

CE407 SEPARATIONS

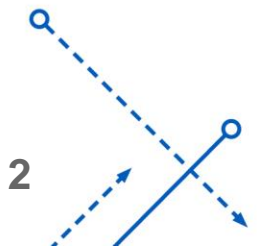
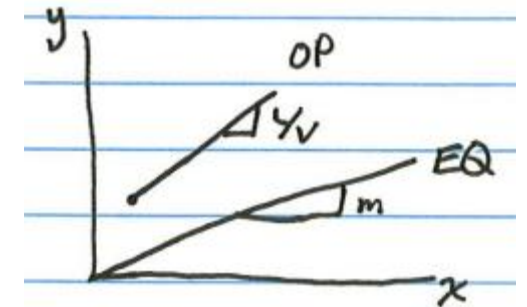
Lecture 03

Instructor: David Courtemanche



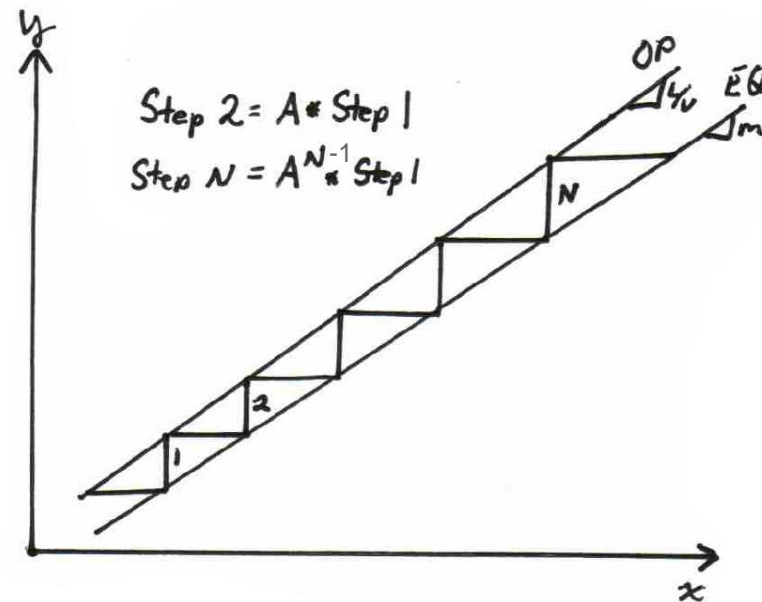
Absorption – Kremser Equation (aka Absorption Factor Method)

- Pages 653-659 of McCabe/Smith/Harriott cover the mathematical derivation. These notes cover the concepts
- 2 Main Conditions for the Kremser Method to be valid
 - Operating Line must be a straight line
 - This is a reasonable assumption if x and $y \ll 1$ ($\sim < 0.1$)
 - Equilibrium Curve is a straight line
 - Raoult's or Henry's Law applies
 - Mixture of similar chemicals
 - As long as EQ curve approximates a straight line over the region of interest
- Slope of OP line $\approx \frac{L}{V}$, this is approximately constant for dilute system
- Slope of EQ line is given by equilibrium relationship (Raoult, etc) and is noted as m
- Absorption Factor **A**: $A = \frac{L/V}{m} = \frac{L}{mV}$ this is the ratio of the OP line slope vs the EQ line slope

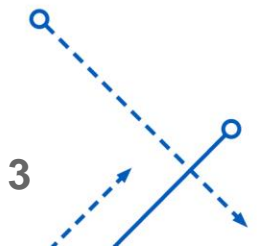


Kremser Equation

- Observe: If the two lines have different slopes, then each successive step will increase in size relative to the previous step.
- The increase is proportional to A
- If you take N steps, then that step is A^{N-1} times the original step



- Take logarithm $\ln(A^N) = N * \ln(A)$ this all leads to the Kremser Equation



Kremser Equation

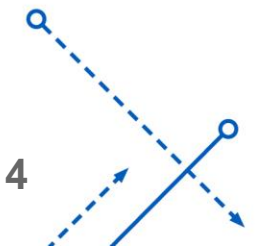
- Various Forms, all are equivalent

$$N = \frac{\ln[(y_b - y_b^*) / (y_a - y_a^*)]}{\ln[(y_b - y_a) / (y_b^* - y_a^*)]} \quad \text{eq 20.24}$$

$$N = \frac{\ln[(y_a - y_a^*) / (y_b - y_b^*)]}{\ln[(y_b^* - y_a^*) / (y_b - y_a)]} \quad \text{eq 20.27}$$

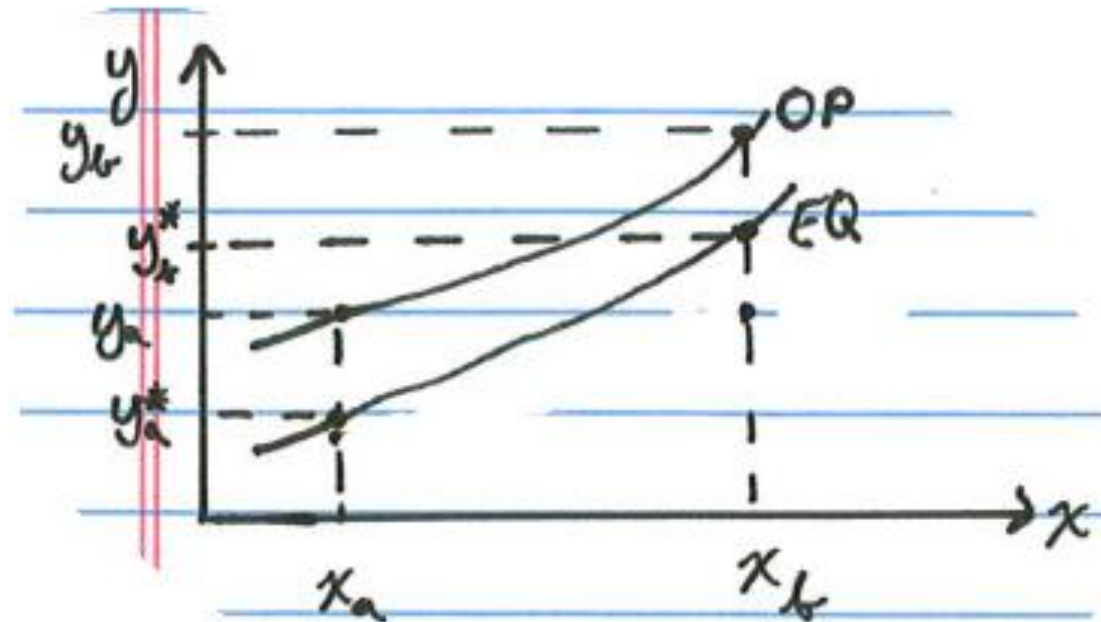
$$N = \frac{\ln[(x_a - x_a^*) / (x_b - x_b^*)]}{\ln[(x_a - x_b) / (x_a^* - x_b^*)]} \quad \text{eq 20.28}$$

$$N = \frac{\ln[(x_b - x_b^*) / (x_a - x_a^*)]}{\ln[(x_a^* - x_b^*) / (x_a - x_b)]}$$



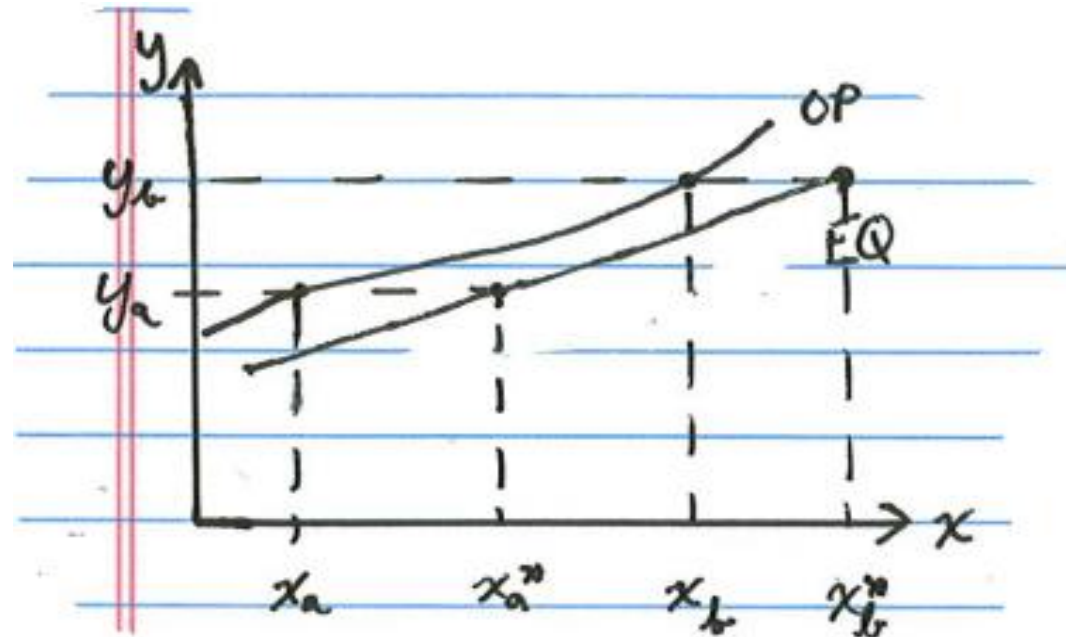
Okay, what are those *s?

- y_a^* is the value of vapor mole fraction which is in equilibrium with liquid mole fraction x_a
- y_b^* is the value of vapor mole fraction which is in equilibrium with liquid mole fraction x_b



Okay, what are those *s?

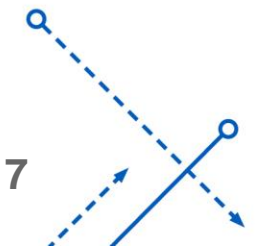
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Kremser Equation

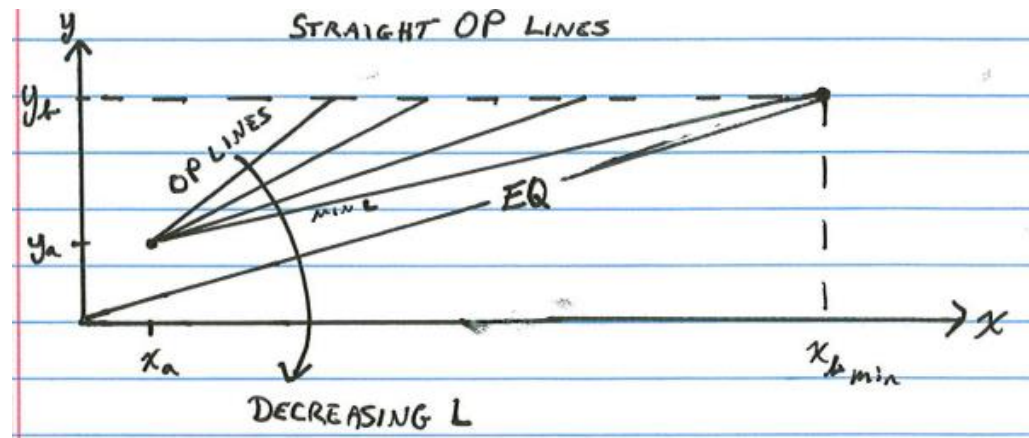
$$N = \frac{\ln[(y_b - y_b^*) / (y_a - y_a^*)]}{\ln[(y_b - y_a) / (y_b^* - y_a^*)]} \quad \text{eq 20.24}$$

- $y_b - y_b^*$ is the difference between entering vapor mole fraction and the mole fraction that could be achieved IF we were to reach equilibrium – this is a driving force
- $y_a - y_a^*$ is the difference between exiting vapor mole fraction and the mole fraction that could be achieved IF we were to reach equilibrium – this is a driving force
- $y_b - y_a$ is the change that we are trying to achieve
- $y_b^* - y_a^*$ is the potential for change if the entering and exiting vapors both achieved equilibrium with their respective liquid counterparts
- Note: **N** will most likely NOT be an integer – Round Up!



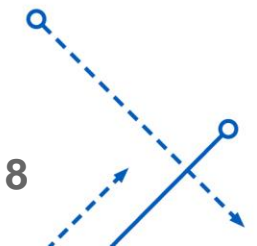
Absorption Tower Minimum Liquid Flow McSH pp 577-578

- Minimum liquid flow is the value which can just achieve the desired removal of solute
 - It unfortunately leads to an infinitely tall tower...
 - However, it's calculation is used as a basis to determine a reasonable liquid flow



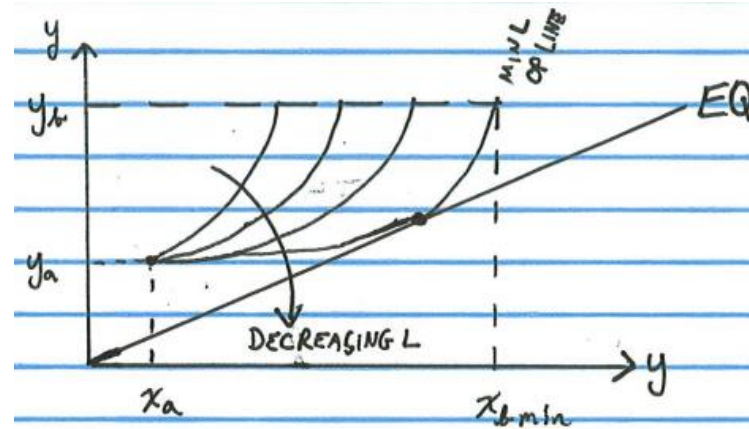
- Decreasing liquid flow leads to lower L/V and decreases the slope of OP Line
- At minimum flow the OP Line intersects the EQ Line at $(x_{b, \min}, y_b)$ and the steps between the lines become infinitely small leading to an infinite number of steps
- With a lower liquid flow you can NEVER reach y_b (where y^* indicates equilibrium)

$$y_b = y^*(x_b)$$



Minimum Liquid Flow with Curved OP Line

- Minimum liquid flow is that for which OP Line first contacts (but does not cross) the EQ Curve



- $x_{b, \min}$ is the value of x that corresponds to y_b on the OP Line for minimum flow
- Also note that

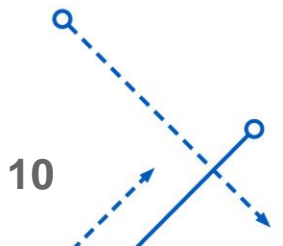
$$(x_b)_{\min} = \frac{(L_i)_b}{(L_i)_b + (L_c)_{\min}}$$
- $(L_i)_b$ is the # of moles of solute exiting b end of tower – calculated by mass balance on solute
- $(L_c)_{\min}$ is the flow of pure liquid that leads to first contact of OP Line and EQ Line
 - i.e. minimum liquid flow of pure absorbing liquid

Recycled Absorbing Liquid

- When using recycled absorbing liquid $x_a \neq 0$

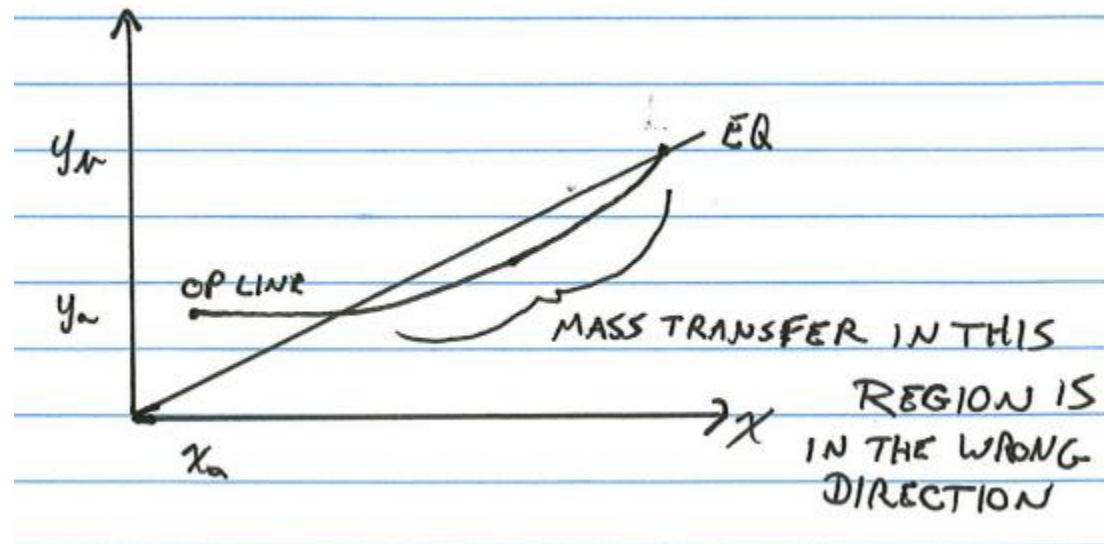
$$(L_a)_{\min} * (1 - x_a) = (L_c)_{\min}$$

$$(L_a)_{\min} = \frac{(L_c)_{\min}}{1 - x_a}$$



Do **Not** Assume that $y_b = y^*(x_b)$

- If there is curvature in the Operating Line that assumption leads to the following situation:

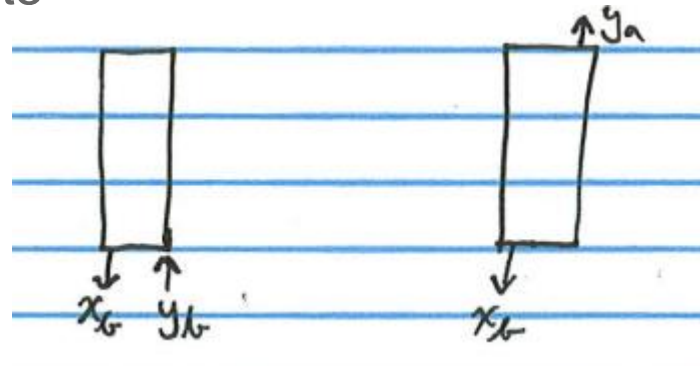


When Op Line is straight...

- When we have a dilute system with straight operating lines and can therefore use

$$x_b = x^*(y_b)$$

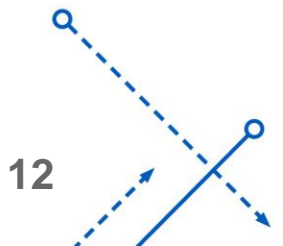
- it is important to note



In equilibrium

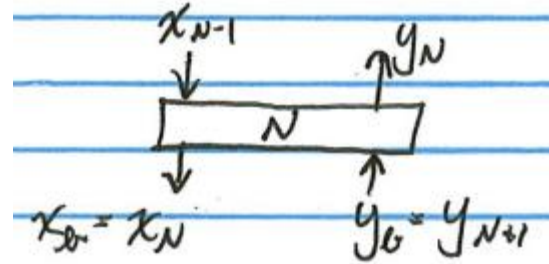
NOT in equilibrium

- x_b** and **y_a** are separated by many, many stages and are never in contact!

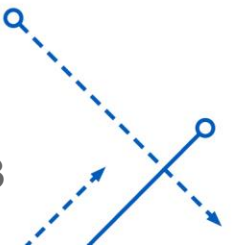


Comment

- Actually x_b and y_b are not technically in equilibrium...



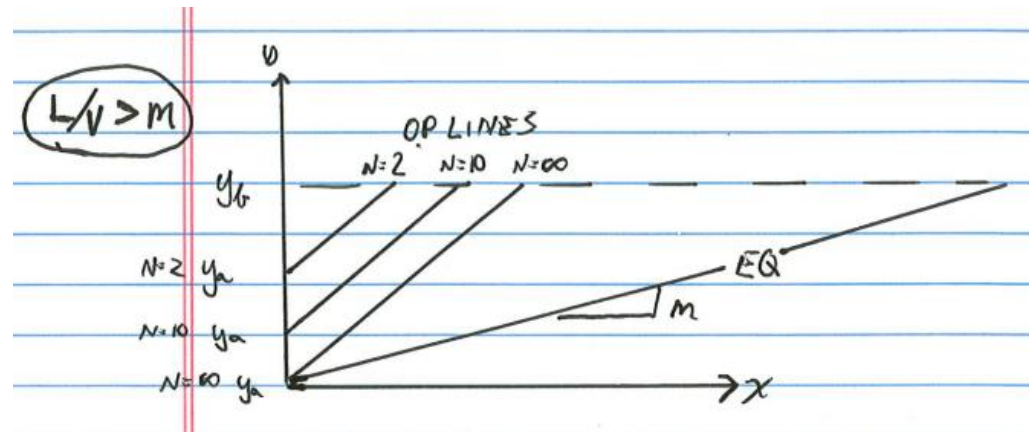
- x_b is in equilibrium with y_N , not $y_b = y_{N+1}$
- However, for minimum liquid flow y_N and y_{N+1} are essentially the same due to the infinitely small steps



How clean can you make the vapor with a set value of L/V ?

$L/V > m$

- OP Line Slope = L/V (approximately)
- EQ Curve Slope = m
 - $y = mx$ with m being supplied perhaps by Raoult's or Henry's Laws
- $N = \#$ of stages

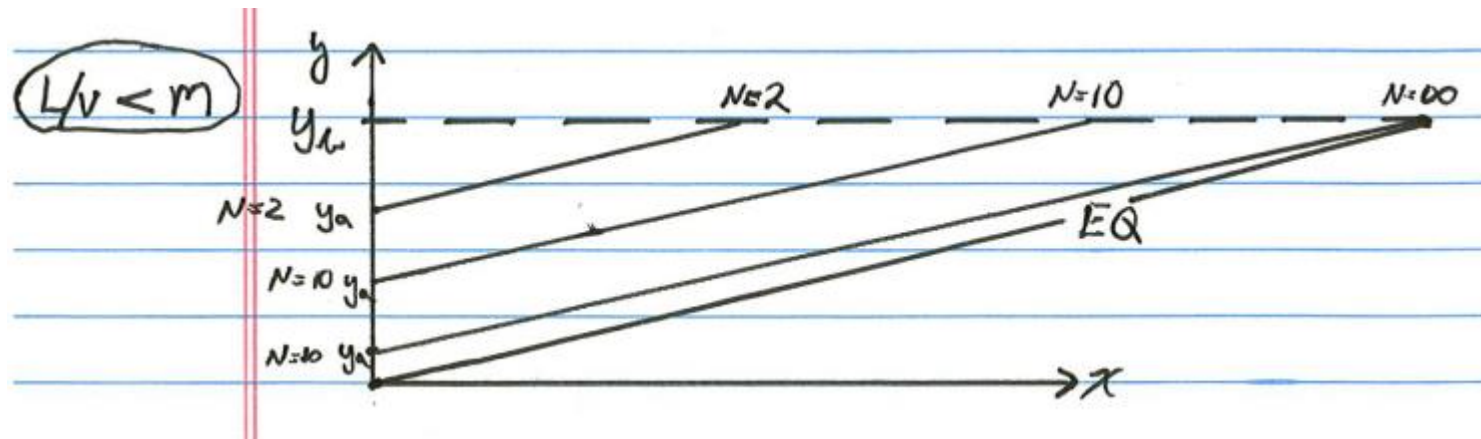


- By increasing the number of stages one can theoretically obtain as low a value of y_a as desired
- You do reach a point of diminishing returns...

How clean can you make the vapor with a set value of L/V ?

$L/V < m$

- When $L/V < m$, eventually the Operating Line contacts the Equilibrium Line at $y = y_b$ and leads to a pinch point



- Continuing to add stages will NOT lead to a lower value of y_a

What Flow Should We Use?

- Using L_{\min} leads to an infinite number of stages and an infinite capital cost
- Using an L that is extremely high reduces capital cost but leads to very high expense for absorbing liquid

Optimize Cost

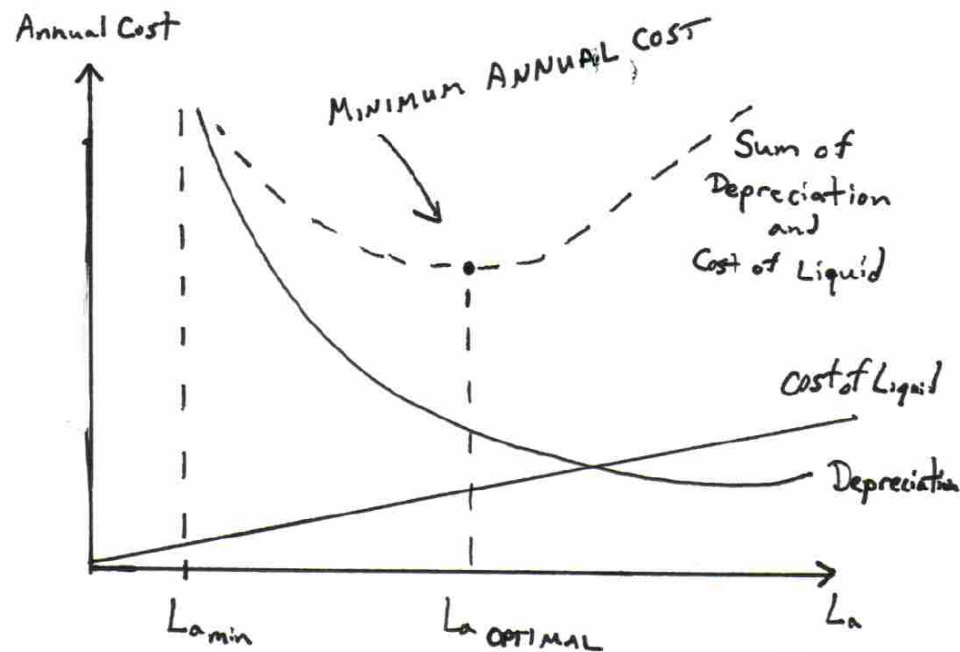
- Capital cost of building tower is spread out over the useful life of the equipment and is called depreciation

$$\text{Simple Depreciation} = \frac{\text{Capital Cost of Equipment}}{\text{\# of years in use}}$$



Optimized Cost

- At $L_{a, \min}$ the capital cost (and therefore annual depreciation) is infinite
- As liquid flow increases the capital cost drops asymptotically
- The cost of liquid is approximately directly proportional to the amount used
- Look for minimum of the sum of capital and liquid cost
- This value is typically $L_{a, \text{optimal}} \approx 1.3 * L_{a, \min}$

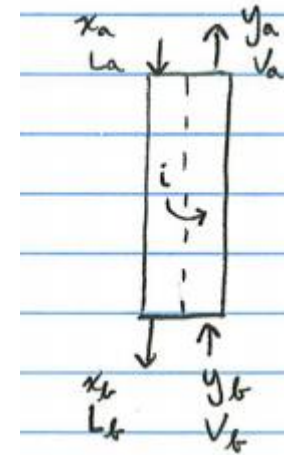


Stripping

- The same equipment can be used to remove solute from a liquid!
- This can be done when the conditions are such that equilibrium drives the mass transfer from liquid to vapor
- It is the reverse of absorption
- The analysis is the same...

Now we know all about the entering liquid (it is what we want to treat)

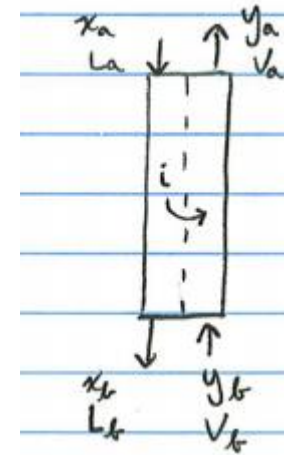
- $L_c = (1 - x_a) * L_a$ where L_c is the moles of pure liquid and is constant
- $(L_i)_a = x_a * L_a$ where $(L_i)_a$ is moles of solute entering in liquid stream
- We will know both L_a and x_a



Stripping

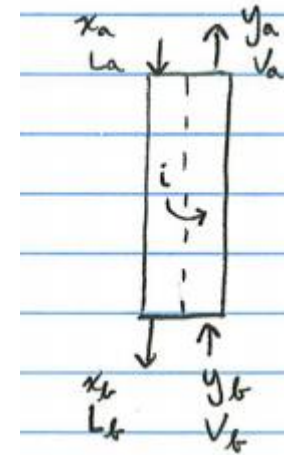
Exiting Liquid

- We will either know: Required x_b
 - Then $(L_i)_b = x_b * [(L_i)_b + L_c]$
 - And therefore $(L_i)_b = \frac{x_b}{1 - x_b} L_c$
- Or we will know that we are required to remove some fraction, R , of incoming molar solute flow
- Then $(L_i)_b = (1 - R) * (L_i)_a$
- And therefore $x_b = \frac{(L_i)_b}{(L_i)_b + L_c}$



Stripping

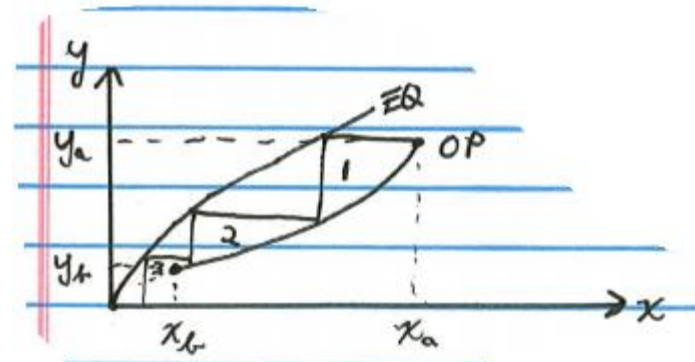
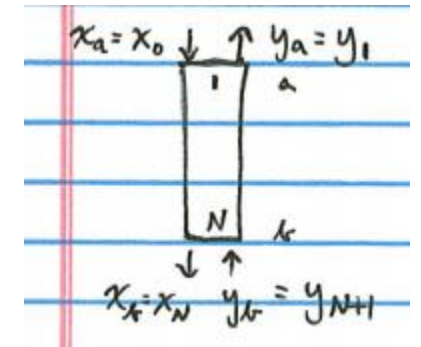
- Entering Vapor: we will know y_b and V_b (for now...)
 - $(V_i)_b = y_b * V_b$ and $V_c = (1 - y_b) * V_b$
 - V_c is constant
- Exiting Vapor: we need to do material balance (similar to the analysis of the exiting liquid stream in an absorption process)
 - Moles of solute in exiting vapor $(V_i)_a = (L_i)_a + (V_i)_b - (L_i)_b$



$$y_a = \frac{(V_i)_a}{(V_i)_a + V_c}$$

McCabe-Thiele and Stripping

- Now the top of the tower is the “dirty” section and bottom of tower is the “clean” section, which is the opposite of an absorption tower
- OP Line is the same equation as for absorption
- EQ Curve is the same as for absorption
- For Stripping the EQ curve is ABOVE the OP Line
 - We are transferring mass in the opposite direction as for absorption
- Now counting from top to bottom means starting in the upper right portion



Kremser Equation and Stripping

- The same equations apply
- Some consider the x forms to be more appropriate for stripping and the y forms more appropriate for absorption
- Can use any of the forms of Kremser as long as OP and EQ are straight lines in the region of interest

Minimum Gas Flow and Stripping

- This is a similar analysis as for absorption
- Straight OP Lines
 - $y_a = y^*(x_a)$
- Curved OP Lines
 - $$y_{a,min} = \frac{(V_i)_a}{(V_i)_a + (V_c)_{min}}$$
 - If entering gas is not pure $(V_b)_{min} = \frac{(V_c)_{min}}{1 - y_b}$
 - If absorbing vapor is steam then $V_b \approx 1.3 * (V_b)_{min}$
 - If absorbing gas is air then $V_b \approx (3 \text{ to } 5) * (V_b)_{min}$
 - (The cost of steam \gg the cost of air)

