CHAPTER II
BACKGROUND AND LITERATURE SURVEY

2.1 Pinch Technology

Pinch technology provides a systematic methodology for analysis of chemical processes and the surrounding utility systems. The concept of pinch was first developed by two independent research groups (Flower and Linnhoff, 1978 and Umeda *et al.*, 1979), based on the applied thermodynamics concepts. The advancement in computer processor made the concept extended into the automated synthesis by using mathematical programming (Floudas, Ciric and Grossmann, 1986). The heuristic approach has limitation on that it could not guarantee that the design topology is optimum, while the automated approach has limitation in complexity, high computational time.

The pinch technology is based on laws of thermodynamics which describe the important point as follows;

The first law states that the heat transferred from the hot stream must equal that transferred to the cold stream. Therefore, of the six process variables (two flow rates and four temperatures), only five can be specified independently.

The second law states that heat can only be transferred from a hot fluid to a cold one. Therefore, the temperature of the cold fluid must be less than that of the hot fluid at all points along the length of the exchanger.

The process design hierarchy can be represented by the "onion diagram" as shown in Figure 2.1. The design starts with the reactors. Once feeds, products, and recycle concentrations are known, the separators can be designed. The basic process heat and material balance is now in place, the heat exchanger network can be designed. The remaining heating and cooling duties are handled by the utility system. The process utility system may be a part centralized site-wide utility system.

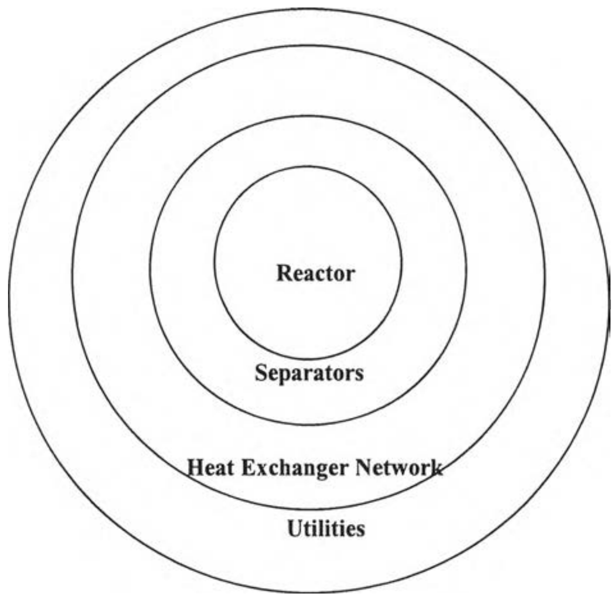


Figure 2.1 "Onion Diagram" of hierarchy in process design.

2.1.1 <u>Problem Table Algorithm</u>

The thermal data from the process, which is obtained after heat and material balance of the process is defined, can be used to set the target for energy saving prior to the design of the heat exchanger networks. The necessary thermal data is supply and target temperature and heat capacity flow rate for each stream as shown in Table 2.1.

Table 2.1 Example of thermal data for process streams (Linnhoff and Hindmarsh, 1983)

No.	Type	Supply temperature (°C)	Target temperature (°C)	Heat capacity flowrate (kW/°C)
1	Hot	150	60	2
2	Hot	90	60	8
3	Cold	20	125	2.5
4	Cold	25	100	3

Here, the hot streams are referred to the streams that required cooling, i.e. the supply temperature is higher than the target. While the cold streams are referred to those required heating, i.e. the target temperature is higher than the supply. The supply and target temperature and flowrate can be combined into new parameter called "heat capacity flowrate (CP)" which is defined as specific heat capacity multiplied by mass flowrate. This can be calculated by using equation 2.1.

$$CP = F \times C_p = \frac{\Delta H}{|T_t - T_s|} \quad (2.1)$$

where:

CP	=	heat capacity flowrate
F	=	stream flowrate
C_p	=	stream specific heat capacity
ΔH	=	heat load of stream
T_t	=	stream target temperature
T_s	=	stream supply temperature

The data used here is based on the assumption that CP is constant. In practice, this assumption is valid because every stream with or without phase change can easily be described in terms of linearized temperature-enthalpy data.

The location of pinch and the minimum utility requirement can be calculated by using the problem table algorithm (Linnhoff and Flower, 1979) for a specified minimum temperature difference (ΔT_{min}). For a ΔT_{min} of 20 °C, the results from this method are shown in Table 2.2.

In the table the stream data are shown on the left. The network is divided into six sub-networks (SN1-SN6) corresponding to the temperature interval. The interval is defined by process stream supply and target temperatures. For example, SN2 is defined by the target temperature of stream No.3 and No. 4. The important feature of this method is the separation between hot and cold streams by ΔT_{min}. This feature ensures the feasibility of complete heat exchange between the hot and cold streams. In other words, for each sub-network there will be either a net heat deficit or surplus as shown in Heat Deficit column (column 4) in Table 2.2. The sign convention for heat deficit is positive while the negative is used for heat surplus.

Table 2.2 The problem table algorithm for stream data given in Table 2.1 (Linnhoff and Hindmarsh, 1983)

Sub network	Temperature (^{o}C)		Heat deficit (W)	Accumulated heat (W)		Heat flow (W)	
	Cold	Hot		Input	Output	Input	Output
		150					
SN1	125	145	-10.0	0.0	10.0	107.5	117.5
SN2	100	120	+12.5	10.0	-2.5	117.5	105.0
SN3	70	90	+105.0	-2.5	-107.5	105.0	0.0
SN4	40	60	-135.0	-107.5	27.5	0.0	135.0
SN5	25		+82.5	27.5	-55.0	135.0	52.5
SN6	20		+12.5	-55.0	-67.5	52.5	40.0

Another important feature of the problem table algorithm is the heat cascade, i.e. heat is transferred from the high to low temperature sub-networks. This idea is used in calculation of accumulated heat as shown in column 5 and 6 of Table 2.2. Initially, it is assumed that no heat supply from external utilities. The output for each sub-network is obtained by adding the surplus to the input of that sub-network. The output is then used as an input for the next sub-networks. The procedure is repeated until all of the network heat flows are calculated as shown in equation 2.2.

$$\text{Heat flow input} = \text{Heat flow output} + \text{Heat deficit} \tag{2.2}$$

To be feasible, the flow of heat from sub-network to sub-network must be non-negative. Therefore, the heat has to be added into a network to ensure that the heat flows are non-negative. The minimum utility usage is observed when zero heat flows occur in the network. The input to the hottest interval for this case is the minimum hot utility requirement for the network, while the cold utility usage is the

the minimum hot utility requirement for the network, while the cold utility usage is the output from the coldest sub-network. The results of the problem table algorithm can be shown diagrammatically called "Transshipment heat flow diagram" as shown in Figure 2.2(a). All heat flows are calculated by problem table algorithm. It can be seen from this diagram, the heat flow from SN3 to SN4 is zero while other flows are positive. The point where the heat flow is zero represents the pinch point.

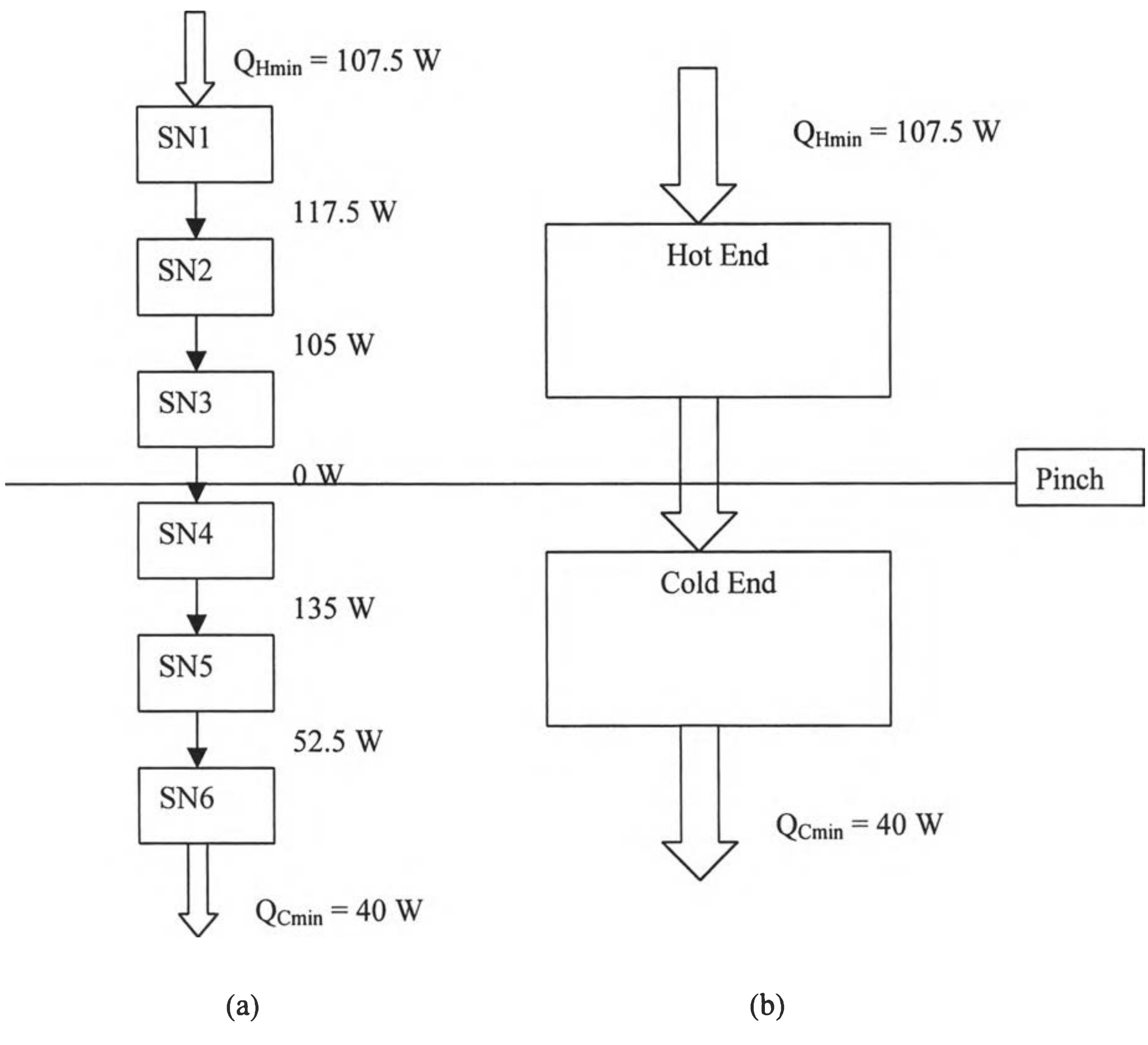


Figure 2.2 (a) Transshipment heat flow diagram for data in Table 2.1. (b) Sub-networks combined into a hot and cold region.
(Linnhoff and Hindmarsh, 1983)

The significance of the pinch is shown in Figure 2.2(b). The pinch separates the problem into two thermodynamic regions, namely, hot end and cold end. The hot end is the region comprising all streams or parts of streams above the pinch temperature. Only hot utility is required in this region but not cold utility. The cold end is the region comprising all streams or parts of streams below the pinch temperature. Cold utility is required in this region but not for hot utility. There is no heat transferring across the pinch, therefore, the utility requirement is minimum.

As described previously, the hot end requires only hot utility so it acts as a heat sink while the cold end requires only cold utility so it acts as a heat source. To achieve this minimum requirement, the design has to obey the pinch principle. The pinch principle comprises of the following rules;

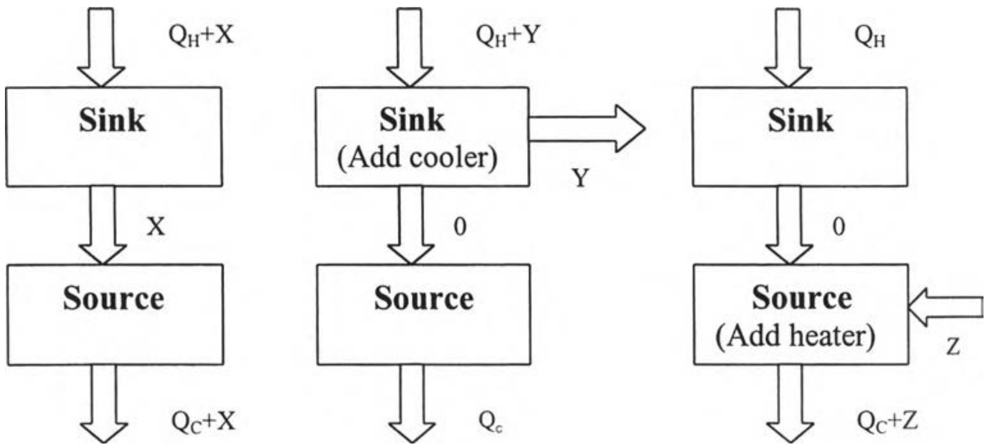
(1) There must be no heat transferring across the pinch

(2) There must be no external utility cooling above the pinch

(3) There must be no external utility heating below the pinch.

Violating this principle will increase the utility requirement as shown in Figure 2.3 The effect of transferring heat, X, across pinch is shown in Figure 2.3(a). Any heat transferred must, by enthalpy balance around the sink, be supplied from hot utility in addition to the minimum requirement. Likewise, the enthalpy balance around the source shows that the heat transferring across pinch also increases in cold utility above the minimum values. In other words, the heat transfer across the pinch incurs the double penalty of increased hot and cold utility requirement for the design task (Linnhoff *et al.*, 1982).

The same argument is applied for the assessment of the effect of cooling above and heating below the pinch. Consider Figure 2.3(b), if the amount of heat Y is let to be removed from the sink, again by enthalpy balance, the utility heating has to be increased to balance the rejected heat. Likewise, in Figure 2.3(c) if we input the heat Z to the source, the utility cooling has to be increased in order to reject the external heat. Thus, to achieve the minimum utility requirement, the pinch principle must not be violated. The principle is very useful to the retrofit studies. Using the above argument, the designer can find which exchangers are placed at fault position.



(a) (b) (c)

Figure 2.3 (a) Effect of heat transferring across the pinch, (b) Effect of utility cooling above the pinch, (c) Effect of utility heating below the pinch.
(Linnhoff and Hindmarsh, 1983)

2.1.2 Composite Curves

The hot and cold streams in a process can be represented on a temperature-heat content (Enthalpy) graph once their input, output temperatures and flowrates and physical properties are known. Starting from the individual streams it is possible to construct one "composite curve" representing all hot streams in the process and the other one representing all cold streams, by simple addition of heat contents over the temperature ranges in the problem.

This is illustrated in the Figure 2.4 for a number of hot streams with heat capacities A, B and C being cooled through the temperature levels indicted.

The result for a set of hot and cold streams is a plot of two composite curves as shown in Figure 2.5. The overlap between the composite curves represents the maximum amount of heat recovery possible within the process.

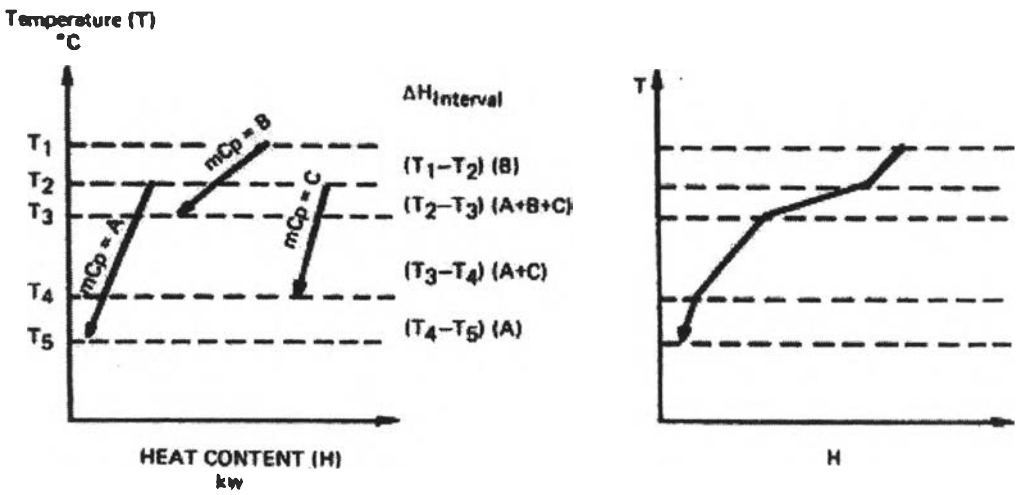


Figure 2.4 Construction of "Composite Curve". (Linnhoff *et al.*, 1982)

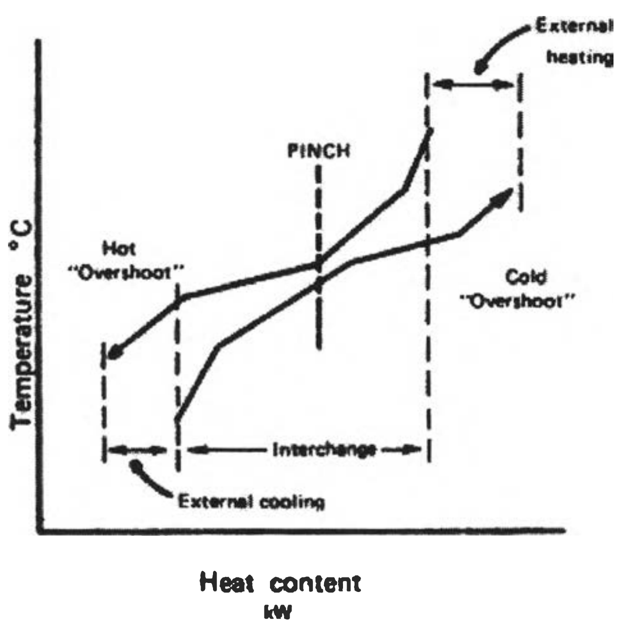


Figure 2.5 Prediction of energy targets using Composite Curve.
(Linnhoff *et al.*, 1982)

The "over-shoot" of the hot composite represents the minimum amount of the external cooling required and the "overshoot" of the cold composite represents the minimum amount of external heating. Because of the "kinked" nature of the curve, they approach most closely at one point. This is called the "pinch".

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In Figure 2.6 (a) the system is separated at the pinch. In the section above the pinch, the composite hot gives all its heat to the composite cold with only residual heating required. The system is therefore a heat sink. Heat goes in from hot utility, but no heat goes out. Conversely, below the pinch the system is a heat achieves the utility targets the heat flow across the pinch is zero. However, Figure 2.6 (b) shows the case where the minimum utility targets are not met. External heating is in excess (by α) of the minimum possible. By heat balance around the heat source and the heat sink, there must be a heat flow α across the pinch and an excess external cooling requirement (α).

2.1.3 Grand Composite Curves

The transshipment heat flow diagrams in Figure 2.2 can be represented by the temperature-enthalpy plots called the grand composite curves. The heat flows from the cascade in each temperature interval are plotted against their respective temperature interval boundary. The result is a graph, which characterizes the process source and sink in temperature-enthalpy terms, this plot is called "Grand Composite Curve (GCC)". The GCC shows the variation of heat supply and demand within the process. Using this diagram, the designer can see how the utility needs of the process can be met. An example of GCC is illustrated in Figure 2.7.

The vertical axis shows process interval temperature. The horizontal distance separating the curve from the vertical axis at the top of temperature scale shows the overall hot utility consumption of the process. Over the span AB the process is consuming hot utility (the line moves toward the vertical axis). Over the span BC the process is in surplus (and the line moves away from the vertical axis). Over the span CE the process is again in deficit and once point D is reached it once more consumes hot utility. Point E is the pinch point. As can be expected, can be supplied over the temperature profile ABDE. This diagram is useful in determining the appropriate load for each utility level as will be discussed in section 2.1.4.

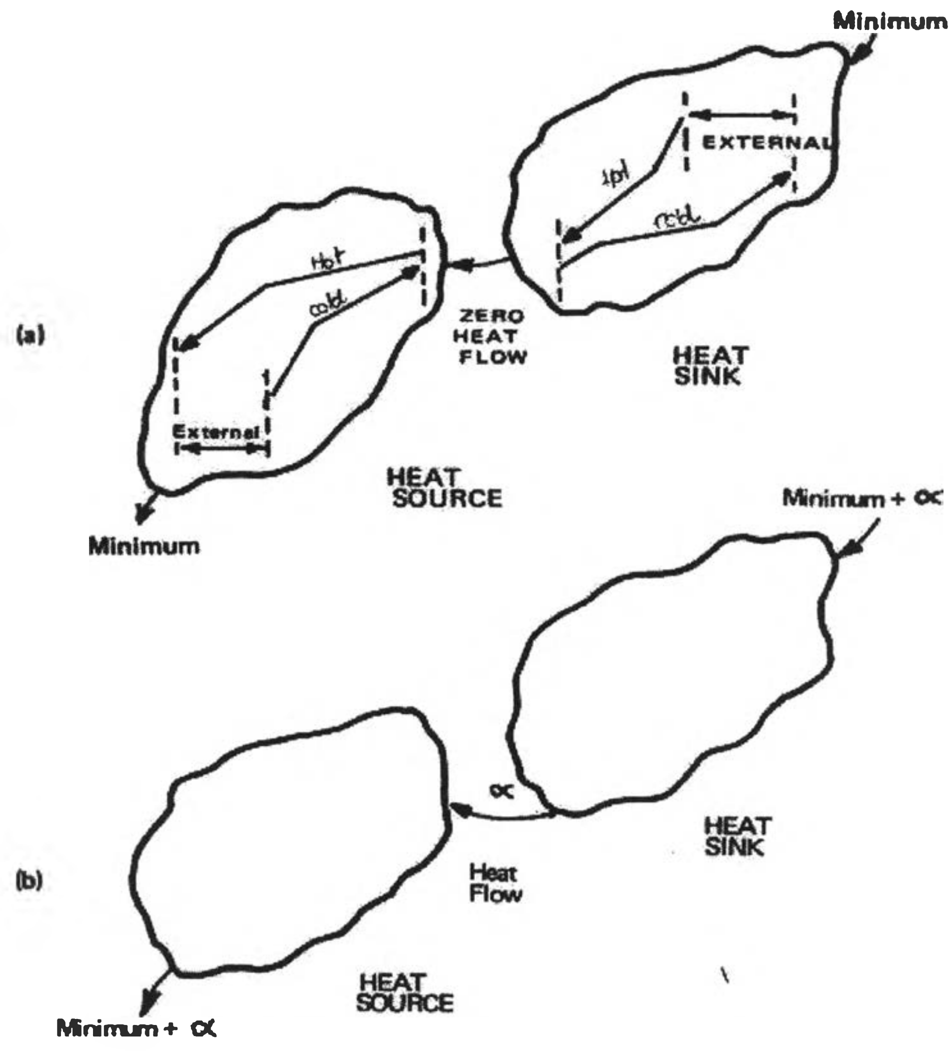

Figure 2.6 The source/sink characteristic of process heat exchanger.
(Linnhoff *et al.*, 1982)

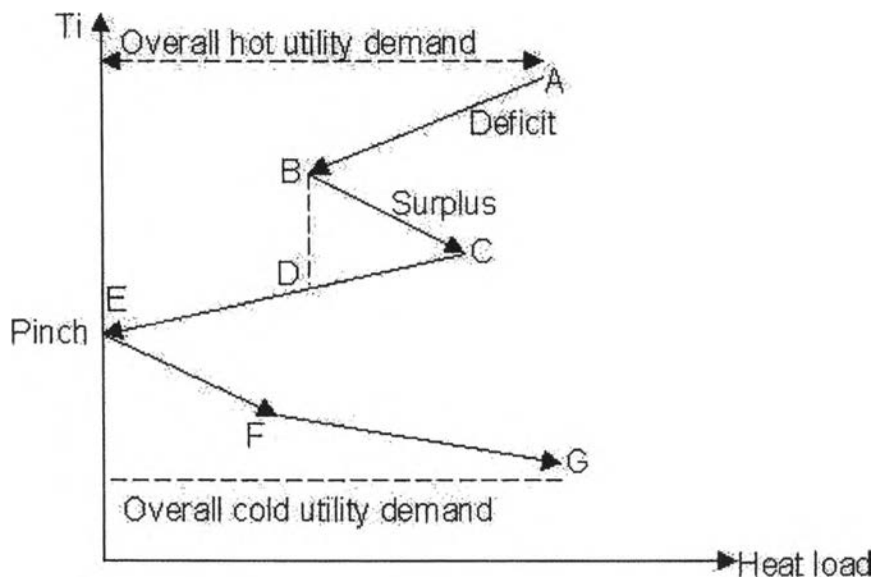

Figure 2.7 The Grand Composite Curve (GCC). (www.pinchtechnology.com, 2003)

2.1.4 Utility Pinches

In the problem table algorithm, it was assumed that the utilities are available at the extreme temperature, i.e. the hot utility is hot enough to supply all process streams and cold utility is cold enough to cool all process requirements. In practice, this is rarely desirable, as less extreme utilities tend to cost less, for example, the low-pressure steam is cheaper than the high-pressure steam. To make the design economically, it is attempted to reduce the extreme utilities and maximize the use of intermediate utilities. From the pinch principle, any new hot utilities must be supplied above pinch and any new cold utilities must be supplied below the pinch. Violating these requirements will incur the energy penalty in the design.

Consider Figure 2.8(a), a new hot utility supply has been introduced to the hot end of the task. As shown in Figure 2.8(b), when the heat load of the new utility increases, the saving in the hottest utility is observed. The heat load of new utility is continually increasing until the heat load of the hottest utility is satisfied with the heat requirement of the hottest part of the process (Figure 2.8 (c)). This result in a separation in hot end into two regions, i.e. there is a new pinch created. This new pinch is caused by the maximization of the utility, so it is called "utility pinch". The problem table algorithm introduced in section 2.1.1 can be modified to calculate the maximum heat load of intermediate utilities and the utility pinch location.

2.2 The Pinch Design Method for Heat Exchanger Network Design

The Pinch Design Method (PDM) was proposed by Linnhoff and Hindmarsh in the year 1983. The method is intended to produce heat recovery network designs that consume minimum energy and total expenditures. The method recognizes the pinch division, which is an important concept in pinch technology. The important feature of this method is the permission to set the economic targets of the network prior to the design calculation. Two targets are involved in the economic of heat exchanger networks. They are energy and capital targets.

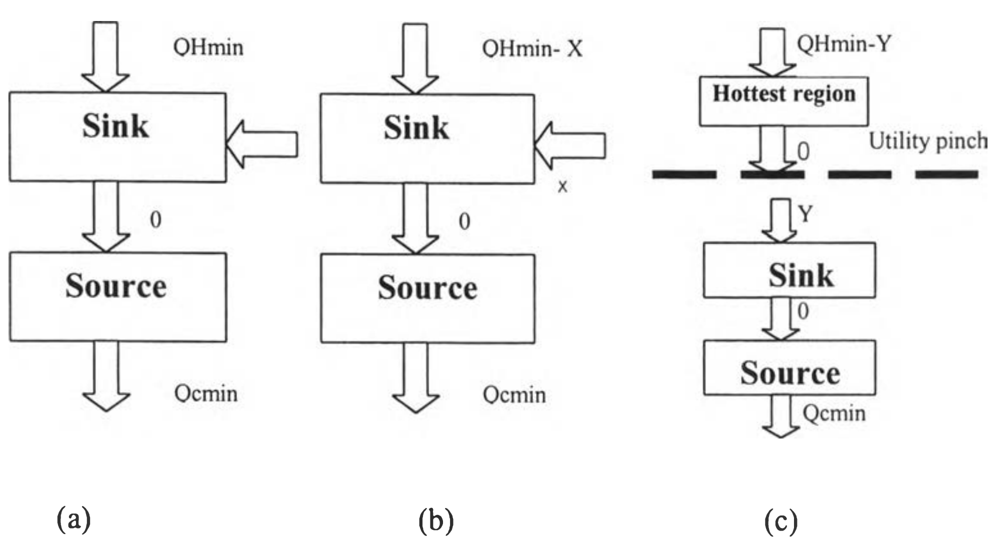

Figure 2.8 (a) The correct placement of a new hot utility, (b) Disturbing the minimum heating requirement, (c) The utility pinch.
(Linnhoff and Hindmarsh, 1983)

Energy targeting is the determination of utility consumption. Capital cost targeting is the determination of network capital cost. Total cost targeting involves bringing these two targets together.

The energy target for the heat recovery network can be set by using either problem table algorithm or composite curves. The capital cost of a heat exchanger network is dependent upon three factors: the number of exchangers, the overall network area, and the distribution of area between the exchangers.

The minimum number of heat exchanger units required for a heat recovery network is determined by equation 2.3 (www.pinchtechnology.com, 2003).

$$N_{units} = N_h + N_c + N_u - N_s \tag{2.3}$$

where:

N_{units} = minimum number of units in the network

N_h = number of hot streams

N_c = number of cold streams

N_u = number of utility streams

N_s = number of separate heat balanced systems

The overall network area ($A_{network}$) can be calculated by using equation 2.4 (www.pinchtechnology.com, 2003). This equation is based on the assumption that the streams have uniform heat transfer coefficient.

$$A_{network} = \sum_{j \in \text{ intervals}} \left(\frac{1}{\Delta T_{LM}}\right)_j \sum_{i \in \text{ streams}} \left(\frac{Q}{h}\right)_i \tag{2.4}$$

where: interval j there are i streams (hot and cold) with their individual heat load, Q_i and their stream film heat transfer coefficient, h_i. $\Delta T_{min,}j$ is the log mean temperature difference in interval j.

The distribution of area between the exchangers cannot be determined ahead of design, by assuming that it is evenly distributed between the units a reasonable prediction of the heat exchanger capital cost of a network can be obtained from equation 2.5 (www.pinchtechnology.com, 2003).

$$C_{network} = N_{units} \times \left\{ C_a + C_b \left(\frac{A_{network}}{N_{units}} \right) \right\}^{C_c} \tag{2.5}$$

where C_a, C_b and C_c are the cost factors.

Unfortunately, the minimum number of units in the network is often mutually incompatible with the minimum utility requirement. Greater ΔT_{min} will result in higher utilities consumption but the required capital will be less and vice versa. Therefore, the difficult task in heat exchanger network design is what should be the appropriate heat recovery level. The trade-off between the network energy usage and capital is an important tool for setting heat recovery level. The economic heat recovery level is that at which the total annual cost is a minimum. Since the amount of utilities consumption in the process and the network capital cost is a function of ΔT_{min}. Therefore, the economic heat recovery level can be determined by varying ΔT_{min}. The value of ΔT_{min} that corresponds to the minimum total annual cost will be used as a design basis.

2.2.2 Grid diagram

In network design development, it is desirable to do 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 can be modified to achieve these objectives. In the grid representation, the hot streams are grouped running from their supply (left) to target (right) temperatures as shown in Figure 2.9. Cold streams are located beneath, running counter currently. The pinch division is represented in the diagram by dividing the stream data at the pinch temperature. Note that the hot and cold streams are separated by ΔT_{min}.

The heat exchangers are represented by vertical lines and circles on the streams matched, heaters and coolers are represented by the circles placed on cold and hot streams, respectively. The duty load of the exchangers is dictated below the circles.

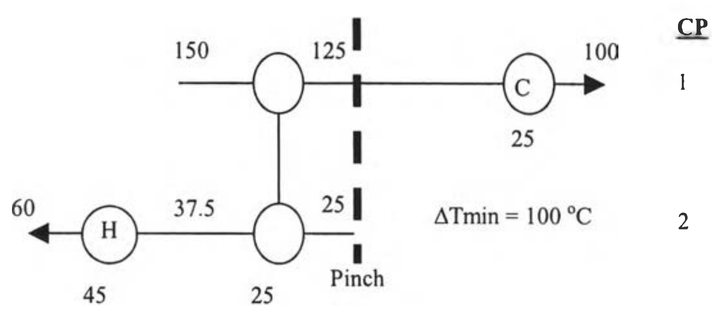

Figure 2.9 Heat exchangers representation in grid diagram.
(Linnhoff and Hindmarsh, 1983)

At the pinch point, the temperature difference is minimum. Therefore, the heat exchangers at the pinch point must be operated at temperature difference; ΔT_{min}. Therefore, the pinch is the most constraint part of the design. To avoid the violation in ΔT_{min}, the heat exchangers at the pinch have to be designed first. This will be obtained when the pinch matching follows the feasibility criteria. After the pinch matches are completed, the designer will have more choices for matching. Thus, the principle of the pinch design method is to start the design at the pinch point first and then moving away.

2.2.3 The Feasibility Criteria at the Pinch

The minimum energy usage will be achieved if the cold utilities are not allowed for the process streams above the pinch point. The criteria will be satisfied when the hot streams are brought to the pinch by the cold stream with one-to-one matching. This situation will be occurred if the number of hot streams is less than or equal to the number of cold streams. If the number of cold streams is less than that of hot streams, then splitting of cold streams is required to fulfill this requirement. The same idea can be applied to the process streams below the pinch point to avoid using hot utilities below the pinch. From the above discussion, the number of process streams coming into the pinch point has to be less than or equal to the number of streams that going from the pinch. Therefore, the criterion to ensure the feasibility of the pinching match is shown in equation 2.6.

$$N_{\text{Stream In}} \leq N_{\text{Stream Out}} \tag{2.6}$$

The pinch is the point where the temperature difference is minimum. No individual exchanger should have a temperature difference smaller than ΔT_{min}. All pinch matches must have larger temperature difference than ΔT_{min} when they are located away from the pinch. Therefore, the heat exchanger profile has to be checked for the temperature difference. The profile is represented in T/H plot, thus the process streams will exhibit straight line in this plot with the slope equal to 1/CP as shown in Figure 2.10.

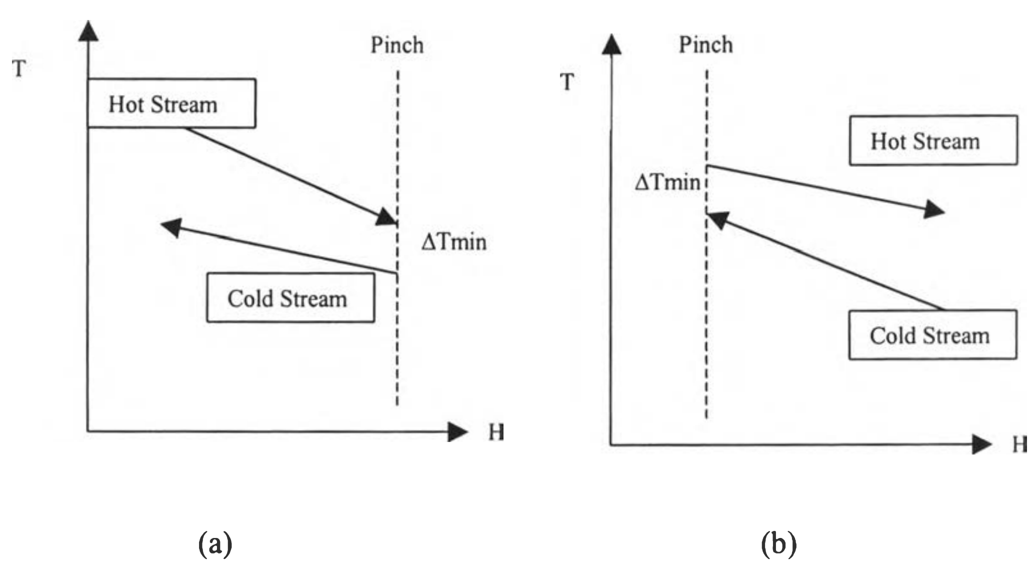

Figure 2.10 Heat Exchanger profile, (a) Above pinch, (b) Below pinch.

Consider Figure 2.10(a), one side of heat exchanger will be operated at ΔT_{min}. This will occurs when the hot streams (streams in) match with the cold streams (streams out) with higher CP, i.e. less steep slope. The same argument is applied to the pinch matches below the pinch as shown in Figure 2.10(b). Therefore, for the temperature feasibility of the matches close to the pinch, the CP of the streams going out of the pinch needs to be greater than the CP of the stream coming into the pinch. Thus for temperature feasibility there is a "CP rule" in equation 2.7.

$$CP_{in} \leq CP_{out} \tag{2.7}$$

If the CP rule does not satisfied for the pinch matches, the stream splitting will be applied for this problem. The algorithm for stream matching and splitting at the pinch point is shown in Figure 2.11.

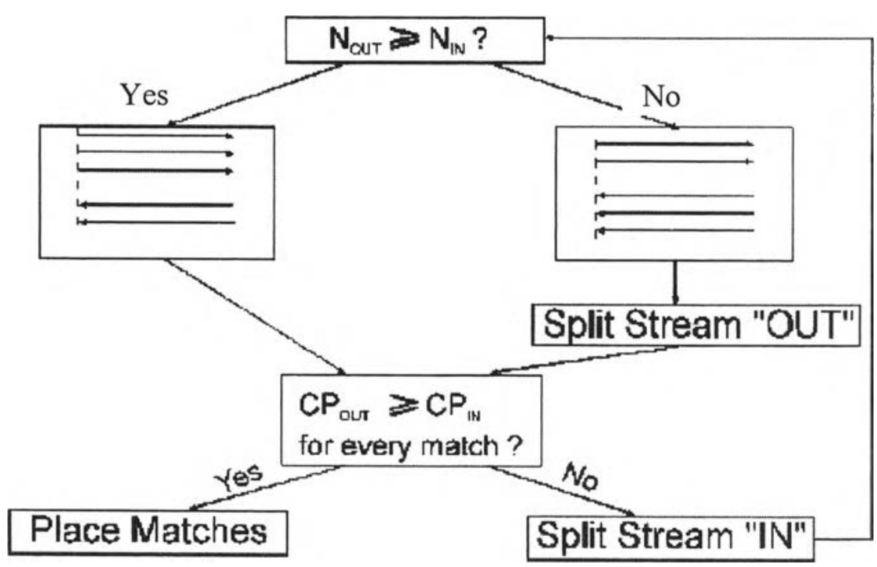

Figure 2.11 The algorithm for stream splitting at pinch point.
(Linnhoff March Limited, 1998)

2.2.4 The "Tick-Off" Heuristic

When the matches were selected, the heat duty of the match will be set so that the capital cost of the network is minimum. This will be achieved when the number of heat exchangers employed in the network is minimum. This is satisfied when every pinch match brings one streams to its target temperature or exhausts a utility. In this case, the match is said to be "tick-off" the stream or utility. This can be done by setting the heat load of the matches to the smaller heat load of the two streams matched.

2.2.5 Complete the Network

After the pinch matches are completed, the designer will have more choices to satisfy the process objectives. The number of feasible solution can be obtained in this stage. However, the process constraints such as start-up, operation flexibility, safety, etc. must be included in the consideration during the design.

2.2.6 Network Evolution

After the network has been designed according to the pinch design rules it can be subjected to further simplification and capital-energy optimization.

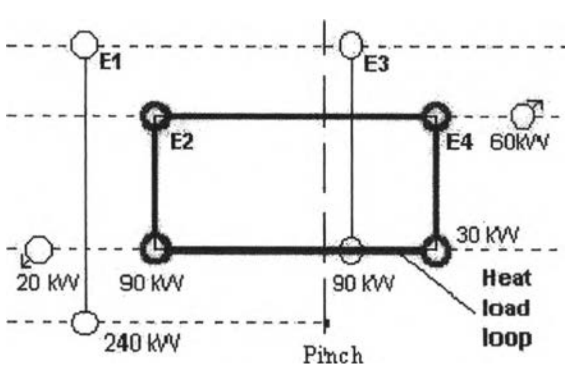

Figure 2.12 Heat load loop (Linnhoff March Limited, 1998)

Figure 2.12 shows a degree of freedom called the "Heat Load Loop". The loop is shown by the solid line marking a circuit between matches 2 and 4. Heat duties can be shifted around a loop without affecting the heat duties imposed on other units in the network, which are not part of the loop. This may result in reducing the heat load on a unit to zero (e.g. exchanger 4). However, such a change will affect the temperature driving forces in the network. The temperature driving force will become less than ΔT_{min} and in some cases it may result in temperature infeasibility.

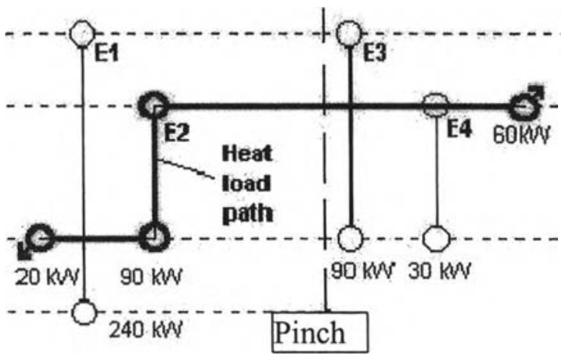

Figure 2.13 Head load path. (Linnhoff March Limited, 1998)

Figure 2.13 illustrates the second degree of freedom for network evolution called the "Heat Load Path". A path provides a continuous connection between two utilities and therefore allows the transfer of heat loads between heat exchanger units and the utilities. In Figure 2.13 the path connects heater, exchangers 2, 4 and the cooler. By changing the heat loads of exchangers 2 or 4, the heater and cooler heat loads will change by the same amount but in an opposite manner. The heating duty can be eliminated if the duty on exchanger 2 is increased by the corresponding amount. Then the cooling duty must also be decreased by this amount to maintain the energy balance on the hot stream. Heat load paths exploit capital-energy trade-off in specific parts of the network.

Heat load loops and paths provide additional degrees of freedom for the designer in order to further simplify the network or reduce the overall network cost.

2.3 The Pinch Design Method for Heat Exchanger Network Retrofit

Energy saving retrofit projects differs from those involving the design of new plants in two important aspects. First, with grass-root projects it is possible to obtain a reasonably accurate prediction of the relationship between capital expenditure and heat recovery without undertaking any design work. In the retrofit, the opportunities cannot be identified without undertaking some design calculations.

Thus, in retrofit projects, the aim of applying economic analysis to the basic stream data is the identification of energy saving opportunities. Evaluation of these opportunities involves combination of design calculation and economic analysis.

Second, the economic analysis applied in retrofit differs from that used in grass-root projects. In the case of grass-root projects the economics is evaluated in terms of capital cost and return on investment. With retrofits the economics are usually evaluated in terms of payback time and capital investment.

2.3.1 Identification of Energy Saving Opportunities

The algorithm for the pinch technology described above can be used to determine the energy consumption and the network area as a function of ΔT_{min} as shown in Figure 2.14.

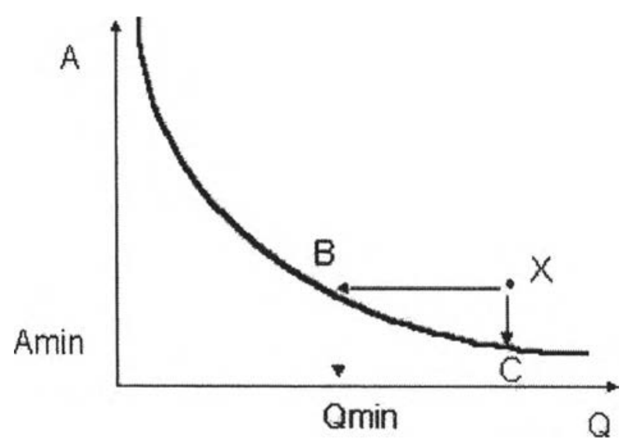

Figure 2.14 Ideal relationships between area-energy. (Tjoe and Linnhoff, 1986)

The existing system, positioned at point X, is found to make quite poor use of the installed heat recovery area. Given the quantity of heat consumed the surface area given by point C is required. With the quantity of surface actually installed, the system could be operated with a quantity of energy associated with point B.

In practice, the investment is required for changing the existing network, thus increasing area. Therefore, the retrofit path is the most important in the identification of saving opportunity. Many approaches have been proposed, the assumption that is used for setting retrofit path is to follow the path that parallel to the ideal area/energy relationship. This path can be translated into saving/investment plot as shown in Figure 2.15.

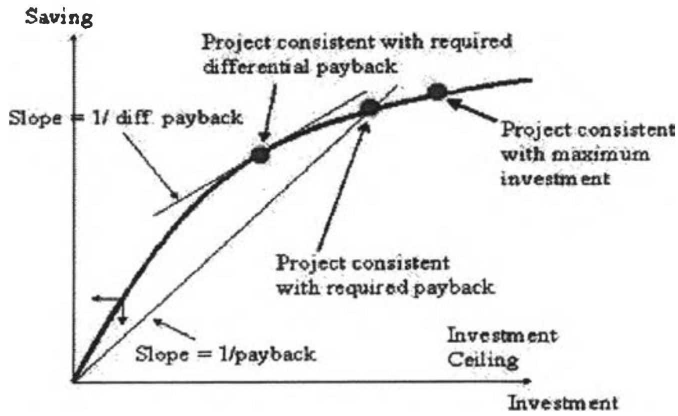

Figure 2.15 Saving-Investment relationships. (Tjoe and Linnhoff, 1986)

When one of the economic criterions, for example, capital expenditure or payback time, is specified the saving opportunity can be obtained directly from the plot. Also, the minimum temperature difference for the retrofit design will be indirectly obtained. Now, the value of saving opportunity and the minimum temperature difference of the project are obtained. Next step is to make change to the existing network to achieve the opportunity.

2.3.2 Retrofit Design

After minimum temperature difference is obtained. The grid diagram for the existing network will be redrawn with the new value of ΔT_{min}. The idea of the retrofit design is to identify the cross-pinch heat exchangers then modify them to minimize the cross-pinch heat transfer.

The steps in retrofit design are as follows:

1) Identify cross-pinch heat exchangers

2) Eliminate cross-pinch heat exchangers from the network.

3) Complete the network by positioning new exchangers using PDM and, where possible, reuse exchangers removed in Step 2.

4) Evolve improvement by improving compatibility with existing network via heat load loops and paths. Reuse area of existing exchangers as much as possible.

2.4. Process Integration

Process heat and power integration has a significant impact on the overall process design. Therefore, it cannot be considered in isolation. It must be considered as an integral part of the system design or "synthesis". Many decomposition schemes have been proposed to break down the design of chemical process systems into subsystems, promoting a systematic and structured approach to synthesis.

Distillation columns are one of the major energy consumption units in chemical processes. The principles for appropriate modifications of distillation columns and their integration with the remaining process are considered. Firstly, pinch analysis for stand-alone modification of distillation columns is considered, followed by principles for appropriate integration of distillation columns with the remaining process.

2.4.1 Stand-Alone Column Modifications (Column Targeting)

There are several options for improving energy efficiency of distillation columns. These include reduction in reflux ratio, feed conditioning and side condensing/reboiling etc. Using pinch analysis it is possible to identify which one of these modifications would be appropriate for the column and what would be the extent of the modification.

The tool used for column thermal analysis is called the Column Grand Composite Curve (CGCC) (Dhole and Linnhoff, 1993). The procedure for obtaining the CGCC starts with a converged column simulation as shown in the Figure 2.16. From the simulation, the necessary column information is extracted on a stage-wise basis. This information can then processed to generate the CGCC.

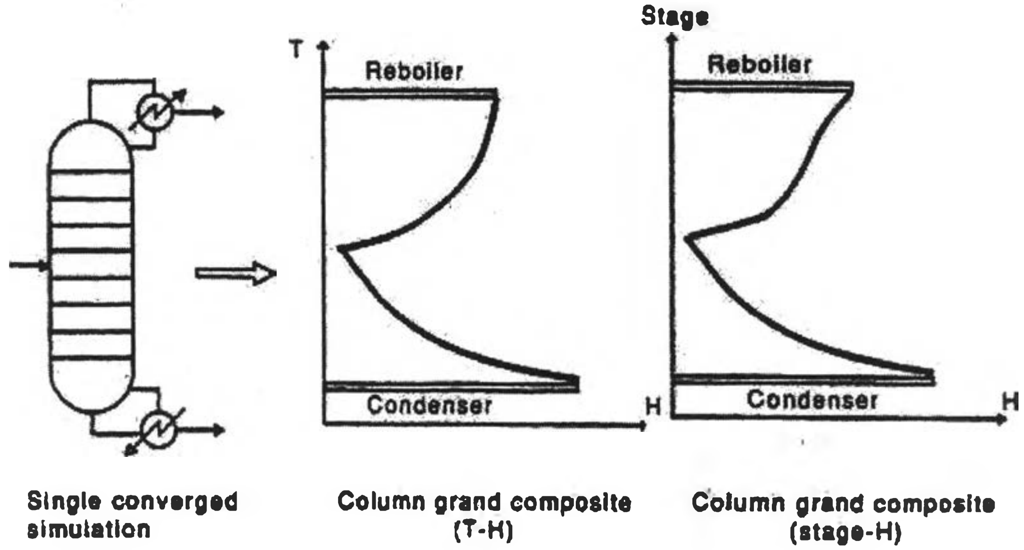

Figure 2.16 The CGCC from a single converged simulation.
(Dhole and Linnhoff, 1993)

The CGCC like the grand composite curve for a process provides a thermal profile for a column and is used for identifying appropriate targets for column modifications such as side condensing and reboiling. In a normal column energy is supplied and rejected to the column at the reboiling and condensing temperatures. The CGCC relates to the minimum thermodynamic loss in the column or ideal column operation. For ideal column operation the column requires infinite number of stages and infinite numbers of side reboilers and condensers as shown in Figure 2.17. In this limiting condition, the energy can be supplied to the column along the temperature profile of the CGCC instead of supplying it at extreme reboiling and condensing temperatures. The CGCC is plotted in either T-H or stage-H dimensions. The occurrence of pinch point on the CGCC is usually caused by the feed.

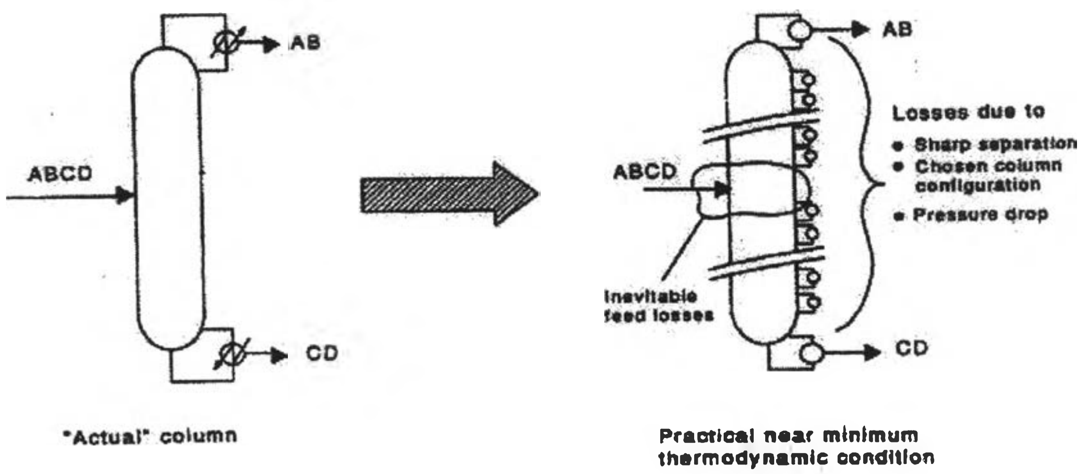

Figure 2.17 practical near-minimum thermodynamic conditions (PNMTC). (Dhole and Linnhoff, 1993)

2.4.1.1 Modifications using the Column Grand Composite Curve

Figure 2.18 shows the use of the CGCC in identifying appropriate stand-alone column modifications. Firstly, the feed stage location of the column must be optimized in the simulation prior to the start of the column thermal analysis. This can be carried out by alternating feed stage location in simulation and evaluating its impact on the reflux ratio. The feed stage optimization is carried out first since it may interact with the other options for column modifications. The CGCC for the column is then obtained.

As shown in Figure 2.18 (a), the horizontal gap between the vertical axis and CGCC pinch point indicates the scope for reflux improvement in the column. As the reflux ratio is reduced, the CGCC will move close to the vertical axis. The scope for reflux improvement must be considered prior to other thermal modifications since it results in direct heat load saving in both at the condenser and reboiler level. In an existing column, the reflux can be improved by adding stages or improving the efficiency of the existing stages.

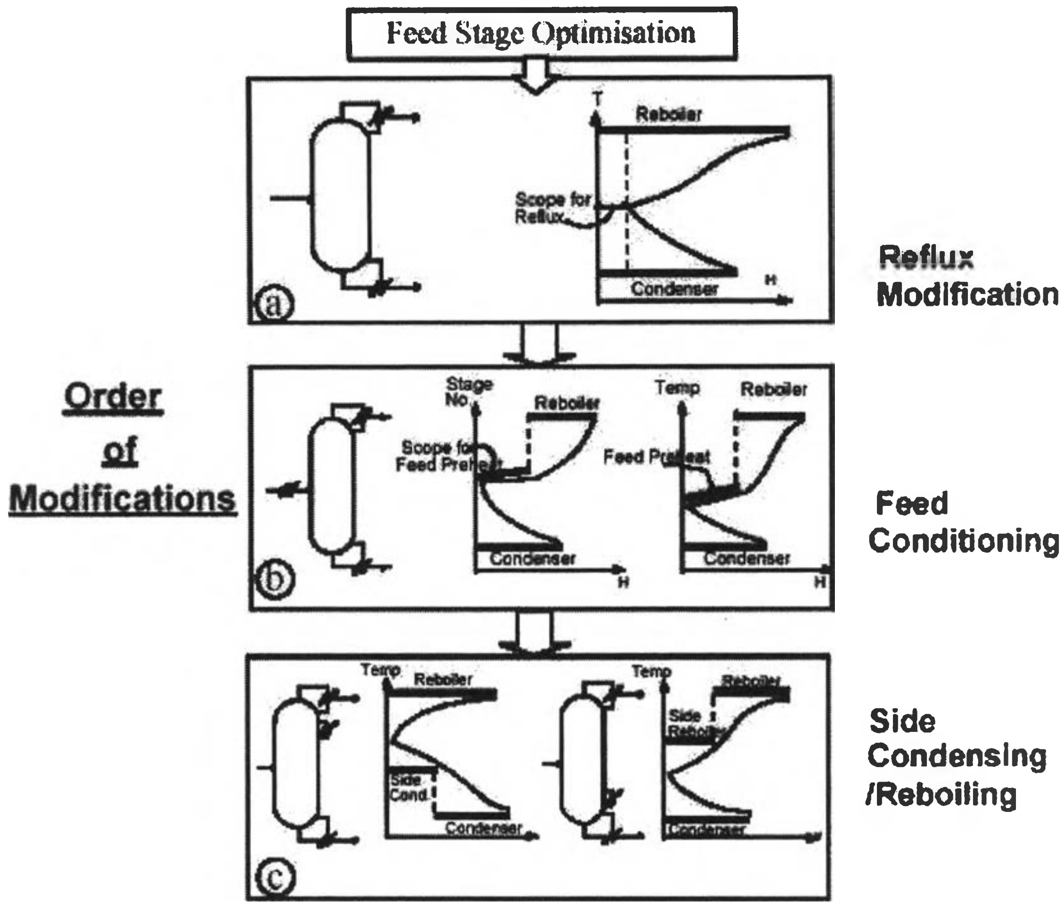

Figure 2.18 Using Column Grand Composite Curve to identify column modifications (Dhole and Linnhoff, 1993).

After reflux improvement, the next priority is to evaluate the scope for feed preheating or cooling (see Figure 2.18 (b)). This is identified by a sharp enthalpy change in the stage-H CGCC shape close to the feed as shown in Figure 2.18 (b) with a feed preheating example. The extent of sharp enthalpy approximately indicates the scope for feed preheating. Successful feed preheating allows heat load to be shifted from reboiler temperature to the feed preheating temperature. Analogous procedure applies for feed pre-cooling.

After feed conditioning, side condensing/reboiling should be considered. Figure 2.18 (c) describes CGCC's, which show potential for side condensing and reboiling. An appropriate side reboiler allows heat load to be shifted to be shifted from reboiler temperature to the feed preheating temperature. Analogous procedure applies for feed pre-cooling.

After feed conditioning, side condensing/reboiling should be considered. Figure 2.18 (c) describes CGCC's, which show potential for side condensing and reboiling. An appropriate side reboiler allows heat load to be shifted from the reboiling temperature to the side reboiling temperature without significantly reflux penalty.

In general, feed conditioning offers a more moderate temperature level than side condensing/reboiling. Also feed conditioning is external to the column and easier to implement than side condensing and reboiling. The sequence for different column modifications can be summarized as follows.

1. Feed stage location
2. Reflux improvement
3. Feed preheating/cooling
4. Side condensing/reboiling

2.4.2 Column Integration

In the previous section, ways of improving column thermal efficiency by stand-alone column were considered. In many situations, it is possible to further improve the overall energy efficiency of the process by appropriate integration of the column with the background process. By column integration, a heat exchange link is implied between column heating/cooling duties and the process heating/cooling with utility levels. Figure 2.19 summarized the principles for appropriate column integration with the background process.

Figure 2.19 (a) shows a column with a temperature range across the pinch temperature of the background process. The background process is represented by its grand composite curve. The overall energy consumption in this case is equal to that of the column plus the background process. In other words, there is no benefit in integrating the column with the background process. The column is therefore inappropriately placed as regards to its integration with the background process.

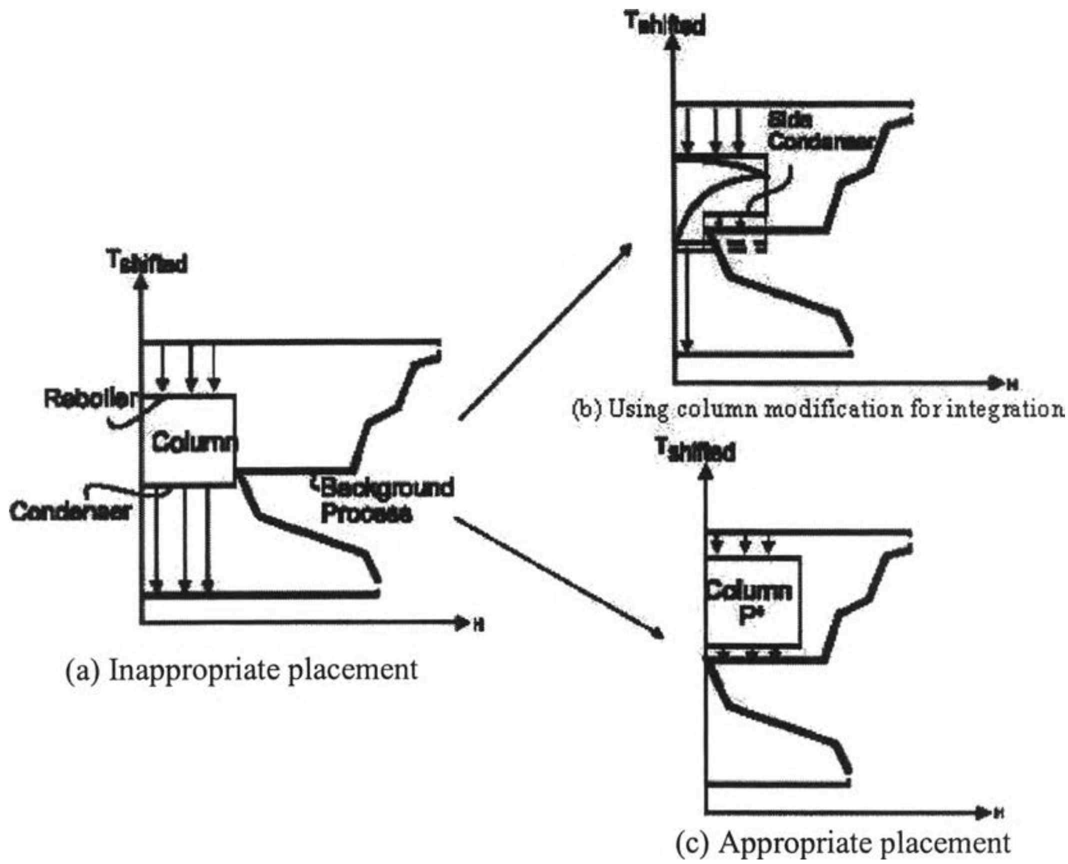

Figure 2.19 Appropriate integration of a distillation column with the background process. (Linnhoff March Limited, 1998).

As an alternative the column pressure could be increased. This will allow a complete integration between the column and the background process via the column condenser as shown in Figure 2.19 (c). The column is now on one side of the pinch (not across the pinch). The overall energy consumption (column and background process) equals the energy consumption of the background process. Energy-wise, the column is running effectively for free. The column is therefore appropriately placed as regards its integration with the background process.

To summarize, the column is inappropriately placed when it is placed across the pinch and has no potential for integration with the background process via side condensers or reboilers and the like. The integration opportunities are enhanced by stand-alone column modification such as feed conditioning and side condensing/reboiling. The column is appropriately placed if it lies on one side of the

To summarize, the column is inappropriately placed when it is placed across the pinch and has no potential for integration with the background process via side condensers or reboilers and the like. The integration opportunities are enhanced by stand-alone column modification such as feed conditioning and side condensing/reboiling. The column is appropriately placed if it lies on one side of the pinch and can be accommodated by the grand composite curve of the background process.

Appropriate column integration can provide substantial benefits. However, these benefits must be compared against associated capital investment and difficulties in operation. In some cases, it is possible to integrate the column indirectly via the utility system, which may reduce operational difficulties.

2.5 Literature Survey

2.5.1. Applications of Pinch Technology

Pinch technology (PT) is proved to be important for engineers to analyze and design chemical processes (Stankiewicz, 1993). By allowing engineers to track the heat or pressure flow all process streams within a plant, PT made it easier to integrate plant design. Rearranging equipment, such as reactors, evaporators, pumps, distillation columns, and separators, can make unit operations more efficient, in energy consumption such as heat exchanger networks. It is available to automate the redesign process and PT is set to move beyond energy, into pressure drop optimization and distillation columns sequencing.

Moreover, the pinch concept is also used to develop a procedure to optimize a licensor's design for complex processes with many utilities and unit operations (Trivedi *et al.*, 1996). The procedure included a method to set the marginal cost for various utility levels. It also illustrates how to use composite and grand composite curves to set the level and load of various. In addition, the method optimizes distillation column using the concepts of column grand composite curves.

In addition to the use of PT as a design tool, it can be combined with exergy analysis to develop a method for process modification (Feng and Zhu, 1997). The graphical representation of pinch analysis combines with the power to identify the cause of thermodynamic imperfection was used to represent the whole system. Omega-H diagram was proposed, energy and exergy balance can be represented in this diagram which helps the process analyst to view the performance and set the target for improvement, and modification can be located by viewing the imperfection of the existing process. The same idea was also applied to heat exchanger network analysis (Sorin and Paris, 1997). Heat exchanger network was treated as a single unit operation, which simplifies the graphical representation of exergy and reduces the computational efforts.

2.5.2. The Pinch Design Method for heat exchanger network design

Linnhoff and Ahmad (1990a) presented a simple methodology for the design of near optimum heat exchanger networks with energy-capital trade-off consideration. The approach is based on setting cost targets, optimizing these targets prior to the design by using simple capital cost model, which gives the results within 5 percent of the optimum solution. The detailed capital cost models, which consider the different in heat transfer coefficient, non-linear heat exchanger cost law, non-counter current exchanger, non-uniform material of construction, pressure rating and exchanger type in the network, gives the more accurate results (Ahmad, Linnhoff and Smith, 1990b).

To make a design economically, most of designers are trying to optimize the use of intermediate utilities. In this situation, the utility pinches are created in the network problems. The PDM is suited for just only one pinch point in the problem. Therefore, Jezowski (1992) reviewed a PDM for multiple pinches problems. The design is started by defining the inverse pinch point. This point will separate a region between pinches into two sub-regions. The PDM proposed by Linnhoff and Hindmarsh (1983) was used for designing with some guidance. The design is started from both pinches simultaneously. The solutions obtained feature the maximum energy recovery and minimum number of units.

The shortfalls of PDM were discussed by Polley and Heggs (1999). Firstly, the designs obtained can be non-optimal designs. Secondly, the nature of process streams is not accounted. Thirdly, it does not consider the impact of network on plant piping and process flow. Finally, the software involved usually complicated and they cannot give an optimal design. A problem decomposition analysis is used for the design instead of PDM. The design obtained is a network in local, which is easily to operate and low cost. The procedure is started from problem simplification, identified the process changes, setting the final problem, decomposition analysis based on flowsheet and decomposition on a thermal basis.

2.5.3. The Pinch Design Method for heat exchanger network retrofit

The parameter concerning with the cost of matching was considered in a new approach for heat exchanger network retrofit (Carlsson, Franck and Berntsson, 1993). The criss-cross matching was believed to give a lower cost solution comparing to the vertical matching. In this approach, the cost of match includes the effect of other parameters. The match cost matrices was proposed. The matrices show the type of matching, cost of matching. The designers will select the match and the new matrices will be calculated for the remaining part. The networks cost is the sum of these chosen matches.

Polley and Amidpour (2000) showed the procedure for retrofitting industrial heat exchanger networks. They indicated that the capital investment and payback time are the important economic indicators for process retrofit. The saving-investment plot was used to determine the retrofit target. The retrofit analysis was started by comparing the performance of the existing unit with the ideal relationship via area efficiency. The analysis is based on assumption that any new area has at least the same efficiency as the existing one. In conventional method, the cross-pinch exchangers were identified and then modified. They also indicated the disadvantages of the existing method. At the same time, they proposed the new procedure by identifying the structure of the revamped units in the first stage and then energy-investment trading-off will be done to size and modify the exchangers.

2.5.4. Process Heat Integration

A process heat integration is concerned about the integration of heat engines, heat pumps, distillation columns with the background processes to achieve as high as benefits over stand alone one. A criterion for placement of heat engines and heat pumps in process networks was first presented by Townsend and Linnhoff

(1983a). The criterion proposed is based on the process network pinch. The appropriate placement is the placement at which we can get advantages over the stand alone engines or pumps. For the heat engines, they showed that an appropriate placement is to place them at either above or below pinch but not across process pinch. The situation for heat pumps is opposite. The appropriate placement in this case is to place them across the pinch. They also showed that to get the 100 percent efficiency using the real engines, we have to use a large number of engines connected in series. In addition, they discussed that in practical, we can never achieve a fully appropriate integration due to the heat has to cross the pinch to the ambient. With this development, an application to distillation column was developed in a next few months.

Townsend and Linnhoff (1983b) applied the use of the criterions proposed above for selection of the best practical technology for any design systems. The process source/sink profile was introduced in this procedure. The procedure is based on the pinch analysis. This method can always form a point of reference and take account of practical design constraints. The procedure can be used to evaluate options at the preliminary design stage and to identify the preferred configuration for chemical and other processes involving integrated heat recovery and power generation. The procedure represents a breakthrough in the general area of process synthesis that takes into account the fundamental importance of the heat recovery pinch.

The development of an approach for shaft-work targeting directly from process data using pinch analysis (PA) was important in designing low-temperature process (Linnhoff and Dhole, 1992). The approach bypasses the design of both heat exchanger network (HEN) and refrigeration system. The combination of PA and exergy concepts was used in developing the method. Comparison with the existing method, in which shaft-work is determined from the refrigeration load, the proposed approach is simpler. It provides a strong tool for understanding and assisting the designer to find the best HEN and refrigeration system simultaneously. An ethylene process design study was chosen for illustrating the approach.