

Design concept of crude oil distillation column design.

Distillation Column Design

The design of a distillation can be divided in the following steps.

- Specify the degree of separation:- Set product specification.
- Select the operating conditions:- Operating pressure.
- Determine the stage and reflux requirement:- The number of equilibrium stages.
- Select type of contacting device:- Plates or packing.
- Size the column:- Diameter, number of real stages.
- Design the column internals:- Plates, Distributors, Packing Supports etc.
- Mechanical design:- Vessel and Internal fittings.

Arrangement of Towers

Three types of arrangements (How heat is removed)

1. Top Tray Reflux : Reflux is only at top tray only

- Reflux is cooled and sent into the Tower.
- Heat input: Through Tower bottom.
- Removal: at the top.
- Thus requires large tower diameter.
- Improper reflux and poor quality of fraction. Economic utilization of heat is not possible.

2. Pump back reflux.

3. Pump around Reflux.

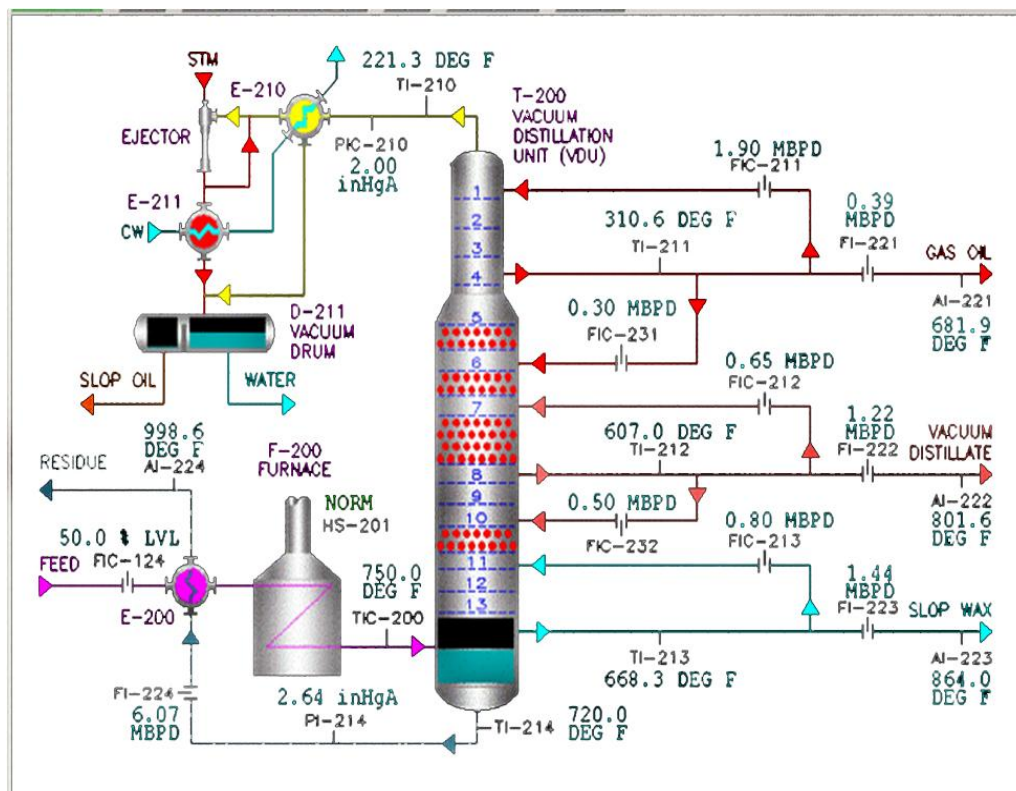


Fig:2.25 Vacuum Distillation Unit Overview [7]**Pump back Reflux:**

- Reflux is provided at regular intervals.
- This helps every plate to act as a true fractionator.(because there is always good amount of liquid).
- Tower is uniformly loaded, hence uniform and lesser diameter tower will do.
- Heat from external reflux can be utilised as it is at progressively higher temperatures.
- However design of such tower is costly, but provides excellent service.
- Most common in refineries.

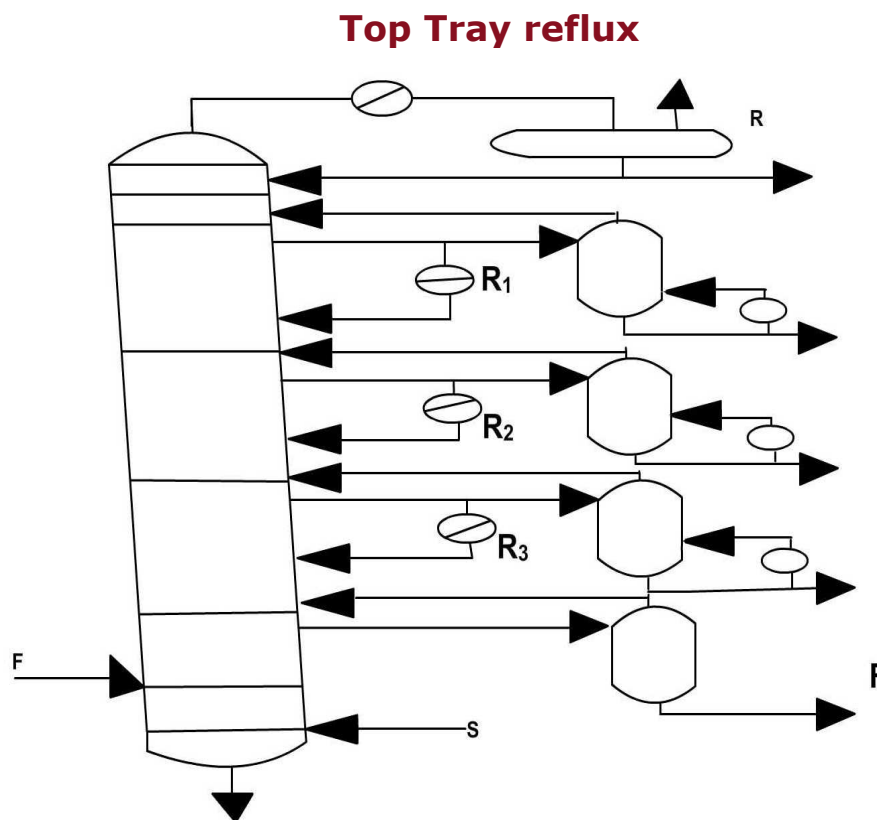


Fig:2.26 Top Tray reflux^[1,2]

Pump Around Reflux:

- In this arrangement reflux from a lower plate is taken, cooled and fed into the column at a higher section by 2 to 3 plates.
- This creates local problem of mixing uneven composition of reflux and liquids present on the tray.
- Designers treat all the plate in this zone as one single plate, the result gives large number of plates and high tower height.

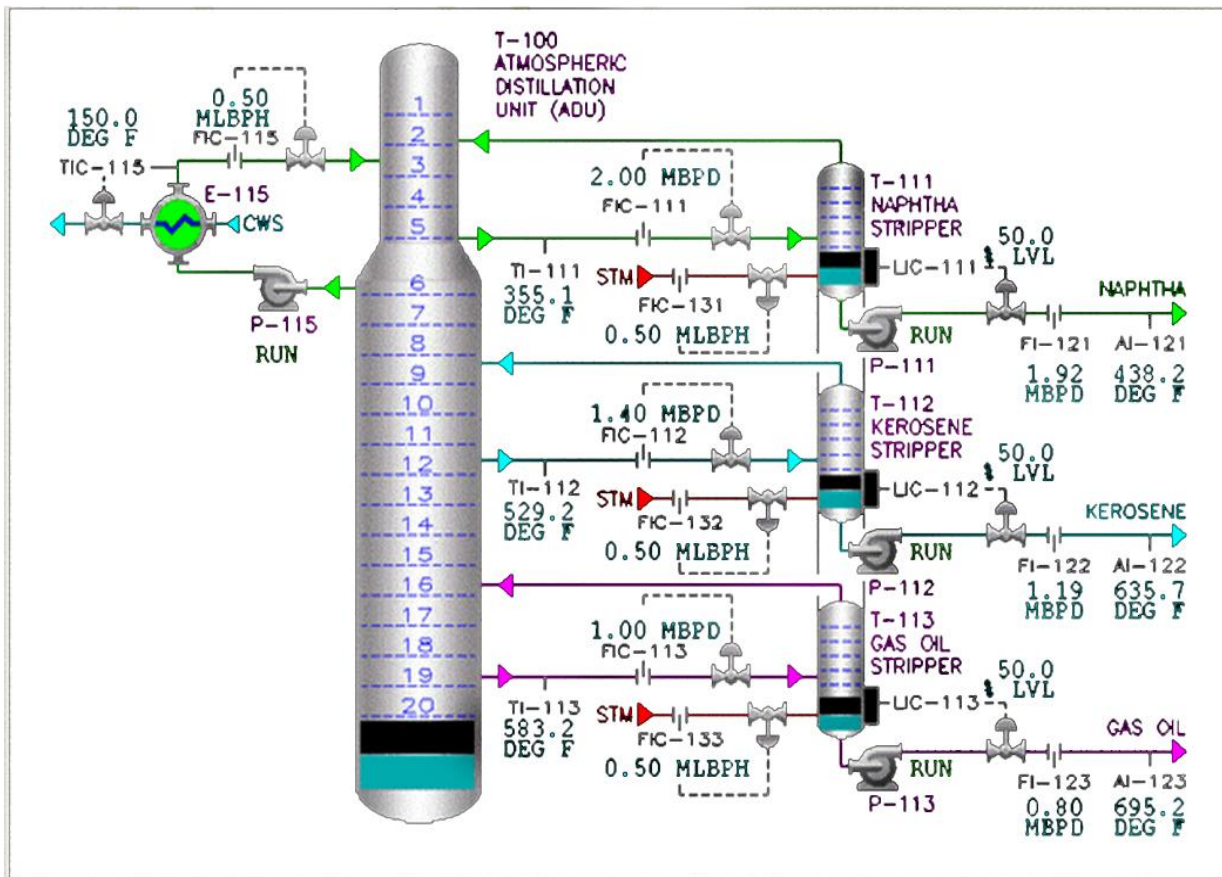


Fig:2.27 Atmospheric Distillation Unit Middle ^[8]

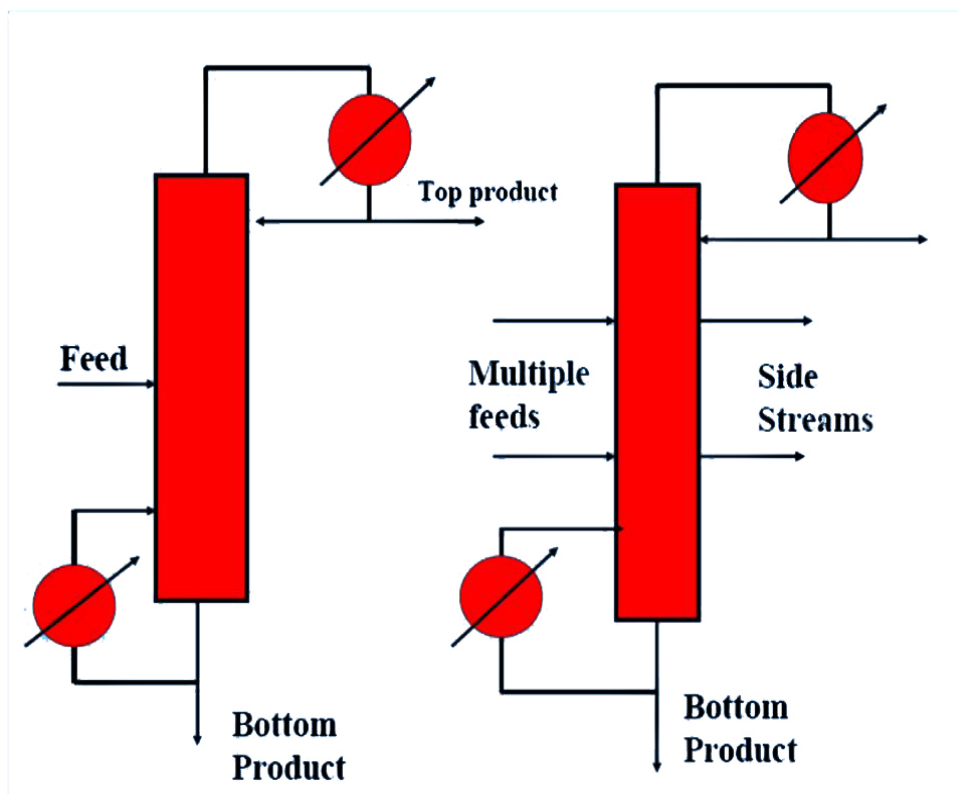


Fig:2.28 Typical Configuration of Single Feed and Multiple Feed into Distillation Unit [1,2,11]

Some Basis

- ▶ Section above feed point-Rectifying/Enrichment Section
- ▶ Section below Feed-Stripping Section
- ▶ Reflux ratio $R = \text{Flow returned as reflux} / \text{Flow of top product design}$
- ▶ Minimum reflux R_{\min} :-Reflux below which stage required is infinity.
- ▶ Optimum reflux ratio typically lies between 1.2 to 1.5 times the minimum reflux ratio.
- ▶ Relative Volatility $\alpha_{ij} = P_i / P_j = K_i / K_j$
- ▶ $y = aX / (1 + (a-1)x)$ for construction of y-x diagram.

Stage Equations

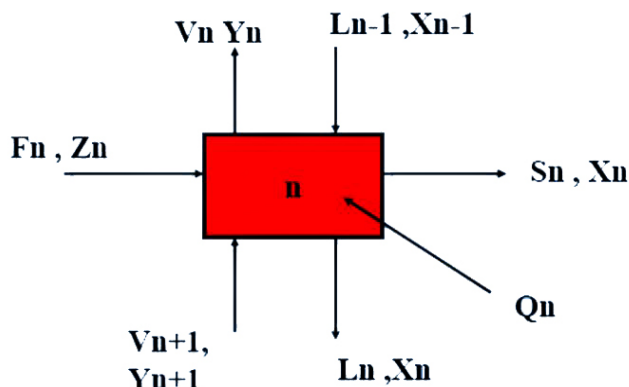


Fig:2.29 Stage Equations For Distillation Unit

Mesh Equations

Material Balance

$$V_{n+1}Y_{n+1} + L_{n-1}X_{n-1} + F_nZ_n = V_nY_n + L_nX_n + S_nX_n \dots \dots \dots \text{Equ 1}$$

Energy Balance

$$V_{n+1}H_{n+1} + V_{n-1}H_{n-1} + F_n h_f + q_n = V_n H_n + L_n h_n + S_n h_n \dots \dots \dots \text{Equ 2}$$

Equilibrium Relation:

$$Y_j = K_j X_j \dots \dots \dots \text{Equ 3}$$

Summation Equation: For Liquid & Vapor composition

$$\sum_{i=1}^n X_i = \sum_{i=1}^n Y_i = 1 \dots \dots \dots \text{Equ 4}$$

These Four equations are the called MESH EQUATION i:e Material Equilibrium, Summation and Heat (Energy)Balance Equation. MESH Equation can be written for each stage and for reboiler and condenser. The Solution of the set of equations forms the basis of rigorous methods.

$$\text{At Bubble Point } \sum_{i=1}^n y_i = \sum_{i=1}^n K_i X_i = 1.0$$

$$\text{At Dew Point } \sum_{i=1}^n X_i = \sum_{i=1}^n \frac{y_i}{K_i} = 1.0$$

Basic Processes

- Separation by Boiling point difference.
- Crude Assay provides estimates of various products obtainable from a particular crude.

Table:2.9^[1,2]

Typical Products	TBP CUT RANGE
Unstabilized Naphtha	IBP-120°C
Heavy Naphtha	120°C-140°C
Kerosene	140°C-270°C
Light Gas Oil	270°C-330°C
Heavy Gas Oil	330°C-370°C
Reduced Crude Oil	370°C +

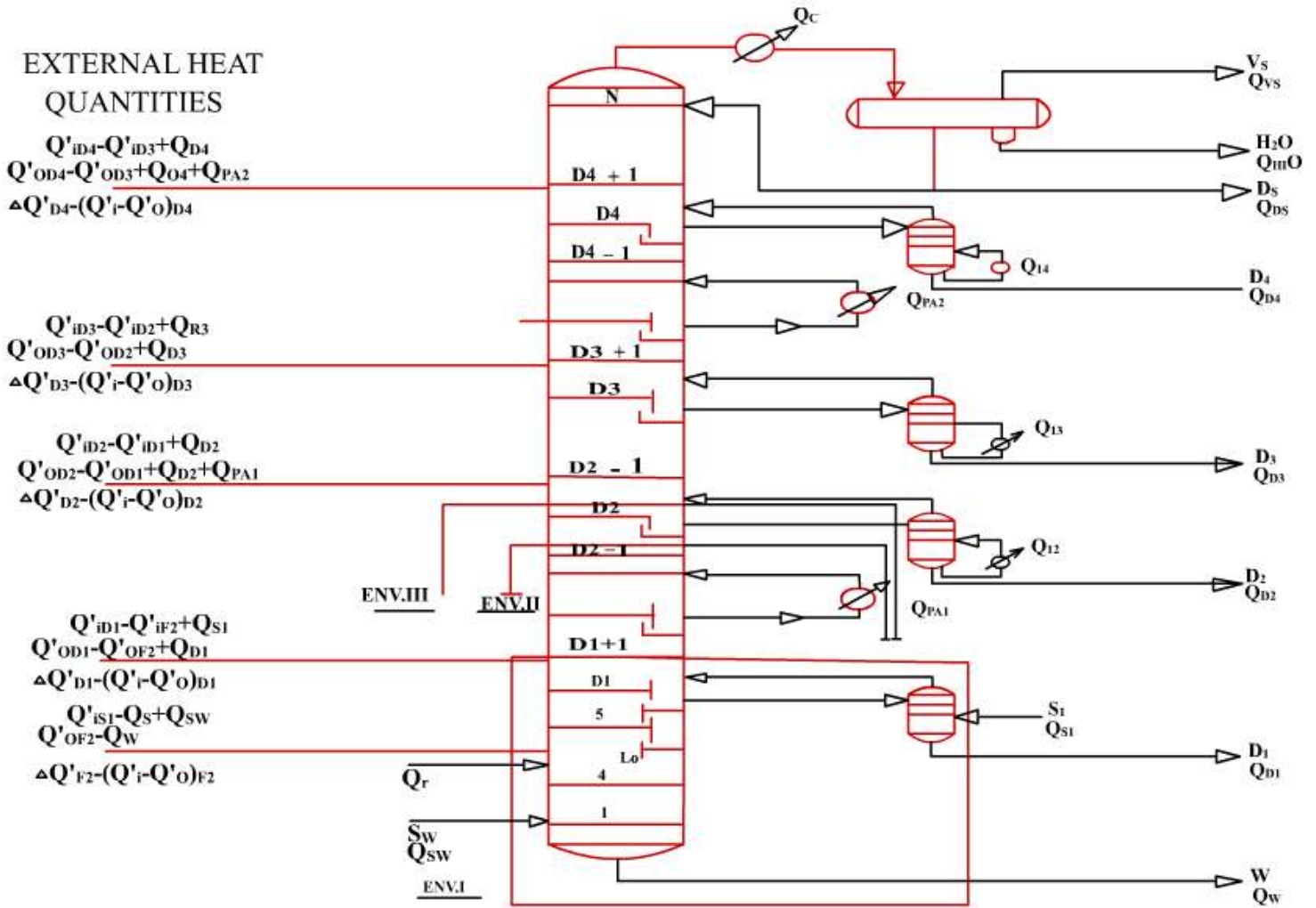


Fig:2.30^[1,2]

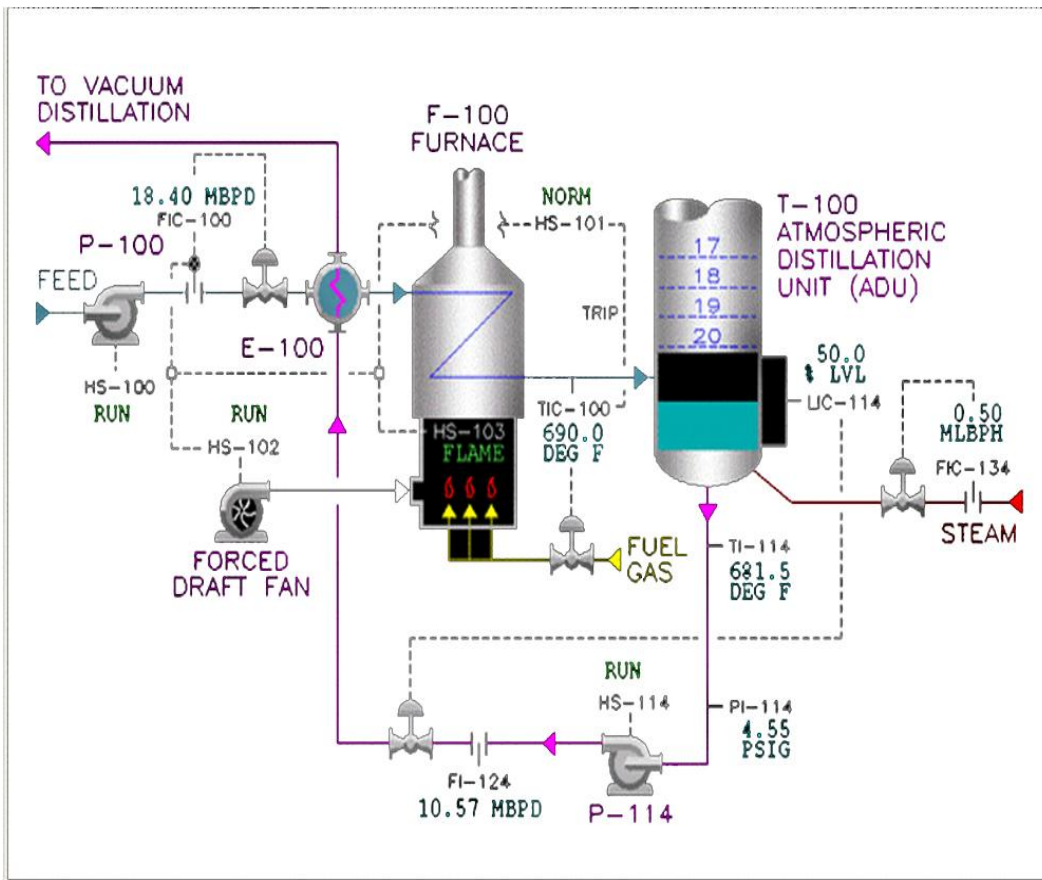


Fig:2.31 Atmospheric Distillation Unit Bottom [9]

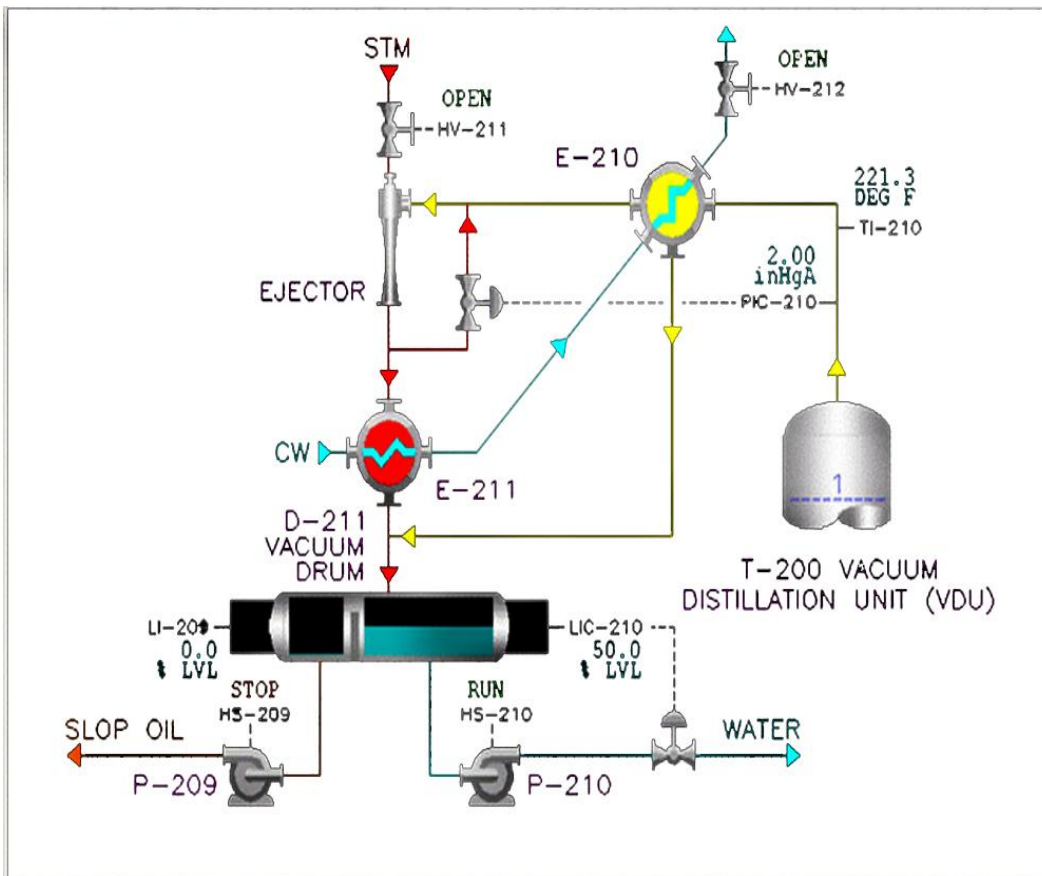


Fig:2.32 Vacuum Distillation Unit Overhead ^[10]

Process Design Basics

Heat and material balance calculations

- Compute hydrocarbon material balance for feed and products.
- Steam rates to stripping sections and steam distributions between overhead distillates vapors and liquids.
- Hydrocarbon material balances around product strippers.
- Atmospheric EFV Temperatures for products corresponding to the estimated strip out for each product.
- Draw Tray locations, Number of trays in each sections and total number of trays in the Tower.
- Heat input to the base section of the tower from feed and bottoms stripping steam, heat outflow in the bottoms liquid and external heat quantities at the flash zone.

Product Yield Determination

- ▶ Desired ASTM distillation of product(s) of interest is decided and ASTM is converted to TBP. Product TBP is applied to the whole crude TBP curve to estimate volumetric yields TBP cut volume is estimate.
- ▶ ASTM(5-95) GAP/OVERLAP between adjacent cuts determined.

Separation Criteria

- **DEGREE OF SEPARATION:** Difference between ASTM- 5% of heavier distillate and ASTM -95% point of lighter distillate.
- **DEGREE OF DIFFICULTY OF SEPARATION:** Difference between ASTM 50% point of the distillate fraction in questions.

Separation Criteria

Degree of Separation

- Defined in terms of product purities or component recoveries.
- Greater the degree of separation, greater will be recovery of the light component in the distillate and the heavy component in bottoms.
- **Degree of difficulty of separation :** Defined as the relative difficulty encountered in separating the two compounds, regardless the purity requirements set by process specifications ~ inversely proportional to the relative volatility between the two components.

ASTM Gap and Overlap

- Fractionation is the difference between 5% ASTM curve of Heavy cut and the 95 % point on the ASTM curve of a lighter cut of two adjacent side product.
- Positive difference is called Gap.
- Negative difference is called overlap.
- ASTM Boiling range gives general composition of fractions.
- **5- 95 GAP:** Defines the relative degree of separation between adjacent fractions.
- Determined by subtracting 95 vol.% ASTM Temperature of a fraction from the 5 Vol. % ASTM temperature of the adjacent heavy fraction.

- ▶ $(5-95) \text{ Gap} = (t_{5H} - T_{95L})_{\text{ASTM}}$
- ▶ 5H=5% OF THE HEAVIER FRACTION
- ▶ 95L= 95% OF THE LIGHTER FRACTION
- ▶ $\text{TBP CUT POINT} = (T_{OH} + T_{100L})/2$
- ▶ $\text{TBP Over lap} = [T_{100L} - T_{OH}]$

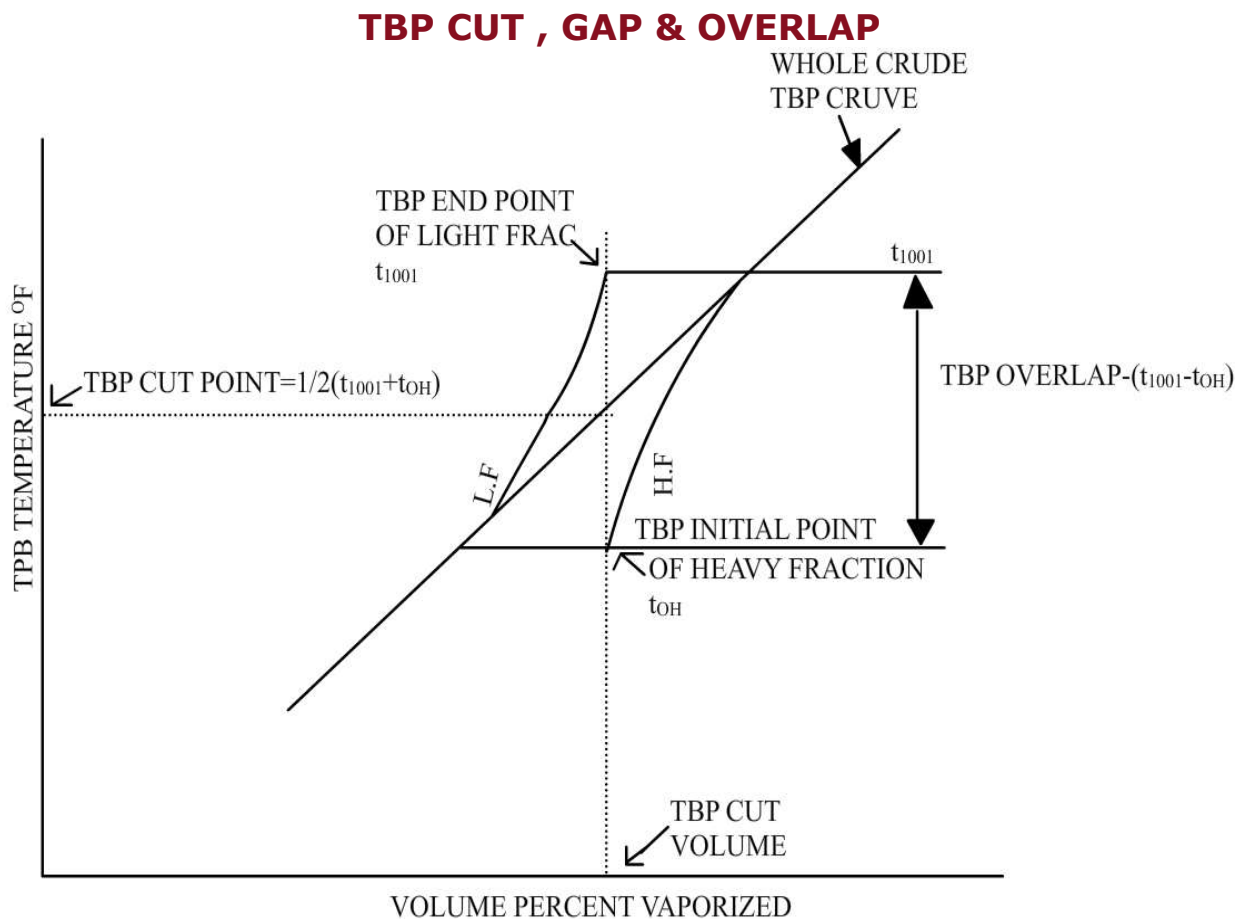


Fig:2.33 TBP Cut , Gap & Overlap^[1,2]

General observation for separation

For a given system

- No. of trays required increases markedly as purity requirement increases, but reflux requirements increases only a small amount.
- Tray and reflux requirements increases as relative volatility decreases i.e separation becomes more difficult.

Separation Criteria

- ▶ For a fixed number of trays, reflux requirement is directly proportional to the degree of difficulty of separation.

Qualitatively

- ▶ At reflux condition exceeding minimum requirements =>Tray requirements are directly proportional to the required degree of separation.
- ▶ The degree of difficulty of separation inherent in the physical chemical system under consideration.

Crude Column Design

INPUT REQUIRED

- ▶ Crude TBP (essential)
- ▶ Density/API gravity (essential)
- ▶ Molecular Weight(optional)
- ▶ Viscosity(optional)

SPECIFICATION REQUIRED

- ▶ Column Pressure
- ▶ Product specification can be given in terms of fix draw or distillation point.
- ▶ Pump around duties need to be specified.
- ▶ Column top temperature can be specified.

Process design

- ▶ Prepare TBP Distillation and equilibrium Flash Vaporisation curves of crude to be processed.
- ▶ Using crude assay data construct TBP curves for all products except gas and reduced crude. Convert these to ASTM & EFV.
- ▶ Convert TBP data to EFV curves.
- ▶ Prepare material balance of crude distillation column, on both volume and weight basis.

Fractionation requirements: ASTM gap and overlap

Knowing gaps as the design parameters correlate deviation or gap with F factor(product of number of plates between two adjacent side draws off stream and internal reflux ratio.

Packie's Method

- **Degree of difficulty of separation** : The difference between 50 vol.% temperatures of the fractions under study.
- Convert 50% TBP temp to ASTM.
- **Separation Capability (F)**:defined as the product of the reflux to feed ratio at the upper draw tray as calculated on the volumetric basis and the number of actual trays in that section.(F, Factor related to gap and overlap).
- **Packie method**: Based on Gap and overlap.

- Number of plates in particular section depends on gap and reflux ratio.
- $F = \text{Reflux ratio} \times \text{Number of plates in that section.}$

$$F = (L_N/D_N)N_T, (N_T: \text{No of trays of distillation column})$$

$L/D = \text{Reflux ratio}$

TBP VS ASTM 50% B.P

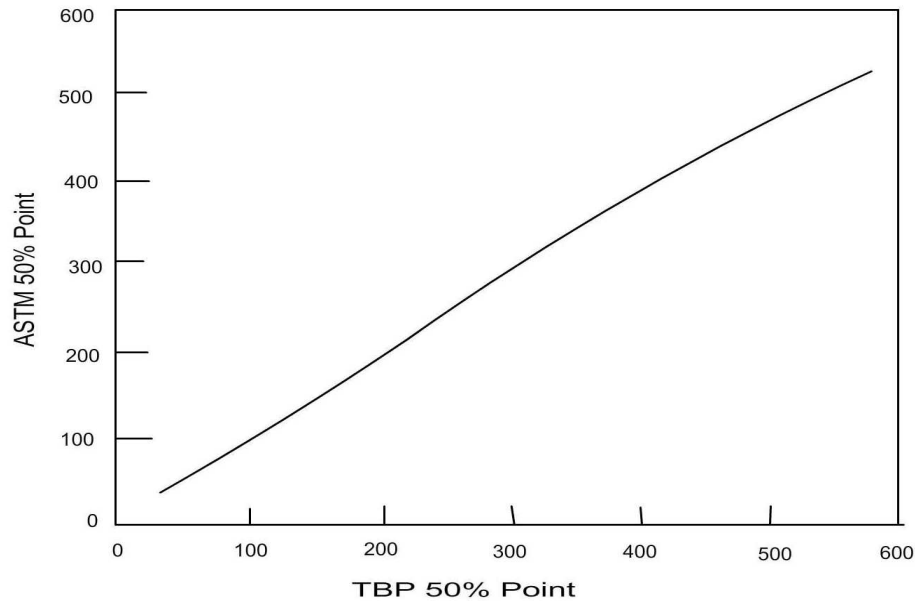


Fig:2.34 TBP VS ASTM 50% B.P^[1,2]

Relation Between TBP and ASTM 50% Boiling Point

IBP AND FBP OF ASTM & TBP

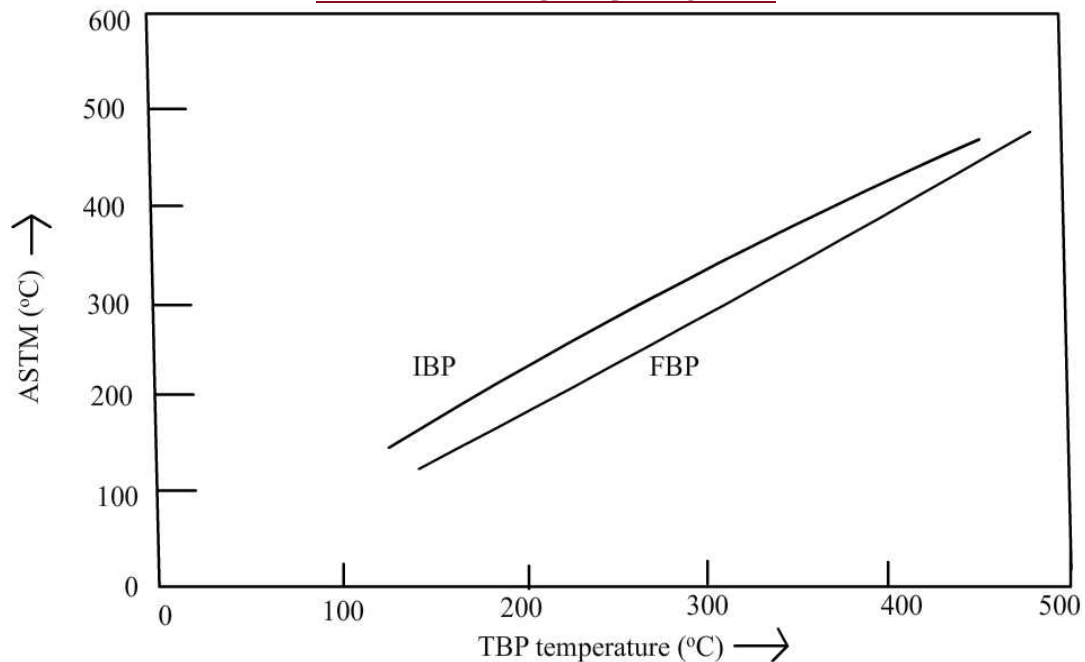


Fig:2.35 IBP AND FBP OF ASTM & TBP^[1,2]

Relation Between IBP and FBP of ASTM and TBP

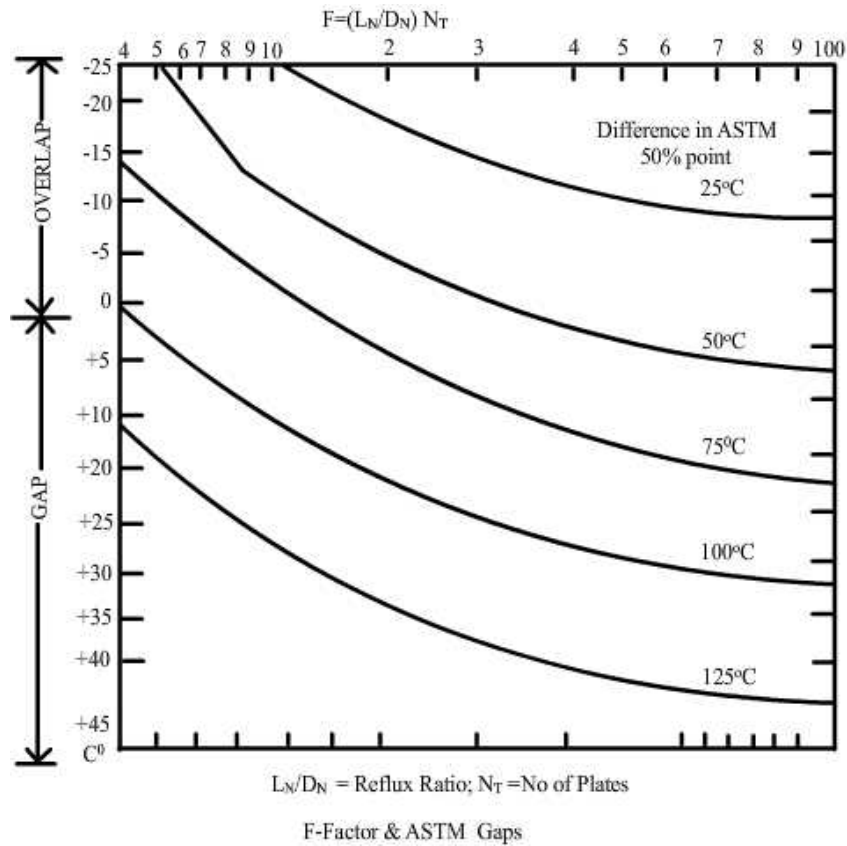


Fig.2.36 Relation Between IBP and FBP of ASTM and TBP^[1,2]

EXAMPLE

In a refinery side stream operation the fraction to be collected is diesel. The diesel entering the side stripper is 4000 bbl/h, the 50 percent point of the cut is 275 °C and contained with Kerosine whose mid boiling point is 145 °C. If the stripper is having 4 plates find the actual amount of diesel coming out of the stripper if the ASTM GAP is 20 °C.

SOLUTION

Calculate F Factor from Packie method for side stream stripper.

$$\text{ASTM } \Delta T_{50\%} = 275 - 145 = 130^\circ\text{C} \quad (254^\circ\text{F})$$

$$\text{ASTM GAP} = 20^\circ\text{C} = 36^\circ\text{F}$$

$$F = (L/D)N_T \Rightarrow L/D = 5/4 = 1.25$$

$$V = L + D = 4000$$

Hence D (Actual amount of diesel) = 1778 bbl.

Calculation of minimum number of stage

Fenske equation is used for N_m

$$N_m = \log [X_{LK} / X_{HK}]_d [X_{HK} / X_{LK}]_b / \log \alpha_{LK - HK}$$

$$\begin{aligned} \alpha_{avg}^{LK - HK} &= (\alpha_{top} \times \alpha_{bottom})^{1/2} \\ &= (\alpha_{top} \times \alpha_{bottom})^{1/3} \end{aligned}$$

Calculation of minimum reflux ratio

Using Underwood Equation:

$$\sum \alpha_i X_i d / \alpha_i - \theta = Rm + 1 \dots \dots \dots Eqn1$$

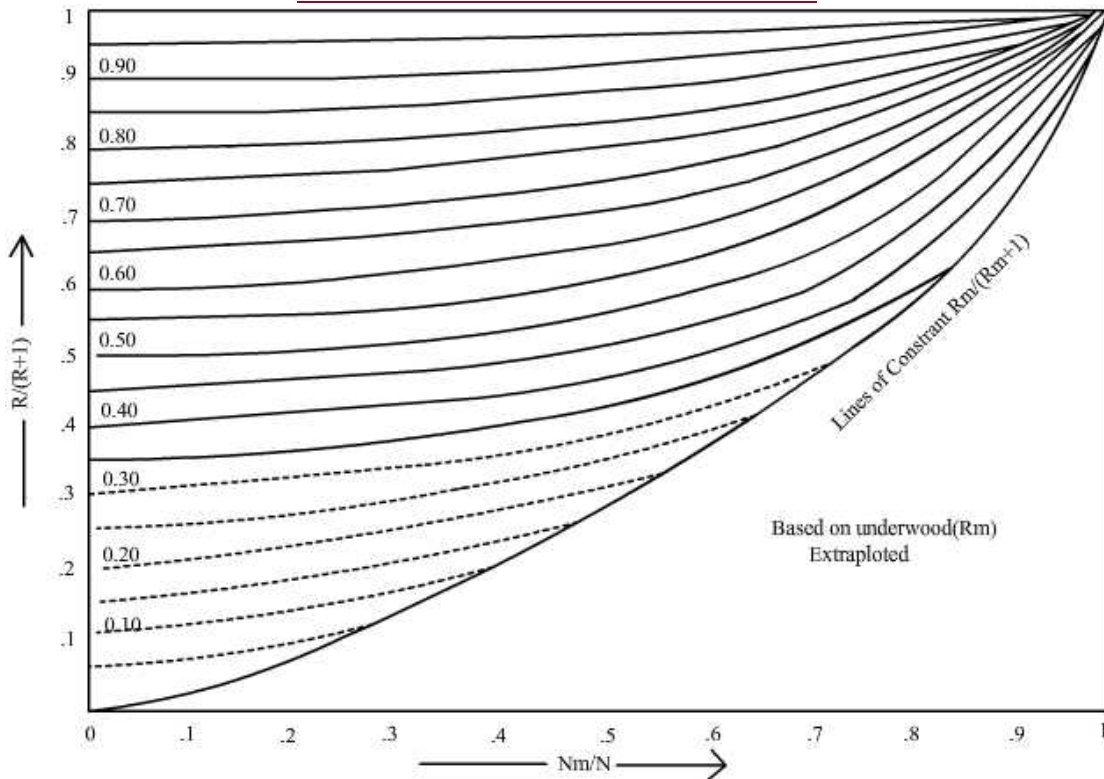
$$\sum \alpha_i X_i f / \alpha_i - \theta = 1 - q \dots \dots \dots Eqn2$$

q = heat to vaporize 1 mole of feed / molar latent heat of vaporization.

θ = Root of underwood equation.

Calculate Rm using Erbar- Maddox(or Gilliland)correlation calculate R actual.

CALCULATION OF REFLUX RATIO



Erbar -Maddox Corellation Erbar -Maddox,1961

Fig:2.37 CALCULATION OF REFLUX RATIO^[1,2]

Kirkbride equation is used for feed tray location.

$$\log[N_r/N_s] = 0.206 \log[(B/D)(X_{f,LK}/X_{d,HK})^2] \dots \dots \dots \text{Kirkbride Equation}$$

Where

N_r = Number of stages above the feed, including any partial condenser.

N_s = Number of stages below the feed, including the reboiler.

B = Molar flow bottom product.

D = Molar flow top product.

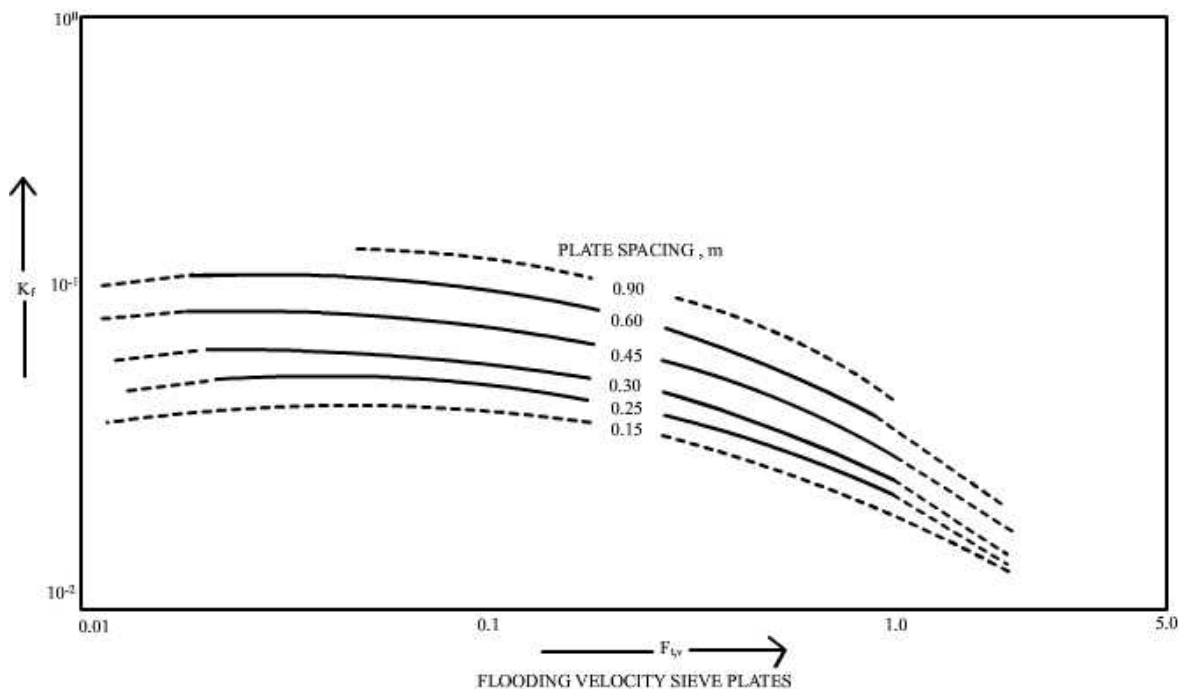
$X_{f,HK}$ = concentration of the heavy key in the feed.

$X_{f,LK}$ = concentration of the light key in the feed.

$X_{d,LK}$ = concentration of the heavy key in the top product.

$X_{b,LK}$ = concentration of the light key in the bottom product.

In simulation method, it is known as short cut method

**Fig:2.38^[1,2]**

Optimization Criteria in Design

- ▶ Maximization of distillates.
- ▶ Maximization of desired product(s).
- ▶ Quality of reduced crude.
- ▶ Overflash control to optimize energy.
- ▶ Optimization of pumparound in yield.

Optimization of particular product(s).

Flash Zone operating conditions-FZ temperature is limited by advent of cracking.

- ▶ FZ pressure is set by fixing the reflux drum pressure and adding to it to the line and tower pressure drop.
- ▶ Over flash:Over flash is the vaporisation of crude over and above the crude overhead and side stream products.
- ▶ Over flash is generally kept in the range of 3-6 liquid volume %. Kept at minimum value as a larger over flash consumes larger utilities.

Over flash prevents coking of wash section plates and carryover of coke to the bottom side streams by and the tower bottom by providing reflux to the plates between the lowest sidestream and the flash zone.

Flash Zone Temperature

- Crude TBP provides estimate of total distillate.
- EFV curve of the crude is derived from the TBP and converted to the flash zone pressure.
- Overflash quantity is selected included this material balance and heat balance around the bottom section including feed section is done to fix the flash zone temperature.
- Flash zone temperature thus fixed ensures desired total distillate yield.

Product Yield Determination^[1,2,6]

- ▶ From ASTM curve:1 ATM EFV curve are developed and extrapolated to(-) 50% VOL% vaporized as an initial estimate.
- ▶ Stripping steam to the stripper is set at about 10LB/BBL of stripped product bubble point of unstripped side stream is estimated.

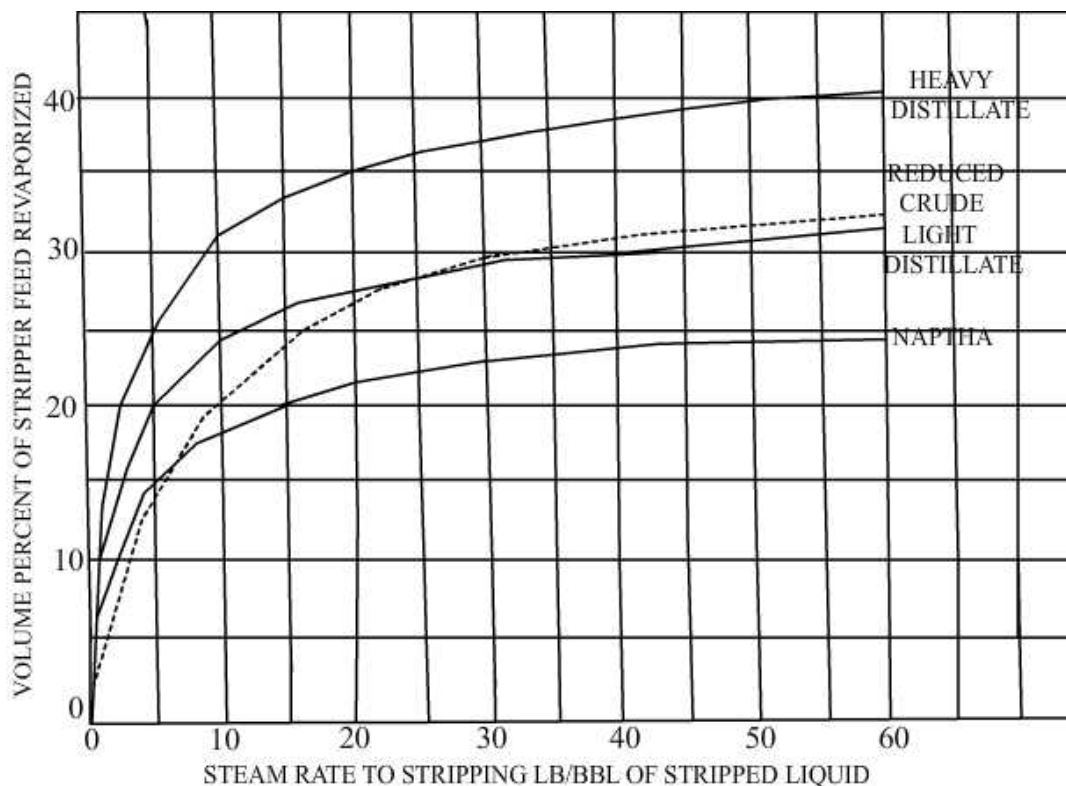


Fig:2.39

EFV TEMP VS DRAW TRAY TEMP

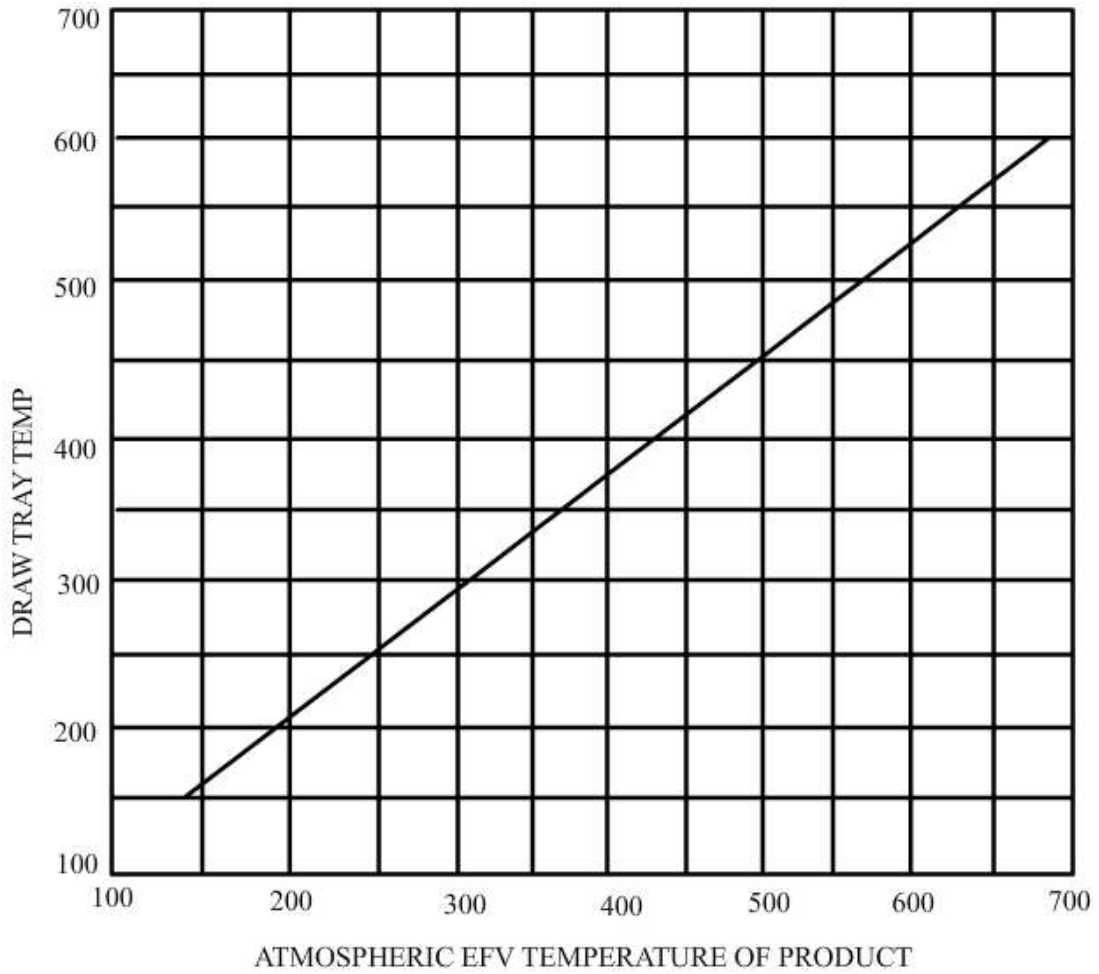


Fig:2.40 EFV TEMP VS DRAW TRAY TEMP^[1,2]

FLASH ZONE

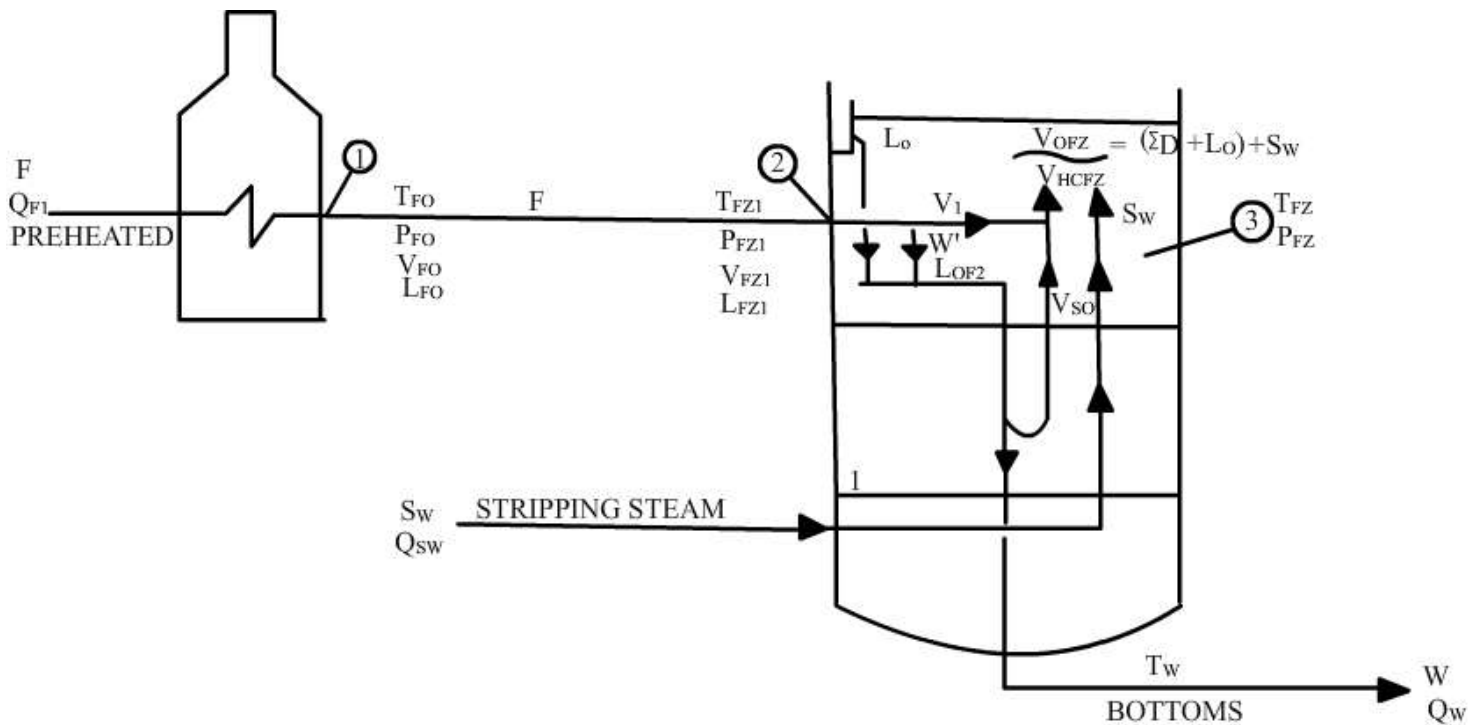


Fig:2.41 FLASH ZONE^[1,2]

- D = Sum of all streams.
- V = % OF VAPORISATION in Flash zone.
- L_o = Overflash.
- S_f = Total amount of hydrocarbons stripped out by steam.
- Thus $V = D + L_o - S_f$
- From the flash curve (EFV) of the crude, the temperature at which this vaporisation is achieved at the FZ Pressure is determined.
- This T should not exceed the maximum permissible temperature. If does quantities of Overflash and stripping steam are changed until a permissible temp is obtained.
- Stripped out HC Fraction (S_f) depends on amount of stripping steam.
- $W = L_{ofz} - V_{so}$, (W = Vol. % Feed leaving the bottom).
- $L_{ofz} = L_o$ (Overflash) + W
- $V = L_o + 100 - W / (1 - S_f)$ vol.% of of feed flashed at FZ inlet.
- $S_f =$ fraction of strip out vapor ($L_{ofz}(1 - S_f) = W$).

EXAMPLE: It is planned to yield as a side stripper from an atmospheric crude tower, 100 bbl per hour of a light distillate product having a TBP cut point range of 400-525 °F (volume range 27-39%, API 39.8). The estimated draw tray temperature is 425°F. The liquid is to be stripped in a 4 tray column using 500°F Steam. The stripping rate is 10 lb/bbl of stripped product. Calculate the temperature of stripped product stripping the bottom of the stripper.

Solution: 100 bbl of LD to be produced, TBP Cut 27-39 % = 12 vol.%, Mid vol % 33

- Strip out vapor = $S_f = 23.8$ vol.%.
- Feed (F) = $w / (1 - s_f)$.
- = $100 / (1 - 23.8)$.
- = 131.2 bbl/h/ 100 BBL OF LD.
- Therefore Feed $F = 12 \times 1.312 = 15.74$ % OF CRUDE.

Heat into FZ, $Q_{FZ1} = V'H + W'H$.

Selection of Column Pressure

Pressure to be adequate that dew point (for the composition of top product) is more than cooling hot water temperature around $45^{\circ}\text{C} + \Delta T(15^{\circ}\text{C})=60^{\circ}\text{C}$ with cooling water inlet temperature of 33°C with condensate temperature of $40^{\circ} - 45^{\circ}$ can be obtained with consideration of $10^{\circ} - 15^{\circ} \Delta T$. The column pressure to be adequate that bubbles point of the top product is $40^{\circ} - 45^{\circ}$.

i.e

$$\sum_{i=1}^n K_i X_i = 1$$

at column pressure and drum temp of 45°
or

$$P_t = \sum_{i=1}^n P_i$$

$\sum P_i$ calculated at 45°C for all the components.

$$\sum P_i = \sum X_i P_i \text{ or } \sum Y_i P_t = \sum X_i P_i$$

For crude Distillation Column

The top product is a mixture of light end and top naphtha ($\text{C}_5\text{-}140^{\circ}$). The naphtha TBP is subdivided 10°C or 20°C cuts eg. $70^{\circ}\text{-}80^{\circ}$, $80^{\circ}\text{-}90^{\circ}$, $90^{\circ}\text{-}100^{\circ}$ etc and midpoint are tabulated.

K values estimated from de-priester chart.

Table:2.10

Comp./cut range(TBP)	B.P.T	K_i $45^{\circ}\text{C}, 1.6$ $\text{Kg}/\text{cm}^2\text{g}$	X_i	K_i	X_i
C_1	B_1	K_1	X_1	K_1	X_1
C_2	B_2	K_2	X_2	K_2	X_2
C_3	B_3	-	-	-	-
C_4	B_4	-	-	-	-
C_5	B_5	-	-	-	-
$70^{\circ}\text{-}90^{\circ}$	80°	-	-	-	-
$90^{\circ}\text{-}110^{\circ}$	100°	-	-	-	-
$110^{\circ}\text{-}130^{\circ}$	115°	-	-	-	-
$130^{\circ}\text{-}150^{\circ}$	140°	K_n	X_n	K_n	X_n
$\sum_{i=1}^n K_i X_i$					

If $\sum K_i X_i = 1$ then the pressure is OK.

If not 1 then repeat trial with another value of pressure till $\sum K_i X_i$ is 1.

Same method is applied for discrete component and mixture of pure component and fixes the reflux drum pressure.

Top Temperature Estimation

Top temperature is dew point of top vapor at column top pressure. Once reflux drum pressure is fixed P_D (say) the column top pressure is estimated after adding the pressure drop across condenser/OH line. Typically $0.3 \text{ kg/cm}^2 - 0.5 \text{ kg/cm}^2$ is taken as pressure drop.

Column top pressure = $P_D + 0.5$

Again calculation is performed at top pressure for determining the dew point. Assume a top temperature and calculate.

$\sum y_i / K_i$ till it becomes 1.

Calculation of Vapor/Liquid Profile

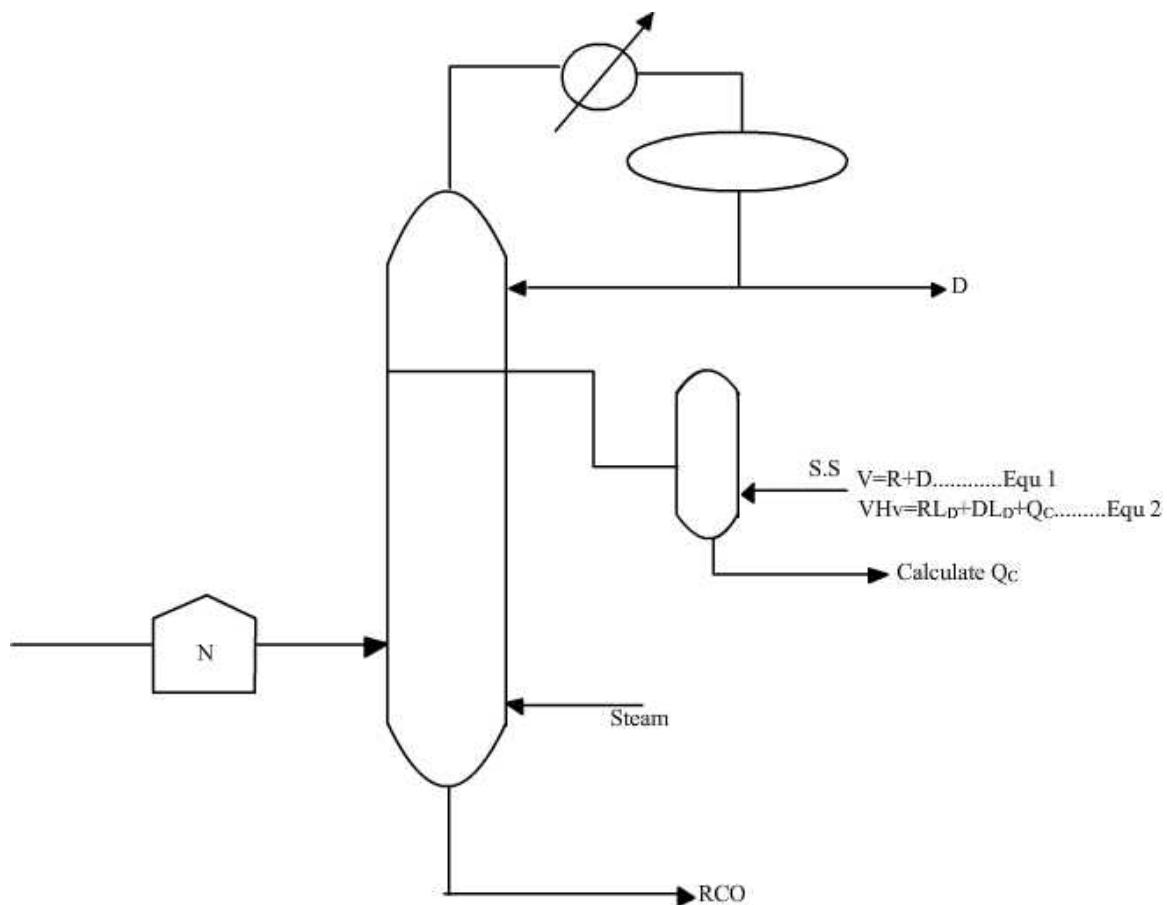


Fig:2.42 Calculation of Vapor/Liquid Profile^[1,2,11]

This is done by performing material balance & heat balance in envelopes.

Atmospheric distillation unit

- ▶ Tower Dia :5- 8 m.
- ▶ No.of Plates : 25-40(depends on No. of draws).
- ▶ Maxm.Allowable pressure drop per plate :0.015 kg/cm²).
- ▶ Pressure drop from furnace outlet to Flash zone : 0.3 – 0.4 kg/cm².
- ▶ Pressure at top of the tower : 1.2 -1.4 kg/cm²
- ▶ No.of plates required for separation.

- ▶ LN – HN (80-130 C): 6-8
- ▶ HN- LD (180C): 5-6
- ▶ LD- MD (250C): 4-6
- ▶ MD- GAS OIL(330 C): 3-4
- ▶ Flash zone to First draw tray: 3
- ▶ FZ TO BOTTOM : 3
- ▶ Reflux drum pressure: 1.1-1.15 kg/cm² abs.
- ▶ Steam rate /bbl of crude: 4-5 kgs
- ▶ Reflux ratios : 2-3 (for light fractions)for Heavy fractions 1.5- 2.5.

Contacting Device

- Cross Flow
- Counter flow

Cross Flow

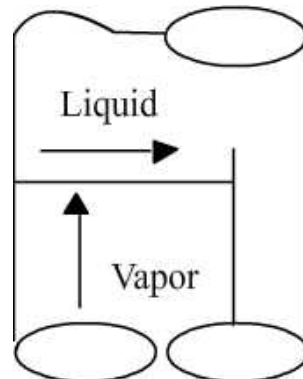


Fig:2.43 Cross Flow

Counter Flow :Packing,Heat transfer trays.

H dry -->dry tray pressure drop,inches.

$$H_{\text{dry}} = C_1 + C_2 V^2 / 2gC$$

$$\Delta P_{\text{dry}} = K_2 (V_H)^2 D_V / D_L - \text{unit full open.}$$

Tray Pressure Drop

$$H_T = H_{\text{dry}} + H_{\text{ow}} + H_w$$

$$\Delta P_T = \Delta P_{\text{dry}} + 0.4 (\text{gpm}/\text{lwi})^{2/3} + 0.4 H_w$$

Pumparound Duties

- ▶ Pumaround duties need to be maximized for energy efficiency point of view.
- ▶ This is limited by Gap/Overlap specification between adjacent products and minimum internal reflux specification.
- ▶ Pumaround duties are maximized and reflux ratio is brought close to 1.5 to 1.8.

Vacuum Column

(ΔT)Hy.Diesel PA :70^oC-90^oC

(ΔT)LVGO PA :50^oC

(ΔT)HVGO PA :55^oC

Stages in vacuum column:-

Top PA =1 stage.

Top Hy.Diesel-LVGO =2-3 stage.

LVGO PA =1 stage.

LVGO-HVGO =1 stage.

HVGO PA =2-3 stage.

Wash =2-3 stage.

Wash liquid at bottom of wash bed ~0.3M³/hr/M²column C.S area.

Thermodynamics - BK10/GSI.

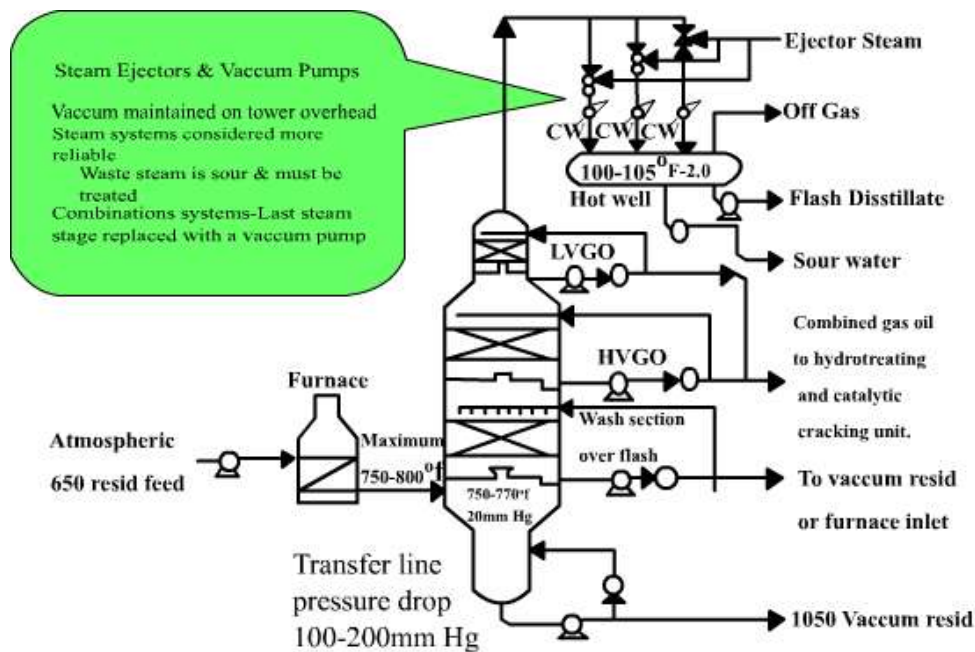
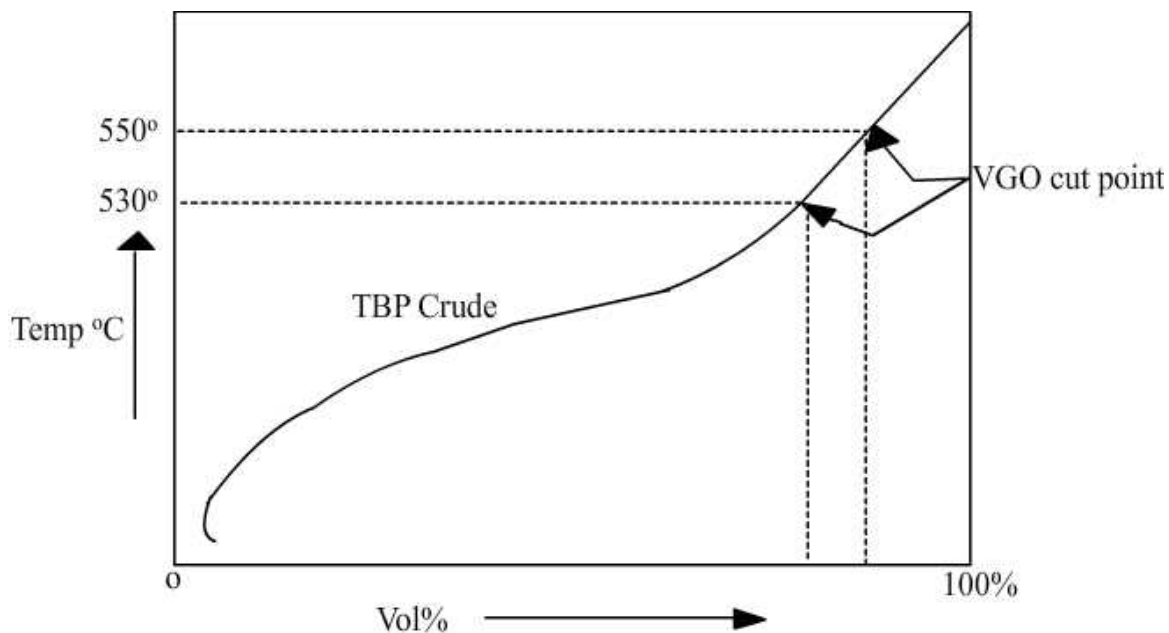
Transport Property - PETRO.

Density - API.

Vacuum Distillation Unit^[1,11]

- The primary objective of a vacuum distillation is to produce either feedstock for FCCU or HCU. This type of vacuum distillation units are termed as Fuel Type Vacuum Unit.
- The other kind of vacuum distillation unit is a Lube Type Vacuum Unit and deployed for production of fractions for Lube Oil Base stocks.
- In a Fuel Type Vacuum distillation Unit the VGO TBP cut point is controlled for Maximizing profitability while containing the level of contaminants acceptable by downstream secondary Units.

VACCUM DISTILLATION

Fig:2.44 VACUUM DISTILLATION^[1,2]**Vacuum Distillation unit:cont**Fig:2.45 Vacuum Distillation unit^[1,2]**Different Configuration of Vacuum Column**

1. Dry (no stripping, no coil steam).
2. Wet (Precondenser limiting column overhead pressure to cooling water temperature limitations).
3. Dump column without stripping (no precondenser, coil steam used to adjust flash zone oil partial pressure).
4. Dump column with stripping steam (no precondenser, coil and stripping steam used).

Different Configuration of Vacuum Column

- The first one operates typically at 8-12 mm Hg (a) at top. The vapour directly goes to ejectors.
- The second type operates at 60-70 mm Hg (a) at top and have a precondenser, the non-condensable are pulled by ejector.

- The third type of operation is done at 18-25 mm Hg (a) at top.
- Without stripping steam has a booster ejector followed by condenser.
- This fourth type again operates with a top pressure of 18-25 mm Hg (a) and uses stripping steam and Coil steam both. This type is considered best to increase cut point of VGO limiting the contaminants like V, Ni etc. in VGO with same number of stages in wash section as compared to other configurations.

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