CE407 SEPARATIONS

Lecture 07

Instructor: David Courtemanche

University at Buffalo
Department of Chemical and Biological Engineering
School of Engineering and Applied Sciences

Partial Condensers McSH pp 674-675

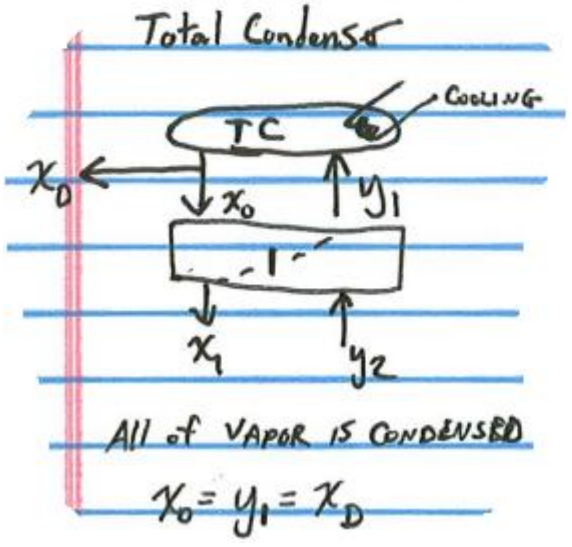
- A total condenser converts the total vapor flow to liquid flow
  - Therefore the entering vapor and exiting liquid have the same composition

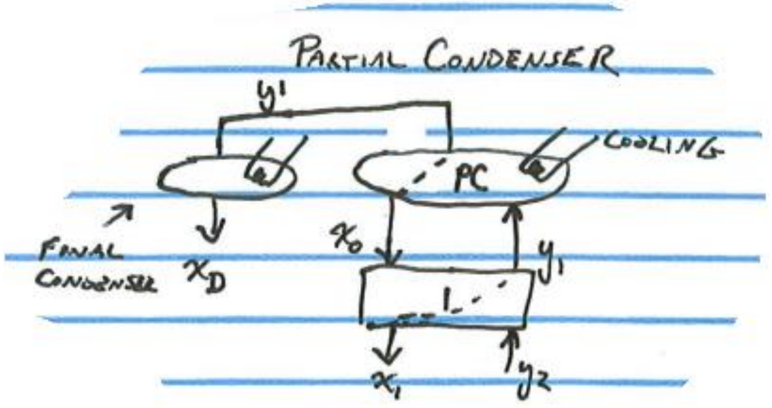
$$x_D = x_0 = y_1$$

- A partial condenser only converts a portion of the vapor flow to liquid
  - The composition of the vapor and liquid exiting are in equilibrium with one another and differ from the composition of the entering vapor.

$$y' = y^*(x_0) = x_D \neq y_1$$

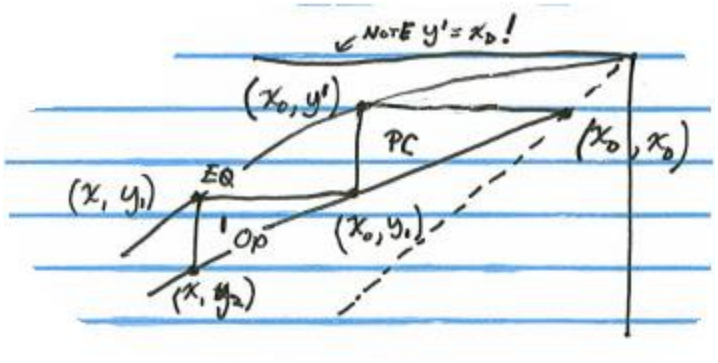
  - A secondary condenser then converts the rest of the vapor to a liquid





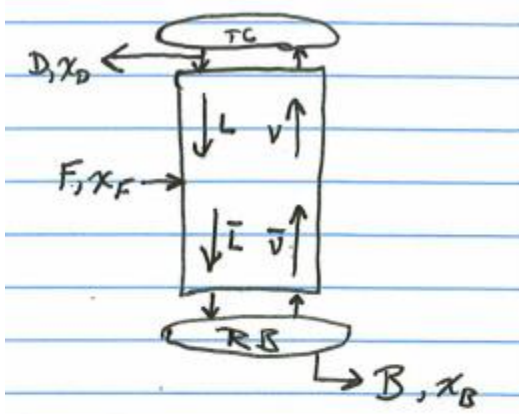
Partial Condensers and McCabe-Thiele

- Because of the equilibrium relationship between the vapor and liquid exiting the partial condenser there is separation being accomplished
- The first step on the McCabe-Thiele is the partial condenser
  - This step does NOT count as a stage
  - Stages are actual trays in the column



- Make sure you know whether the condenser is a Total Condenser or a Partial Condenser

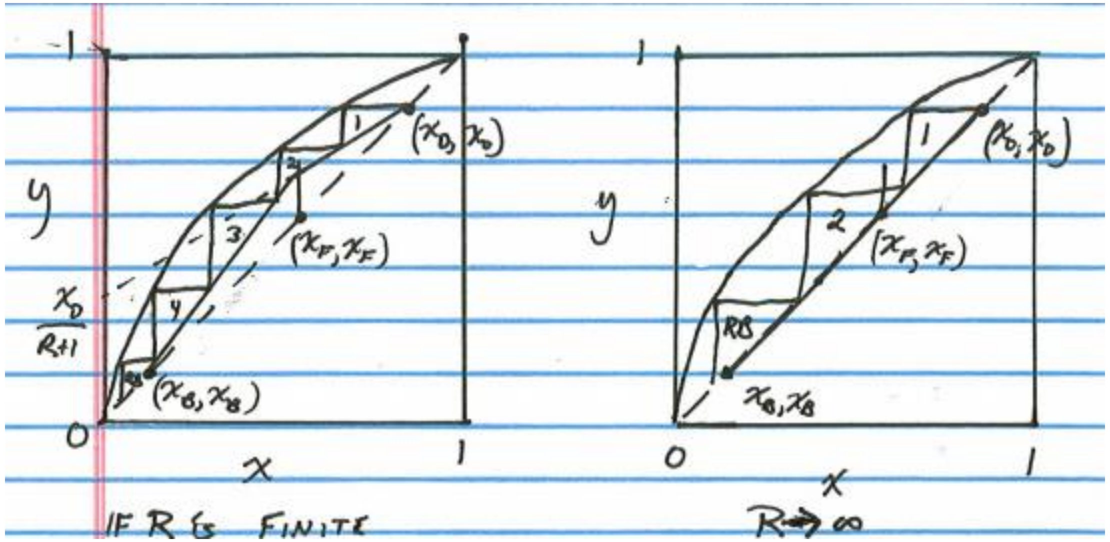
Minimum Number of Plates McSH pp 687-688



- Occurs when **R** → ∞, or "Total Reflux"
- **L** = **R** * **D**
- **B** and **D** are set by the initial mass balance with **F**, $\mathbf{x_F}$, $\mathbf{x_D}$, and $\mathbf{x_B}$
  - **R** does not affect them
- As **R** increases, **L** increases. There is more liquid to do the absorption and therefore less stages are required
- $\bar{L}$, **V**, and $\bar{V}$ are also increased. These increased flows lead to increased duties (energy requirements) in the condenser and reboiler. This adds expense. (Particularly in the Reboiler)
- The column diameter must increase to accommodate the increased flows, particularly the vapor flow (due to high volumetric flow of the vapor)
- Again, **D** and **B** do not increase but the internal flows in the column do

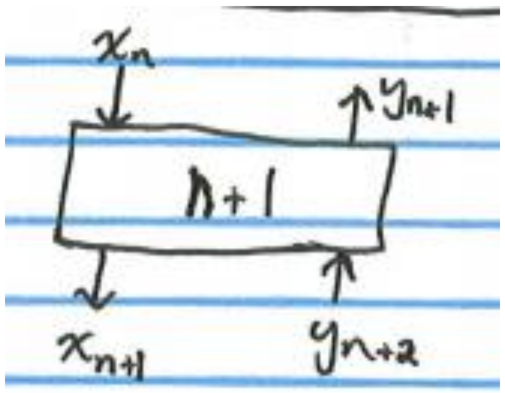
Minimum Plates and McCabe-Thiele

- $y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$
  - As **R** → ∞ Operating Line becomes $y_{n+1} = x_n$



- Each step covers more space as the OP Line is as far from the EQ curve as it can get
- The number of steps on right diagram is $\mathbf{N_{min}}$ **+1**
- One cannot operate here because you have infinitely large flows in the tower

Analytical Approach to Minimum Number of Plates



- Relative Volatility $\alpha = \dfrac{y_1/x_1}{y_2/x_2} = \dfrac{y/x}{(1-y)/(1-x)}$

- For stage **n+1**:

$$\alpha = \frac{y_{n+1}/x_{n+1}}{(1 - y_{n+1})/(1 - x_{n+1})}$$

- This can be rearranged to:

$$\frac{y_{n+1}}{1 - y_{n+1}} = \alpha \frac{x_{n+1}}{1 - x_{n+1}}$$

- Because we have total reflux the operating line has collapsed to be $y_{n+1} = x_n$
- Substitute into previous equation:

$$\frac{x_n}{1 - x_n} = \alpha \frac{x_{n+1}}{1 - x_{n+1}}$$

- This relates one stage to the next

Analytical Approach to Minimum Number of Plates

- If α is a constant…
- n = 0 $\frac{x_0}{1-x_0} = \alpha \frac{x_1}{1-x_1}$ but note that $\frac{x_1}{1-x_1} = \alpha \frac{x_2}{1-x_2}$
- So… $\frac{x_0}{1-x_0} = \alpha(\alpha \frac{x_2}{1-x_2}) = \alpha^2 \frac{x_2}{1-x_2}$ but note that $\frac{x_2}{1-x_2} = \alpha \frac{x_3}{1-x_3}$
- So… $\frac{x_0}{1-x_0} = \alpha^2(\alpha \frac{x_3}{1-x_3}) = \alpha^3 \frac{x_3}{1-x_3}$
- Which finally leads to:

$$\frac{x_0}{1-x_0} = \alpha^{N_{min}+1} \frac{x_{N_{min}+1}}{1-x_{N_{min}+1}}$$

after $\mathbf{N_{min}+1}$ steps (which is $\mathbf{N_{min}}$ stages plus reboiler)

- This assumes a total condenser

Analytical Approach to Minimum Number of Plates

- Note that $x_o = x_D$ and $x_{N_{min}+1} = x_B$
- Therefore: $$\frac{x_D}{1-x_D} = \alpha^{N_{min}+1} \frac{x_B}{1-x_B}$$
- Do some rearranging to obtain:

$$N_{min} + 1 = \frac{\log\left[\frac{x_D(1-x_B)}{x_B(1-x_D)}\right]}{\log \alpha}$$

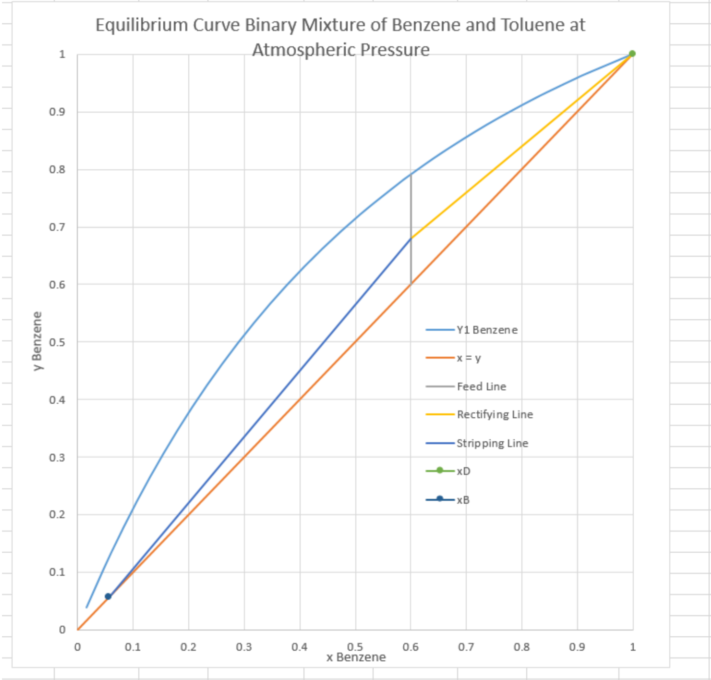
Fenske Equation eq 21.45

- Applies only if you have constant or near constant relative volatility, α
- If α is not constant, use McCabe-Thiele graphical method
- Can use natural logarithm or base 10 logarithm
  - Need to be consistent and use same type in both numerator and denominator

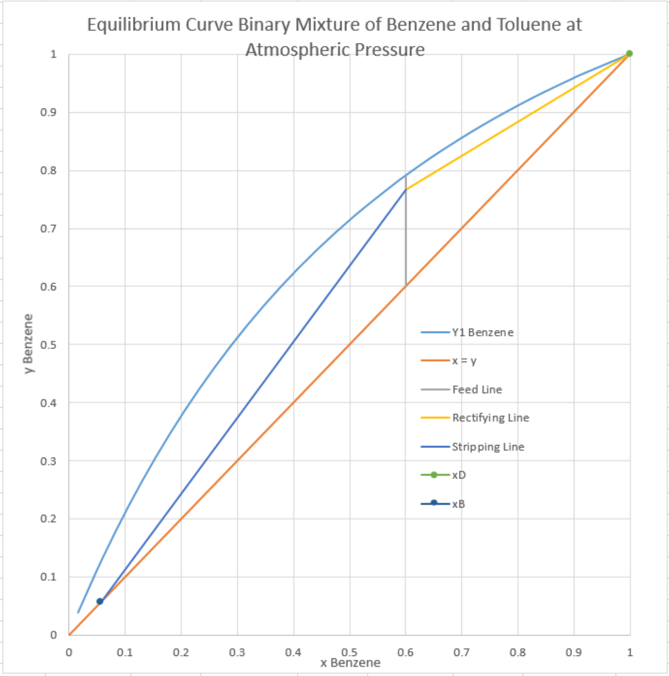
Minimum Reflux Ratio McSH pp 688-691

- As the reflux ratio decreases: the intercept of the R OP Line, $\frac{x_D}{R+1}$, increases. This drives the Operating Lines closer to the EQ Curve and increases the number of steps required.
- When **R** = **R**$_{\mathbf{min}}$, the OP Lines touch the EQ Curve, the steps become infinitely small and an infinite number of steps are required

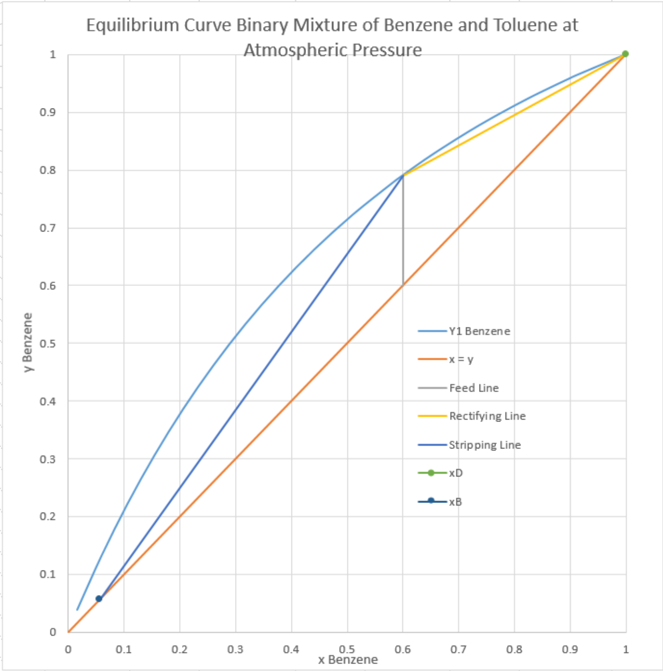
R = 4



R = 1.5

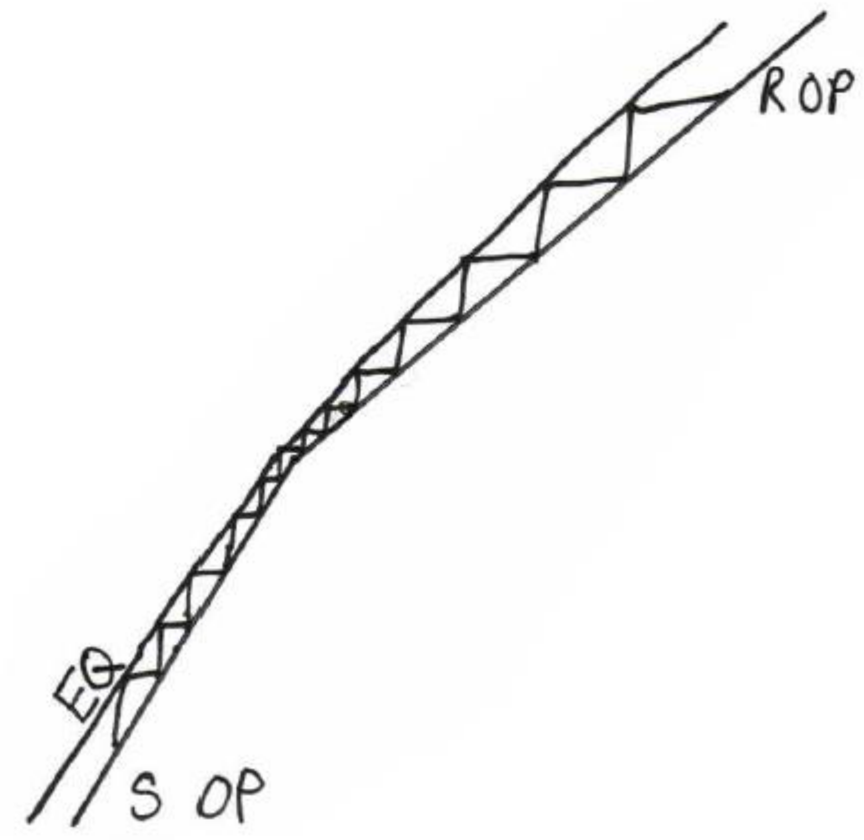


R = Rmin

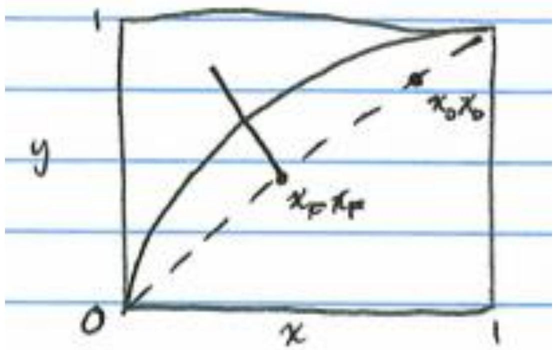


Pinch Point aka Invariant Zone

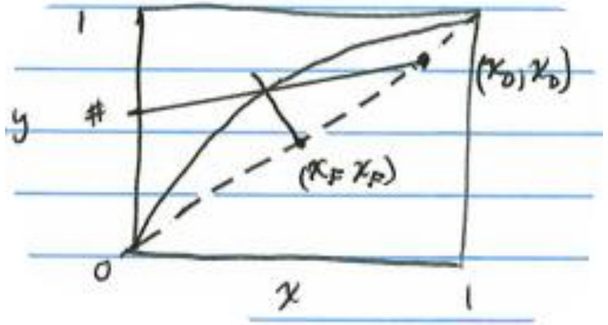
- If $R > R_{min}$ by a small amount you will not have an infinite number of stages, but the change in composition from one stage to the next will be very small
- These stages are not being well used



How to Determine R_{min}



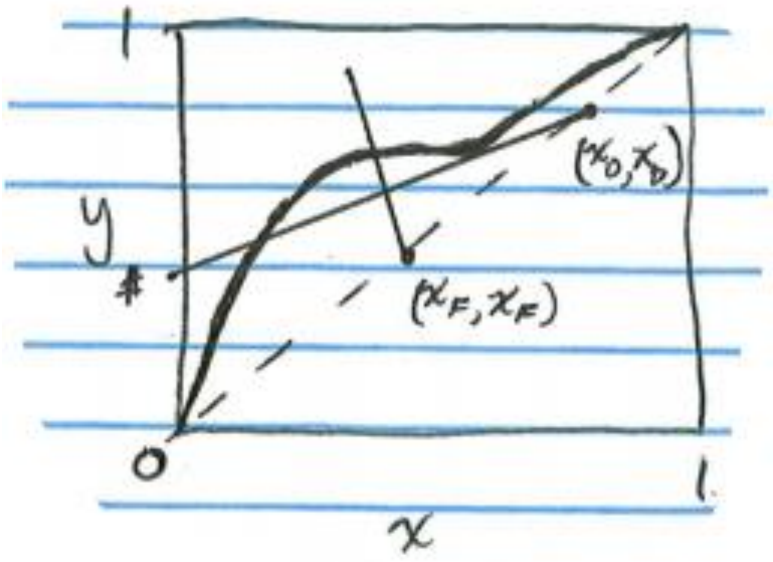
- Plot EQ curve
- Plot (x_D, x_D) and (x_F, x_F)
- Plot Feed Line
- Place ruler on (x_D, x_D) and rotate it until it first contacts the EQ Curve in the region between Feed Line / EQ Curve Intersection and (x_D, x_D)

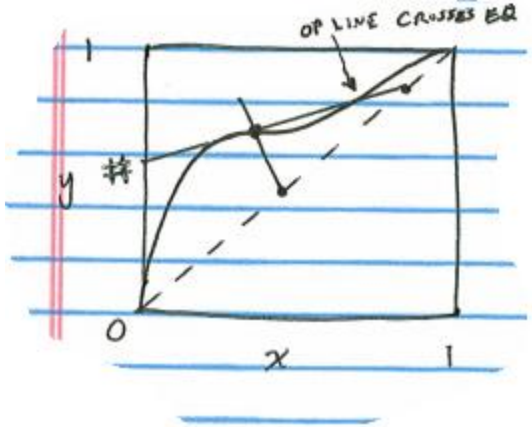


- Read off the value of the intercept
  - Designated as # here
- $\frac{x_D}{R_{min}+1}$ = # Solve for $\mathbf{R_{min}}$
- Note that Stripping Operating Line is not involved in this calculation

How to Determine R_{min}

- In previous example we had an ideal EQ Curve and first contact occurred right at the intersection of the Feed Line and the EQ Curve, that is not always the case
- With this non-ideal EQ Curve the R OP Line tangentially contacts the EQ Curve to the right of the intersection
- NEVER do this!
  - If one just assumes that the R OP Line will cross the intersection and it actually crosses the EQ curve then your work will be just meaningless
  - Dr. Courtemanche may cry
- After you have determined Rmin you will want to start a new diagram with the actual Operating Lines, etc
  - If you continue to use the original diagram it will become too cluttered to be of use

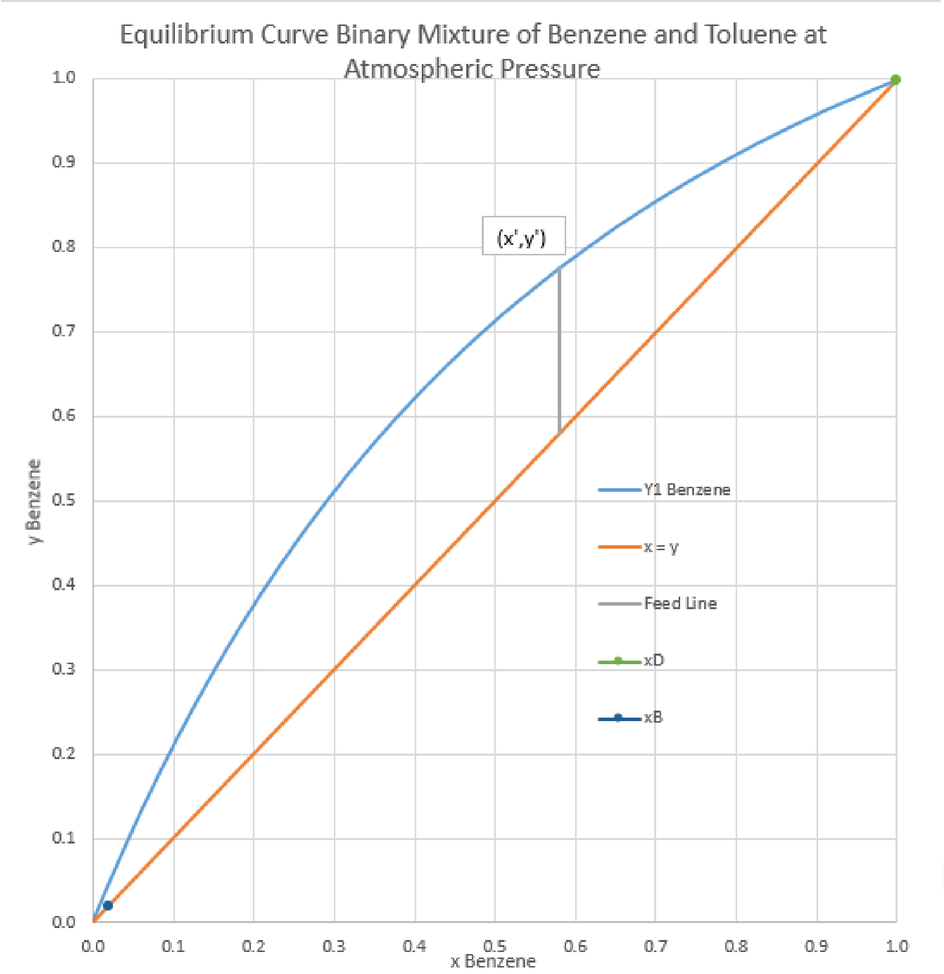




University at Buffalo
Department of Chemical and Biological Engineering
School of Engineering and Applied Sciences

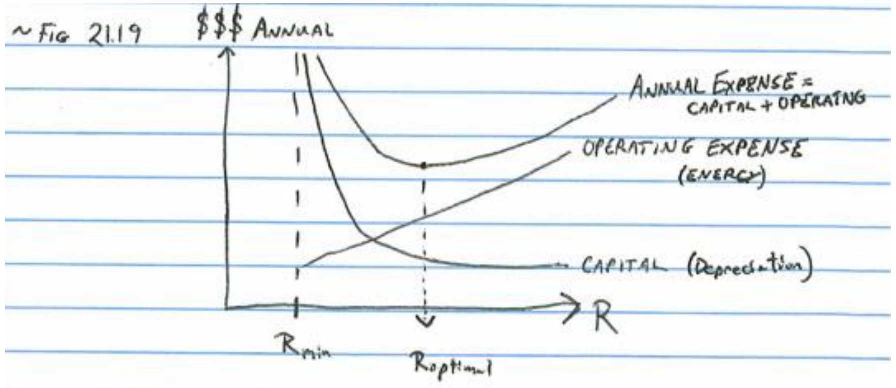
Alternate Method to Determine R_{min}

- For an ideal curve, there is another method for determining R_{min}
- Find the intersection of the Feed Line and the VLE curve, (x', y')
- $R_{min} = \frac{x_D - y'}{y' - x'}$ Eq. 21-47
- This can sometimes lead to a more accurate value if you use your VLE calculation to get a precise location of this point
  - As opposed to reading the y intercept of a line which goes from ($\mathbf{x_D}$, $\mathbf{x_D}$) through this point



Optimum (Operating) Reflux Ratio

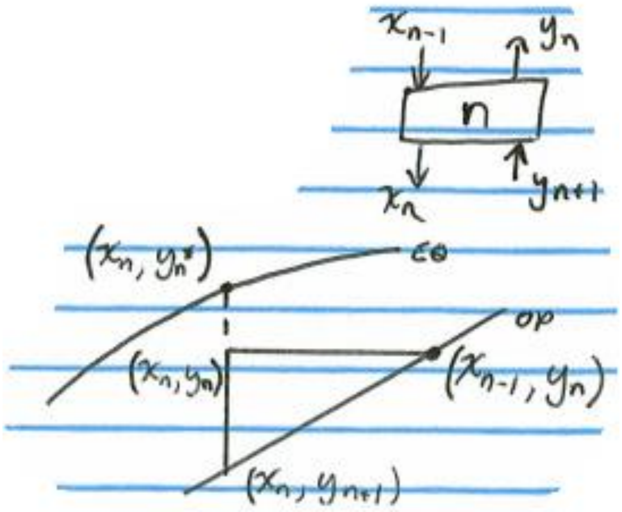
- Cost Optimization
- Equipment Cost/Capital Cost
  - Annual Cost of Tower = Depreciation = (Capital Cost) / (# years useful life)
- Operating Expenses are somewhat linear to R because the flows are proportion to R and energy use in the Reboiler and Condenser are roughly proportional to the flow rates internal to the column



- Optimal **R** is near **R_{min}** because the depreciation curve is so steep in that region
- **$R = 1.3 * R_{min}$** is a typical result, it depends on materials of construction, etc
- This is just a guideline, you may choose to run a higher **R** in order to assure meeting specs
- In an actual plant design you would do an actual cost estimation for more accuracy

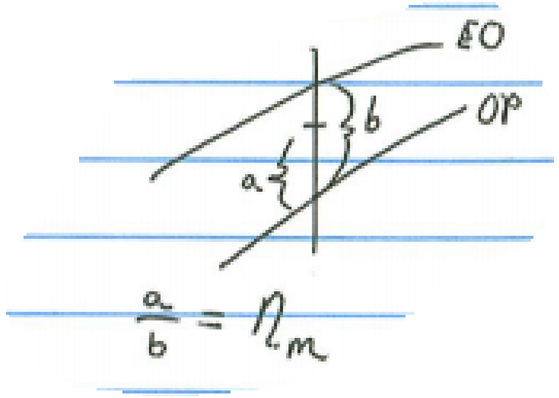
Stage Efficiency McSH pp 712-722

- What if $\mathbf{x_n}$ and $\mathbf{y_n}$ leaving each stage have not actually reached equilibrium?
  - Due to low residence time or less than perfect mixing, etc…
- First define Overall Efficiency $\eta_O = \frac{N_{ideal}}{N}$ or $N = \frac{N_{ideal}}{\eta_O}$
  - It's logical and easy to understand
  - It's not very useful, because you need to know the answer to the number of stages before you can use it
  - It is not useful in predicting the effect of any changes you may want to make
- Murphree (Plate) Efficiency
  - $\eta_M = \frac{y_n - y_{n+1}}{y_n^* - y_{n+1}}$ where $y_n^* = y^*(x_n)$
  - This acknowledges that you are falling short of reaching the equilibrium value of **y** at each stage
  - Not as straightforward as overall efficiency but much more useful



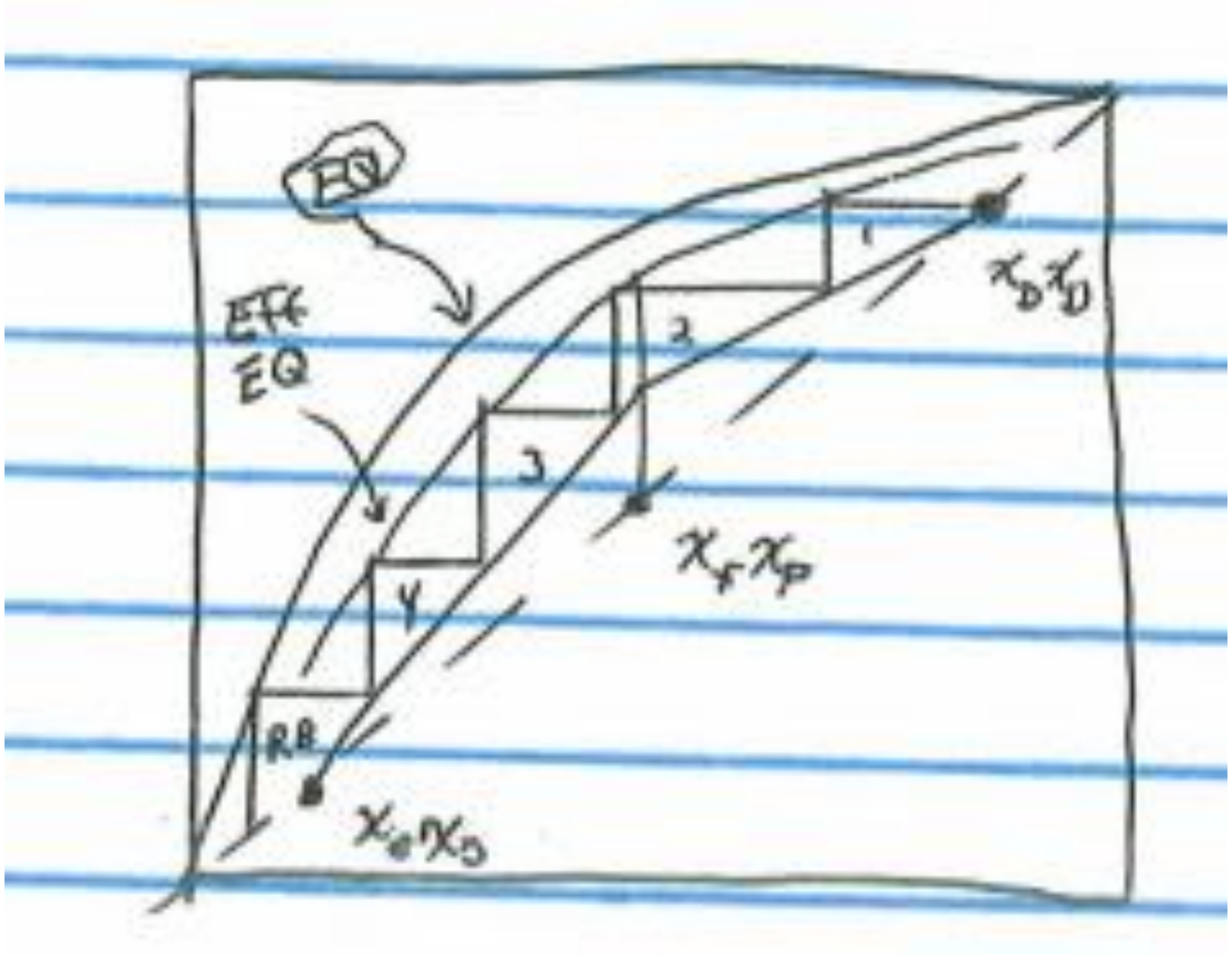
Murphree Efficiency, continued

- $\eta_M = \frac{y_n - y_{n+1}}{y_n^* - y_{n+1}} = \frac{Change\ in\ Vapor\ Composition\ Actually\ Achieved}{Change\ in\ Vapor\ Composition\ Possible\ if\ Equilibrium\ Achieved}$
- Could have been defined in terms of liquid phase composition but it is traditionally done with vapor compositions
- We will discuss how to determine a value for η_M later in the course
- **Graphical Method**
- Create Effective Equilibrium Curve
- $Eff\ EQ = y + (y^* - y)\,\eta_M = \eta_M y^* + (1 - \eta_M)\,y$
- Where **y*** is the equilibrium value of **y** for a given value of **x** and **y** is the OP Line value of **y** for that same value of **x**
- Generate values of effective EQ for a series of values of x and plot that curve
- Put another way, say that η_M is 0.75. The effective EQ Curve is composed of points that are ¾ of the way up from the operating line to the actual EQ Curve



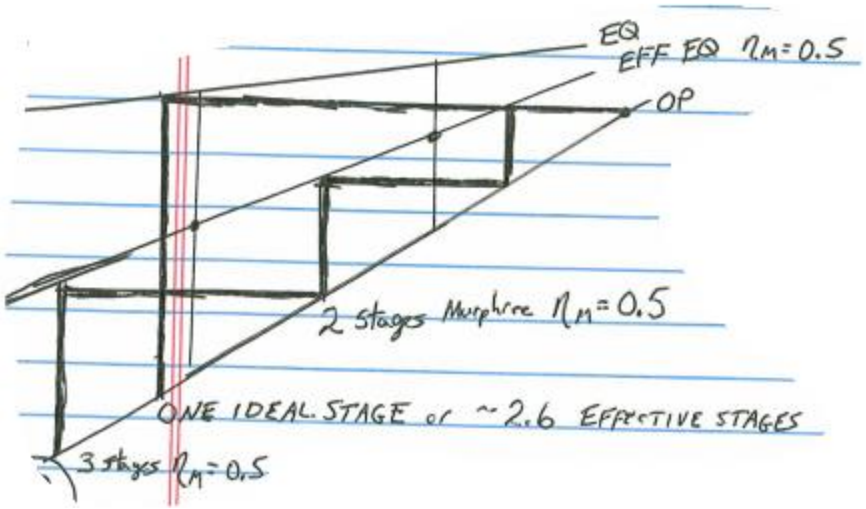
Murphree Efficiency, continued

- Now one can do the McCabe-Thiele Method



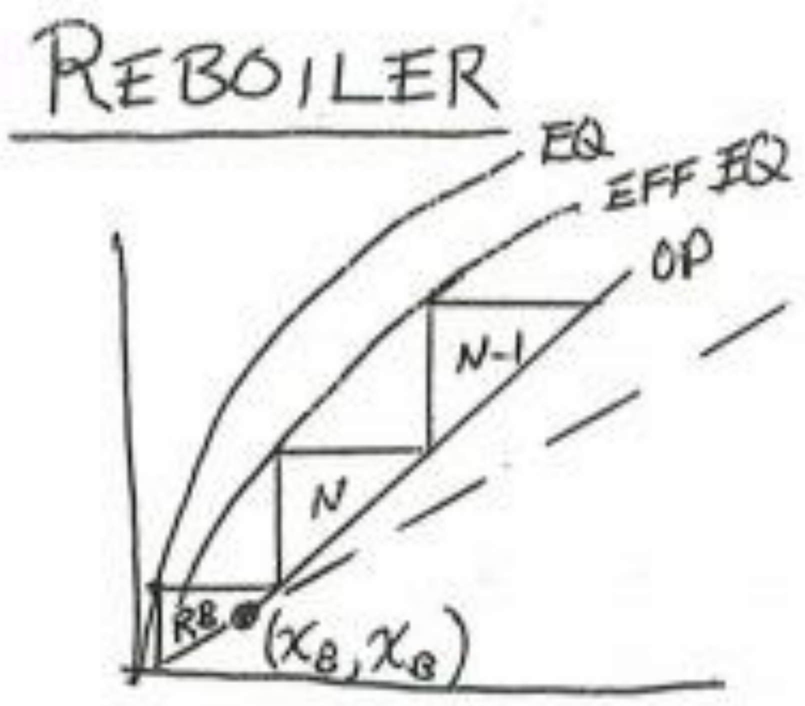
Overall Efficiency is NOT Equal to Murphree Efficiency in General

- Diagram shows a $\boldsymbol{\eta_M = 0.5}$
- There are 2.6 stages required to accomplish the same change in composition as one ideal stage
- $\boldsymbol{\eta_O = \frac{\#\, ideal}{\#\, actual} = \frac{1}{2.6} = 0.38 \neq 0.5}$
- Relative value of $\boldsymbol{\eta_O}$ to $\boldsymbol{\eta_M}$ depends on the relative slopes of the EQ Curve and Operating Lines



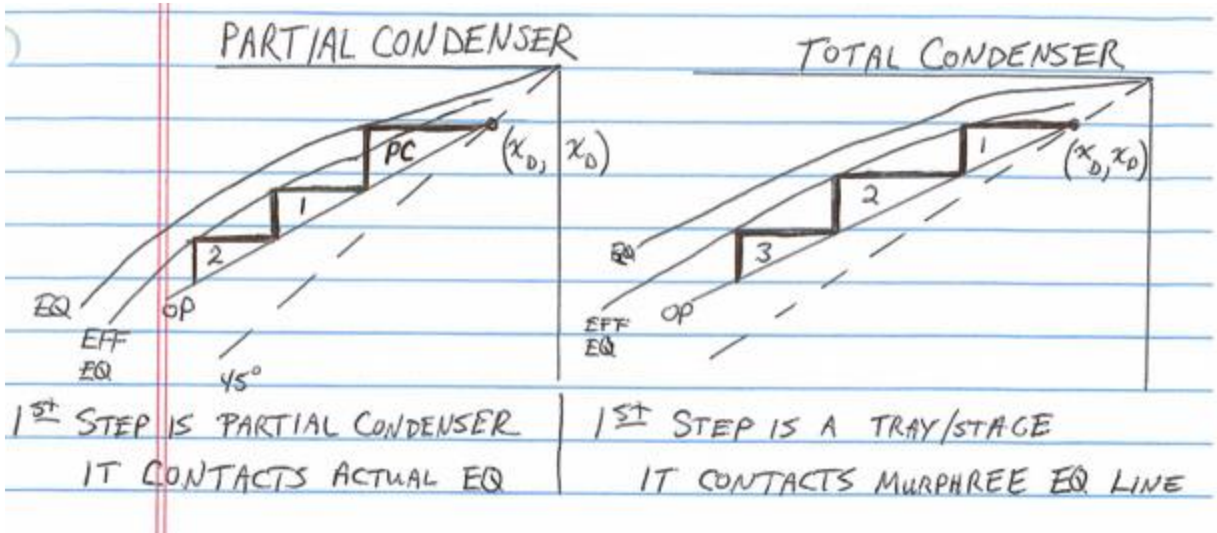
Reboiler

- Notice that the last step (the Reboiler) is drawn going to the actual EQ Curve and not to the effective curve
  - The reboiler is not a tray or stage, it does not have the non-ideality of the trays and the vapor and liquid leaving the reboiler will be in equilibrium with one another



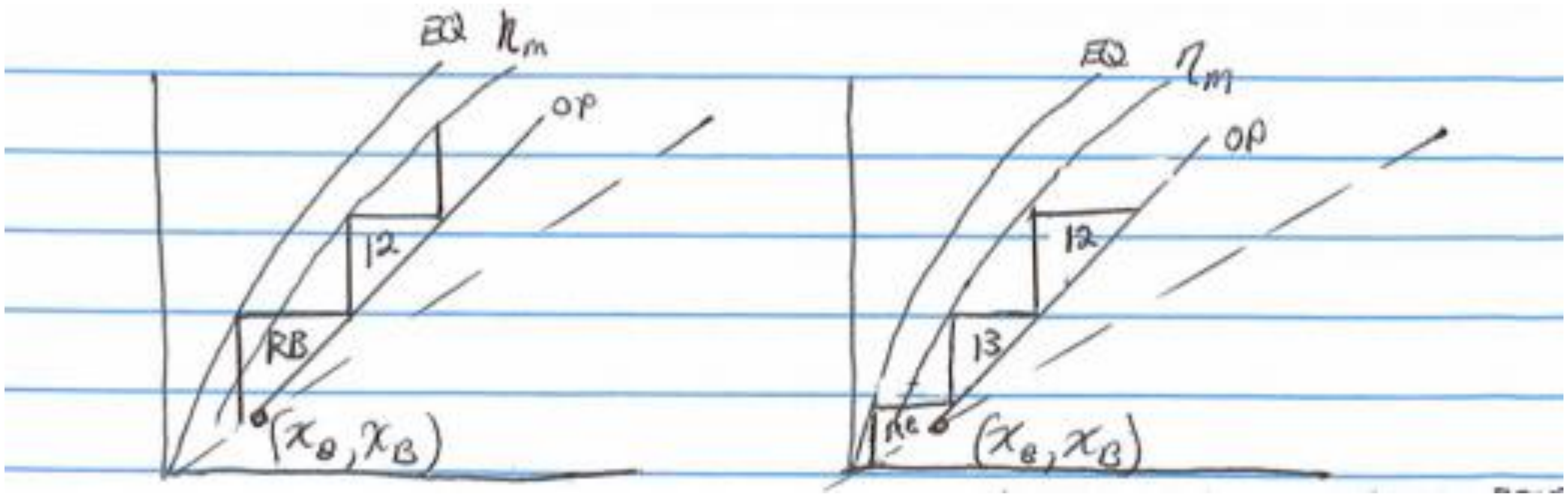
Condenser

- If a total condenser is used then it does not appear on the McCabe-Thiele diagram and is irrelevant to the effective efficiency
- If a partial condenser is used then it shows up as the first step in the McCabe-Thiele diagram
  - Like the reboiler it will still behave in an ideal fashion and should be drawn in contact with the actual EQ Curve, not the effective one
- You **WILL** lose points if you draw the reboiler or partial condenser step as contacting the effective EQ Curve and not the actual EQ Curve (even though it will not necessarily change the answer)



Reboiler Step Caution

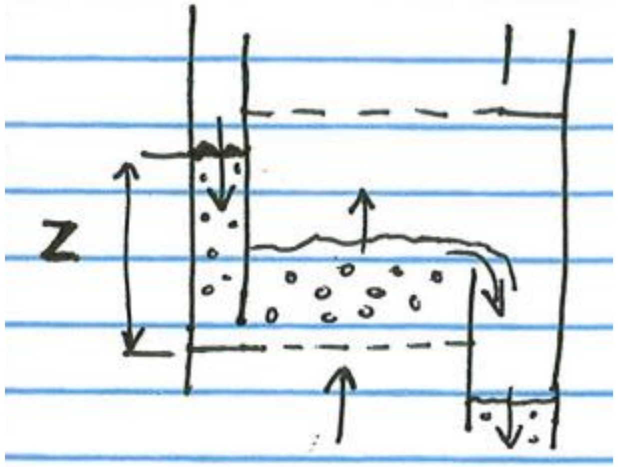
- Notice that on right hand diagram the person doing this analysis drew step 13 as going to the effective EQ Curve and then correctly drew their reboiler step as going all the way to the actual EQ Curve
- However, as you can see on the left hand diagram: if step 13 had been recognized as the reboiler and drawn reaching all the way to the actual EQ Curve, then it would have reached past $\mathbf{x_B}$ and been the final step
- Use caution to make sure you don't include an unnecessary step!



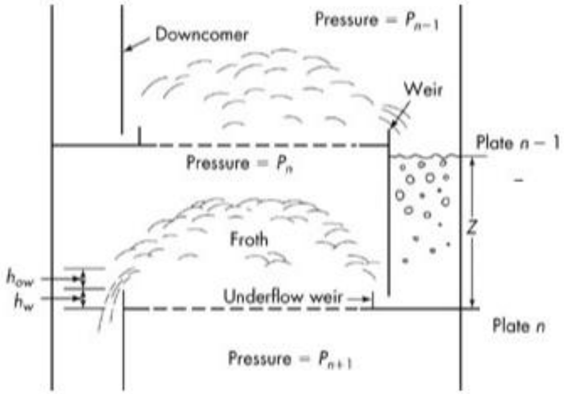
Continuous Distillation – Tower Design

McSH pp 701-712

Design of Sieve Plate Trays

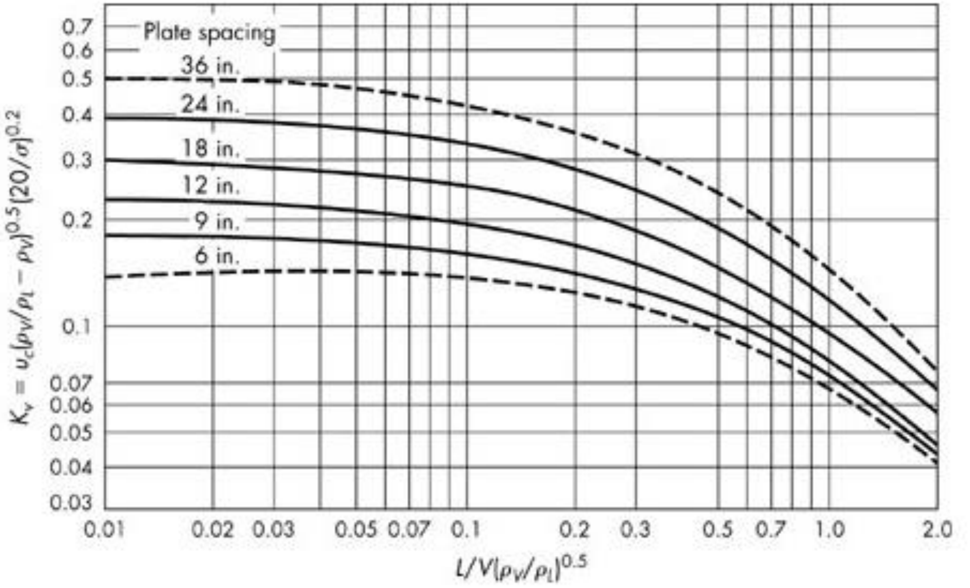


- Pressure increases as you progress down the tower
- The pressure is needed to motivate the vapor through the holes in the tray and through the liquid held up on the tray
- Due to the ΔP, a column of liquid is held up in the downcomer (similar to a monometer) of height **Z**
- The text discusses methods for calculating **Z**, but we won't touch on it at this point
- The important point is that if **Z** exceeds the distance to the weir on the plate immediately above then the column experiences **FLOODING** and the plates won't function properly
- The diameter of the column must be specified such that the vapor velocity does not exceed the **"Flooding Velocity"**



Flooding

- Figure 21.26 in McSH: Note that this is a log-log graph!
- Choose curve corresponding to your tray spacing
- Calculate $\frac{L_{mass}}{V_{mass}}\sqrt{\rho_V/\rho_L}$
  - Note that **L** and **V** are MASS flow rates
  - Note that $\boldsymbol{\rho_V}$ and $\boldsymbol{\rho_L}$ are MASS densities
  - **L/V** we have used in the past were molar flows
- Find $\boldsymbol{K_V}$ from chart
- Use equation 21.68 to calculate flooding velocity



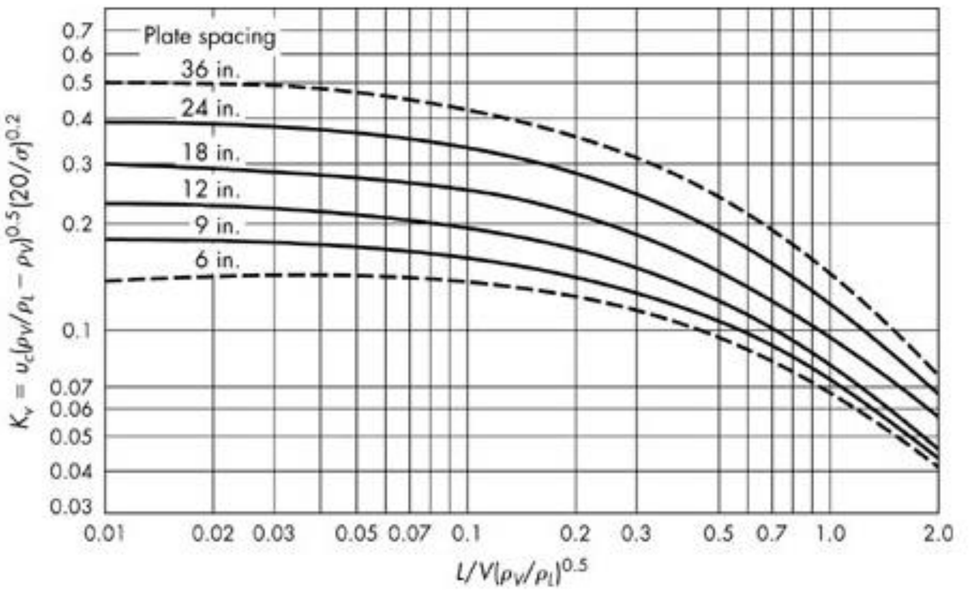
$$u_c = u_{flooding} = K_V\sqrt{\frac{\rho_L - \rho_V}{\rho_V}}\left(\frac{\sigma}{20}\right)^{0.2}$$

- σ is the surface tension in dyn/cm, **u** is in ft/s on this graph
- A given chart will correspond to **u** in ft/s or m/s: *be sure you know which it is!*

Flooding

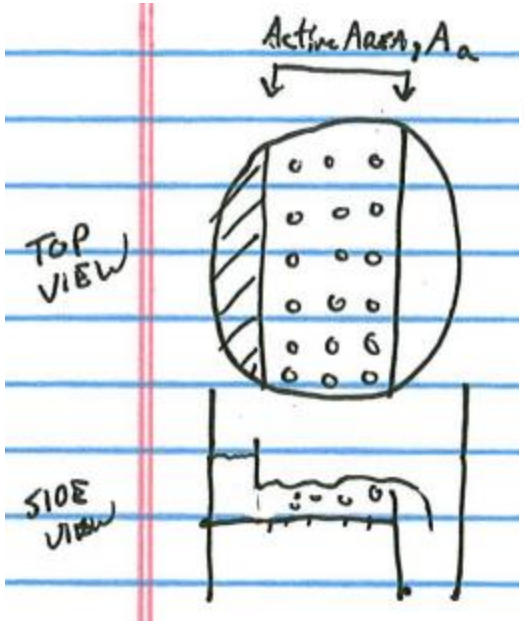
- Calculate $\frac{L_{mass}}{V_{mass}}\sqrt{\rho_V/\rho_L}$
  - Note that **L** and **V** are MASS flow rates
  - Note that $\boldsymbol{\rho_V}$ and $\boldsymbol{\rho_L}$ are MASS flow densities
  - **L/V** we have used in the past were molar flows

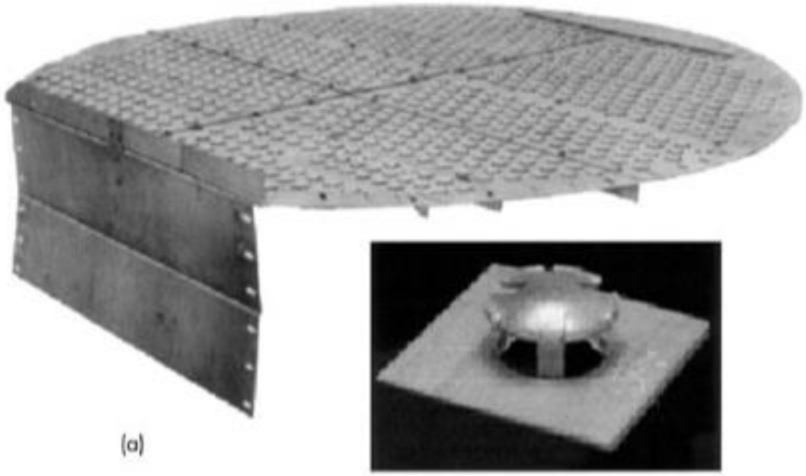
  - $\frac{L_{mass}}{V_{mass}} = \frac{L\,\overline{MW_L}}{V\,\overline{MW_V}}$
  - When we are evaluating at the top of the tower the flows are often close to pure light component and $\overline{MW_L} \approx \overline{MW_V}$
  - Therefore $\frac{L_{mass}}{V_{mass}} \approx \frac{L}{V}$
  - $\frac{L}{V} = \frac{R}{R+1}$ can be used for $\frac{L_{mass}}{V_{mass}}$ as long as we are aware that it only applies when $\overline{MW_L} \approx \overline{MW_V}$



Flooding, Continued

- Now we have a value for the a vapor velocity that will cause flooding.
- We will add a safety factor because we don't want to operate on the edge of flooding conditions
  - Various sources use different factors, let's choose $u \approx 0.7u_{flood}$
- Most of the plate is covered by holes
- $A = Total\ Area = \frac{\pi D^2}{4}$
- Downcomer, etc cover 15% of total area
- Net area for flow = **0.85A**





(a)

(b)

Flooding, Continued

$$V = u\, A_n \frac{P}{RT}$$

Molar vapor flow = (volumetric flow) * (moles/volume)

- From ideal gas law PV = nRT you get $\frac{P}{RT} = \frac{n}{V} = \frac{moles}{Volume}$
- In this context V is just a volume

- $A_n = 0.85 \frac{\pi D^2}{4}$ net area for flow
- Steps
  - Calculate u_{flood} and apply safety factor
  - Use molar flow rate V to calculate A_n
  - Calculate required column diameter

- **Note: Column is most susceptible to flooding at the top of the tower. Use conditions corresponding to the top of the tower in this evaluation!**