Binary Distillation

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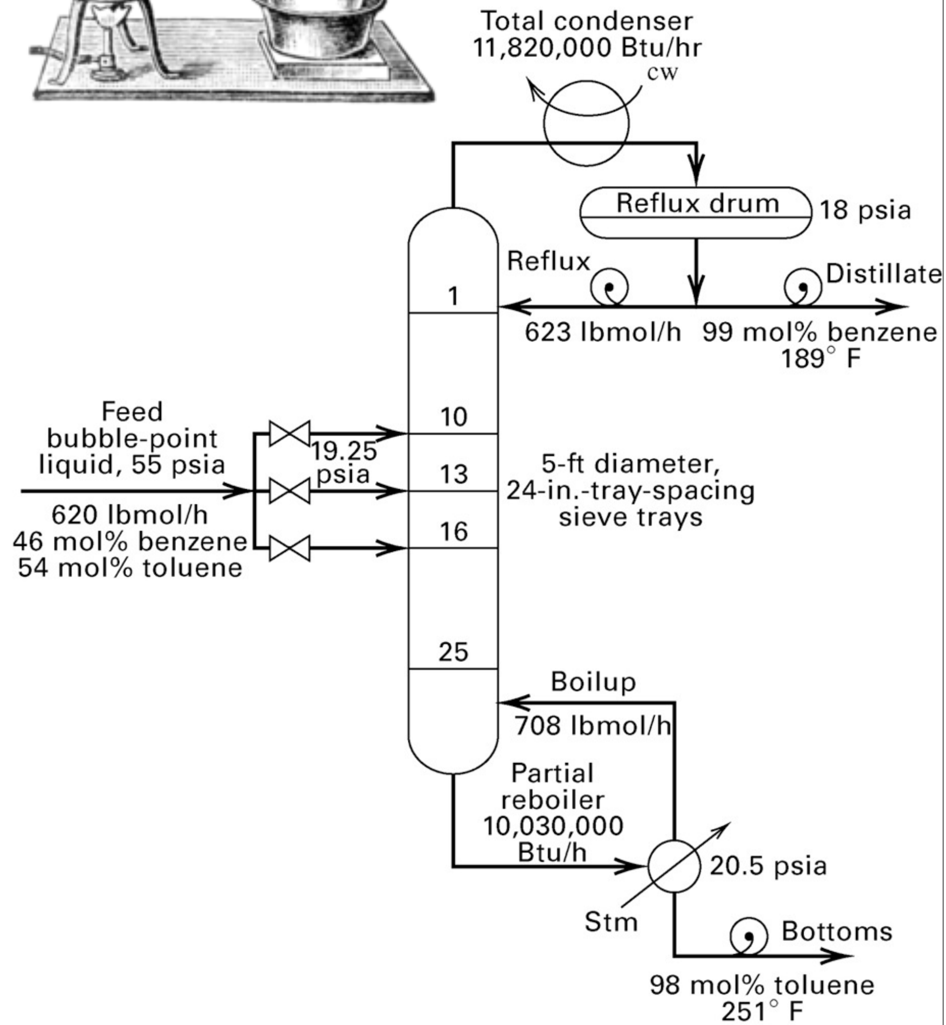
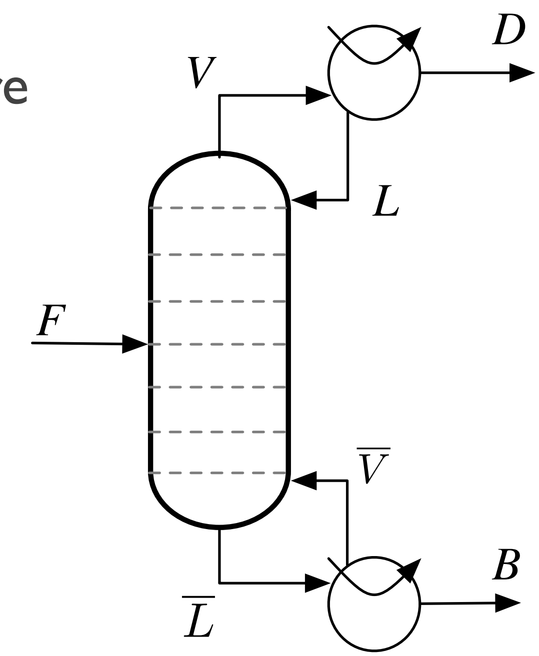
Introduction

- Dates back to 1st century AD
  - first used in a batch mode (distillate changes in time)
- Goal: separate "heavy key" (less volatile) from "light key" (more volatile) by exploiting $\alpha \neq 1$.
  - for $\alpha \gg 1$ or $\alpha \ll 1$, this can be done very effectively unless an azeotrope exists (where $\alpha = 1$).
    - then we recover the azeotrope and the light or heavy key, depending on which side the feed lies.
  - By 16th century, multiple stages were in use to improve separation.
- By 1976, distillation accounted for nearly 3% of the US energy consumption!
  - mostly in petroleum refineries
- Binary distillation is simplest & most well-understood.
  - we will limit our discussion to binary distillation
- Third Law of Thermo - typically low thermodynamic efficiency.



Design Considerations

- Operating pressure - "knob 1"
  - below ambient pressure requires vacuum operation
  - many things may influence choice of operating pressure
    - Thermo: azeotrope formation, α, etc.
    - Column operating temperature range (avoiding reactions, corrosion, etc.)
  - most analyses do not account for pressure variation through the column



- Operating temperature - "knob 2"
  - Reboiler & Condenser:
    - Bottoms above ambient requires additional energy input to the reboiler
    - Distillate below ambient requires energy removal from the condenser.
  - Thermodynamics: critical points of fluids

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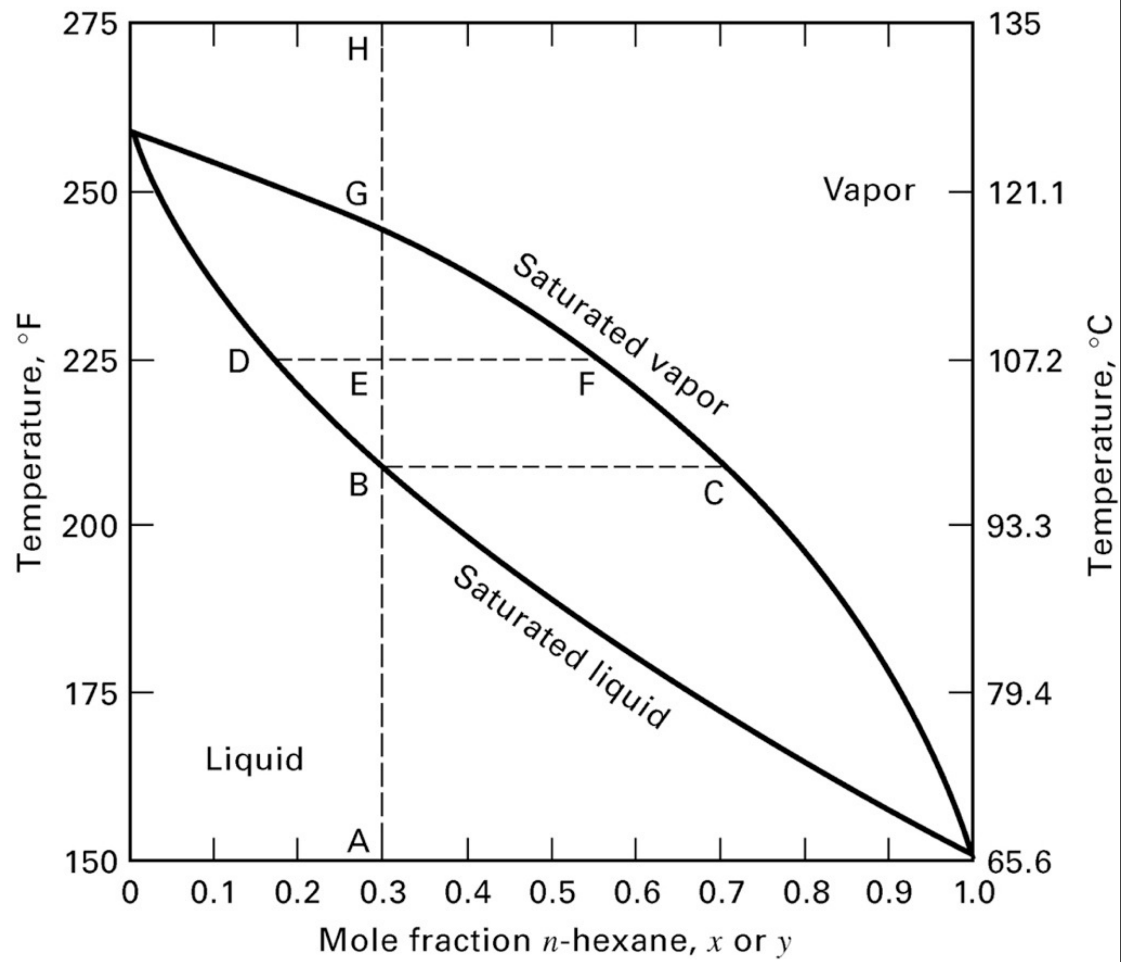
Batch Distillation

- Conceptually, follows the *T-x-y* diagram.
- More rigorous analysis in SHR chapter 13



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The McCabe-Thiele Graphical Method

1925
Continuous (staged) distillation

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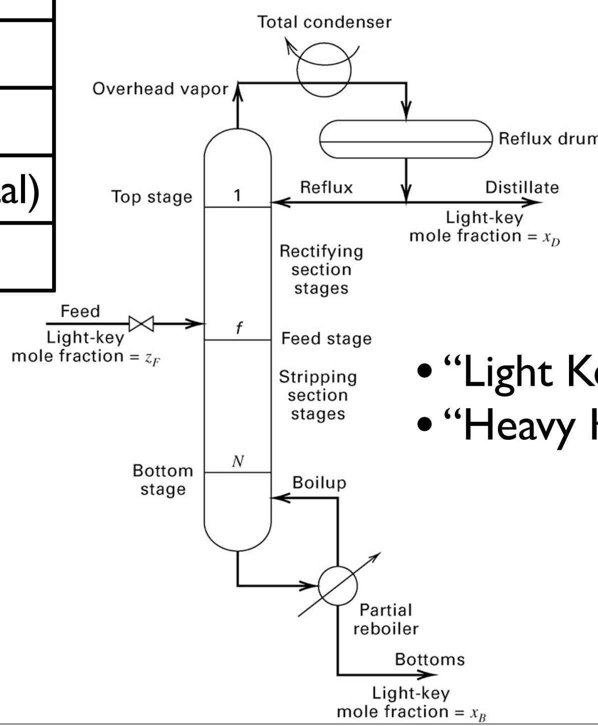
Nomenclature

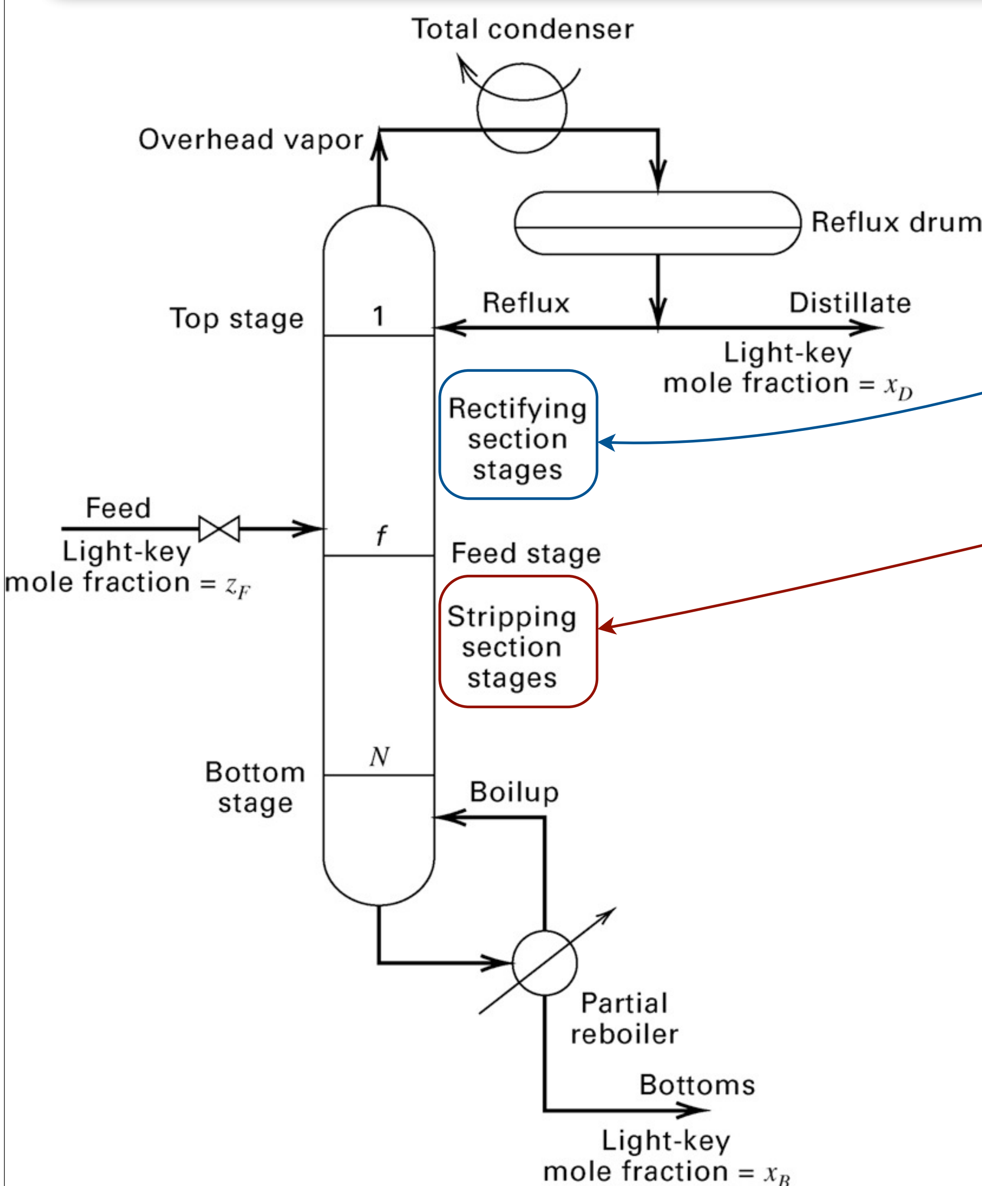
Specifications	
F	total (molar) feed rate
z	LK mole fraction in feed
P	Column operating pressure
x	LK mole fraction in distillate
x	LK mole fraction in bottoms
R/R	reflux ratio
	Feed phase condition
	VLE data (y/x plot)
	Type of condenser (partial/total)
	Type of reboiler (partial/total)

Results	
D	Distillate (molar) flow rate
B	Bottoms (molar) flow rate
N	minimum number of stages
R	minimum reflux flow rate
V	Boilup ratio
N	Number of equilibrium stages
	Feed stage location
	Stage compositions (



- "Light Key" (LK) - more volatile component
- "Heavy Key" (HK) - less volatile component

Preliminaries



Rectifying section - like an absorber

- Feed & reboiler supply vapor
- Condenser supplies liquid

Stripping section - like a stripper

- Feed & condenser supply liquid
- Reboiler supplies vapor

overall mole balance: $F = D + B$

light-key mole balance: $F z_F = x_D D + x_B B$

combine to eliminate B & solve for D: $D = F\left(\frac{z_F - x_B}{x_D - x_B}\right)$

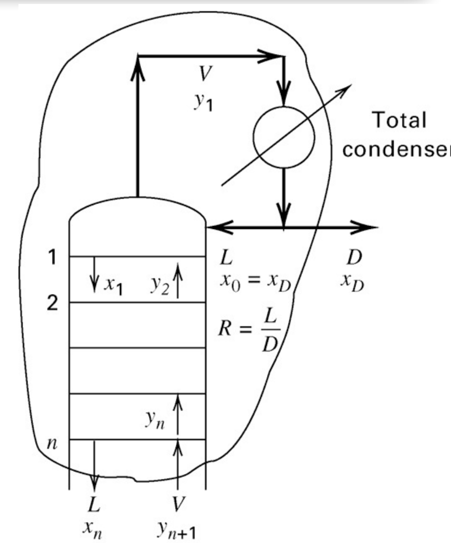
Rectifying Section Operating Line

Overall mole balance: $V = L + D$

Light key mole balance: $V y_{n+1} = L x_n + D x_D$

$$y_{n+1} = \frac{L}{V} x_n + \frac{D}{V} x_D$$

relates light-key compositions in passing streams (streams on a stage are assumed to be in equilibrium)



If L and V are constant, then this is a straight line.

The "McCabe-Thiele Assumptions"

- Both components have equal and constant molar enthalpies of vaporization (latent heats).
- Sensible heat, $C_p \Delta T$, is negligible compared to latent heat.
- Column is insulated (no heat loss on each stage).
- Column pressure is constant (thermodynamics can be done at a single pressure).

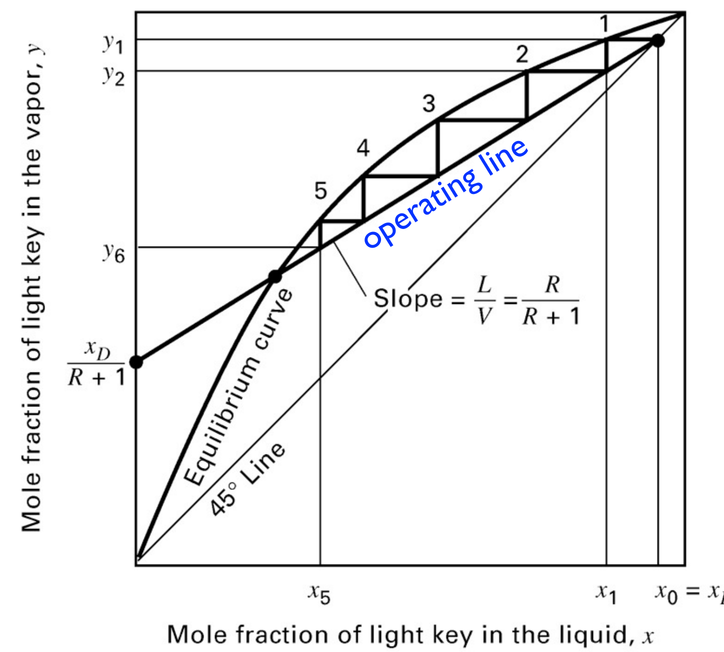
Big assumptions, but allow for simple analysis, since L and V are constant under these assumptions.

$$\frac{L}{V} = \frac{L}{L+D} = \frac{L/D}{L/D + D/D} = \frac{R}{R+1}$$

$R \equiv \frac{L}{D}$ reflux ratio

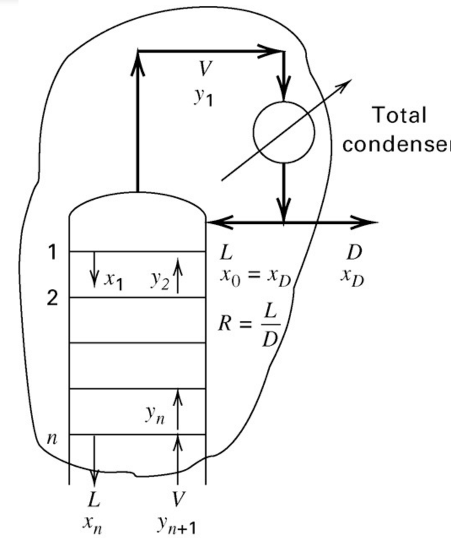
$$\frac{D}{V} = \frac{1}{R+1}$$

$$y = \left(\frac{R}{R+1}\right) x + \left(\frac{1}{R+1}\right) x_D$$



Range of Reflux Ratios

$$y = \frac{L}{V}x + \frac{D}{V}x_D \qquad R = \frac{L}{D}$$

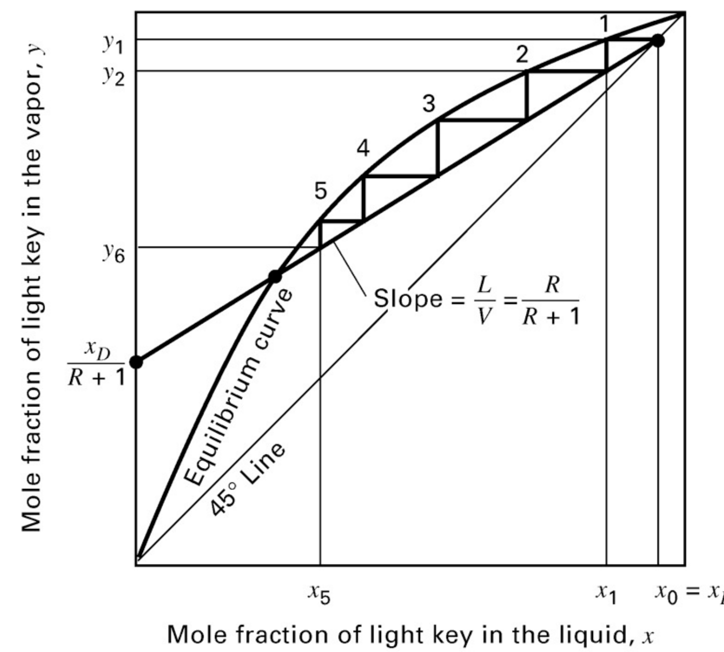


$$0 \le \left(\frac{L}{V} = \frac{R}{R+1} \right) \le 1 \quad \text{because} \quad 0 \le R \le \infty$$

- What happens at $R = 0$?
- What happens at $R = \infty$?

What is the minimum R that allows separation?

(We will answer this question shortly)



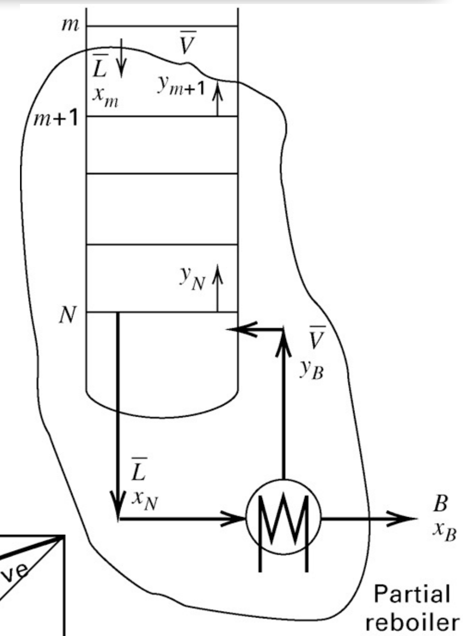
Stripping Section Operating Line

Overall mole balance: $\overline{L} = \overline{V} + D$

Light key mole balance: $\overline{L} x_m = \overline{V} y_{m+1} + B x_B$

McCabe-Thiele assumptions have been applied.

The feed stage material balance relates L and V to $\overline{L}$ and $\overline{V}$

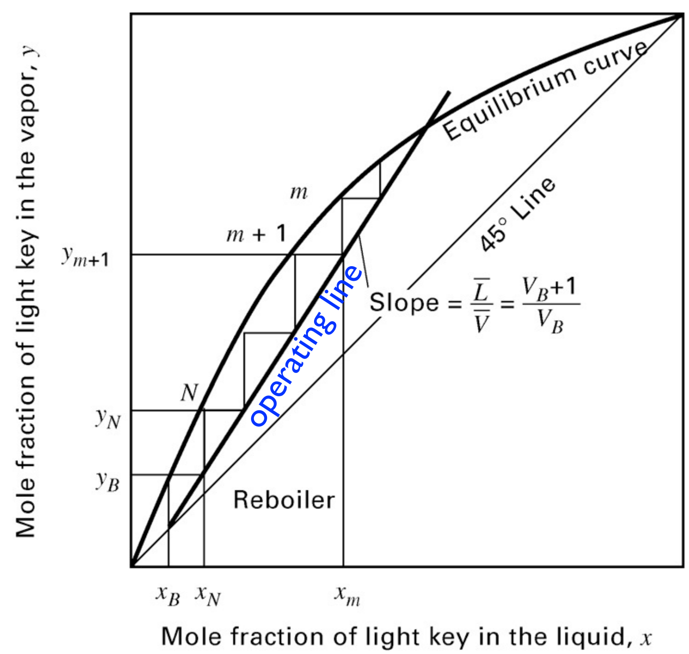


$$y_{m+1} = \frac{\overline{L}}{\overline{V}} x_m - \frac{B}{\overline{V}} x_B$$

relates light-key compositions in passing streams (streams on a stage are assumed to be in equilibrium)

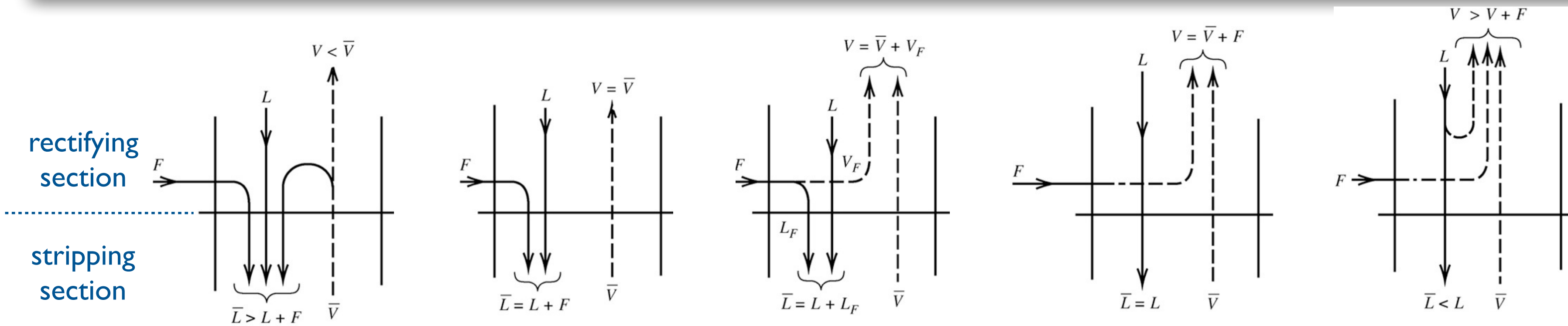
$$y = \left(\frac{V_B + 1}{V_B}\right) x - \left(\frac{1}{V_B}\right) x_B$$

$V_B \equiv \dfrac{\overline{V}}{B}$ boilup ratio



SHR §7.2.3

Feed Stage & the "q-Line"

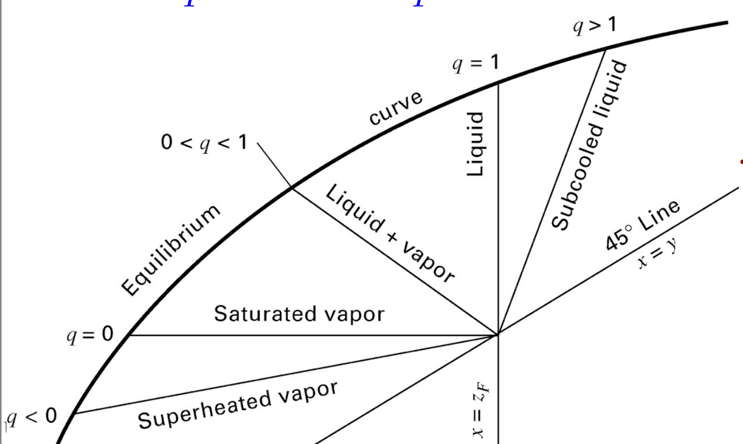


subcooled liquid	saturated liquid	partially vaporized	saturated vapor	superheated vapor
$q > 1$	$q = 1$	$q = {}^{L_F}/_{F}$	$q = 0$	$q < 0$

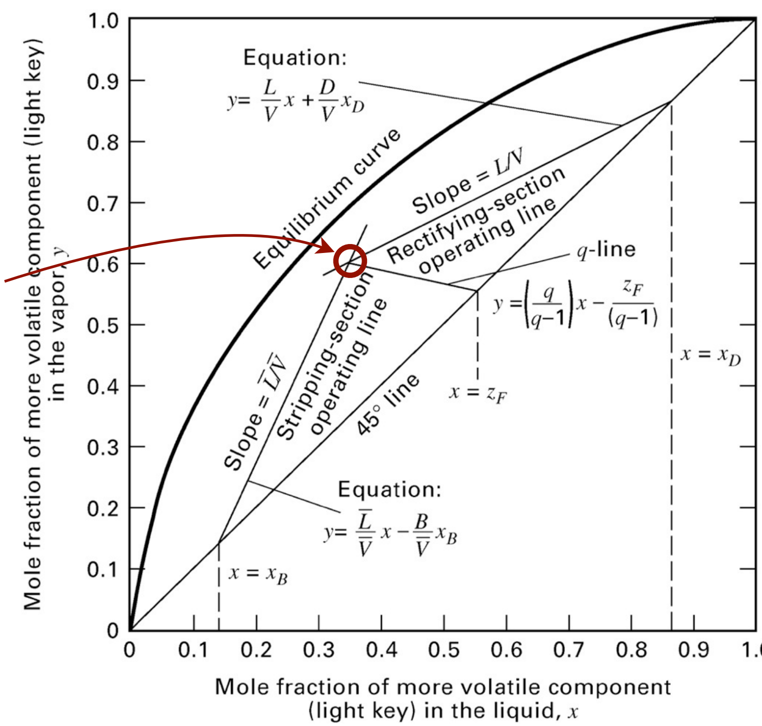
$$q = \frac{\overline{L} - L}{F} = 1 + \frac{\overline{V} - V}{F}$$

liquid flow increase across feed rate normalized by feed rate.

$$q = \frac{h_F^{\text{sat. vapor}} - h_F}{h_F^{\text{sat. vapor}} - h_F^{\text{sat. liquid}}}$$



Operating lines & q-line must intersect at a single point.
$\therefore$ cannot specify q, V_B and R independently.



More on the q-line

rectifying section:

$$y = \frac{L}{V}x + \frac{D}{V}x_D$$

stripping section:

$$y = \frac{\overline{L}}{\overline{V}}x - \frac{B}{\overline{V}}x_B$$

$$q = \frac{\overline{L}-L}{F} = 1 + \frac{\overline{V}-V}{F}$$

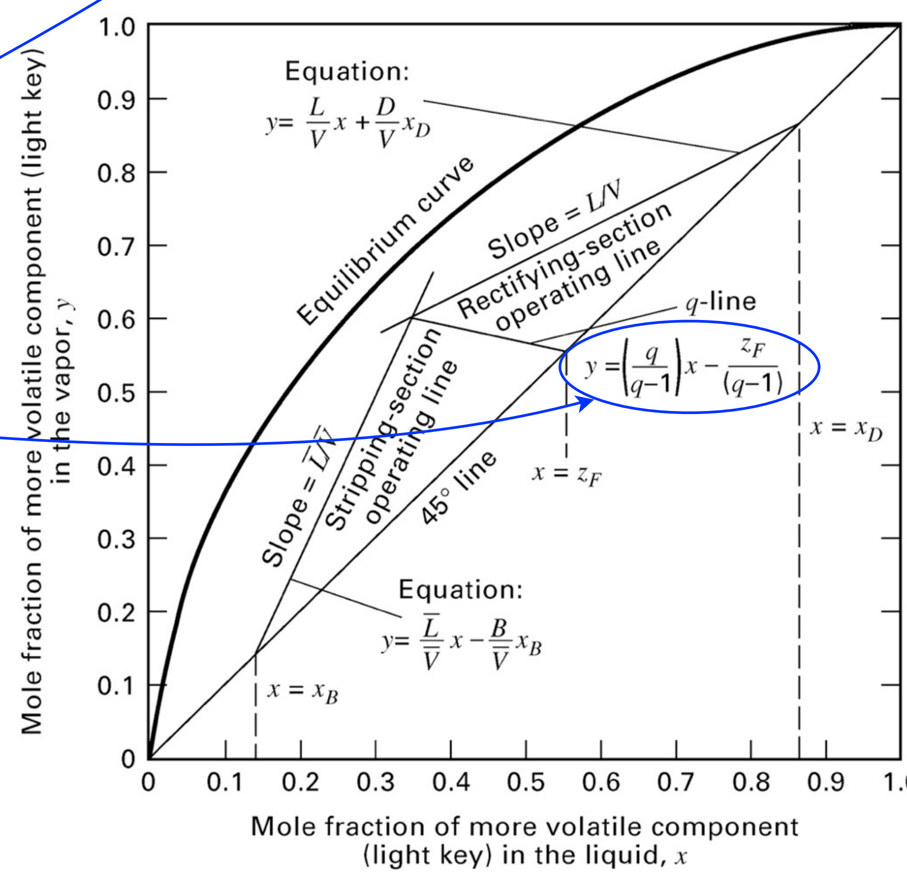
subtract

$$y\left(V-\overline{V}\right) = x\left(L-\overline{L}\right) + \underbrace{Dx_D + Bx_B}_{Fz_F}$$

$$y\left(\frac{V-\overline{V}}{F}\right) = \left(\frac{L-\overline{L}}{F}\right)x + z_F$$

$$y\left(1-q\right) = -qx + z_F$$

$$\boxed{y = \left(\frac{q}{q-1}\right)x - \frac{z_F}{q-1}}$$



Typically the feed condition is known (specifying q).
Then we can choose V_B or R.

Note: specifying R implies V_B.

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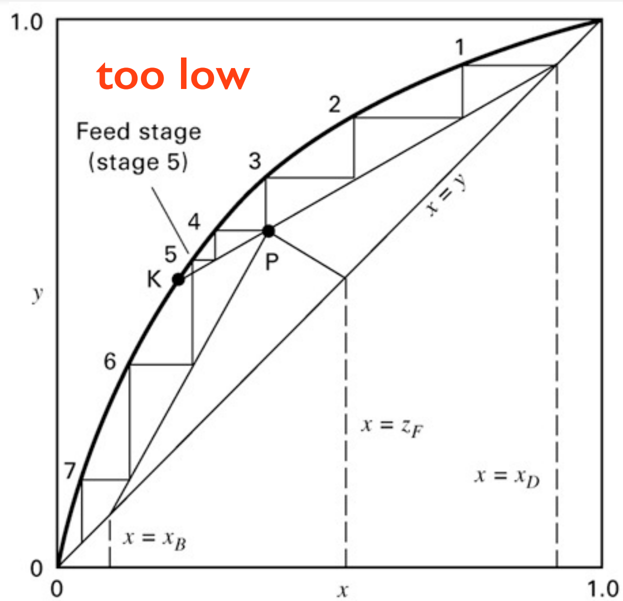
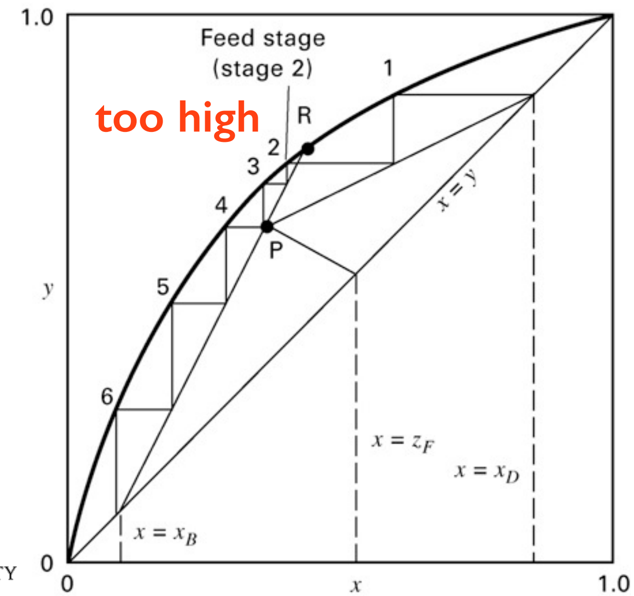
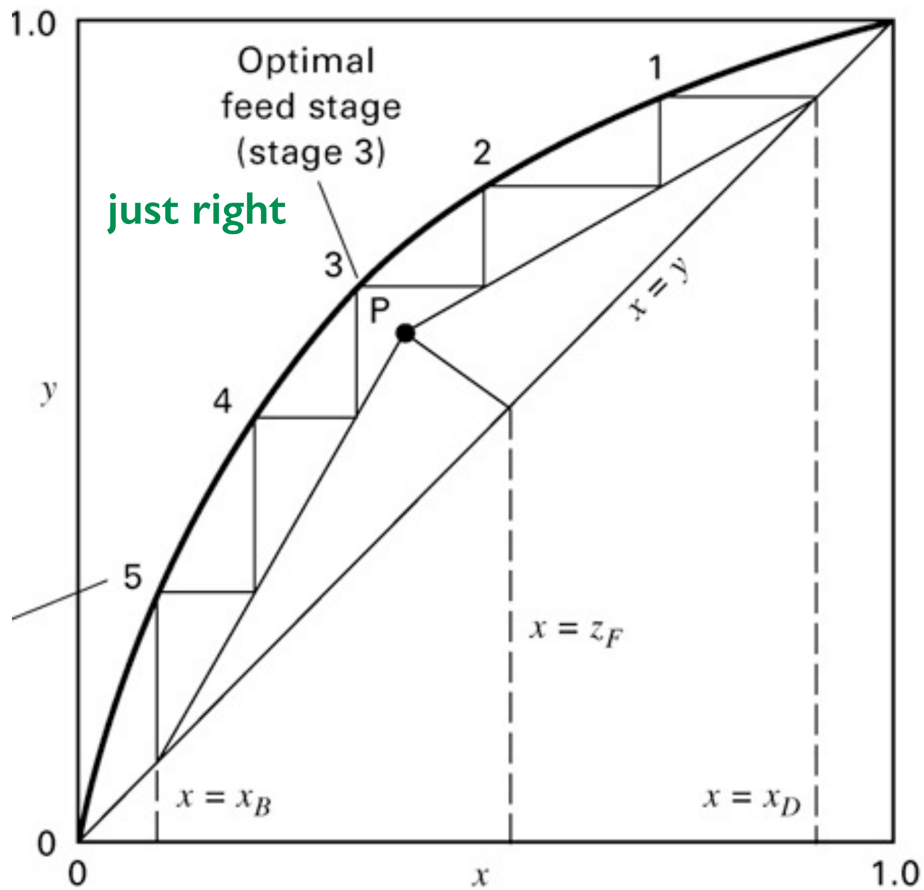
Feed Stage & Number of Stages



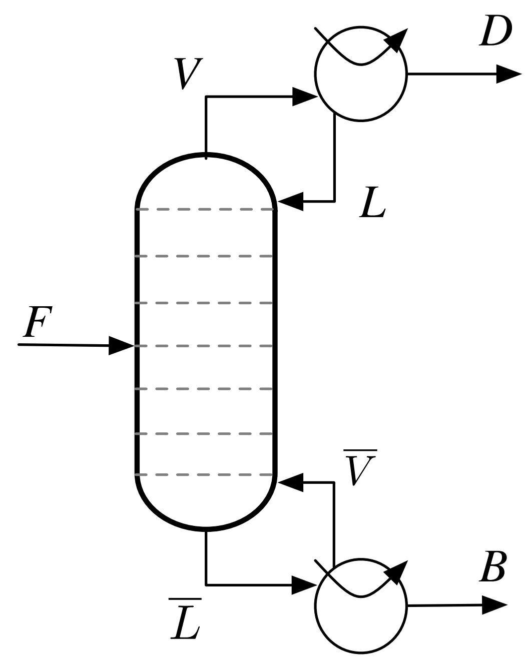




Locate feed stage nearest to the intersection of the operating lines & q-line as possible (just after the horizontal line on the staircase passes "P"

Partial Reboilers & Condensers

- Total Reboiler:
  - all liquid is turned back to vapor
- Partial reboiler:
  - bottoms product is liquid, boilup is vapor
  - **This is another equilibrium stage!**
  - very common...
- Total condenser:
  - all vapor is condensed back to liquid
- Partial condenser:
  - distillate is vapor, reflux is liquid
  - **This is another equilibrium stage!**



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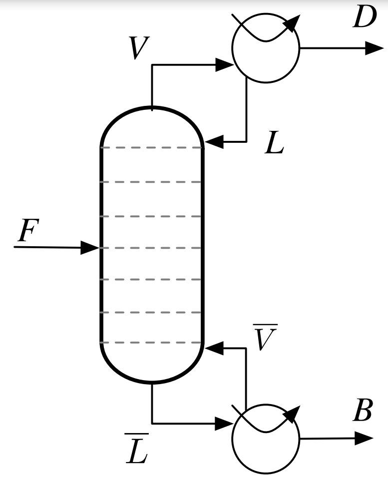
Limiting Cases: $R_{\min}$, $N_{\min}$.

"Total reflux"

- $R = \infty$, $V_B = \infty$.
- $L = V$, $D = B = F = 0$.
- $F = 0$, $N = N_{\min}$.
- $y = x$ is operating line.
- No product...



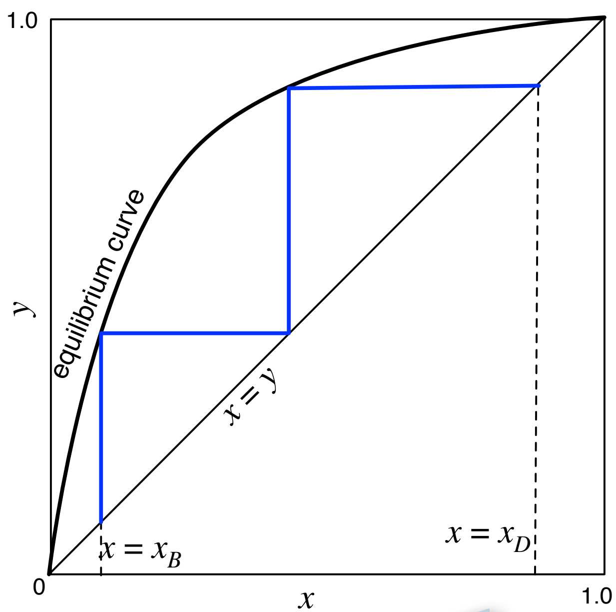
"Minimum reflux"

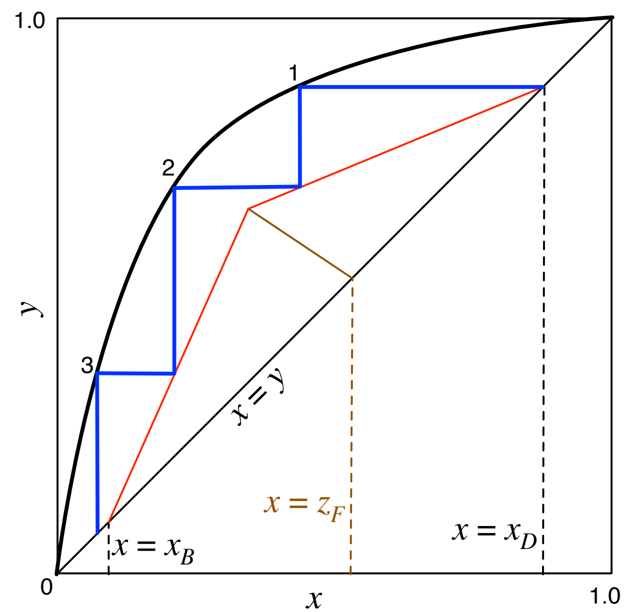
- $N = \infty$.

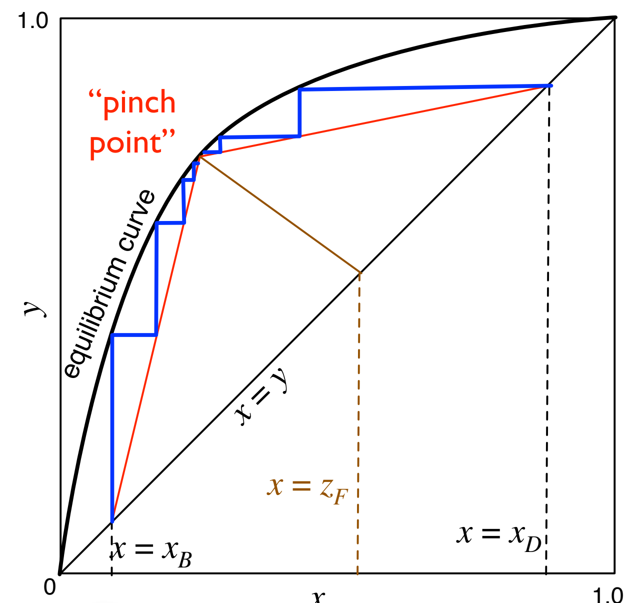
$$(L/V)_{\min} = \frac{R_{\min}}{R_{\min}+1}$$

$$R_{\min} = \frac{(L/V)_{\min}}{1-(L/V)_{\min}}$$

$$(V_B)_{\min} = \left[\left(\overline{L}/\overline{V}\right)_{\max} - 1\right]^{-1}$$



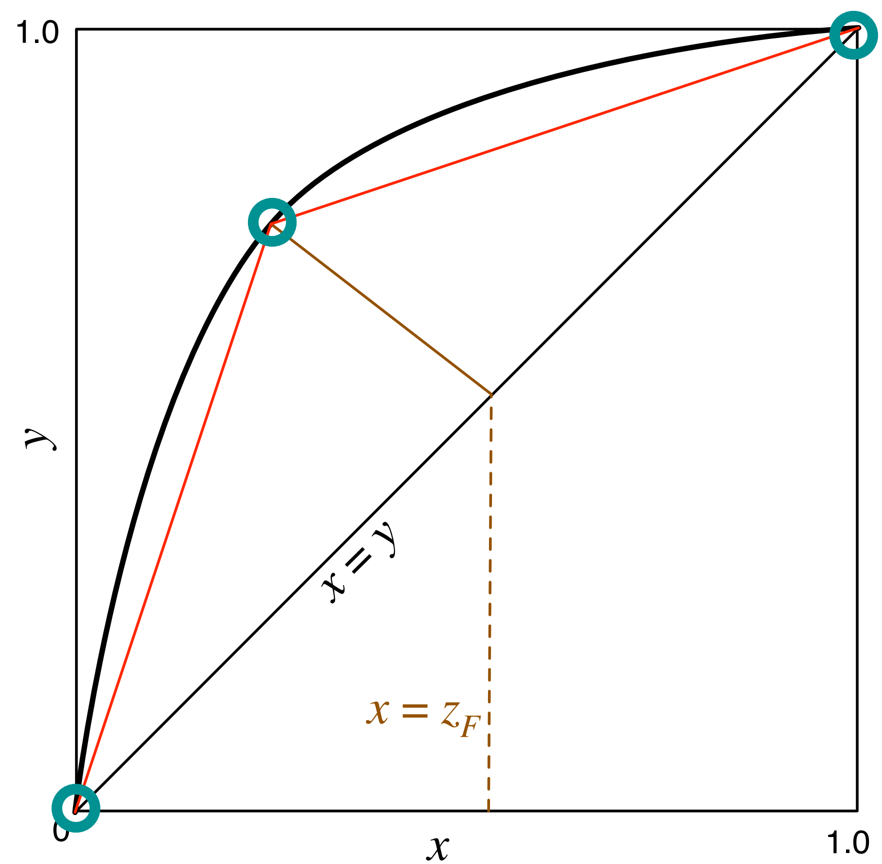




higher operating costs ⟵⟶ higher capital costs

Perfect Separation - Another "Limiting Case"

- Perfect separation: $x_B = 0, x_D = 1$.
- Pinch points form in each section of the column.
- Theoretical value for minimum reflux ratio and boilup to achieve perfect separation.
- To find this:
  - Obtain x-y data from thermo.
  - Determine q-line
  - Determine slope of rectifying operating line = $R_{min}/(R_{min}+1)$.

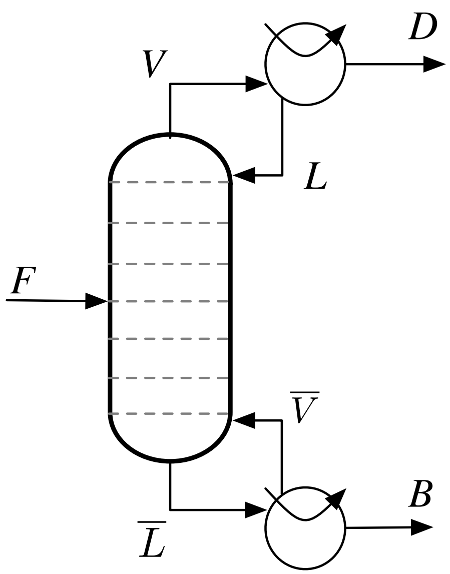


For saturated liquid feed, $R_{\min} = \dfrac{1}{z_F(\alpha-1)}$

Example

We want to separate a mixture of n-heptane and n-octane using distillation at atmospheric pressure.

If the feed is 40 mole% n-heptane as a saturated vapor, determine the minimum reflux ratio and minimum number of stages required to obtain product streams with 95% and 5% n-heptane.



Known:

- $x_D = 0.95$
- $x_B = 0.05$
- $z_F = 0.4$, saturated vapor

Needed:

- K-values (equilibrium curve)
- q-line
- operating lines