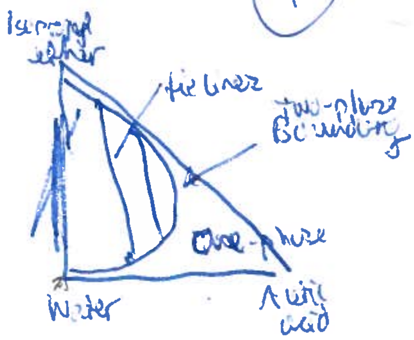
Exam Sep.tek. Des. 2016. Solution

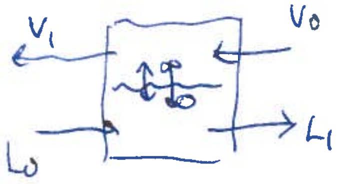
1



Problem. Extraction (25%)

(a) see figure next page

(b) Single-stage extraction



100% isopropyl ether
1 kg/s

26.5% acetic acid
73.5% water
1 kg/s

Mix L_0 and V_0: Get mix M which is 50% isopropyl ether (see figure).

Products L_1 and V_1 lie on tie line through M.

From diagram (approximately) in the middle between two of the given points

L_1: Acetic acid: $\frac{13.3+25.2}{2} = 19.3\%$

Water: $\frac{84.4+71.1}{2} = 77.8\%$

Isopropyl ether: $\frac{2.3+3.4}{2} = 2.9\%$

V_1: Acetic acid: $\frac{4.8+11.4}{2} = 8.1\%$

Water: $\frac{1.9+3.9}{2} = 2.9\%$

Isopropyl ether: $\frac{\cancel{93.3}\ \cancel{84.7}}{2} = \cancel{90.2}\ 89.0\%$

Alternative (simpler but less accurate): Use figure

Amounts: From balance isopropyl ether

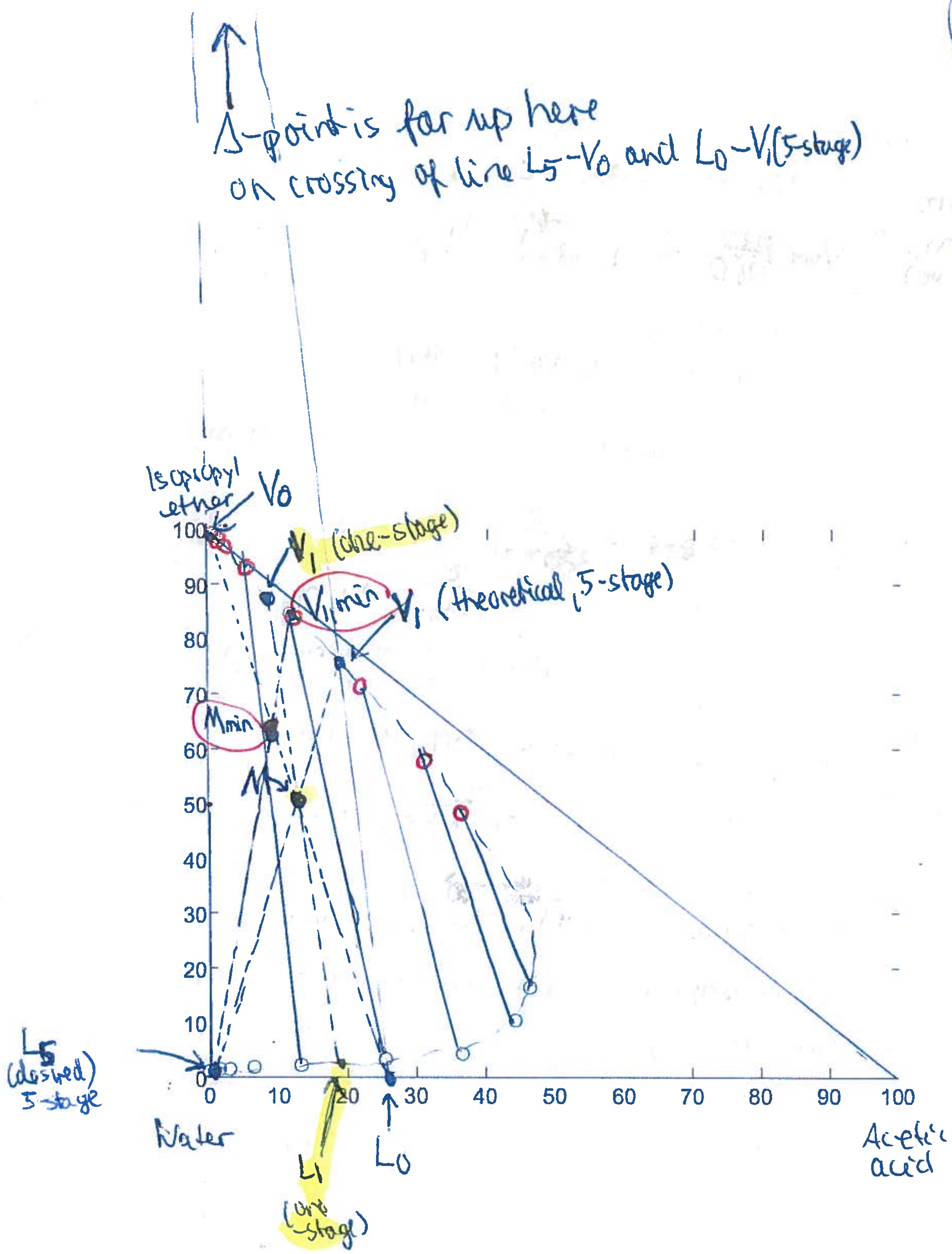
In = Out

$1\,\mathrm{kg/s} = L_1 \cdot 0.029 + V_1 \cdot 0.89$, $V_1 = (2-L_1)$

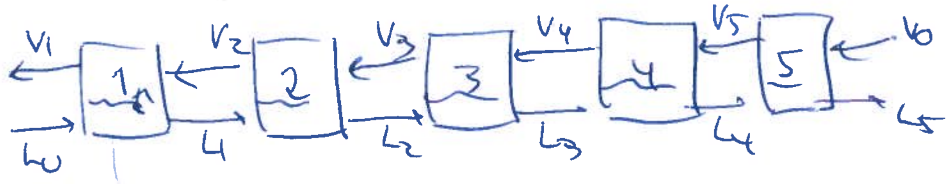
$\Rightarrow L_1 = \frac{2 \cdot 0.89 - 1}{0.89 - 0.029}\ \frac{\mathrm{kg}}{\mathrm{s}} = 0.906\ \mathrm{kg/s}$

$V_1 = 2 - 0.906 = 1.094\ \mathrm{kg/s}$

(Can alternatively use ~~weight~~ lever arm rule.)


Δ-point is far up here
on crossing of line L_5-V_0 and L_0-V_1(5-stage)
Isopropyl ether
V_0
V_1 (one-stage)
$V_{1,min}$
V_1 (theoretical, 5-stage)
M_{min}
M
L_5 (desired) 5-stage
Water
L_1 (one-stage)
L_0
Acetic acid
0
10
20
30
40
50
60
70
80
90
100

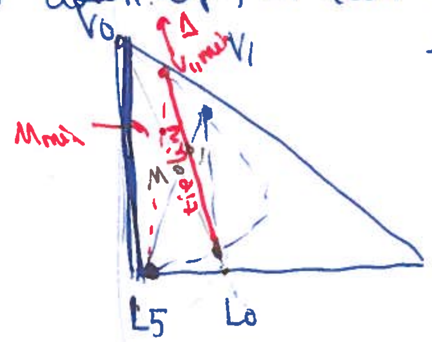
(c) 5-stage countercurrent. (3)



Definition of Δ is net flow through system

$$\Delta = L_0 - V_1 = L_1 - V_2 \cdots = L_5 - V_0$$

It will be on the crossing of line through inlet L_0 ~~&~~ V_1 and line through outlet L_5 and V_0. The Δ point will be located ~~far~~ ~~down~~ up, at least it will be far outside the triangle (but this in itself does not mean anything).



We note that V_1 is located to the right of the tie line through L_0. The separation will therefore not be possible, even with an infinite number of stages.

(d) Minimum amount of isopropyl ether ($V_{0,min}$).

We find the ~~tie~~ tie line through L_0 and locate the point ~~on~~ $V_{0,min}$ on the other side of the tie line. The new mixture point (M_{min}) is shown on the figure. The amount ($V_{0,min}$) may be found from the weight arm rule.

Distances: $\overline{L_0V_0} = 96$ cm

$\overline{V_0M_{min}} = 33$ cm

$\overline{L_0M_{min}}$ 63 cm

Weight arm rule

$L_0 \, \overline{L_0M_{min}} = V_{0,min} \, \overline{V_0M_{min}}$

1 kg/s — 63 cm — 33 cm

$$\Rightarrow V_{0,min} = \frac{63}{33} \frac{kg}{s} = \frac{1.90}{\cancel{1.74}} \text{ kg/s (ca.)}$$

Problem (Absorption and equilibrium, 30%)

(a) Henry's law $P_{CO_2} = H \cdot x_{CO_2}$,, x

$P_{CO_2} = y \cdot P$ is the partial pressure of CO_2. Let

$$yP = H \cdot x$$

$$y = \underbrace{\frac{H}{P}}_{m} x$$

Example: $m = \frac{1402 \text{ bar}}{1 \text{ bar}} = 1402$

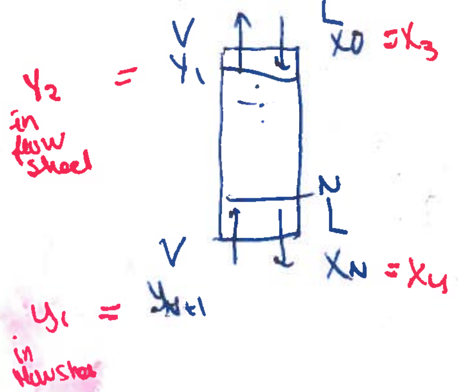
	0°C	10°C	20°C
1 bar	719	1027	1402
24 bar	30.0	42.8	58.4

NB: For absorpsjon it is best with a large value for A.

(b) Absorption factor, $A = \frac{L/V}{m}$

Kremser equation: 1) Straight eq-curve (m constant) and 2) straight operations line (L/V constant)

- If the temperature and pressure is constant then assumption 1 is OK (i.e., m constant), at least for dilute mixtures.
- But since $y = 0.17$ in feed the mixture is not really dilute so V will vary through the column, that is V will be larger at the bottom where we have a lot of CO_2.
- The expression for A given in the Kremser equation is derived by assuming L and V constant.



Mass balance for A (= CO_2 in this case)

In A = Out A

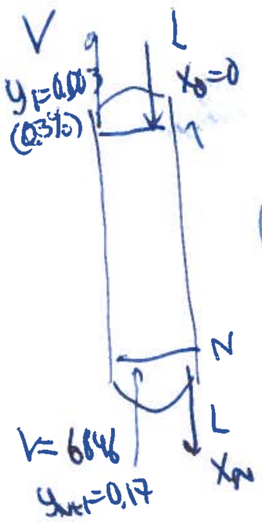
$$V y_{N+1} + L x_0 = V y_1 + L x_N$$

$$\Rightarrow \frac{L}{V} = \frac{(y_{N+1} - y_1)}{x_N - x_0}$$

$$\Rightarrow A = \frac{L/V}{m} = \frac{y_{N+1} - y_1}{m(x_N - x_0)} = \frac{y_{N+1} - y_1}{y_N^* - y_0^*} \quad \text{q.e.d.}$$

(c) Minimum water flow is when we have equilibrium in the bottom of the tower, so when $x_N = x_N^* = \frac{y_{N+1}}{m} = \frac{0.17}{42.8} = 0.0040$

From the mass balance for CO_2 we then have (assuming constant V):



Mass balance for CO_2

$$V y_{N+1} - V y_1 = -L_{min} x_0 + L_{min} x_N^*$$

(More correct: $\frac{V'}{1-y_{N+1}} y_{N+1} - \frac{V'}{1-y_1} y_1 = \frac{L'}{1-x_N} x_N - \frac{L'}{1-x_0} x_0$)

(Note: This V_1 should really be $V'/(1-y_1) = \frac{\overbrace{V(1-y_{N+1})}^{V'}}{1-y_1} = \frac{6646\cdot(1-0.17)}{1-0.003} = 5533$ but since $y_1 = 0.003$ is small the term Vy_1 is small anyway so the error is negligible.)

Get $L_{min} = \frac{V(y_{N+1} - y_1)}{x_N^* - x_0} = \frac{6646 \cdot (0.17 - 0.003)}{0.0040 - 0} = 277470 \frac{kmol}{h}$

To get in m^3/h: (It is mostly water)

$L_{min} = 277470 \frac{kmol}{h} \cdot 18 \frac{kg}{kmol} / 1000 \frac{kg}{m^3} = 4994 \, m^3/h$

(d). Use $L = 1.1 \cdot L_{min}$ $= 305217$ kmol/h. From mass balance: $x_N = \frac{V(y_{N+1} - y_1)}{L} = 0.00364$

Number of equilibrium stages using Kremser

$$A = \frac{L/V}{m} = \frac{277470 \cdot 1.1 / 6646}{42.8} = 1.073$$

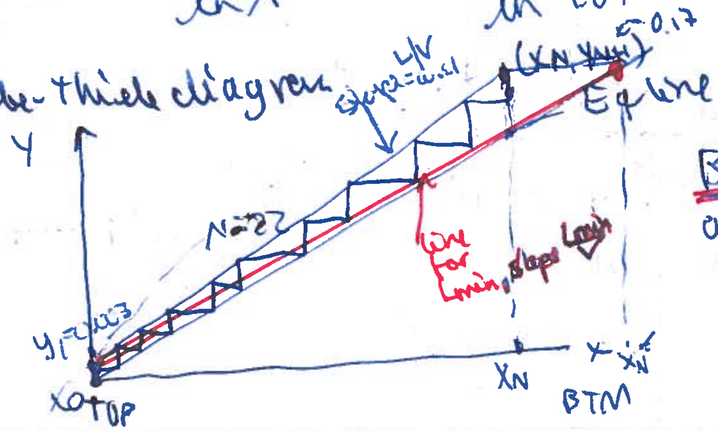
If I used the other formula I get ~~a slightly different num~~ the same (:

$$A = \frac{y_{N+1} - y_1}{m(x_N - x_0)} = \frac{0.17 - 0.003}{42.8 \cdot (0.00364)} = 1.073$$

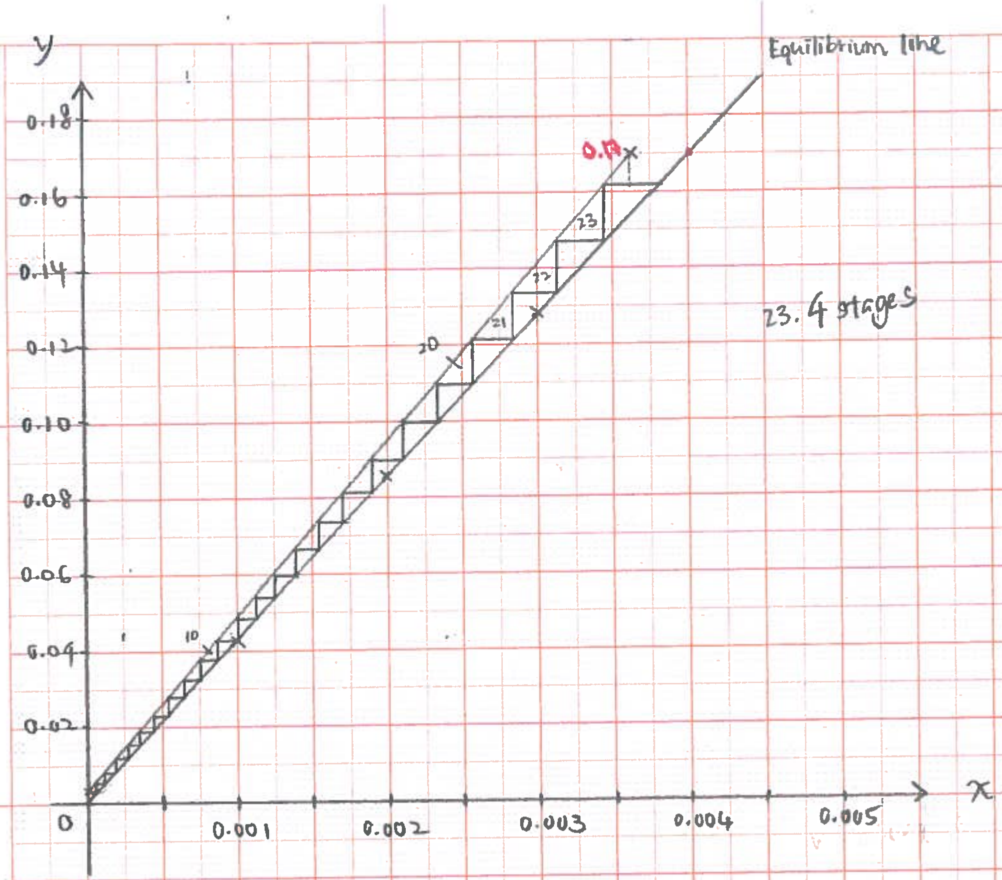
$$N = \frac{\ln \frac{y_{N+1} - y_N^*}{y_1 - y_0^*}}{\ln A} = \frac{\ln \frac{0.17 - m \cdot x_N}{0.003 - 0}}{\ln 1.073} = 22.1$$

($m = 42.8$, $x_N = 0.00364$; $\frac{4.736}{0.156}$)

In McCabe-Thiele diagram



But. In practice V is a little smaller in the top so L/V is "better" so we need a little less stages than N = 22.1. (so Kremser is conservative)


y
x
Equilibrium line
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0.001
0.002
0.003
0.004
0.005
10
20
21
22
23
23.4 stages

5B

(e) If N=50. Then we must solve for y_1 using Kremser. A is unchanged. So

$$\cancel{N = \frac{\ln \frac{\overset{0.17}{y_{N+1}} - y_N^{*} \approx 0}{y_1 - \underset{0}{y_0}}}{\ln A} = 50}$$

or better

$$\frac{\overset{0.17}{y_{N+1}} - \overset{0.00364 \cdot 42.8 = 0.1558}{y_N^{*}}}{\underset{\text{To be found}}{y_1} - \underset{0}{y_0^{*}}} = A^N = 1.073^{50} = 33.88$$

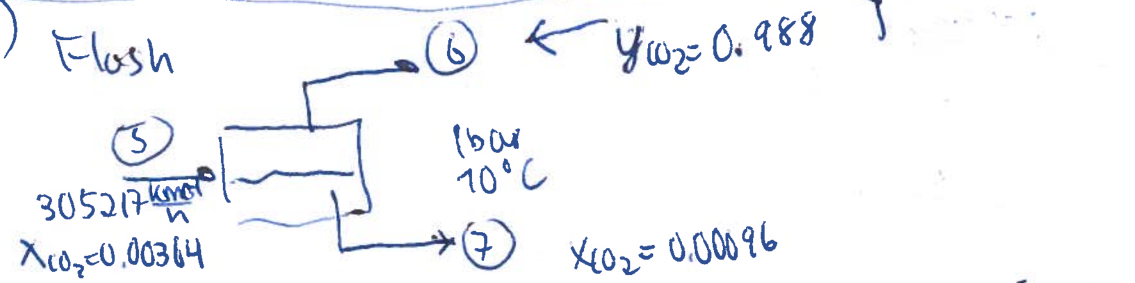
$$\Rightarrow y_1 = \frac{0.17 - 0.1558}{33.88} = 0.00042$$

$(= 0.042\ \%\ CO_2)$

so almost 10 times lower,

Comment: In reality, x_N will be slightly larger than before (0.00364), but this will not change the result much.

(f) Flash



We can assume the liquid product is almost pure water so $x_{H_2O} \cong 1$. The partial pressure of water is then (Raoult's law)

$$P_{H_2O} = x_{H_2O} \cdot P_{H_2O}^{sat} = \underbrace{1}_{\text{approx}} \cdot 0.012\text{ bar}$$

In stream 6

$$P_{H_2O} + P_{CO_2} = P = 1\text{ bar} \Rightarrow P_{CO_2} = 0.988\text{ bar}$$

(so $y_{CO_2} = 0.988$)

From Henry's law

$$P_{CO_2} = H \cdot x_{CO_2} \Rightarrow \underset{(x_7)}{x_{CO_2}} = \frac{0.988\text{ bar}}{1027\text{ bar}} = 0.00096$$

$(\approx 0.1$ wt% CO_2

Amount of CO_2 in the product (stream 6)

Recovered: $V_6 \cdot y_6 = L_5 x_5 - \underbrace{L_7}_{\approx L_5} x_7$

$= 305217\,(0.00364 - 0.00096) = 818 \ \frac{kmol}{h}$

Original in feed:

$6646 \cdot \frac{kmol}{h} \cdot 0.17 = 1129 \ \frac{kmol}{h}$

Percent recovered: $\frac{818}{1129} \cdot 100\% = \underline{\underline{72.4\%}}$