HEAT EXCHANGER NETWORKS

CHE 396
SENIOR DESIGN

Submitted
by

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Heat Exchanger Networks

Energy conservation is important in process design. In industrial experience, the calculation of the minimum heating and cooling requirements reveal significant energy savings. Specifically, Imperial Chemical Industries in the United Kingdom and Union Carbide in the United States have both stated the results of numerous case studies that indicate 30% to 50% energy savings compared to traditional practice. Therefore, energy integration design procedure is a very beneficial tool and is an important phase in determining the cost of preliminary design.

The first step in the energy integration analysis is the calculation of the minimum heating and cooling requirements for a heat-exchanger network. In any process flow sheet, there are several streams that need to be heated and there are some that need to be cooled. In the acetic anhydride production, for example, the reaction stream in the second reactor must be cooled, while the liquid product coming out of the same reactor must be heated for distillation. For that reason, cooling water is needed to lower the temperature of the reactor stream, and steam is needed for heating in the distillation column.

There are two laws for heat integration analysis. The first law states that the difference between the heat available in the hot streams and the heat required for the cold streams is the net amount of heat that must be removed or supplied. Consider this example. Suppose there are 6 streams given, three that need to be heated and the other three need to be cooled. The heat associated with each stream can be calculated by using the following equation:

$$Q_i = F_i Cp_i)T_i \qquad (1)$$

For our case study, six representative streams, three streams to be cooled and three to be heated up, were chosen. Figure A and Table 1 shows the descriptions of the chosen streams.

Figure A Schematic Diagram of Case Study Acetic Anhydride Plant

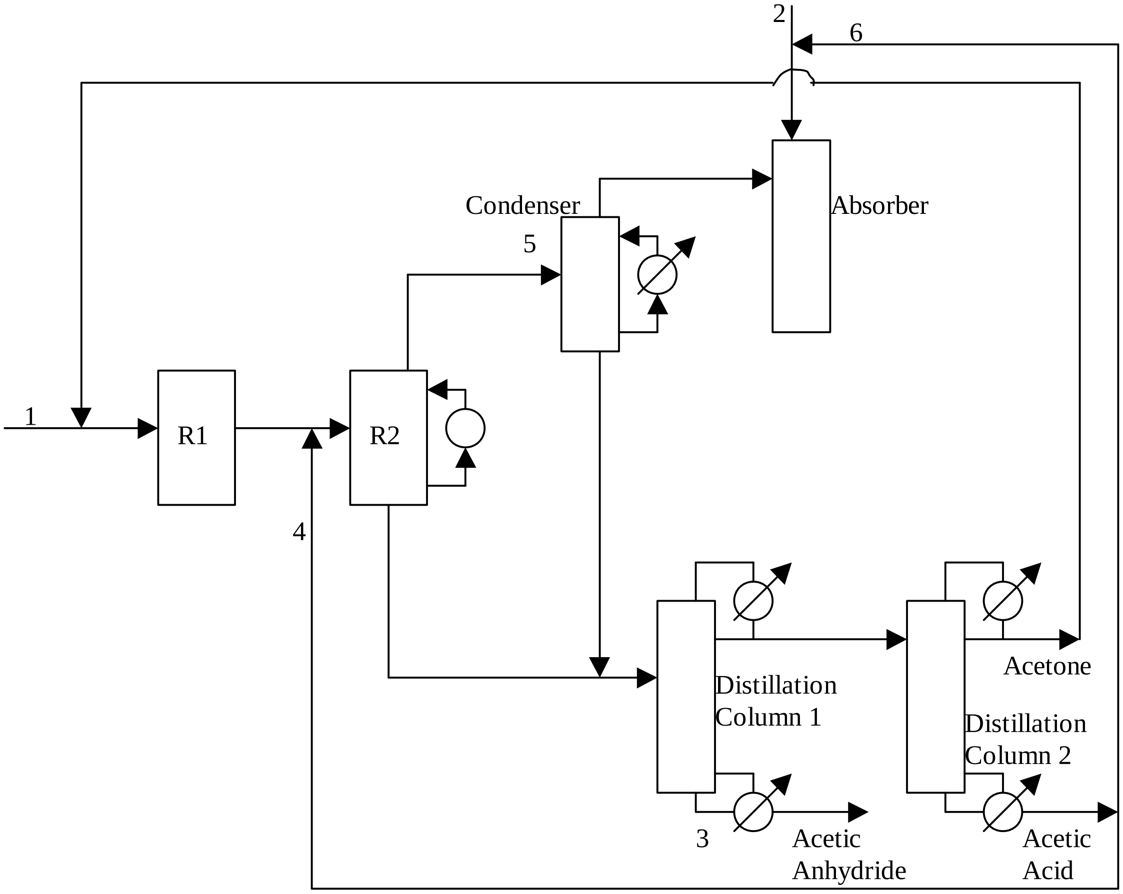


Table 1 Descriptions of Streams

Stream	Description
1	Fresh acetone going in the system.
2	Fresh acetic acid going in the system.
3	Distillation column 1 reboiler.
4	Recycle acetic acid going to reactor 2.
5	Flash/condenser
6	Recycle acetic acid going to absorber

For stream 1, Q_1 = (1000 Btu/hr°F)(250-120) = 130 x 10^3 Btu/hr

Table 2 shows the results for each stream.

Table 2 First Law Calculation

Stream No.	Condition	FCp (Btu/hr°F)	T_{in} (°F)	T_{out} (°F)	Q available 10^5 Btu/hr
1	Cold.	4893	77	133	-2.74
2	Cold	2173	77	129	-1.13
3	Cold	5.0×10^5	156	196	-205
4	Hot	1.23×10^4	244	77	21.0
5	Hot	2.75×10^5	176	128	132
6	Hot	1046	244	129	1.2
				Total =	-50.25

As shown in the table, 50.25x 10^5 Btu/hr must be supplied from utilities if no restrictions on temperature-driving forces are present. However, the calculation for the first law does not consider the fact that heat can only be transferred from a hot stream to a cold stream if the temperature of the hot stream surpasses that of the cold stream. Therefore, a second law states that a positive temperature driving force must exist between the hot and the cold streams. For any heat-exchanger networks, the second law must be satisfied as well as the first law.

A simple way to encompass the second law was presented by Hohmann, Umeda et al., and Linhoff and Flower. A description of their analysis is shown in accordingly. If a minimum driving force of 10°F between the hot and the cold streams is chosen, a graph can be established showing two temperature scales that are shifted by 10°F, one for the hot streams and the other for the cold steams. Then, stream data is plotted on this graph (Figure 1). Next a series of temperature intervals are generated corresponding to the heads and the tails of the arrows on the graph (Figure 2).

Figure 1 Shifted Temperature Scale

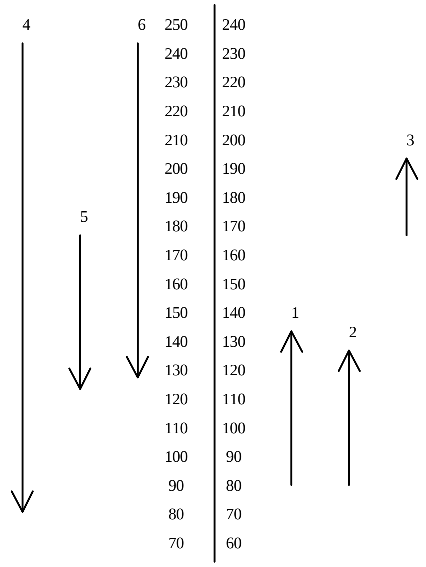
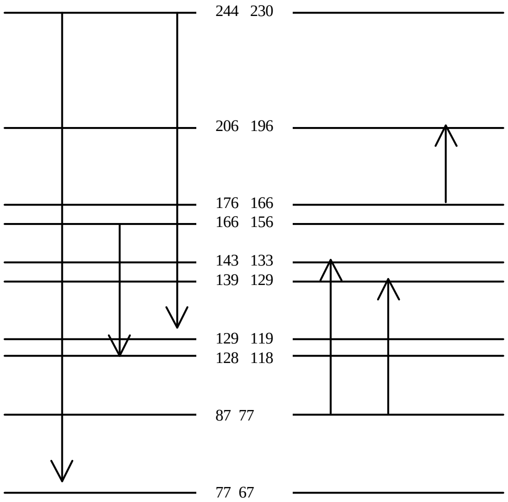


Figure 2 Temperature Intervals



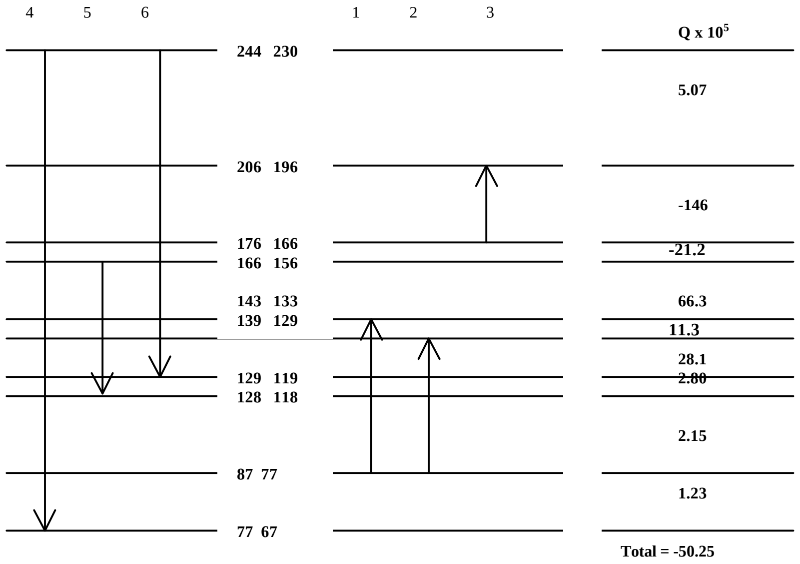
In each interval, heat from any hot streams in the high-temperature intervals can be transferred to any of the cold streams at lower-temperature intervals. For a starting point, heat transfer in each interval would be considered separately. The necessary equation is shown below.

$$Q_i = [\Sigma(FCp)_{hot,i} - \Sigma(FCp)_{cold,i}]\Delta T_i \quad (2)$$

For example: $Q_1 = [1046+1.12x^4](244-206) = 5.07 \times 10^5$

Thus, for the first interval, a value of 5.07×10^5 is obtained. The values for other intervals are shown in Figure 3. Notice that the summation of the heat available in all the intervals is the same as the net difference between the heat available in the hot streams and that in the cold streams obtained using the first law.

Figure 3 Net Energy Required at Each Interval



Taking all the heat available at the highest interval (206 to 244°F), transfer it to the next lower-temperature interval (176 to 206°F) and repeat for all intervals. Since the heat is transferred to a lower-temperature interval, the second law is satisfied. From Figure 4, it can be seen that the available heat from the higher-temperature interval is not adequate to satisfy the deficit in the second interval. Therefore, a heat amount of 1.4093×10^7 Btu/hr must be supplied. Also, a heat amount of 2.12×10^6 Btu/hr must be supplied to the third interval to supply the deficiency of 2.12×10^6 Btu/hr. Then, there would be no heat transfer between the third and the fourth temperature intervals. The total energy needed for the second and the third interval is 1.6213×10^7 Btu/hr. For the fourth temperature interval, the excess heat can be rejected to the cold utility or transferred to a lower-temperature interval then rejected to the cold utility as shown in Figure 4

Figure 4 Cascade Diagram

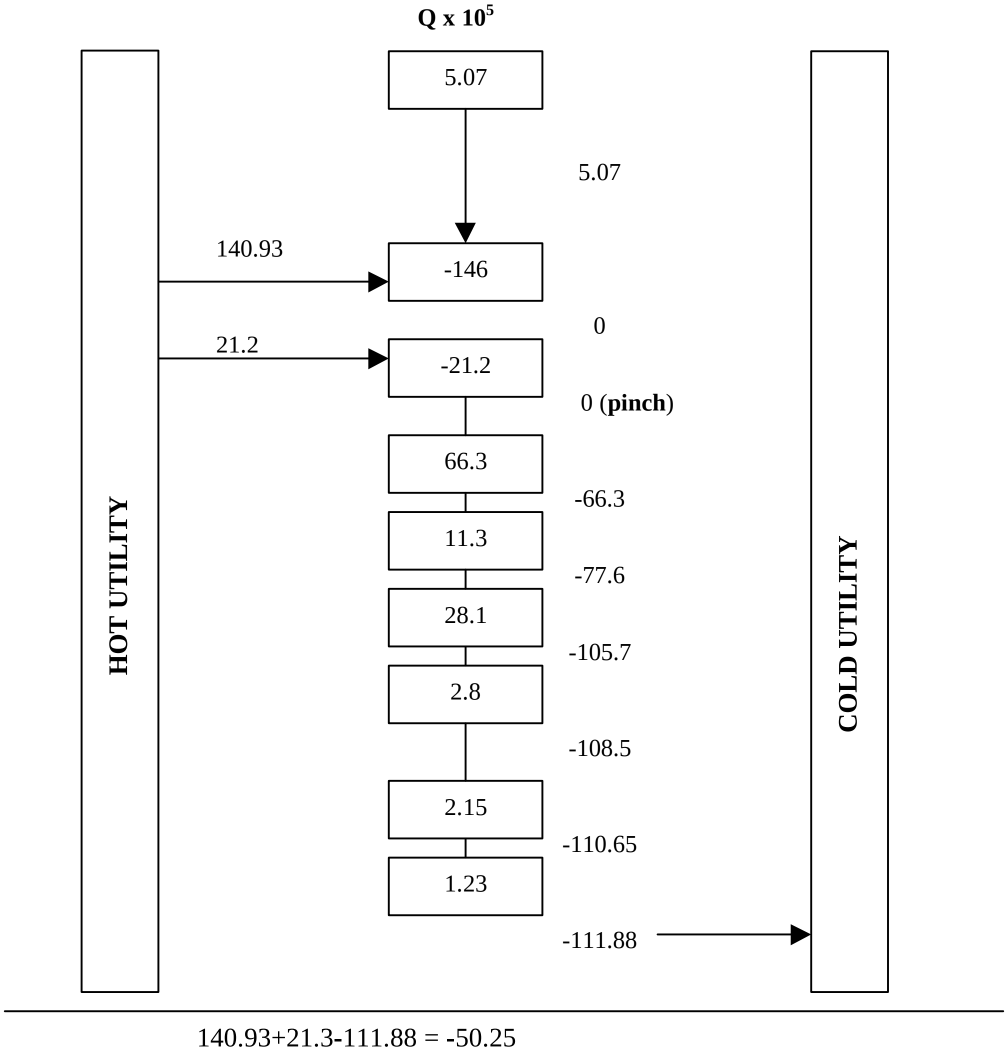


Figure 4 is called a *cascade diagram* because it shows how heat cascades through the temperature intervals.

From Figure 4, it is shown that the total minimum heating requirement is 1.6213×10^7 Btu/hr and the minimum cooling requirement is 1.1188×10^7 Btu/hr. The difference between the two values (5.025×10^7 Btu/hr) is still consistent with the first law requirement. However, the minimum heating and cooling loads have now been fixed to satisfy the second law.

Furthermore, it is observed from Figure 4 that there is no transfer of energy between the third and fourth temperature intervals. This is called the *pinch point* (166°F for the hot streams and 156^{o}F for the cold streams; sometimes the average of 161^{o}F is used). The temperature at the pinch point provides a breakdown of the design problem. Heat is supplied above the pinch point temperature only and below it, heat can be rejected to a cold utility

The following are heuristics associated with the use of utilities:

1. Do not transfer heat across the pinch.
2. Add heat only above the pinch.
3. Cool only below the pinch.

In addition, if the minimum approach temperature of 10^{o}F that was used for as a criterion for the second law is adjusted, then the temperature scales on Figure 1 will be altered. The heat intervals shown on Figure 2 will also change, and the minimum heating and cooling loads will alter. To visualize these changes easily, a temperature-enthalpy diagram must be constructed.

To construct a temperature-enthalpy diagram, the minimum heating and cooling loads must first be calculated using the procedure above. Then the enthalpy corresponding to the coldest temperature of any hot stream will be defined as the base condition; ie., at $T = 77^{o}$F (Figure 2), $H = 0$. The next step is to calculate the cumulative heat available in the sum of all the hot streams moving from lower to higher-temperature intervals. Hence, from Figure 2, the following values are obtained:

Table 2 Enthalpy Values and Cumulative H for Hot Streams

Hot streams		**Cumulative H (Btu/hr)**
77^{o}F	$H_0 = 0$	0
87 F	$H_1 = (1.23x10^4)(87-77) = 1.23x10^5$	$1.23x10^5$
128^{o}F	$H_2 = (1.23x10^4)(128-87) = 5.04x10^5$	$6.27x10^5$
129^{o}F	$H_3 = [(1.23x10^4)+(2.75x10^5)](129-128) = 2.87x10^5$	$9.14x10^5$
139^{o}F	$H_4 = [(1.23x104)+(2.75x10^5)+(1046)](139-129) = 2.28x10^6$	$2.28x10^6$
143^{o}F	$H_5 = [(1.23x104)+(2.75x10^5)+(1046)](143-139) = 1.15x10^6$	$3.194x10^6$
166^{o}F	$[(1.23x104)+(2.75x10^5)+(1046)](166-143) = 6.63x10^6$	$1.15x10^7$
176^{o}F	$[(1.23x104)+(2.75x10^5)+(1046)](176-166) = 2.88x10^6$	$1.27x10^7$
206^{o}F	$[(1.23x10^4)+(1046)])(206-176) = 4.00x10^5$	$1.31x10^7$
244^{o}F	$[(1.23x10^4)+(1046)])(244-206) = 5.07x10^5$	$1.36x10^7$

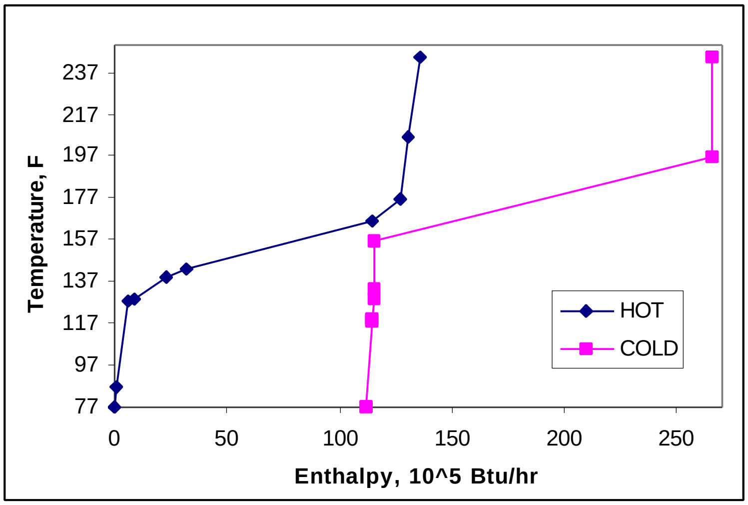
Then, the cumulative H will be plotted versus T (Figure 5). This is called *composite curve* for the hot streams because it includes the effect of all the hot streams.

Likewise, the composite curve for the cold streams can be created by calculating the cumulative enthalpy of each cold stream. Table 3 shows the results from the cold stream calculations.

Table 3 Enthalpy Values and Cumulative H for Cold Streams

Cold Stream		**Cumulative H (Btu/hr)**
77°F	$H_1 = 1.1188x10^7$	$1.1188x10^7$
118°F	$H_2 = [(4893)+(2173)](118-77 = 2.90x10^5$	$1.1478x10^7$
119°F	$H_3 = [(4893)+(2173)](119-118) = 7.066x10^3$	$1.1485x10^7$
129°F	$H_4 = [(4893)+(2173)](129-119) = 7.066x10^4$	$1.1555x10^7$
133°F	$H_5 = (4893)(133-129) = 1.96x10^4$	$1.1575x10^7$
156°F	$H_6 = 0$	$1.1575x10^7$
166°F	$H_7 = (5.0x10^5)(166-156) = 5.0x10^6$	$1.6575x10^7$
196°F	$H_8 = (5.0x10^5)(196-166) = 1.5x10^7$	$3.1575x10^7$
244°F	$H_9 = 0$	$3.1575x10^7$

Figure 5 Temperature-Enthalpy Diagram (Approach Temperature = 10°F)



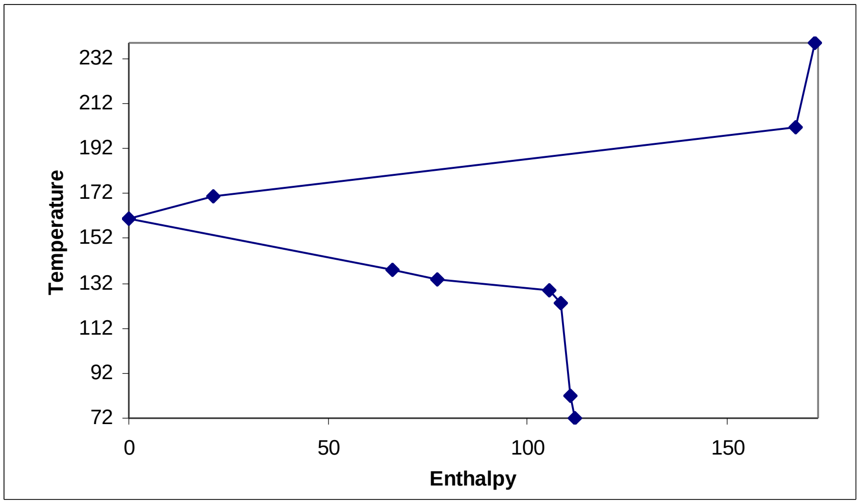
Notice from Figure 5 that when $T_H = 166^oF$ and $T_C = 156^oF$ the minimum approach exists, ie., the heating and cooling curves are closest together.

Another diagram that might be useful is the *grand composite curve*. To prepare this curve, begin with the pinch temperature, assigning a zero value to it. For the case study, the pinch temperature is 161°F. Then for the next higher temperature interval, again define the average temperature and calculate the total heat flow. Sample calculations are shown in the table below.

Table 4 Sample Calculations for Grand Composite Curve

T (^oF)		10^5H (Btu/hr)
72	H = 66.3+11.3+28.1+2.8+2.15+1.23	111.88
82	H = 66.3+11.3+28.1+2.8+2.15	110.65
123	H = 66.3+11.3+28.1+2.8	108.5
128.5	H = 66.3+11.3+28.1	105.7
134	H = 66.3+11.3	77.6
138	H = 66.3	66.3
161	H = 0	0
171	H = -21.2	21.2
201	H = 21.2+146	167.2
239	H = 21.2+146+5.07	172.24

Figure 7 Grand Composite Curve



In addition, the system changes if the ΔT_{min} is changed. Figure 8 shows the cascade diagram, Figure 9 shows the T-H plot using a ΔT_{min} of 20^{o}F, and Figure 10 shows the grand composite curve.

Figure 8 Cascade Diagram of System Using DT_{min} = 20°F

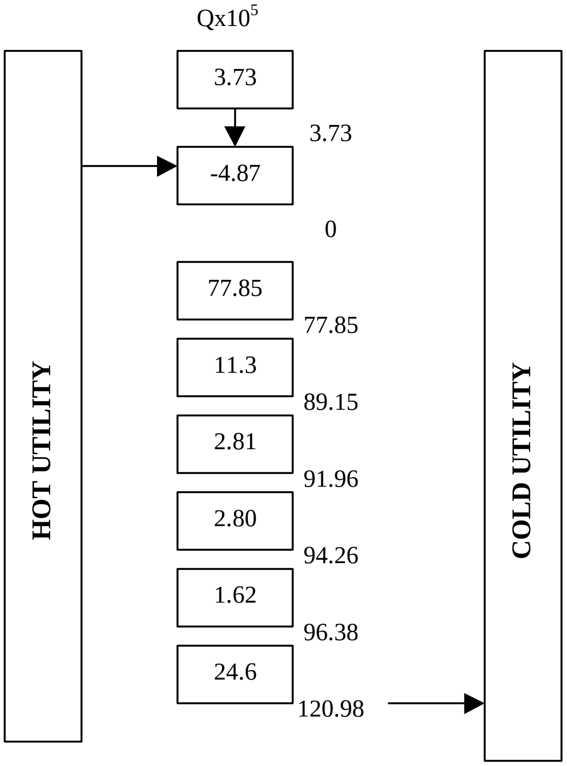


Figure 9 T-H Plot for the case study using DT_{min}=20°F

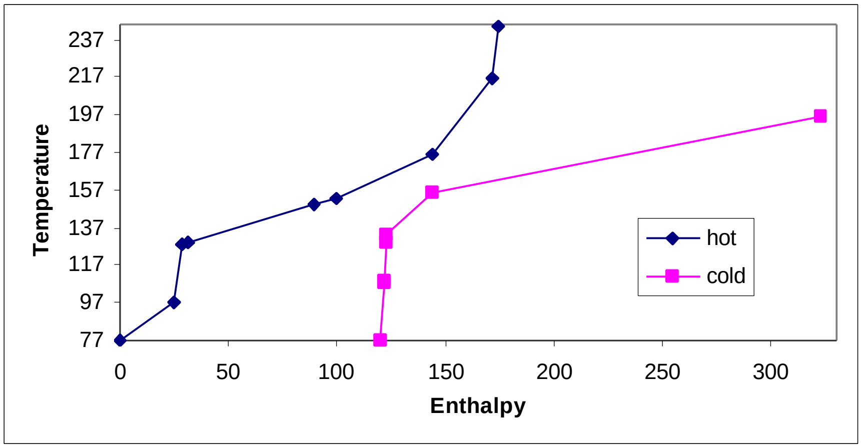
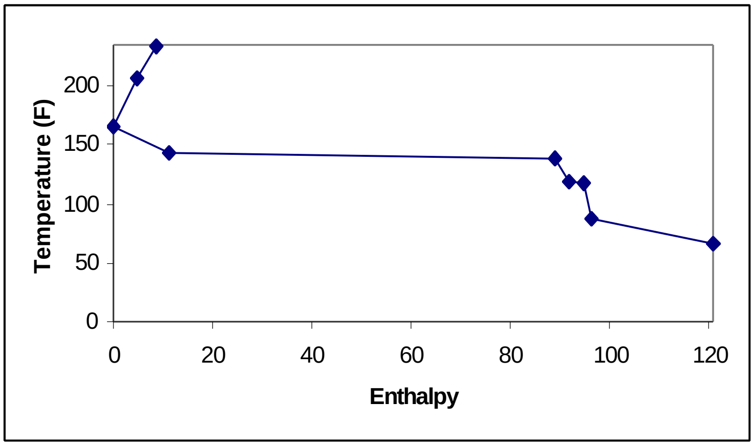


Figure 10 Grand Composite Curve using DT_{min} = 20°F



The Minimum Energy Heat Exchanger Network.

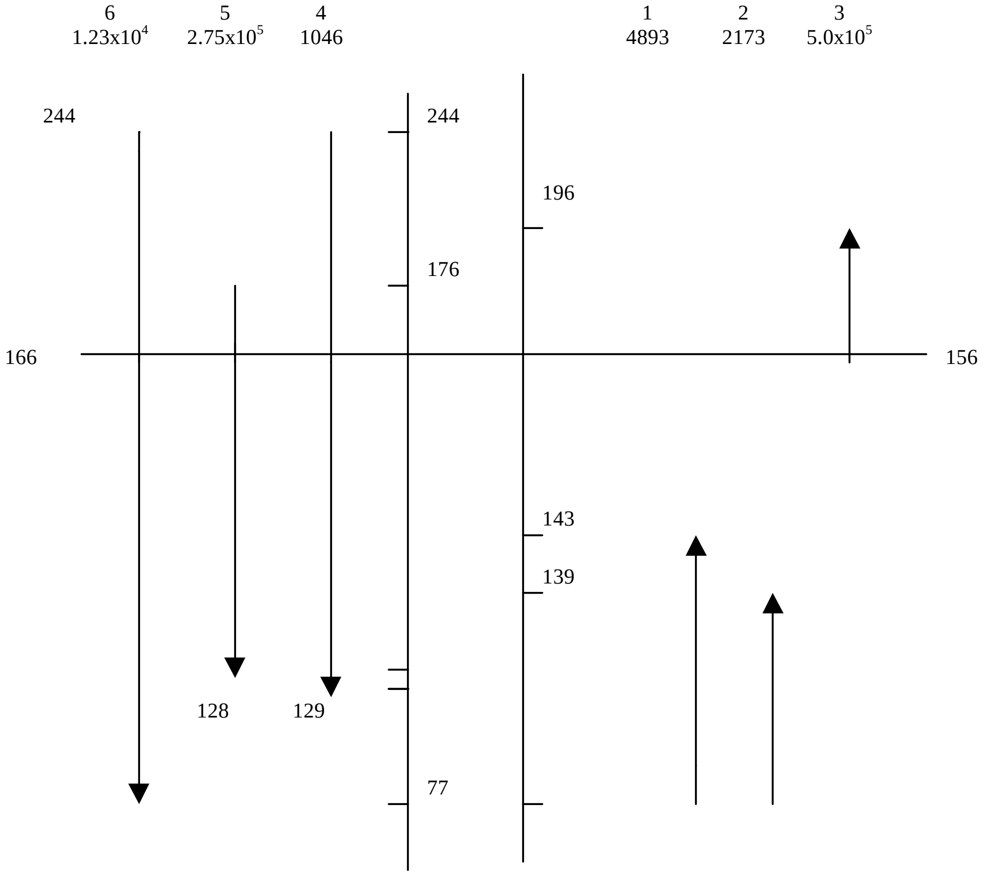
Knowing the minimum heating and cooling energy requirement and the number of heat exchangers, we can proceed with the design of heat exchanger network. According to Linnhoff and Hindmarsh, the appropriate procedure is to design two sub networks of exchangers. One is above the pinch temperature and the other below the pinch. We continue with our case study on this entire section to illustrate the step-by-step method of designing a minimum energy heat exchanger network.

Design above the pinch temperature:

+ Determine the inlet or outlet temperatures for each stream. These temperatures can be found from Figure 10. For example, the inlet and outlet temperatures of stream 3 are 156 and 196 respectively.

+ Calculate the heat loads for each stream using the FCp values. Take stream 5 for example the heat load: $Q= 2.75x10^{5}(176-166) = 2.75x10^{6}$ Btu/hr

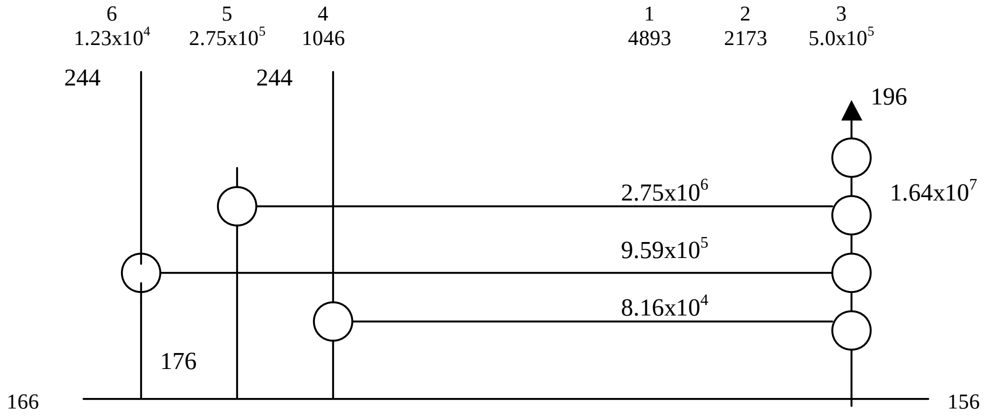
Figure 10 Heat Load for Streams



+ Match a hot stream with a cold stream. In our case, we can match each hot stream with the cold stream. The heat load remaining from the hot stream is determined by subtracting heat load of each of the cold stream from the hot stream. The heat load values are shown in Figure 11. The temperature can also be determine after each matching. For example, the temperature of the match 5 and 3 is :

$2.75\text{x}10^5 = 5\text{x}10^5\ (T_{out} - 156)$; $T_{out}=161.5$

igure 11 Design Above the Pinch



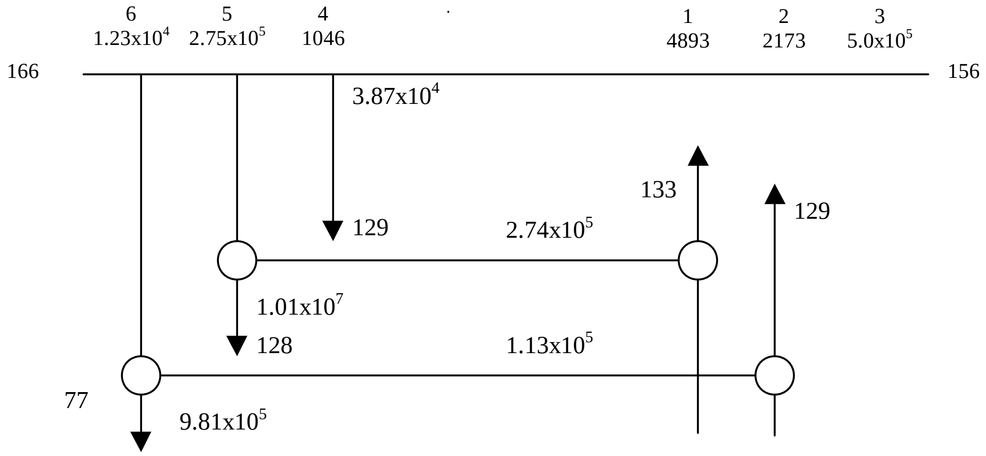
When matching the stream, we can only add heat above the pinch temperature and remove heat below the pinch. Here we transfer all the heat from the three hot streams to the cold stream. As shown in Figure 11, we need 4 heat exchangers above the pinch. One exchanger is used for each matching and one utility heat exchanger for the remaining heat load.

Design below the pinch

The procedure for determining the minimum number of exchangers below the pinch temperature is analogous to that of above the pinch. The difference is that we can are only allowed to reject heat to a cold utility. Therefore coolers are used instead of heat exchangers.

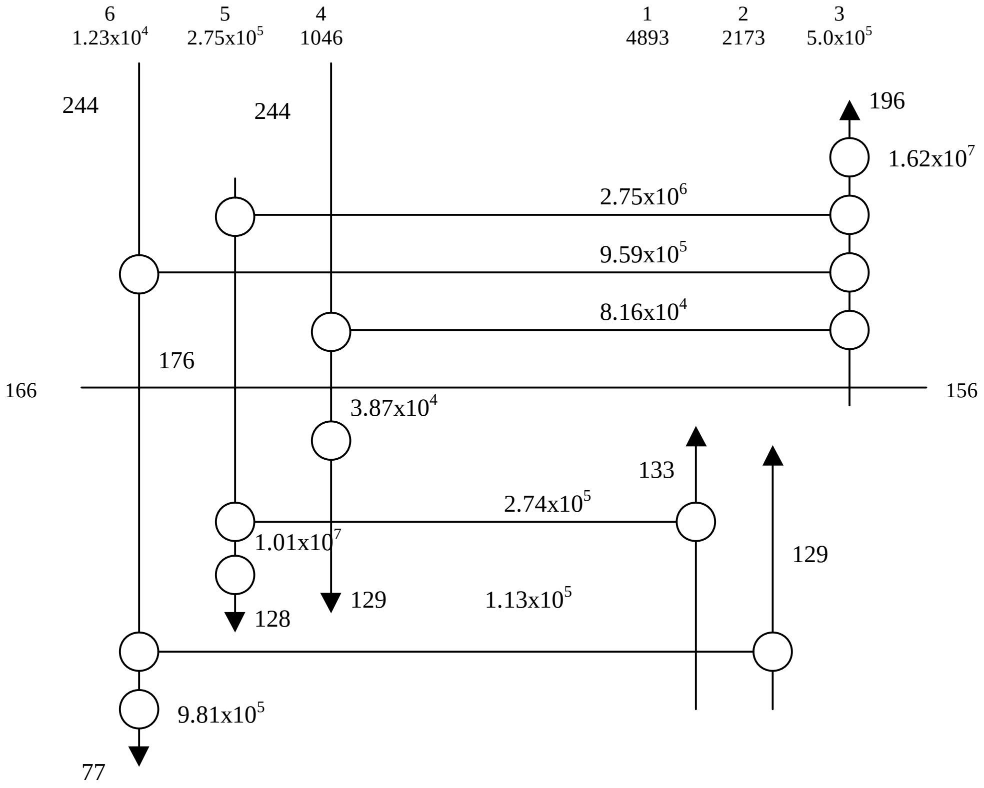
The streams and heat load values are shown Figure 12. We can match stream 5 with 1 and 4 with 2. The amounts of heat remaining from each stream are cooled using utilities. Stream matches and heat load remaining are shown in Figure 12. From this figure we can see that the number of coolers below the pinch is 5 of which three coolers are utilities.

Figure 12 Exchanger. Matches Below the Pinch



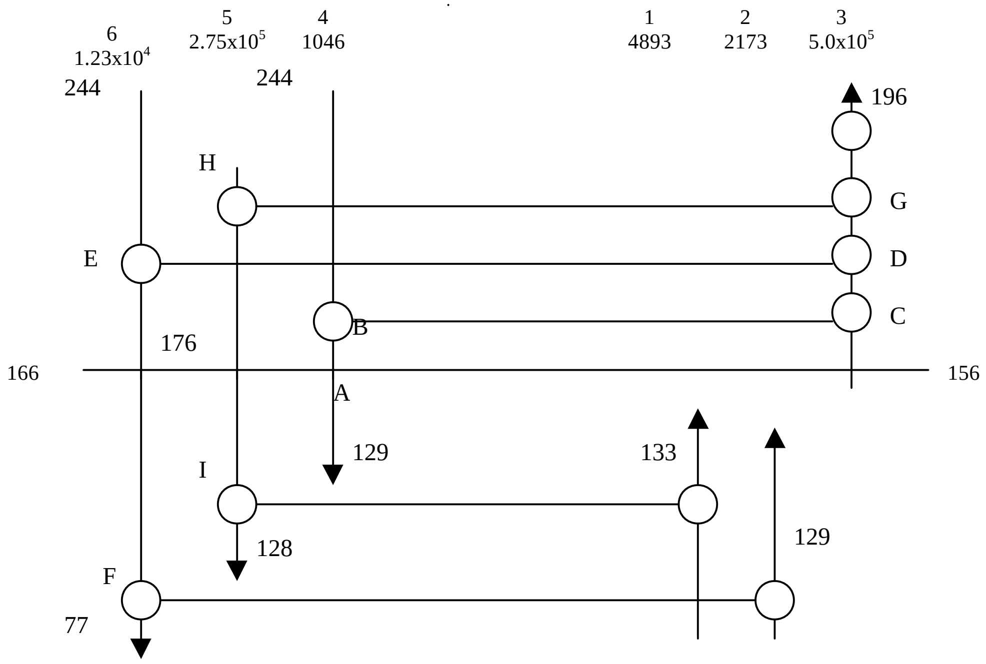
Summing the number of exchangers of above and below the pinch temperature, the total number of exchanger is 9. As shown in Figure 13, the total heating load is 16,459,012 Btu/hr and the total cooling requirement is 11,196,398 Btu/hr.

Figure 13 Complete Minimum Energy Design



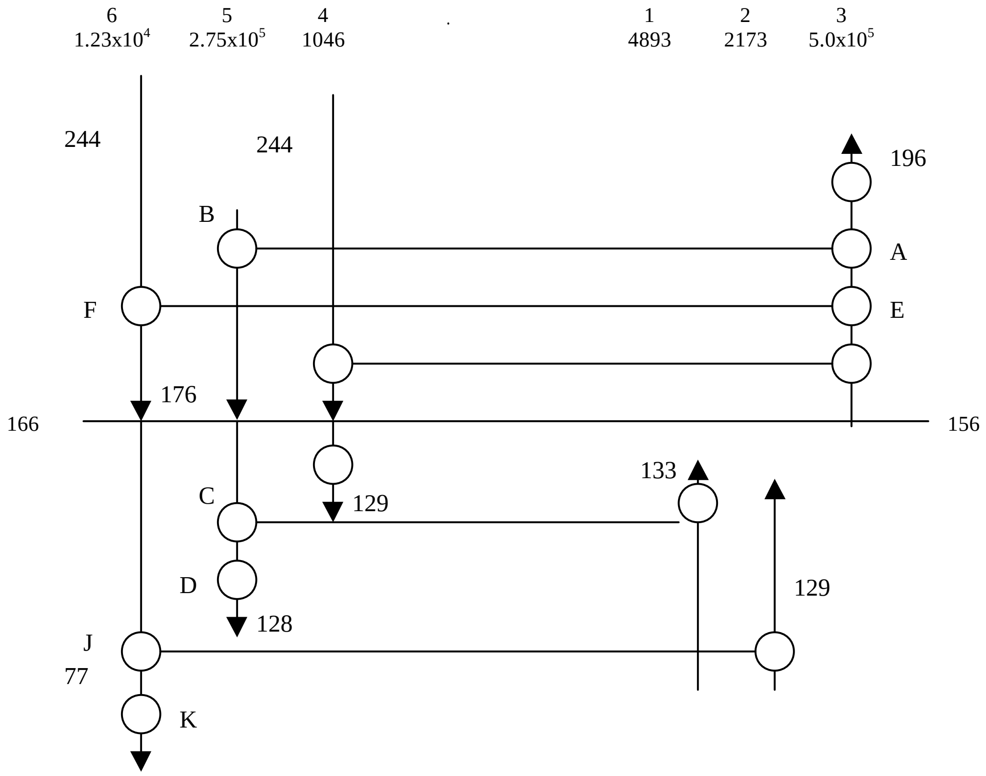
Loops and Paths

Figure 14



A loop is defined as a connection between exchanger that starts from one exchanger and returns to the same exchanger. A loop can also pass through a utility. As shown in Figure 14, ABCDEF and ABCGHI can be considered as loops. A path is a way that connects a heater and a cooler. For example, ABCD and EFJK are two paths as shown in figure 15.

Figure 15



Reducing the number of exchangers

$$\begin{pmatrix}\text{Number of}\\ \text{Heat Exchangers}\end{pmatrix}=\begin{pmatrix}\text{Number of}\\ \text{Streams}\end{pmatrix}+\begin{pmatrix}\text{Number of}\\ \text{Utilities}\end{pmatrix}-\begin{pmatrix}\text{Number of}\\ \text{Independent}\\ \text{Problems}\end{pmatrix} \qquad (3)$$

Using equation 3, the number of heat exchangers for the case study is only seven. However from our minimum energy design, the total number of exchangers is nine. In order to fulfill our prediction in equation 3, the number of exchangers has to be reduced. Reducing the number of exchangers will definitely lower the cost for equipment (capital cost). However it will increase the cost for utilities (operating cost). Therefore the main objective of this stage is to search for the lowest annual cost for our exchanger network.

According to Douglas, the number heat exchangers required for the overall process is always less than or equal to that for a minimum energy network (Douglas, 251). Reducing the number of exchangers involves breaking small loops determined in the previous section. Unfortunately for our case study we can not break any loop. Therefore the number of exchangers stays equal to that for the minimum network. Further study or a different set of streams may enable us to reduce the number of heat exchangers. Please refer to Douglas (251-256) for a complete procedure of breaking loops and reducing number of exchangers.

A summary of the general rules concerning the design procedure are as follows:

1. The number of exchangers required for the overall process is always less than or equal to that for the minimum energy network.
2. If the design procedure for the minimum energy network is used, there will normally be loops across the pinch point.
3. We can break these loops by transferring heat across the pinch point, but we will introduce at least one violation of the specified ΔT_{min}
4. We can restore ΔT_{min} by shifting heat along a path, which increases the energy consumption of the process.

This is the basic procedure one should follow for reducing the number of heat exchangers at the expense of consuming more energy. We want to find the heat-exchanger network, which has the smallest total annual cost.

Heat Integration of distillation columns

Distillation is basically the most widely used separation process in the chemical industry today. It uses energy in great amounts, in the forms of cooling water and steam, due to operating costs of distillation column condensers and reboilers. In order to conserve energy, it is usually wise to heat integrate a distillation column into an overall process, or possibly with another column in the process.

For most distillation processes, heat is supplied to the reboiler at high temperatures, and this same heat is removed from the condenser at a lower temperature. This can be seen in figure 1, assuming the column to be like a black box.

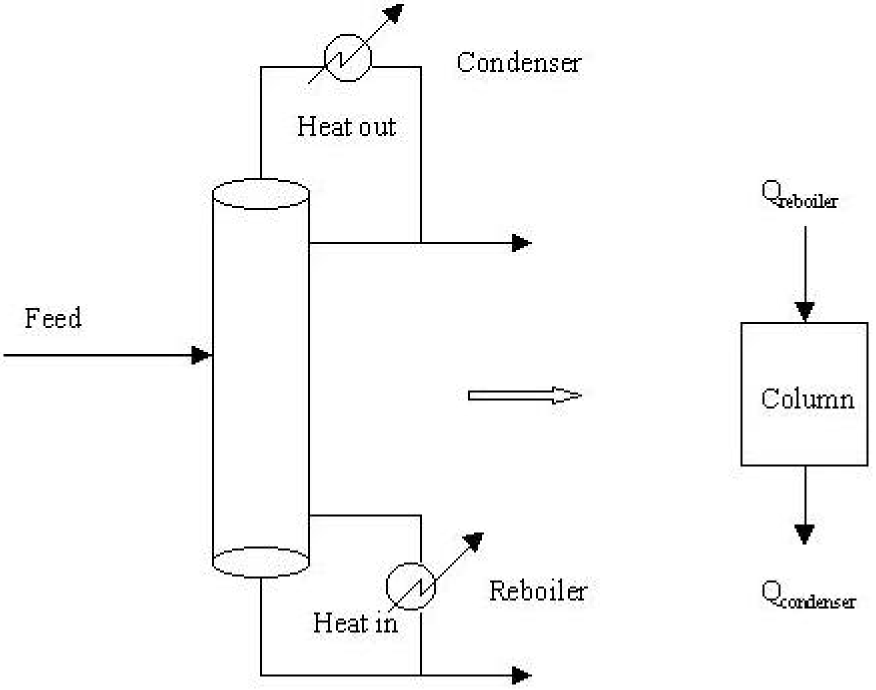


Figure 21. Distillation column takes in and rejects heat.

From this we can say that heat is degraded across a certain temperature range. This temperature range is equal to the difference in boiling points of the two components. Below are some shortcut methods to estimate the heat load and degraded temperature range. A shortcut method used over narrow temperature ranges is depicted below relating vapor pressure to temperature:

$$P_i^o = P_{i,o} \exp\{(\Delta H_i / R)((1/T) - (1/T_o)\} \quad \textbf{(4)}$$

For low-pressure systems, the K value is given by:

$$K_i = P_i^o / P_{total} = \alpha_i / \Sigma\alpha_i x_i \quad \textbf{(5)}$$

For close-boiling ideal mixtures, the heats of vaporization of all the components are similar, so replacing ΔH_I by an average of $\Delta H_{average}$, and letting $\sigma_k = \Sigma\alpha_i x_{i,k}$, we obtain an expression relating the temperatures of any two points in a column:

$$\{(1/T_2) - (1/T_1)\} = (R/\Delta H_{average})\ln(\sigma_2 / \sigma_1) \quad \textbf{(6)}$$

Relating the temperature of the distillate and the bottoms to the feed temperature, we can write an expression for the temperature drop across the column as:

$$\Delta T = (RT_F^2 / \Delta H)\ln(\sigma_D / \sigma_B) \quad \textbf{(7)}$$

In estimating the heat load of the column, one can say that the heat supplied to the reboiler and removed by the condenser is given by:

$Q = \Delta HV$ where ΔH = heat of vaporization, and V = vapor flow rate **(8)**

Knowing that $V = D(R + 1) = D(1.2R_{min} + 1)$, and combining equations 4 and 5, we obtain:

$$Q\Delta T = RVT_F^2\ln(\sigma_D / \sigma_B) \quad \textbf{(9)}$$

This equation relates both the heat load of the column and the degraded temperature range of the column.

Multiple Effect Distillation

Multiple effect distillation is a special feature in which the condenser of a high-pressure column is linked to the reboiler of a low-pressure column. This is shown in figure 22 below:

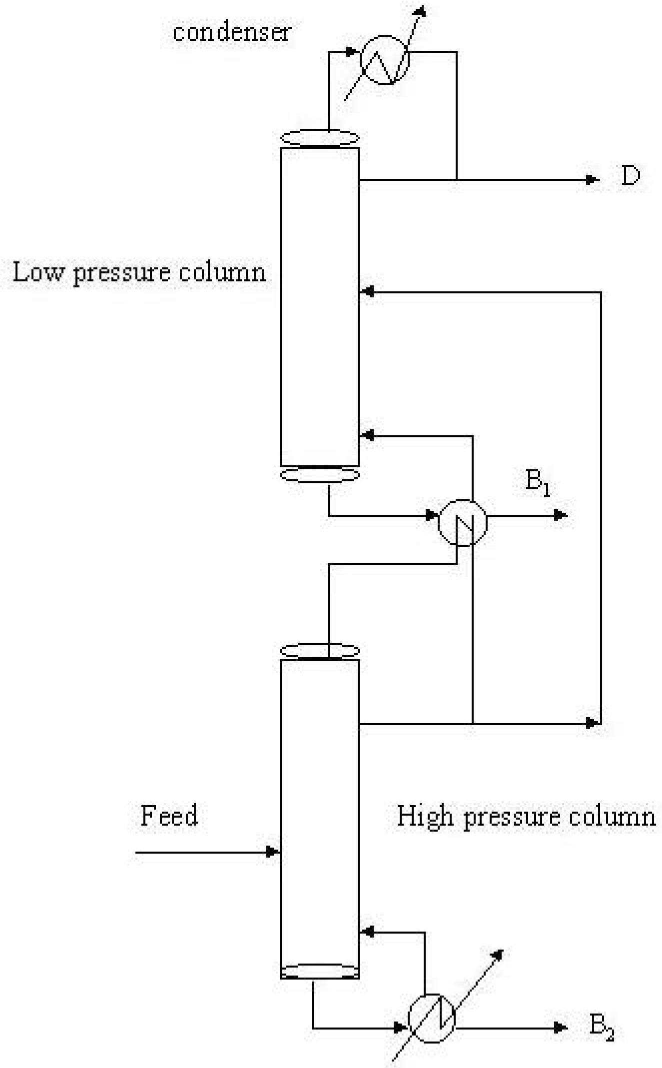


Figure 22. Multiple effect distillation: forward feed of one product

What we desire is a high-pressure column and a low-pressure column, where if we shift the pressure of both columns, the condenser temperature in the high-pressure column is greater than the reboiler temperature in the low-pressure column. This would allow us to combine the condenser of the high-pressure column with the reboiler of the low-pressure column. In figure 2 above, the sequence of distillation columns follows an indirect sequence where there is a forward feed of one product. The reboiler stream in the low-pressure column is used to cool down the condenser stream in the high-pressure column.

Because of this heat integration, you can see that we lose a heat exchanger, which reduces both capital and operating costs of our process

This heat integration can be done by changing the operating pressures of the 2 distillation columns or by keeping one the same and altering the pressure of the other column. Therefore, this change of operating pressure influences many design parameters throughout the column including relative volatility, height and diameter of the column, temperature, reflux, etc. The one thing we are looking to change is the temperatures of the condenser and reboiler, and hence the heating and cooling requirements. So we can either increase or decrease the pressure, and thus changing both columns position relative to the pinch temperature of the heat cascade derived in the previous sections. These instances are shown in figure 3a and b below.

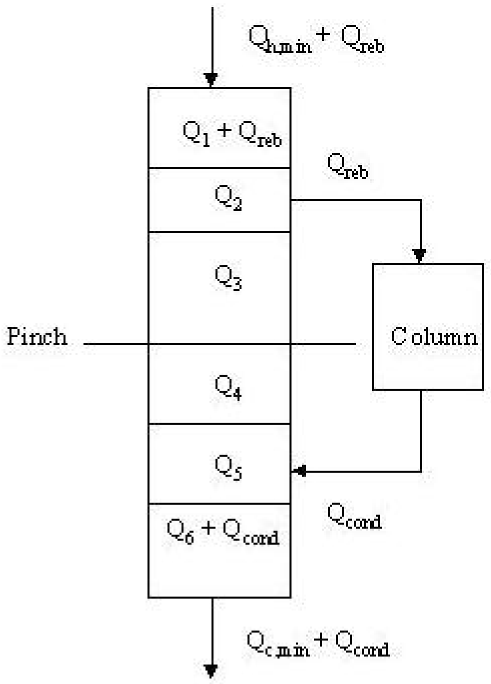


Figure 23a) Distillation across the pinch

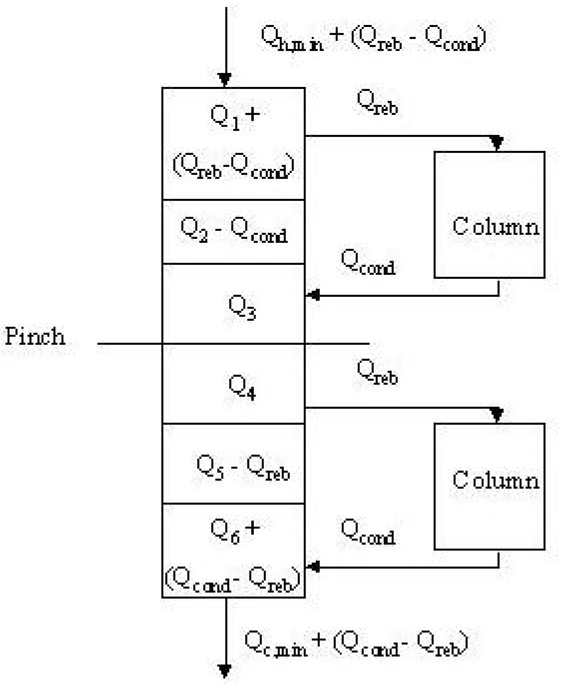


Figure 23b) Distillation not across the pinch.

If we raise the pressure, we can integrate a column condenser by lifting it above the pinch temperature. However, this has some negative effects on the column. The separation will become more difficult because of the decrease in relative volatility. Hence we would require more plates in the column or a larger reflux ratio which would equate to more capital costs. If we keep the pressure constant, the condenser temperature for the multi-effect and single columns will be the same. Therefore operating costs will be the same. Although, if we lower the pressure of the other column, we can integrate a column reboiler, which in turn would make the separation easier. The trade-off here is that we lower capital costs of the process, but increase our operating costs for steam in the high-pressure column. This is because we must supply the heat to the reboiler of the high-pressure column at a higher temperature in comparison to a single column where the temperature is lower.

A lower bound on utility consumption must also be taken into consideration because as we introduce more effects into our distillation separation, we continue to decrease energy requirements. A simple procedure for estimating a lower bound for the utility consumption is shown below. If you define the change in temperature available, ΔT_{avail} , as the difference between the temperatures of the highest hot utility available and the lowest cold utility, the minimum utility required is:

$$Q_{min} = (Q\Delta T) / (\Delta T_{avail}) \qquad \textbf{(10)}$$

where $Q\Delta T$ was solved earlier from equation 6

Pinch Method

The network temperature pinch represents a bottle neck to feasible heat recovery in HEN design. This method is referred to the pinch design method. This method can be used to identify the best starting value of ΔT_{min}. ΔT_{min} is used to correspond to a minimum energy solution. The pinch design method also involves a controlled reduction in the number of "units" (i.e. process and utility exchangers) This may require "backing-off" from the minimum utility usage. In addition, the pinch design method identifies situations where stream splitting is inevitable for a minimum utility design.

The task of locating the pinch and applying the pinch design method is illustrated by using stream data taken from the acetic anhydride design process. It is important to note that data for all examples is based on constant CP. This is due to the fact that every practical process with and without phase changes can easily be described in terms of linearized (i.e. CP = constant) temperature enthalpy data. The data is divided into nine temperature intervals corresponding to "subnetworks". Each of these subnetworks includes all streams or parts of streams which fall within a defined temperature interval. The temperatures T_1, T_2,…T_{n+1} are determined by the following method. T_2 and so on. Generally the following expression holds with the equality applying

$$n \leq 2z - 1$$

where n = number of subnetworks
z = number of streams

in cases where no two temperatures coincide. It is important to note that to ensure the feasibility of complete heat exchange, hot and cold streams are separated by ΔT_{min}.

An important feature of the problem table algorithm is the feasibility of complete heat exchange between all hot and cold streams This feasibility indicates that for each subnetwork there will be a net heat deficit of surplus but never both. When listed the sign convention is such that surplus is denoted as a negative value and a deficit is a positive value.

Another important feature of the problem table algorithm is the feasibility of heat transfer from higher to lower subnetworks (cascading). Heat surplus from higher temperature subnetworks can be used to satisfy the heat deficit of lower subnetworks (

refer to Figure 4). It is initially assumed that the heat input from external utilities is zero. The point of zero heat flow represents the pinch.

The pinch partitions the problem into two regions; a hot end and a cold end. The hot end is comprised of all streams or part of streams hotter than the pinch temperature and only requires process exchange and utility heating. The cold end is comprised of all streams or parts of streams cooler than the pinch temperature and requires only process exchange and utility cooling. It is important to remember that there is no heat transfer across the pinch.

As mentioned previously, the problem can be decomposed into a hot end and a cold end. The hot end is referred to as a heat "sink" as only utility heating is required. The cold end is referred to as a heat "source" as only utility cooling is required. Any heat transferred must, by enthalpy balance around the sink, be supplied from hot utility in addition to the minimum requirement. Similarly, enthalpy balance around the source shows that heat transfer across the pinch also increases the cold utility above the minimum required. Heat transfer across the pinch incurs the double penalty of increased hot and cold utility requirement for the HEN design task. For minimum utility usage, cooling is not permitted above the pinch and utility heating is not permitted below the pinch. In complex networks, exchangers and utility heaters and coolers will almost inevitable be placed in positions which violate the pinch. This results in more utility heating and cooling than otherwise would have been required. The pinch highlights existing utility or process exhcangers which are at "fault" i.e. violate the pinch and prevent a minimum utility design.

A pinch does not occur in all HEN 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 $\Delta T_{thresh.}$ For this reason, such problems are referred to as "threshold problems."

The concept of a threshold problem can be exemplified as a "very hot" hot stream matched to a "very cold" cold stream. The design for this "network" consists of a single exchanger and utility heater. The single exchanger completely satisfies the smaller of the two stream heat loads. The utility heater is required only to achieve the enthalpy balance for the total problem. The hot utility heat load remains constant, unaffected by any specification of $\Delta T_{min,}$ providing the specified ΔT_{min} is less than the smallest temperature driving force in the exchanger. However, when $\Delta T_{min\ exceeds}$ ΔT_{thresh} the need for both utility heating and cooling is introduced. This is due to a complete heat exchange between the two streams is no longer feasible without violating $\Delta T_{min.}$

A borderline situation occurs when at the specified ΔT_{min} equals the threshold value. The problem has become pinched, but the utility usage is the same as for lower values of $\Delta T_{min\ .}$ This borderline case is a general feature of a threshold problem. When ΔT_{min} is less than ΔT_{thresh} the result is no pinch and only utility cooling is required. When ΔT_{min} equals ΔT_{thresh} a pinch is introduced into the problem and there is no increase in utility usage. The utility usage only increases when the minimum allowed driving force is increased above ΔT_{thresh}. Both hot and cold utilities are then required and the problem is pinched.

It is usually assumed that the utilities needed are available at extreme temperatures, i.e. the hot utility was hot enough and the cold utility cold enough for all process requirements. In practice this is rarely desirable, as less extreme utilities tend to cost less, e.g. low pressure steam for process heating cost less than high pressure steam, cooling water costs less than refrigeration, etc. There is often a good cost incentive for reducing extreme temperature utility loads by the introduction of intermediate temperature utilities. Pinch significance states that any new hot utility must be supplied above the pinch and any new cold utility must be supplied below the pinch. Failure to do so would incur the double penalty of increased utility heating and cooling.

In figure 24(a), a new hot utility supply has been introduced to the hot end of a hypothetical problem. As the heat load on this new utility increases, savings are made on the hottest utility supply (see Fig 1(b).) There comes a point when the hottest utility load is reduced to such an extent that it just satisfies the heating requirements in the hottest region of the problem (see Fig. 1 (c)). The result is a division of the hot end of the HEN design task into two separate regions, i.e. a new pinch has been created. Due to the fact that it is a direct consequence of the introduction of a new utility, this division is referred to as a utility pinch.

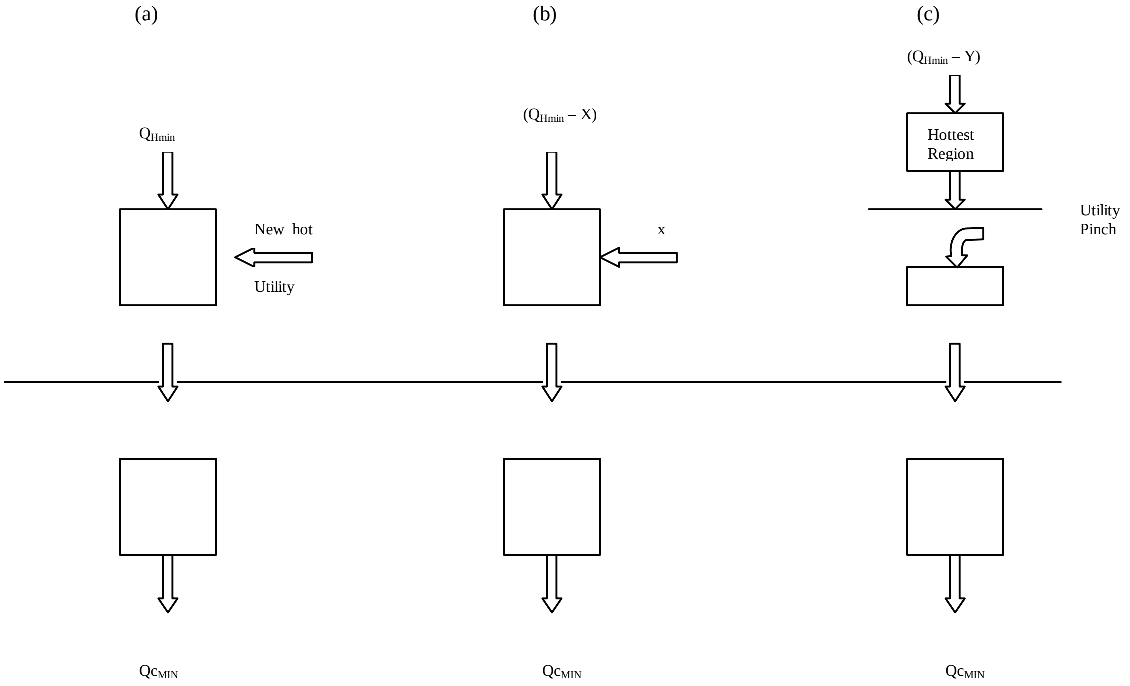


Fig. 24 (a) The correct placement of a hot utility. (b) Distributing the minimum heating requirement. (c) The utility pinch.

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

The pinch represents the most constrained region of a design; after all ΔT_{min} exists between all hot and cold streams at the pinch. As a result, the number of feasible matches in this region is severely restricted. Quite often there is a crucial or "essential" match. If this match is not made, this will result in heat transfer across the pinch and thus in increased hot and cold utility usage. The pinch design method, therefore

*recognizes the pinch division
*starts the design at the pinch developing it separately into two remaining problems

This approach is completely different from the natural approach of starting a process design with the hot end and developing it towards the cold end. Initial design decisions may later necessitate follow-up decisions which will violate the pinch if the design is started at the hot side. On the other hand, should the design start at the pinch, the initial design decisions are made in the most constrained part of the problem and are less likely to lead to difficulties in the future.

Commencing a design at the pinch ahas the distinct advantage of allowing the designer to identify essential matches or topology options in the most restrictive region of the design which are in keeping with minimum utility usage. Other advantages include having the option to violate the pinch if required with full knowledge of the final penalties which may occur. When a match is placed consciously in violation of the pinch, the heat flow is equivalent to the final increase in hot and cold utility.

The number of topology options usually increases once away from the pinch. This increase in the number of options can be used to advantage by the designer. In addition to being cost optimal, the design should also be safe and controllable. By discriminating between match options the designer can steer his design, using his judgement and process knowledge, towards a safe, controllable, and practical network.

The pinch design method does not "tell" the designer which matches to make, but rather it informs him of his options. The temperature constrained area near the pinch, essential matches are identified using feasibility criteria. The same criteria will inform the designer whether there are options available at the pinch and whether stream splitting is required. The need for feasibility criteria diminishes as the design is geared away from the pinch, and the method allows the designer to choose topologies based on the process requirements. In summary, the pinch design method incorporates two fundamentally important features. First, it realizes the pinch is the most temperature constrained region. The design is started at the pinch and developed moving away. Second, it allows the designer to choose between options.

The identification of essential matches at the pinch, of available design options and of the need to split streams is achieved by the application of three feasibility criteria to the stream data at the pinch. In developing these feasibility criteria, reference is made to "pinch exchangers" (sometimes called "pinch matches"). These are exchangers which have the minimum temperature approach $\Delta T_{min,}$ on at least one side and at the pinch.

The first feasibility criterion concerns the stream population of hot and cold streams has to be such that it will allow an arrangement of exchangers compatible with minimum utility usage. Utility cooling above the pinch would violate the minimum utility objective. Therefore, each hot stream has to be cooled to the pinch temperature by process exchange. This is attempted in Figure 2(a), a hot end design (not the design example) by placing pinch matches between hot stream No. 2 and cold stream No. 4 and hot stream No. 3 and cold stream No. 5. Notice, however, that having made these matches, hot stream No. 1 cannot be matched with either cold stream without violating the ΔT_{min} constraint. Utility cooling would now be required above the pinch to cool stream No. 1 to the pinch temperature. In such circumstances, we say the original stream data at the pinch is not compatible with a minimum utility design.

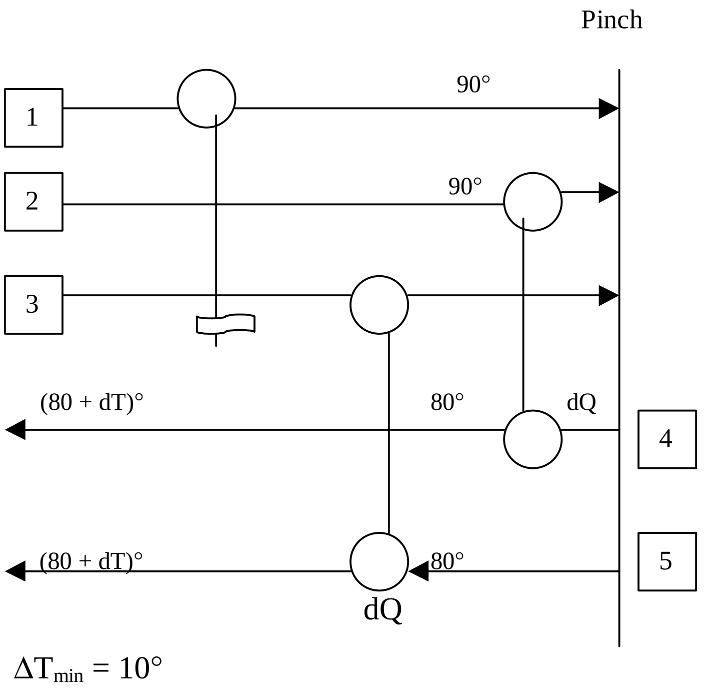
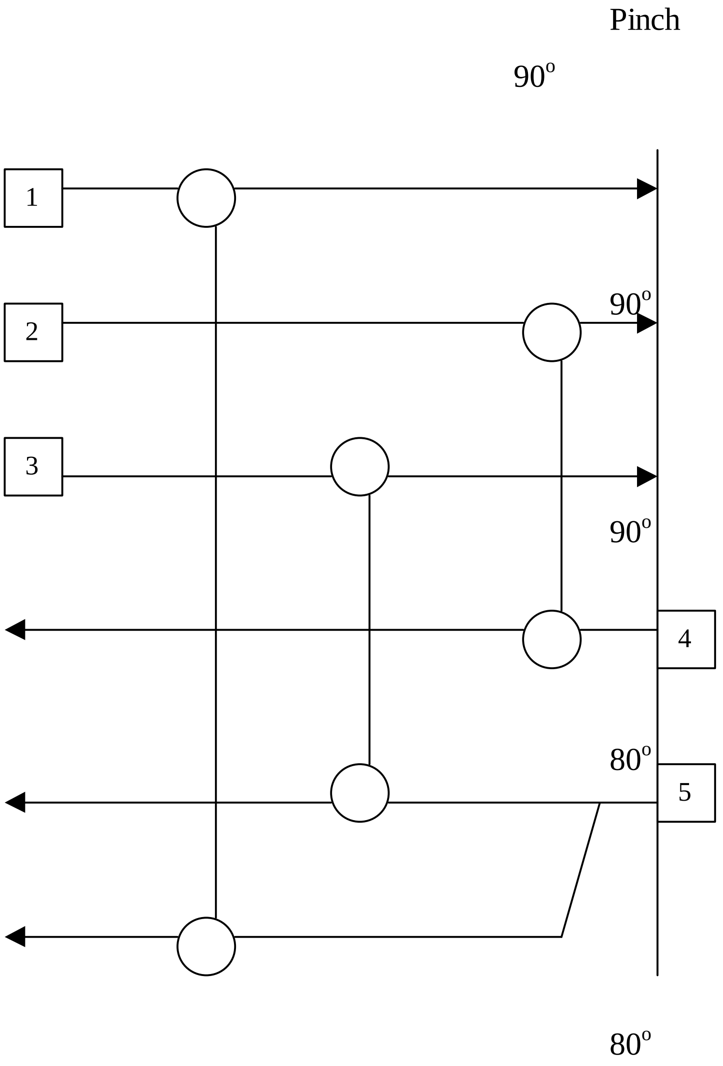


Figure 25(a). An infeasible hot end design at the pinch

When this incompatibility occurs, the streams at the pinch need “correcting” by stream splitting (see figure 2(b)). By splitting a cold stream an extra cold “branch” is created, allowing a pinch match with hot stream No. 1.



$\Delta T_{min} = 10^o$

Figure 25(b). Stream splitting at the pinch.

In summary, the hot end stream population at the pinch is compatible with a minimum utility design only if a pinch match can be found for each hot stream. For this to occur, the inequality must apply.

$$NH \leq NC$$

Where NH = number of hot streams or branches

NC = number of cold streams or branches. Stream splitting may be needed to ensure that the inequality is fulfilled. The opposite arguments apply below the pinch. To avoid utility heating each cold stream must be brought to the pinch temperature by process exchange. As a result, a pinch match is required for each cold stream at the pinch and this is possible only if the following inequality holds.

$$NH \geq NC$$

Once again, stream splitting may be necessary to ensure that this inequality is fulfilled.

The second inequality criterion is concerned with temperature feasibility criterion is concerned with temperature feasibility. Temperature driving force in a pinch match connot decrease away from the pinch. For this condition to be fulfilled, the following CP inequalities must apply in every pinch match.

Hot end pinch match

$$\mathrm{CP}H \leq \mathrm{CP}C$$

Cold end pinch match

$$\mathrm{CP}H \geq \mathrm{CP}C$$

Where $\mathrm{CP}H$ = the heat capacity flowrate of a hot stream or stream branch

$\mathrm{CP}C$ = the heat capacity flowrate of a cold stream or stream branch

If an arrangement of matches fulfilling these inequalities is not possible then it is necessary to change one or more CP's by stream splitting. It should be noted that the CP inequalities sonly apply at he pinch. Away from the pinch, temperature driving forces may have increased sufficiently to allow matches in which the CP's of the streams matched violate the inequalities.

To understand the third feasibility criterion at the pinch, it is necessary to define the "CP difference."

For a hot end pinch match

CP difference = CPC – CPH

For a cold end pinch match

CP difference = CPH – CPC

Similar equations can be written for differences in the overall sum of hot stream CP's at the pinch.

Immediately above the pinch

Overall CP difference $\sum_{1}^{NC} CPC - \sum_{1}^{NH} CPH$

Immediately below the pinch

Overall CP difference $\sum_{1}^{NH} CPH - \sum_{1}^{NC} CPC$

The concept of CP difference can be used for an early identification of matches that are feasible themselves but are not compatible with a feasible overall network. The CP differences of all pinch matches must always be bound by the overall CP difference.

References

Douglas, J.M. Conceptual Design of Chemical Engineering, McGraw-Hill, New York, 1988.

King, C.J. Separation Processes. McGraw-Hill, New York, 1971.

Linnhoff, B. "The Pinch Design Method for Heat Exchanger Networks", Chemical Engineering Science, vol 38, No. 5, pp, 745. Great Britain.

Wankat, P.C. Equilibrium staged Separations. Prentice Hall, Englewood Cliffs, New Jersey, 1988.