Continuous Fractionation (Rectification):

Fractionation Process:

There are three methods used in distillation, each offering a varying degree of separation:

- Flash or equilibrium distillation
- Differential distillation
- Continuous Fractionation

Fractionation is the most important as it offers a greater degree of separation. It is the most widely used unit operation process in the chemical industry. It is a multistage counter-current operation, where the liquid flows counter current to vapor with the feed introduced at some intermediate point. Some of the vapor is condensed (mainly lvc) and some of the liquid is vaporized (mainly mvc). This partial condensation and vaporization continuously enriches the vapor phase with the mvc, with the net result of a better separation.

The operation takes place in a vertical cylindrical pressure vessel (called distillation column or tower, or a fractionator), divided into compartments by a series of perforated plates which permit the upward flow of vapor. The fractionator consists of two main sections:

- Top section above the feed point called absorption, enriching, or rectifying section
- Bottom section below the feed point called exhausting or stripping section.

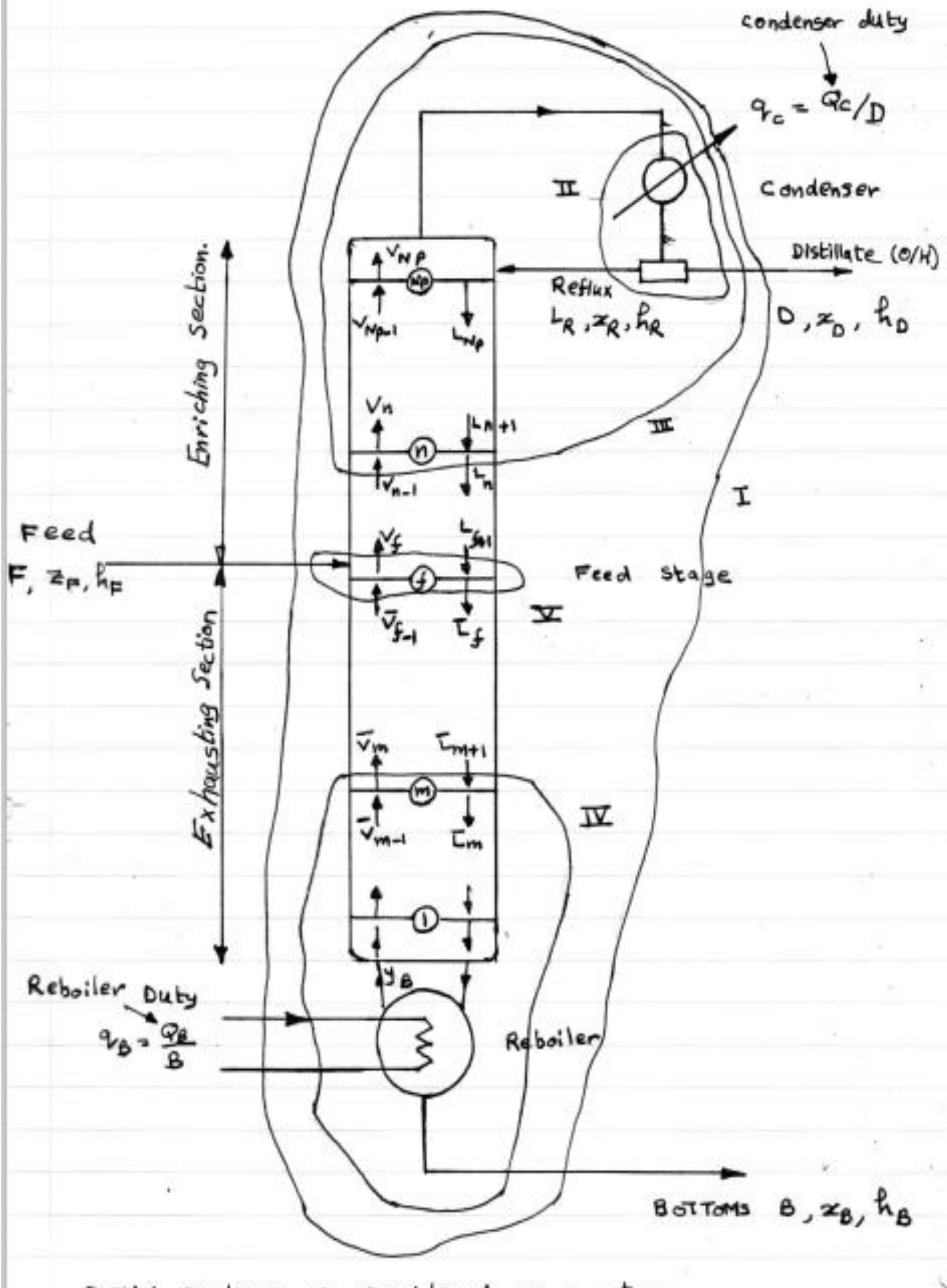
The feed is introduced continuously into the fractionator where it is eventually split into two products. One removed from the top of the column richer than the feed in the mvc (called distillate, top product, overheads product, or light product); the other product withdrawn from the bottom of the column weaker in the mvc (called bottom product, waste, residue or heavy product). The purities of the products depend on the liquid/gas ratio and the number of stages.

In some cases, multiple feeds and side streams are available. Some distillation columns consist of the top section only and they are called rectification columns.

Vapors rising from the top are totally (or partially) condensed in a condenser and some of the liquid is returned to the top of the column. This liquid is called reflux. The ratio of reflux to distillate is called reflux ratio or sometimes external ratio.

The liquid at the bottom is either heated by a coil placed at the base of the column or by an external reboiler; the more volatile material returns as vapor to the column.
Inside the tower liquids and vapors are always at their bubble points and dew points respectively. Their flow rates are not constant along the column.

Material and Energy Balances



Partial Condenser : Considered as a stage

Partial Reboiler : Considered as a stage

Overall Balances:

Material Balances:

Envelope I: $F = D + B$ 1

Envelope II: $V_{NP} = L_R + D$ 2a

let $R = \frac{L_R}{D}$ = reflux ratio

$V_{NP} = RD + D$

$V_{NP} = D(R+1)$ 2b

Envelope III: Down to stage n

$V_{n-1} = L_n + D$ 3a

$V_{n-1} - L_n = D$ [Net flow of vap up : Constant] 3b

Envelope IV: up to stage m

$\bar{L}_{m+1} = \bar{V}_m + B$ 4a

$\bar{L}_{m+1} - \bar{V}_m = B$ [Net flow of liquid down: Constant] 4b

Envelope V : Feed stage

$F + L_{f+1} + \bar{V}_{f-1} = V_f + \bar{L}_f$

Component Balances: (For any component)

Envelope I $z_F . F = x_D.D + x_B B$

$$x_D = \frac{z_F.F - x_B.B}{F-B}$$

$$x_B = \frac{z_F.F - x_D.D}{F-D}$$

Enriching Section: Envelope III

$$y_{n-1}.V_{n-1} = x_n.L_n + D.x_D$$

[Dx_D : net flow]

$$\boxed{y_{n-1} = \frac{L_n}{V_{n-1}} . x_n + \frac{Dx_D}{V_{n-1}}}$$

operating line for enriching section.

Stripping Section: Envelope IV

$$x_{m+1} . \bar{L}_{m+1} = y_m . \bar{V}_m + x_B . B$$

$$\boxed{y_m = \frac{\bar{L}_{m+1}}{\bar{V}_m} . x_{m+1} - \frac{B}{\bar{V}_m} . x_B}$$

Enthalpy Balances: (Calculation of Q_c and Q_B)

Envelope II   (Q_c : Condenser duty)

$$V_{NP} . h_{V_{NP}} = Q_c + L_R . h_R + Dh_D$$

$L_R = RD$

$$Q_c = V_{NP} . h_{V_{NP}} - D(Rh_R + h_D).$$

$V_{NP} = D(R+1)$

$$Q_c = D[(R+1) . h_{V_{NP}} - (Rh_R + h_D)]$$

Rate of cooling water $= \frac{m\,Q_c}{c_p \Delta t}$

$\Delta t = T_{out} - T_{in}$; $T_{in} = 20 - 25\,°C$

Envelope I:

$$F \cdot h_F + Q_B = D \cdot h_D + B \cdot h_B + Q_c + \cancel{\boxed{Q_L}} \rightarrow$$

negligible if
well Insulated
[Total losses]

$$Q_B = D\left(h_D + \frac{Q_c}{D}\right) + B h_B - F \cdot h_F + \cancel{\boxed{Q_L}}$$

Envelope III

$$V_{n-1} \cdot h_{V,n-1} - L_n h_{L_n} = D\left(\frac{Q_c}{D} + h_D\right) = \Delta D \qquad (P')$$

$$= D(q_c + h_D)$$

= Net Flow

Envelope IV :

$$\bar{L}_{m+1} \cdot h_{\bar{L},m+1} - \bar{V}_m \cdot h_{\bar{V},m} = B\left(h_B - \frac{Q_B}{B}\right) = \Delta W \qquad (P'')$$

$$= B(h_B - q_B)$$

= Net Flow.

The previous relations together with equilibrium relations give the necessary equations for the design of distillation Columns.

At the end of design Calculations, one hopes to have:

- N_p
- Product flow rates, compositions
- Operating conditions (T, P)
- Q_c , Q_B

Specifications:

Two types of problems may be encountered with any equipment, in this ca distillation column:

- Design Problem
- Simulation Problem

Design Problem: Desired separation is set and column is designed that will achieve this separation

Simulation Problem: Column is already built and the procedure should predict how much separation can be achieved for a given feed.

For both problems we usually specify:

- Column pressure, (sets equilibrium data)
- Feed composition
- Feed flow rate.
- Feed temperature and pressure (or enthalpy or quality – state of the feed L_f and V_f).
- Reflux temperature or enthalpy (usually saturated liquid) (Simulation Problem).

Other variables which must be set for adequate specification.
For a binary system the most usual specifications and the resulting calculated variables are:

Specifications	Calculated variables
Design: - x_D, x_B (mvc) - R (L_R/D)	D, B, Q_c, Q_B, N_p, feed location. Column Diameter.
Simulation: - Np, feed location - column diameter - Reboiler size (gives max vapor) and	
- x_D and x_B	R, B, D, Q_c, Q_R Check $v<v_{max}$
or - R, x_D (or x_B)	x_B (or x_D),B,D,Q_c,Q_R Check $v<v_{max}$
or - x_D (or x_B), $V=V_{max}$	R, x_B (or x_D), B, D, Q_c, Q_R Check $v<v_{max}$

Two approaches may be used:

- Approximate: simple sequential, (adequate in many cases), graphs, simple algorithms
- Rigorous: requires detailed stage to stage calculations (simulation), handles all situations

Binary Rectification:

Approximate Methods:

Simplifying assumptions:

1. Constant molal overflows: valid if (over range of temperature and Pressure):

   - Molar heats of vaporization of both species of the binary system are equal
   - Heats of mixing, stage heat losses and sensible heat changes of both liquid and vapor are negligible

   This assumption indicates that every mole of condensing vapor vaporizes exactly ONE mole of liquid.

   This means that on molal basis in each section of a column;

   $$\frac{Molesof\ Liquid}{Moles\ of\ Vapor} = constatnt\ \ ;\ \ Ln = L\ ,\ Vn = V\ \ and\ \bar{L}_m = \bar{L}\ ,\ \bar{V}_m = \bar{V}$$

   This results in a straight line operating line for each section.

2. Distillation takes place at constant pressure (small variations of pressure inside the column)

Plate to plate calculations: Lewis-Sorel Method

Consider the following case for the distillation of a binary mixture:

Given Information:

$F, \overrightarrow{Z}, x_D\ , x_B, R, P_{Column}$

Feed, Distillate, Bottoms product and reflux are saturated liquids at their bubble points.

Required: Np and Feed location.

Analysis:

- Operating lines give relations between vapour and liquid compositions of passing streams:

  Rectifying Section: $y_{n-1} = \frac{L}{V}.x_n + \frac{D}{V}.x_D$

  Stripping Section: $y_m = \frac{\bar{L}}{\bar{V}}.x_{m+1} - \frac{B}{\bar{V}}.x_B$

- Equilibrium data give relations between liquid and vapour compositions leaving a stage

$$x_n = f(y_n)$$

Calculation Procedure:

- Use column balances to calculate D, B, L and V, $\bar{L}$, $\bar{V}$

- Starting with top specification, find ……….. from ……………………….

- Find………from …………………

- Repeat for stage ………

- Repeat for stages below until …….... calculated is nearly the same as ………

- Change ……………………….., and starting with ……………..

- Find………from …………………

- Repeat for stages below until …….... calculated is nearly the same as ………

- Stop