CHAPTER II
BACKGROUND AND LITERATURE SURVEY

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 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.

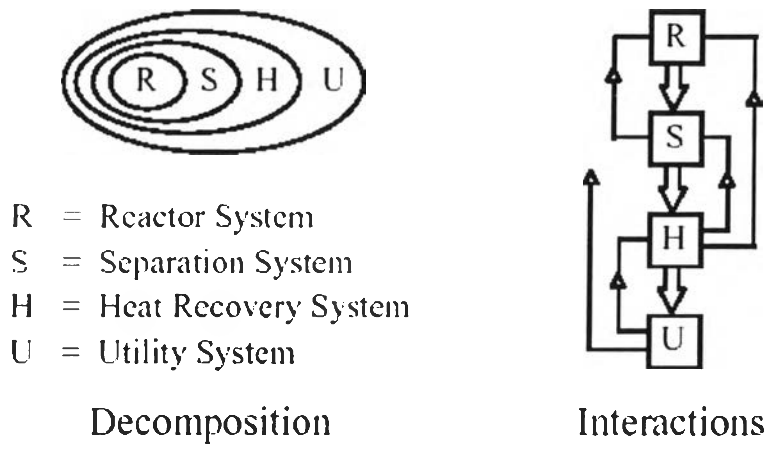

Figure 2.1 "Onion Diagram" of Hierarchy in Process Design.
(SINTEF Energy Research 2002)

Another frequently used representation, especially within Pinch Technology, is the Rubic Cube as shown in Figure 2.2. It indicates the start of Pinch Technology, focusing on Heat Exchanger Networks with minimum energy consumption for grassroots designs. During the 80's and the 90's, Pinch Technology has expanded in all three dimensions of the cube to cover almost complete Process design.

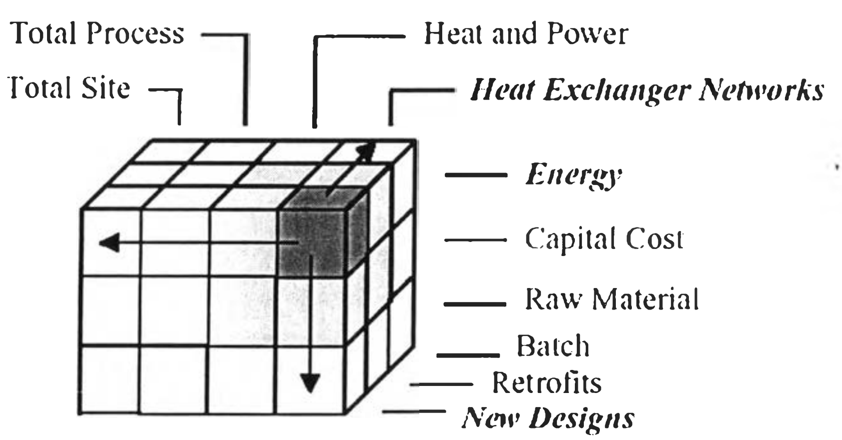

Figure 2.2 The Rubic Cube Indicating the Development of Pinch Technology.

2.1 Basis of Pinch Analysis

Pinch Technology presents a simple methodology for systematically analyzing chemical processes and the surrounding utility systems with the help of the first and second laws of thermodynamics. The first law of thermodynamics provides the energy equation for calculating the enthalpy changes (H) in the steams passing through a heat exchanger. The second law determines the direction of heat flow, which is that heat only flows from hot to cold stream. This prohibits temperature crossovers of the hot and cold steam profiles through the exchanger unit. In a heat exchanger unit neither a hot steam can be cooled below cold steam supply temperature nor a cold steam can be heated to a temperature larger than the supply temperature of hot steam. In practice the hot steam can only be cooled to a temperature defined by the minimum temperature approach of the heat exchanger. The minimum temperature approach is the minimum allowable temperature difference (ΔTmin) in the steam temperature profiles, for the heat exchanger unit. The temperature level at which ΔTmin is observed in the process is referred to as pinch point or pinch condition. The pinch defines the minimum driving force allowed in the exchanger unit.

2.2 Data Extraction Flowsheet

Data extraction relates to the extraction of information required for Pinch Analysis from a given process heat and material balances. Figure 2.3(a) shows an example process flow-sheet involving a two stage reactor and a distillation column. The process already has heat recovery, represented by the two process to process heat exchangers. The hot utility demand of the process is 1200 units (shown by H) and the cold utility demand is 360 units (shown by C). Pinch Analysis principles will be applied to identify the energy savings potential (or target) for the process and subsequently to aid the design of the heat exchanger network to achieve energy savings target.

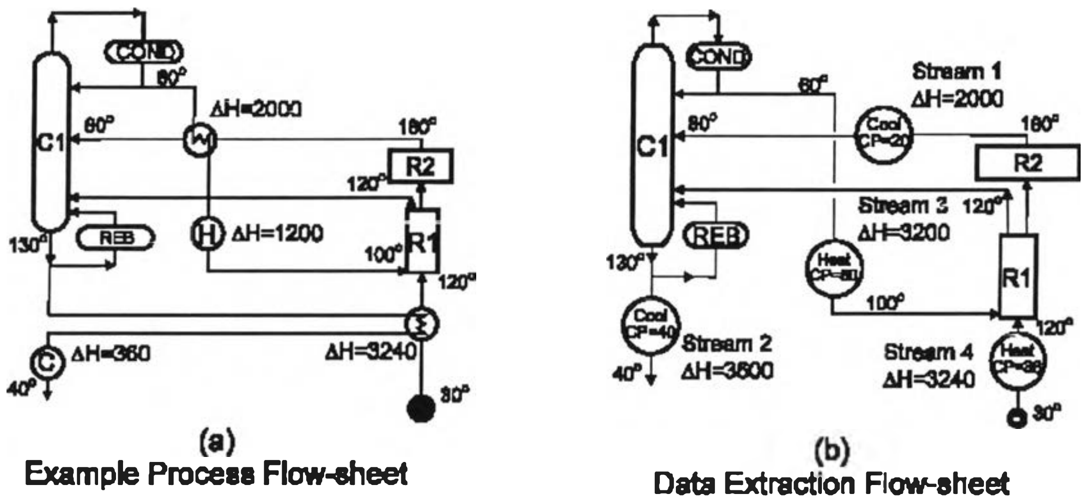

Figure 2.3 Data Extraction for Pinch Analysis. (Linnhoff and Hindmarsh, 1983)

In order to start the Pinch Analysis the necessary thermal data must be extracted from the process. This involves the identification of process heating and cooling duties. Figure 2.3(b) shows the flow-sheet representation of the example process which highlights the heating and cooling demands of the streams without any reference to the existing exchangers. This is called the data extraction flow-sheet representation. The reboiler and condenser duties have been excluded from the analysis for simplicity. In an actual study however, these duties should be included. The assumption in the data extraction flow-sheet is that any process cooling duty is available to match against any heating duty in the process. No existing heat exchanger is assumed unless it is excluded from Pinch Analysis for specific reasons.

2.3 Steps of Pinch Analysis

In any Pinch Analysis problem, whether a new design project or a retrofit situation, a well-defined stepwise procedure is followed. It should be noted that these steps are not necessarily performed on a once-through basis, independent of one another. Additional activities such as re-simulation and data modification occur as the analysis proceeds and some iterations between the various steps are always required, as shown in Figure 2.4.

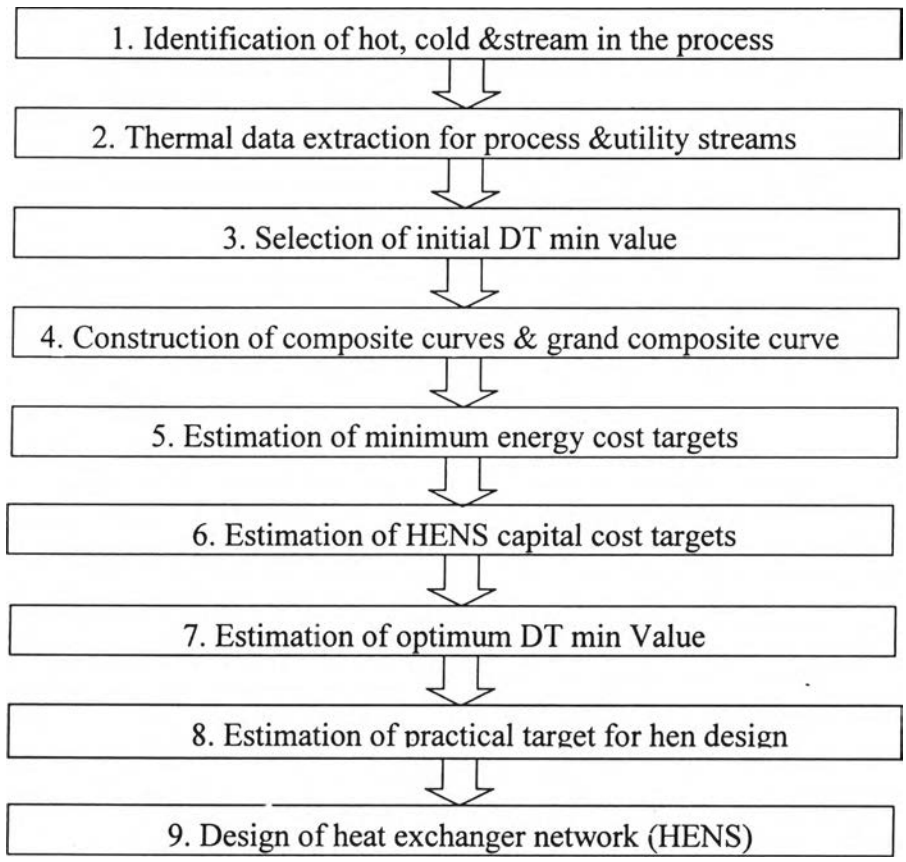

Figure 2.4 Steps of Pinch Analysis. (Linnhoff and Hindmarsh, 1983)

2.3.1 Identification of the Hot, Cold and Utility Streams in the Process

1. Hot Streams are those that must be cooled or are available to be cooled. e.g. product cooling before storage
2. Cold Streams are those that must be heated e.g. feed preheating before a reactor.
3. Utility Streams are used to heat (hot utilities) or cool (cold utilities) process streams, when heat exchange between process streams is not practical or economic.

The identification of streams needs to be done with care as sometimes, despite undergoing change in temperature, the stream is not available for heat exchange such as the stream that temperature rises because of the conversion of mechanical energy into heat.

2.3.2 Thermal Data Extraction for Process & Utility Streams

Hot streams are referred to streams that required cooling i.e. the supply temperature (TS) is higher than the target temperature (TT). While the cold streams are referred to those required heating. i.e. the target temperature is higher than the supply temperature. Therefore, in thermodynamic law, it must have heat exchanging between hot and cold streams:

1. Supply temperature (TS °C) : the temperature at which the stream is available.
2. Target temperature (TT °C) : the temperature the stream must be taken to.
3. Heat capacity flow rate (CP kW/°C) : the product of flow rate (m) in kg/sec and specific heat (Cp kJ/kg °C).

$$CP = \dot{m} \times Cp$$

4. Enthalpy Change (H) associated with a stream passing through the exchanger is given by the First Law of Thermodynamics without mechanical work:

$$\text{Enthalpy change, } H = CP \times (TS - TT)$$

** Here the specific heat values have been assumed to be temperature independent within the operation range.

2.3.3 Selection of Initial ΔTmin Value

The temperature of the hot and cold streams at any point in the exchanger must always have a minimum temperature difference (ΔTmin). This ΔTmin value represents the bottleneck in the heat recovery. Thus, at any point in the exchanger

$$\text{Hot stream Temp. } (T_H) - (T_C) \text{ Cold stream Temp.} \geq \Delta Tmin$$

The value of ΔTmin is determined by the overall heat transfer coefficient (U) and the geometry of the heat exchanger. In network design, the type of the heat exchanger will determine the practical ΔTmin for the network, for example, an initial selection for shell and tubes may be 3-5 °C. The heat transfer equation, which relates Q, U, A and LMTD (Logarithmic mean Temperature difference) is depicted in Figure 2.5.

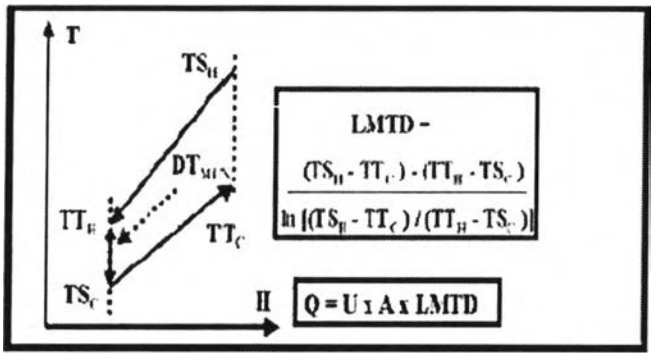

Figure 2.5 Heat Transfer Equation. (www.cheresources.com)

For a given value of heat transfer load (Q), if smaller values of ΔTmin are chosen, the area requirements rise causing the heat recovery in exchanger increase and demand of external utilities decrease. Thus, the selection of ΔTmin value has implications for both capital and energy costs.

Just as for a single heat exchanger, the choice of ΔTmin (or approach temperature) is vital in the design of a heat exchanger networks. To begin the process an initial ΔTmin value is chosen and pinch analysis is carried out. Typical ΔTmin values are base on experience, available in literature for reference. A few values based on Linnoff March's application experience are tabulated below in Table 2.1 for shell and tube heat exchangers.

Table 2.1 Typical ΔTmin Values Reference (www.cheresources.com)

No	Industrial Sector	Experience DT_{min} Values
1	Oil Refining	20-40°C
2	Petrochemical	10-20°C
3	Chemical	10-20°C
4	Low Temperature Processes	3-5°C

2.3.4 Construction of Composite Curves and Grand Composite Curves

COMPOSITE CURVES: Temperature – Enthalpy (T-H) plots have been used for many years to set energy targets ahead of design. They consist of temperature (T)-enthalpy (H) profiles of heat availability in the process (the hot composite curve) and heat demands in the process (the cold composite curve) together in the graphical representation. In general any stream with a constant heat capacity (CP) value is represented on a T - H diagram by a straight line running from supply to target temperature. When there are a number of hot and cold streams, the construction of hot and cold composite curves simply involves the addition of the enthalpy changes of the streams in the respective temperature intervals. An example of hot composite curve construction is shown in Figures 2.6(a) and (b).

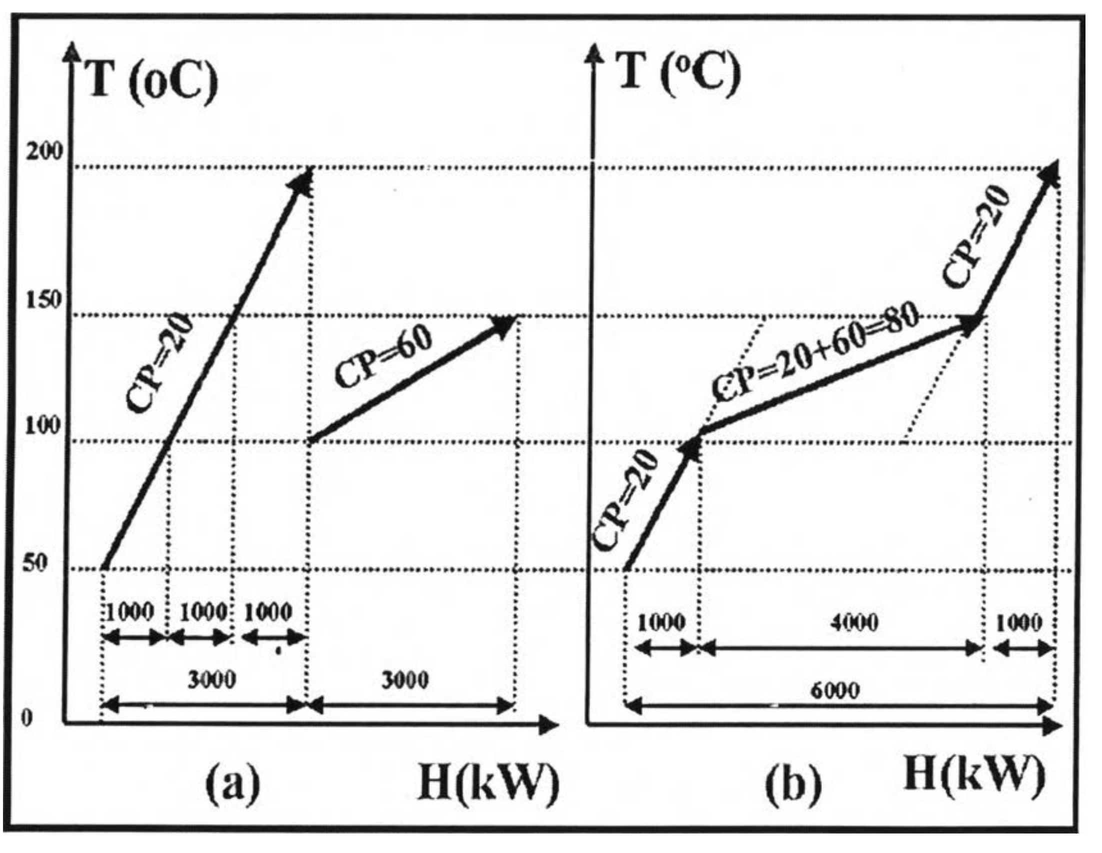

Figure 2.6 Temperature-Enthalpy Relations use to Construct Composite Curves. (Linnhoff, 1982)

For transferring heat from the hot to cold stream, the hot composite curve must lie above the cold composite curve. Because of the kinked nature of the composite curves (Figure 2.7), they approach each other most closely at one point defined as the minimum approach temperature (ΔTmin). This point of minimum temperature difference represents a bottleneck in heat recovery and is commonly referred to as the Pinch. At a particular ΔTmin value, the overlap shows the maximum possible scope of heat recovery within the process. The overshoots of hot and cold ends indicate minimum hot and cold utility requirements (QHmin and QCmin), respectively, of the process for the chosen ΔTmin.

To summarize, the composite curves provide overall energy targets but do not clearly indicate how much energy must be supplied by different utility levels. The utility combination is determined by the Grand Composite Curve.

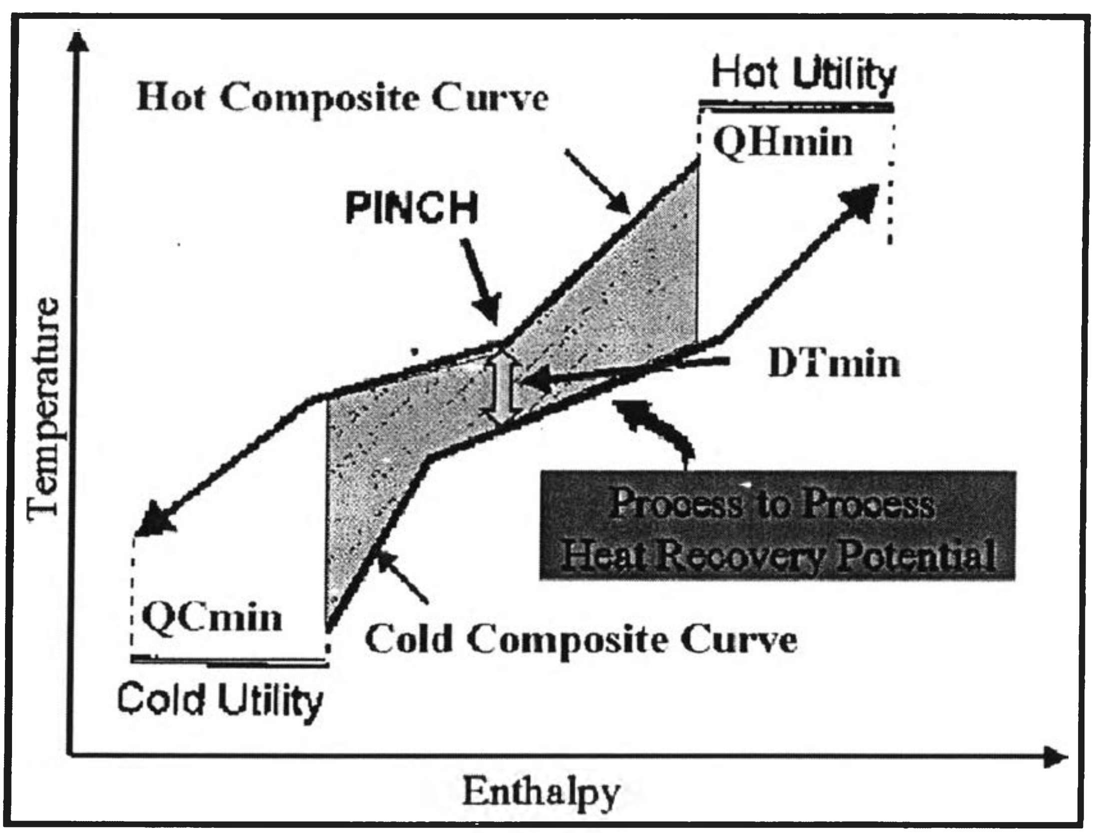

Figure 2.7 Combined Composite Curves.

GRAND COMPOSITE CURVE (GCC) : The introduction of a new tool, the Grand Composite Curve (GCC), was introduced in 1982 by Itoh, Shiroko and Umeda. The GCC (Figure 2.8) shows the variation of heat supply and demand within the process. Using this diagram, the designer can find which utilities are used. The designer aims to maximize the use of the cheaper utility levels and minimize the use of the expensive utility levels to reach the energy cost savings.

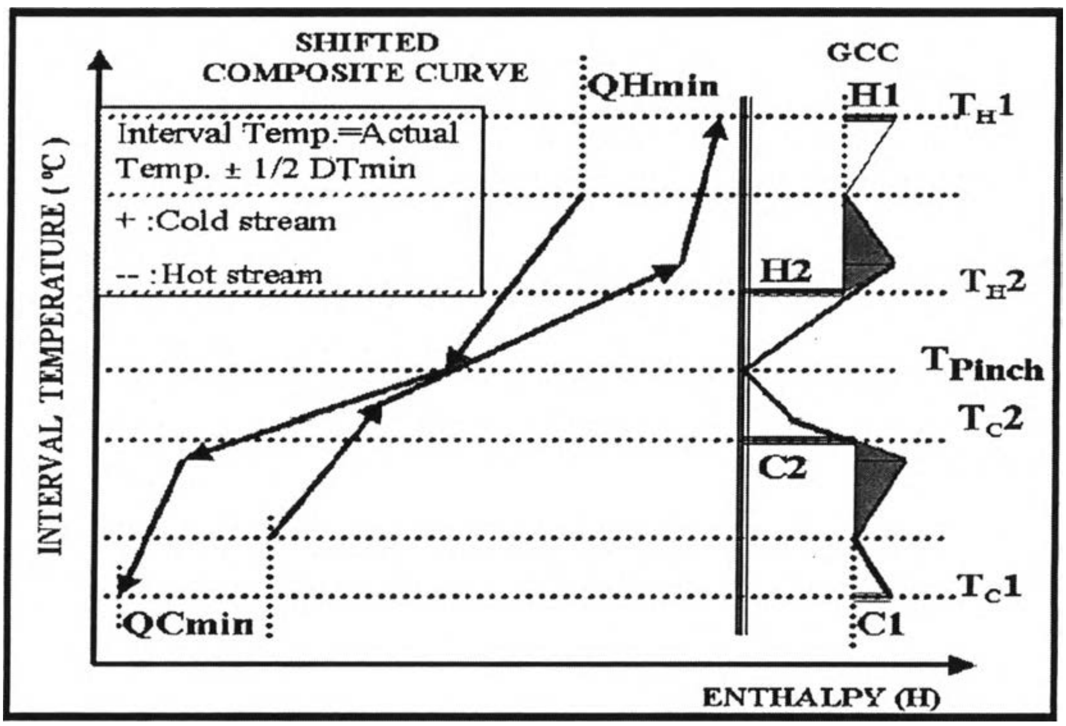

Figure 2.8 Grand Composite Curve.

The method involves shifting (along the temperature [Y] axis) of the hot composite curve down by ½ ΔTmin and that of cold composite curve up by ½ ΔTmin. The Grand Composite Curve is then constructed from the horizontal enthalpy differences between the shifted composite curves at different temperatures. On the GCC, the horizontal distance between two composite curves at the highest temperature scale shows the overall hot utility consumption of the process.

Figure 2.8 shows that it is not necessary to supply the hot utility at the top temperature level. The GCC indicates that we can supply the hot utility over two temperature levels T_{H1} (HP steam) and T_{H2} (LP steam). Recall that, when placing utilities in the GCC, intervals and utility temperatures should not be used. The total minimum hot utility requirement remains the same: QHmin = H1 (HP steam) + H2 (LP steam). The points T_{H2} and T_{C2} where the H2 and C2 levels touch the grand composite curve are called the "Utility Pinches." The shaded pockets represent the process-to-process heat exchange.

2.3.5 Estimation of Minimum Energy Cost Targets

From the minimum energy requirements of composite curves and the utility levels selected from GCC, the total energy cost can be calculated if the unit cost of each utility is known by using the energy equation given below. (Linnhoff and Polley, 1988)

$$\text{Total energy cost} = \sum_{U=1}^{U} Q_U * C_U$$

Where Q_U = Duty of utility U ,kw

C_U = Unit cost of utility U ,$kw/yr

U = Total number of utilities used

2.3.6 Estimation of Capital Cost Heat Exchanger Networks (HENS)

The capital cost of a heat exchanger network depends upon:

1. The number and type of exchangers
2. The overall network area,
3. The distribution of area between the exchangers

Setting Area Targets

The composite curves make it possible to determine the energy targets for a given value of ΔTmin. The composite curves can also be used to determine the minimum heat transfer area required to achieve the energy targets:

$$\text{Network Area, } A_{min} = \sum_i \left[\frac{1}{\Delta T_{LM}} \sum_j \frac{q_j}{h_j} \right]$$

where:

i: denotes *i*th enthalpy interval

j: *j*th stream

ΔT_{LM}: log mean temperature difference in interval

q_j: enthalpy change of *j*th stream

h_j: heat transfer coefficient of *j*th stream

This target area is based on the assumption that "vertical" heat exchange will be adopted between the hot and the cold composite curves across the whole enthalpy range as shown in Figure 2.9. This vertical arrangement, which is equivalent to counter-current area within the overall network, has been found to give a minimum total surface area. For a case where the process streams with uniform heat transfer coefficients is rigorous. In a new design situation, it should design a network close to these new design targets.

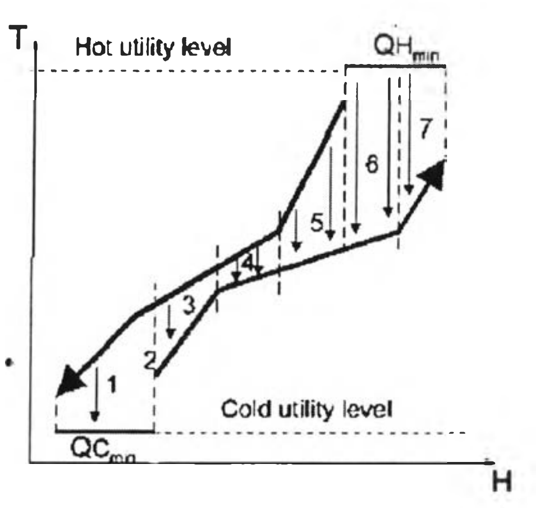

Figure 2.9 Vertical Heat Transfer Between the Composite Curves Leads to Minimum Network Surface Area.

Setting Minimum Number of Units Target

It is also possible to set a target for the minimum number of heat exchanger units in a process. The minimum number of heat exchange units depends fundamentally on the total number of process and utility streams (N) involved in heat exchange. This can also be determined prior to design by using a simplified form of Euler's graph theorem.

$$U_{min} = N - 1$$

where:

Umin: Minimum number of heat exchanger units

N: Total number of process and utility streams in the heat exchanger network

This equation is applied separately on each side of the pinch, as in an MER (maximum energy recovery) network there is no heat transfer across the pinch and therefore the network is divided into two independent problems: one above, and one below the pinch.

Determining the Capital Cost Target

The targets for the minimum surface area and the number of units (Umin) can be combined together with the heat exchanger cost law equations to generate the targets for heat exchanger network capital cost. The capital cost target can be super-imposed on the energy cost targets to obtain the minimum total cost target for the network as shown in Figure 2.10.

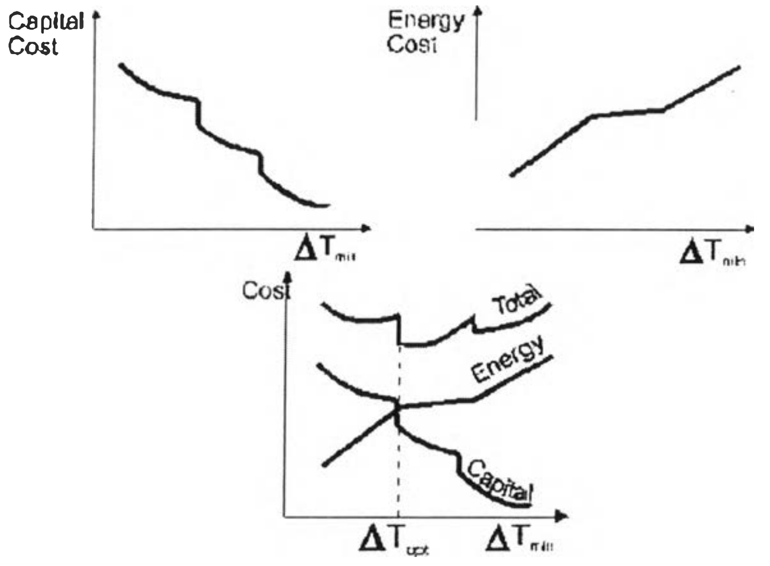

Figure 2.10 The Trade-Off between Energy and Capital Costs gives the Optimum ΔTmin for Minimum Cost in New Designs.

This provides an optimum ΔTmin for the network ahead of design. It is important to note that the capital cost targeting algorithm is based on the simplified assumption that any hot stream can match against any cold stream. It does not consider matching constraints between specific hot and cold streams. Therefore the capital cost targeting technique and ΔTmin optimization is particularly applicable for systems with fewer matching constraints such as atmospheric and vacuum distillation preheat trains, FCC unit, etc..

The above description has assumed direct counter-current heat exchangers. However, in SuperTarget Process there is an additional option to target based on shell and tube exchangers with one shell pass and two tube passes. This is the most common exchanger type found in industrial use.

2.3.7 <u>Estimation of Optimum ΔTmin Value by Energy-Capital Trade off</u>

To achieve an optimum ΔTmin value, the total annual cost is plotted with varying ΔTmin values. Three key observations can be found from Figure 2.11:

a. An increase in ΔTmin values results in higher energy costs and lower capital costs.

b. A decrease in ΔTmin values results in lower energy costs and higher capital costs.

c. An optimum ΔTmin exists where the total annual cost of energy and capital costs are minimized.

Thus, by systematically varying the temperature approach the optimum heat recovery level or the ΔTmin $_{OPTIMUM}$ can be determined for the process.

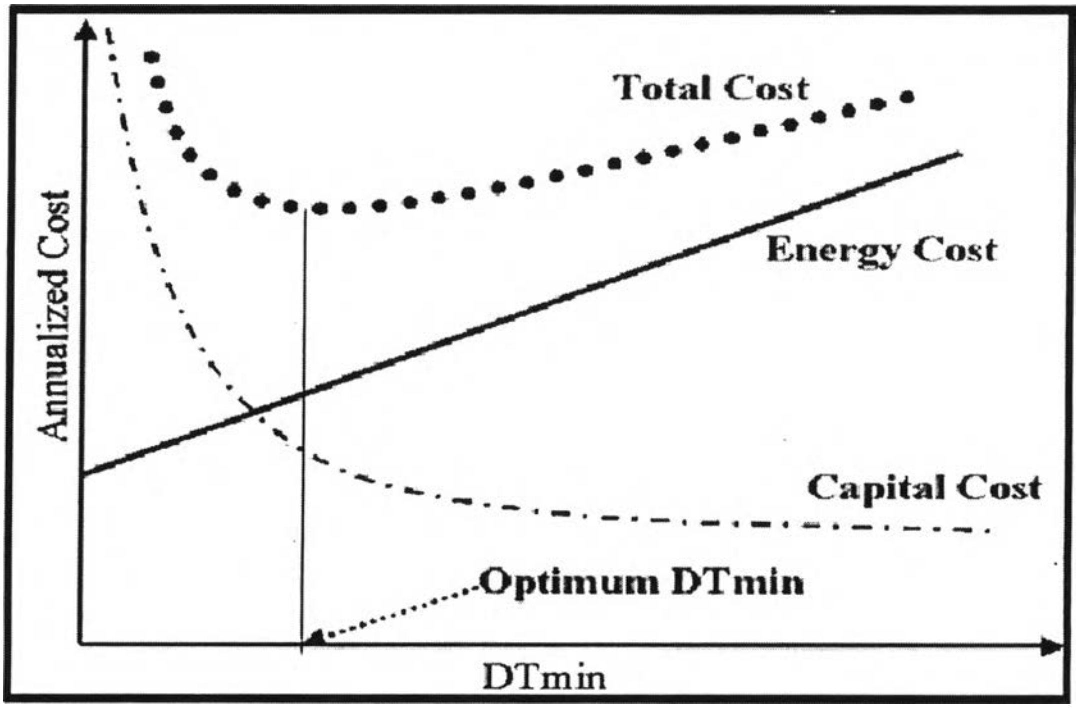

Figure 2.11 Energy-Capital Cost Trade Off. (Optimum DTmin)

2.3.8 Estimation of Practical Targets for HEN Design

The heat exchanger network designed on the basis of the estimated optimum ΔTmin value is not always the most appropriate design. A very small ΔTmin value, about 8 ^{0}C, can lead to a very complicated network design with a large total area due to low driving forces. The designer, in practice, selects a higher value (15 ^{0}C) and calculates the marginal increases in utility duties and area requirements. If the marginal cost has very small increase, the higher value of ΔTmin is selected as the practical pinch point for the HEN design.

Recognizing the significance of the pinch temperature allows energy targets to be realized by design of appropriate heat recovery network. The pinch divides the process into two separate systems each of which is in enthalpy balance with the utility. The pinch point is unique for each process. Above the pinch, only the hot utility is required. Below the pinch, only the cold utility is required, hence, for an optimum design, no heat should be transferred across the pinch. This is known as the key concept in pinch technology.

To summarize, Pinch technology gives three rules forming the basis for practical network design.

- No external heating below the pinch
- No external cooling above the pinch
- No heat transfers across the pinch

2.3.9 Design of Heat Exchanger Networks

Using the Pinch Design Method (PDM) the design of network examines which hot streams can be matched to cold streams via heat recovery. This can be achieved by employing tick off heuristics to identify the heat loads on the pinch exchanger. Every match brings one stream to it target temperature. As the pinch divides the heat exchange system into two thermally independent regions, HENs for both above and below pinch regions are designed separately. When the heat recovery is maximized the remaining thermal needs must be supplied by hot utility. The graphical method of representing flow streams and heat recovery matches is called a grid diagram (Figure 2.12). The design of a network is based on certain guidelines like the CP inequality rule, stream splitting, driving force plot and remaining problem analysis

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 2.12. 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 depicted below the circles.

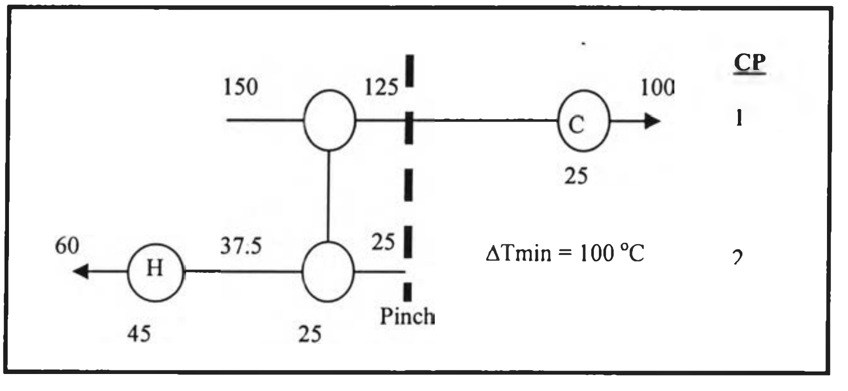

Figure 2.12 Heat Exchangers Representation in Grid Diagram.
(Linnhoff and Hindmarsh, 1983)

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.

2.4 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, 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 below

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

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 2.13.

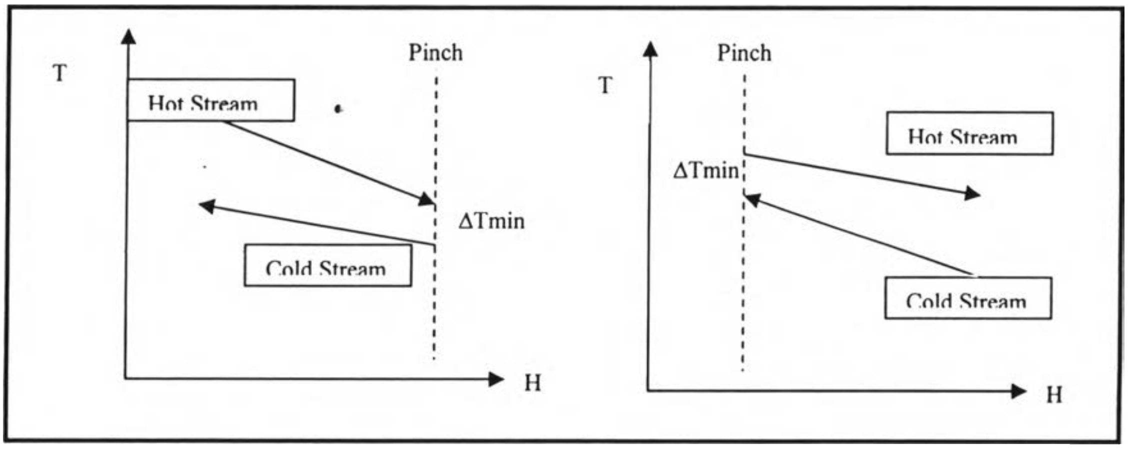

Figure 2.13 Heat Exchanger Profile, (a) Above Pinch, (b) Below Pinch

Consider Figure 2.13(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 2.13(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 to the pinch. Thus for temperature feasibility there is a "CP rule" in this equation.

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

If the CP rule is not satisfy 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 2.14.

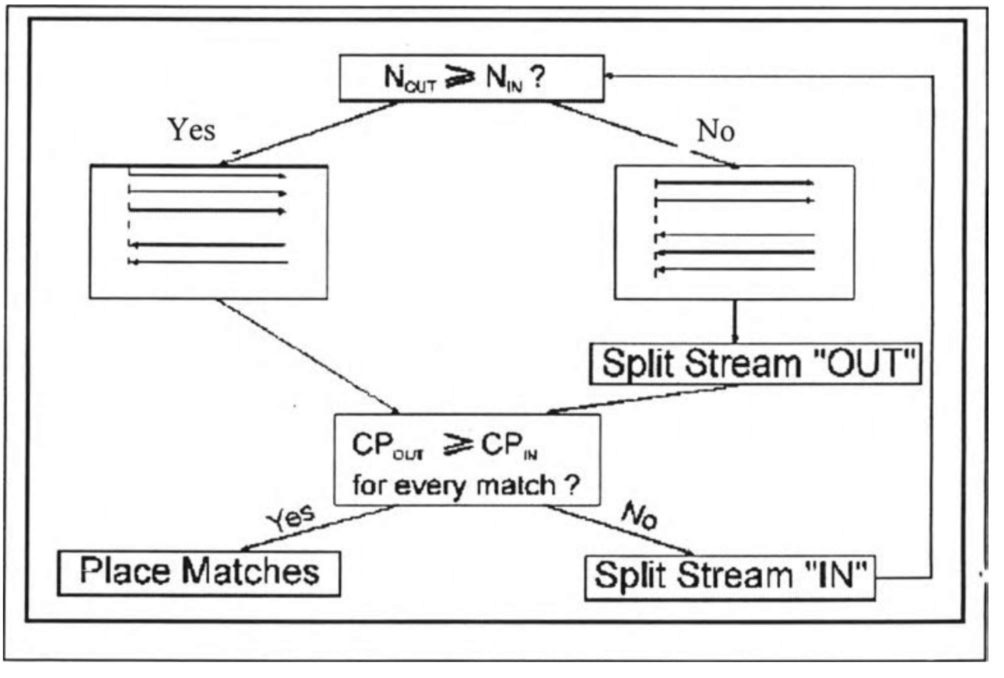

Figure 2.14 The Algorithm for Stream Splitting at Pinch Point.
(Linnhoff March Limited, 1998)

2.5 Retrofit

Pinch Technology is applicable to both new design and retrofit situations. The number of retrofit applications is much higher than the number of new design applications. In this section, retrofit techniques are discussed for setting targets for energy savings of an existing plant based on capital-energy trade-off.

The SuperTarget Process module was developed by Linnhoff March [4] to do retrofit of the existing process.

2.5.1 Retrofit Targeting based on Capital-Energy Trade-Off

Figure 2.15 provides an understanding of the capital - energy trade-off for a retrofit project using an area-energy plot.

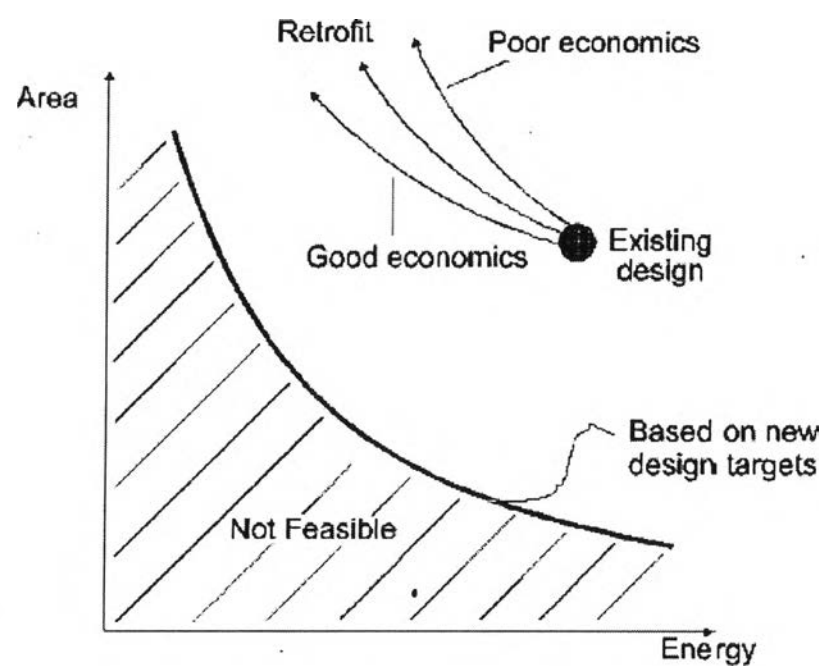

Figure 2.15 Capital Energy Trade Off for Retrofit Applications.

The curve (enclosing the shaded area) is based on new design targets for the process. The shaded area indicates performance better than the new design targets (which is infeasible for an existing plant). An existing plant will typically be located above the new design curve. The closer the existing plant is to the new design curve the better the current performance. In a retro fit modification, for increased energy saving, the installation of additional heat exchanger surface area is expected. The curve for the additional surface area that is closest to the new design area-energy curve provides the most efficient route for investment (good economics). The following section explains how such a curve for a retrofit application can be developed ahead of design.

2.5.2 Payback

From the area-energy targeting curve the saving versus investment curve for the retrofit targeting can be developed. This is shown in Figure 2.16.

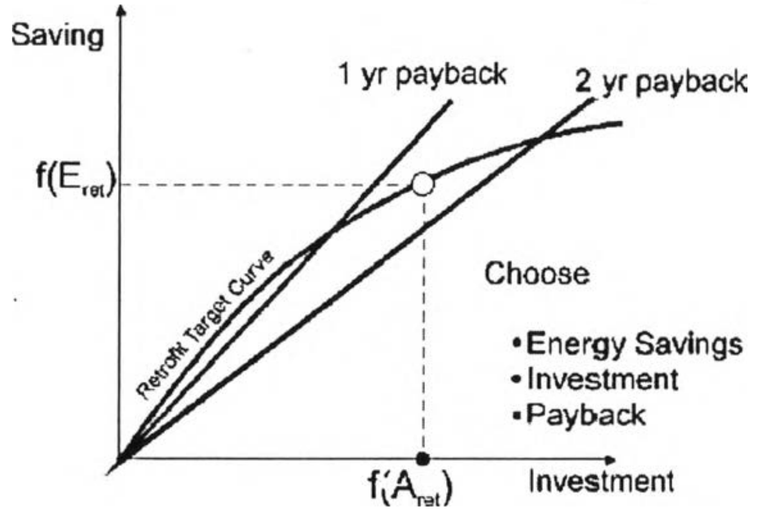

Figure 2.16 Targeting for Retrofit Applications.

Various pay-back lines can be established as shown in the figure. Based on the specified payback or investment limit, the energy saving target can be set. This will in turn determine the targeted ΔTmin value for the network. From the target ΔTmin value, the cross pinch heat flow and the cross pinch heat exchangers need to be removed.

2.5.3 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.

2.6 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.

2.7 Distillation Columns

Distillation columns are one of the major energy consuming units in chemical processes. In this section the principles for appropriate column modifications and their integration with the remaining process are considered. First, pinch analysis for stand-alone column modifications is considered, followed by principles for appropriate column integration with the remaining process. The SuperTarget Column module developed by Linnhoff March provides an advanced software tool for the implementation of stand alone column modifications.

PinchExpress and SuperTarget Process provide tools for assessing the impact of column heat integration within a process.

2.7.1 Stand-Alone Column Modifications

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 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 Column Grand Composite Curve

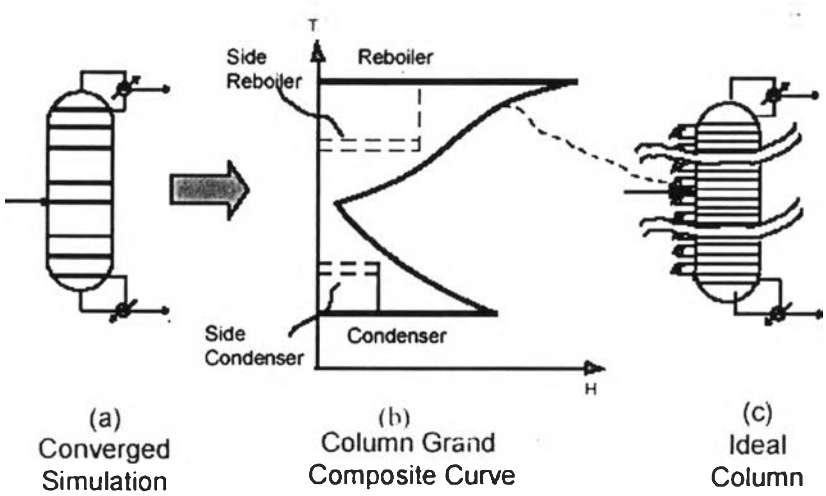

Figure 2.17 Procedure for Obtaining Column Grand Composite Curve.

The tool used for column thermal analysis is called the Column Grand Composite Curve (CGCC), an example of which is shown in Figure 2.17. The procedure for obtaining the CGCC starts with a converged column simulation as shown in the figure. From the simulation, the necessary column information is extracted on a stage-wise basis. This information can then processed (for example by using the SuperTarget Column module) to generate the CGCC as shown in Figure 2.17(b).

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 the column modifications such as side condensing and reboiling as shown in the figure. In a conventional column energy is supplied to the column at reboiling and condensing temperatures. The CGCC relates to minimum thermodynamic loss in the column or "Ideal Column" operation (see Figure 2.17(c)). For ideal column operation the column requires infinite number of stages, side reboilers and condensers as shown in Figure 2.17(c). 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 pinch point on the CGCC is usually caused by the feed.

2.7.2 Construction of Column Grand Composite Curve

The CGCC construction requires data from a converged simulation of the distillation column. Normally the outputs from simulations provide molar flows and compositions on a stage-by-stage basis. Let us consider a light and heavy key model. By key components mean the two main separating components in the feed mixture whose separation is specified. The more volatile components are the light keys and the less volatile are the heavy keys (King, 1980; Kister, 1992). The compositions of liquid and vapor streams emerging from the same stage are the equilibrium compositions at the stage temperature. Thus in order to solve the equilibrium line and the operating line equations simultaneously, all we need to do is to incorporate the equilibrium compositions of the vapor and liquid streams emerging from the same stage into our mass balance equations.

Before feed stage

$$G_{min}\,Y^*_L - L_{min}X^*_L = D_L$$

$$G_{min}Y^*_H - L_{min}X^*_H = D_H$$

After feed stage

$$G_{min}\,Y^*_L - L_{min}X^*_L = D_L - F_L$$

$$G_{min}Y^*_H - L_{min}X^*_H = D_H - F_H$$

Where:

G_{min}, L_{min} = minimum vapor and liquid flow

Y^{*}_{L}, X^{*}_{L} = light composition of vapor and liquid

Y^{*}_{H}, X^{*}_{H} = heavy composition of vapor and liquid

D_L, D_H = light and heavy component flow of distillate

F_L, F_H = light and heavy component flow of feed

These equations establish the minimum vapor flow (G_{min}) and the liquid flow (L_{min}) at the stage temperature. Usually simulation outputs also provide stage-by-stage vapor and liquid streams emerging from the same stage are in equilibrium with each other. The enthalpies of these equilibrium vapor and liquid streams are termed here as H^{*}_{G} and H^{*}_{L}. The enthalpies for the minimum vapor and liquid flows (H_{Gmin} and H_{Lmin}) are obtained from H*G and H*L by direct molar proportionality.

$$\mathbf{H_{Gmin} = H^{*}_{G}\,(G_{min}/G^{*})}$$
$$\mathbf{H_{Lmin} = H^{*}_{L}\,(L_{min}/L^{*})}$$

Where:

H_{Gmin}, H_{Lmin} = enthalpy of the minimum vapor and liquid flow

H^{*}_{G}, H^{*}_{L} = enthalpy of equilibrium vapor and liquid flow

G^{*}, L^{*} = molar flows of equilibrium vapor and liquid steam

After calculating H_{Gmin} and H_{Lmin}, next can set up enthalpy balances at each of the stage temperatures and evaluate the net enthalpy deficit (H_{def}) at each of these temperatures (Figure 2.18(a)).

Before feed stage

$$H_{def} = H_{Lmin} - H_{Gmin} + H_D$$

After feed stage

$$H_{def} = H_{Lmin} - H_{Gmin} + H_D - H_{feed}$$

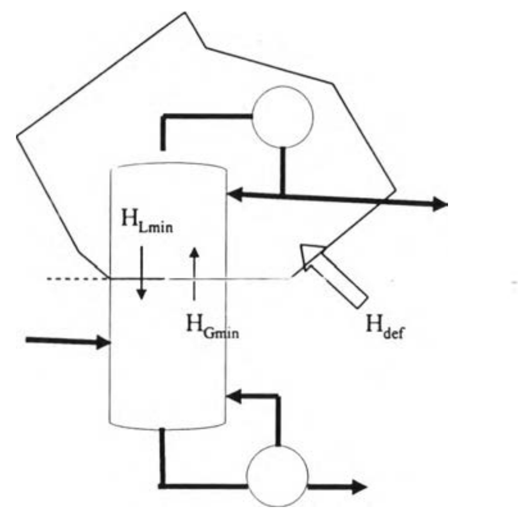

Figure 2.18(a) Evaluating Enthalpy Deficit at a Stage.

Figure 2.18(b) demonstrates how the individual enthalpy deficits are cascaded to construct the CGCC. The values of the stage temperatures and the corresponding heat deficits are plotted in the T-H dimension. The algorithm used for developing the cascade is identical to the problem table algorithm introduced by Linnhoff and Flower (1978). The feed enthalpy strongly influences the shape of the CGCC near the feed stage. The CGCC usually shows a pinch point near the feed stage.

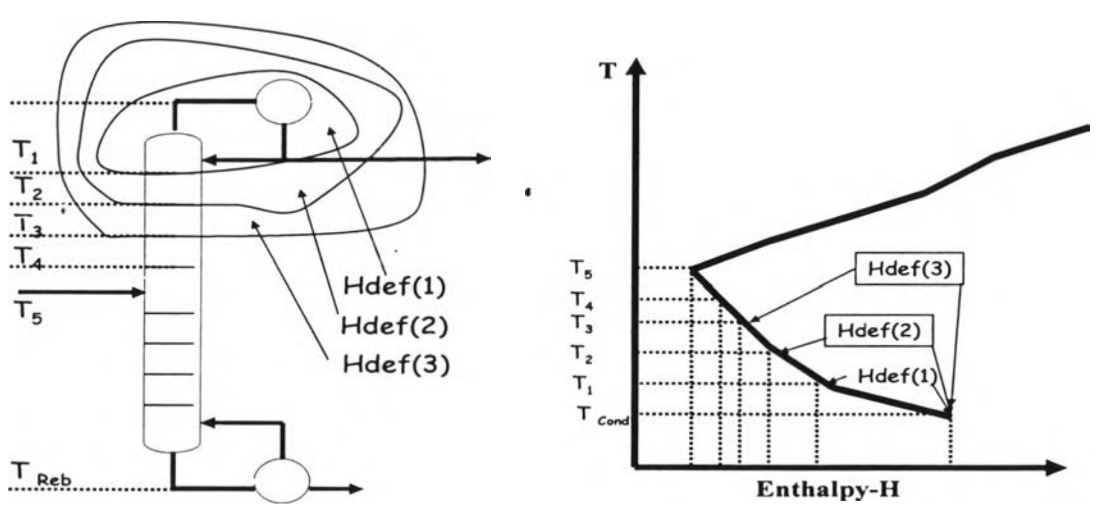

Figure 2.18(b) Constructing the CGCC from Stage Wise Enthalpy Deficits.

2.7.3 Modifications Using the Column Grand Composite Curve

Figure 2.17 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 trying alternate feed stage locations in simulation and evaluating its impact on the reflux ratio. The feed stage optimization is carried out first since it may strongly interact with the other options for column modifications. The CGCC for the column is then obtained.

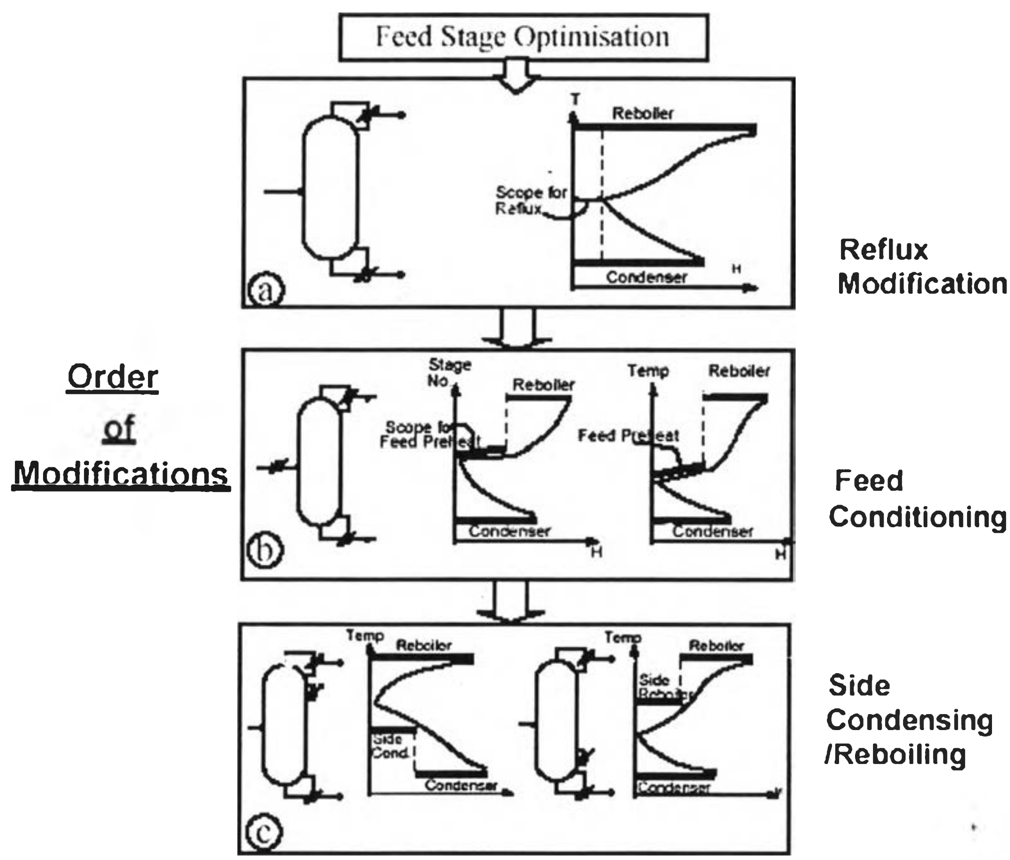

Figure 2.19 Using Column Grand Composite Curve to Identify Column Modifications.

As shown in Figure 2.19(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 first prior to other thermal modifications since it results in direct heat load savings both at the reboiler and the condenser level. In an existing column the reflux can be improved by adding of stages or improving the efficiency of the existing stages.

After reflux improvement the next priority is to evaluate the scope for feed preheating or cooling (see Figure 2.19(b)). This is identified by a "sharp change" in the stage-H CGCC shape close to the feed as shown in the figure with a feed preheating example. The extent of the sharp change 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 2.19(c) shows CGCC's with the scope of side condensing and reboiling. An appropriate side reboiler allows heat load to be shifted from the reboiling temperature to a side reboiling temperature without significant 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 is therefore easier to implement than side condensing and reboiling. The sequence for the different column modifications can be summarized as follows:

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

2.7.4 Column Integration

In the previous section, ways of improving column thermal efficiency by stand alone column modifications 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 the column heating/cooling duties and the process heating/cooling duties or with the utility levels. Figure 2.20 summarizes the principles for appropriate column integration with the background process.

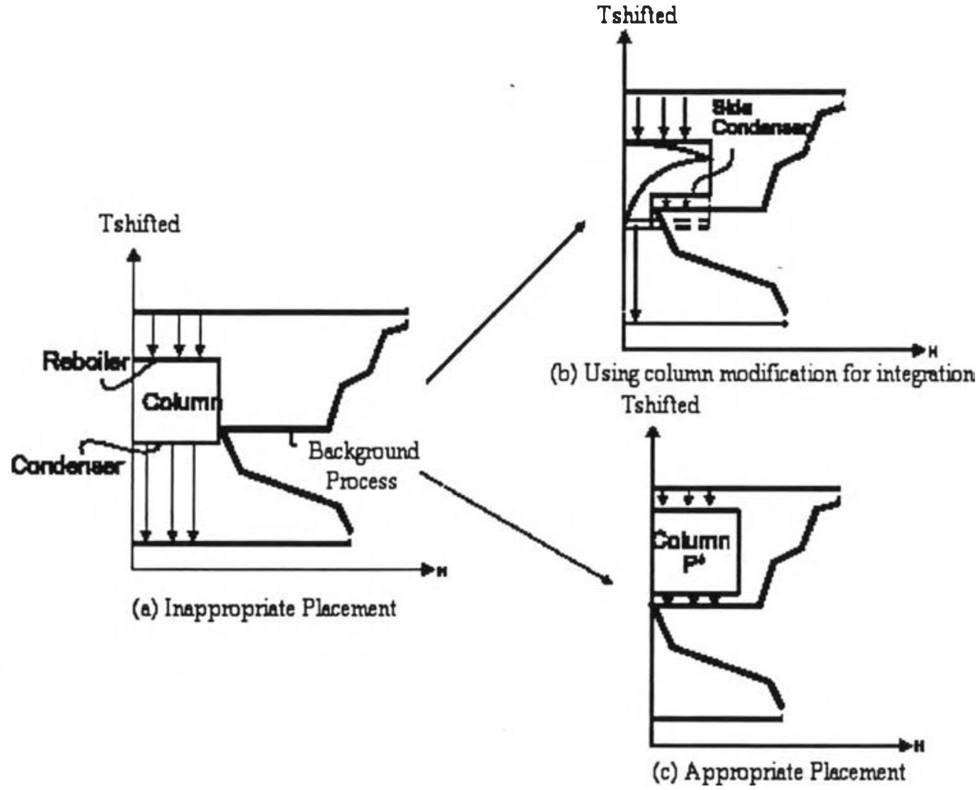

Figure 2.20 Appropriate Integration of a Distillation Column with the Background Process.

Figure 2.20(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 its integration with the background process.

Figure 2.20(b) shows the CGCC of the column. The CGCC indicates a potential for side condensing. The side condenser opens up an opportunity for integration between the column and the background process. Compared to Figure 2.20(a) the overall energy consumption (column + background process) has been reduced due to the integration of the side condenser.

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 (Figure 2.20(c)). The column is now on one side of the pinch (not across the pinch). The overall energy consumption (column + 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 if it is placed across the pinch and has no potential for integration with the background process via side condensers or reboilers etc. The integration opportunities are enhanced by stand-alone column modifications 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 of the background process.

Appropriate column integration can provide substantial energy benefits. However these benefits must be compared against associated capital investment and difficulties in operation. In some cases it is possible to integrate the columns indirectly via the utility system which may reduce operational difficulties. The principle of appropriate column integration can also be applied to other thermal separation equipment such as evaporators.

2.8 Literature Survey

2.8.1 Applications of Pinch Technology

Pinch technology (PT) is proved to be important for process 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.

The major area in which the pinch analysis is applied (Hallae, 2001) is Process integration (PI). PI is not only the pinch analysis and energy integration by it had been extended its uses to various applications. The four major areas of PI are 1) process operations 2) energy efficiency 3)emission reduction and 4) efficient use of raw materials. Many applications of pinch technology were discussed, they are used in hydrogen management, total site analysis and integration, heat exchanger networks design and retrofit, column analysis and integration and water management. All of these applications start from generating composite curve, locating pinch point, setting targets and then designing or modifying to achieve the targets.

2.8.2 <u>The Pinch Design Method for New Heat Exchanger Network Design</u>

In pinch analysis, after the designers have set the target for the problem, the next step they have to do is to design a network topology that satisfied the setting target. The first design methodology is call "The pinch design method

(PDM)" (Linnhoff and Hindmarsh,1983). The synthesis starts at the pinch and moving away to the remaining parts. The design at the pinch is employed by stream splitting to satisfy pinch principles and the feasibility criteria. The procedure is sped up by tick-off heuristic but this can penalize the energy usage. In the final step, the design topology is trade-off between energy and capital cost by using heat load loop and heat load path.

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.

Almost two decades of development, the analysis of the PDM problems was seen by many research groups. Polley and Heggs (1999) showed the problems of the pinch design method (PDM). 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 can not 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 flow-sheet and decomposition on a thermal basis.

2.8.3 The Pinch Design Method for Heat Exchanger Network Retrofit

The above discussion is made only to the grass-root design. In practice, there are many petrochemical plants that have been invested for the exchangers. The discussion above is not appropriate for this case, since many of invested heat exchangers have to be eliminated to achieve the energy target. The approach has been developed about the same period as for the grass-root one. The development of method for retrofitting plants based on pinch analysis is discussed below.

Tjoe and Linnhoff (1986) presented a method that used pinch design method for process retrofits. The assumption in this method is that a good retrofit will make the process similar to optimum grass-root design. The first step is to set the target by using area-energy curve. The design was done by assuming that the new area will have the same efficiency as the existing one. The minimum temperature and energy saving are set under a specified payback time or investment. The retrofit is to identify the cross-pinch exchangers and modify them. The method was also applied for ethylene plant retrofit (Linnhoff and Witherell, 1986)

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.

Al-Riyami, Klemes and Perry (2001) showed the procedure for retrofitting industrial heat exchanger network of a fluid catalytic cracking plant. The incremental area efficiency methodology was used for the targeting stage of the design and the design was carried out using the network pinch method consisting of both a diagnosis and optimization stage. They used SPRINT software in diagnosis stage. They do many designs for energy saving and the best design can save 74% of energy. This corresponds to 27% utility cost savings with a payback period of 1.2 years. The modifications include addition of four heat exchanger units and repiping of one existing exchanger.

2.8.4 Process Heat Integration

A process heat integration is concerned about the integration of heat engines, heat pumps and 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 with advantages over the stand alone engines or pumps. For the heat engines, 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. To get the 100 percent efficiency using the real engines, a large number of engines connected in series are used. In addition, a fully appropriate integration can never be achieved practically due to the heat across 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 used of the criterions proposed above for selecting 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.

As mentioned before, the heat engine placement was lead to the development of a criterion to place distillation columns into process streams. The discussion was first given by Linnhoff, Dunford and Smith (1983). They discussed about the placement of columns and got the interesting conclusions. First, if the good integration between columns and process is achieved, the columns can be run with free of utility charges. Second, they found that the conventional column integration methods, e.g., multiple effect columns, can prevent the good integration. The good integration is obtained by placing column in one side of pinch, i.e. not go across the pinch and either the re-boiler or condenser being integrated with the process. If these criteria can be met, energy cost of distillation column can effectively be zero.

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 illustrated the approach.

2.8.5 Distillation Column

Dhole and Linnhoff (1992) presents a methodology based on a combination of thermodynamics and practical aspects of column modification. They studied Column Grand Composite Curve, Column integration and Column Composite Curve. The sequence for considering different column modifications is recommended as 1) Reflux and pressure modifications 2) Feed preheating/cooling 3) Side condensing/reboiling. A converged simulation is done to develop column profiles for column with multiple components, complex column configurations and variable relative volatilities. The profiles identify appropriate column modifications and essentially set target in terms of heat loads and temperatures for the modifications. The designer is easily made aware of energy cost and capital cost implications. The combined use of the background process enhances the reliability of column integration in comparison to conventional pinch analysis.