CHAPTER II
LITERATURE REVIEW

2.1 Process Integration

Process integration was emerged in the 80's and has been extensively used in the 90's to describe certain systems oriented activities related primarily to process design. Some definition used to explain process integration by the IEA since 1993:

"Systematic and General Methods for Designing Integrated Production System, ranging from Individual Processes to Total Sites, with special emphasis on the Efficient Use of Energy and reducing Environmental Effects"

While heat recovery was the initial focus of process integration, the scope has been expanded considerably during the late 80's and the 90's to cover several aspects of process design. A key feature of this expansion has been the use of basic concepts from heat recovery in other areas through the use of analogies. In conclusion, with this technology, it is possible to significantly reduce the operating cost of existing plants, while new processes often can be designed with reductions in both investment cost and operating cost.

2.2 Pinch Technology

In late 1978, Bodo Linnhoff a Ph.D. student from the corporate laboratory, Imperial Chemical Industries Limited, ICI, under the supervision of Professor John Flower, University of Leeds, introduced a new approach to describe energy flows in process heat exchanger networks. Today, it is called Pinch technology

Pinch technology provides simple and easy ways of optimization based on thermodynamic principles towards energy saving in industrial processes. The term of pinch analysis is often used to represent the application of the tools and algorithms of pinch technology.

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.

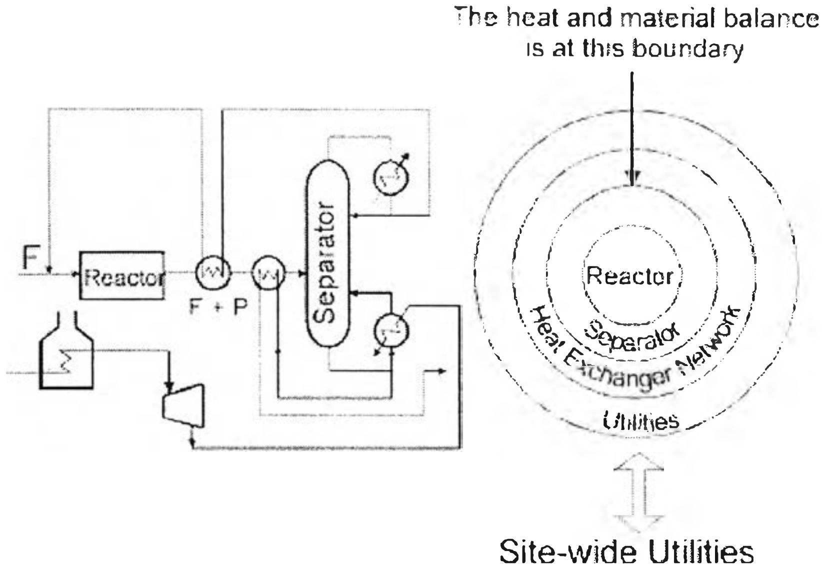


Figure 2.1 "Onion Diagram" (www.linnhoffmarch.com).

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 grass-roots 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.

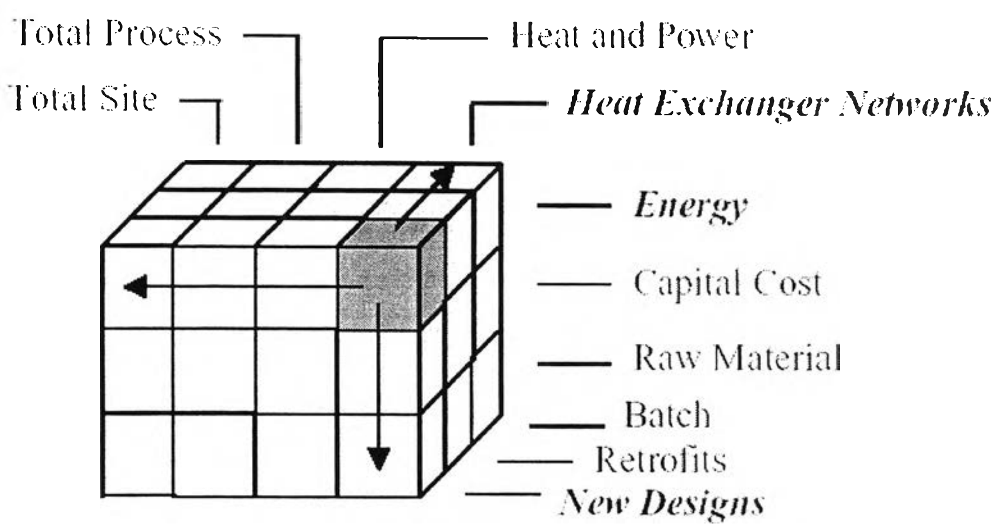


Figure 2.2 Rubic cube indicating the development of pinch technology (Gunderson, 2002).

2.2.1 Basic Concepts of Pinch Analysis

Pinch technology is based on the first and second laws of thermodynamics. The first law of thermodynamics provides the energy equation for calculating the enthalpy changes in steams passing through a heat exchanger. The second law determines the direction of heat flow, which is that heat only flow from higher temperatures to lower temperature. This prohibits temperature crossovers of the hot and cold steam profiles through the exchanger unit. Applying the combined composite curve in Figure 2.3 illustrates the pinch point which is defined an adequate amount of minimum temperature driving force (i.e. the minimum allowable temperature difference (ΔTmin)) and it also divides a process into two parts: a high temperature heat sink part (above the pinch) where heat is only supplied by hot utility and a low temperature heat source part (below the pinch) where heat is only drawn by cold utility.

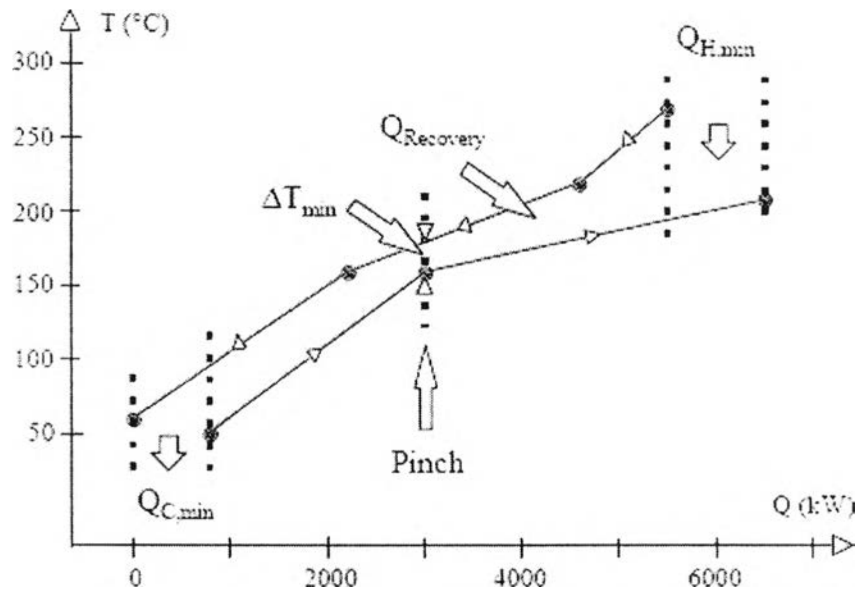
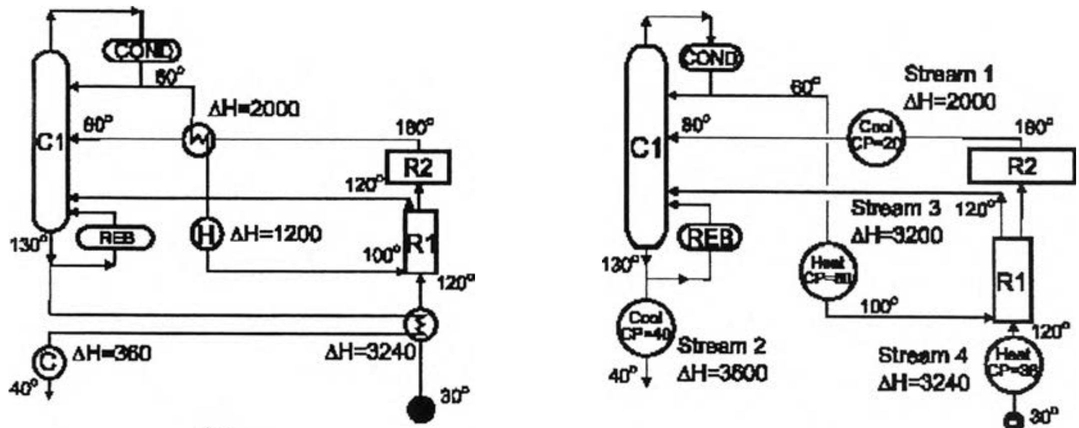


Figure 2.3 Combined composite curves (Gunderson, 2002).

2.2.2 Data Extraction Flow Sheet

Data extraction relates to the extraction of information required for Pinch Analysis from a given process heat and material balances. Figure 2.4(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.



(a)
Example Process Flow-sheet

(b)
Data Extraction Flow-sheet

Figure 2.4 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 2.4(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.

2.2.3 Steps of Pinch Analysis

In any Pinch Analysis problem, whether a new project or a retrofit situation, a well-defined stepwise procedure is followed (Figure 2.5). 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 iteration between the various steps is always required.

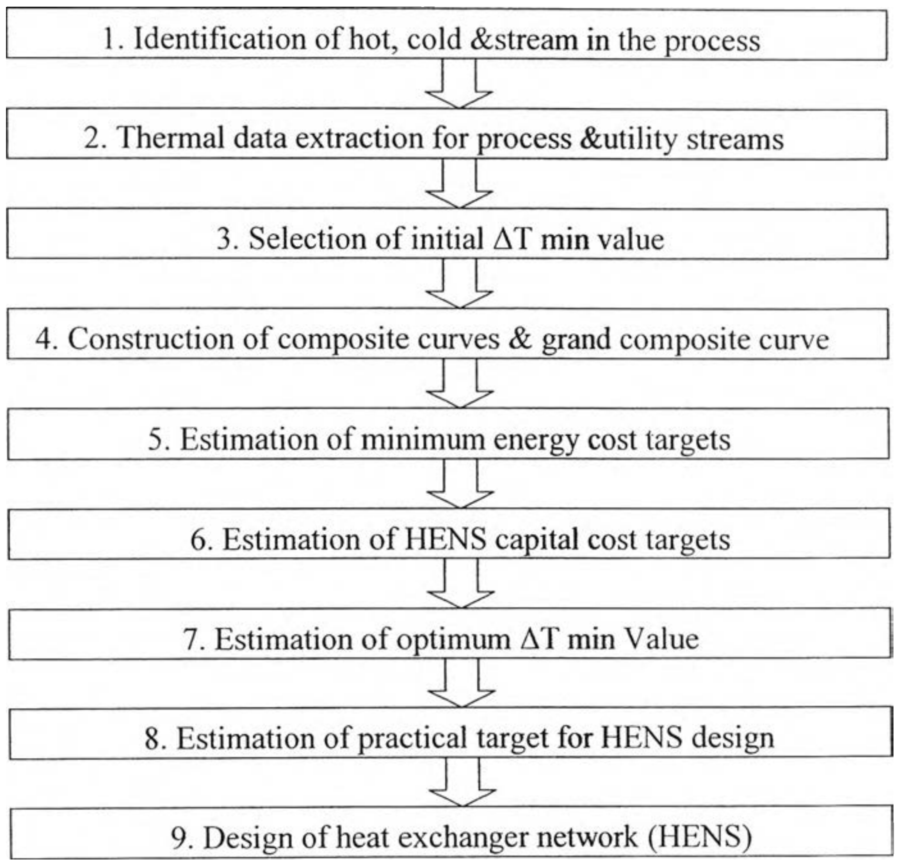


Figure 2.5 Steps of pinch analysis for new design of heat exchanger networks (Linnhoff and Hindmarsh, 1983).

2.2.3.1 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 pre-heating before a reactor.

3. Utility streams are used to heat (hot utilities) or cool (cold utilities) process streams, when heat exchanged between process streams is not practical or economic. A number of different hot utilities (steam, hot water, flue gas, etc.) and cold utilities (cooling water, air, refrigerant, etc.) are used in industry.

2.2.3.2 Thermal Data Extraction for Process and Utility Streams

Hot streams are the streams that need cooling (i.e. heat sources) while cold streams are the streams that need heating (i.e. heat sink). For each hot, cold and utility stream identified, the following thermal data is extracted from the process material and heat balance flow sheet as shown below.

(1) Supply temperature (TS, °C) is the temperature at which the stream is available.

(2) Target temperature (TT, °C) is the temperature the stream must be taken to.

(3) Heat capacity flow rate (CP, kW/°C) is the product of mass flow rate (**m**) in kg/sec and specific heat (Cp, kJ/kg °C).

$$CP = \mathbf{m} \times Cp \tag{2.1}$$

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

$$\text{Enthalpy change, } \Delta H = CP \times (TS - TT) \tag{2.2}$$

For example, the data extracted is presented in Table 2.1.

Table 2.1 Thermal data required for pinch analysis (www.linnhoffmarch.com)

Stream No.	Stream Type	Supply Temperature (TS, °C)	Target Temperature (TT, °C)	Heat Capacity Flow Rate (CP, kW/°C)
1	Hot	180	80	20
2	Hot	130	40	40
3	Cold	60	100	80
4	Cold	30	120	36

2.2.3.3 Selection of Initial ΔTmin Value

The design of any heat transfer equipment must always adhere to the second law of thermodynamics that prohibits any temperature crossover between the hot and the cold stream i.e. a minimum heat transfer driving force must always be allowed for a feasible heat transfer design. Thus 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. In a network design, the type of heat exchanger to be used at the pinch will determine the practical ΔTmin for the network. If smaller values of ΔTmin are chosen, the area requirements rise. If a higher value of ΔTmin is selected the heat recovery in the exchanger decreases and demand for external utilities increases. Thus, the selection of ΔTmin is very more important, it values has implications for both capital and energy costs. It is therefore recommended that the use of experience based on ΔTmin is treated with caution and also provides a good starting ΔTmin for the network. Table 2.2(a), 2.2(b) and 2.3(c) show typical ΔTmin values based on Linnhoff March's application experience.

Table 2.2(a) Typical ΔTmin values for various types of processes (www.linnhoff march.com)

No	Industrial Sector	Experience DT_{min} Values	Comments
1	Oil Refining	20-40°C	Relatively low heat transfer coefficients, parallel composite curves in many applications, fouling of heat exchangers
2	Petrochemical	10-20°C	Reboiling and condensing duties provide better heat transfer coefficients, low fouling
3	Chemical	10-20°C	As for Petrochemicals
4	Low Temperature Processes	3-5°C	Power requirement for refrigeration system is very expensive. DT_{min} decreases with low refrigeration temperatures

Table 2.2(b) Typical ΔTmin values for process-utility matches (www.linnhoff march.com)

Match	DT_{min}	Comments
Steam against Process Stream	10-20°C	Good heat transfer coefficient for steam condensing or evaporation
Refrigeration against Process Stream	3-5°C	Refrigeration is expensive
Flue gas against Process Stream	40°C	Low heat transfer coefficient for flue gas
Flue gas against Steam Generation	25-40°C	Good heat transfer coefficient for steam
Flue gas against Air (e.g. air preheat)	50°C	Air on both sides. Depends on acid dew point temperature
CW against Process Stream	15-20°C	Depends on whether or not CW is competing against refrigeration. Summer/Winter operations should be considered

Table 2.2(c) Typical ΔTmin values for refinery processes (www.linnhoffmarch.com)

Process	DT_{min}	Comments
CDU	30-40°C	Parallel (tight) composites
VDU	20-30°C	Relatively wider composites (compared to CDU) but lower heat transfer coefficients
Naphtha Reformer/Hydrotreater Unit	30-40°C	Heat exchanger network dominated by feed-effluent exchanger with DP limitations and parallel temperature driving forces. Can get closer DT_{min} with Packinox exchangers (up to 10-20°)
FCC	30-40°C	Similar to CDU and VDU
Gas Oil Hydrotreater/Hydrotreater	30-40°C	Feed-effluent exchanger dominant. Expensive high pressure exchangers required. Need to target separately for high pressure section (40°C) and low pressure section (30°C).
Residue Hydrotreating	40°C	As above for Gas Oil Hydrotreater/Hydrotreater
Hydrogen Production Unit	20-30°C	Reformer furnace requires high DT (30-50°C). Rest of the process: 10-20°C

2.2.3.4 Construction of Composite Curves and Grand Composite Curves

In 1978, Linnhoff and Flower developed the problem table algorithm (PTA) to calculate the energy target algebraically. Moreover the data obtained from calculation is also used to construct the grand composite curve. The data requirements are the inlet and outlet temperature and heat capacity flow rate of each stream (Thermal data). For each step of algorithm is illustrated in the example below. Table 2.3 shows the thermal data that consists of temperature inlet, temperature outlet and heat capacity flow rate. The minimum temperature approach (ΔT_{min}) equal to 10 °F is chosen to calculation.

Table 2.3 Thermal data for PTA

Stream No.	Condition	MCp (Btu/hr °F)	Tin (°F)	Tout (°F)
1	Hot	1000	250	120
2	Hot	4000	200	100
3	Cold	3000	90	150
4	Cold	6000	130	190

(1) Setting the temperature interval: By choosing ΔT_{min} equal to10°F, a graph can be established, showing two temperature scales that are shifted by 10°F, one for the hot streams and the other for cold streams as shown in Figure 2.6.

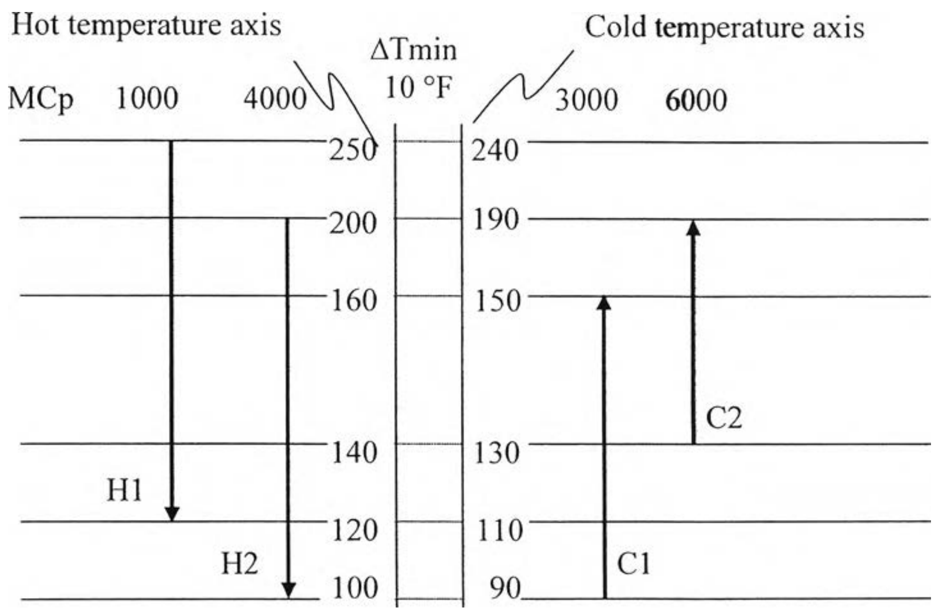


Figure 2.6 Shifted temperature scale and temperature intervals.

From the second law of thermodynamics, heat from any hot streams in the high-temperature intervals can be transferred to any of the cold streams at lower-temperature intervals. For a starting point, heat transfer in each interval would be considered separately. The necessary equation is shown below

$$Q_{interval} = \{ \Sigma (mCp)_{hot,interval} - \Sigma (mCp)_{cold,interval} \} \Delta T_{,interval} \quad (2.3)$$

For example, the first interval obtains Q1 = (1000)(250-200) = 50 x 10^3 Btu/hr. Figure 2.7 shows net energy required at each interval.

(2) <u>Generating cascade diagram</u>: As mention above, energy will transfer from high-temperature interval to low-temperature interval. Figure 2.8 shows the energy transfer in this case.

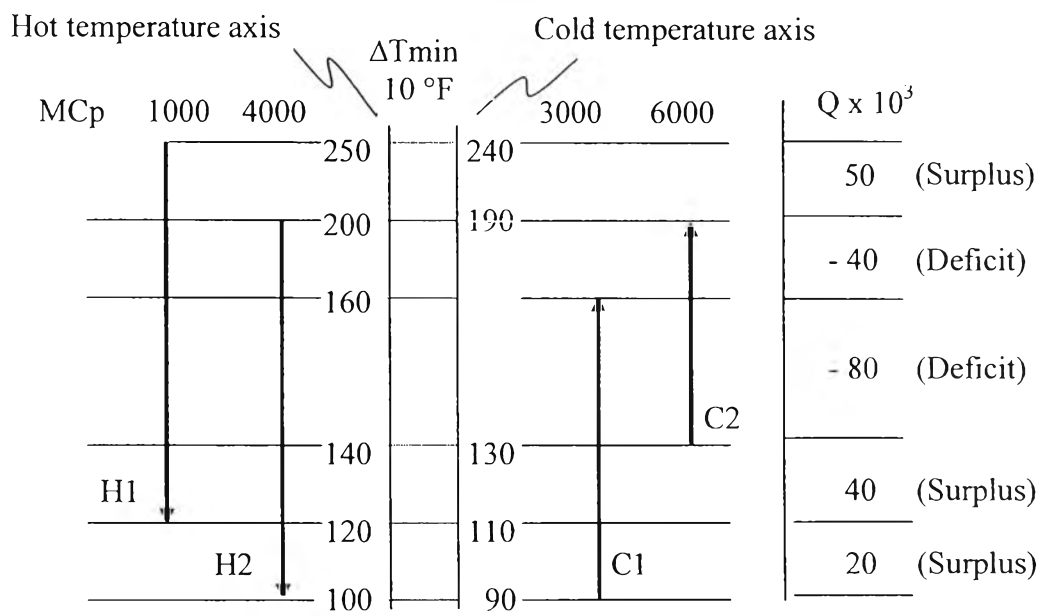


Figure 2.7 Net energy required at each interval.

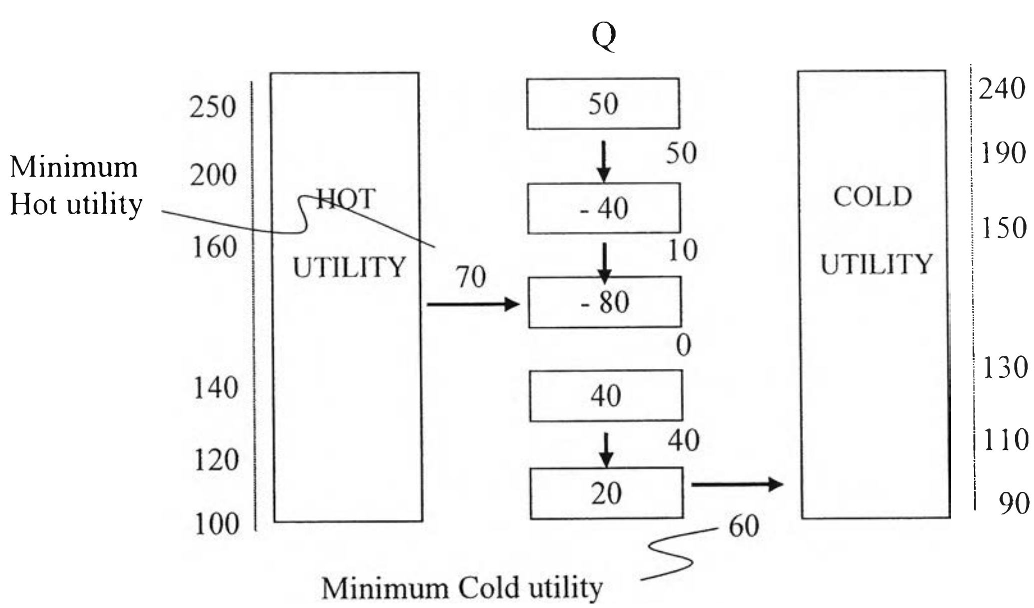


Figure 2.8 Cascade diagram.

The hot and cold utilities are required to satisfy energy demand in the interval. In this case, energy deficit is observed in third temperature interval and 70 Btu/hr from hot utility is used to supply energy needed in the interval. At the end of the temperature interval, the remaining energy will reject to a cold utility. This diagram is called cascade diagram that reveals the minimum hot and cold utility required in the process and show heat cascade through the temperature intervals.

(3) Generating the Grand Composite Curve (GCC): The GCC is constructed by rearranging the cascade diagram from Figure 2.8. The minimum hot utility is taken at the highest temperature interval and the same amount of energy is transferred energy same as procedure down to the lowest temperature interval. After that plotting between average temperatures versus heat transfer of each temperature intervals, we can generate the GCC as shown in Figure 2.9.

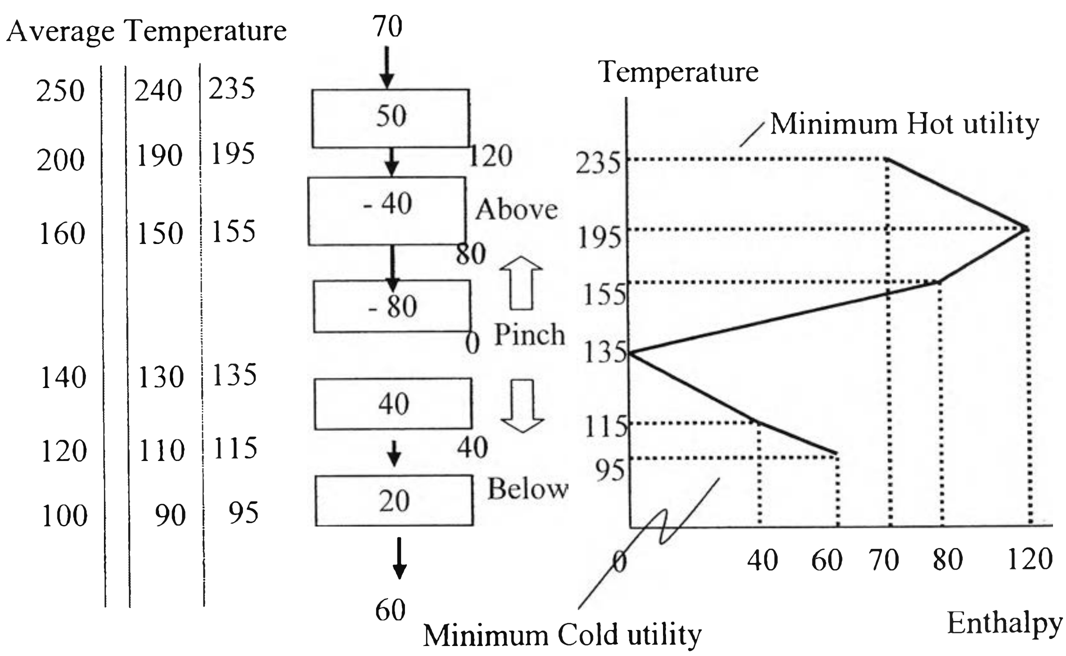


Figure 2.9 Generation of the grand composite curve.

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 (shown in Figure 2.10), which involves increasing the cold composite temperature by ½ ΔTmin and decreasing the hot composite temperature by ½ ΔTmin. This temperature shifting of the process streams and utilities levels ensures that even when the utility levels touch the GCC, the minimum temperature difference of ΔTmin is maintained between the utility levels and the process streams. The GCC shows the heat available in various temperature intervals. It also is a representation of the net heat flows in the process, which are zero at the pinch. On this curve, a process sink segment shows an increase in temperature and an increase in enthalpy. A process source segment shows a decrease in temperature and, contrary to convection, an increase in enthalpy. Moreover, the GCC is particularly useful in deciding the placement of hot and cold utilities and also useful for profile matching during total energy integration.

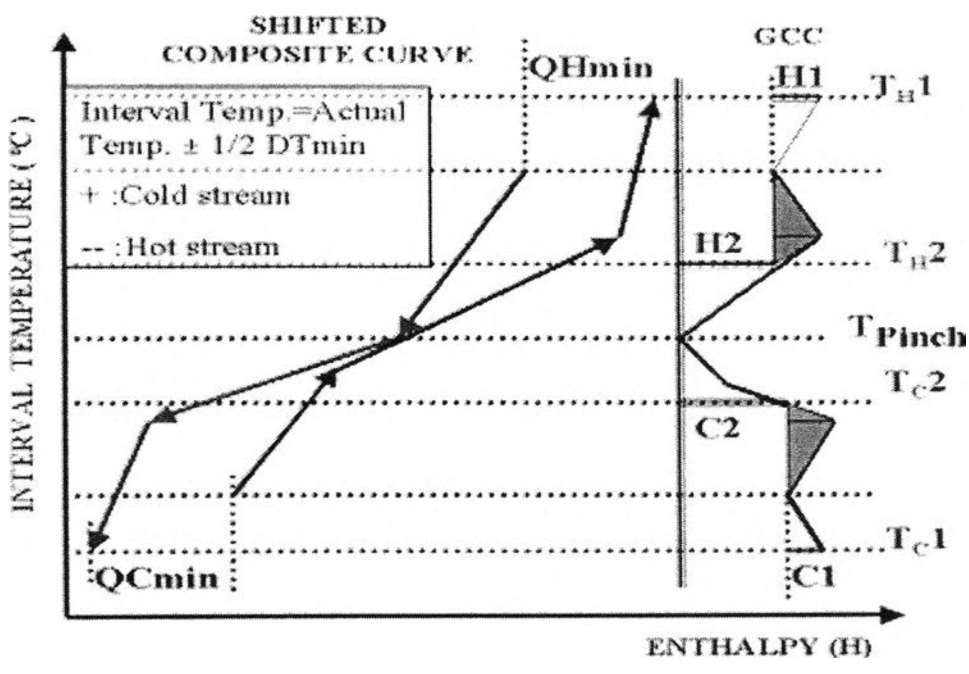


Figure 2.10 Grand composite curve (www.cheresources.com).

COMPOSITE CURVES (CC): Temperature - Enthalpy (T - H) plots known as 'Composite Curves' have been used for many years to set energy targets ahead of design. The composite curves consist of temperature (T) – enthalpy (H) profiles of heat availability in the process (a hot composite curve (HCC)) and heat demands in the process (a cold composite curve (CCC)) due to a certain process together in a graphical representation. Moreover, the combination of both the HCC and CCC to get combined composite curve. This curve can indicate the minimum hot and cold utilities (Q_{Hmin} and Q_{Cmin}) required in addition to the minimum temperature driving force (ΔTmin) required for the process, the point of minimum temperature difference represents a bottleneck in heat recovery and is commonly referred to as the "Pinch". Increasing ΔTmin value results in shifting of the curves horizontally apart resulting in lower process to process heat exchange and higher utility requirements. At a particular ΔTmin value, the overlap shows the maxim. To generate the hot composite curve (HCC) is very simple done by summing up the CP values of all hot streams in the same kind within each temperature interval as shown in Figure 2.11(a) and 2.11(b). The method for generating the cold composite curve (CCC) is identical to the HCC. Figure 2.12 shows the combined composite curves.

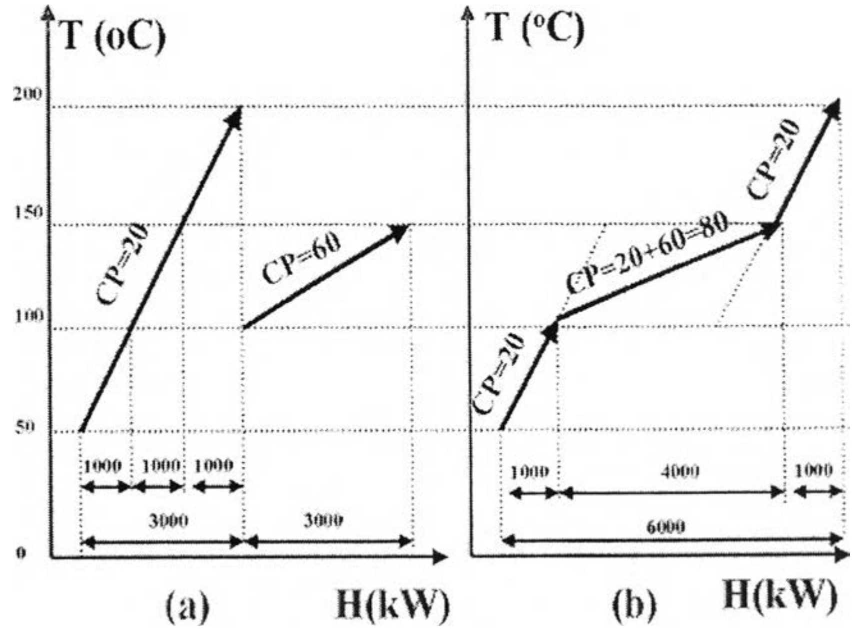


Figure 2.11 Temperature-Enthalpy relations use to construct hot composite curve (www.cheresources.com).

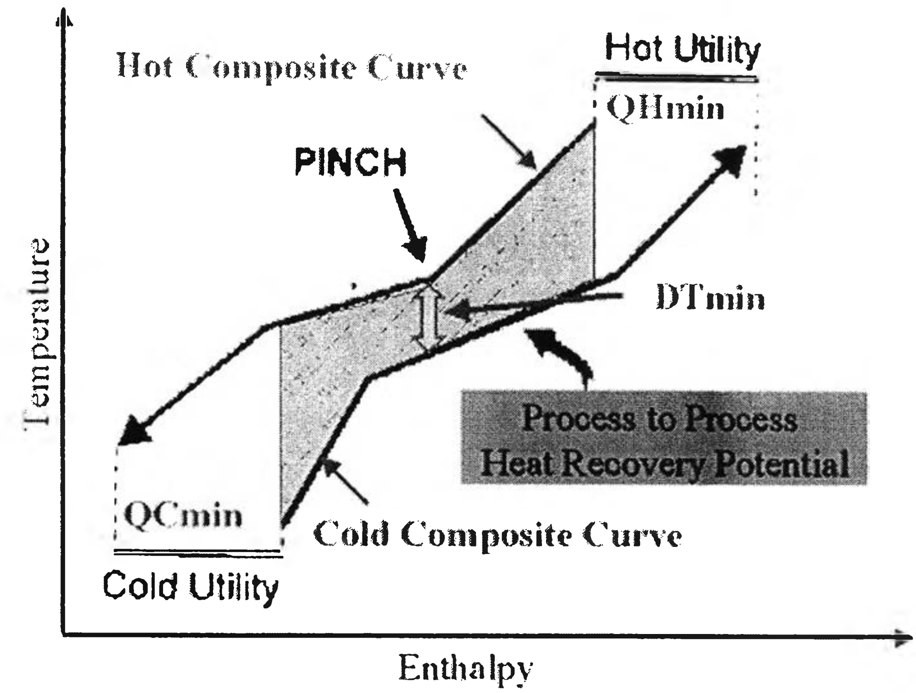


Figure 2.12 Combined composite curves (www.cheresources.com).

2.2.3.5 Estimation of Minimum Energy Cost Targets

The energy cost or operating cost (OC) is a function of the energy requirements. Once the ΔTmin is chosen, minimum hot and cold utility requirements can be evaluated from the composite curves. The GCC provides information regarding the utility levels selected to meet Q_{Hmin} and Q_{Cmin} requirements. If the unit cost of each utility is known, the energy cost can be calculated using the energy equation given below.

$$\text{Energy cost} = (C_{HU}*Q_{H,min})+(C_{CU}*Q_{C,min}) \tag{2.4}$$

Where C_{HU} and C_{CU} are the cost of unit load of hot and cold utilities respectively. $Q_{H,min}$ and $Q_{C,min}$ are the minimum requirements of hot and cold utilities respectively.

2.2.3.6 Estimation of HENs Capital Cost Target

The capital cost of a heat exchanger network is dependent upon three factors that are the number of exchangers, the overall network area and the distribution of area between the exchangers. Pinch analysis enables targets for the overall heat transfer area and minimum number of units of a heat exchanger network (HEN) to be predicted prior to detailed design. It is assumed that the area is evenly distributed between the units. The area distribution cannot be predicted ahead of design.

AREA TARGETING: The composite curves can also be used to determine the minimum heat transfer area required to achieve the energy targets by using equations below (Townsend and Linnhoff, 1984; Linnhoff and Ahmad, 1990).

$$A = \sum_i \left(\frac{1}{F * LMYD} \right)_i \sum_j \left(\frac{Q_j}{h_j} \right)_i \tag{2.5}$$

$$\sum_j \left(\frac{Q_j}{h_j} \right) = \sum_{jh} \left(\frac{Q}{h} \right)_{jh} + \sum_{jc} \left(\frac{Q}{h} \right)_{jc} \tag{2.6}$$

Noting that $Q = MC_p dT$

then,
$$\sum_j \left(\frac{Q_j}{h_j} \right) = (dT_h)_i \sum_{jh} \left(\frac{MC_p}{h} \right)_{jh} + (dT_c)_i \sum_{jc} \left(\frac{MC_p}{h} \right)_{jc} \tag{2.7}$$

where,	A	=	The area target
	F	=	The correction factor accounting for noncountercurrent
	LMTD	=	The logarithmic mean temperature difference
	Qj	=	The enthalpy change of the j-th stream
	hj	=	The heat transfer coefficient of the j-th stream
	dTh	=	The hot temperature difference
	dTc	=	The cold temperature difference
	Subscript i=		The i-th enthalpy interval
	Subscript j=		The j-th stream

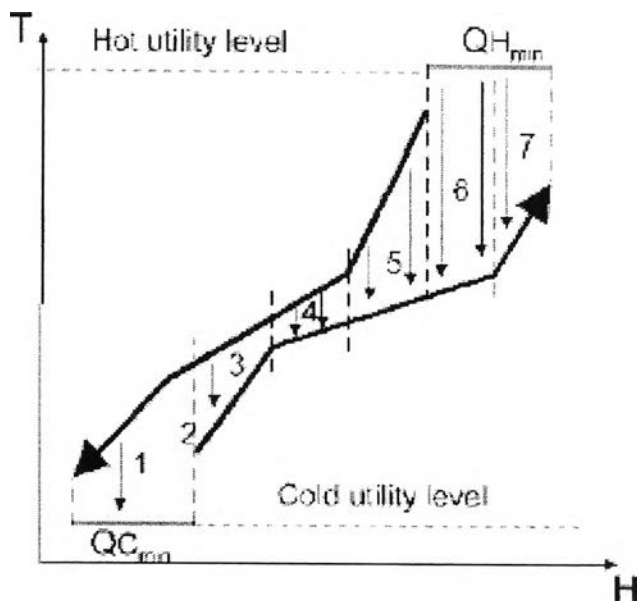


Figure 2.13 Vertical heat transfer between the composite curves leads to minimum network surface area (www.linnhoffmarch.com).

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.

$$\text{Umin} = N - 1 \tag{2.8}$$

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.

2.2.3.7 Calculation of the Capital Cost

The starting point is an expression for the capital cost (CC) of a single heat exchanger. If A is the surface area, then a simple cost law typically used has the form:

$$CC = a + bA^{C} \qquad \text{for a single exchanger} \qquad (2.9)$$

Where a, b and, c are the cost law coefficients which depend on the material of construction, the pressure rating and the type of heat exchanger.

When establishing capital cost targets for a network, the area distribution among the individual exchanger comprising the network (yet to be designed) is not known. Consequently, it is simplest to assume each individual exchanger to have the same area. With this assumption that appears to give good capital cost predictions (Ahmad et al., 1990), the expressions for the network capital cost based on Equation 2.9 are

$$CC = N_{u,mer}[a + b(A_C / N_{u,mer})^{C}$$

for a network of countercurrent exchangers (2.10)

$$CC = aN_{u,mer} + bS_{min}(A_{12} / S_{min})^{C}$$

for a network of 1-2 shell and tube exchangers (2.11)

Where $N_{u,mer}$ is the minimum number of units in an MER network, A_C and A_{12} are the appropriate area targets and S_{min} is the minimum shell target.

2.2.3.8 Estimation of Optimum ΔTmin Value by Energy-Capital Trade Off

Three key observations can be made from Figure 2.14.

(1) An increase in ΔTmin results in higher energy costs and lower capital costs.

(2) A decrease in ΔTmin results in lower energy costs and higher capital costs.

(3) An optimum ΔTmin exists where the total annual cost of energy and capital costs is minimized.

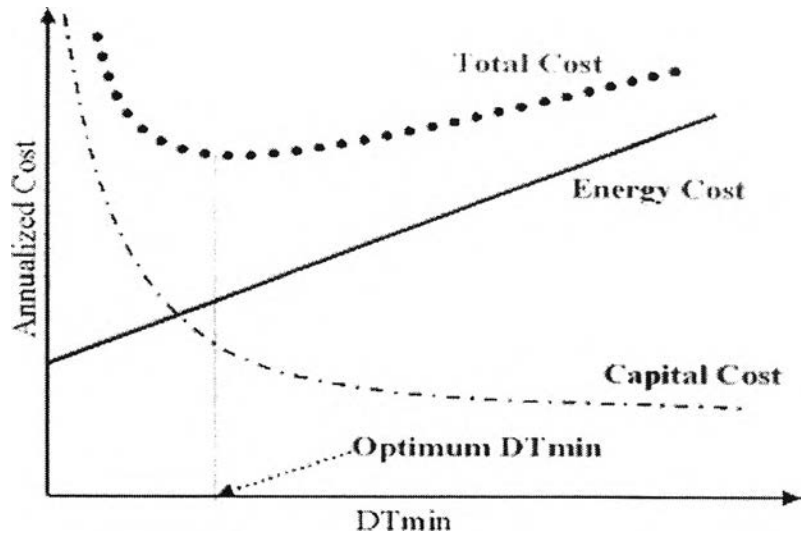


Figure 2.14 Energy-Capital cost trade off (www.cheresources.com).

2.2.3.9 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. If the marginal cost has very small increase, the higher value of ΔTmin is selected as the practical pinch point for the HEN design. 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

Violation of any of the above rules results in higher energy requirements than the minimum requirements theoretically possible.

2.2.3.10 Design of Heat Exchanger Networks

Design of Heat Exchanger Network in various industries is primarily carried out using the now classical "Pinch Design Method" (Linnhoff and Hindmarsh, 1983). While the original method focused on minimum energy consumption and the fewest number of units, later graphical and numerical additions made it possible also to consider heat transfer area and total annual cost during design. Both the original features and the later extensions have been implemented in current state of the art commercial software package for Heat Exchanger Network Design.

The basic Pinch Design Method respects the decomposition of process and utility pinch points and provides a strategy and matching rules that enable the engineer to obtain an initial network, which achieves the minimum energy target. The Grid Diagram is very useful in the design and acts as a drawing board, where the engineer places one match at a time using these matching rules. Hot streams are shown by arrows running from left to right and cold streams by arrows running from right to left. The dot line refers to as the pinch temperature. The circles represent heat exchangers. Unconnected circles represent exchangers using utility heating and cooling. The Pinch Design Method also indicates situations where stream splitting required reaching the minimum energy target.

The design strategy mentioned above is simply to start design at the pinch, where the driving force are limited and the critical matches for maximum heat recovery must be selected. The matching rules simply ensure sufficient driving force, and they attempt to minimize the number of units. The design then gradually moves away from the pinch.

The matching rules for the pinch exchanger can be expressed by

Above Pinch	Below Pinch
$N_{hp} \leq N_{cp}$	$N_{hp} \geq N_{cp}$
$CP_{hp} \leq CP_{cp}$	$CP_{hp} \geq CP_{cp}$

Where N_{hp} = number of hot streams at the pinch

N_{cp} = number of cold streams at the pinch

CP_{hp} = heat capacity flow rate of hot streams at the pinch

CP_{cp} = heat capacity flow rate of cold streams at the pinch

Making sure that every unit fully satisfies the enthalpy change of either the hot and cold stream (the "tick-off" rule) minimize the number of units. If the equalities above are not satisfies for a complete set of pinch exchanger, stream splitting has to be considered in order to reach Maximum Energy Recovery (MER).

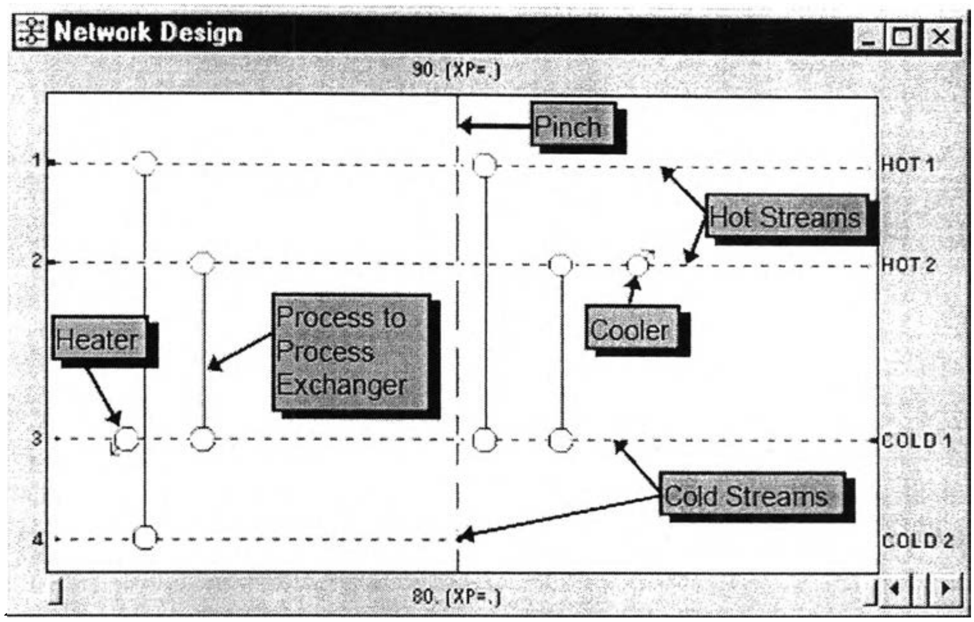


Figure 2.15 Grid diagram of the heat exchanger network (www.linnhoffmarch.com).

2.3 Retrofit of Heat Exchanger Networks

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, by Tjoe and Linnhoff.

2.3.1 Retrofit Targeting Based On Capital-Energy Trade-Off

Figure 2.16 provides an understanding of the capital - energy trade-off for a retrofit project using an area-energy plot.

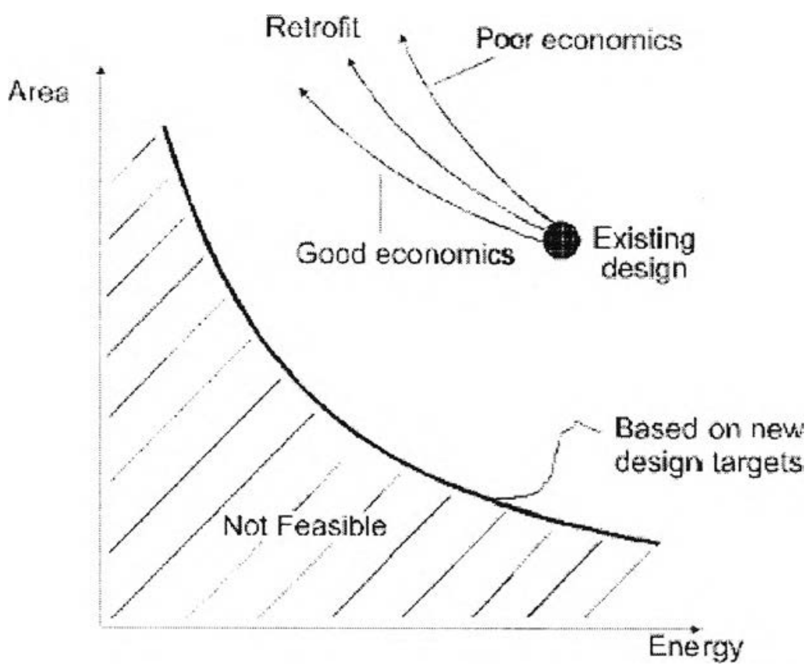


Figure 2.16 Capital-Energy trade off for retrofit applications (www.linnhoffmarch.com).

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 retrofit 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.

PAYBACK PERIOD: From the area-energy targeting curve the saving versus investment curve for the retrofit targeting can be developed. This is shown in Figure 2.17.

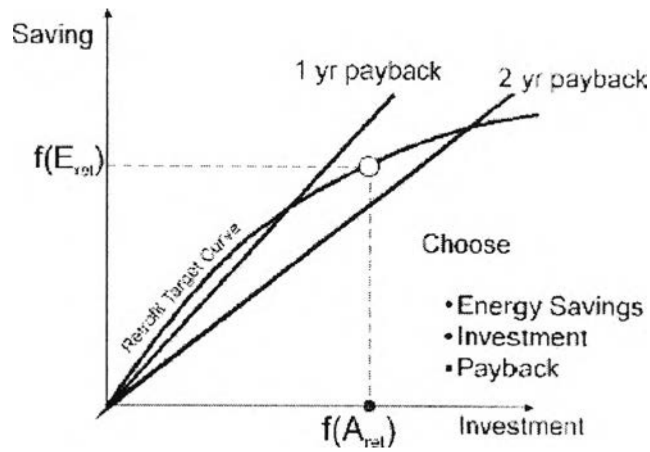


Figure 2.17 Targeting for retrofit applications (www.linnhoffmarch.com).

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.

2.3.2 Retrofit Targeting Based On ΔTmin - Energy Curve

In this section a simpler approach to retrofit targeting based on the analysis of energy target variation with ΔTmin is described.

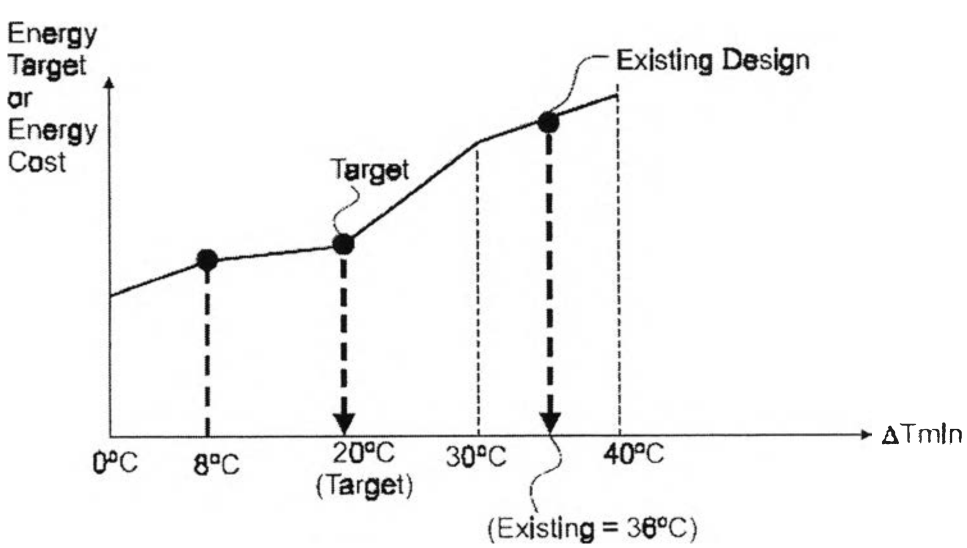


Figure 2.18 Targeting based on ΔTmin - Energy curve (www.linnhoffmarch.com).

Figure 2.18 shows an example of a ΔTmin- Energy plot for a process. The plot can be directly obtained from the process composite curves. The vertical axis can represent energy target or energy cost. Existing design corresponds to the ΔTmin of 36°C between the composite curves. The plot shows that the variation of energy target (or energy cost) is quite sensitive to ΔTmin in the temperature range of 30°C to 20°C. However between 20°C and 8°C the energy target is not sensitive to ΔTmin. On the other hand the capital cost may rise substantially in this region. It therefore implies that 20°C is an appropriate target for the retrofit. Although the ΔTmin - Energy plot does not directly account for the capital cost dimension, it is expected that dominant changes in the energy dimension will have an impact on the capital-energy trade-off.

2.3.3 Retrofit Targeting Based On Experience ΔTmin Values

It is expected that retrofit projects involving similar cost scenarios (fuel and capital costs etc.), and similar levels of process technology may result in similar target ΔTmin values. In such cases previous applications experience provides a useful source of information for setting the target ΔTmin for the process. (see in section 2.3.3)

2.3.4 Retrofit Design

The retrofit design using one of the three methods:

(1) PDM with maximum re-use of existing exchangers

(2) Correction of cross-pinch exchangers

(3) Analysis of exchanger paths

The first step in retrofit design is to decide which retrofit method is most suitable for the project. The hierarchical diagram shown in Figure 2.19 indicates when each of the three methods is suitable.

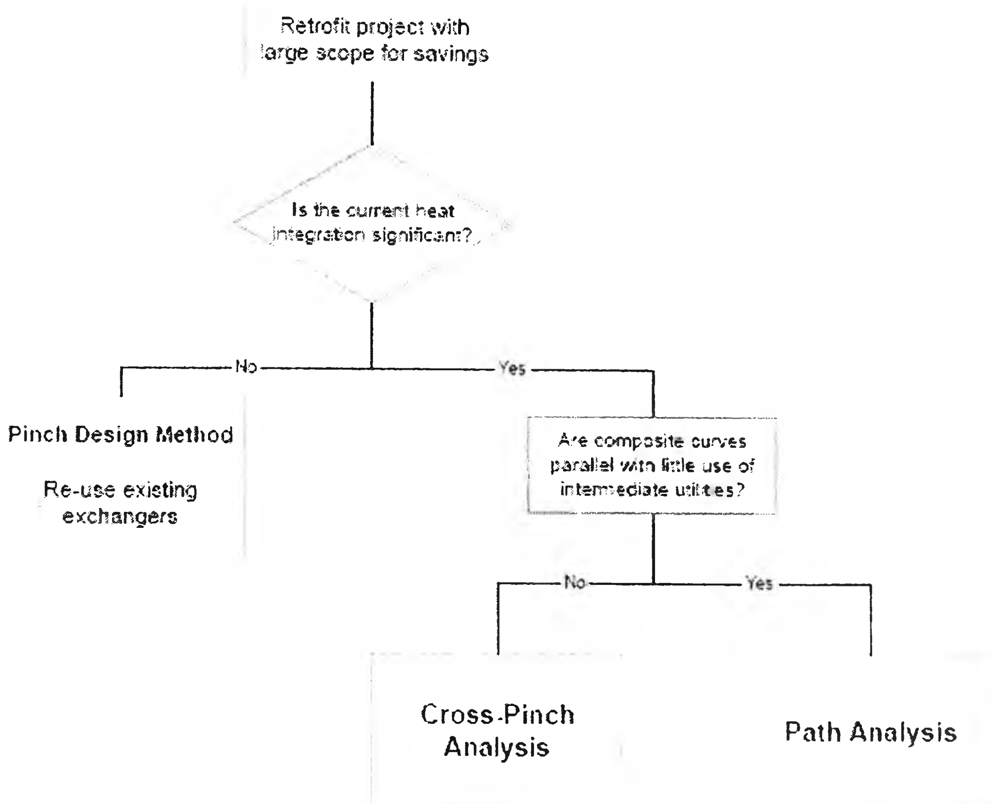


Figure 2.19 Hierarchy of retrofit design (Linnhoff and Hindmarsh, 1983).

However, in situations where the existing network already involves many process-process heat exchangers, it is not appropriate to delete the entire network in order to apply the Pinch Design Method. Instead, it is better to apply a method that makes incremental changes to the existing network, with a corresponding quantification of the benefits.

2.4 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.

2.4.1 Distillation 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 is possible to identify which one of these modifications would be appropriate for the column and what would be the extent of the modification.

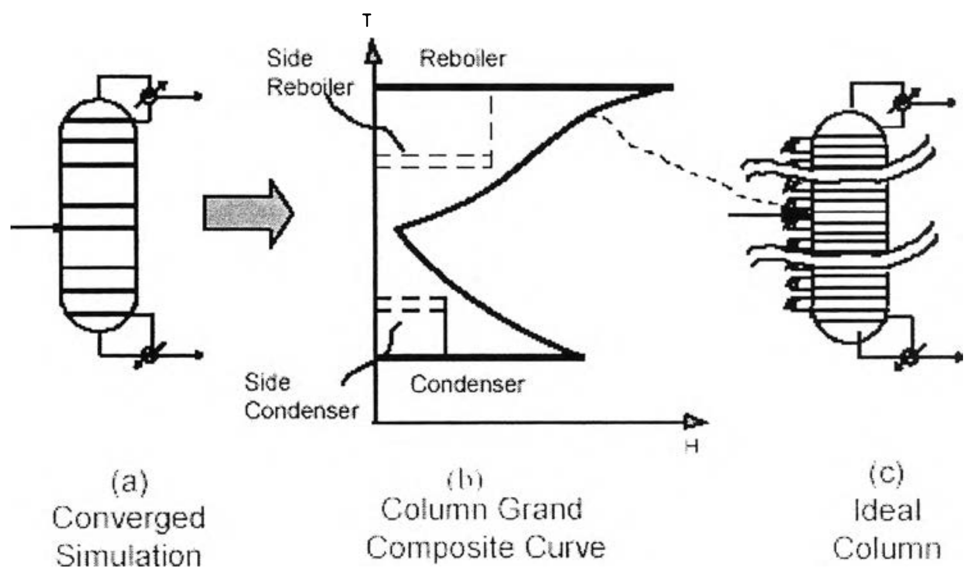


Figure 2.20 Procedure for obtaining the column grand composite curve (www.linn hoffmarch.com).

The tool used for column thermal analysis is called the Column Grand Composite Curve (CGCC), an example of which is shown in Figure 2.20. This method is based on a practical near-minimum thermodynamic condition (PNMTC) that accounts for inevitable inefficiencies (i.e., losses due to sharp separation, pressure drop, chosen configuration and, feed) through an actual column simulation because of most industrial columns have certain inevitable losses or inefficiencies. In order to set realistic targets for the design modifications of these columns, we need to allow for these losses. 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 to generate the CGCC as shown in Figure 2.20(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 2.20(c)). For ideal column operation the column requires infinite number of stages, side reboilers and condensers as shown in Figure 2.20(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.

2.4.1.1 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

$$G_{min} Y^*_L - L_{min} X^*_L = D_L \tag{2.11a}$$

$$G_{min} Y^*_H - L_{min} X^*_H = D_H \tag{2.11b}$$

After feed stage

$$L_{min} X^*_L - G_{min} Y^*_L = B_L \quad (2.12a)$$

$$L_{min} X^*_H - G_{min} Y^*_H = B_H \quad (2.12b)$$

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

B_L, B_H = Light and heavy component flow of bottom

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.

$$H_{Gmin} = H^*_G (G_{min}/G^*) \quad (2.13a)$$

$$H_{Lmin} = H^*_L (L_{min}/L^*) \quad (2.13b)$$

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 2.21(a)).

Before feed stage

$$H_{def} = H_{Lmin} - H_{Gmin} + H_D \quad (2.14a)$$

After feed stage

$$H_{def} = H_{Lmin} - H_{Gmin} + H_D - H_{feed} \quad (2.14b)$$

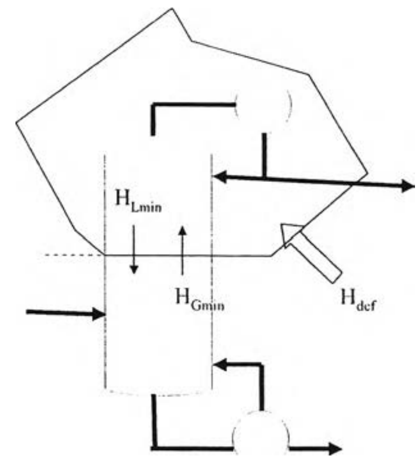


Figure 2.21(a) Evaluating enthalpy deficit at a stage (Dhole and Linnhoff, 1992).

Figure 2.21(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.

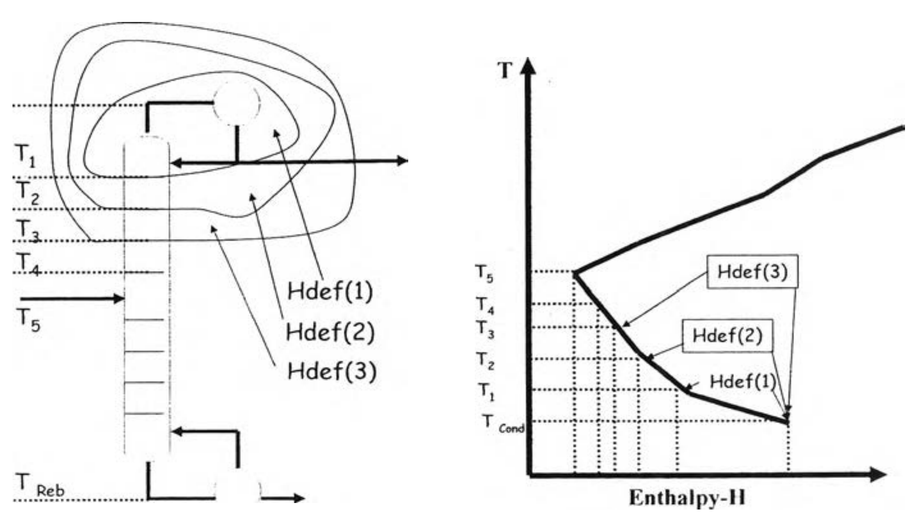


Figure 2.21(b) Constructing the CGCC from stage wise enthalpy deficits (Dhole and Linnhoff, 1992).

2.4.1.2 Modifications Using the Column Grand Composite Curve

Figure 2.22 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.

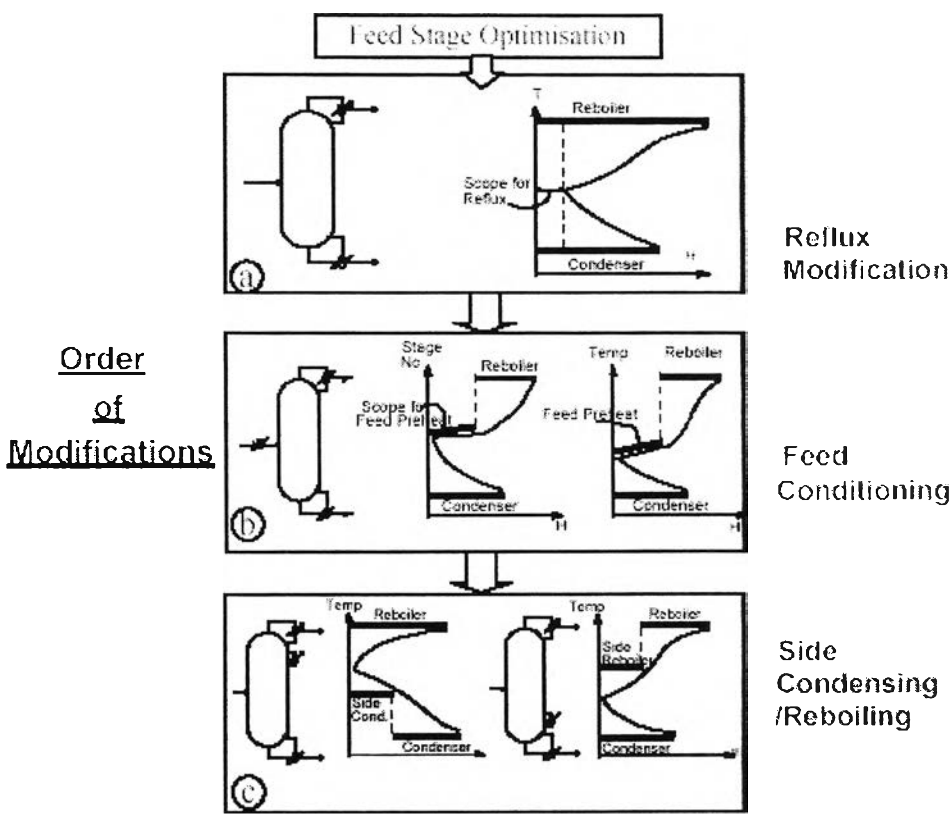


Figure 2.22 Column modifications (Dhole and Linnhoff, 1992).

As shown in Figure 2.22(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 2.22(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 2.22(c) shows CGCC 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.

2.5 Process Heat 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 2.23 summarizes the principles for appropriate column integration with the background process.

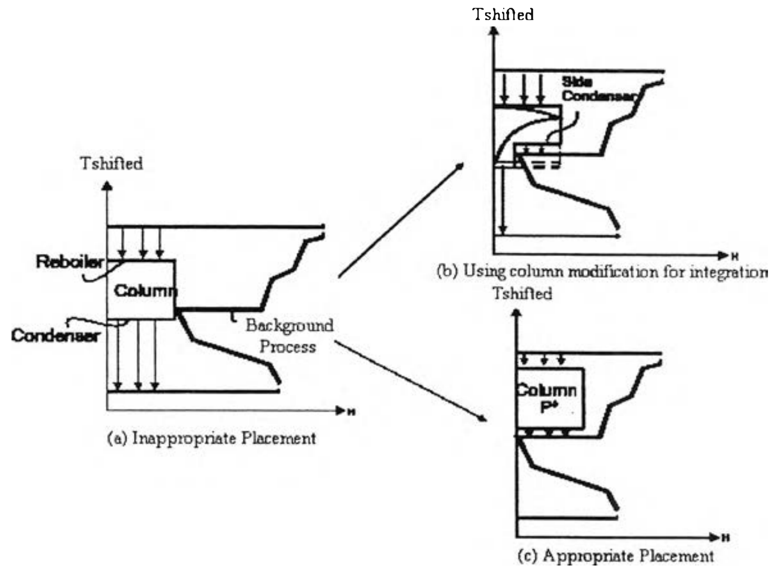


Figure 2.23 Appropriate integration of a distillation column (www.linnhoff march.com).

Figure 2.23(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 2.23(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 2.23(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 2.23(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 summaries, 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.

2.6 Refrigeration System

The refrigeration cycle (shown in Figure 2.24 below) begins with the refrigerant in the evaporator. At this stage the refrigerant in the evaporator is in liquid form and is used to absorb heat from the product. When leaving the evaporator, the refrigerant has absorbed a quantity of heat from the product and is a low-pressure, low-temperature vapor. This low-pressure, low-temperature vapor is then drawn from the evaporator by the compressor. When vapor is compressed it rises in temperature. Therefore, the compressor transforms the vapor from a low-temperature vapor to a high-temperature vapor, in turn increasing the pressure. This high-temperature, high-pressure vapor is pumped from the compressor to the condenser; where it is cooled by the surrounding air, or in some cases by fan assistance. The vapor within the condenser is cooled only to the point where it becomes a liquid once more. The heat, which has been absorbed, is then conducted to the outside air. At this stage the liquid refrigerant is passed through the expansion valve. The expansion valve reduces the pressure of the liquid refrigerant and therefore reduces the temperature. The cycle is complete when the refrigerant flows into the evaporator, from the expansion valve, as a low-pressure, low-temperature liquid.

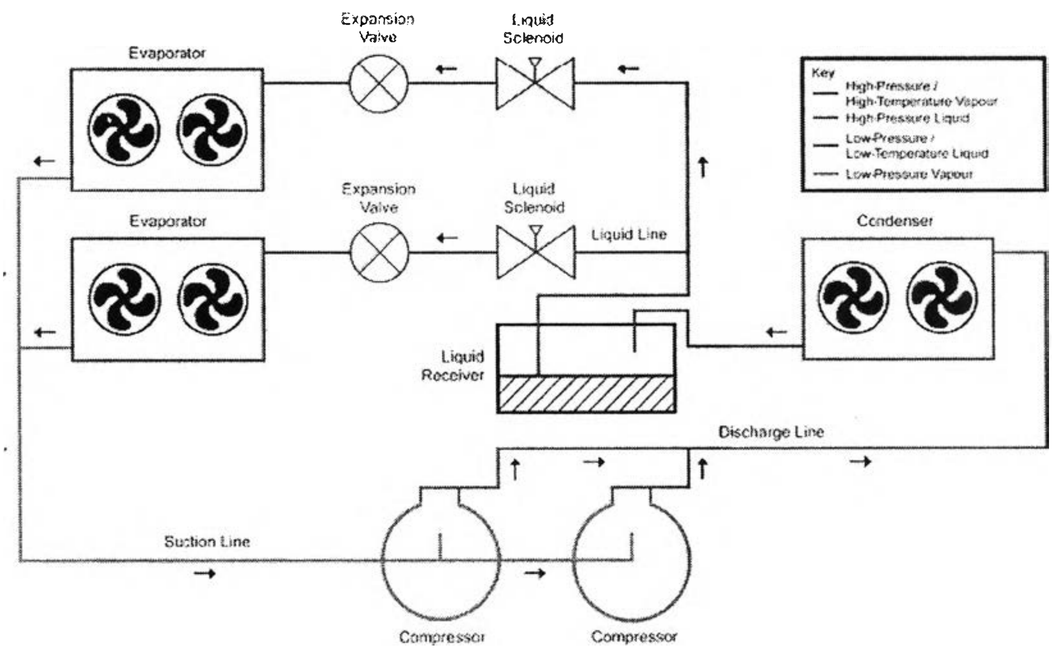


Figure 2.24 The refrigeration cycle (www.honeywell.com).

2.7 Literature Survey

2.7.1 Development of Pinch Technology

Over the past 20 year, pinch technology has evolved. It provides tools that allow us to investigate the energy flows within a process, and to identify the most economical ways of maximizing heat recovery and minimizing the demand for external utilities. The approach can be used to identify energy-saving projects within a process or utility systems.

In 1971, Heat Exchanger Network Synthesis (HENS) was introduced by Nishida et al. and Hohmann. This is applied for determination of a cost-effective network to exchange heat among a set of process stream, where any heating and cooling not satisfied by exchange among these streams must be provided by external utilities. Three year later, Ponton and Donaldson (1974) presented a useful tool for designing HENS "fast matching algorithm" to provides near-minimum area solution.

After that Umeda et al.,(1978), Linnhoff and Flower (1978) identified the heat recovery pinch point where is defined an adequate amount of minimum temperature driving force and represents the most constrained region for heat recovery, and developed the problem table algorithm (PTA) to calculate the energy target algebraically.

Towards the end of the seventies and beginning of the eighties, driven strongly by increased energy prices, the pinch design method (PDM) was proposed based on pinch concept by Linnhoff and Hindmarch (1983). The PDM recognizes that no heat must cross the pinch and develops the design into two separate problems (namely, one above the pinch and another below it). Recognizing the pinch division allows the PDM to generate maximum energy recovery (MER) network that meet the energy target. During the same year, a criterion for placement of heat engines and heat pumps in process networks was first presented by Townsend and Linnhoff. 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.

In 1984, Linnhoff and Vredeveld introduced the vertical temperature difference between the hot composite curve (HCC) and the cold composite curve (CCC) against the cold composite temperature that called "The driving force plot (DFP)" which provides a useful picture of the appropriate driving forces for the matches during the network design. However, it is not always clear which of a number of candidate matches should be chosen, although some will be critical in the determination of the eventual cost of the complete network.

Linnhoff and Tjoe (1986) presented a method that used pinch design method for process retrofits. The methodology makes use of capital-energy trade-offs in the form of area-energy curve and applies the concept of area efficiency. It consists of a first stage at which the project scope is identified and a second stage which involves the identification of the cross pinch exchangers, the elimination of the cross-pinch exchangers, the positioning of new heat exchangers, the reuse of removed heat exchangers, and the final evolution of improvements in view of existing loops between process and utility matches.

Because of the increasing demand of energy-saving, Ahmad and Smith (1989) discuss the use of remaining problem analysis (RPA) to estimate the penalty incurred during network synthesis with regard to the area and shell targets. Like the DPF, it allows the designer to distinguish between bad matches and good matches in the network. Moreover, 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.

During 1992, Dhole and Linnhoff presented a methodology based on a combination of thermodynamics and practical aspects of column targeting. By using column grand composite curve (CGCC), its can accounts for inevitable inefficiencies (i.e., losses due to sharp separation, pressure drop, chosen configuration and feed) through an actual column simulation and then introduces many modifications of existing column that include feed stage location, reflux improvement, feed preheating/cooling, side condensing/reboiling etc..

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.

Asante and Zhu (1997) developed a two-stage methodology for HEN retrofit design using the network pinch. The first stage is a search for topology changes to maximize heat recovery and the second stage is the optimization of the fixed topology to evaluate the capital-energy trade-offs. Possible topology modifications include resequencing or repiping exchangers, adding a new exchanger and stream splitting. Resequencing involves changing the location of an existing exchanger, but maintaining the same hot and cold streams. Repiping involves changing the location of an existing exchanger and changing either the hot or cold stream.

Adding a new exchanger involves creating a new match between hot and cold streams. Stream splitting involves rearranging exchangers in parallel.

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.

Semra Ozkan and Salih Dincer (2001) presented the improved problem algorithm table IPAT. This technique improves the disadvantage of PTA that has been published by Linnhoff and Flower. IPAT allows engineer to make calculations without using shifted temperature, thus all the results are viewed clearly in a single table.

2.7.2 Applications of Pinch Technology

Pinch technology (PT) is proved to be important for process engineers to analyze and design chemical processes (Stankiewicz, 1993). PT is applied for energy saving toward many industrial processes. It is available to automate the redesign process and PT is set to move beyond energy, into pressure drop optimization and distillation columns sequencing.

Haitham M.S. Lababidi et al., (2000) applied pinch technology in a ammonia plant by using retrofit techniques. Hot and cold utility targets are evaluated by performing the Problem Table Analysis (PTA). The minimum approach temperature (ΔTmin) used in the analysis is 10°C. They found that utility loads demanded by the existing process were found to be very close to the calculated minimum targets. This indicated that the selected ammonia plant is well integrated, and not much saving is expected through process-to-process energy integration. Alternatively, the retrofit study concentrated on better placement of available utilities. Two promising retrofit options have been investigated. The first one benefit from the flue gases wasted energy and the second one targeted the boiler feed water stream. Lowering the flue gas temperature in the convection section of the primary reformer would result in 6.2 GCal/H recoveries. The second retrofit option considered shifting heating load from the back-end to the front-end heat up the BFW stream. This results in decreasing the boiler load, reducing the cooling water requirement in the back-end, and 7.6% savings in total fuel consumption. Total benefit claimed amounted to 17.6% reduction in combustion fuel consumption.

M. Markowski (2000) applied pinch technology to HEN reconstruction in a crude distillation unit. The modification aimed at reducing the leakage between the tube bundle and the exchanger shell causes the heating duty to increase. The result shown that heat saving in the reconstructed HEN was estimated 7.5 MW.

During the same year, K. Urbaniec et al. were also applied pinch concept in a sugar industry. They perform retrofit design procedure in two stages: targeting for various options of the evaporator structure and selecting the most promising one, and designing both subsystems for targets so determined. This problem is conveniently solved using the network pinch approach. The energy saving is estimated at 29%. The pay-back period of 4 years reflects the combined effect of increased sugar output and reduced specific energy consumption.

The fluid catalytic cracking (FCC) is a dominant process in oil refineries and there has been a sustained effort to improve the efficiency and yield of the unit over the years. Badr Abdullah Al-Riyami et al., (2001) applied pinch technique to reduce energy consumption; the retrofit design was undertaken using network pinch method. The suggested retrofit design provided energy saving of 8.955 MW, about 74% of the scope of the design and the utility cost saving is $2,388,600 (27% decrease in the utility bill) by adding four heat exchangers and repiping of one existing exchanger.

L. Matijasevix and H. Otmaeix (2002) studied in a nitric acid plant. By applying pinch technology, it is possible to reduce requirements for cooling water and medium pressure steam. With the problem table algorithm, data were quickly extracted from the flow sheet and were analyzed for energy saving. In order to enable these savings, three heat exchangers should be replaced with new ones. Energy consumption in steam power system increases slightly. However, the final result is a reduction of energy costs with a payback time of 14.5 months.

Yao Wang et al., (2003) exploited pinch technology with several tools, including grid diagram, composite curve (CC), grand composite curve (GCC), balance grand composite curve (BGCC) and splitting grand composite curve (SGCC), to diagnosis of process energy-utilizing in a ammonia plant. The design pinch calculation revealed that 1150 kg/h of fuel gas and 1322 t/h of cooling water could be saved through optimizing the heat-transfer temperature-difference contribution value of each stream in the existing ammonia plant. Finally, a retrofitting proposal is given. Three possible configurations are proposed. A total energy saving of 7210 kW is expected to be achieved. The successful application of this technology in more than 10 Chinese plants has generated a profit of about 80 million RMB per year.

Adrian L. Querzoli et al., (2003) investigated improving the energy efficiency of two key refining processes: the crude distillation unit (CDU) and the residue cracking unit (RCU). A two-stage method was used with initial targeting followed by a retrofit analysis, the latter focused on reducing the ΔT_{min} of the pinching network exchangers. In the case of the CDU, a retrofit design was carried out and heat recovery of an additional 2MW had a payback of around 6 years. In the case of the RCU, the retrofit design for an additional 3.5MW of MPS had a payback of 1.6 years. The integration of the CDU and RCU also was investigated, and from a Total Site Analysis it appeared to offer a large potential for hot utility savings (40% reduction). However, because these savings could only be achieved through a reduction in MPS generation, the integration of the two units had a negative economic return.

In 2006, Anna Fritzon and Thore Berntsson studied opportunities for process integration toward a slaughter and meat processing plant in Sweden. By applying heat pinch analysis, they observed that has potentials for saving both shaftwork and external heat demand. The result of this work is very good performance. They could save 30% of the external heat demand by installing a new heat pump and more than 10% of the shaftwork in the refrigeration system, by changing some loads and one temperature level in the refrigeration plants.