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

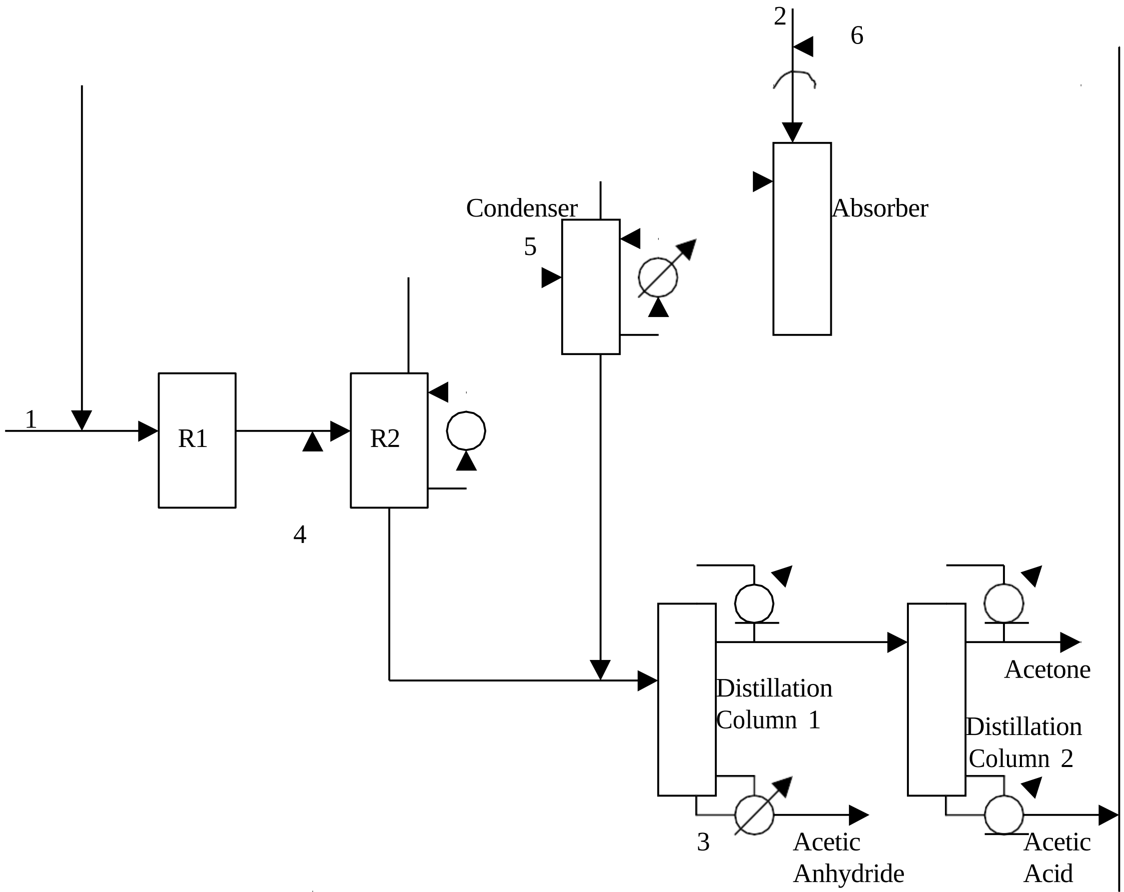


Table 1 Descriptions of Streams

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

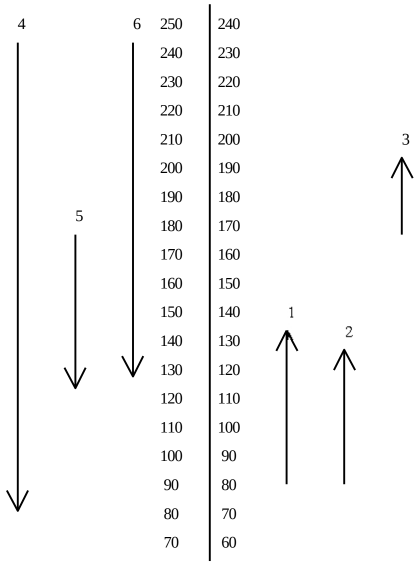
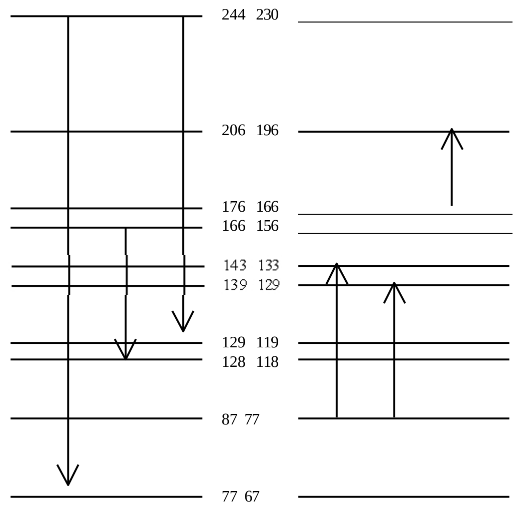


Figure 2 Temperature Intervals



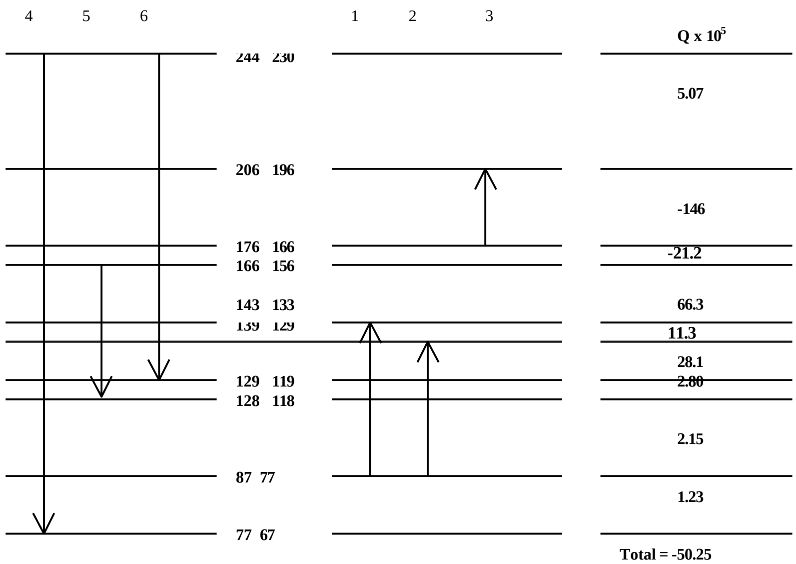
In each interval, heat from any hot streams in the high-temperature intervals can be transferred to any of the cold streams at lower-temperature intervals. For a starting point, heat transfer in each interval would be considered separately. The necessary equation is shown below.

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

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 x 10^7 Btu/hr must be supplied. Also, a heat amount of 2.12 x 10^6 Btu/hr must be supplied to the third interval to supply the deficiency of 2.12 x 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 x 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

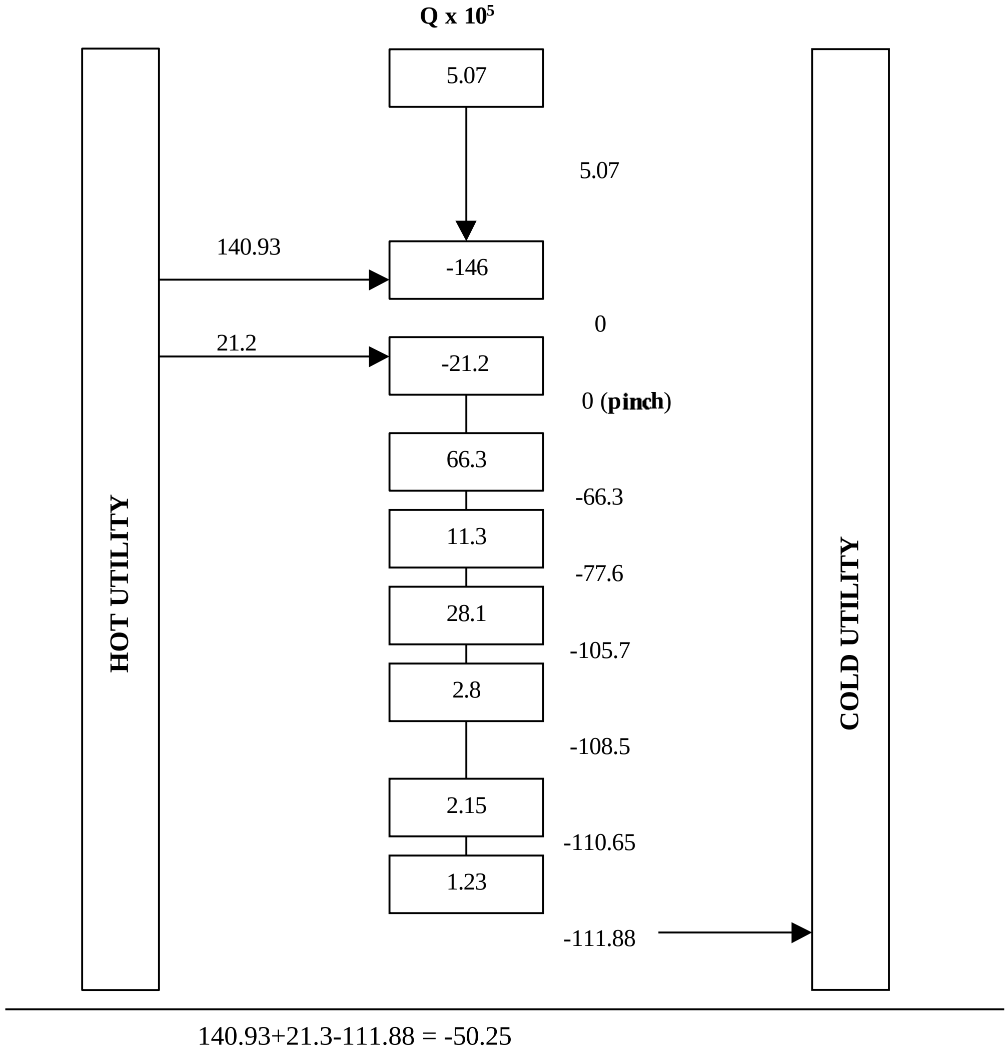


Figure 4 is called a *cascade diagram* because it shows how heat cascades through the temperature intervals.

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°F for the cold streams; sometimes the average of 161°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°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°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°F	$H_0 = 0$	0
87 F	$H_1 = (1.23x10^4)(87\text{-}77) = 1.23x10^5$	$1.23x10^5$
128°F	$H_2 = (1.23x10^4)(128\text{-}87) = 5.04x10^5$	$6.27x10^5$
129°F	$H_3 = [(1.23x10^4)+(2.75x10^5)](129\text{-}128) = 2.87x10^5$	$9.14x10^5$
139°F	$H_4 = [(1.23x104)+(2.75x10^5)+(1046)](139\text{-}129) = 2.28x10^6$	$2.28x10^6$
143°F	$H_5 = [(1.23x104)+(2.75x10^5)+(1046)](143\text{-}139) = 1.15x10^6$	$3.194x10^6$
166°F	$[(1.23x104)+(2.75x10^5)+(1046)](166\text{-}143) = 6.63x10^6$	$1.15x10^7$
176°F	$[(1.23x104)+(2.75x10^5)+(1046)](176\text{-}166) = 2.88x10^6$	$1.27x10^7$
206°F	$[(1.23x10^4)+(1046)])(206\text{-}176) = 4.00x10^5$	$1.31x10^7$
244°F	$[(1.23x10^4)+(1046)])(244\text{-}206) = 5.07x10^5$	$1.36x10^7$