CHAPTER II

BACKGROUND AND LITERATURE SURVEY

2.1 The Atmospheric Distillation Unit

2.1.1 Process Flow

Figure 2.1 shows a typical process flow scheme of an atmospheric distillation unit. The heat exchanger system is simplified. Alternative process flow schemes are discussed in distillation system options section. The atmospheric distillation unit consists of a desalter, an atmospheric tower, three side stripper and a debutanizer/splitter. Crude oil is preheated by exchanging heat with pump-around reflux streams and then sent to a desalter to remove salts, solids and water. The desalted crude oil is further preheated by exchanging heat with products and a pump-around reflux stream, and then finally heated by a crude oil furnace to a temperature which provides the required degree of vaporization. The heated crude oil is then introduced to the flash zone of the atmospheric tower. The number of trays installed in the tower is 35-50, depending on the number of side-stream products and the required degree of fractionation. The liquid portion of the flashed crude oil flows down to a bottom stripping section of the atmospheric tower, where distillate fractions dissolved in the liquid are vaporized with steam stripping.

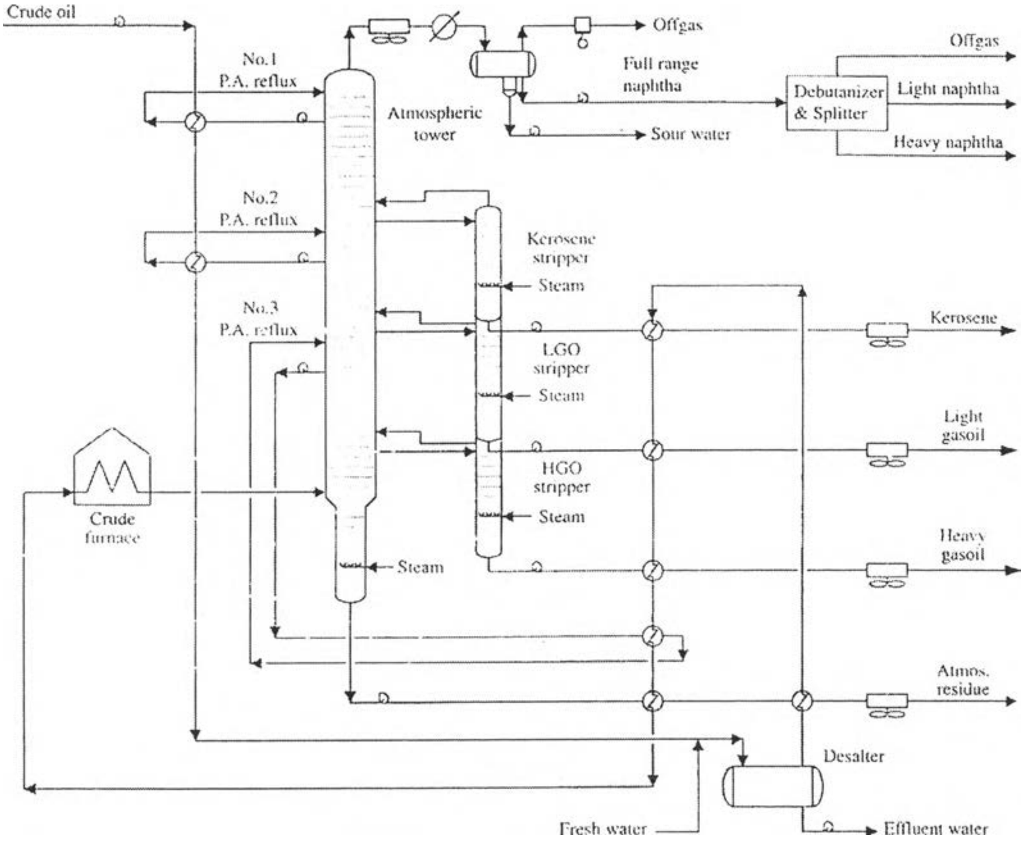

Figure 2.1 The process flow scheme of an atmospheric distillation unit.

The steam-stripped bottom product is withdrawn as atmospheric residue. A mixture of stripped oil vapor, the flashed vapor of the feed crude oil and the stripping steam ascends within the tower. This mixed vapor stream contacts down-flowing internal reflux liquid on the trays, where condensation and fractionation of distillate products takes place. The internal reflux liquid is created by condensation of the ascending oil vapor that has contacted cooled pump-around liquid. Use of the several pump-around reflux systems prepares reflux streams of different temperature levels, and enables effective utilization of the reflux heat load for heating the crude oil feed. The condensed liquid is withdrawn as side-stream products such as kerosene, light gas oil and heavy gas oil. These streams are sent to side strippers, where the lighter gas and oil fractions are removed by steam stripping for adjustment of the flashpoint. The bottoms of the side strippers are withdrawn as distillate products such as kerosene, light gas oil and heavy gas oil. The overhead vapor of the atmospheric tower is condensed by an overhead condenser(s). The condensed liquid, called full boiling range naphtha, is sent to a debutanizer to remove the butane and lighter gases that it contains. The debutanizer offgas and gases not condensed in condenser(s) of the atmospheric tower are sent to a gas concentration unit to recover propane and butane (LPG). The debutanized full range naphtha is separated into light naphtha and heavy naphtha by a splitter.

2.1.2 Distillation System Options

Even though the basic flow scheme is not changed from Figure 2.1, the atmospheric distillation unit has many options in the process flow scheme. Typical options for this scheme are discussed below.

2.1.2.1 Feed Charge System

The atmospheric distillation unit is classified into the following four types in terms of feed charge system, which are summarized in Figure2.2.

2.1.2.2 Non-Preflash System

The feed charge system in Figure 2.1 corresponds to this system. Crude oil is sent directly to the atmospheric tower without being processed by any preliminary separation equipment such as a flash drum or a fractionation tower. Although this system is simple, pressure drop through the crude oil furnace is high, and maldistribution of feed to the furnace tube passes may occur due to vaporization at the inlet of the furnace.

2.1.2.3 Preflash Drum System

The desalted crude oil is heated, and then introduced to a preflash drum where flashed water and light hydrocarbons are separated. The flashed vapor is sent directly to the atmospheric tower. The flashed liquid is further heated by heat exchangers and a crude oil furnace. This system reduces pressure drop through the crude oil to the furnace tube passes.

2.1.2.4 Prefractionator System

A prefractionator is installed to remove gas and a part of the naphtha fraction from the crude oil. Since gas and part of the naphtha are removed in the prefractionator, the diameter of the atmospheric tower can be reduced. The pressure drop through the feed furnace may also be reduced. This system is often applied when processing crude oil that are rich in gas and naphtha fractions. It is also applied as a means of increasing the capacity of an existing unit.

2.1.2.5 Dual Flash System

This system is applied to process two or more kinds of crude oil whose properties (sulphur content of residue, for example) are very different. An additional crude feed train(s) provided with flash drum(s) is installed to yield separately the residue from each crude.

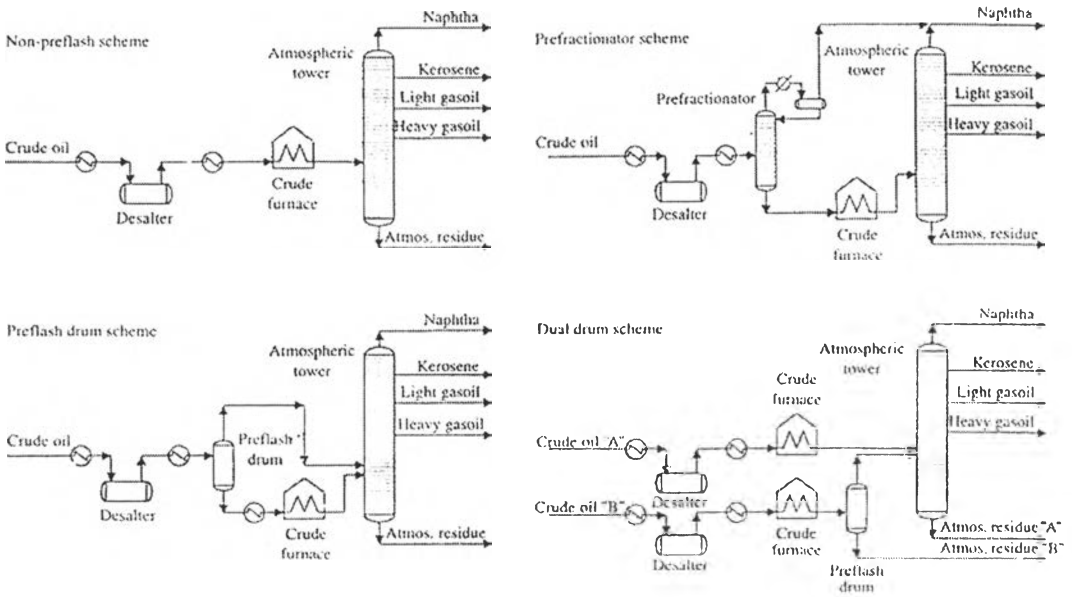

Figure 2.2 The charge systems of atmospheric distillation columns.

2.1.2.6 Tower Top Reflux System

Figure 2.3 shows two types of top reflux system. One is a pump-around reflux system, and the other is an overhead reflux system. The overhead reflux system may be further classified into a cold reflux system and a hot reflux system:

2.1.2.7 Pump-Around Reflux System

This system is alternatively called a side reflux system or a circulating reflux system. The tower top reflux system in Figure 2.1 corresponds to this system. Part of the ascending vapor to the top section of the atmospheric tower is condensed on the top section trays by contacting the cooled pump-around liquid reflux liquid, and the condensed liquid flows down as internal reflux. The heat load of the top pump-around reflux is effectively utilized to heat the feed crude oil. Due to the large amount of pump-around reflux liquid, the diameter of the tower top is comparatively large.

2.1.2.8 Overhead Reflux System

In this system, overhead vapor is condensed by an overhead condenser and the condensed liquid returns to the top of the atmospheric tower as a reflux. The overhead reflux systems; that is, a cold reflux system and a hot reflux system.

2.1.2.9 Cold Reflux System

The overhead vapor is condensed by an overhead condenser and enters an overhead reflux drum where hydrocarbon liquid, gasses and water are separated. Part of the hydrocarbon liquid is withdrawn from the drum as a naphtha product. The remaining hydrocarbon liquid is returned to the top of the atmospheric tower. This system is simple in operation, the diameter of the tower top section is small and trays for heat transfer are not required.

2.1.2.10 Hot Reflux System

Two sets of overhead condensers and drums are arranged in series in this system. A heavy fraction in the overhead vapor is condensed in the first condenser and sent to the first drum. All the condensed hydrocarbon liquid accumulated in this drum is returned to the top of the atmospheric tower as a reflux. The flashed hydrocarbon vapor and steam from the first drum is then condensed in the second condenser, and the condensed hydrocarbon liquid is withdrawn as a naphtha product. Since the temperature of the reflux liquid is higher than that of the cold reflux system, this system is called a hot reflux system. Although this system is complex in operation due to additional equipment and operating variables, correspond at the tower top section is reduced, and the same dimensional advantage mentioned for the cold reflux system is expected.

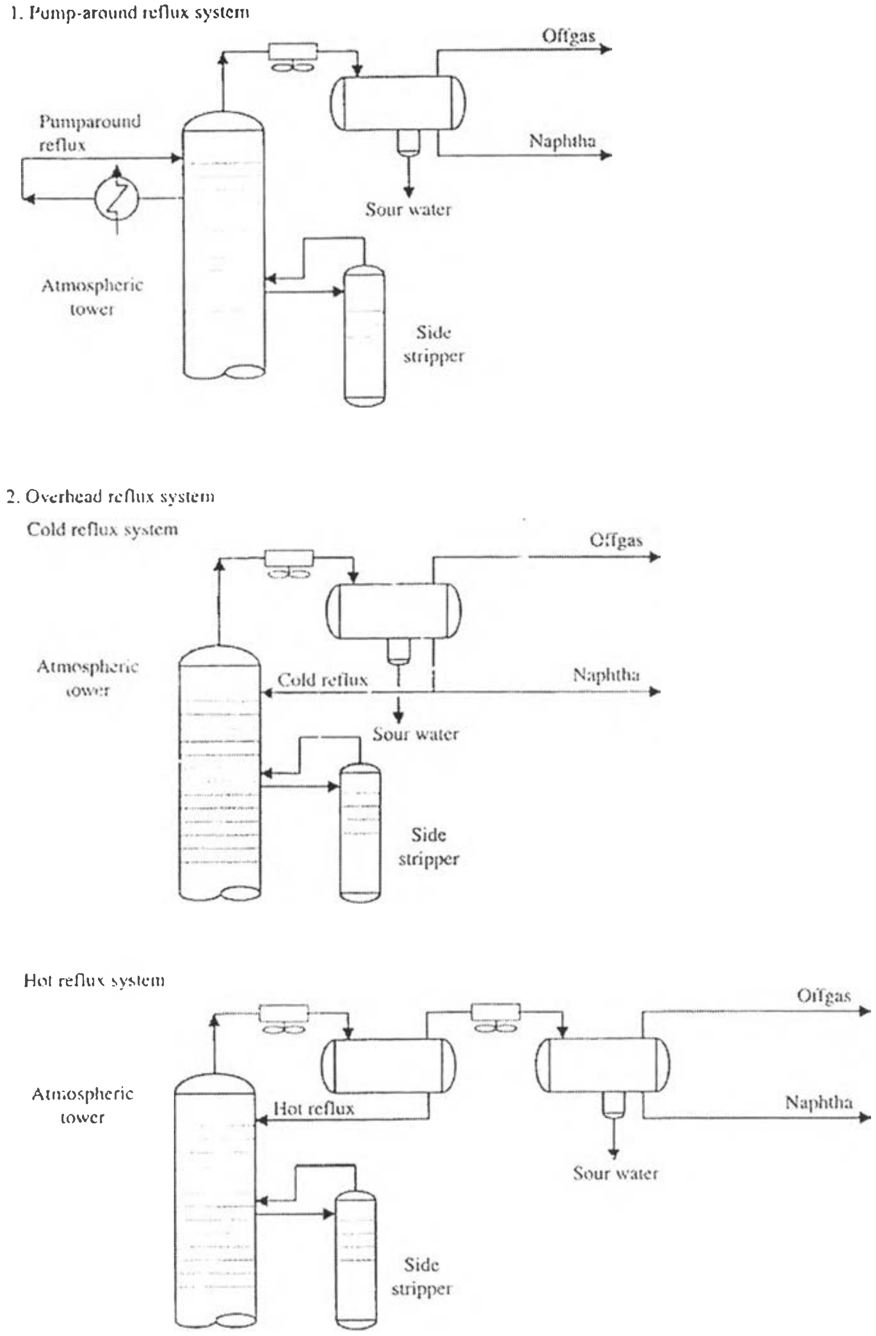

Figure 2.3 The top reflux systems of atmospheric distillation units.

2.1.2.11 Naphtha Separation System

In Figure 2.1, the full range naphtha withdrawn from the overhead is separated into light naphtha and heavy naphtha with the naphtha splitter, followed by the debutanizer. As an alternative to using the naphtha splitter, light naphtha and heavy naphtha can be withdrawn as an overhead product and a side-stream product, respectively, from the atmospheric tower. If the full range naphtha is hydrotreated before being separated to light naphtha and heavy naphtha, the naphtha splitter is installed in the naphtha hydrotreating unit.

2.1.3 Processing of Several Kinds of Crude Oil

Four alternative operating modes to process several kinds of crude oil simultaneously, sequentially or in parallel within the atmospheric distillation unit, are described below:

2.1.3.1 Mixing Operation

This is a simple method to process mixed crude oil, and is applied to process crude oils whose properties are similar.

2.1.3.2 Blocked-Out Operation

This is a method to process several crude oils with blocked-out operation, and is applied to yield all the products separately from different crude oils whose properties are different.

2.1.3.3 Multiple Preflash System Operation

Reference is made to the 'Dual flash scheme' shown in Figure 2.2. Multiple feed trains for heating crude oil and for separating residues are installed to yield individual residues. The flashed distillate streams are processed in one atmospheric tower. This system is applied when processing crude oils whose residue properties are greatly different and where residue segregation is required.

2.1.3.4 Multiple Units Operation

This is a method to process separately different types of crude oils in different atmospheric distillation units. It is typically applied to process paraffinic and naphthanic crude oils separately, or to process high-sulphur and low-sulphur crude oil separately, usually in a refinery of large capacity.

2.1.4 Operating Conditions

2.1.4.1 Temperature

Most crude oils begin thermal decomposition at 340-370 °C, the actual decomposition temperature varying with the type of crude oil. The coil outlet temperature of the crude furnace, which is the highest operating temperature of the atmospheric distillation unit, should be selected to prevent excessive thermal decomposition, which results in coking of furnace tubes and poor quality of the distillate products. The typical temperature at the furnace coil outlet is in the range 310-370 °C.

2.1.4.2 Pressure

The operating pressure will be set as low as possible to achieve the desired vaporization at the lowest temperature. A typical operating pressure at the overhead drum lies in the range 0.11-0.20 MPa. In some rare cases, a higher pressure is adopted in order to maximize the dissolution of offgases into naphtha, and avoid installation of an offgas compressor.

2.1.4.3 Sripping Steam

Stripping steam to the bottom of the atmospheric tower and side strippers is applied at the rate of 10-50 kg/m^3 of the bottoms. Where heavy naphtha is withdrawn as a side-stream product, the side sripper may be equipped with a reboiler instead of injecting stripping steam.

2.2 Heat Demand-Supply Diagram

Heat demand-supply diagrams are an extension of the concept of temperature-enthalpy diagrams (Hohmann, 1971; Huang and Elshout, 1976; Naka *et al.*, 1980; Andrecovich and Westerberg, 1985; Terranova and Westerberg, 1989; Dhole and Linnhoff, 1993). In the demand-supply diagram, a curve represents a stream that is the product of mass flow rate and specific heat capacity (true or apparent in the case of phase changing streams) as a function of temperature. A schematic heat demand-supply diagram for typical crude fractionation units, like the one of Figure 2.1, is shown in Figure 2.4.

In constructing the diagram, a heat demand line is first drawn and used as the background. The crude is only the cold stream. In some cases, water at room temperature to produce steam is also considered a cold stream (Liebmann and Dhole, 1998). Nevertheless, in many refineries, low-pressure steam is in surplus that can be considered as a cheap or even free heat source. To set the hot streams (heat supply), the usual minimum temperature difference is used. Therefore, the temperatures of hot streams are shifted to the left by this minimum difference that has been typically named the heat recovery minimum approximation temperature (HRAT or ΔT_{min}). The area under the heat demand line represents the total heat demand of the unit excluding heat recovery.

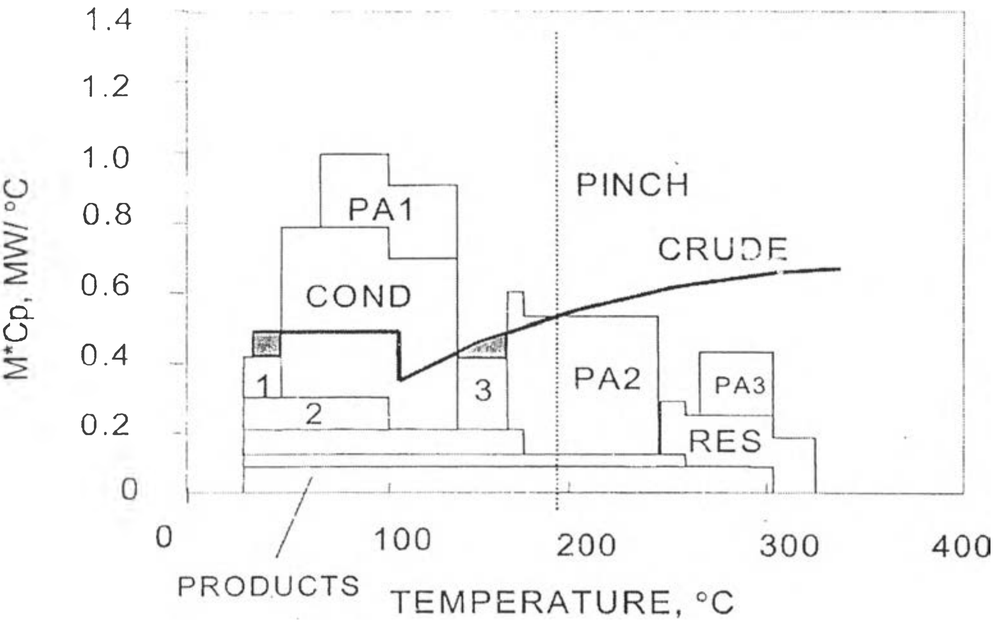

Figure 2.4 Heat demand-supply diagram of an atmospheric crude distillation unit. (1. Naphtha and condenser water, 2. Sour water from the desalter, 3. Pump-around 1, COND: condenser, PA: pump-around, RES: residue, Products (from top to bottom): kerosene, diesel, and gas oil). (Bagajewicz and Ji; 2001)

In Figure 2.4, this curve is divided into two different regions:

Regions where heat supplies are larger than demands
Regions where heat supplies are smaller than demands

When the supply exceeds the demand, one can shift the surplus part of the supply to a lower temperature region where the supply is deficient. Two areas where the supply is in deficit (gray areas), are shown in Figure 2.4. The left gray area can be covered by the heat surplus from the condenser or PA1. The right area can be covered by using the surplus of PA2. This diagram is neglected, assuming that this area matching is implicit.

This diagram can achieve the location of the pinch point that is the lowest temperature at which the demand is larger than the supply after the shifting and area matching has been completed. Finally, the unmatched demand on the right is obtained by the heating utility, and the extra supply on the left is obtained by the cooling utility.

Three options to reduce energy consumption exist: decreasing demand, increasing supply and improving the match between the supply and the demand.

2.2.1 Decrease of Demand

a) A decrease in heat demand can be realized by moving the demand line down, that is, decreasing the flow rate. One way to do this is to flash the crude at lower temperatures and feed the vapor to a tray above the flash zone. In practice, vaporization before the furnace inlet is pressure suppressed to avoid two-phase flow. This reduces energy saving opportunities.

b) Another way to decrease heat demand is to reduce the target temperature of the crude. This can be realized by lowering the pressure drop from the outlet of the furnace to the overhead reflux drum of the column. In this practice, a vacuum operation is even better, but the other reasons, mainly cost, exclude in this operation. Another way to decrease the final temperature is using larger amount of steam, but the introduction of steam has complicating effects on the energy consumption.

2.2.2 Increase of the Supply and/or the Thermal Quality

Withdrawing certain products in the vapor phase in place of in a liquid phase has the advantage that condensation heat is released at a higher temperature.

2.2.3 Improvement of Match between Demand and Supply

Assume that there is a larger heat surplus in a moderate temperature range and a heat deficit in a higher temperature range. One way of improving this mismatch is to move a part of the heat surplus to a higher temperature by increasing the duties of the pump-around circuits.

2.3 Pump-Around Circuits and Heat Recovery

The original purpose of adding pump-around circuits was to reduce vapor and liquid traffic at the top section of the column. Without pump-around circuits, all condensation heat has to be removed from the condenser, which results in a large vapor flow rate at the top trays. In this work the limit of heat that could be removed from a pump-around circuit is explored.

2.3.1 Maximum Heat Duty of Pump-Around Circuits

In Figure 2.5, envelope III contains *k* pump-around circuits. To identify the maximum pump-around duty, a heat balance for this envelope is performed.

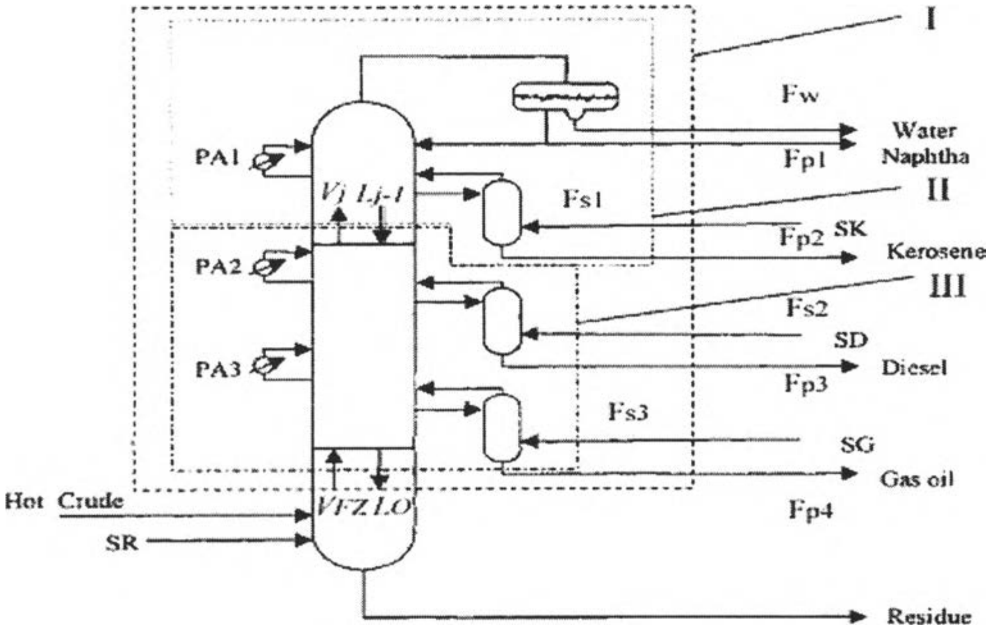

Figure 2.5 Heat balance of the distillation column (Bagajewicz and Ji; 2001).

$$\begin{aligned} &V_{FZ}^{W}h_{FZ}^{W} + V_{FZ}^{O}h_{FZ}^{O} + L_{j-1}h_{L_{j-1}} + \sum_{i\in III} F_{si}h_{si} + \sum_{k\in III} Q_k \\ &= L_O h_{L_O} + \sum_{i\in III} F_{pi}h_{pi} + V_j^{W}h_{V_j}^{W} + V_j^{O}h_{V_j}^{O} \end{aligned} \qquad (1)$$

In Eq 1, V_{FZ}^{W} and V_{FZ}^{O} are the steam flow rate at the flash zone and the hydrocarbon vapour flow rate at the flash zone respectively, V_j^{W} and V_j^{O} are the steam flow rate at tray *j* and the hydrocarbon vapor flow rate at tray *j*, respectively. Note that $V_{FZ} = V_{FZ}^{W} + V_{FZ}^{O}$ and $V_j = V_j^{W} + V_j^{O}$. Assuming water is insoluble in liquid streams.

By applying material balance of hydrocarbons to envelope I, one obtains

$$V_{FZ}^{O} = L_O + \sum_{i\in I} F_{pi} \qquad (2)$$

Likewise, material balances for envelopes II and III are

$$V_j^O = L_{j-1} + \sum_{i \in II} F_{pi}$$

$$V_j^W = V_{FZ}^W + \sum_{i \in III} F_{si} \qquad (3)$$

Replacing V_{FZ}^O , V_j^w , and V_j^O in eq 1, one obtains

$$\begin{aligned} \sum_{k \in III} Q_k &= L_O (h_{L_O} - h_{FZ}^O) + \sum_{i \in III} F_{pi} (h_{pi} - h_{FZ}^O) + \\ &\sum_{i \in II} F_{pi} (h_{V_j}^O - h_{FZ}^O) + V_{FZ}^W (h_{V_j}^W - h_{FZ}^W) + \\ &\sum_{i \in III} F_{si} (h_{V_j}^W - h_{si}) + L_{j-1} (h_{V_j}^O - h_{L_{j-1}}) \end{aligned} \qquad (4)$$

There are six terms on the right-hand side of eq 4. The first through the fifth terms represent the condensation heat of the overflash stream L_O , the condensation heat of the products leaving envelope III, the apparent heat released by the hydrocarbon vapor V_j^O , and the apparent heat released by steam streams. The last term stands for the vaporization heat of the internal reflux L_{j-1}. Apparently, when L_{j-1} goes to zero, the heat removal from envelope III reaches maximum. By including more pump-arounds in envelope III and applying Eq 4 accordingly, one can calculate the maximum heat duty for each pump-around circuit.

The amount of heat to be removed from the column depends on the yields of the products. In addition to shift heat from envelope II to envelope III, resulting in a decrease of L_{j-1} . Therefore, the shifting can take place as long as L_{j-1} remains positive.

2.3.1.1 *Effect of Heat Shifting on Separation*

Heat shifting reduces separation efficiency. The presence of the pump-around circuit decreases the number of effective ideal trays. The effect can be even more detrimental to separation if the flow rate of a pump-around circuit is increased. One way to compensate these effects by increasing the steam rates in the side strippers. Another way to solute is to increase the number of trays.