharp decrease by reducing the number of units.

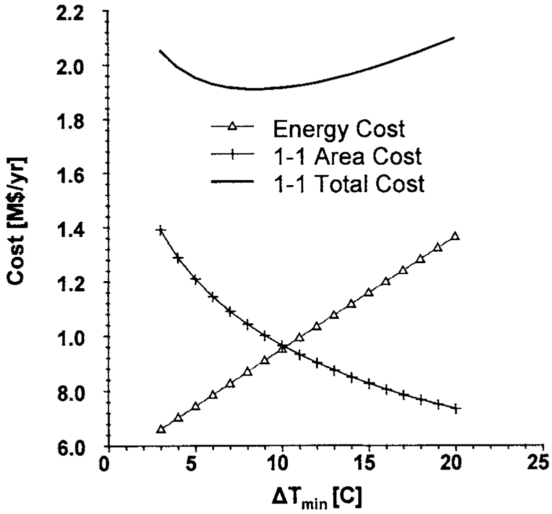

Figure 10.19 Targeting of ΔT_{min} by minimisation of capital and utility costs

10.3 PLACEMENT OF UTILITIES

This subchapter emphasises the advantage of selecting utilities well ahead the detailed design of heat exchangers. Again, a number of design decisions with great impact on the process economics can be taken at the targeting level.

10.3.1 Threshold problems

Not all heat recovery problems have a Pinch. Sometimes only hot or cold utility is required. Figure 10.20a illustrates a typical situation. Initially (right case), the analysis indicates a pinched problem with both hot and cold utilities. By lowering ΔT_{min} the cold composite curve shifts to the left up to a position where there is no need for hot utility. The value of ΔT_{min} when this situation occurs is called *threshold*. Lowering ΔT_{min} below the threshold leads to the need of a second cold utility, this time at the hot end. Similarly, a problem with both hot and cold utility can turn into a problem that needs only hot utility below a threshold value of ΔT_{min} (Figure 10.20b). The above situations can be understood since utility requirements vary proportionally with ΔT_{min}. Hence, a problem apparently with both cold and hot utilities might hide a threshold problem.

Below the threshold ΔT_{min} the cost of energy remains constant. As a result, the trade-off between capital and energy can be considered only at ΔT_{min} values equal or above the threshold. Because the occurrence of utility at the opposite end increases the number of units, the probability of optimum near ΔT_{min} at threshold is more likely.

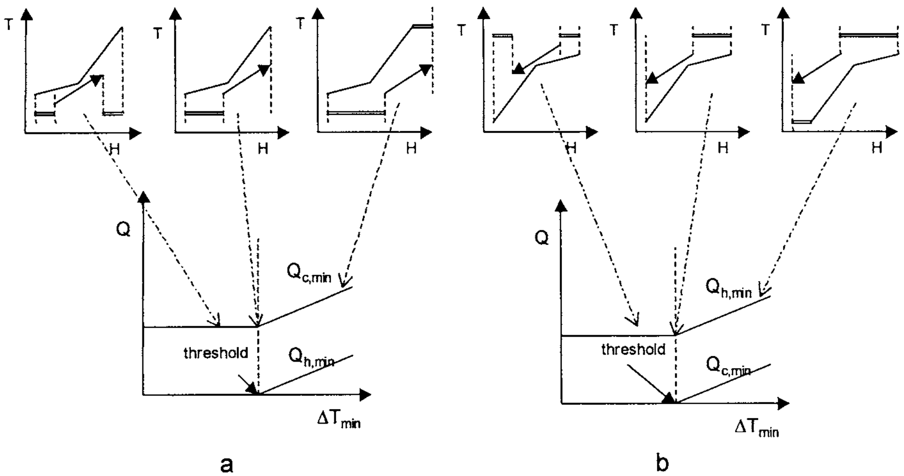

Figure 10.20 Threshold problems

Note that a threshold problem may turn into a pinch problem when multiple utilities are used. Figure 10.21 gives a graphical explanation. In Fig. 10.21 left the cold utility is covered by both cooling water (CW) and steam generation. A new utility Pinch occurs at steam-generation side. In Fig. 10.21 right, only hot utility is required. If the utility is covered by both high-pressure (HP) and low-pressure (LP) steam, then a new Pinch occurs at LP-process side. The only utility above this Pinch is HP steam. The design of HEN in a threshold problem keeps the same rules as for a normal pinch problem.

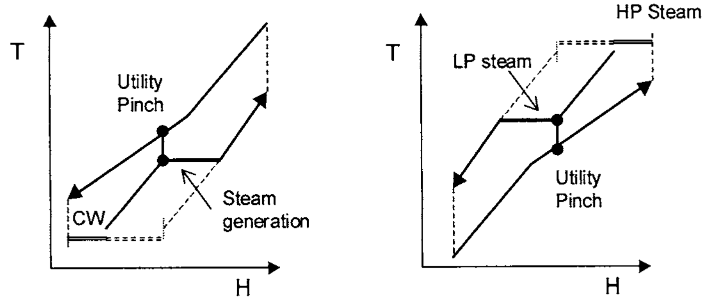

Figure 10.21 Threshold problem turned into a problem with utility Pinch

EXAMPLE 10.2 Threshold problem

Examine the targeting of the following streams:

	T_s, °C	T_t, °C	Duty, kW	*CP*, kW/°C	h_i, kW/m²K
hot1	220	60	16000	100	0.5
hot2	180	90	18000	200	0.5
cold1	40	150	38500	350	0.5

Utility and cost data are the same as for Example 10.1.

Solution. We use SUPERTARGET™ for targeting by varying ΔT_{min}. The plots indicate a threshold problem. Figure 10.22-left displays the utility consumption. Up to a $\Delta T^*_{min} = 20$, the threshold, there is no need for cold utility. Hot utility remains constant at 4500 kW. For $\Delta T > \Delta T^*_{min}$ a certain amount of cold utility is necessary, proportionally with the difference $\Delta T - \Delta T^*_{min}$. For example, for ΔT_{min}=25 °C Q_h=5000 kW and Q_c=500 kW, the difference remaining at 4500 kW.

Figure 10.22-right illustrates the costs of capital and energy, as well as the total cost. Capital cost is calculated as purely counter-current. Up to threshold both capital and energy costs are constant. There are three units: two process/process heat exchangers, plus a heater. After this point, a sudden increase in capital occurs due to a new unit, a cooler. From this point on, the problem is pinched. Capital cost decreases with ΔT_{min} because of larger driving force. Hence, it is advantageous to work below the threshold. HEN design will be solved in the Example 10.4.

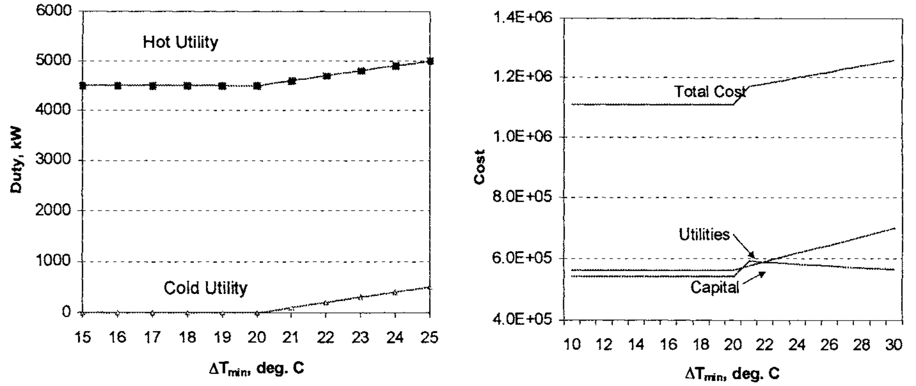

Figure 10.22 Targeting in the case of a threshold problem

10.3.2 Multiple utilities

Several hot or cold utilities may be used in a heat recovery project. GCC is the appropriate conceptual tool. Let's review the heat integration of the streams presented in Table 10.1. The same hot load as in Fig. 10.14 can be shared between two steam levels: high-pressure (HP) and low-pressure (LP) steam. In the GCC the solution is simple represented by horizontal segments placed at temperatures corresponding to their pressures, as in Fig. 10.23 for three steam levels. This feature makes possible to specify exactly the amount required by each utility. Simple targeting can be applied to optimise their amount if the prices are significantly different.

Similarly, the cold utility can be split into cold water and other cold utilities, as brine solution or refrigerant. Rising low-pressure steam is another possibility of cooling at temperatures above 100 °C! In this case, boiling feed water (BFW) is used to recover a part of energy by preheating. LP-steam can be upgraded at higher temperature by thermal compression. Each additional utility above the highest and coldest utilities introduces a new utility Pinch. A minimum temperature approach is required for each.

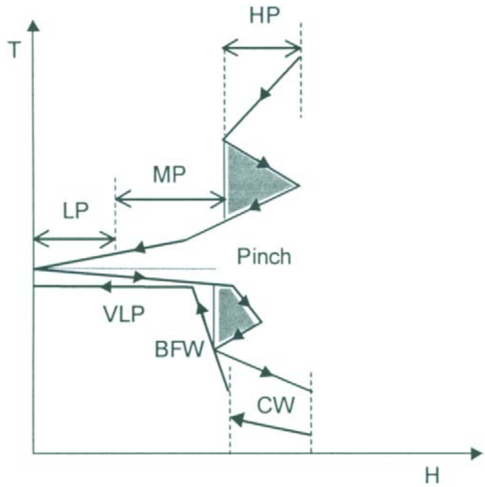

Figure 10.23 Multiple utilities

10.3.3 Variable temperature utilities

In this category we can consider flue gases, hot oil or other thermal fluids. The main problem is that the use of such utilities is more constrained with respect to the temperature level. Figure 10.24 illustrates two situations encountered when using flue gases for heating. Firstly, larger ΔT_{min} contribution utility-process must be assumed, say of 50 °C, because of poor heat transfer on the gas-side. Figure 10.24a presents the case when the constraint is the exit gas temperature. The graphical representation permits to visualise easily the stack losses. Increasing the theoretical flame temperature by air preheating or by low air excess can reduce the heat losses. Note that other factors as the Pinch can limit the flue gas temperature. This can be the process away from the Pinch, as illustrated by the Fig. 10.24b, or the dew point of the acid components in the gas stack. As an exercise the user may examine the use of hot oil as thermal agent.

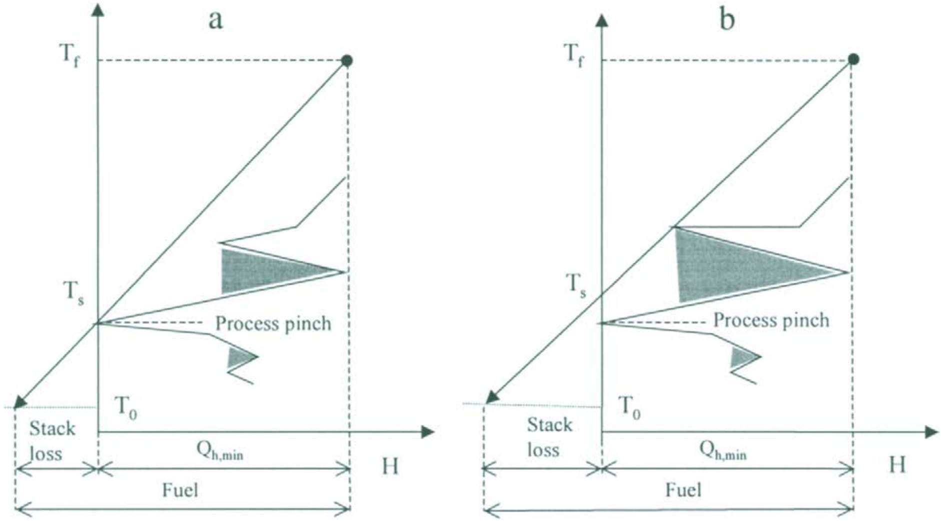

Figure 10.24 Flue gas as variable temperature utility. a) Constraint by process Pinch; b) limitations by a process away from the Pinch

10.4 DESIGN OF THE HEAT EXCHANGER NETWORK

The systematic procedure for designing the Heat Exchanger Network based on Pinch principle is designated as the *Pinch Design method* (Linnhoff et al., 1978, 1983). The methodology consists of the following steps:

1. Select streams for integration. Only streams useful for effective energy integration should be considered. Some simple rules could be mentioned:
   a. Examine the heat integration of reactors separately.
   b. In a first approximation do not consider reboilers and condensers.
   c. In the case of a larger flowsheet decompose the problem in subsystems, taking into account the proximity of streams.
2. Select utilities.
3. Estimate process/process saving and process/utility loads.
4. Construct Composite Curve and Grand Composite Curve. Identify process and utility pinches.
5. Determine targets for design: ΔT_{min}, Minimum Energy Requirements, number of units, capital and utility costs.
6. Construct the grid diagram.
7. Find the matches of heat exchangers by applying the rules of Pinch Design method.
8. Improve the design by eliminating small heat exchangers.

9. Optimise the Heat Exchanger Network.

The points 1 to 5 belong to the targeting procedure already presented. The points 6 to 9 form the core of the Pinch Design method that will be explained in the subsequent sub-chapters. Particularly the point 7 deserves more attention.

10.4.1 Topological analysis

Number of matches

It can be demonstrated that the minimum number of units (matches) N_E necessary to recover the energy between N_S process streams using N_U utilities is (Linnhoff, 1994):

$$N_E = N_S + N_U - 1 \qquad (10.8)$$

If loops are presents in the network then the number of heat exchangers is given by the formula:

$$N_E = N_S + N_U - 1 + \text{(loops)} \qquad (10.9)$$

Paths and Loops

The concepts of paths and loops are very useful for optimising a heat exchanger network. As noted, the application of the Pinch Design method generates redundancy in the number of units. Actually, reducing the number of heat exchangers can contribute more significantly in the cost saving than the incremental optimisation of the exchange area. Merging some units could violate the Pinch principle in the sense of increasing both hot and cold energy loads. In a number of cases an important reduction in capital may be obtained only with a marginal increase of energy above minimum requirements. This problem can be solved effectively by the approach explained below.

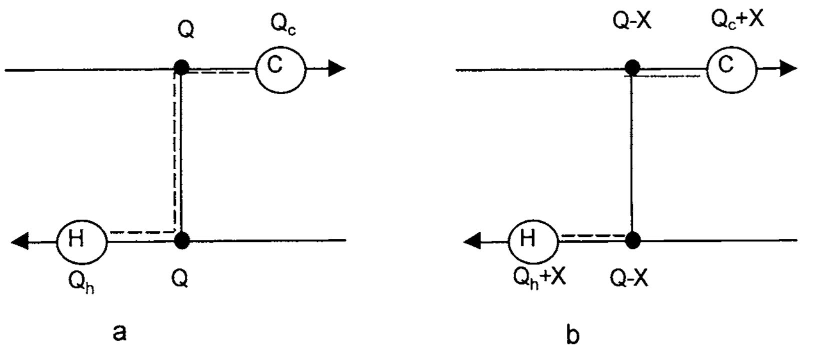

Figure 10.25 Concept of paths

Path means a physical connection through streams and heat exchangers for shifting energy between hot and cold utilities. Consequently, a path allows the modification of the temperature difference between the hot and cold streams. Figure 10.25 illustrates the idea. Initially the utility loads are Q_c and Q_h. In between there is a heat exchanger of duty Q_c (Fig. 10.25a). By rising Q_h with X units, the cold utility duty Q_c must rise exactly with the same amount. Consequently, the heat exchanger duty becomes (*Q-X*), as in Fig. 10.25b. The outlet temperature of the hot side will decrease. The same happens with the outlet temperature of the cold side. Thus, the temperature differences at both ends are enlarged. Note that the heat exchangers outside the path are not affected, but well the utility heat exchangers.

Loop is a closed trajectory passing through several heat exchangers (Figure 10.26). Note that a loop can link several heat exchangers with the same utility. Changing a duty with *X* modifies the duties of the other exchangers with exactly the same amount, because conservation of energy. Setting the duty to zero eliminates the heat exchanger. The operation will change the temperatures of the units involved in the loop, and might lead to infeasible temperature profiles. Feasible ΔT can be restored if the loop is connected with both hot and cold utilities through a path. Example 10.4 will illustrate the approach, but after learning how to perform matches.

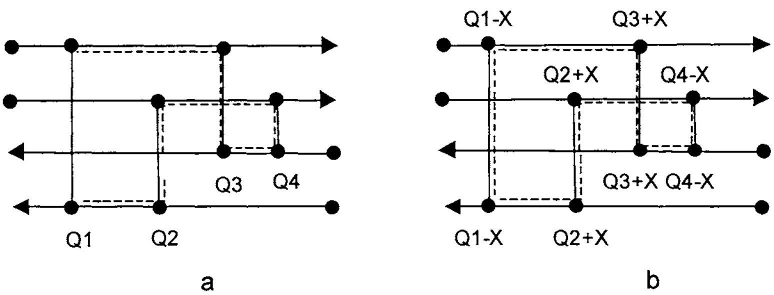

Figure 10.26 Concept of loops

10.4.2 HEN design in the grid diagram

The design of the Heat Exchanger Network takes place in the balanced grid diagram. This means that the utilities have been placed on the Grand Composite Curve. As illustrated by the Fig. 10.3, the hot streams run from left to right at the top, and cold streams run counter-currently at the bottom.

The Pinch split the diagram in two regions: above (at the left) and below (at the right) the Pinch. A vertical 'bubble headed' stick linking two streams represents a heat exchanger. Temperature and/or duty and area are also normally displayed.

The design starts at the Pinch, where the heat transfer is the most constrained. The match procedure has to respect some feasibility rules. Remember that in this context *CP* means (flowrate)x(specific heat capacity).

For a match above the Pinch, the following heuristic has to be respected:

$$CP_{hot} \leq CP_{cold} \tag{10.10}$$

Intuitively, the rule can be justified by the fact that above the Pinch there is need only for hot utility, such that the *CP*'s of cold streams must be greater than the *CP*'s of hot streams. A more accurate reason can be found in the fact that the temperature difference

(T_h-T_c) at the end looking to the Pinch is always smaller, at most equal to the temperature difference on the other side. It is also clear why the above rule is not so strict for a match away from the Pinch.

Similarly, below the Pinch the following heuristic holds:

$$CP_{hot} \geq CP_{cold} \tag{10.11}$$

Finally, the following relation can capture both heuristics:

$$CP_{in} \leq CP_{out} \tag{10.12}$$

Thus, for a match close to the Pinch, *CP* of the incoming stream must be smaller that the *CP* of the outgoing stream.

EXAMPLE 10.3 Heat Exchange Network design

Consider the streams given in the Table 10.1. Develop the Heat Exchanger Network in a grid diagram for Minimum Energy Requirements.

Solution. Figure 10.27 presents the grid diagram, on which stream supply and target temperatures, as well as the *CP*'s are marked. In Example 10.2 the Pinch was located at 130-140 °C for ΔT_{min}= 10 °C. We recall that the heat loads of streams were:

hot1	ΔH_1=100×(220-60)=16000	**hot2**	ΔH_2=200× (180-90)=18000
cold1	ΔH_3=150× (50-150)=-15000	**cold2**	ΔH_4=400× (130-180)=-20000

The targeting procedure found Q_h=7000 and Q_c=-6000 units. The process-process heat exchange can recover a maximum of 28000 units.

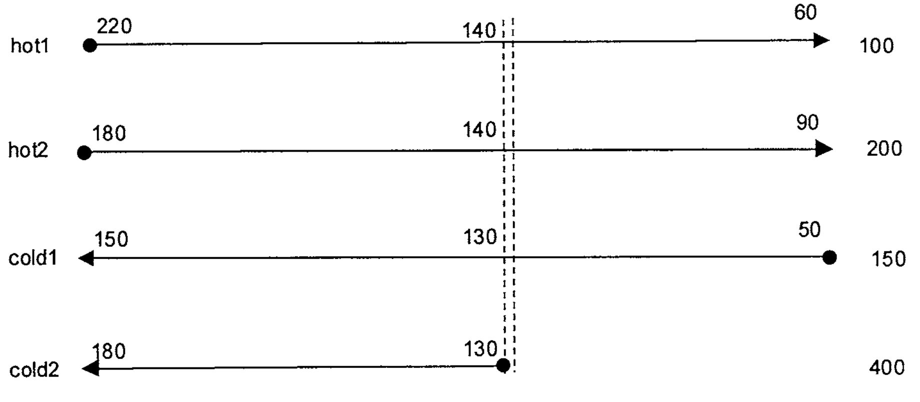

Figure 10.27 Grid diagram for Example 10.3

a. Region above the Pinch.

Figure 10.28 illustrates the approach. The investigation begins near the Pinch, keeping in mind the rule $CP_h \le CP_c$. Matches that could tick-off streams completely are preferred. Let's consider firstly the streams **hot1** and **cold1**. The match rule is fulfilled. Moreover, the stream **cold1** is completely recovered. Hence, the first match **E1** looks as follows:

E1	*CP*	*T'*	*T''*	ΔT_{stream}	Duty
Hot side	100	170	140	30	3000
Cold side	150	150	130	20	3000
ΔT		20	10		

Note that at the cold-end facing the Pinch, $\Delta T''=\Delta T_{min}$=10 °C, while at the hot-end the temperature approach is sensible larger. Similarly, we can take the second match **E2** as **hot2/cold2**, because CP_h=200 < CP_c=400. Again, the whole stream **hot2** is recovered. Because duty is Q_2=400×(150-130)=8000 units, the exit temperature of **hot2** is 140 °C. The third match takes the remaining of **hot1** with **cold2**. *CP* rule is respected, CP_h=100 < CP_c=400. Heat balance gives Q_3=100×(220-170)=400×(162.5-150)=5000 units. Because this match is far from Pinch, the temperature approach is larger than ΔT_{min} at the both ends. Finally, to close the heat balance we must place a heater on the stream **cold2**. The total enthalpy is ΔH_4=400×(180-130)=20000, and the heater load becomes Q_4=20000-(8000+5000)=7000 units. Summing up, there are four units above the Pinch.

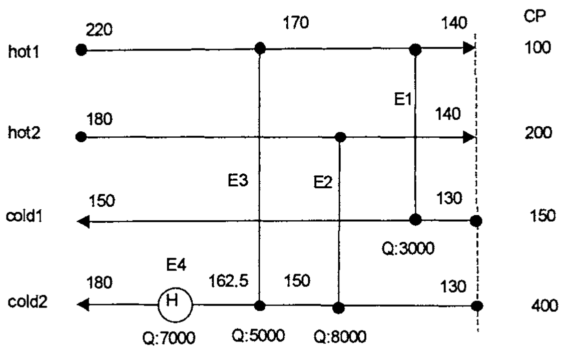

Figure 10.28 HEN above the Pinch

b. Region below the Pinch

The graphical construction of the network is given in Fig. 10.29. As before, we start at Pinch by keeping in mind that this time the matching rule is $CP_c \le CP_h$. Firstly, we try to tick-off the stream **hot1**. The only available stream is **cold1**. Unfortunately, in this case the feasibility rule is not respected, because CP_c=150 > CP_h=100. Therefore, we have to consider the other stream **hot2**. Now CP_c=150 < CP_h=200, the match is feasible. We may tick-off the residual load of the stream **hot2**, such the match duty becomes 10000. The heat balance of **E5** is Q_5=200× (140-90)=150× (130-63.3)=10000.

The remaining 2000 units of **cold1** can be matched against **hot1** in **E6**, even if the *CP* rule is not respected. This is because the previous match has lowered the temperature of the cold outlet corresponding to the hot inlet (located at Pinch). For this heat exchanger the heat balance is Q_6=100×(140-120)=150×(63.3-50)=2000.

Finally, the residual load of **hot1** is rejected to the cooler **E7** with the duty Q_7=6000 units. Note that the placement of the cooler may create another alternative, by exchanging the place with **E6**. This choice may be motivated by technological reasons. In this case the cooler Q_7 could be coupled with a closed-loop heating system using pressurised water that could work between 70 and 130 °C.

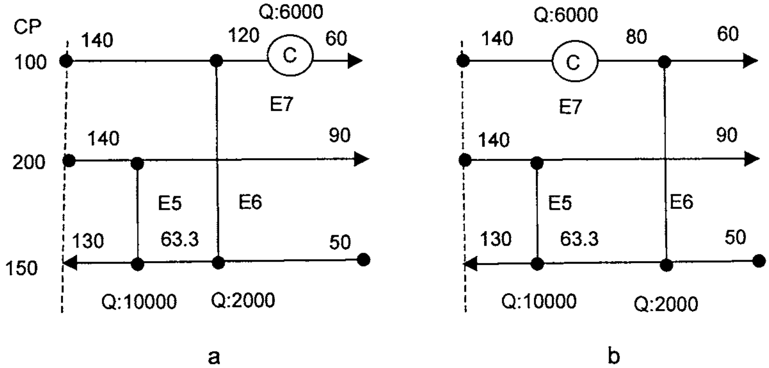

Figure 10.29 HEN below the Pinch

The Heat Exchanger Network assembling the subsystems is given in Fig. 10.30. This HEN corresponds to the maximum energy recovery thermodynamically possible for a given $\Delta T_{\min}$. However, this is not the most economical network, if the costs of both energy and heat exchangers are taken into account. The network can be further reduced.

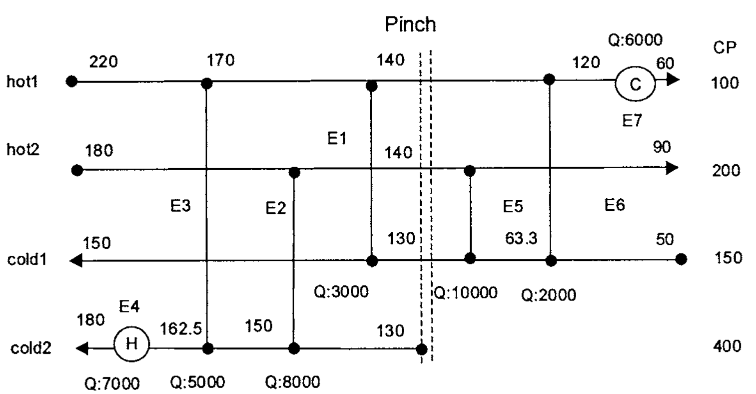

Figure 10.30 Overall Heat Exchanger Network (alternative 1)

Note that the solution is not unique. Figure 10.32 presents another alternative. Consider that the match **E5** (below the Pinch) involving **cold1** and **hot2** has a duty of only 4000. The remaining enthalpy of **cold1** is taken-off completely against **hot1** in the unit **E6**. Note that for this match the *CP* rule is not respected, since $CP1 < CP2$. This is possible if the hot end is far from the Pinch. The remaining part of **hot2** is finally cooled in **E7**. The cooler **E7** moves from the stream **hot1** to the stream **hot2**. The change in temperatures can be read on the figure.

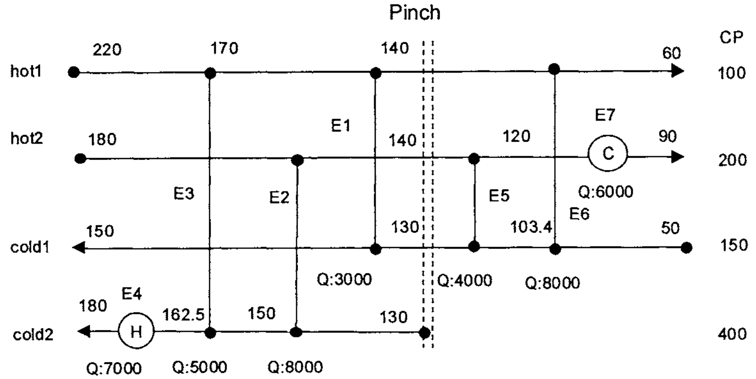

Figure 10.31 Overall Heat Exchanger Network (alternative 2)

10.4.3 Stream splitting

By stream splitting we can find practical solutions for cases where, apparently, the matches at Pinch are not feasible because the rules for *CP*'s do not hold. Some common situations are depicted in Figs. 10.32. The following explanations address the subsystem above the Pinch. Two situations will be examined:

a) The number of hot streams smaller than the number of cold streams.

In Fig. 10.32a-left there are two hot streams against one cold streams. Whatever *CP*'s might be, there are not sufficient cold streams, because above the Pinch we cannot use cold utility. Thus, in addition to *CP*'s rule a 'count rule' regarding the pairing of streams at Pinch must be satisfied. Above the Pinch, this rule is:

$$N_{hot} \leq N_{cold} \tag{10.13}$$

By splitting the cold stream in two segments two matches become possible. Moreover, the split must be done such to respect the CP's rule, as in Fig. 10.32a-right.

b) Count rule is satisfied, but not the *CP*'s rule.

Figure 10.32b-left illustrates this situation by one hot stream and two cold streams. The hot stream must be split in two parts such as the *CP*'s of hot streams becomes smaller than *CP*'s of the corresponding cold streams, as in the Fig. 10.32b-right.

It may appear also that the 'count rule' is satisfied, but the *CP*'s rule fulfilled only partially. In this case the largest cold stream should be split.

The analysis can be extended below the Pinch, where the 'count rule' becomes:

$$N_{cold} \leq N_{hot} \quad (10.14)$$

Considering that the hot and cold streams are *in* and *out* respectively, we may formulate the 'count rule' more generally as:

$$N_{out} \leq N_{in} \quad (10.15)$$

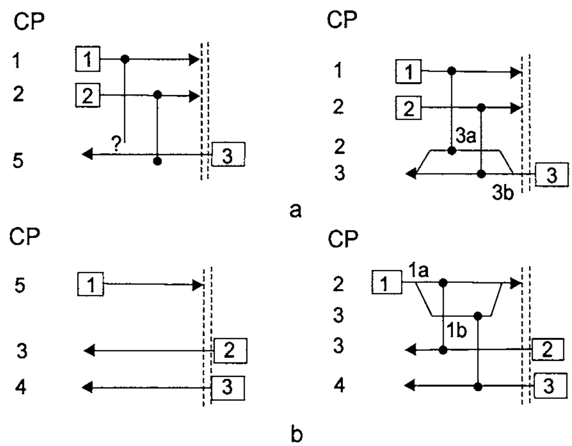

Figure 10.32 Principle of stream splitting at Pinch

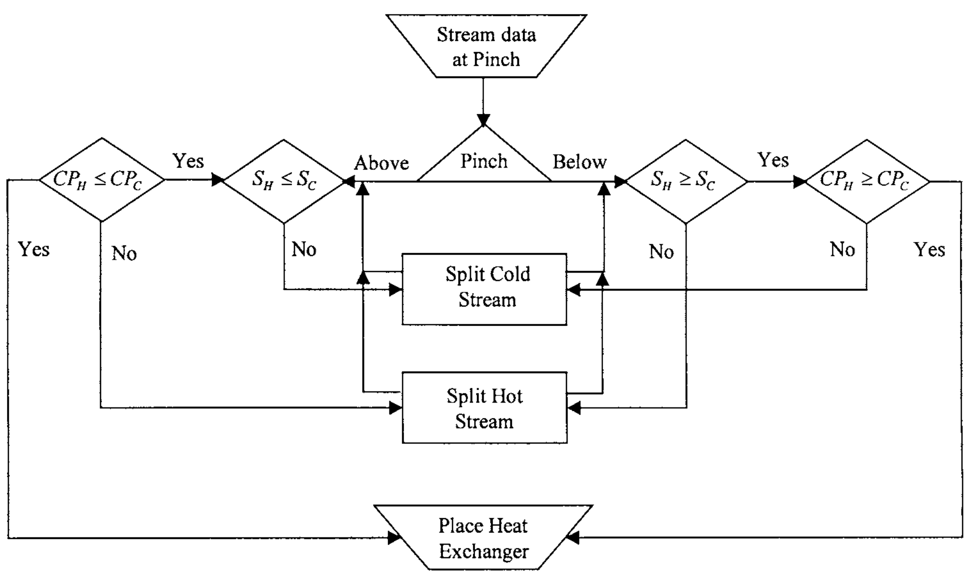

Figure 10.33 General HEN design procedure at Pinch

The above rules can be put together into a general design procedure at Pinch, as illustrated by the Fig. 10.33. Firstly, the stream count rule is checked. If not fulfilled, a first stream split is performed to balance streams, cold stream above the Pinch, or hot stream below the Pinch. Then the *CP*'s rule is checked for matches close to the Pinch. If not fulfilled, again stream splitting is executed, this time opposite to the first. Note that the above rules might be not respected away from Pinch.

EXAMPLE 10.4 Stream splitting

Develop a heat exchanger network for the streams given in the Example 10.2.

Solution. Figure 10.34 presents the grid diagram. We notice that there is only a cold stream, but three hot streams including the hot utility. There is no process Pinch. However, we may consider a utility Pinch on the cold side. In this case we select $\Delta T_{\min}$ =15 °C, a lower value that the threshold of 20 °C, as calculated in the Example 10.2. Hence, we are at the left of the cold utility Pinch.

We may apply the same design method by starting with the matches at Pinch. The *CP* rule is respected, because the *CP*'s of the **hot1** and **hot2** streams entering the Pinch are smaller than the *CP* of the **cold1** leaving the Pinch. However, the stream count gives a problem: there are not enough cold streams. Because two hot streams, we need at least one cold stream more. The stream **cold1** should be split in two branches proportionally with the duty of streams **hot1** and **hot2** used for matching. Hence, the split fractions are 16/34 and 18/34 respectively. After matching, a mixer is necessary to recompose the stream **cold1**. Figure 10.34 presents the matches, with three units, as predicted by the topological analysis.

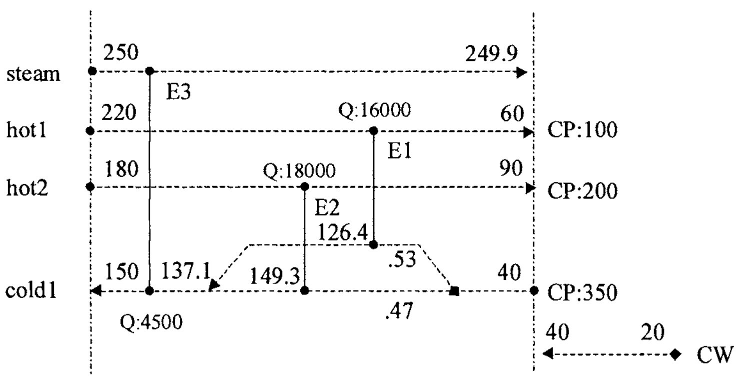

Figure 10.34 Example 10.4: streams and matches

10.4.4 Reducing the HEN

The synthesis of the heat exchanger network for Minimum Energy Requirements ensures the best energy recovery from thermodynamic point of view. However, taking into account the cost of heat exchangers could change the analysis substantially. The decomposition of the system in subsystem increases the number of units above those required by the first law analysis. The difference is given by the loops crossing the Pinch. Further reduction is paid by increasing both heating and cooling requirements. The trade-off depends on the costs of energy and of hardware in a particular situation. As a rule of thumb, the following two heuristics are recommended:

1. Break firstly the loop including the smallest heat exchanger.
2. Remove the unit with the smallest load in a loop.

The explanation is that the capital reduction for small units is by far more important for the same incremental area than for large units. For small heat exchangers the contribution of the fixed capital term, which accounts for installation, instrumentation, control, supervising and maintenance costs, can largely overcome the cost of area.

EXAMPLE 10.5 Reduction of the Heat Exchanger Network

The maximum energy recovery network found in the Example 10.3 has seven heat exchangers. First law analysis indicates a minimum number of five units because of four streams and two utilities. Two units could be removed. Identify the loops and redesign the network for $\Delta T_{\min} = 10$ °C.

Solution. The original network is presented in Fig. 10.35. The smallest unit **E6** has a duty of 2000. Visual inspection can identify a loop passing through the units **E1** and **E6**. The next step is to suppress the unit **E6** by shifting its load to **E1**. The unit **E1** becomes **E1a**, its duty going from 3000 to 5000. This operation keeps constant the enthalpy balance of the streams **hot1** and **cold1**, but modifies the temperatures.

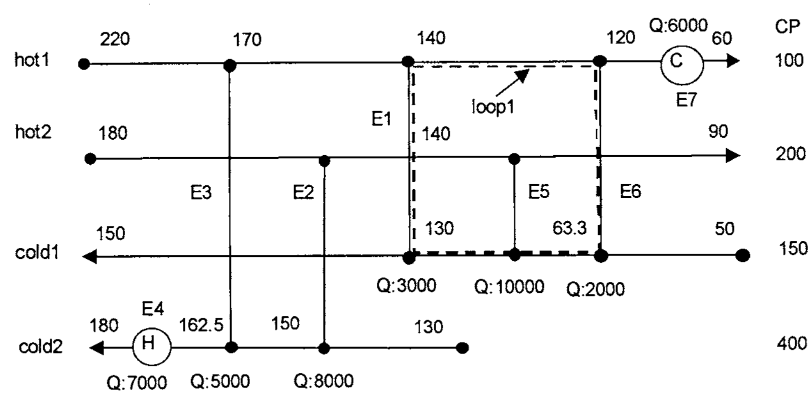

Figure 10.35 Network with minimum energy requirements

Figure 10.36 shows the situation after breaking the first loop. A simple heat balance around **E1** shows that the exit temperature of **hot1** changes from 140 to 120 °C, while the inlet temperature of **cold1** passes from 120 to 116.7 °C. The approach temperature at the cold-end becomes 3.3 °C, thus smaller than 10 °C. Restoring ΔT_{min} can be achieved by increasing simultaneously the utility loads, as depicted in Fig. 10.37. Indeed, there is a path linking the cooler **E7** with the heater **E4** through **E3**. It may be observed that by adding a duty of 1000 to **E7** will restore the exit temperature of **E1**a to 130 °C, while the temperature of the cold side remains unchanged. In this way a value of ΔT larger than 10 °C is achieved, such the match is feasible. Note that the duty of **E3** has been reduced with 1000, while the inlet temperature of **E3** passed from 162.5 to 160 °C. Hence, the reduction of a unit has been paid by reducing the amount of recovered energy by (1000/27000) ×100=3.7%.

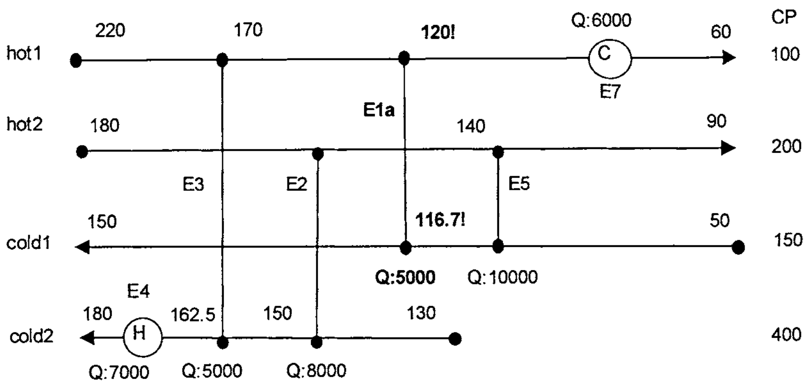

Figure 10.36 Breaking the first loop

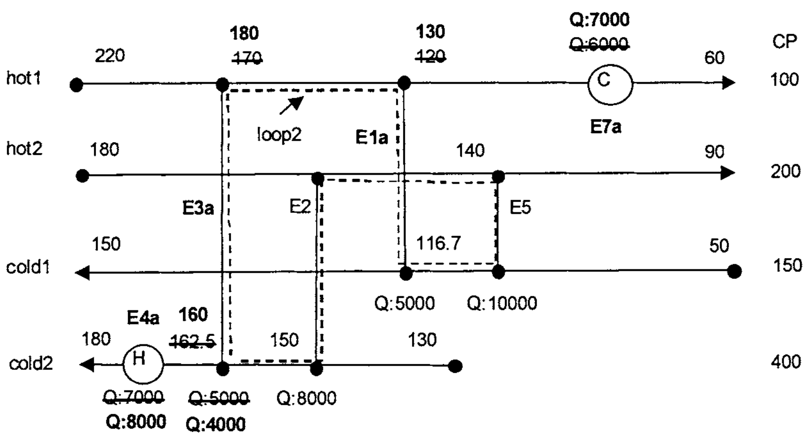

Figure 10.37 Restoring the temperature difference

The smallest unit is now the **E3a**. This is involved in a loop passing through the units **E3a-E1a-E5-E2**. We may combine **E3a** with **E1a**. Figure 10.38 shows the new temperatures after this operation. Note that the units **E2** and **E5** became **E2a** and **E5a**, because changed duties. The reader can check that the enthalpy balance is conserved. It may be seen that an infeasible temperature difference appeared at the cold-end of **E2a**, such as ΔT became –10 °C! For restoring it an increase in utilities is needed. It is easy to see that a supplementary load of 4000 will restore ΔT of **E2a** at 10 °C. Figure 10.39 displays the final network. There are now three process/process heat exchangers of loads 5000, 8000 and 10000, in total 23000 units. The utility consumption is 11000 units for cooling and 12000 units for heating. Hence, the loss in heat recovery is (4000/27000) ×100=14.8%.

As an exercise the user is encouraged to reduce the alternative 2 from Fig. 10.31. The final result is a HEN with 5 units, **E2**=8000, **E3**=1000, **E5**=15000, Q_c=10000 and Q_h=11000, with a ΔT_{min}=10 °C in E2.

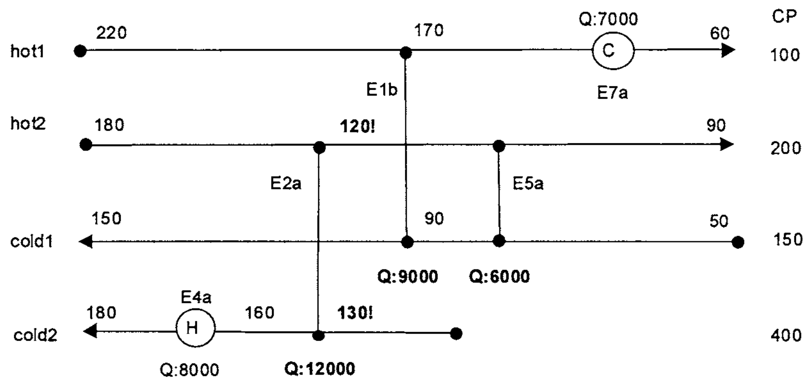

Figure 10.38 Breaking the second loop

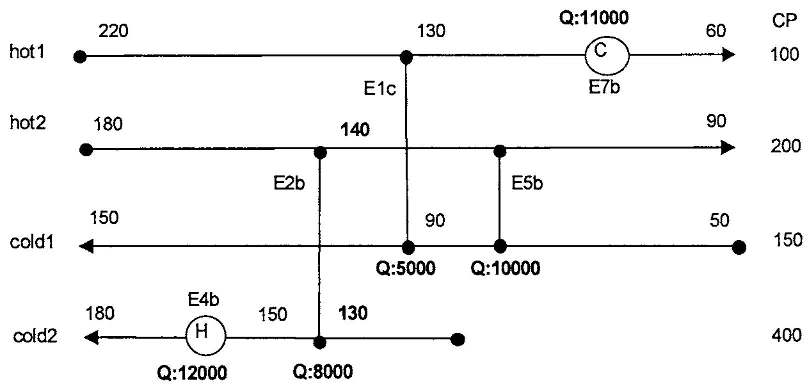

Figure 10.39 Final network with the minimum number of units

10.4.5 Network optimisation

As explained, the Pinch Design method generates a network with a certain degree of redundancy. The reduction of units can contribute to major saving in capital costs. However, more energy is necessary to inject into the network to restore infeasible driving forces. This task can be treated elegantly by optimisation.

Another application is the split of streams at Pinch in order to fulfil the feasibility criteria of matches. Some insights can be obtained from the grid diagram. However, the exact split fraction is a typical optimisation problem. The same is valid for splitting streams far from Pinch. Note that bypasses of streams around heat exchangers can be used for temperature control.

The above description shows that optimisation is a powerful method in handling the design of a heat exchangers network. Because the whole approach is founded on a linear enthalpy-temperature relation, the problem can be solved by Linear Programming (LP). The optimisation is essentially a parametric one, because the network structure is not affected. If the streams involved in matches are not longer constraint by the *CP*'s rule, as for matches away from the Pinch, then the optimisation becomes structural, and the problem is of type Mixed Integer Linear Programming (MINLP).

Optimisation is also a powerful manner for designing networks submitted to constraints. Usually these can be duties, inlet/outlet temperatures, area, heat transfer coefficients, and split and bypass fractions of streams. The approach is particularly powerful for revamping existing networks, where the number of old exchangers is by far larger than the new units to be inserted.

EXAMPLE 10.6 Network optimisation

Optimise the network for minimum energy requirements developed in Example 10.3 as Alternative 1 with data from the Example 10.1. The objective function is the total annual cost of both energy and capital.

Solution.

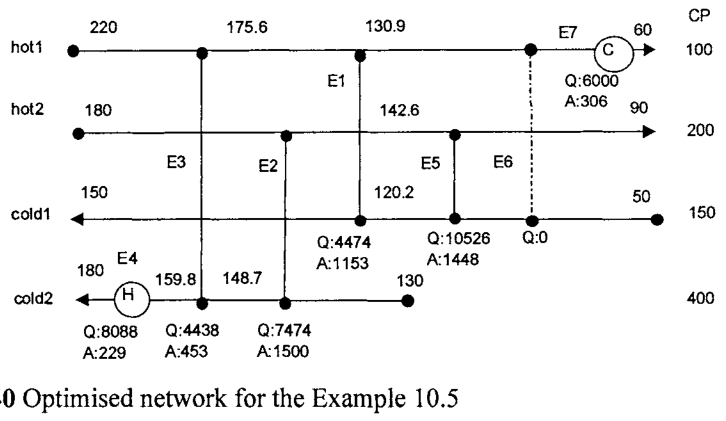

Figure 10.40 Optimised network for the Example 10.5

The heat exchanger area can be calculated in the hypothesis of counter-current 1-2 heat exchangers, as expressed by the relation 10.6. Then the cost of capital can be computed by considering a cost law. The number of shells is found straightforward by assuming a maximum area per unit of 500 m^2. The optimisation variable is the minimum temperature approach.

Figure 10.41 displays the optimised HEN found by using the design software SUPERTARGET™. A reduction in cost of about 10% is possible with respect of the MER network for ΔT_{min}=10 °C, but with the penalty of increasing the utility consumption with 15%. The reduction in total cost is explained by lower capital obtained by eliminating the heat exchanger **E6**. Note that ΔT_{min} is practically the same at 10.7 °C, but shifted between 130.7 and 120.2 °C.

10.5 MATHEMATICAL PROGRAMMING

Generally speaking, Mathematical Programming represents a class of alternative techniques that can be employed to solve energy saving problems. Numerous researches have been devoted to this subject. A good introduction in this area can be fund in the Chapter 16 of he book written by Biegler, Grossmann, and Westerberg (1998). He distinguished between *sequential* and *simultaneous* approaches.

The *sequential method* makes possible the development of partial optimised networks that satisfy one of the criteria among minimum utility, minimum investment or minimum number of units. Note that the solution of the minimum utilities may be seen analogue with the *transhipment problem* in linear programming (LP). Hot streams can be regarded as sources and cold streams as destinations. The heat can be transferred from sources to destinations through some intermediates exchange places, where a ΔT_{min} driving force must be ensured. This is equivalent with temperature intervals in the Problem Table algorithm, as it was formulated in the subchapter 10.2. The energy starts to flow from the hot utility source. The excess energy that cannot be transferred to cold streams can be cascaded at lower temperature intervals, and finally, to the cold utility. The result is a fully targeting of the recovery problem, as it was developed in section 10.3, where a Pinch can be clearly defined. Further, the problem can be extended to take into account physical matches by means of a Mixed Integer Linear Programming (MILP) algorithm. It is important to note that the solution may be not unique. There might be several networks for the same cost of utility and hardware. Conversely, the same network may have different distributions of heat loads if loops are present. It is worthy that the method can treat directly forbidden or imposed matches.

In the *simultaneous method* an existing superstructure is optimised rigorously by a Mixed Integer Non-linear Programming (MINLP). The modelling is based on a stage-wise build-up of the superstructure for each temperature interval. Within each stage potential heat exchange between any pair of hot and cold streams may take place. Accordingly, each stream is split and directed to match all cold streams, and reciprocally. In a first approximation the outlets of the exchangers are well mixed.

These are also optimisation variables. The number of stages can be put equal to the temperature intervals. Finding the number of matches is similar with the extended transhipment model. However, the constraint of the Pinch can be removed easier, and by consequence, leading to networks that minimise simultaneously units, capital and energy. Other structural features, as steam splitting and bypassing, can be considered.

In the past, Pinch Analysis and Mathematical Programming have been seen often as opposite. They are in fact highly complementary. Pinch Analysis remains an invaluable systematic investigation method, solidly anchored in Thermodynamics and based on simple intuitive graphical tools. It offers a step-wise global picture of the problem to be solved, suggest intermediate solutions, and therefore stimulate greatly the creativity. On the other hand, when the computations become tedious or excessive, the use of an automatic algorithmic tool is highly desirable. Hence, embedding Mathematical Programming into packages based on Pinch Point Analysis is the most efficient way to solve conceptual design problems in the field of energy saving.

10.6 DESIGN EVOLUTION

The most radical way to obtain substantial energy saving is to review the basic process design, namely the material balance envelope given by Reactor and Separators. Conversely, energy saving projects should also seen as an opportunity to bring important changes to the original process, from the revamp of some units to the debottlenecking of the whole plant.

Replacing the reactor is a hard decision, unlikely in an energy saving project. However, changing the reactor's parameters, particularly the temperature, might be possible when new operation mode can be envisaged, as for example switching on a new catalyst. Increasing the operating temperature of reactors is better for energy integration, particularly in the case of exothermal reactions.

The next important step is the revision of the distillation trains, above all the duties of reboilers and condensers, as well as the pressures and temperatures in top and bottoms. A simple list of these variables can identify possible thermal couplings between reboilers and condensers. If the thermal coupling is possible, the direct integration in the frame of a more complex distillation device should also be checked.

It should be keept in mind that only energy saving is never the ultimate goal. In fact, any process change should be investigated as a trade-off of both energy and capital costs. From a practical viewpoint, the targeting of subsystems based on the proximity principle can lead rapidly to a good integration that can be finally optimised without excessive effort. The last but not the least, the solution of a heat integration problem must always be examined from the point of view of operability and controllability.

There are two theoretical principles to consider in bringing conceptual changes with energy saving impact: *Appropriate Placement* and *Plus/Minus Principle* (Linnhoff et al., 1982, 1994). The first ensures an optimal use of energy provided that the placement of the unit operations in with respect to Pinch respects some rules. Chapter 11 will present this topic in more detail. The second is based on the examination of the composite curves, and will be briefly comment here.

Plus/Minus principle states that a reduction in the utility requirements can be obtained if the following actions are taken (Smith, 1995):

- Increase the total hot stream load above the Pinch.
- Increase the total cold stream load below the Pinch.
- Decrease the total cold stream heat duty above the Pinch.
- Decrease the total hot stream heat duty below the Pinch.

An example has been given in the introductory part (Fig. 10.6). Figure 10.41 presents another example. A cold stream is removed from the region above the Pinch and placed below the Pinch. The shape of the cold composite changes accordingly. By removing a hot stream, the hot utility diminishes, and by exactly the same amount the cold utility load. Similarly, by moving a hot stream from the region below to above the Pinch reduces the cold utility load, and as a result the hot utility consumption. We may generalise the above observation as a generic heuristic in energy integration:

- Shift hot streams from below above the Pinch.
- Shift cold stream from above to below the Pinch.

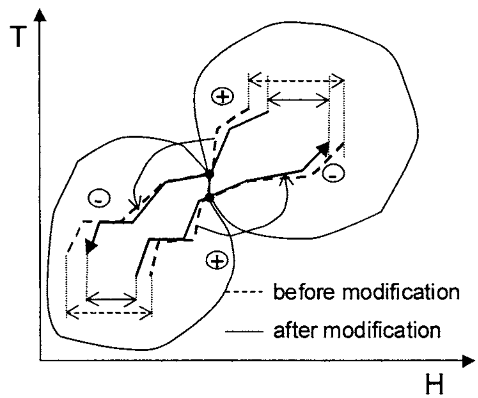

Figure 10.41 The use of Plus/Minus principle for energy saving

10.7 EXTENSIONS OF THE PINCH PRINCIPLE

By analogy with the energy saving, the Pinch concept has been extended to the treatment of other valuable resources in process industries as water, hydrogen or solvents. Saving process water is one of the most important issues in industry. Much more efficient use of water can be achieved by recycling it to the places for which is sufficiently clean, and not send it to the wastewater re-treatment. How to handle this in a systematic manner can be investigated by a method analogue to the thermal Pinch. The systematic investigation of wastewater management by Water Pinch has been started with the paper of Wang & Smith (1994) and continued since with other co-workers. Similar with temperature-enthalpy composite curves, composite concentration curves can be built having as co-ordinate the concentration in contaminant versus the mass of contaminant (Fig. 10.42 left). The slope of each segment is inverse proportional with the stream flow rate; steeper slope means lower water flow rate. By taking into account the variation of contaminant in all the process streams, the water Pinch can be located. The slope of the line passing through this Pinch allows the identification of a minimum feasible overall water flow needed to supply the system (Fig. 10.42 right), which becomes a target for design. In this way the saving in process water can be precisely quantified. The water Pinch method has been developed to a mature technology that can be applied to industrial problems, namely by combination with MILP optimisation methods.

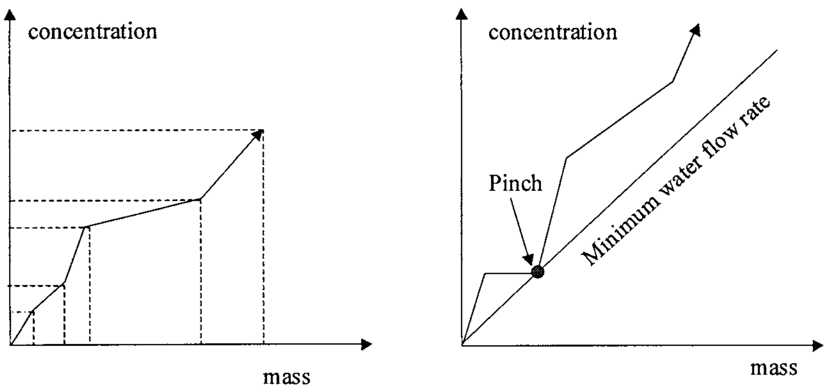

Figure 10.42 Water Pinch principle: concentration composite curve (left), targeting water consumption (right)

Another important application of the Pinch concept is the hydrogen management in refineries. Again, recycling hydrogen of convenient purity instead of high-purity hydrogen, can lead to important saving. The problem has been addressed recently by Towler et al. (1996) by means of Hydrogen Pinch.

The above examples suggest that mass-exchange operations could be treated by Pinch-modelling. However, unlike thermal Pinch, where the temperature is a general measure of the energy content, the identification of a unique measure of mass-exchange is difficult, because of large dimensionality of the problem. A general approach has been proposed by El-Halwagi and Manousiouthakis (1989) by means of the Mass Exchange Network concept, but its application in engineering calculations is difficult. However, practical solutions can be found in situations where lumping of components is possible, as in wastewater or emissions. These topics are developed in by El-Halwagi (1997) in this book over Process Integration in solving environmental problems.

The waste minimisation can take profit from Pinch Point Analysis. This issue is not mentioned here, but the reader can found more information in specialised works, as in the series of articles of Petela and Smith (1991-92), as well as in the book written by Smith (1995).

However, the application of Pinch principle for optimising mass exchange networks cannot be so powerful as in heat integration, because of higher dimensionality of the problem in term of chemical species. On the contrary, this area is an example where optimisation techniques are more suitable, particularly of mixed integer non-linear programming (MINLP) type. The number of structural alternatives is rather limited by problem definition itself, whereas the number of streams and of components can be very large. In addition, a global optimisation can handle better the optimisation of costs of different operations and equipment involved in the mass exchange network. An example of such approach for waste minimisation has been published by Papalexandri, Pistikopoulos and Floudas (1994).

10.8 SUMMARY OF PINCH POINT ANALYSIS

1. Pinch Point Analysis is a systematic process design methodology consisting of a number of concepts and techniques that ensure an optimal use of energy. The Pinch is characterised by a minimum temperature difference ΔT_{min} between hot and cold streams, and designates the location where the heat recovery is the most constraint.
2. The fundamental computational tool is the Problem Table algorithm. This tool allows the identifications of the Pinch, as well as of targets for hot and cold utilities.
3. The net heat flow across Pinch is zero. Consequently, the system can be split into two stand-alone subsystems, above and below the Pinch. Above the Pinch there is need only for hot utility, while below the Pinch only cold utility is necessary. For given ΔT_{min} the hot and cold utility consumption identified so far becomes Minimum Energy Requirements (MER). No design can achieve MER if there is a cross-pinch heat transfer.
4. The partition of the original problem in subsystems may introduce redundancy in the number of heat exchangers. When the capital cost is high, it might be necessary to remove the Pinch constraint in order to reduce the number of units. The operation will be paid by supplementary energetic consumption, which has to be optimised against the reduction in capital costs. The result is that heat recovery problem becomes an optimisation of both energy and capital costs, constraint by a minimum temperature approach in designing the heat exchangers.
5. Stream selection and data extraction are essential in Pinch Analysis for effective heat integration.
6. The key computational assumption in Pinch Point Analysis is constant CP on the interval where the streams are matched. If not, stream segmentation is necessary.
7. The counter-current heat flow of the streams selected for integration may be represented by means of Composite Curves (CC). Another diagram, Grand Composite Curve (GCC) allows the visualisation of the excess heat between hot and cold streams. against temperature intervals. This feature helps the selection and placement of utilities, as well as the identification of the potential process/process matches.

8. The synthesis of a Heat Exchanger Network consists of three main activities:
   a. Targeting. Set a reference basis for energy integration, namely:
      - Minimum Energy Requirements (MER).
      - Utility selection and their placement.
      - Number of units and heat exchange area.
      - Cost of energy and hardware at MER.
   b. Synthesis of heat exchanger network (HEN) for minimum energy requirements and maximum heat recovery. Determine matches in subsystems and generate alternatives.
   c. Network optimisation. Reduce redundant elements, as small heat exchangers, or small split streams. Find the trade-off between utility consumption, heat exchange area and number of units. Consider constraints.
9. The improvement of design can be realised by Appropriate Placement and Plus/Minus principle. Appropriate Placement defines the optimal location of individual units against the Pinch. It applies to heat engines, heat pumps, distillation columns, evaporators, furnaces, and to any other unit operation that can be represented in terms of heat sources and sinks.
10. The Plus/Minus principle helps to detect major flowsheet modifications that can improve significantly the energy recovery. Navigating between Appropriate Placement, Plus/Minus Principle and Targeting allows the designer to formulate near-optimum targets for the heat exchanger network, without ever sizing heat exchangers.
11. Pinch Point principle has been extended to operations involving mass exchange. Saving water can be treated systematically by Water Pinch methodology. Similarly, the inventory of hydrogen in refineries can be efficiently handled by Hydrogen Pinch. Other applications of industrial interest have been developed in the field of waste and emissions minimisation. The systematic methods in handling the integration of mass-exchange operations are still in development. In this area the methods based on optimisation techniques are very promising.

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