CHAPTER 2

A REVIEW OF PINCH CONCEPT

Heat exchanger network (HEN) design is a key aspect of chemical process design. Typically, 20-30% energy saving, coupled with capital savings, can be realized in state-of-the-art flowsheets by improved HEN design. The task involves the placement of process and utility heat exchangers to heat and cool process streams from specified supply to specified target temperature. The objective is to minimize total costs, i.e., capital and operating costs expressed as annual charges. Development of systematic procedures to meet this objective has been an active area of interest in the chemical engineering literature for more than two decades.

In principle, there is an extremely large number of feasible network configurations that can be developed. In order to avoid the large combinatorial problem, the heat exchanger network design problem can be conveniently partitioned into two major steps. In the first, one can preanalyze the problem to set targets for it. In the second part, the actual network is invented. The first step can be further subdivided into two substeps: network performance targets and the network temperature pinch.

The network temperature pinch represents a bottleneck to feasible heat recovery in HEN design. Its location was first described by Linnhoff et al. (1978). Network performance targets exist for the minimum utility usage, the minimum overall surface area, and the minimum number of "units" (i.e. process and utility exchangers). Calculation of these targets is simple and independent of design.

2.1 The Pinch

In this section the phenomenon of the pinch itself is discussed. First, a brief review is given of how the pinch is located. Second, the physical significance of the pinch and its implications on utility usage are described. Third, a powerful representation for both the pinch and HEN stream data is explained. Fourth, the factors affecting the occurrence of pinches in industrial HEN problems are highlighted and a reason is given why the majority of industrial HEN problems have pinches. Finally, the implications of pinches on capital costs are considered.

2.2 Locating the pinch

The task of locating the pinch and indeed the application of the pinch design method is illustrated by using an example problem for which stream data are given in Table 2.1. The example problem is call Test Case No. 3 (TC3) following the convention of Linnhoff and Flower (1978) who introduced Test Case No 1. and Test Case No 2. Note that the data for all Test Case is based on constant heat capacities.

The pinch location for a HEN problem, together with the minimum utility requirement, can be calculated using the problem algorithm of Linnhoff and Flower (1978) for a specified value of ΔT_{min}. The results of the procedure, when applied to TC3 with a ΔT_{min} of 20 ^{o}C, are shown in Table 2.2.

In the table the stream data are shown on the left, divided into six temperature intervals, corresponding to "subnetworks" and therefore called SN1-SN6. These intervals are defined by process stream supply and target temperatures. For example, SN3 is defined by the target temperature of stream No. 4 and the supply temperature of stream No. 2.

Table 2.1. Stream data for Test Case No. 3

Stream Number and Type	Heat Capacity Flowrate, FCp (kW/^{o}C)	Supply Temperature, T_s (^{o}C)	Target Temperature, T_t (^{o}C)
(1) HOT	2	150	60
(2) HOT	8	90	60
(3) COLD	2.5	20	125
(4) COLD	3.0	25	100

$$\Delta T_{min} = 20\ ^{o}C$$

Note that to ensure the feasibility of complete heat exchange, the hot and cold streams are separated by ΔT_{min}. For example, the upper boundary of SN3 is defined by cold stream No. 4 at 100 ^{o}C while the hot stream at this point is at 120 ^{o}C.

The feasibility of complete heat exchange between all hot and cold streams is an important feature of the problem table algorithm. It means that for each subnetwork there will either be a net heat deficit or surplus but never both. These deficit or surplus figures are shown in column 1 of Table 2.2. The sign convention is such that a surplus is negative and a deficit positive.

Another important feature of the problem table algorithm is the feasibility of heat transfer from higher to lower subnetworks (cascading). In other words, heat surplus from higher temperature subnetworks can be used to satisfy heat deficit of lower temperature subnetworks. The calculation of the amount of heat which can be passed on in this manner is performed in column 2 and column 3 of Table 2.2. It is initially assumed that the heat input from external utilities is zero. This is represented in Table 2.2 by a zero input for SN1 (column 2). Having made this assumption, it is an easy task to calculate the output from SN1 by simply adding the surplus to the input. This then forms the input to SN2. The procedure is repeated for all subnetworks.

Table 2.2. The problem table for Test Case No. 3

							1	2	3	4	5
Sub-network	Cold streams		T (^{o}C)		Hot streams		Deficit	Accumulated		Heat flows	
	(3)	(4)			(1)	(2)		Input	Output	Input	Output
				150							
SN 1			125	145	2	8	-10	0	10	107.5	117.5
SN 2	2.5		100	120	2	8	+12.5	10	-2.5	117.5	105
SN 3	2.5	3	70	90	2	8	+105	-2.5	-107.5	105	0
SN 4	2.5	3	40	60	2	8	-135	-107.5	27.5	0	135
SN 5	2.5	3	25				+82.5	27.5	-55	135	52.5
SN 6	2.5	3	20				+12.5	-55	-67.5	52.5	40

To be feasible, the flow of heat from high temperature subnetworks to low temperature subnetworks must not be negative. Thus if negative values are generated in column 2 and 3 of Table 2.2, the heat input to SN1 must be increased. The minimum increase guarantees that all heat flows are positive or zero - see columns 4 and 5. The minimum hot utility usage is then given by the input to SN1 (column 4). The minimum cold utility usage is given by the heat flow out of the coldest subnetwork (column 5).

The results of the problem table analysis in Table 2.2 are shown diagrammatically in Fig. 2.1(a). Each subnetwork is shown with all heat flows as calculated by the problem table algorithm. Notice that the heat flow from SN 3 to SN4 is zero. All other flows are positive. The point of zero heat flow represents the pinch.

In Fig. 2.1(b), the pinch is shown partitioning the problem into two regions, a hot and a cold end. The hot end, which comprises all streams or parts of streams hotter than

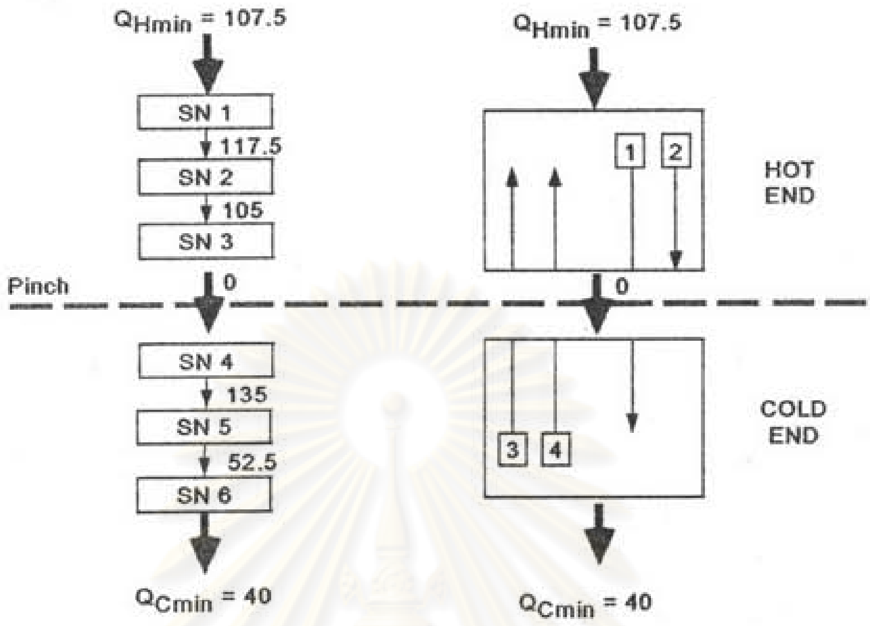

Figure 2.1. (a) Subnetwork heat flow diagram for TC3. (b) Subnetworks combined into a hot and cold region.

the pinch temperature, requires only process exchange and utility heating. Utility cooling is not required. The cold end, which comprises all streams or parts of streams cooler than the pinch temperature, requires only process exchange and utility cooling. Utility heating is not required. There is no heat transfer across the pinch. Also, both utility requirements are minimum theoretically.

2.3 Significance of the pinch

We are now in a position to discuss the causes and effects of using more than the minimum utility usage. We shall use TC3, decomposed into its hot and cold ends as an example (see Fig. 2.2). Note that in Fig. 2.2 the hot end is referred to as a heat "sink" as only utility heating is required. The cold end is referred to as a heat "source" as only utility cooling is required.

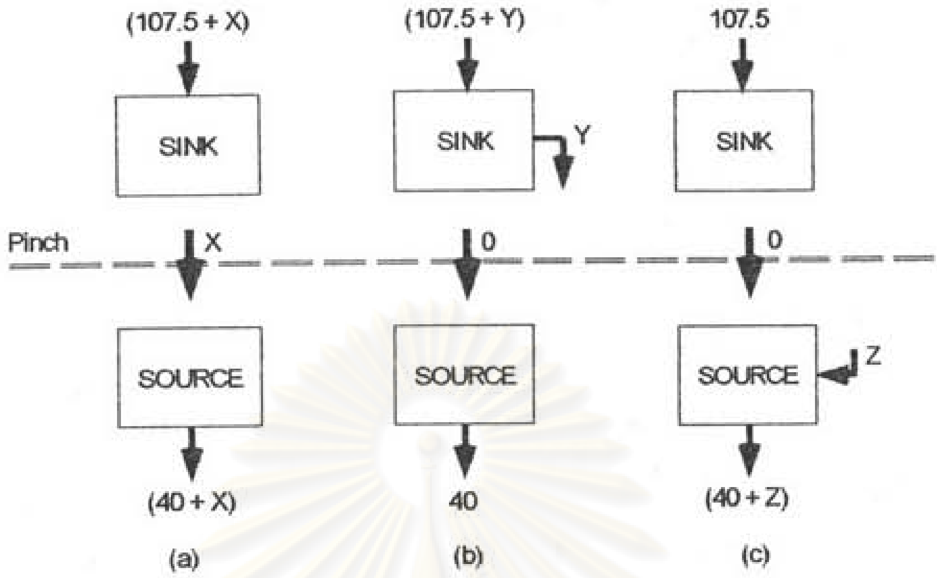

Figure 2.2. (a). Effect of heat transfer across the pinch. (b) Effect of utility cooling above the pinch. (c) Effect of utility heating below the pinch.

First consider the effects of transferring heat across the pinch (see Fig. 2.2(a)). Any heat transferred must, by enthalpy balance around the sink, be supplied from hot utility in addition to the minimum requirement. Similarly, enthalpy balance around the source shows that heat transfer across the pinch also increases the cold utility above the minimum required. In other words, heat transfer across the pinch incurs the double penalty of increased hot and cold utility requirement for the HEN design task.

Using an equivalent argument, the effect of utility cooling above and utility heating below the pinch can be assessed (see Fig. 2.2 (b) and 2.2 (c)). A removal of heat Y from the sink increases both utilities by Y (see Fig. 2.2 (b)). A supply of heat Z to the source has the analogous effect (see Fig. 2.2 (c)). Thus for minimum utility usage utility cooling is not permitted above the pinch and utility heating is not permitted below.

2.4 The pinch in the grid representation

It is desirable when developing a design, whether new or retrofit, to do so on a representation which shows the stream data and the pinch together. In addition, the presentation ought to be sufficiently flexible to allow easy manipulation of matches.

The grid representation, first introduced by Linnhoff and Flower (1978), can be modified to achieve these objectives. To illustrate this, TC3 has been drawn in the modified grid (see Fig. 2.3). Hot streams are grouped together at the top and run left to right from their supply to target temperatures. Cold streams beneath run counter current. The pinch division is represented in the diagram by dividing the stream data at the appropriate temperatures, remembering to separate hot and cold stream by ΔT_{min}.

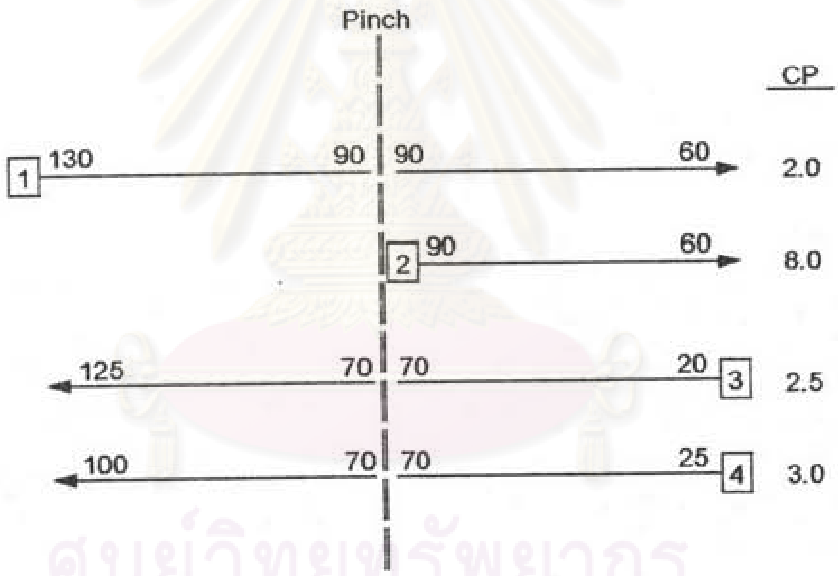

Figure 2.3. Pinch division of TC3 shown in the grid.

Process exchangers are represented by vertical lines and circles on the streams matched (see Fig. 2.4). Heaters are represented in the grid by circles on the cold streams and coolers by circles on the hot streams (see Fig. 2.4). As indicated in Fig. 2.3, heat exchange from the cold end of the problem to the hot end is not feasible with $\Delta T_{min} = 20$ ^oC. Exchange from the hot end to the cold end is not desirable as this would constitute heat transfer across the pinch incurring the energy penalties shown in Fig. 2.2 (a). Thus, Fig. 2.3 provides a "grid" for two completely separate design tasks, the hot end and the cold end.

2.5 Threshold problems

A pinch does not occur in all HEN problems. Certain problem remain free of a pinch until the minimum allowed driving force, ΔT_{min}, is increased up to or beyond a threshold value ΔT_{min}. It is for this reason that we call these problem "threshold problems".

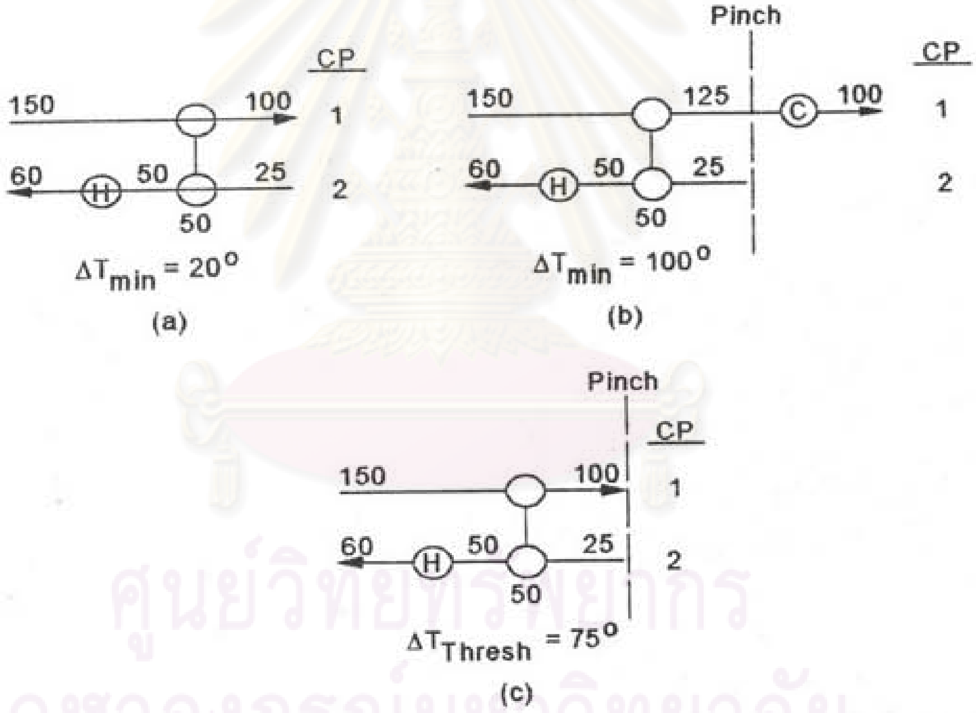

Figure 2.4. (a) A threshold problem. (b) A pinched problem. (c) The threshold ΔT_{min}.

The concept of a threshold problem can be envisaged as a "very hot" hot stream matched to a "very cold" cold stream (see Fig. 2.4 (a)).

It is apparent from Fig. 2.4 (a) that the hot utility heat load remain constant, unaffected by any specification of ΔT_{min}, providing the specified ΔT_{min} is less than the smallest temperature driving force in the exchanger, which is 75 ^{o}C in the example. (It is assumed, for the purposes of this example, that the hot utility supply temperature is such that the smallest ΔT will always occur in the exchanger.) However, when the specified ΔT_{min} exceeds ΔT_{thresh}, as in Fig. 2.4 (b), the need for both utility heating and cooling is introduced. This is because complete heat exchange between the two streams is no longer feasible without violating ΔT_{min}. Notice also that a pinch has been introduced into the problem.

A borderline situation occurs when the specified ΔT_{min} equals the threshold value (see Fig. 2.4 (c)). The problem has become pinched but the utility usage is the same as for lower values of ΔT_{min}. This borderline case is a general feature of a threshold problem.

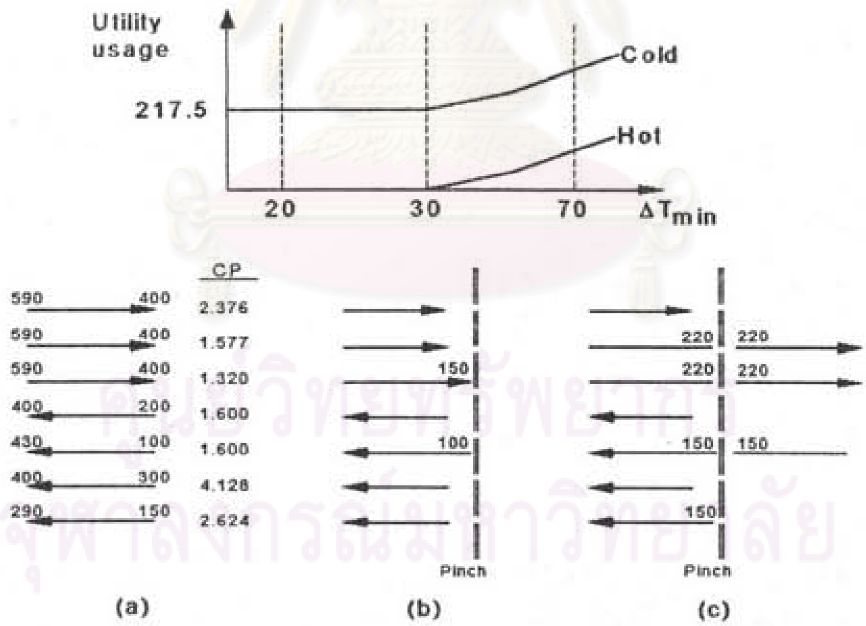

Figure 2.5. (a) Data for 7SP2. (b) The threshold ΔT_{min} for 7SP2.

(c) $\Delta T_{min} > \Delta T_{thresh}$ for 7SP2.

Figure 5 shows the threshold behavior in terms of a plot of utility requirements vs. ΔT_{min} for the HEN problem "7SP2". This problem was first introduced by Masso and Rudd (1969). In Fig 5(a), the specified ΔT_{min}, at 20 ^{o}C, is less than ΔT_{thresh}. As a result there is no pinch and only utility cooling is required. When ΔT_{min} equals ΔT_{thresh} a pinch is introduced into the problem (see Fig. 2.5 (b)). As for the simple two stream problem discuss above, there is no increase in utility usage. The utility usage only increased when the minimum allowed driving force is increased above ΔT_{thresh} (see Fig. 2.5 (c)). Both hot and cold utilities are then required and the problem is pinched.

2.6 <u>The utility pinch</u>

In applying the problem table procedure to TC3 it was assumed that the utilities were available at extreme temperature, i.e. the hot utility was hot enough and the cold utility cold enough for all process requirements. In practice, this is rarely desirable as less extreme utilities tend to cost less, e.g. low pressure steam for process heating costs less than high pressure steam, cooling water costs less than refrigeration, etc. There is often a good cost incentive for reducing extreme temperature utility loads by the introduction of intermediate temperature utilities. The reasoning in "significance of the pinch", tells us that any new hot utility must be supplied above the pinch and any new cold utility must be supplied below the pinch. Failure to do so would incur the double penalties of increased utility heating and cooling.

In Fig. 2.6 (a). a new hot utility supply has been introduced to the hot end of a hypothetical problem. As the heat load on this new utility increases, savings are made on the hottest utility supply (see Fig. 2.6 (b)). There comes a point when the hottest utility loadis reduced to such as extent that it just satisfies the heating requirements in the hottest region of the problem (see Fig. 2.6 (c)). The result is a division of the hot end of the HEN design task into two separate regions, i.e. a new pinch has been created. As it is a direct consequence of the introduction of the new utility, we call it a utility pinch.

With this understanding it is hardly surprising to find that, in industrial HEN design, the occurrence of an unpinched or threshold problem is extremely rare. The pinched problem is the norm.

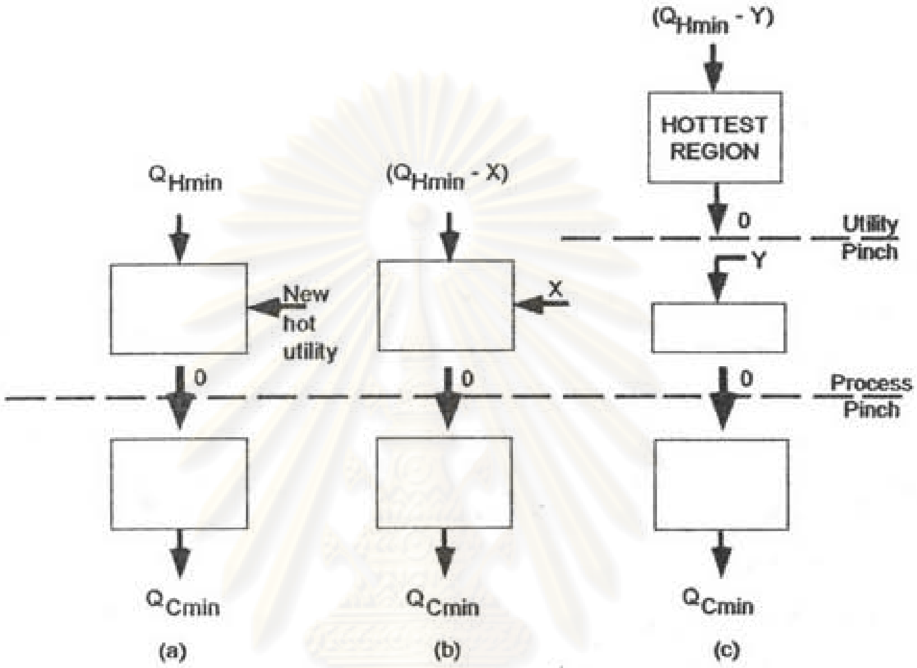

Figure 2.6. (a) The correct placement of a new hot utility. (b) Distributing the minimum heating requirement. (c) The utility pinch.