CE407 SEPARATIONS

Lecture 05

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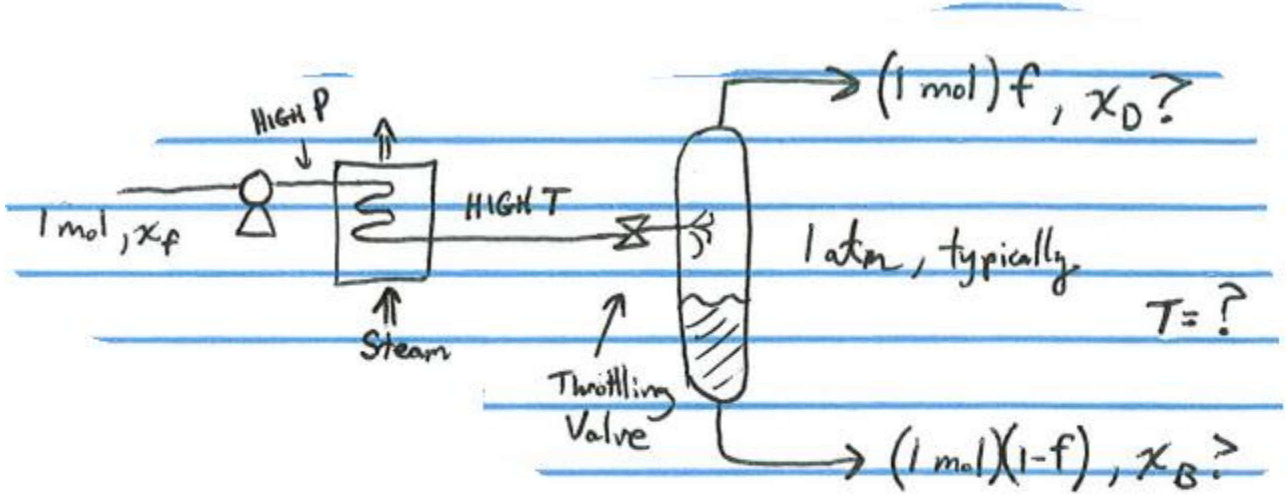
Flash Distillation

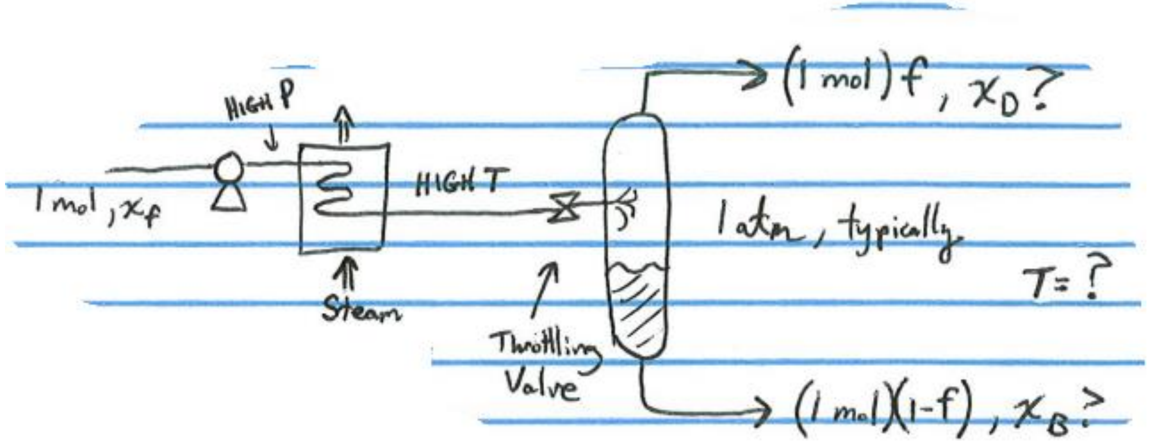
McSH pp 663-667

- A liquid mixture is heated under pressure
  - Back pressure in the line (provided by the throttling valve) keeps the mixture in the liquid phase
- Downstream of the throttling valve the liquid “flashes” into a combination of liquid and vapor
  - The temperature places the mixture in the two phase region for the lower pressure
- The lighter component preferentially goes into the vapor phase



Flash Distillation, continued

- The mole fractions $\mathbf{x_d}$ and $\mathbf{x_b}$ are in equilibrium with one another
- f is the molar fraction of the feed that goes to the vapor phase
  - For 1 mole of feed there will be f moles of vapor and **(1 – f)** moles of liquid
- In our course we will be specifying f and $\mathbf{x_f}$, the mole fraction in the feed stream
- The preheating of the feed provides the enthalpy needed for the phase change to occur
- We won’t deal with design of the Flash Drum
  - Sized so that upward velocity of vapor is slow enough to allow liquid droplets to fall
  - Residence time of 5 to 10 minutes



Flash Distillation, continued

- Material Balance

Total Moles $1 \text{ mol} = (1 \text{ mol})f + (1 \text{ mol})(1-f)$

Light Component $(1 \text{ mol})\, \mathbf{x_f} = (1 \text{ mol})\, f\, \mathbf{x_D} + (1 \text{ mol})\,(1-f)\, \mathbf{x_B}$

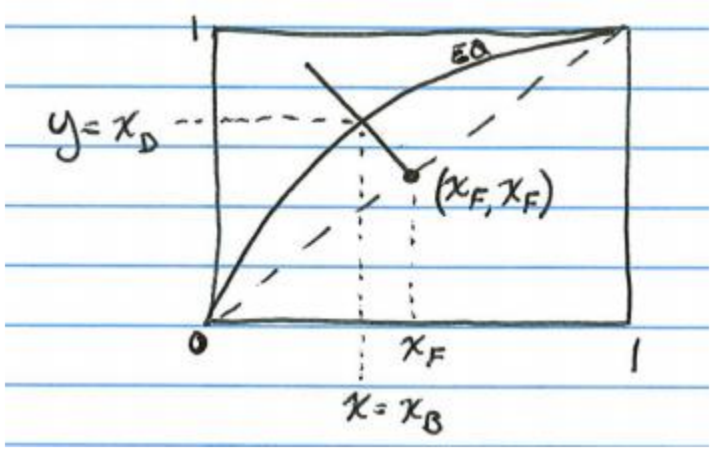
- $\mathbf{x_D} = \mathbf{y}$ and $\mathbf{x_B} = \mathbf{x}$

$$\mathbf{x_f} = f\, \mathbf{y} + (1-f)\, \mathbf{x}$$

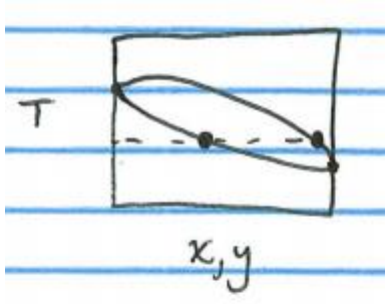
- Rearrange $y = \frac{x_F}{f} - \left(\frac{1-f}{f}\right)x$ This is a mole balance

Flash Distillation Graphical Method

- Want to determine what the mole fractions of both the liquid and vapor phases will be
- The solution must satisfy material balance and equilibrium conditions
  - All solutions satisfying material balance will fall on this line: $\boldsymbol{y = \frac{x_F}{f} - \left(\frac{1-f}{f}\right)x}$
  - The line will have slope = $-\left(\frac{1-f}{f}\right)$ and will pass through point (**x_F**, **x_F**)
  - All solutions satisfying equilibrium conditions will lie on VLE curve
  - The intersection of this line and the VLE curve will satisfy both conditions



- Now that you have (**x**, **y**), you can determine the Flash temperature on the **T$_{xy}$** diagram



Flash Distillation Analytical Method McSH pp 741-742

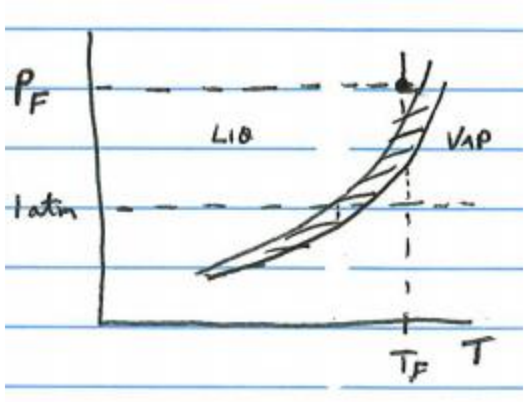
- This method applies to both binary and multicomponent flash calculations
  - i runs from 1 to N, where N is the number of components
  - $y_i = x_{iD}$ and $x_i = x_{iB}$ (first subscript refers to component, second to phase)
- Mole Balance $x_{iF} = f\, y_i + (1-f)\, x_i$
- Equilibrium Condition $y_i = k_i\, x_i$
- Substitute EQ into mole balance $x_{iF} = f\, k_i\, x_i + (1-f)\, x_i = [f\,(k_i - 1) + 1]\, x_i$
- Which leads to $x_i = \frac{x_{iF}}{f(k_i - 1) + 1}$
- We know that the sum of all the liquid mole fractions has to be equal to 1
- $\sum_{i=1}^{N} \frac{x_{iF}}{f(k_i - 1) + 1} = 1$ eq 22.12 in McSH
  - We know all of the x_{iF}
  - The k_i depend on Temperature and Pressure
  - As we know the pressure that leaves one unknown (Temperature) in the equation

Flash Distillation Analytical Method McSH pp 741-742

- Alternate method leads to $y_i = \frac{k_i x_{iF}}{f(k_i - 1) + 1}$
- Which leads to $\sum_{i=1}^{N} \frac{k_i x_{iF}}{f(k_i - 1) + 1} = 1$
- In either case one solves for the temperature that results in a sum = 1
  - Temperature is hiding in $\mathbf{k_i}$ as part of $\mathbf{P_i}^{\mathbf{sat}}$, which depends on Antoine equation
  - This is extremely non-linear but relatively simple to solve using Matlab or the Solver function in Excel

Flash Distillation

- Pressure change across the throttling valve is key
- If we were to heat feed up to $\mathbf{T_F}$ at 1 atm, we would start to boil in the pipe and not achieve the separation.
- The higher pressure in the pipe allows us to add enthalpy without having any phase change
- By dropping the pressure we can enter the two-phase region
    - Note that in this drawing dropping all of the way to 1 atmosphere would lead to entering an all-vapor phase condition, so you would drop to an intermediate pressure or heat to a lower temperature



Flash Distillation

- What determines f?
- Enthalpy Balance

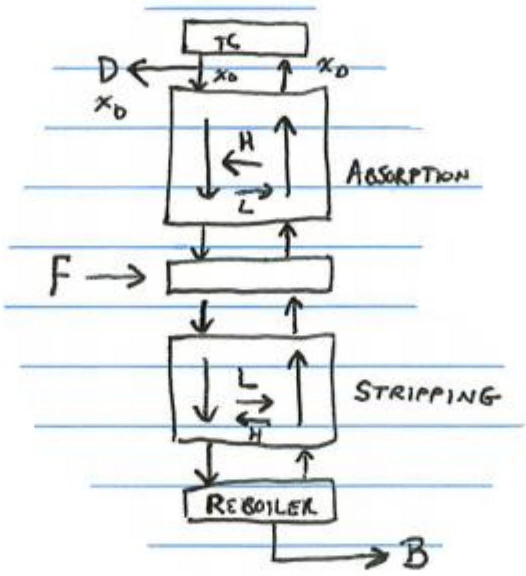
$$H \text{ in} = H \text{ out}$$

$$(1 \text{ mol})\ H_F(T_F, x_F) = (1 \text{ mol})\, f\ H_y(T, y) + (1 \text{ mol})\ (1-f)\ Hx(T,x)$$

- Enthalpy is dependent on Composition and Temperature
  - Very little dependence on Pressure
- Procedure (given T_F and x_F)
  - Guess a value for f
  - Solve Flash problem as before to get T, x, and y
  - Calculate enthalpies
  - Check enthalpy balance. If it doesn't work out, adjust f until it converges

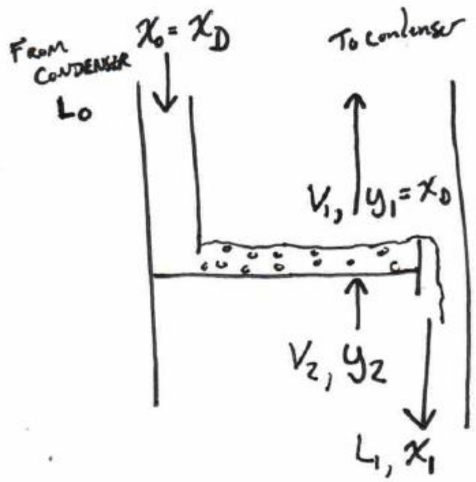
Continuous Distillation with Reflux McSH pp 668-670

- In absorption and stripping we clean one stream by introducing a second one and contaminating that second stream
- Flash distillation splits a stream in two streams, one having increased mole fraction of the light component, one of increased mole fraction of heavy component
  - Unfortunately, flash is limited in the amount of enrichment achievable
- Distillation with Reflux can lead to high purity in both streams
  - Column has both Absorption and Stripping section
  - Liquid flows down column / vapor flows up column
  - Light component transfers from liquid to vapor stream
  - Heavy component transfers from vapor to liquid stream
  - Feed stream is split into two streams of high purity
  - Above feed entrance the column uses condensed vapor as absorbing liquid **(aka Reflux)**
  - Below feed the column uses boiled liquid as stripping vapor
  - No additional stream is introduced



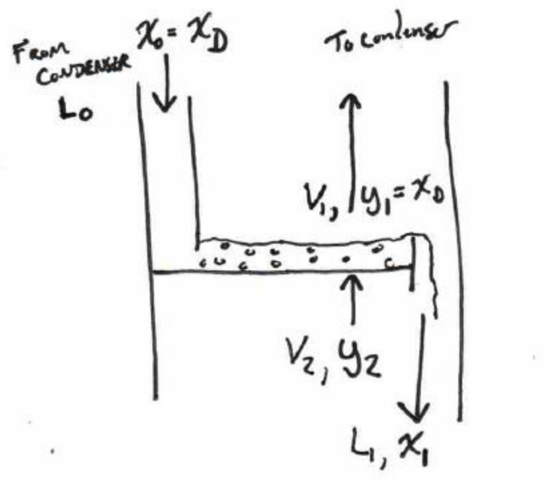
Continuous Distillation with Reflux

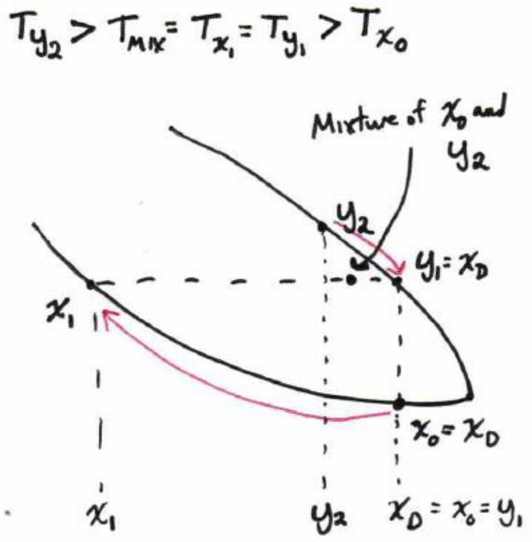
- Vapor leaving the top of the column has mole fraction $\mathbf{y_1}$ and passes through a total condenser which removes enthalpy to create a liquid with mole fraction $\mathbf{x_D}$. Because all of the vapor is condensed the two streams have the same mole fraction. $\mathbf{x_D} = \mathbf{y_1}$
- The condensed stream is split into distillate stream, **D**, which leaves the column as a product and the reflux stream, which re-enters the column and flows back down to the first stage. Both of these streams have the same mole fraction, $\mathbf{x_D}$
- Entering Tray #1 we have liquid stream $\mathbf{L_0}$ coming back from condenser with mole fraction $\mathbf{x_0} = \mathbf{x_D}$ this mixes with vapor steam $\mathbf{V_2}$, which has mole fraction $\mathbf{y_2}$
- Exiting Tray #1 we have vapor stream $\mathbf{V_1}$ which has mole fraction $\mathbf{y_1} = \mathbf{x_D}$, also exiting is liquid stream $\mathbf{L_1}$, which has mole fraction $\mathbf{x_1}$



Continuous Distillation with Reflux

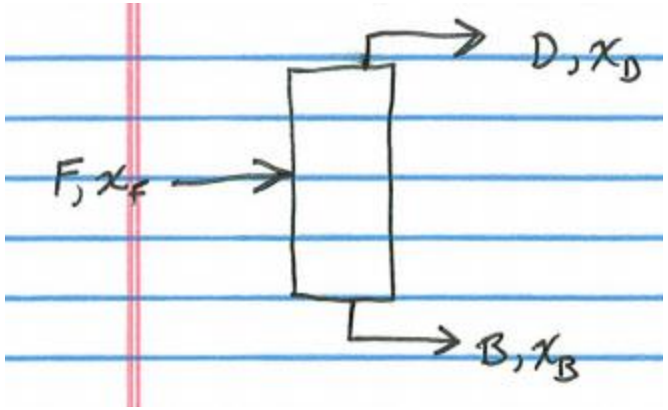
- Steams $\mathbf{L_0}$ and $\mathbf{V_2}$ combine to form two phase mixture which has a composition and temperature which is intermediate of both of the original streams (Due to molar balance and enthalpy balance)
- The vapor and liquid which exit are in equilibrium with one another at the “mixture” temperature
  - The vapor has composition $\mathbf{x_D}$ and the liquid has composition $\mathbf{x_1}$
- The vapor has come in with composition $\mathbf{y_2}$ and left with composition $\mathbf{x_D}$. Note that $\mathbf{x_D} > \mathbf{y_2}$
- The liquid has come in with composition $\mathbf{x_D}$ and left with composition $\mathbf{x_1}$. Note that $\mathbf{x_1} < \mathbf{x_D}$
- Vapor is being enriched and liquid is being stripped of the light component





Binary Distillation

- Mole fractions refer to the light component
- Feed enters at a rate of **F** moles/min with composition $\mathbf{x_F}$
- Distillate exits from condenser at a rate of **D** moles/min with composition $\mathbf{x_D}$
- Bottoms exit from Reboiler at a rate of **B** moles/min with composition $\mathbf{x_B}$
- **F** and $\mathbf{x_F}$ are a given (the stream you are trying purify sets these values)
- The mole fractions of the product ($\mathbf{x_D}$ and $\mathbf{x_B}$) are specified to meet the customers' needs



Overall Material (Mole) Balances

- Total Moles $F = D + B$ eq 1
- Moles of Light Component $Fx_F = Dx_D + Bx_B$ eq 2
- Substitute eq 1 into eq 2 $Fx_F = Dx_D + (F - D)x_B$

$F(x_F - x_B) = D(x_D - x_B)$

- Leads to

$$\boxed{\begin{gathered} D = F\left(\frac{x_F - x_B}{x_D - x_B}\right) \\[2em] B = F\left(\frac{x_D - x_F}{x_D - x_B}\right) \end{gathered}}$$

- These equations are just material balances!
  - I usually just do the material balances directly and don’t memorize these equations, but most students like to use the equations as shown in the box…

Percent Recovery Specification

- Rather than specify the mole fraction of distillate and bottoms it is also common to specify the percentage of moles of the light component in the feed stream that make it to the distillate stream (also percentage of moles of heavy component in feed that reach the Bottoms)

DO NOT CONFUSE THIS WITH x_D AND x_B

- Percent Recovery of light component in the distillate =

$$\frac{\text{molar flow of light component in distillate}}{\text{molar flow of light component in feed}}\ x\ 100\% = \frac{Dx_D}{Fx_F}\ x\ 100\%$$

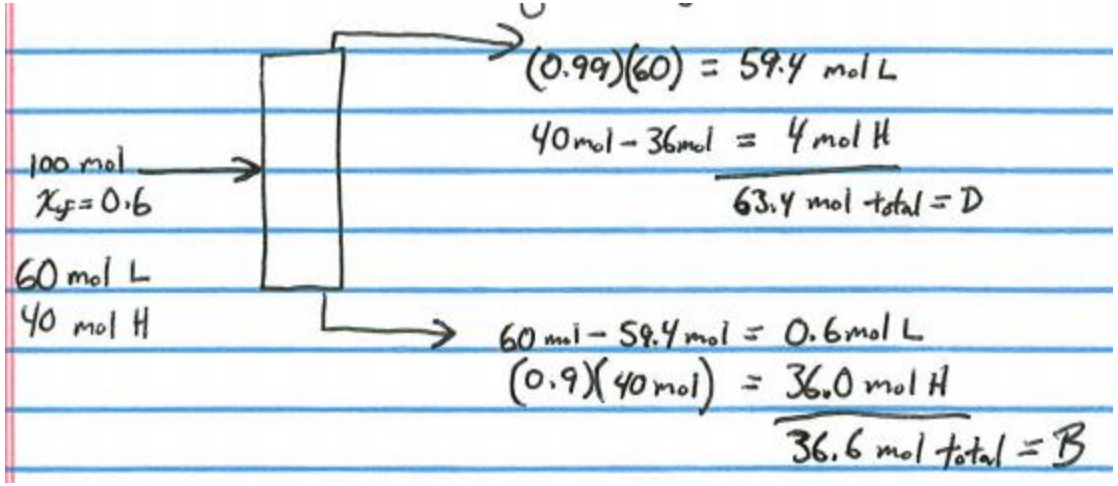
- Percent Recovery of heavy component in the bottoms =

$$\frac{\text{molar flow of heavy component in bottoms}}{\text{molar flow of heavy component in feed}}\ x\ 100\% = \frac{B(1 - x_B)}{F(1 - x_F)}\ x\ 100\%$$

- If the specification is a “fractional” recovery, then the “x 100%” part does not apply

Working with % Recoveries

- Specification: 99% recovery of light component in distillate
- Specification: 90% recovery of heavy component in bottoms



- $x_D = {}^{59.4}/_{63.4} = \mathbf{0.9369}$
- $x_B = {}^{0.6}/_{36.6} = \mathbf{0.0164}$
- Interestingly high recovery of light component does not necessarily lead to $\mathbf{x_D}$ very close to **1**, but it does mean that $\mathbf{x_B}$ will be quite close to **0**
- High recovery of heavy component does lead to $\mathbf{x_D}$ very close to **1**, but not necessarily $\mathbf{x_B}$ quite close to **0**