CHAPTER III

DISTILLATION COLUMN

Refinery processes are the processes that separate crude oil, which is a liquid mixture consisting principally of hydrocarbons, to many products used as fuels or petrochemical feeds--such as liquefied petroleum gas (LPG), naphtha, kerosene, gas oil, lubricating oil and heavy fuel oil, and asphalt. Most refinery processes can be grouped into one of three classes[7] as follows:

1. Separation, usually distillation, gives the desired type of compounds,
2. Conversion, usually cracking, changes molecular weight and boiling point,
3. Upgrading, e.g., hydrotreating, meets product-quality specifications.

An overall flow diagram of refinery processing steps is shown in Figure 3.1. Crude oil is fed into distillation units to separate into semiproducts. Light and middle semiproducts are generally fed to upgrading units (e.g., alkylation, extraction, catalytic reforming and hydrotreating units) to improve product quality. Heavy semiproducts are often fed to conversion units (e.g., hydrocracking, steam cracking, catalytic cracking, coking and visbreaking) to increase middle products and produce heavy products. Details of those units have been described in many references[7,8,9].

For this work, the case study is the topping unit of the plant No.2 in Bangchak Refinery. It is an important unit separating the crude feed into main semiproducts before being fed into conversion and upgrading units, shown in Figure 3.2. Bangchak Refinery consists of (1)plant No.2 (40 KBD) and (2) plant No.3 (80KBD) (plant No.1 was retired), shown in Figure 3.2 and 3.3, respectively.

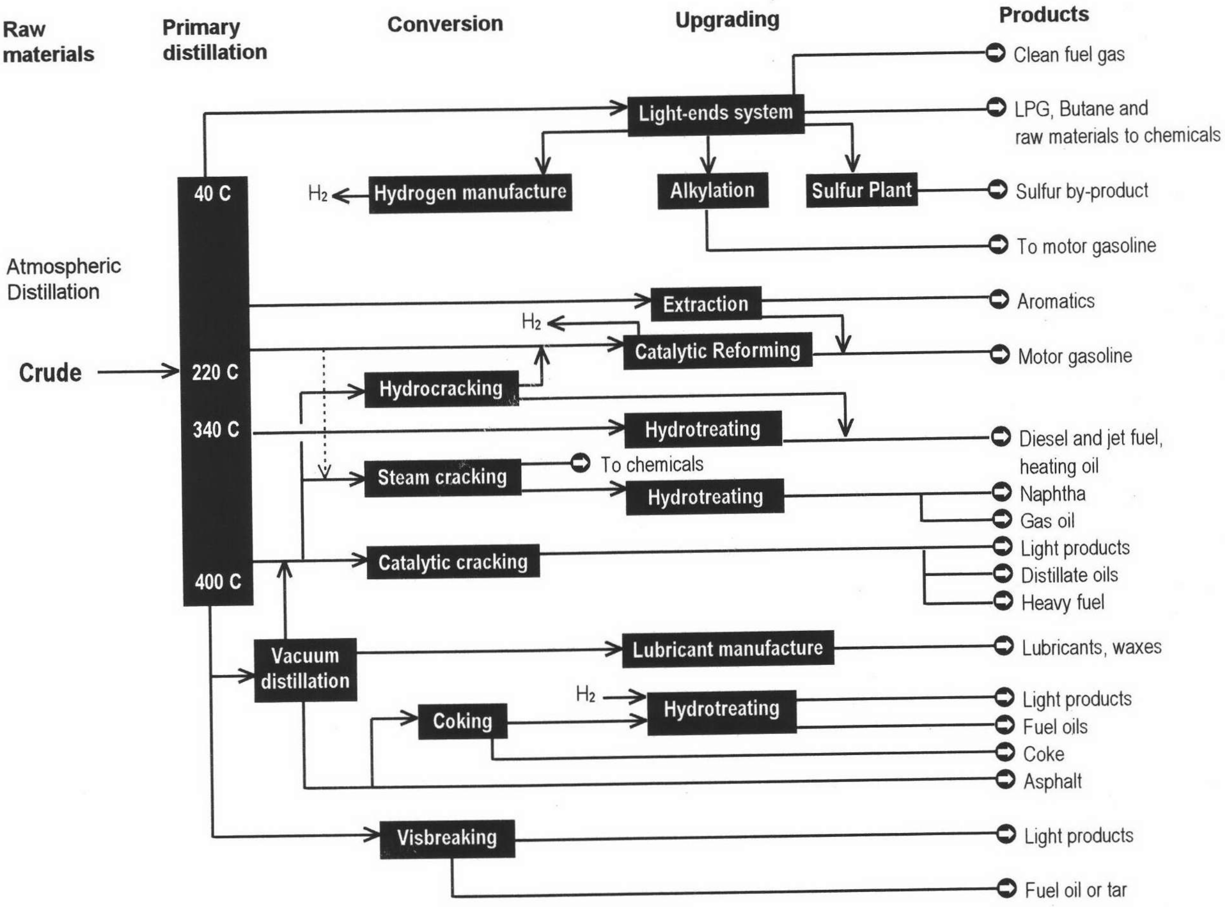

Figure 3.1 Overall petroleum-refining processing[7].

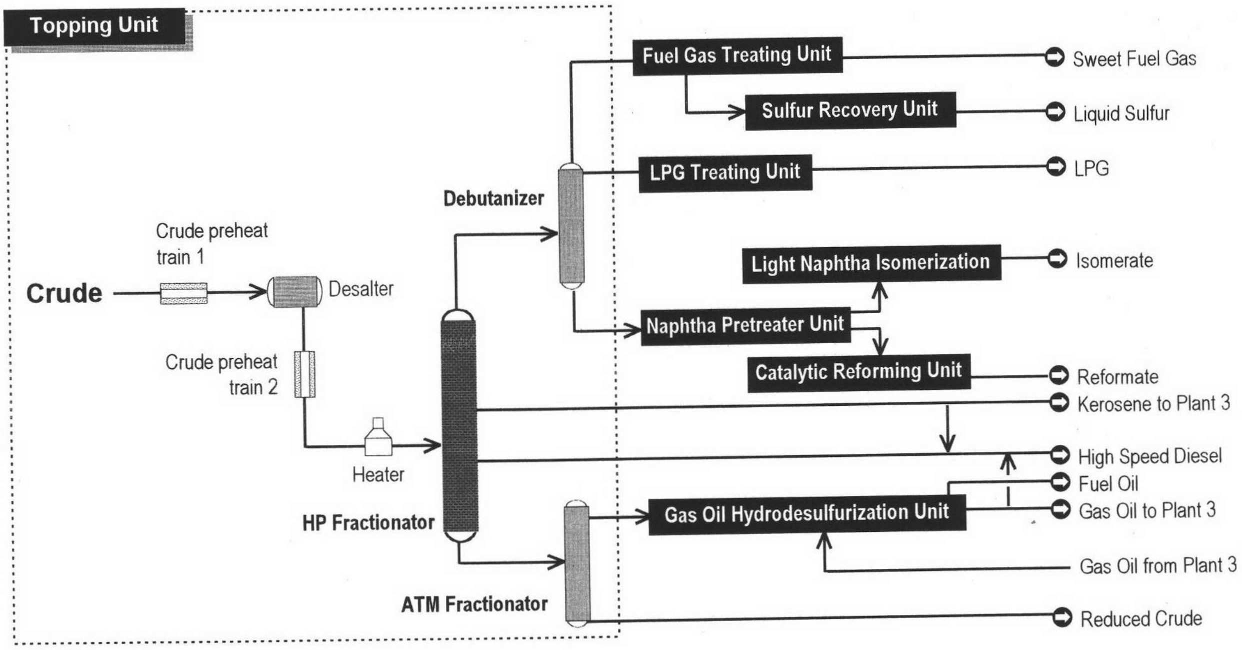

Figure 3.2 Overall Processing of Plant No. 2 in Bangchak Petroleum Refinery.

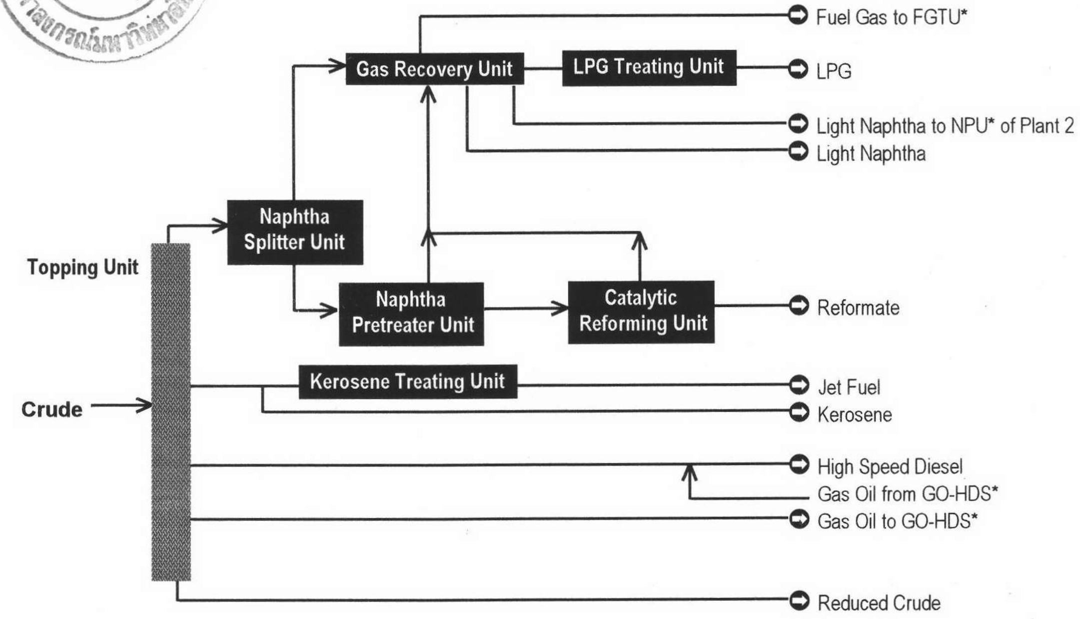

Figure 3.3 Overall Processing of Plant No. 3 in Bangchak Petroleum Refinery.

*** Note:**
FGTU = Fuel Gas Treating Unit
NTU = Naphtha Pretreater Unit
GO-HDS = Gas Oil Hydrodesulfurization Unit

Distillation Column

Distillation columns, the main units of refinery process, frequently are limiting factors (bottlenecks) in capacity (hydraulic) or product quality (efficiency) [10]. To debottleneck the existing tray columns, there are three methods [10,11] -- redesigning them or replacing them with higher capacity and/or efficiency packings or both. Using the methods requires basic design and criteria of column modifications (presented in following sections). In general, distillation columns are divided into two classes as tray and packed column [12]. Tray are of four types, i.e., bubble-cap, dual-flow, sieve, and valve. Packing includes three types; random or dump packings, structured or systematically arranged packings, and grids.

Tray Column

Sieve and valve trays are most frequently encountered in industrial practice. For bubble-cap trays, they are specified only for special applications (operating at low vapor and liquid rates). A dual-flow tray is a sieve tray without downcomers, thereby having the greatest capacity. Detail information of comparison of trays is shown in Table 3.1.

Table 3.1 Comparison of the Common Tray Types[12]

Type	Sieve tray	Valve tray	Bubble-cap tray	Dual-flow tray
Capacity	High	High to very high	Moderately high	Very high
Efficiency	High	High	Moderately high	Lower than others types
Turndown	About 2:1. Not generally suitable for operation under variable loads	About 4-5:1. Some special designs achieve (or claim) 10:1 or more	Excellent, better than valve trays. Good at extremely low liquid rates	Low, even lower than sieve trays. Unsuitable for variable load operation
Entrainment	Moderate	Moderate	High, about 3 times higher than sieve trays	Low to moderate
Pressure drop	Moderate	Moderate. Early designs somewhat higher. Recent designs same as sieve trays	High	Low to moderate
Cost	Low	About 20 percent higher than sieve trays	High. About 2-3 times the cost of sieve trays	Low
Maintenance	Low	Low to moderate	Relatively high	Low
Fouling	Low	Low to moderate	High. Tends to collect solids	Extremely low. Suitable where fouling is extensive and for slurry handling.
Effects of corrosion	Low	Low to moderate	High	Very low
Availability of design information	Well know	Proprietary, but information readily available	Well known	Some information available
Other				Instability sometimes occurs in large diameter (> 8 feet) columns
Main applications	Most columns when turndown is not critical	1. Most columns, 2. Services where turndown is important	1. Extremely low flow conditions 2. Where leakage must be minimized	1. Capacity revamps where efficiency and turndown can be sacrificed 2. Highly fouling and corrosive services
Share of the market (1981)	25%	70%	5%	No information

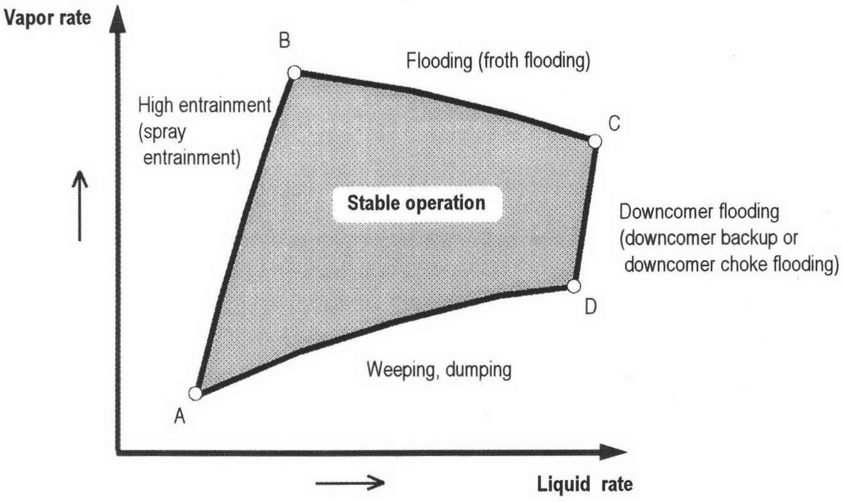

Figure 3.4 Stable operating range for crossflow plates[13].

Tray capacity limits are flooding (upper limit) and weeping (lower limit) as shown in Figure 3.4. Flooding is excessive accumulation of liquid inside column, and is generally caused by one of four mechanisms [12,14]. First, spray entrainment flooding occurs at low liquid flow rate with high vapor velocity. Second, froth entrainment flooding occurs at high vapor and liquid rates in a tray column which has a small spacing (<18 in.). Third, downcomer backup flooding is that aerated liquid is backed up into the downcomer until it exceeds tray spacing because of tray pressure drop, liquid height on the tray, and friction losses in the downcomer apron. Fourth, downcomer choke flooding causes liquid accumulation on the tray above when velocity of aerated liquid in a downcomer exceeds friction losses in the downcomer and downcomer entrance so that frothy mixture can not be transported to the tray above. For lower capacity limit, weeping occurs at low vapor rate where liquid descends through the tray perforation and short-circuits the primary contacting zone, causing a reduction in tray efficiency.

In general tray design, the tray spacing is at least 24 inch to avoid the froth entrainment flooding, and tray cross-sectional downcomer area is at least 10% of total column cross-sectional area to avoid the downcomer (backup or choke) flooding. Thus, the usual design limit is the spray entrainment flooding. Souders and Brown theoretically analyzed the spray entrainment flooding in terms of droplet settling velocity. Flooding occurs when the upward vapor velocity is high enough to suspend a liquid droplet, giving Eq. (3.1)

$$U_{S,\text{flooding}} = C_{SB}\sqrt{\frac{\rho_L - \rho_V}{\rho_V}} \tag{3.1}$$

From Eq. (3.1) the Souders and Brown flooding constant, C_{SB}, can be defined

$$C_{SB} = U_{S,\text{flood}}\sqrt{\frac{\rho_V}{\rho_L - \rho_V}} \tag{3.2}$$

The Souders and Brown constant, C_{SB}, is the C-factor at flooding point, which describes the maximum vapor loads in tray design (detail in reference No. 12). Trays are usually design at vapor load less than 85% C_{SB}. Therefore, tray columns should be designed or modified for capacity debottlenecking in the following constraints (Fig. 3.5) [12,15]:

1. The percent of flooding in trays is in range 80 - 85%.
2. Pressure drop per tray is about 0.08 - 0.12 psi.
3. Tray spacing should range from 24 to 36 in., to avoid froth entrainment.
4. Froth height in downcomer should be less than 80% of spacing height and weir height, preventing downcomer flooding.

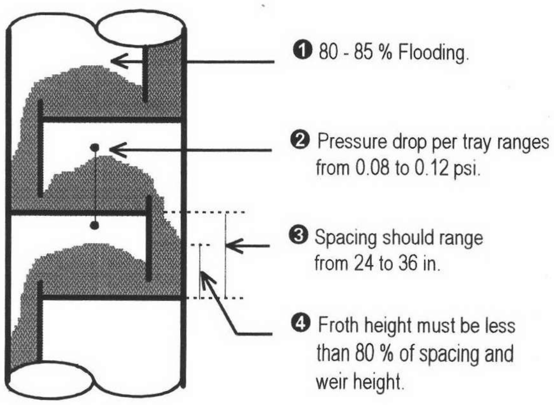

Figure 3.5 Tray constraints for satisfactory operation.

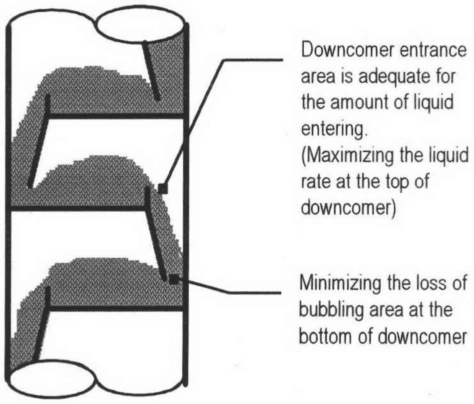

Figure 3.6 Sloped downcomer[14].

Moreover, the sloped downcomer shown in Fig. 3.6 can be used to handle higher capacity when downcomer area exceeds 20 to 30 percent of the tower area. Its ratio of the top area to the bottom area ranges 1.5 to 2.0 (commonly, 1.7) [14,15].

Packing

Random packings are by far the most common in commercial practice. Structured packings are less common, but their share of the packing market has rapidly grown over the last decade. The application of grids is limited primarily to heat transfer and wash services and/or where a high fouling resistance is required. Two important objectives of using packing column are maximizing efficiency and capacity.

1. Maximum efficiency objective

   By maximizing the surface area per unit volume of packing, the vapor-liquid contact areas are maximized; thereby maximizing efficiency. A corollary is that for random packings, efficiency generally increases as the particle size is decreased; for structured packings, efficiency generally increases with the space between adjacent layers is decreased, and for grids, efficiency generally increases as the lattice openings are narrowed.

2. Maximum capacity objective

   By maximizing the void space per unit column volume, resistance to vapor upflow are minimized; thus enhancing packing capacity. A corollary is that for random packings, capacity increases with particle size; for structured packings, capacity increases with the space between adjacent layers, and for grids, capacity increases as the lattice openings are widened. Comparing to the first objective for maximizing efficiency, this corollary states that the packing size that maximizes capacity also minimizes efficiency. A trade-off therefore exists; the ideal size of packing is a compromise between maximizing efficiency and maximizing capacity.

Random packings can be classified into three generations as follows [12]:

1. First-generation packings are seldom used in modern distillation practice, e.g., Raschig rings, Lessing rings, and Berl saddles.
2. Second-generation packings are still popular and extensively used, e.g., Intalox® saddles and Pall® rings.
3. Third generation has produced a multitude of popular geometries, most of which evolved from the Intalox® saddles and Pall® rings, e.g., Intalox Metal Tower Packing (IMTP®), and Cascade® Mini-Rings (CMR®).

Improvements in either capacity or efficiency or both from the first generation to the next are significant, but from the second to the third generation are less pronounced.

Structured packings are of two types -- wire-mesh structured packings (e.g., Goodloe®, Hyperfil®, etc.) and corrugated structured packings (e.g., Mellapak ®, Flexipac®, etc.). At low (< 20 gallons per minute per square foot (GPM/ft^2)) liquid rates, they have greater efficiency than random packings. But, failures have been experienced by the industry in the high-pressure and/or high-liquid rate services. In vacuum distillation, they are used better than random packings because of low pressure drop per theoretical stage; however, they are more expensive.

Grids are designed to promote desirable features, i.e., high open area, high capacity, high resistance to fouling and plugging, and low pressure drop. The efficiencies of grids are considerably lower than those of both random and structured packings. Grids are primarily used in direct-contact heat transfer, scrubbing, and deentraining services. Examples of grids include Glitsch C-Grid® and Koch Flexigrid® #2.

In many references [12,13,16], there are many explicit descriptions of random and structured packings and grids on their geometry, efficiency and capacity. The simplest packed column consists of a vertical shell with random packing on a packing support and a liquid distributor above the packing that distributes the liquid uniformly across the packed bed. A packed column with two packed beds and a midcolumn feed is shown in Figure 3.7.

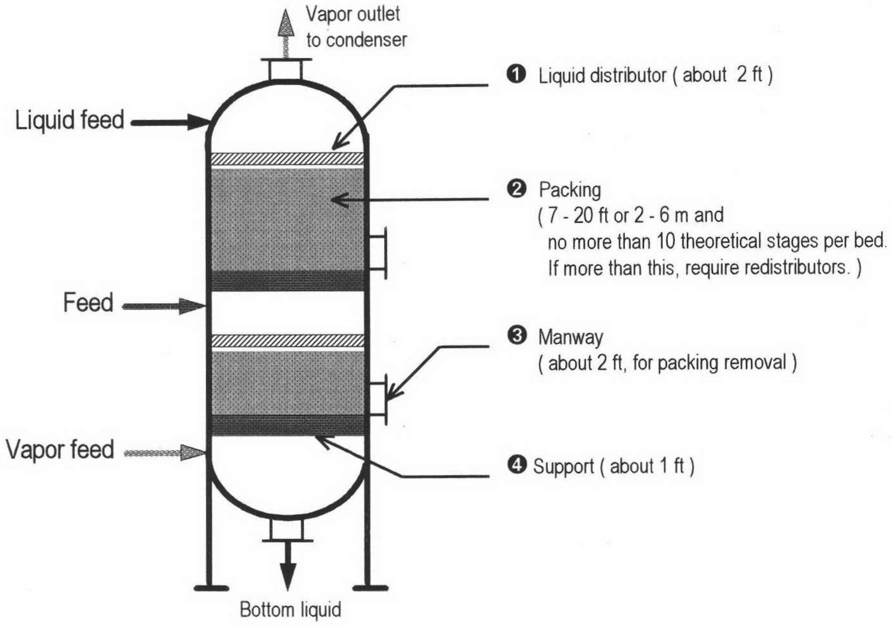

Figure 3.7 Typical packed column shell and internals[13].

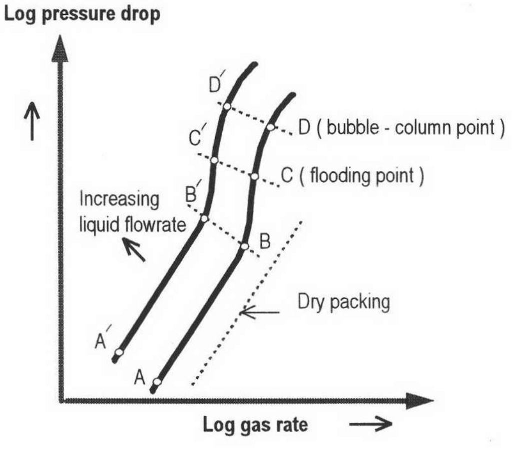

Figure 3.8 Typical pressure drop characteristics of packed towers[12].

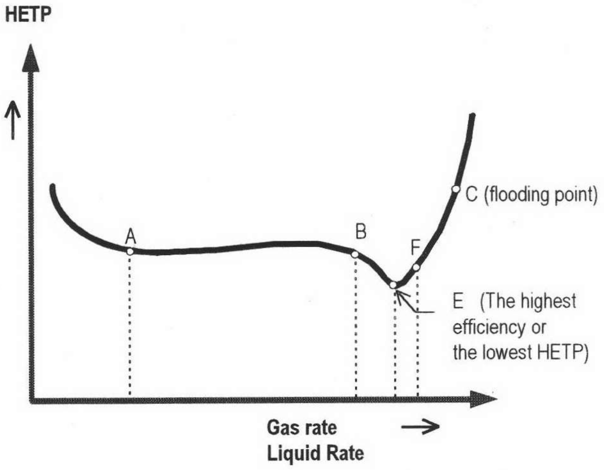

Figure 3.9 Typical efficiency characteristics of packed towers[12].

Being the same as tray column, packing capacity limits are flooding and weeping. In Figure 3.8 and 3.9, two characteristics of packed towers -- pressure drop and HETP (height equivalent of a theoretical plate) -- are plotted against vapor or liquid rates. Weeping occurs at very low liquid rates (less than point A in Fig. 3.8 and Fig. 3.9). At low liquid rates (point A to B in Fig. 3.8), the open cross-sectional area of the packing is about the same as in a dry bed. When the liquid rates are raised above point B (Fig. 3.8), the packing voids will fill up with frothy liquid, and pressure drop will rise quickly. At point C (Fig. 3.8), all of the packing void are filled with frothy liquid; the column is flooded. Pressure drop increases very quickly with a little increasing liquid rates, and then the packing column is inverted to a bubble column at point D (Fig. 3.8). Packed towers are usually designed or operated for region A-B (Fig. 3.8 and Fig. 3.9). Although region B-C (at point E-F in Fig.3.9) gives the highest efficiency, it is usually avoided because of the proximity of the flood point. To design packed towers in satisfactory operation for replacing bottleneck trays, the following constraints must be satisfied [12,13,15]:

1. The packing flooding ranges from 70 to 80%.
2. Pressure drop per foot of packing must be lower than 2 in of water to prevent the flooding.
3. Liquid rate must be more than 3 gal/ft^2 for operating without weeping effect.
4. The ratio of tower to packing diameter (D_T/D_P) should range from 10 to 75 (preferably, 10 to 40) to avoid maldistridution which leads to reduce a packing efficiency.
5. The height of individual packed beds is limited in 2 - 9 m (commonly, 2 - 6 m and no more than 10 theoretical stages per bed) by the mechanical strength of the packing or by the need to redistribute the liquid so that good mass transfer efficiency can be maintained.