CHAPTER II
BACKGROUND AND LITERATURE SURVEY

2.1 Process Integration

The term of process integration was emerged in the 80's. The initial focus of this technology is heat recovery and has expanded considering to cover several aspects of process design during the late 80's and the 90's. In the 90's, it has been extensively used to describe certain systems oriented activities related primarily to process design and become to a major strategic design and planning technology for industrial companies.

Now process integration is a strongly growing field of process engineering. It is a standard curriculum for process engineers in both chemical and mechanical engineerings at most universities around the world. By definition of International Energy Agency (IEA) in 1993 that describes process integration which is the systematic and general method for designing integrated production systems, ranging from individual process to total sites, with special emphasis on the efficient use of energy and reducing environment effect. With this technology, it is possible to significantly reduce cost of existing plants, while new processes can often be designed with reduction in both investment and operating costs.

2.2 Pinch Technology and Pinch Analysis

The most important concept and the one that originally gave birth to the field of process integration is pinch concept. Course and development of pinch technology started with Bodo Linnhoff (1978), a PhD. student from the corporate laboratory Imperial Chemical Industries Limited (ICI), under the supervision of Professor John Flower, university of Leeds, devised a new approach to describe energy flow in process heat exchanger network. It was an introduction of thermodynamic principles into what was then called process synthesis and heat exchanger network design. Over the last two decades it has emerged as an unconventional development in process design and energy conservation. This approach was developed and become pinch technology finally. Pinch technology provides a systematic methodology for energy savings in processes and total sites. These techniques give process engineers a clear picture of optimum energy needed for any processes and has been proved to be efficient in developing the best integrated process design for both new plant and retrofits. The term of pinch analysis is often used to represent the application of the tools and algorithms of pinch technology for studying industrial process. The development of pinch technology can be represented in rubic cube as shown in Figure 2.1. It indicated the start of pinch technology focusing on heat exchanger network with minimum energy consumption of grassroots design. During the 80's and 90's, pinch technology has expanded in all three dimension of the cube to cover almost process design.

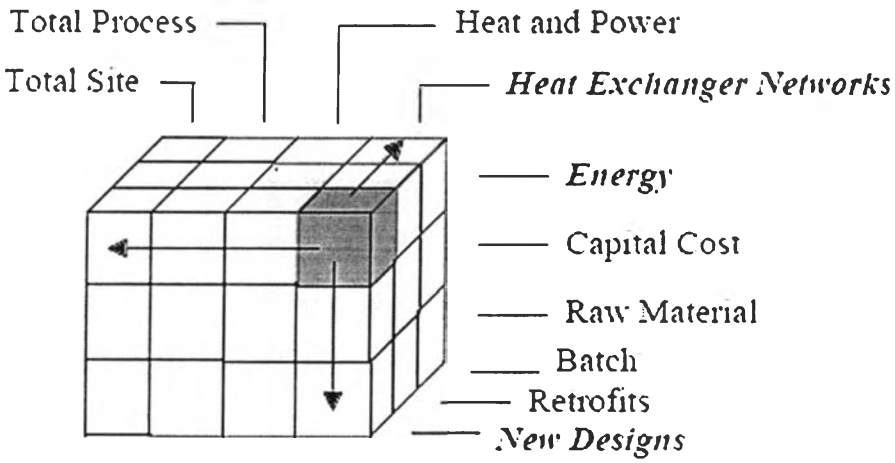


Figure 2.1 The rubic cube indicating the development of pinch technology (Gunderson, 2002).

As mentioned above, pinch technology presents a simple methodology for systematically analysis of chemical processes and the surrounding utility systems with the help of fundamental thermodynamics of the first and second laws. Thus we should know this principle for aid to understand concept of pinch technology. The first law of thermodynamics provides the energy equation for calculating the enthalpy changes in the stream passing through a heat exchanger. Meanwhile the second law determines the direction of heat flow that heat energy may only flow from hot to cold streams. This prohibits temperature crossovers of the hot and cold stream temperature profile through the exchanger unit.

The example of process integration by pinch technology can be illustrated in Figure 2.2 and 2.3. Consider the simple process on Figure 2.2, where feed stream is heated before entering to a reactor and product stream is cooled after outlet. Steams are used to heat the feed stream in heat exchanger 1. At the same time, cooling water is used to cool product stream in heat exchanger 2. Temperature-Enthalpy (T-H) diagram for feed and product streams depicts the hot (steam) and cold (cooling water, CW) utility load when there is no vertical overlap of the heat and cold stream profiles.

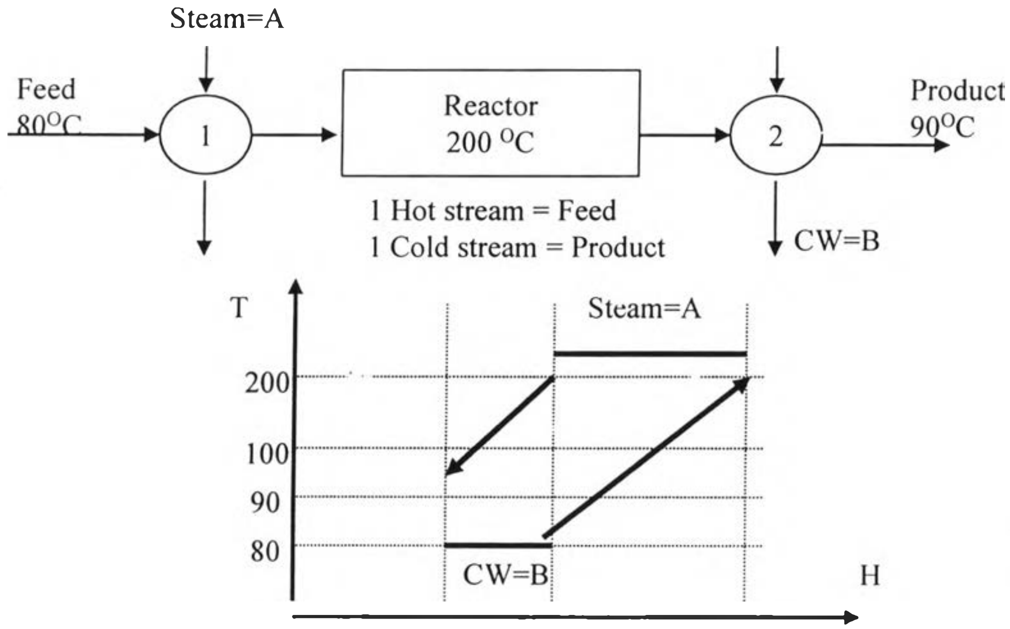


Figure 2.2 A simple flow scheme with temperature-enthalpy profiles (www.chersources.com).

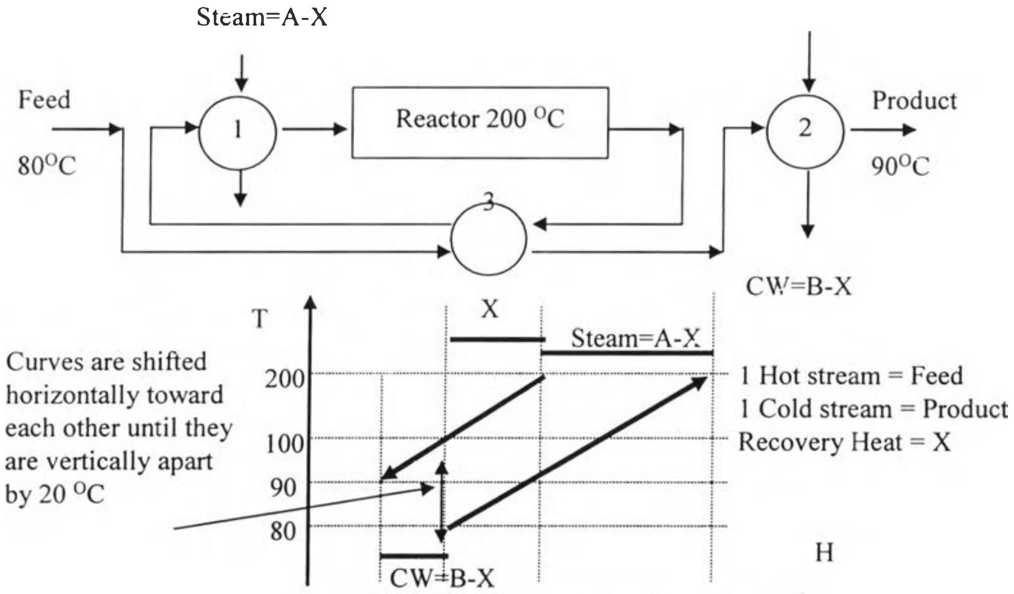


Figure 2.3 Improving flow scheme with temperature-enthalpy (www.chersources.com).

Applying to develop this process is presented in Figure 2.3. Adding a new heat exchanger 3 recovers product heat (X) to preheat the feed. The hot and cold utilities (steam and CW) are reduced by the same amount of X. The amount of heat recovered (X) depends on the minimum approach temperature that is allowable minimum temperature difference approach (ΔT_{min}) in the stream profiles for heat exchanger unit. The point where ΔT_{min} occurs is defined as the "pinch". From T-H diagram, the amount of X corresponds to ΔT_{min} of 20 ^{O}C. Based on second law of thermodynamics that prohibits any temperature crossover between the hot and the cold streams, 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 (ΔT_{min}). This ΔT_{min} value represents the bottleneck of the heat recovery.

The effect of ΔT_{min} is very important for making decision not only in designing but also in economic criteria. Increasing the ΔT_{min} values leads to higher utility requirement and lower area requirement. Thus the selection of ΔT_{min} value has implication for both capital and operating costs. Table 2.1 shows typical ΔT_{min} value for several types of processes. These are values based on Linnhoff March's application experience.

Table 2.1 Typical ΔT_{min} values for various types of processes (www.linnhoffmarch.com)

No	Industrial Sector	Experience ΔT_{min} Values	Comment
1	Oil Refining	20-40 °C	Relatively low heat transfer coefficients, parallel composite curves in many application, 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 ΔT_{min} decreases with low refrigeration temperatures

To summarize, the integration of new process into the existing facility provides significant improvement in the design of process plants that would minimize the net cost of energy purchase. The most useful tool that enables this design advance is the pinch technology, a systematic techniques for optimization.

2.3 Pinch Analysis for Heat Exchanger Networks (HENs)

Generally, applications of pinch analysis for heat exchanger can be divided into two cases. The first one is pinch analysis for new plant designs and the other is pinch analysis of existing facilities retrofits. The former are used to identify opportunities for heat integration and distillation improvement while the latter commonly used to identify opportunities for improving heat integration and to optimize the use of existing utilities system. The stepwise procedure of pinch analysis used and related in this work can be divided into four steps. The example calculation is proposed for easy to understand. Table 2.2 shows the hot and cold streams data that consists of temperature inlet, temperature outlet and mass heat flow capacity. The minimum temperature approach (ΔT_{min}) equal 10 ^{O}F is chosen to calculation.

Table 2.2 The hot and cold streams data

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

2.3.1 Setting the Temperature Interval

By choosing ΔT_{min} equal 10 ^{O}F, a graph can be established showing two temperature scales that are shifted by 10 ^{O}F, one for the hot streams and the other for cold streams as shown in Figure 2.4.

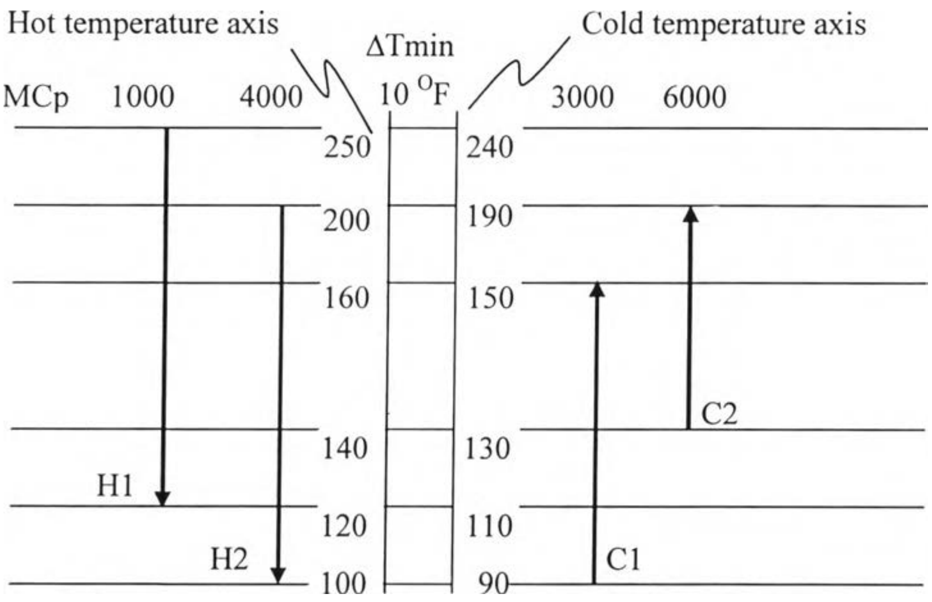


Figure 2.4 Shifted temperature scale and temperature intervals.

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

$$Q_{interval} = \{ \Sigma\, (mCp)hot,interval - \Sigma\, (mCp)cold,interval \}\Delta T,interval \qquad (2.1)$$

For example, the first interval obtains Q1 = (1000)(250-200) = 50 x 10^3 Btu/hr. Figure 2.5 shows net energy required at each interval.,

2.3.2 Generating Cascade Diagram

As mentioned above, energy will transfer from high-temperature interval to low-temperature interval. Figure 2.6 shows the energy transfer in this case.

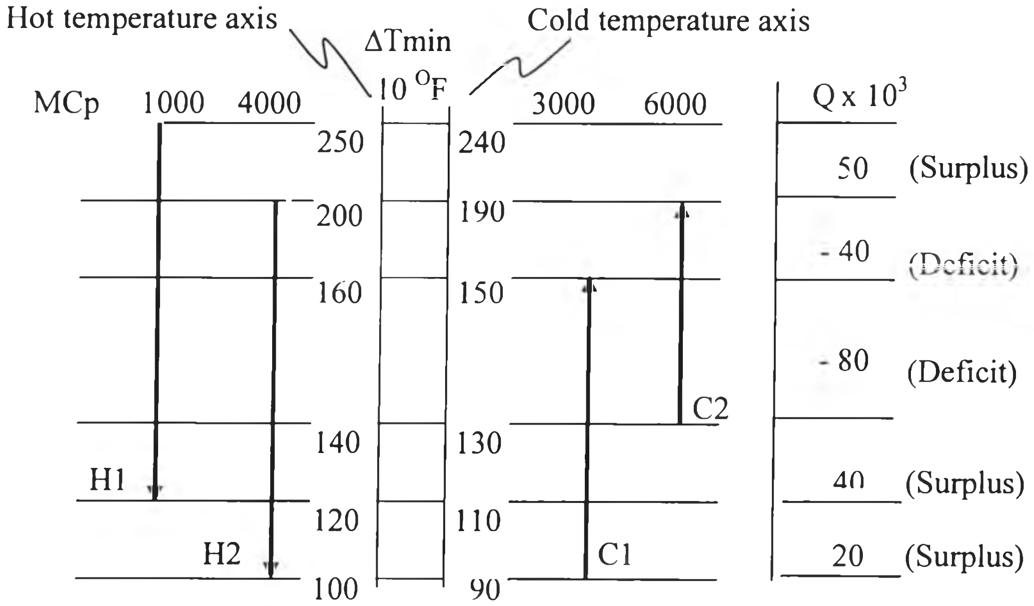


Figure 2.5 Net energy required at each interval.

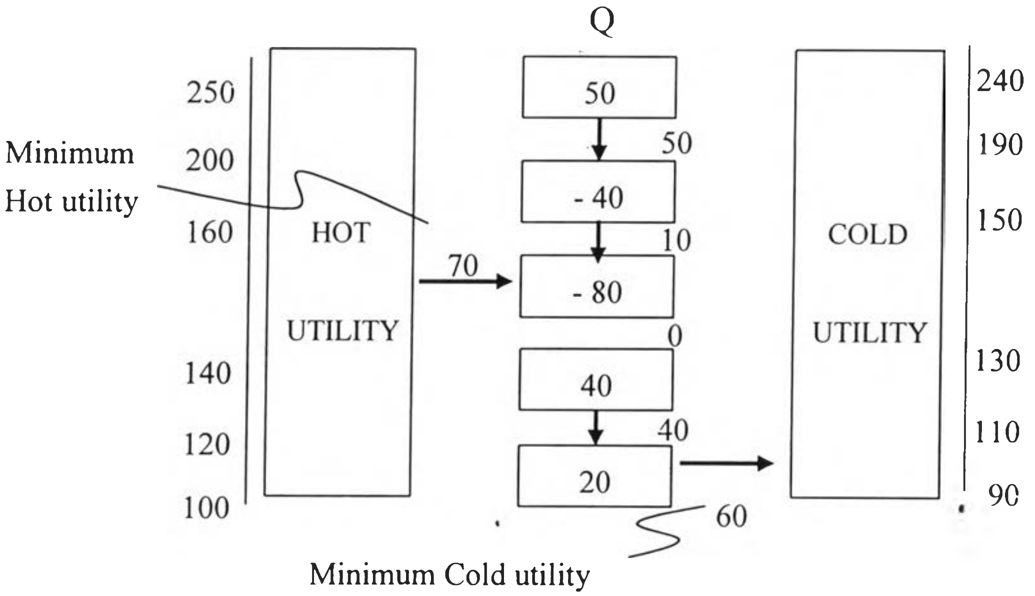


Figure 2.6 Cascade diagram.

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

2.3.3 Generating Grand Composite Curve (GCC)

GCC is a tool for determinating utility temperature and deciding on utility requirements. The GCC is constructed by rearranging the cascade diagram from Figure 2.6. 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 temperature vs. heat transfer of each temperature intervals, we can generate the GCC as shown in Figure 2.7.

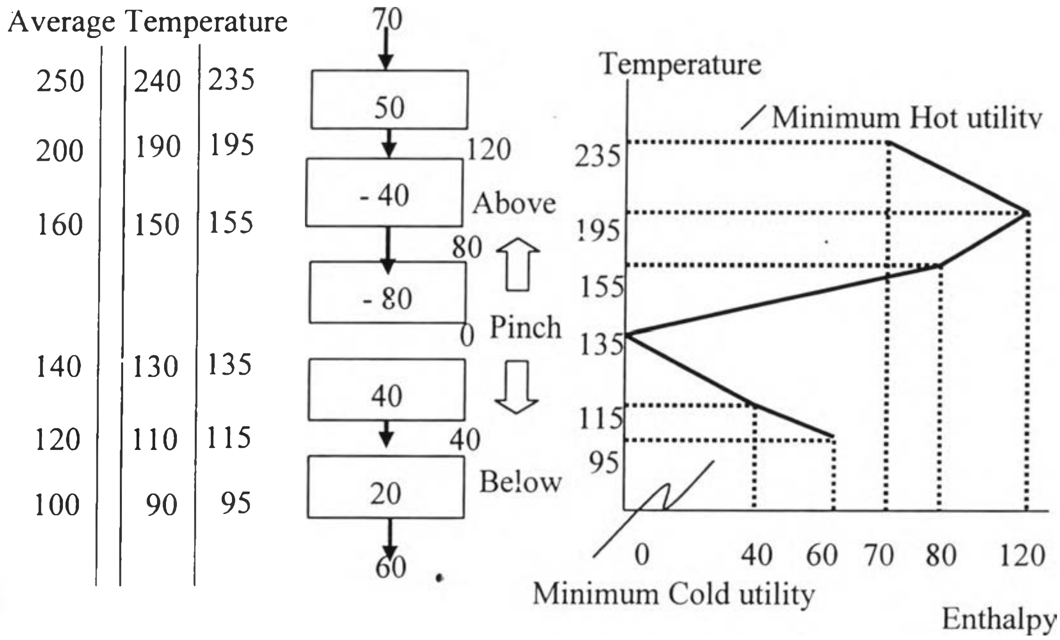


Figure 2.7 Generating grand composite curve.

This technique was used in 1982 by Itech, Shiroken and Umeda. It shows the variation of heat supply and demand within the process. This tool helps maximize the use of cheaper utility levels and minimize the use of expensive utility levels. Figure 2.8 shows advantage of grand composite curve in the utility consumption. From this figure, it is not necessary to supply the hot utility at the highest temperature level but the utility can be supplied over two temperature levels T_H1 (HP steam) and T_H2 (LP steam). The total minimum hot utility requirement remains the same: $Q_H$min = H1 (HP steam) + H2 (LP steam). Similarly, $Q_C$min = C1 (Refrigerant) + C2 (Cooling water). The point at T_H2 and T_C2 levels with utility duty of H2 and C2 on the GCC are called the utility pinch.

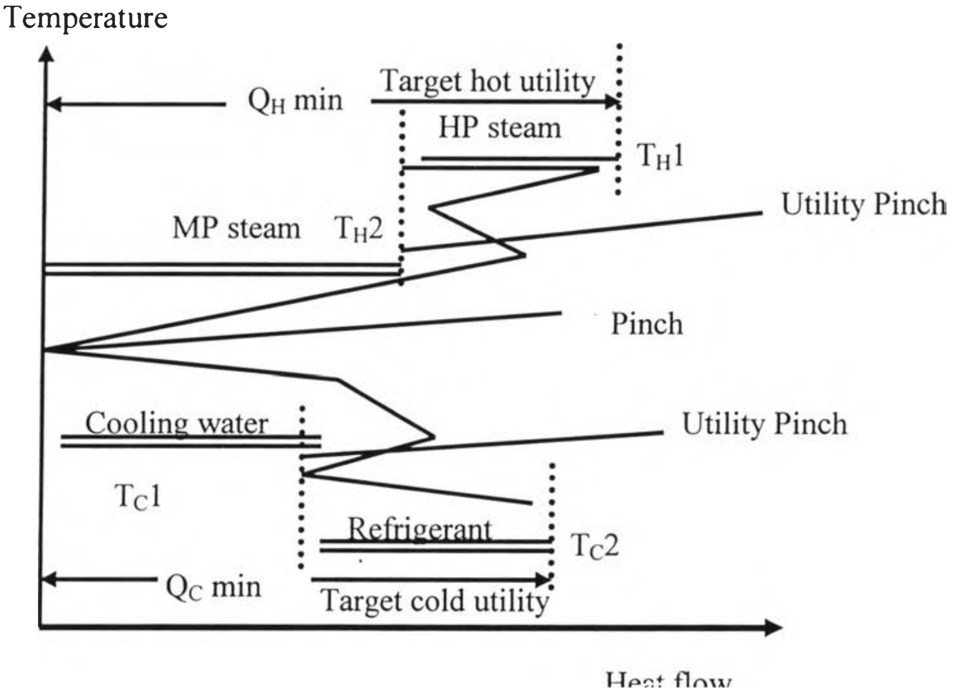


Figure 2.8 The advantage of Grand composite curve in utility consumption.

2.3.4 Design of Heat Exchanger Network

The design of heat exchanger network is best executed using the Pinch Design Method (PDM, Linnhoff and Hindmarsh, 1983). The basic PDM respects the decomposition of process and utility pinch points provide a strategy and matching rules enable the engineer to obtain an initial network, which achieves the minimum energy target. The design strategy simply starts at the pinch point. From Figure 2.7, there is no energy transfer between the third and fourth temperature intervals. This point is called pinch point, where driving forces are limited and the critical matches for maximum heat recovery must be selected. The matching rules simply ensure sufficient driving forces to minimize the number of units. The design then gradually moves away from the pinch, making sure that hot streams are utilized above pinch and vise versa for cold streams below pinch.

The matching rules for pinch exchangers can be expressed mathematically by

Above pinch $\dot{m}Cp_{,Cj} \geq \dot{m}Cp_{,Hi}$

$n_C \geq n_H$

Below pinch $\dot{m}Cp_{,Hi} \geq \dot{m}Cp_{,Cj}$

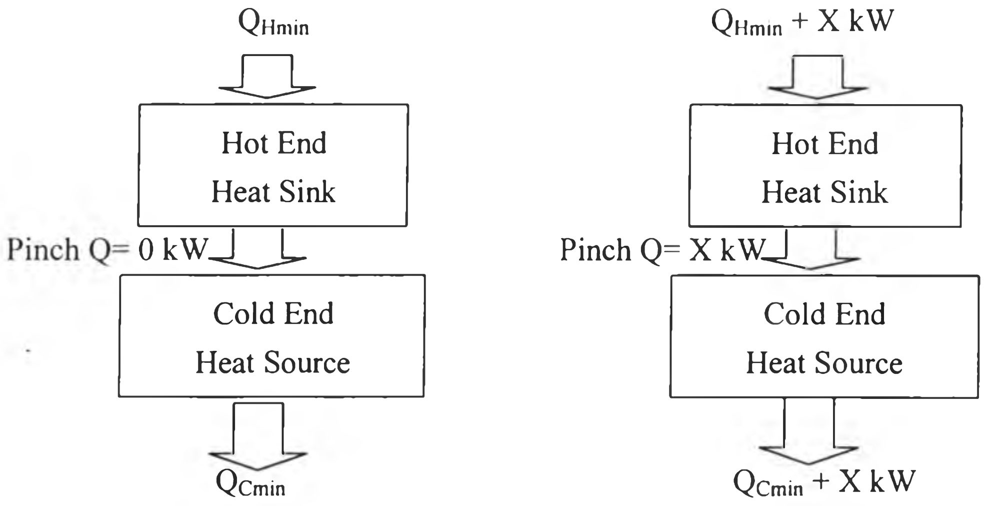
$n_H \geq n_C$

where Hi and Cj are potential streams to be matched in a heat exchanger
n_H and n_C are number of hot and cold streams, respectively
$\dot{m}$ is mass flow rate

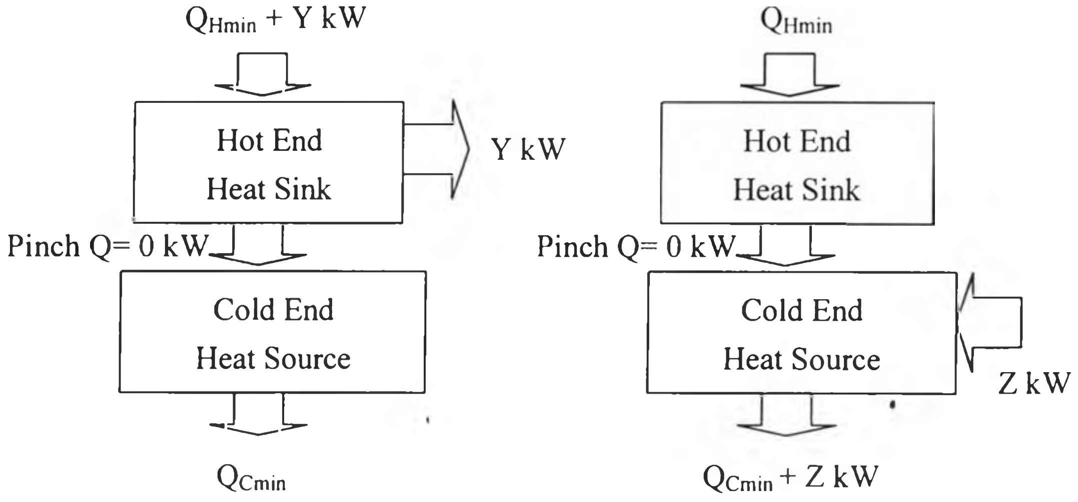
If the above equalities are not satisfied for a complete set of pinch exchangers, stream splitting has to be considered in order to reach maximum energy recovery (MER). It is always possible to split stream splitting to satisfy all inequalities, that total $\dot{m}Cp$ of cold stream are larger than total $\dot{m}Cp$ of hot streams above pinch, and vice versa for ones below pinch. Moreover, there are three rules forming the basis for practical network can be summarized below,

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

The violation of any of the above rules results in the higher energy requirements than the minimum requirements theoretically possible. These rules are called “rule of thumb”. For more understanding, Figure 2.9 (a) and (b) explain the effect of heat transfer across pinch. Figure 2.9 (a) shows the simple block diagram in general case that no heat transfer across pinch and (b) shows the heat transfer across pinch amount of X kW. The utilities requirement is twice as much as case (a). The same energy penalty occurs in case of adding cold utility above pinch point and adding hot utility below pinch point as shown in Figure 2.9 (c) and (d), respectively



(a) No heat across pinch **(b) Heat transfer across pinch**



(c) Add cooling above pinch point **(d) Add heating below pinch point**

Figure 2.9 The effect of "rule of thumb" (Linnhoff and Hindmarsh,1983).

However, a pinch does not occur in all heat exchanger network problems. Certain problems remain free of a pinch until the minimum allowed driving force, ΔT_{min}, is increased up to or beyond a threshold value ΔT_{thresh}.

The concept of a threshold problem can be exemplified as a "very hot" hot stream matched to a "very cold" cold stream so the design for the network consists of only hot or cold utilities. Figure 2.10 shows the behavior in term of a plot between utility requirements and ΔT_{min}.

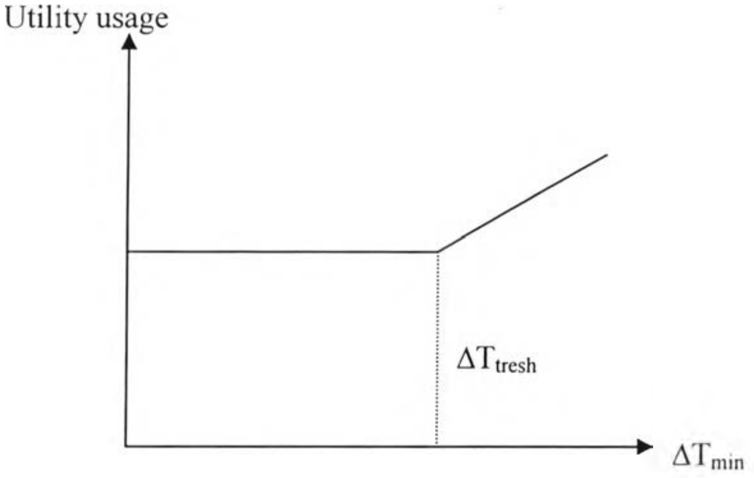


Figure 2.10 Threshold problem behavior.

To design the unpinch heat exchanger network, fast matching algorithm of Ponton and Donalson (1974) was presented. It is also referred to as the hottest/highest matching heuristic and allows networks to be generated with relative ease and rapidity. It does not specify stream splits and generates only one network. The method is based on heuristic of matching as follows.

"The hot stream having the highest supply temperature with the cold stream having the highest target temperature"

Once a match is chosen, some heuristic is required to fix its load. An appropriate heuristic may transfer the maximum possible heat subject to ΔT_{min} constraints.

For both PDM and threshold problem, the graphical method for representing flow stream and heat recovery match called a gird diagram (Figure 2.11). All cold and hot streams are represented by horizontal lines.

The inlet and outlet temperatures are shown at either ends. The vertical line in the middle represents the pinch temperature. The circle represents heat exchanger and unconnected circles represent exchanger using hot and cold utility.

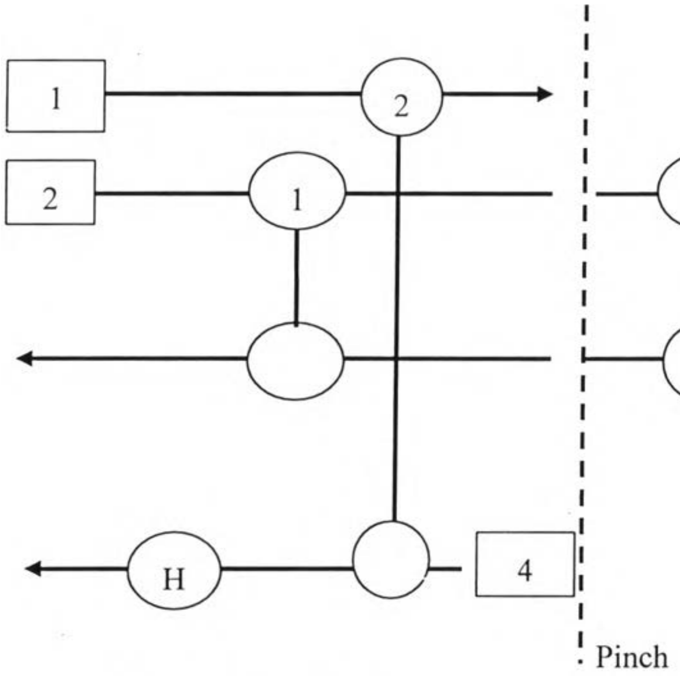


Figure 2.11 Grid diagram.

2.4 Pinch Analysis for Distillation (Distillation Column Targeting)

One of the major energy-intensive units in chemical separation process is distillation column. Similar to pinch analysis for HEN, distillation column can be simply represented in term of graphical representation by using pinch analysis. Distillation column targeting method (Dhole and Linnhoff, 1992) is useful to identify design targets for improvements in energy consumption and efficiency. This capability is based on the concept of practical near-minimum thermodynamic condition (PNMTC) that accounts for evitable inefficiencies (i.e, loss due to sharp separation, pressure drop, chosen configuration, and feed) through an actual column simulation. Figure 2.12 shows the PNMTC. The column at PNMTC will still require infinite stages and infinite side exchangers as shown in the Figure 2.12.

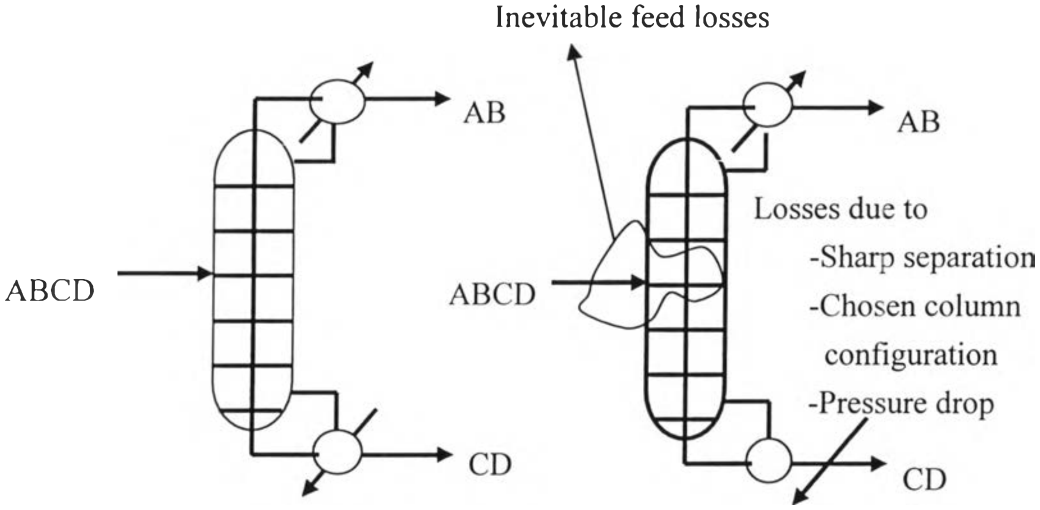


Figure 2.12 Practical near-minimum thermodynamic condition (PNMTC).

This method can be divided into five steps. Similar to HENs, the example calculation is proposed to make it easy to understand. Considering the data properties of feed and product as illustrated in Table 2.3.

Table 2.3 Data specification of feed (F), distillate (D) and bottoms (B)

Properties	Feed	Distillate	Bottoms
Pressure (kPa)	200	100	102.5
Temperature (^{O}C)	100	40	125
Molar flow (kmol/hr)	1000	599.9	400.1
Mole fraction liquid	0.5795	1.0	1.0
Mole fraction component 1 (c1)	0.200	0.3328	0.0008
Mole fraction component 2 (c2)	0.200	0.3279	0.0081
Mole fraction component 3 (c3)	0.200	0.3225	0.0163
Mole fraction component 4 (c4)	0.200	0.0157	0.4764
Mole fraction component 5 (c5)	0.200	0.0011	0.4984

2.4.1 Converge Simulation of Distillation Column and Indication of Light and Heavy Keys

The computer simulations such as Aspen plus, PROII and Hysis are used to design distillation column. Normally the output data of simulation provides molar flow rates and compositions on a stage-by-stage basis. Table 2.4 presents the result of the simulation for ten stages (feed stage = 5) based on a total condenser (with the condenser temperature specified at 40 ^{O}C). Consider a light and heavy key model with components c4 and c5 are considered as heavy keys. The more volatile of these components is the light and the less volatile is the heavy key. Heavy keys and light keys are denoted subscript H and L respectively. Also, X and Y denote the mole fraction in the liquid (L) and vapor (G) respectively.

Table 2.4 Simulation results for column with ten stages

Stage No.	X_H*	Y_H*	L*	G*	H_L*	H_G*
1	0.0167	0.0167	246.3	-	384	-
2	0.2212	0.0168	196.7	846.3	510	8226
3	0.4965	0.0673	162.4	796.6	697	8406
4	0.6342	0.1189	149.3	762.4	789	8593
5	0.6858	0.1457	624.2	222.8	3553	2601
6	0.7066	0.1700	625.4	224.2	3728	2686
7	0.7575	0.2305	627.2	225.3	4118	2861
8	0.8412	0.3747	636.4	227.1	4873	3254
9	0.9238	0.6150	655.8	236.3	5866	4009
10	0.9748	0.8439	400.1	255.8	3995	5005

Units: flows (L*,G*) in kmol/hr and enthalpies (HL*,HG*) in kW

2.4.2 Calculation of Minimum Vapor and Liquid Flow Rates and Minimum Vapor and Liquid Enthalpies

As a close approximation to PNMTC, the equilibrium and operating line equations for the key components are shown below

$GY_L\text{-}LX_L = D_L$ Light key above feed stage (2.2a)
$GY_H\text{-}LX_H = D_H$ Heavy key above feed stage (2.2b)
$LX_L\text{-}GY_L = B_L$ Light key at/below feed stage (2.2c)
$LX_H\text{-}GY_H = B_H$ Heavy key at/below feed stage (2.2d)

These equations must be solved simultaneously with the equilibrium line equations. The stagewise compositions from the simulation (denoted by *) provide the equilibrium compositions. Using these compositions, and noting that the equilibrium and operating curves are coincident at the minimum thermodynamic condition, yields

$G_{min}Y_L^*\text{-}L_{min}X_L^* = D_L$ Light key above feed stage (2.3a)
$G_{min}Y_H^*\text{-}L_{min}X_H^* = D_H$ Heavy key above feed stage (2.3b)
$L_{min}X_L^*\text{-}G_{min}Y_L^* = B_L$ Light key at/below feed stage (2.3c)
$L_{min}X_H^*\text{-}G_{min}Y_H^* = B_H$ Heavy key at/below feed stage (2.3d)

Equation 2.3 establishing the minimum vapor flow (G_{min}) and the liquid flow (L_{min}) at the stage temperature. In order to obtain the temperature-enthalpy representation for PNMTC, it needs to express the minimum vapor and liquid flows in term of enthalpies. Usually simulation outputs also provide stage-by-stage vapor and liquid enthalpy values as shown in Table 2.4 (H_G^* and H_L^* respectively) and these values are in equilibrium. Thus, the enthalpies at the minimum vapor and liquid flow (H_{Gmin} and H_{Lmin}) are obtained from H_G^* and H_L^* by direct molar proportionality following this equation. The results of G_{min}, L_{min}, H_{Gmin} and H_{Lmin} are shown in Table 2.5.

$H_{Gmin} = H_G*(G_{min}/G*)$ (2.4a)

$H_{Lmin} = H_L*(L_{min}/L*)$ (2.4b)

Table 2.5 The result of calculation of minimum vapor and liquid flow rates and minimum vapor and liquid enthalpies

Stage No.	L_{min}	G_{min}	H_{Lmin}	H_{Gmin}
1	-	-	-	-
2	0.0	599.90	0	5834
3	70.84	670.77	305	7079
4	119.00	718.93	630	8104
5	614.15	214.08	3494	2498
6	600.03	199.95	3576	2396
7	565.08	167.04	3711	212
8	514.65	114.58	3942	1640
9	466.22	66.15	4171	1122
10	400.10	0.0	3995	0

2.4.3 Calculating of Net Heat Deficit (H_{def})at Each Stage Temperature

After calculating $H_{G,min}$ and $H_{L,min}$, enthalpy balances are set up at each of the stage temperatures and the net enthalpy deficits (H_{def}) are then evaluated at each of these temperatures. Figure 2.13 presents the evaluating enthalpy deficit at a stage.

From this figure, the enthalpy deficit on each stage is given by

$H_{def,1} = H_{l,min} - H_{Gmin} + H_D$ above feed stage (2.5a)

$H_{def,2} = H_{l,min} - H_{Gmin} + H_D - H_F$ below feed stage (2.5b)

Table 2.6 shows the result from calculation of net heat deficit (H_{def}) at each stage temperature

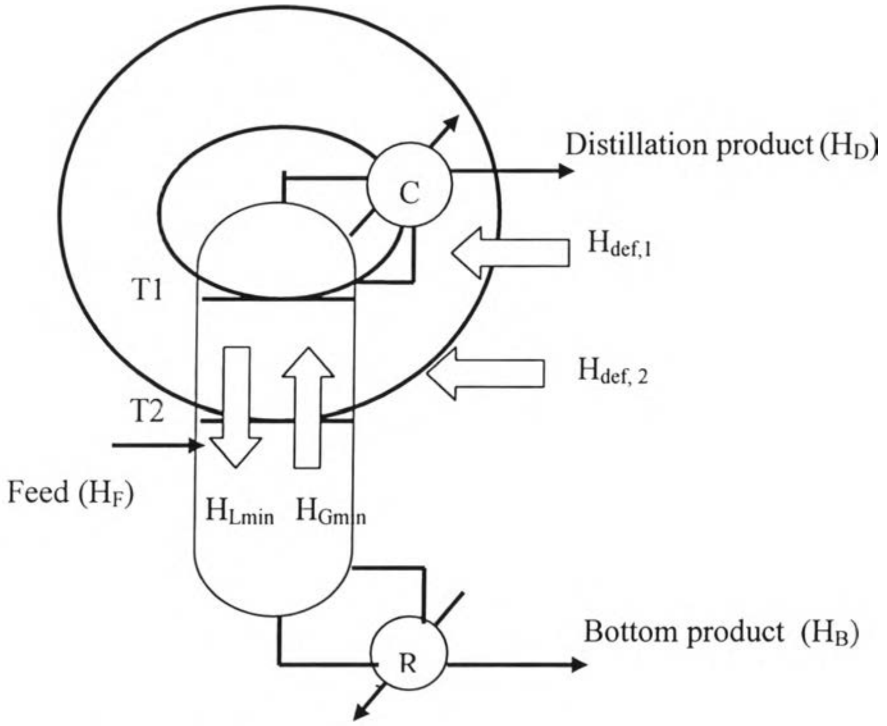


Figure 2.13 Evaluation of enthalpy deficit.

Table 2.6 The result from calculating of net heat deficit (H_{def}) at each stage temperature

Stage No.	H_{Lmin}	H_{Gmin}	H_{def}
1	-	-	-
2	0	5834	-5029
3	305	7079	-5969
4	630	8104	-6669
5	3494	2498	-6959
6	3576	2396	-6775
7	3711	212	-6364
8	3942	1640	-5653
9	4171	1122	-4906
10	3995	0	-3960

2.4.4 Cascading of Heat Deficit and Generating Column Grand Composite Curve (CGCC)

Column grand composite curve (CGCC) is a graphical representation which can generate by the same method as GCC. Constructing CGCC is done by adding the condenser load (7091 kW) to the H_{def} on each stage. The result cascade (H_{cas}) may be plotted against the stage temperature to arrive the CGCC. Table 2.7 shows the data of H_{cas} and Figure 2.13 demonstrates how the individual enthalpy deficits are cascaded to construct the CGCC

Table 2.7 Data of H_{cas} to construct CGCC

Stage No.	H_{def}	H_{cas}
1	-	7091
2	-5029	2062
3	-5969	1122
4	-6669	422
5	-6959	132
6	-6775	316
7	-6364	727
8	-5653	1438
9	-4906	2185
10	-3960	3131

There are many ways for improving energy efficiency of distillation columns such as reduction in reflux ratio, feed conditioning and side condensing/reboiling etc. Using pinch analysis, it is possible to identify which one of these column modifications would be appropriate for energy cost saving. The column modifications using the CGCC are illustrated in Figure 2.14. First, feed stage location of the column is optimized prior to starting the column thermal analysis. This can be carried out by trying to alternate feed stage location in simulation and evaluating its impact on the reflux ratio.

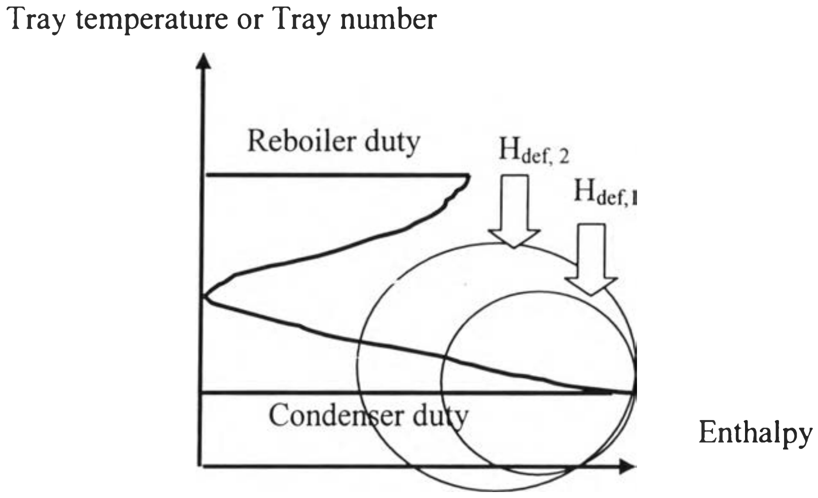


Figure 2.14 Constructing the CGCC using stagewise enthalpy deficits modification of CGCC.

Too high feed location in the column will show a sharp enthalpy change on the condenser side on the stage-H CGCC and it should be located lower. On the other hand, too low feed location in the column will show a sharp enthalpy change on the reboiler side on the stage-H CGCC and it should be located upper. An appropriate feed location not only removes the distributions in the stage-H CGCC but also results in the reduction of condenser and reboiler duties. After feed stage optimization is carried out, it may strongly interact with the other options for column modification. The CGCC for the column is obtained.

Figure.2.14(a), the horizontal gap between the vertical axis and CGCC pinch point indicates the scope for reflux improvement in the column. When reflux ratio was reduced, the CGCC will move close to the vertical axis, resulting in savings on both the reboiler and condenser levels. The reflux can be improved by adding more stages or improving the efficiency of existing stage in case of existing column. In order to make a judicious choice for the reflux ratio, increase in the capital cost due to the increase in the number of stages should be trade-off against the savings in the operating costs of reduced condenser and reboiler loads. The next step after reflux improving is to evaluate the scope for feed condition (pre-heating or cooling) as shown in Figure 2.14(b). This figure is identified by a sharp change in the stage-H CGCC shape close to the feed with a feed preheating modification example. The extent of sharp change approximately indicates the scope for feed preheating. Feed preheating allows heat load to be shifted from reboiler to the feed preheater. Similarly, when pre-cooling is supplied, the heat load is shifted from condenser to feed precooler. Feed preheating reduces not only the reboiler duty but also the temperature level at which the hot utility (for the reboiler and for the pre-heating the feed) needed to be supplied.

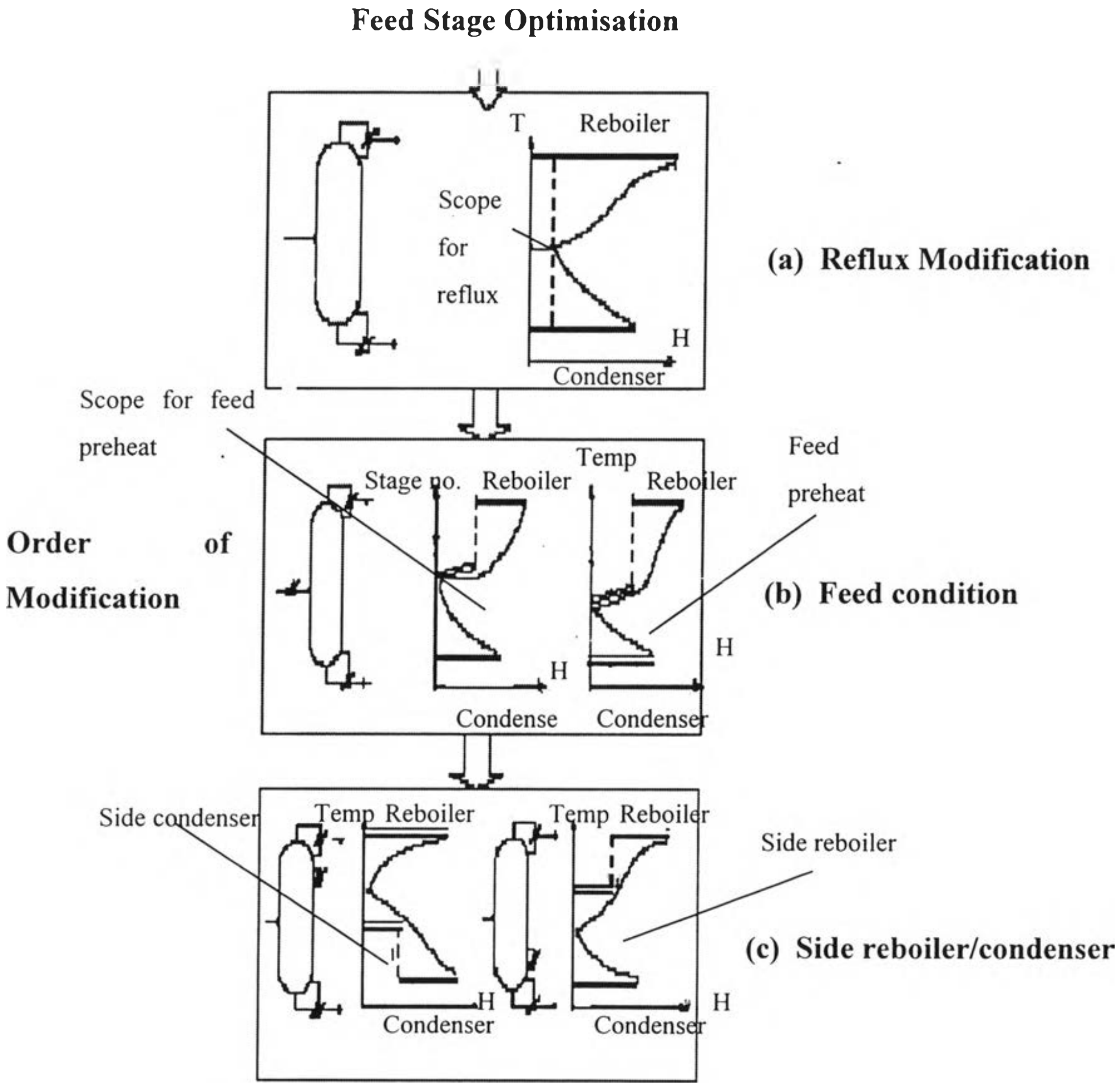


Figure 2.15 Using column grand composite curve to identify column modifications (Dhole and Linnhoff, 1992).

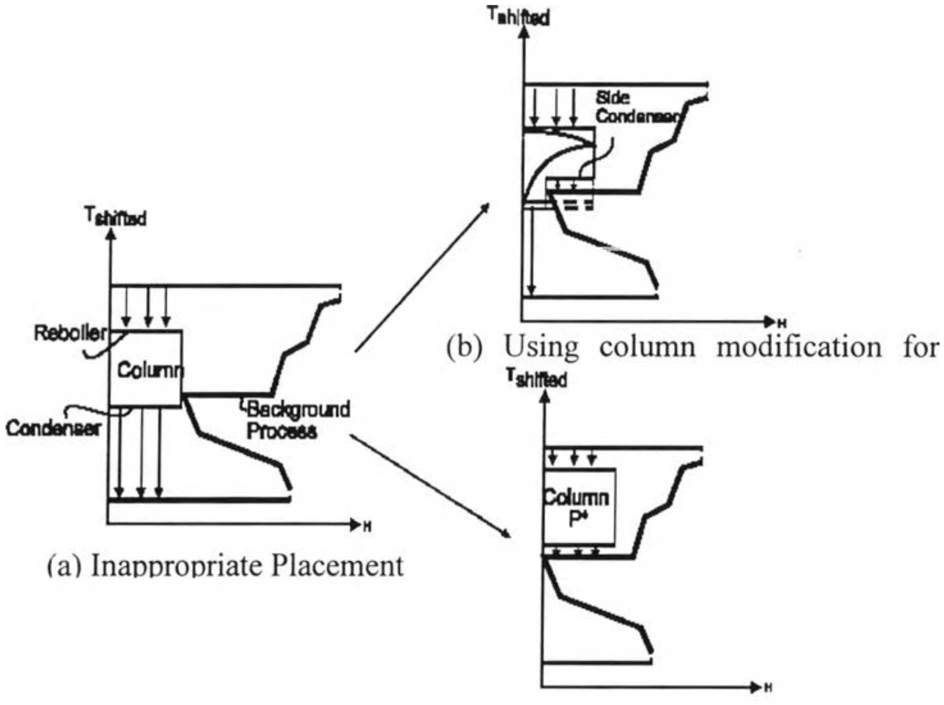
The feed which needs excessively sub-cooled will show a sharp enthalpy change on the reboiler side of CGCC. The extent of this change determines the approximate feed heating duty required. Change in the heat duty of feed pre-heater or pre-cooler will lead to similar duty change in the column reboiler or condenser loads, respectively.

The last step is side condensing/reboiling. Figure 2.14(c) describes the CGCC's which show potential for side condensing and reboiling. An appropriate side reboiler allows heat load to be shifted from reboiler to the side reboiler temperature without significant reflux penalty. The scope for side condensing/reboiling can be identified from the area beneath or above the CGCC pinch point (area between the ideal and actually enthalpy profiles). If a significant area exists, say below the pinch, a side condenser can be placed it on appropriate temperature level. This allows heat removal from the column using a cheaper cold utility. The addition of side reboiler, reduces not only the main reboiler duty but also the temperature levels at which the hot utility (for the main reboiler and for the side reboiler) needed to be supplied.

Normally, feed preheating is at the moderate temperature level because it operates outside the column and is easier to be implemented than side condensing/reboiling.

2.5 Energy Integration

To improve the overall energy efficiency of the process, it is possibly done by appropriate integration of the column with the background process. A heat exchange link is implied between the column heating/cooling duties and the process heating/cooling duties with the utility levels. Figure 2.15 summarizes the principle for appropriate column integration with the background process.



(a) Inappropriate Placement

(b) Using column modification for

(c) Appropriate Placement

Figure 2.16 Appropriate integration of a distillation column with the background process.

Figure 2.15(a) shows a column with the temperature range across the pinch temperature of the background process. There is no benefit in integrating the column with the background process because the overall energy consumption remains the same. The column is therefore inappropriately placed as integration with the background process.

Figure 2.15(b) shows the CGCC of the column that indicates a potential for side condensing. The side condenser opens up an opportunity for integration between the column and the background process. Therefore the overall energy consumption has been reduced due to the integration of the side condenser.

Figure 2.15(c) shows an alternative the column pressure that could be increased to allow complete integration between the column and background process via the column condenser. The column is now on one side of the pinch (not across the pinch). The column is therefore appropriately placed as integration with the background process.

In conclusion, the integration opportunities are enhanced by stand-alone column modifications such as feed conditioning and side condensing/reboiling. If the column is placed across the pinch, there is no potential integration with the background process. On the other hand, it is appropriate, if it lies on one side of pinch and can be accommodated by the GCC of the background process.

2.6 Literature Review

2.6.1 Development of Methodology for Pinch Analysis

The methodology of pinch analysis is developed for more than ten years. The method is widely used for main reason which is simple to understand and more efficient. In 1982, Linnhoff and Hindmarsh presented the design method of heat exchanger networks. The method is to combine sufficient simplicity with hand calculations to identify best design. It is so simple and straight-forward that is possible to proceed such designs for large problem quickly. This method is done by offering three feasibility criteria at the pinch to choose stream match for designing heat exchanger network and using tick-off heuristic to ensure the design is steered towards the fewest possible unit and solution of the remaining problem allowing consideration of process constraints and other requirements. Moreover, this design topology is trade-off between energy and capital costs 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 based on cost targets. These targets prior to the design give the results within five percent of the optimum solution. The detailed capital cost models, was considered the difference 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, (Ahmad, Linnhoff and Smith, 1990b).

The method described above is suitable for just only one pinch point in the problem. Therefore, the multiple pinch design method was proposed by Jezowski (1992). He reviewed a pinch design method (PDM) for multiple pinch 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 (1982) was used for designing with some guidance. The design is started from both pinches simultaneously. The solutions feature the maximum energy recovery and minimum number of units.

Ten years later, Distillation column targeting (Dhole and Linnhoff, 1992) was presented to design distillation columns using a combination of thermodynamic and practical aspects of column modifications. Column optimization involves options such as different reflux, pressures side condensing/reboiling and feed preheating/cooling. This method establishes heat load and temperature level for such modifications and identifies the best combined option. Moreover, it can clarify the effect of design modification on column capital cost.

The integration of heat exchanger network and distillation column is discussed by Linnhoff *et al.*, (1983). There were two observations of this idea, First, if the good integration between columns and process is achieved, the columns can be run with free of utility charges. Second, the conventional column integration methods, e.g., multiple effect columns, can prevent the good integration. They showed that the good integration was obtained by placing column in one side of pinch, i.e. not across the pinch and either the reboiler or condenser being integrated with the process. If these criteria can be met, energy cost of distillation column can effectively be reduced.

In practice, there are many petrochemical plants having been invested for the exchangers. The design for new plants is not appropriate for this case, since many 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. To apply pinch analysis in industrial existing plant, Tjoe and Linnhoff (1986) presented a method using pinch analysis for process retrofits. The assumption is a good retrofit that makes 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 savings 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.

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.

At the same time, Briones and Kokossis (1996) presented a rigorous and systematic optimization method for the retrofit of heat exchanger networks. This work makes use of both pinch analysis and mathematical programming. The limitation behind the conventional method due to the assumption of area and incremental efficiency as well as to its in ability to target modification and account for design constrains which appear regularly in retrofit problem. The new approach solve this problem by using pinch to conceptualize the stage of decomposition and instantly the different design task and using mathematical programming to enable an effective search among the available option.

Two years later, structural targeting for integration retrofit (Reissen *et al.*, 1998) is a new targeting method for retrofit of heat exchanger networks. It combines existing targeting and design method for retrofit with the concept of zoning used in grassroots design. This method gives targets not only for utility saving and exchanger area investment but also for extent and location of the required modifications. The result of this method gives simplier design than existing method and identifies alternatives and additional possibilities.

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

2.6.2 Applications of Pinch Analysis

The previous literature survey is the development of methodology in Pinch analysis and this part is applications of this method in industrial plant.

Pinch technology (PT) was proved to be important for engineers to analyze and design chemical processes (Stankiewicz, 1993) . By allowing engineers to track the heat or pressure flows in all process streams within a plant, PT made it easier to integrate plant design. Rearranging equipments, such as reactors, evaporators, pumps, distillation columns, and separators, can improve efficiency of unit operations, 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.

Al-Riyami *et al.*, (2001) applied pinch technology in Fluid catalytic cracking (FCC) plant by using retrofit technique. SPRINT software is used for calculation and modifying existing heat exchanger networks in FCC. The result of this work is very good performance. They can save energy 8.955 MW (74% energy savings of the scope of design) and utility cost savings is about 2,388,600$ (27% cost savings decrease) by adding of four heat exchanger and repiping of an existing exchanger with payback period of nineteen months.

In the same year Pinch technology was applied to a nitric acid plant, Croatia by Matijasevix and Otmaeix. The result show that application of pinch technology can lead towards great energy savings and reduce cooling water and medium pressure stream by adding of three new heat exchanger with payback period of 14.5 month. (Matijasevix and Otmaeix, 2001)

Phipps.M.A and Andrew F.A Hodley (2003) offer the application of pinch analysis by using heat integration software to determine retrofit opportunities within a refinery process. The application is done in MEK (Methyl Ethyl Ketone) unit of Dewaxed oil solvent recovery plant. Data and information are collected from Exxon Mobil. For saving time consumption in trial and error simulation and getting more accurate, SPRINT software was selected and the result of this work shows 15 % of energy savings.

The successful one for pinch analysis is applications of total process energy integration in retrofitting an ammonia plant (Yao Wang and et.al., 2003). They use pinch analysis to save 1150 kg/h of fuel gas and 1322 t/h of cooling water by reconstructing and repiping of stream lines in ammonia plant. It is very achievable because they apply this technology for more than ten Chinese plants and has generated a profit about 80 million RMB per year.