Distillation:
A core unit operation in Chemical Processes

Lecture presented at Université Catholique de Louvain

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Learning objectives

- Separation process: Why and how?
- The distillation process
- Basics of distillation column design
- Factors that affect the performance of distillation column

Objectives developed based on the course: LBIRC2109, UCLouvain

Separation processes

Separation processes: A pillar of Chemical Engineering

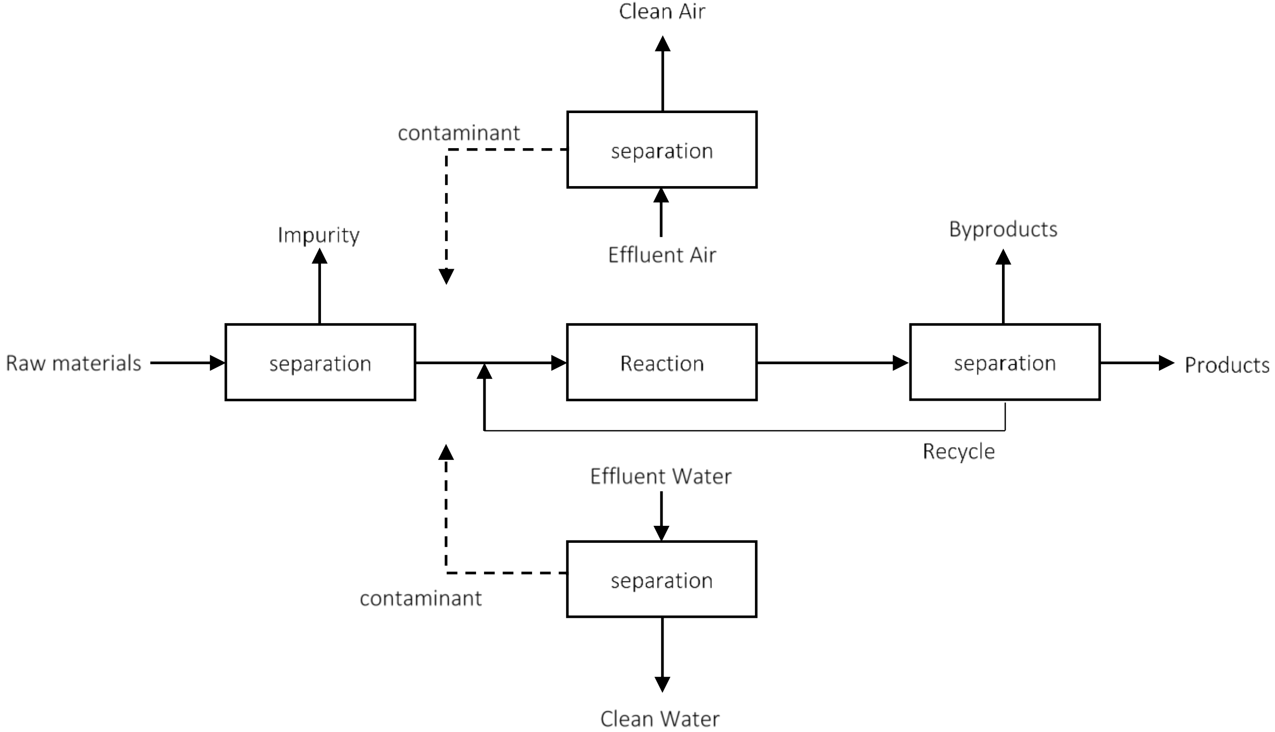

Fig. 1.: Separation process: why?

Separation processes

Separation processes;

- Influence the Chemical Process Industry (CPI) feasibility i.e. processing plant economics
- Influence the price of recovering the target product (Fig. 2)
- Determine the functionality of the product streams

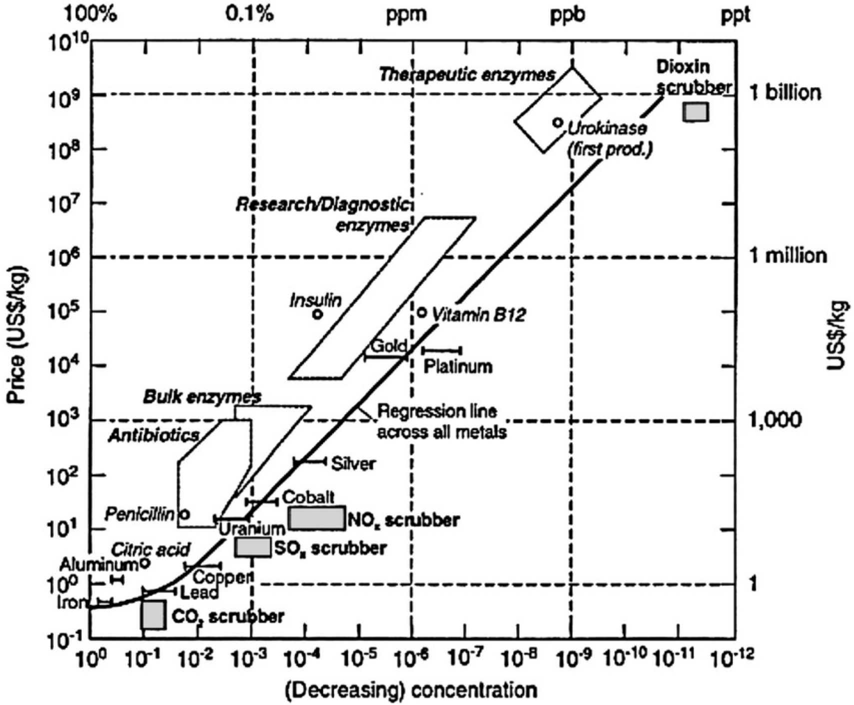

Fig. 2.: A Sherwood plot (Grubler 1998)

Distillation process

- Methods of separation ? Distillation (Fig. 3), crystallization etc.

- Distillation: separation component mixtures in the liquid phase based on differences in volatilities or boiling temperatures i.e benzene (80.1 °C) and methanol (64.7 °C) .

- The differences in volatilities are presented in terms of their relative volatility (α). For a binary system of A and B , the of A relative to be is as follows;

$$\alpha_{AB} = \frac{P_A^{sat}}{P_B^{sat}} = \frac{y_A / x_A}{y_B / x_B}$$

Recall Raoult's law

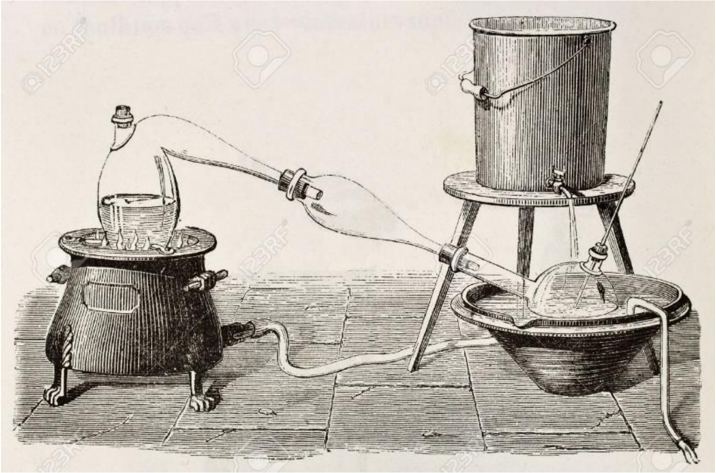

Fig. 3 Simple distillation apparatus (www.alamy.com)

Distillation process

Common types of distillation processes include;

Types	Brief Notes
Simple distillation	For mixture with sufficiently different volatilities
Steam Distillation	Steam employed as a heating utility via direct introduction to the mixture
Vacuum Distillation	Simple distillation under a vacuum
Fractional Distillation	Distillation of a mixture of components
Azeotropic Distillation	Distillation of an azeotropic mixture (i.e. min. and max. azeotropic mixtures)
Extractive Distillation	Distillation of mixture with similar volatilities

Distillation process

In the CPI, distillation is achieved using a distillation column

Plates/trays, packing

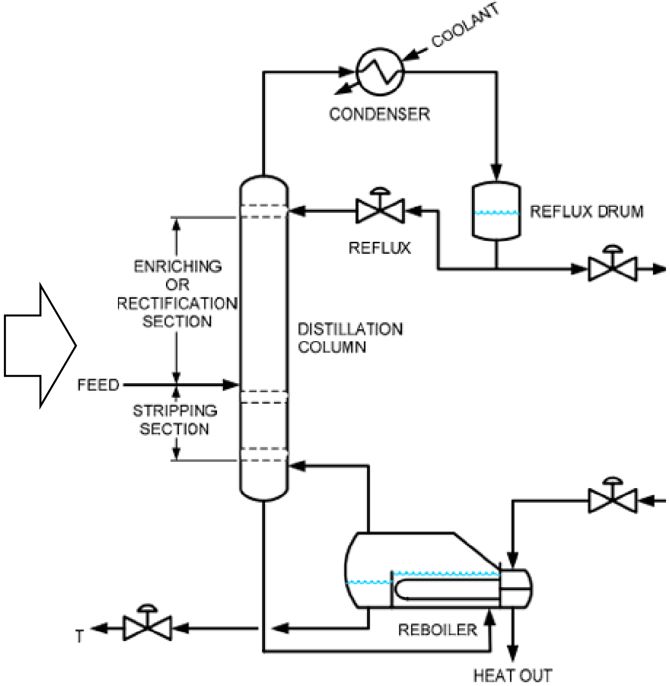

Fig. 4.: A simplified illustration of a distillation column

Distillation column design

When designing a distillation column in scaled-up projects several design parameters must be considered ;

- ❑ Vapor-Liquid Equilibrium
- ❑ Column Operating Objectives
- ❑ Operating Pressure
- ❑ Reflux ratio and number of distillation stages and Feed stage location

Distillation column design

Methods employed in distillation column design:

❑ Lewis-Sorel method:
In this method material balance equations are solved stage by stage starting at the top or bottom of the column

❑ McCabe-Thiele method:
Employs operating lines which are based on material balance equations

❑ Ponchon-Savarit method:
Material and energy balance calculations

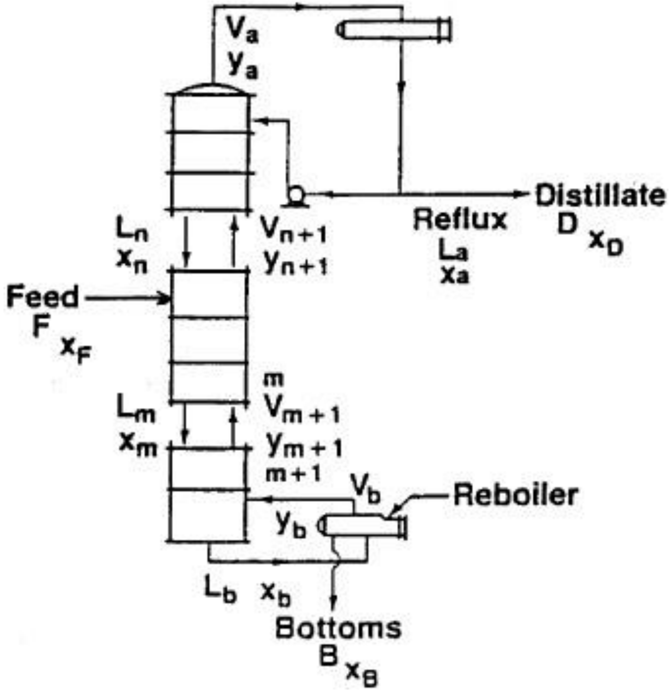

Fig. 5 Material balance for the development of distillation operating lines

Distillation column design

McCabe-Thiele method is a well-established method that may be used in the design of distillation columns

Major steps for McCabe-Thiele method

- 1. Define xy phase diagram and draw a diagonal line across the plane
- Specify given data and the distillation goals
- Drawing operating lines

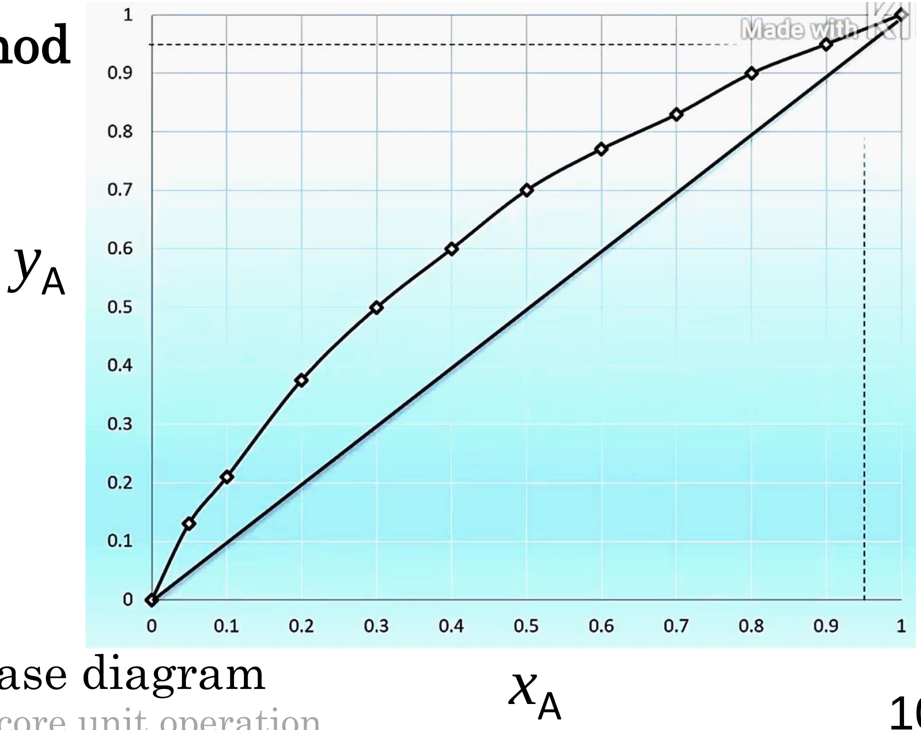

Fig. 5 Example xy phase diagram

Distillation column design

Draw the **operating line for the rectifying section** defined as follows;

$$y = \frac{R}{R+1}x + \frac{x_D}{R+1}$$

where R =reflux ratio and x_D =mole fraction of the volatile component in the distillate

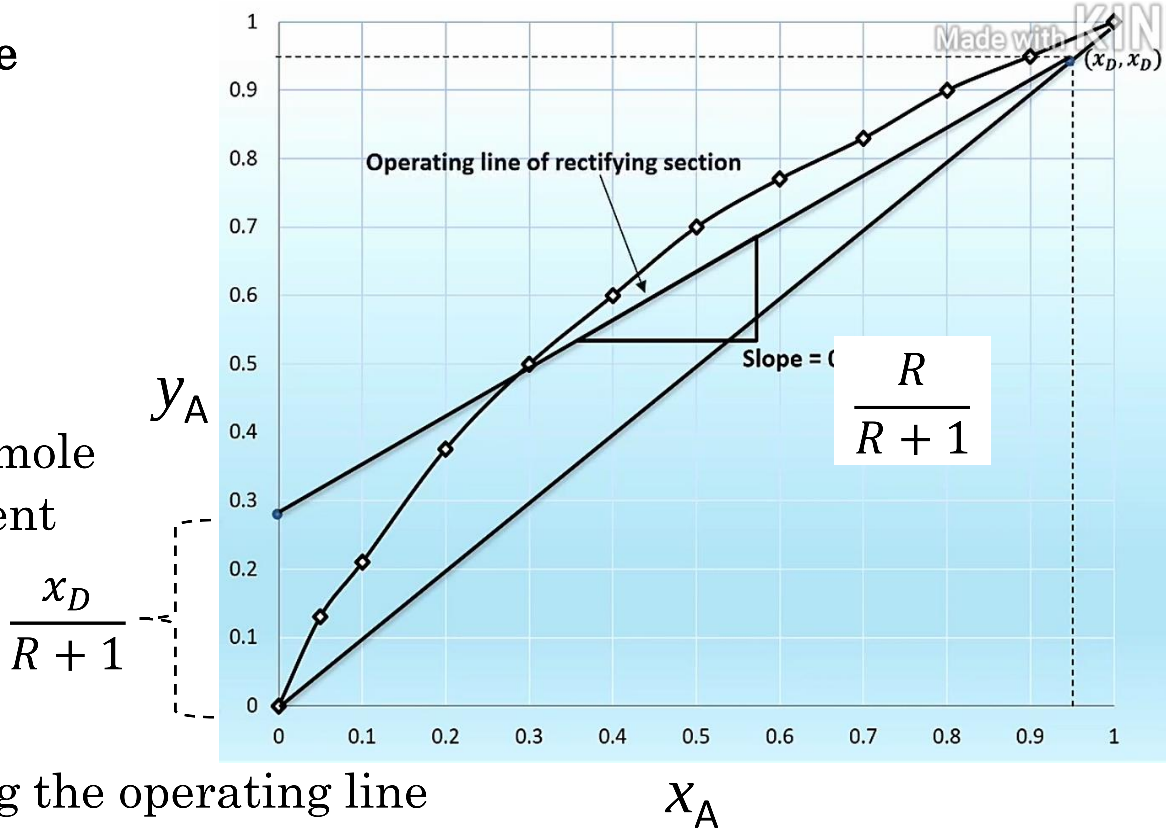

Fig. 6 xy phase diagram showing the operating line for the rectifying section

Distillation column design

Draw the feed operating line (or *q*-line) defined as follows;

$$y = \frac{-q}{1-q}x + \frac{x_F}{1-q}$$

where q =feed quality and x_F =mole fraction of the volatile component in the feed

Recall that the feed occurs where the two lines operating lines intersect

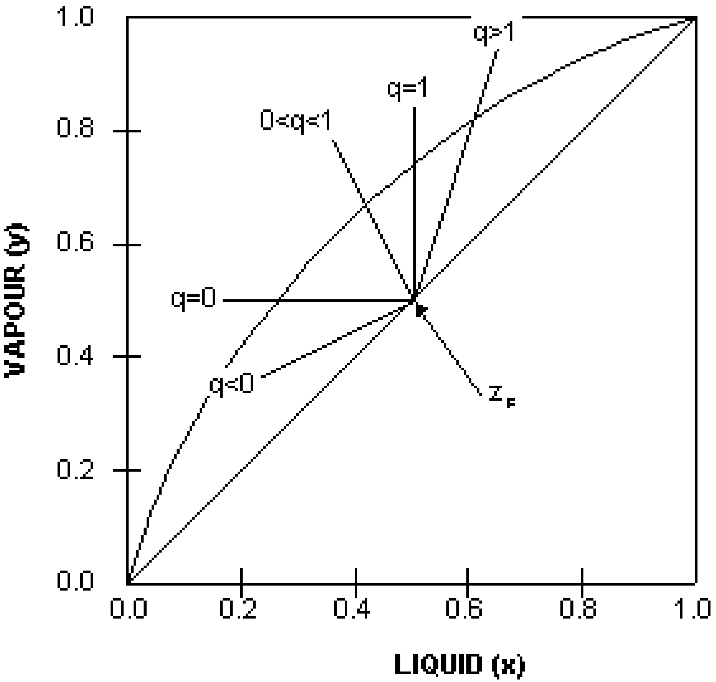

Fig 7. Feed operating line for different values of *q*

Distillation column design

3. Draw the feed line defined as follows;

$$y = \frac{-q}{1-q}x + \frac{x_F}{1-q}$$

In Fig 6 the feed line is specified for q=1

F in Fig 8 is the feed mole fraction of the volatile component assumed to be 0.6

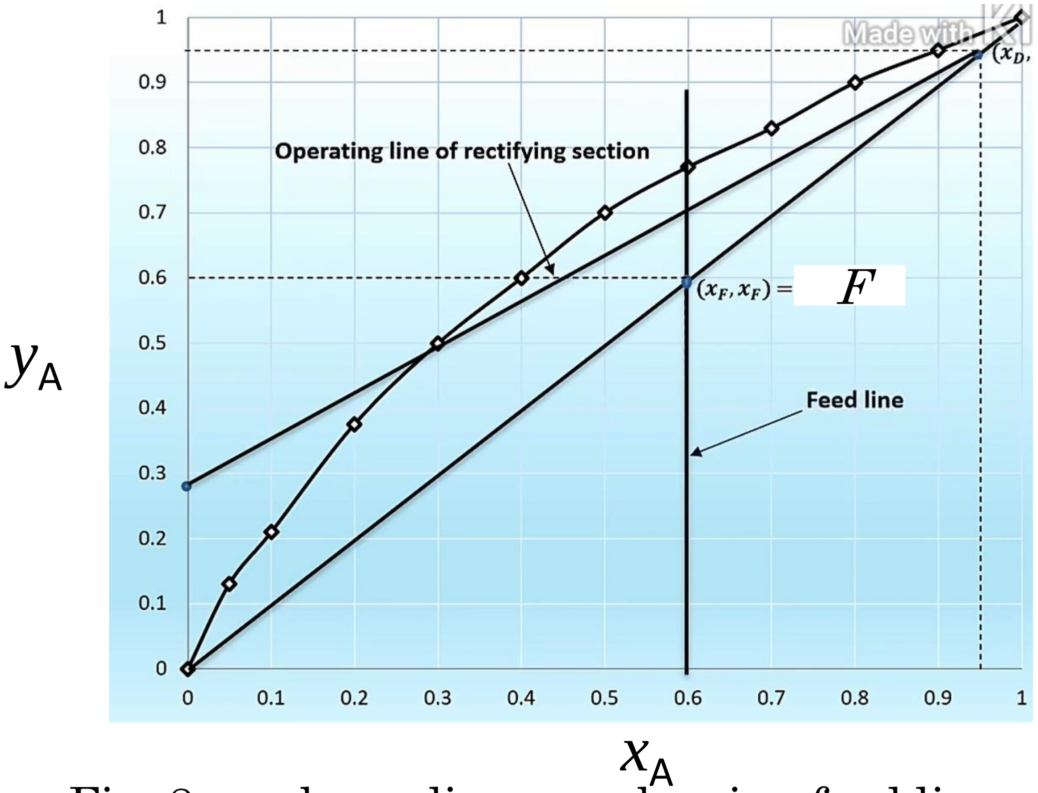

Fig. 8 xy phase diagram showing feed line

Distillation column design

4. Draw the operating line for the stripping section

5. Construct triangles from $(x_d\ x_d)$ between the equilibrium curve and operating line of rectifying section and stripping section till the point $(x_w\ x_w)$ is reached

B in Fig 9 is the mole fraction of the volatile component in the bottom

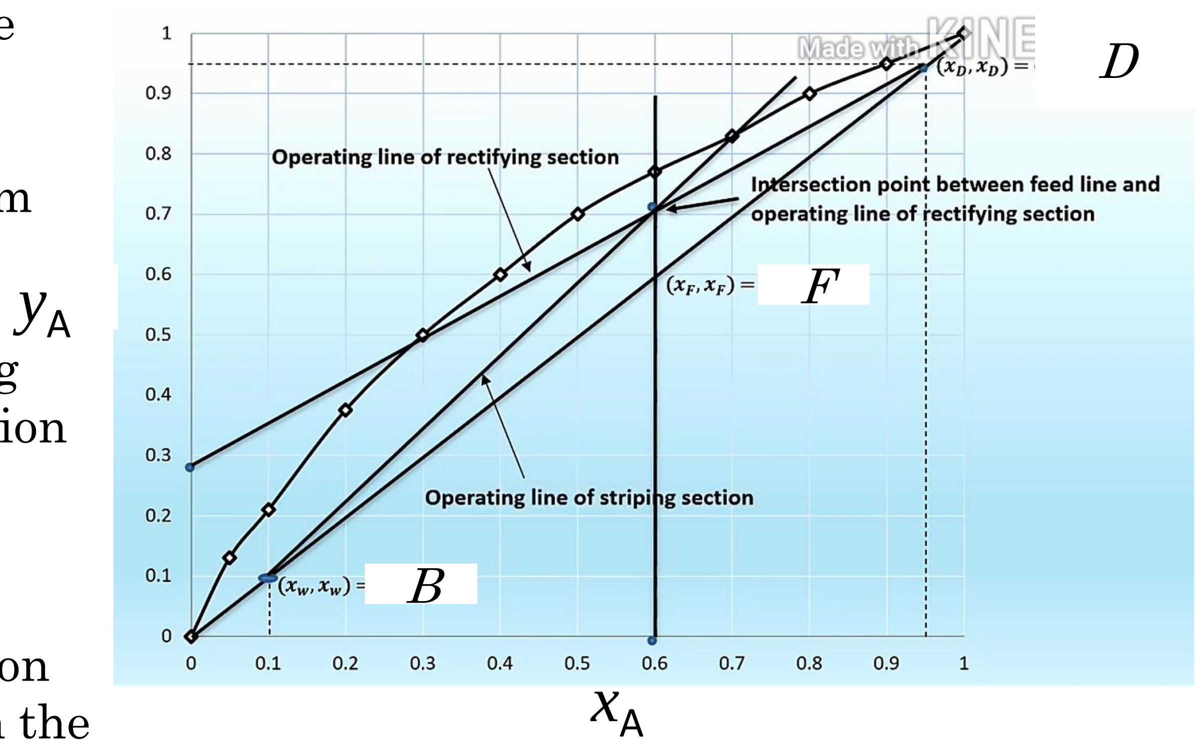

Fig. 9 xy phase diagram showing operating line for the stripping section

Distillation column design

6. Finally count the number of triangles (Fig. 8) i.e. Ideal number of trays including the reboiler = 10 .Hence the number of trays =10-1=9

Note that the feed tray is where the rectifying line and the stripping line intersect i.e tray 5 from the top of the column

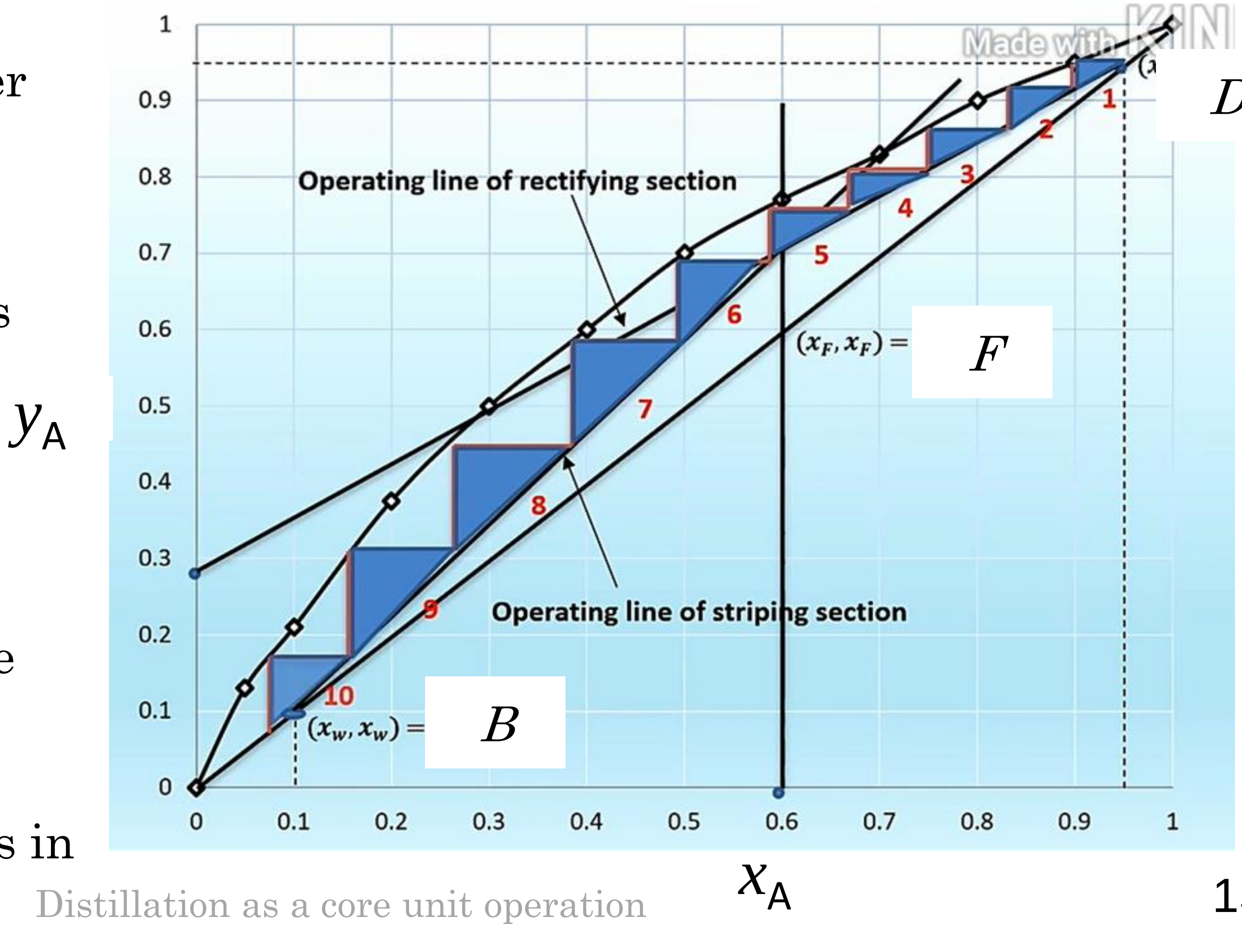

Fig. 10 xy phase diagram showing the number of trays in the distillation column

Distillation column design

Shortcut methods may also be employed in column design:

The shortcut method involves the use of;

1. Fenske method estimates the minimum number of stages
2. Underwood method estimates minimum reflux ratio.
3. Gilliland method estimates the number of theoretical stages required.

- 1-3 constitute the Fenske-Underwood-Gilliland (FUG) method

4. While the Kirkbride method can be used in estimating the feed tray location (numbered from top of the column).

Factors that affect performance

Considering Fig. 10, it may be immediately clear some of the factors that may influence the performance of the distillation column such as;

- ❑ Feed condition
- ❑ Feed tray location
- ❑ Reflux condition
- ❑ Vapor Flow Conditions

Today we learned that

- The importance of separation operations to Chemical Engineering process feasibility
- The importance of distillation processes
- The factors that influence the design of a distillation column
- Short cut approaches to distillation column design
- Factors that influence distillation column performance

Further reading

1.Couper, J.R., Penney, W.R., Fair, J.R., Walas, S.M., Eds. 2005.Chapter 13 - Distillation and Gas Absorption. In Chemical Process Equipment (Second Edition), Gulf Professional Publishing: Burlington, 2005; pp. 397-482.

2.Olujić, Ž. Distillation: Equipment and Processes. In Distillation, Górak, A., Olujić, Ž., Eds.; Academic Press: Boston, 2014; pp. ix-x.

3.Grübler A (1998) Technology and Global Change (Cambridge Univ Press, Cambridge, UK).

Thank you for listening !