CE407 SEPARATIONS

Lecture 06

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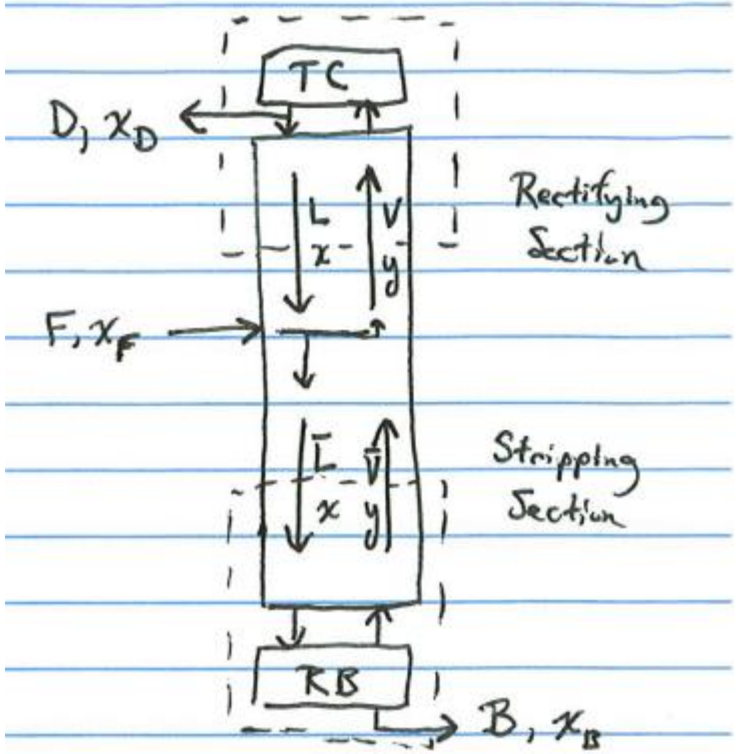
Continuous Distillation with Reflux McSH pp 670-682

- V is the molar flow of vapor above the feed
- L is molar Flow of liquid above the feed
- D is the molar flow of Distillate leaving the column



Rectifying Section Control Volume

- Total Moles: $V = L + D$
- Light Component $Vy = Lx + Dx_D$

$$y = \frac{L}{V}x + \frac{D}{V}x_D$$ (divide both sides by V)

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

$$y = \frac{L/D}{L/D + 1}x + \frac{x_D}{L/D + 1}$$ (divide top and bottom by D)

Constant Molal Overflow

- Assumes that L and V are both approximately constant throughout the rectifying section. This is almost always an excellent approximation.

Continuous Distillation with Reflux

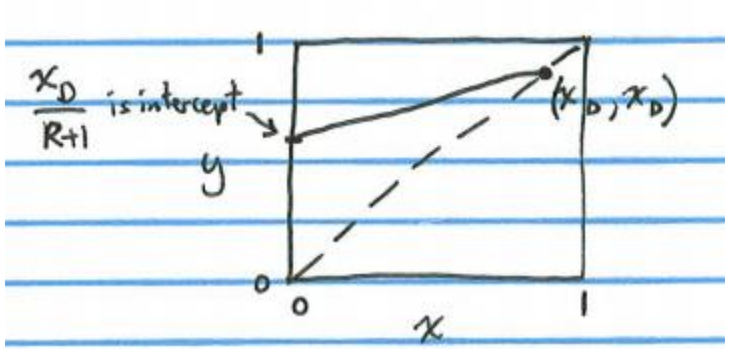
- Define Reflux Ratio $R = {}^{L}/_{D}$, this is the ratio of how much of the liquid exiting the condenser is returned to the column as Reflux versus how much exits the column as Distillate
- Book refers to this as $\mathbf{R_D}$
- Rectifying Operating Line

★ $$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$$ eq 21.22

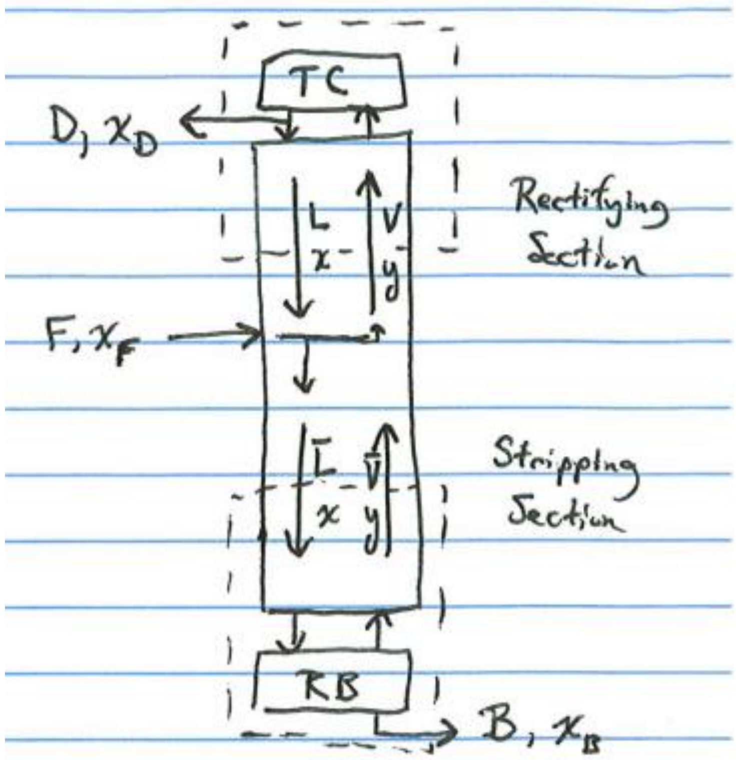
- The Operating Line is a material (mole) balance for the section of the column above the feed
- It relates the value of y to the value of x at the same location (height) in the column

Continuous Distillation with Reflux

- $y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$
  - When $x_n = x_D$ $then$ $y_{n+1} = x_D$
  - When $x_n = 0$ $then$ $y_{n+1} = \frac{x_D}{R+1}$
- Assuming Constant Molar Overflow make the Operating Line a straight line



Continuous Distillation with Reflux



- $\bar{V}$ is the molar flow of vapor below the feed
- $\bar{L}$ is molar Flow of liquid below the feed
- B is the molar flow of Bottoms leaving the column

Stripping Section Control Volume

- Total Moles $\bar{L} = \bar{V} + B$
- Light Component $\bar{L}\,x = \bar{V}\,y + B\,x_B$

Constant Molal Overflow

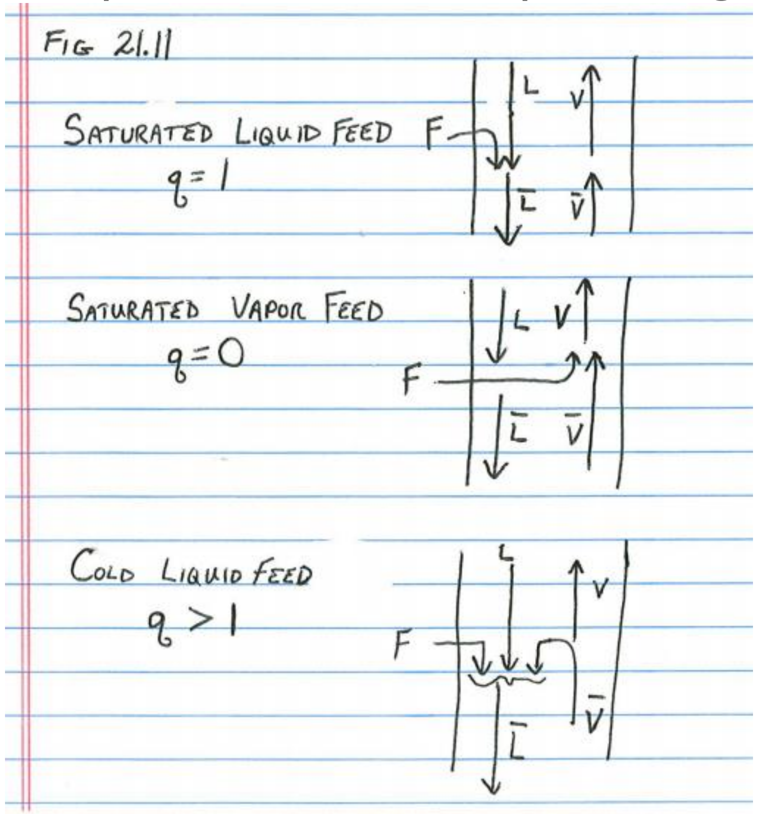
  - Assumes that $\bar{L}$ and $\bar{V}$ are both approximately constant throughout the stripping section. This is almost always an excellent approximation.

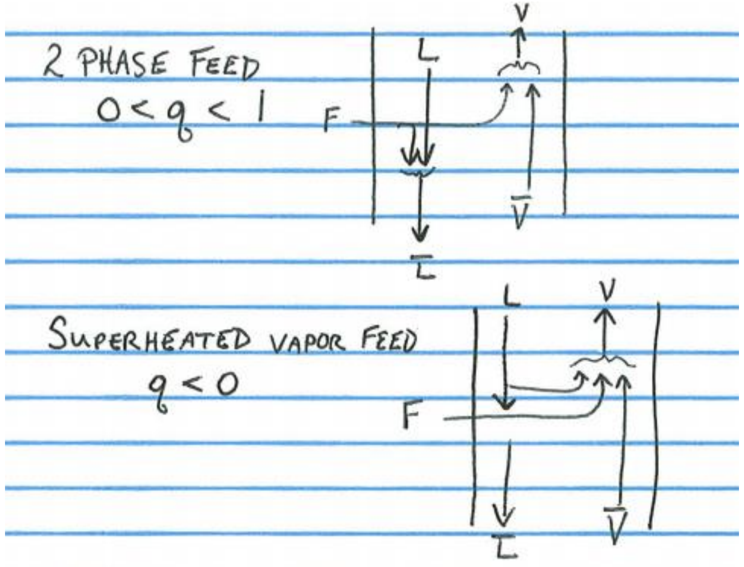
- Using similar algebra as in rectifying section
- $y = \frac{S+1}{S}x - \frac{x_B}{S}$ where Boil Up Ratio $S = \bar{V}/B$

- Note that when **x = x_B**, **y = x_B**
- We typically don't work with this equation

Feed Quality, q

- Note: $L \neq \bar{L}$ and $V \neq \bar{V}$ in many cases. This is because the feed steam enters in the middle of the column and is added to one or the other or distributed to both
- q = moles/time of liquid that get added to the Reflux (L) per mole/time of feed





$$\bar{L} = L + q\,F \qquad \text{eq 21.29}$$

$$V = \bar{V} + (1 - q)F \qquad \text{eq 21.30}$$

See equations 21.27 and 21.28 for discussion of how to calculate q for cold liquid feed and superheated vapor

Feed Line

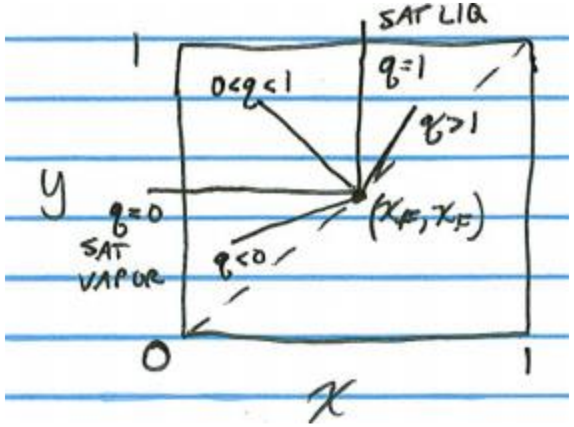
- This is a line that shows all of the points that satisfy both equations of the Rectifying Operating Line and the Stripping Operating Line
- Let's look at the mole balances for each section:
  1) R Op Line $\boldsymbol{V\,y = L\,x + D\,x_D}$ eq 21.12 / 21.31
  2) S Op Line $\boldsymbol{\bar{V}y = \bar{L}\,x - B\,x_B}$ eq 21.18 / 21.32
- A point (x,y) that is on both operating lines must satisfy both equation 1) and 2)
- Subtract eq 2) from eq 1)
  - Both sides of eq 2 are equal, so we are subtracting the same value from each side of eq 1 and will still have an equality
- $\boldsymbol{(V - \bar{V})\,y = (L - \bar{L})\,x + D\,x_D + \mathrm{B}\,x_B}$
  - We know that $\boldsymbol{(V - \bar{V}) = (1 - q)\,F}$ eq 21.30
  - We know that $\boldsymbol{(\bar{L} - L) = q\,F}$ eq 21.29
  - We know from molar balance of light component across the entire tower
    - $\boldsymbol{D\,x_D + \mathrm{B}\,x_B = F\,x_F}$

Feed Line

- Making substitutions…
- $(1 - q)\, F\, y = -q\, F\, x + F\, x_F$ this can be rearranged to

$$y = \left(\frac{-q}{1-q}\right) x + \frac{x_F}{1-q}$$

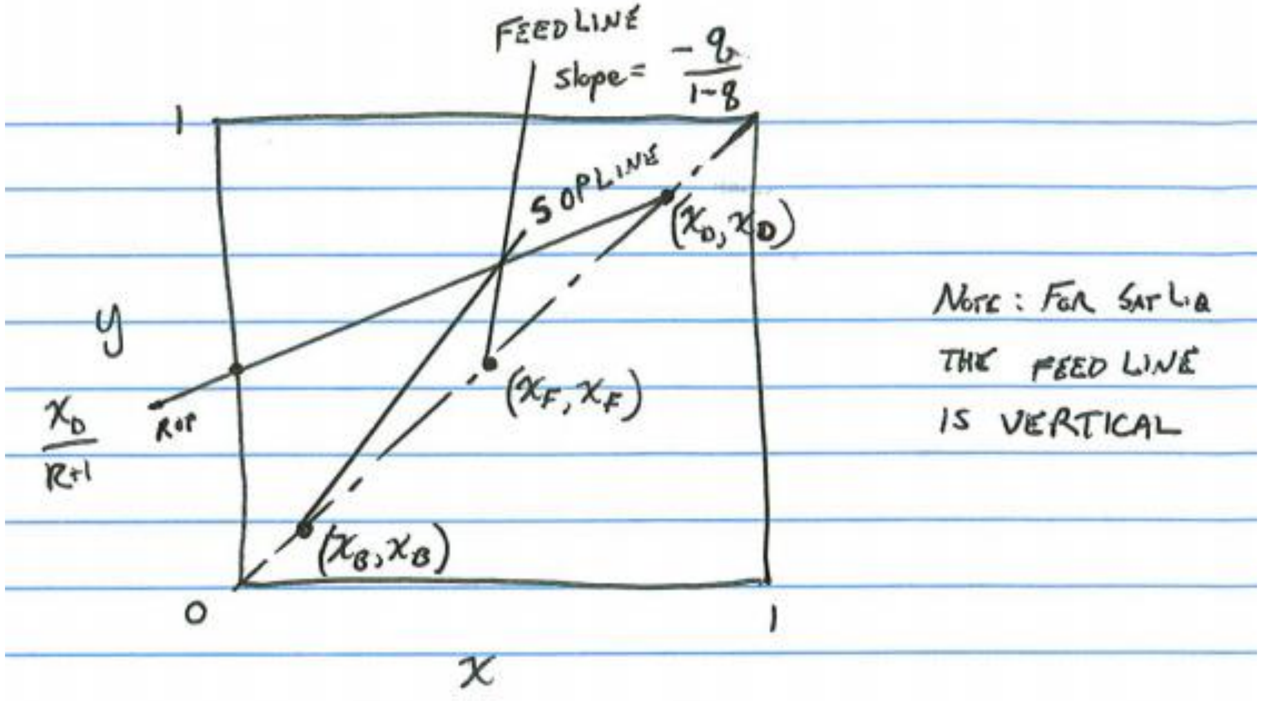
eq 21.34



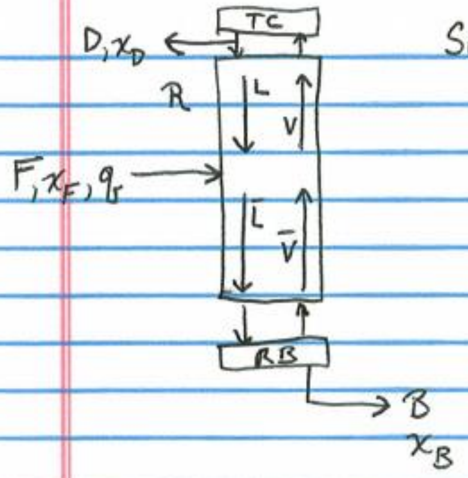
- The feed line is the collection of all points that satisfy the intersection of all possible pairs of R and S Op Lines
  - Notice that there is no mention of Reflux Ratio, Boil Up Ratio, $\mathbf{x_D}$, or $\mathbf{x_B}$
  - Those are used to define the various possible Operating Lines
- When $\mathbf{x} = \mathbf{x_F}$, $\mathbf{y} = \mathbf{x_F}$ so the point ($\mathbf{x_F}$, $\mathbf{x_F}$) is on the feed line
- The slope of the feed line is $\frac{-q}{1-q}$
  - Note that for saturated liquid (q = 1) the slope is infinite, which corresponds to a vertical line

Let's put these lines together…

- **R OP Line:** Draw line from point (x_D, x_D) to intercept $\frac{x_D}{R+1}$
- **Feed Line:** Draw line from point (x_F, x_F) with slope = $\frac{-q}{1-q}$
- **S OP Line:** Remember it includes point (x_B, x_B)
  - Remember that the feed line is the collection of points that satisfy both the R OP Line and the S OP Line
  - Therefore the intersection of the feed line and our R OP Line MUST be on our S OP Line!
  - Draw S OP line from (x_B, x_B) to the intersection of feed line and R OP Line



Recap



SPECIFIED:

F, x_F, q, x_D, x_B, R

WE CAN CALCULATE THE REST AS FOLLOWS

$$D = F\left(\frac{x_F - x_B}{x_D - x_B}\right)$$

$$B = F\left(\frac{x_D - x_F}{x_D - x_B}\right)$$

$$L = RD$$

$$V = L + D = (R+1)D$$

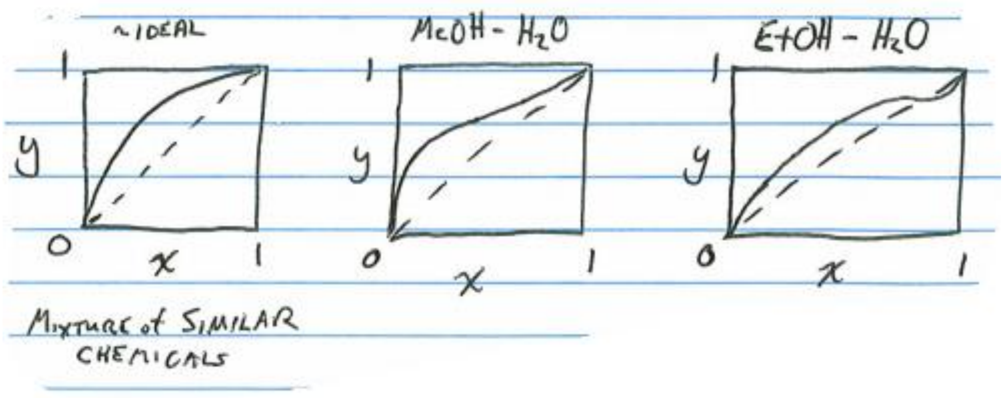
$$\bar{L} = L + qF$$

$$\bar{V} = V - (1-q)F$$

$$\text{reboil ratio} = \bar{V}/B$$

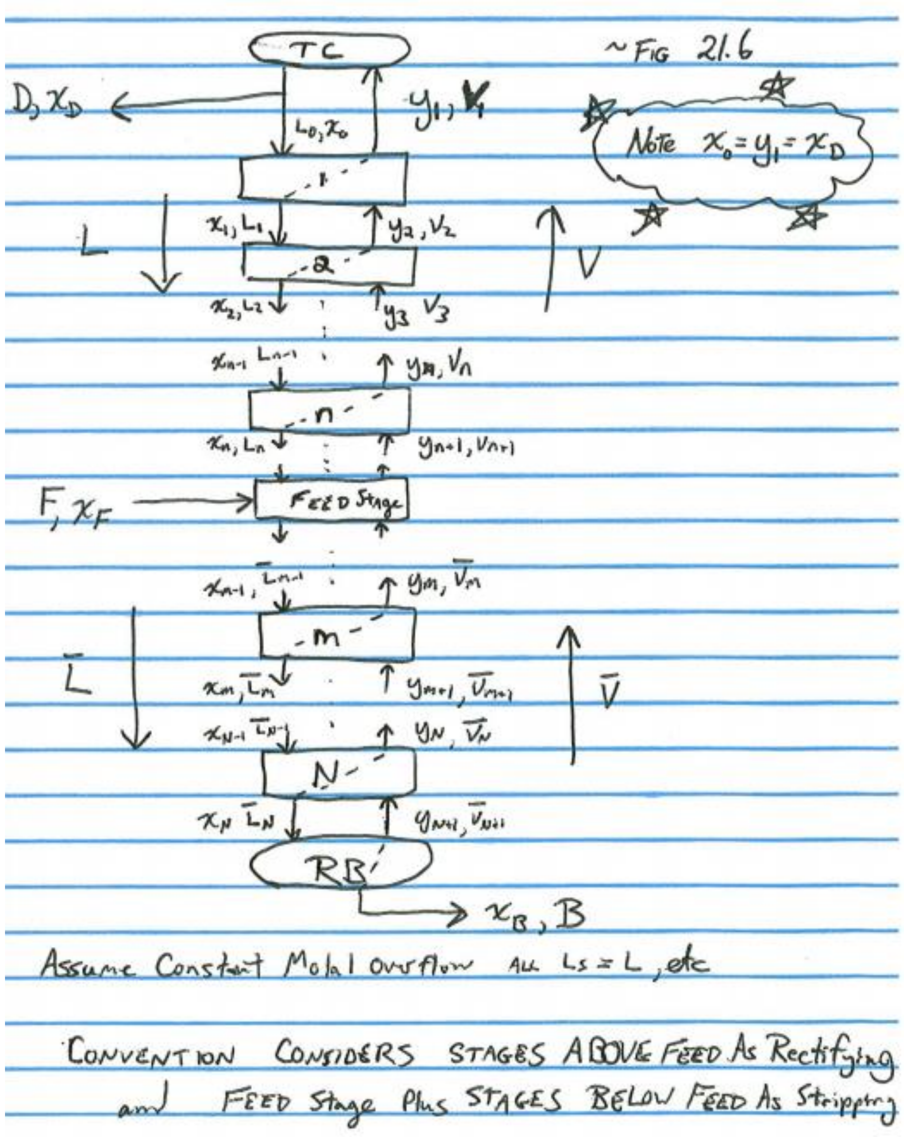
Equilibrium Curves

- $y_i P = x_i \gamma_i P_i^{sat}(T)$
- Because distillation is a high temperature and low/moderate pressure operation the vapor phase will behave ideally (left hand side of equation)
- Liquid may or may not behave ideally…



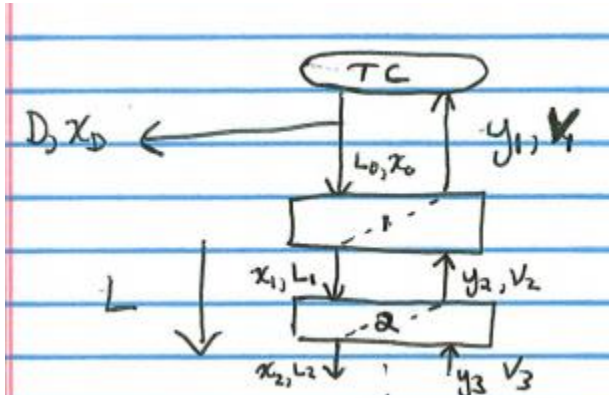
- EtOH – H_2O system has azeotrope
  - Eq curve crosses 45° line
  - Cannot distill to an x_D greater than the Azeotrope
- Equilibrium Curve will ALWAYS pass through points (0, 0) and (1, 1)

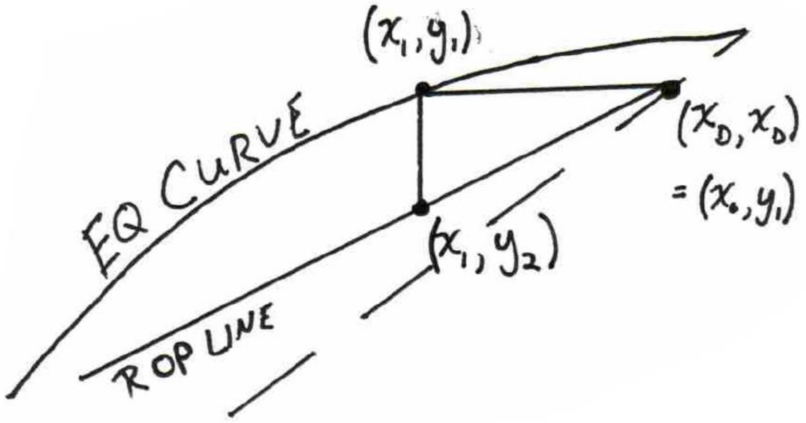
McCabe-Thiele for Continuous Distillation with Reflux



McCabe-Thiele for Continuous Distillation with Reflux

- Start at point ($\mathbf{x_0}$, $\mathbf{y_1}$) = ($\mathbf{x_D}$, $\mathbf{x_D}$)
  - $\mathbf{L_1}$ leaves stage 1 and must be in equilibrium with $\mathbf{V_1}$. Therefore it must lie on equilibrium curve at same y value as ($\mathbf{x_0}$, $\mathbf{y_1}$)
  - Draw horizontal line from ($\mathbf{x_0}$, $\mathbf{y_1}$) to EQ curve
  - This is point ($\mathbf{x_1}$, $\mathbf{y_1}$)
- Stream $\mathbf{V_2}$ is at the same height as stream $\mathbf{L_1}$
  - The point ($\mathbf{x_1}$, $\mathbf{y_2}$) must therefore be on the Operating Line
  - This point has the same **x** value as point ($\mathbf{x_1}$, $\mathbf{y_1}$) and can be located by drawing a vertical line from point ($\mathbf{x_1}$, $\mathbf{y_1}$) to the OP Line
- We have just progressed one stage!
  - We are taking steps by alternating between looking at equilibrium between flows exiting and mass balance for flows at same column height

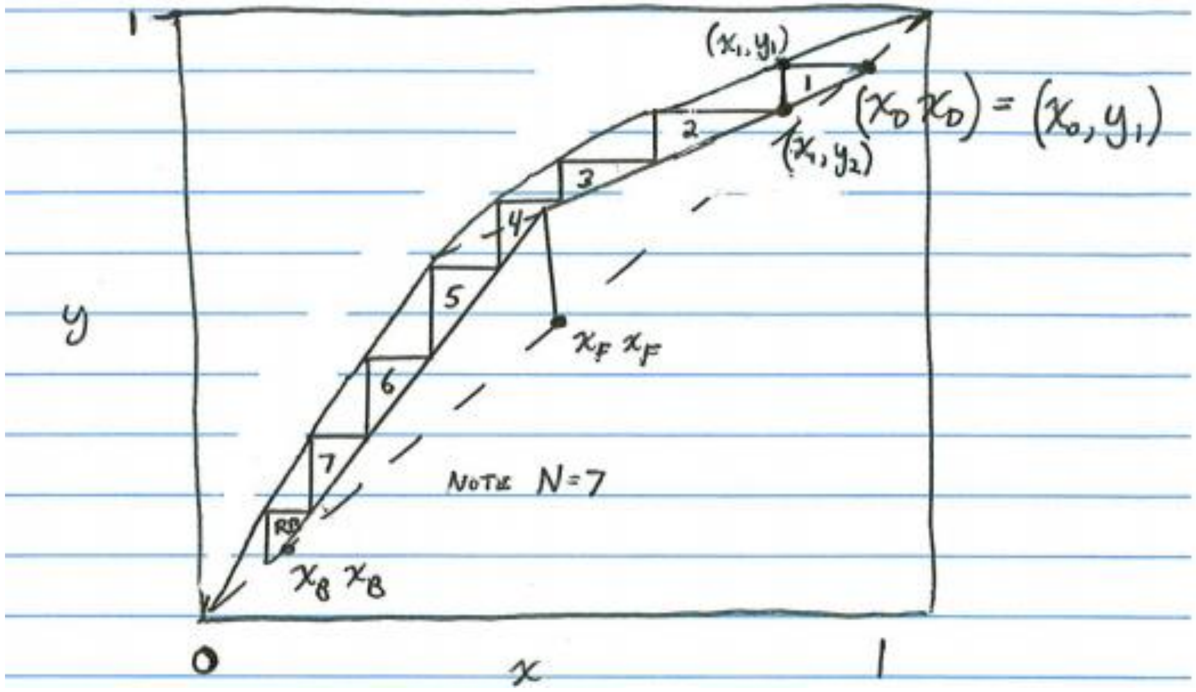




McCabe-Thiele for Continuous Distillation with Reflux

- Continue on in this method until you reach or pass point ($\mathbf{x_B}$, $\mathbf{x_B}$)
- Notice that at stage 4 we switched from using the R OP Line to using the S OP Line because we have crossed the Feed Line and therefore the S OP Line represents the appropriate molar balance equation
- Last step is the Reboiler (Liquid and vapor leaving reboiler are in equilibrium with one another)

- Last step will most likely not land on $\mathbf{x_B}$. Round up
- Report stages as **N** stages plus Reboiler. Feed enters on stage # **n**
- Let's all agree to number stages with stage number one starting at upper right (i.e. by $\mathbf{x_D}$)



Feed Location

- Feed should be introduced at stage where it contacts the intersection of the two OP Lines
  - This leads to minimum number of steps