Øving 3

1

You may have noted that vapor-liquid equilibrium (VLE) data for distillation is always at a given pressure (and no specified temperature), whereas data for absorption/stripping, for example, Henry's law ($y_A = mx_A$), are at a given pressure **and** temperature.

To understand this, one may consider a column with given pressure and assume we know the liquid stage composition of A (x_A) (or vapor stage composition y_A). In a distillation column (separating A and B), the stage temperature is then given, but not in an absorber/stripper (transferring A between inert B and C).

Explain why using Gibbs' phase rule.

Comment: The important implication of this is the following:

1. In distillation, we have a "boiling mixture" on all stages. If you in a distillation column decrease the temperature of the feed (so maybe it is subcooled), then this will lead to some condensation of vapor at the feed stage (which you would have to compensate for by increasing the boil up), but the temperature change inside the column will be very small.
2. In absorption/stripping, we do NOT have a "boiling mixture". In an absorption column, if you decrease the temperature of the liquid feed (in the top), then this will lead to a decrease in temperature in the entire column (the vapor will also be cooled, but it does not condense because it is "inert", for example, air will not condense).

Thus, one can independently control temperature and composition in absorption but not in distillation.

Gibbs faseregel: $F = C - P + 2$

Destillasjonskolonne: Har 2 faser, komponenter A og B,

$\Rightarrow F = 2 - 2 + 2 = 2$

Vi har to grader av frihet, dersom vi "bruker" en av dem på å bestemme x_A eller y_A, og en på trykket, så er det ingen igjen. Dermed vil temperaturen være gitt.

Absorpsjon/stripper: $A \leftrightarrow B + C$, 2 faser, 3 komponenter,

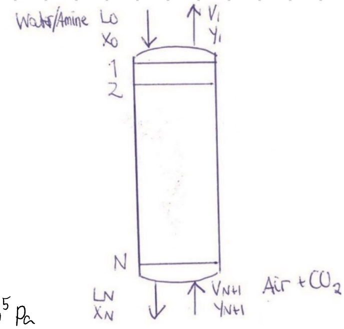
$F = 3 - 2 + 2 = 3$

Selv om vi velger både x_A/y_A og P, så er det en frihetsgrad igjen. Temperaturen kan derfor også velges fritt.

2

This exercise will give you some understanding of the problems with the "moon landing" project on Mongstad (which is even more difficult because the gas from a natural gas power plant contains less than 5% CO_2).

A combustion gas (22 kmol/s) from a large coal-fired power plant contains 11.76% CO_2 (mole-%); the rest is air with a bit low O_2-content. We want to remove about 90% of the CO_2 so that the cleaned gas contains 1.16% CO_2. This is done by contacting the combustion gas with a water-amine solution[1] in a packed absorption column at about 60C and 1.2 bar. The water-amine feed solution contains 2.19% CO_2 (it comes from a stripping column used for regeneration), and the enriched solution leaving the bottom contains 5.32% CO_2.



a) Assume constant inert flows for air (V') and water-amine (L') through the column. Find L' and V', the total feed of amine solution (L_0), and the product rates (L_N and V_0).

Baserer alle beregninger på CO_2:

$V_{N+1} = 22$ kmol/s

$y_{N+1} = 0{,}1176$

$y_1 = 0{,}0116$

$x_0 = 0{,}0219$

$x_N = 0{,}0532$

$P = 1{,}2$ bar $= 1{,}2 \cdot 10^5$ Pa

$T = 60°C = 333$ K

Antar at med inert, menes alle gasser i luftstrømmen som ikke er CO_2: $\Rightarrow V' = V_{N+1} \cdot y_{N+1}^{inert} = V_{N+1}(1 - y_{N+1})$

$\Rightarrow \underline{\underline{V' = 19{,}41 \text{ kmol/s}}}$

Molbalanse over systemet med hensyn på CO_2 gir:

$$V_{N+1} \cdot y_{N+1} + L_0 \cdot x_0 = V_1 y_1 + L_N \cdot x_N$$

Tilsvarende som for V', vil $V' = V_{N+1} \cdot (1 - y_{N+1})$

$$\Rightarrow V_{N+1} = \frac{V'}{1 - y_{N+1}}$$

Får:

$$\frac{V'}{1 - y_{N+1}} \cdot y_{N+1} + \frac{L'}{1 - x_0} x_0 = \frac{V'}{1 - y_1} y_1 + \frac{L'}{1 - x_N} x_N$$

Likningsløser gir: $L' \approx 69{,}806$ kmol/s

$\underline{\underline{L' = 69{,}81 \text{ kmol/s}}}$

$$\underline{\underline{L_0 = \frac{L'}{1 - x_0} = 71{,}37 \text{ kmol/s}}}$$

Tilsvarende, blir dermed: $\underline{\underline{L_N = 73{,}73 \text{ kmol/s}}}$ og $\underline{\underline{V_1 = 19{,}64 \text{ kmol/s}}}$

b) What is the diameter of the column, given that the superficial gas velocity (neglecting the area taken by the packings and liquid) is 2 m/s.

$$V = A \cdot v$$

$$\Rightarrow A = \frac{V}{v}$$ Antar ideell gass:

$$\Rightarrow A = \frac{V_{N+1} \cdot R \cdot T}{p \cdot v} = \frac{22 \cdot 10^3 \text{ mol}/\cancel{s} \cdot 8{,}314 \text{ m}^2 \cancel{kg}/(\cancel{s}^2 \cancel{K} \text{ mol}) \cdot 333 \cancel{K}}{1{,}2 \cdot 10^5 \cancel{Pa} \cdot 2 \cancel{m}/\cancel{s}}$$

$$A = 253{,}8 \text{ m}^2$$

$$A = \pi r^2 = \pi \left(\frac{D}{2}\right)^2 = \frac{\pi}{4} D^2$$

$$\Rightarrow D = \sqrt{\frac{4A}{\pi}} = 17{,}98 \text{ m}$$

c) Equilibrium data is given in the table below. Is it reasonable to use Henry's law in this case?

$\boxed{\text{Henry's lov: } K_i = \frac{y_i}{x_i} \text{ (} K_i \text{ er konstant)}}$

	xCO_2(%)	yCO_2(%)
1	2.227	1.162
2	3.001	2.917
3	3.339	3.783
4	4.101	6.057
5	4.700	8.448
6	5.324	11.60

La $y_i = k_i x_i$, da er

$$k_i = \frac{y_i}{x_i}$$

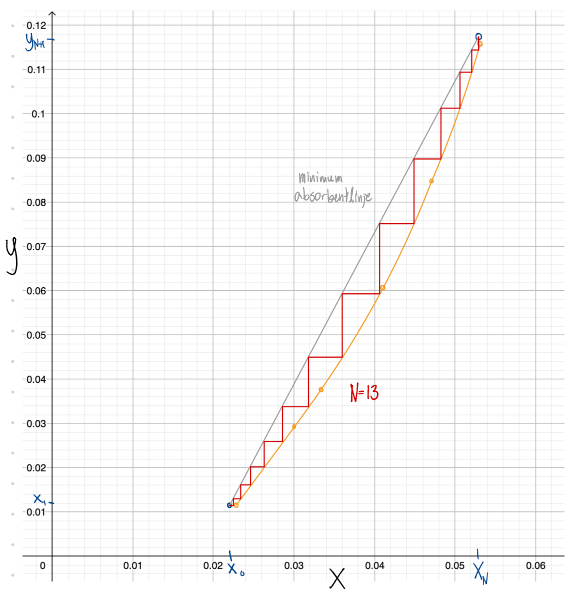
$k_1 = 0{,}52$
$k_2 = 0{,}97$
$k_3 = 1{,}13$
$k_4 = 1{,}47$
$k_5 = 1{,}79$
$k_6 = 2{,}18$

$\Rightarrow$ Nei, Henrys lov er ikke fornuftig. X_i og y_i er ikke tilnærmet lineært avhengige

d) Determine the number of stages required (using a graphical solution).

Data fra tabellen

Får at det trengs 13 steg



e)

Comment: The operating line is (show this!)

$$y_{n+1} = \frac{L_n}{V_{n+1}} x_n + \frac{y_1 V_1 - x_0 L_0}{V_{n+1}}$$

It is not quite linear, but it goes through the points (x_0,y_1) and (x_N,y_{N+1}) (explain why!). To simplify, you may assume that the operating line is a straight line between these two points (which corresponds to using a constant $\frac{L}{V} = \frac{y_{N+1} - y_1}{x_N - x_0}$).

Molbalanse over systemet med hensyn på CO_2 gir:

$$V_{N+1} \cdot y_{N+1} + L_0 \cdot x_0 = V_1 y_1 + L_N \cdot x_N$$

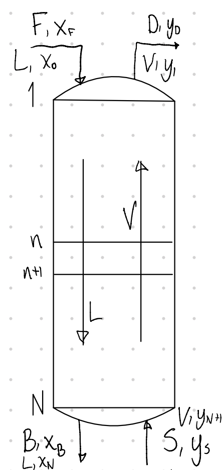
$$V_{N+1} \, y_{N+1} = L_N \cdot x_N + y_1 V_1 - x_0 L_0$$

$$\boxed{y_{N+1} = \frac{L_N}{V_{N+1}} x_N + \frac{y_1 V_1 - x_0 L_0}{V_{N+1}}}$$

Å vise at linja går gjennom (x_0, y_1) gjøres ved å sette

$$n = 0, \Rightarrow y_1 = \frac{L_0}{V_1} x_0 + \frac{y_1 V_1 - x_0 L_0}{V_1} = \frac{y_1 V_1}{V_1} = y_1$$

Årsaken til at linja også passerer gjennom (x_N, y_{N+1}) kommer fra massebalansen, og kan sees fra utledningen av uttrykket.



3

A liquid feed at the boiling point contains 3.3 mol % ethanol and 96.7 mol % water and enters the top tray of a stripping tower. Saturated steam is injected directly into the liquid in the bottom of the tower. The overhead vapor which is withdrawn contains 99% of the alcohol in the feed. Assume equimolar overflow for this problem. Equilibrium data for mole fraction of alcohol are as follows at 101.32 kPa abs pressure (1 atm abs):

x	y	x	y
0	0	0.0296	0.250
0.0080	0.0750	0.033	0.270
0.020	0.175		

Note: This column is a "cross" between a distillation column and a stripper. It separates a binary mixture of ethanol-water, so from this point of view, it is similar to distillation, but without a top section and with direct steam injection instead of a reboiler.

Stripper som destillasjonskolonne, og konstante molare strømmer

$S = D (= V)$

$F = B (= L)$

a)

For an infinite number of theoretical steps, calculate the minimum moles of steam needed per mole of feed. (Note: Be sure to plot the q line.)

Fra oppgaven: $x_F = 0{,}033$

$$D y_D = 0{,}99 \cdot F x_F$$

$$B x_B = 0{,}01 \cdot F x_F \overset{F=B}{\Rightarrow} x_B = 0{,}01 x_F$$

$$x_B = 0{,}00033$$

Siden væsken og dampen er i like vekt i det øverste trinnet, kan y_D hentes fra tabellen

$$x_F = 0{,}033 \Rightarrow y_D = 0{,}270$$

Får uttrykk for operating line fra molbalanse av etanol (bunnen):

$$V y_{n+1} + L x_N = V y_{N+1} + L x_n$$

$$V y_{n+1} + L x_B = V \underset{\substack{\parallel \\ 0}}{y_s} + L x_n$$

$$V y_{n+1} = L(x_n - x_B)$$

$$\underline{y_{n+1} = \frac{L}{V}(x_n - x_B)}$$

Destillasjonskolonne: op. line begynner i (x_B, y_s) og slutter i q-line,

q-line er vertikal siden feed er væske (med mindre op. line krysser eq. line, men det gjør den ikke)

$\Rightarrow$ slutter i (x_F, y_D)

$$\Rightarrow \frac{L}{V} = \frac{y_D - y_s}{x_F - x_B} = \frac{0,270}{0,033 - 0,00033} = 8,26$$

$$\frac{V}{L} = \frac{S}{F} = \frac{1}{8,26} = 0,121$$

$\Rightarrow$ minst $0,121 \ \frac{\text{mol damp}}{\text{mol feed}}$ trengs

b) Using twice the minimum moles of steam, calculate the number of theoretical steps needed, the composition of the overhead vapor, and the bottoms composition.

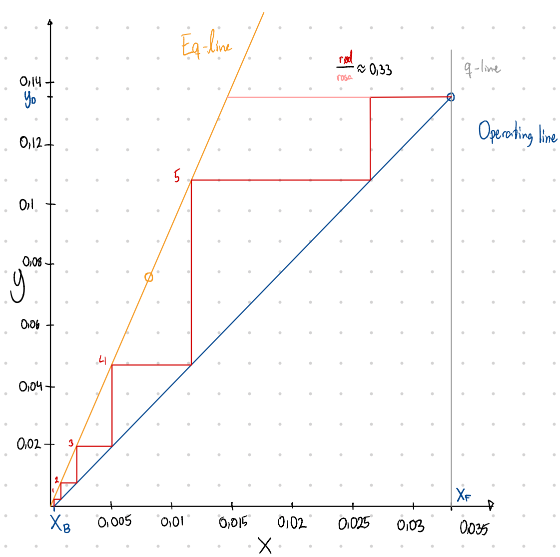
Dobbelt av minimum $= 0,242$

$$D y_D = 0,99 \cdot F x_F$$

$$S y_D = 0,99 \cdot F x_F$$

$$y_D = 0,99 \cdot \frac{F}{S} x_F$$

$$y_D = \frac{0,99 \cdot 0,033}{0,242} = 0,135$$



Får antall steg = 5,33

$y_D = 0,135$, $x = 0,00033$

c) Use the Kremser formula to check the result from (b) (where you should determine the number of stages graphically).

Kan Henry's lov brukes?

Sjekk: La $y = kx$

$k = \frac{y}{x}$

	x	y		x	y
	0	0	3	0.0296	0.250
1	0.0080	0.0750	4	0.033	0.270
2	0.020	0.175			

$k_1 = 9{,}375$

$k_2 = 8{,}75$

$k_3 = 8{,}44$

$k_4 = 8{,}18$

Intervallet vi ser på bruker kun første datapunkt, det er rimelig å anta Henry's lov på intervallet, ettersom det er lite.

Velger k_1 ettersom dette punktet bestemte stigningstallet grafisk

Kremser formelen:

$$N = \frac{\ln\left[\left(\frac{x_0 - \frac{y_{N+1}}{k}}{x_N - \frac{y_{N+1}}{k}}\right)\cdot(1-A) + A\right]}{\ln\left(\frac{1}{A}\right)}$$

$$A = \frac{L/V}{k_1} = \frac{1/0{,}242}{9{,}375} = 0{,}44077$$

$$y_{N+1} = y_5 = 0$$

$$\Rightarrow N = \frac{\ln\left[\frac{x_0}{x_N}(1-A)+A\right]}{\ln\frac{1}{A}} = 4{,}92$$

Det er et avvik på $\approx 0{,}4$, dette skyldes antakeligvis antakelser og upresis tegning grafisk.

$$\underline{\underline{N = 4{,}92}}$$