<u>**Exam Separation Technology 2009**</u>
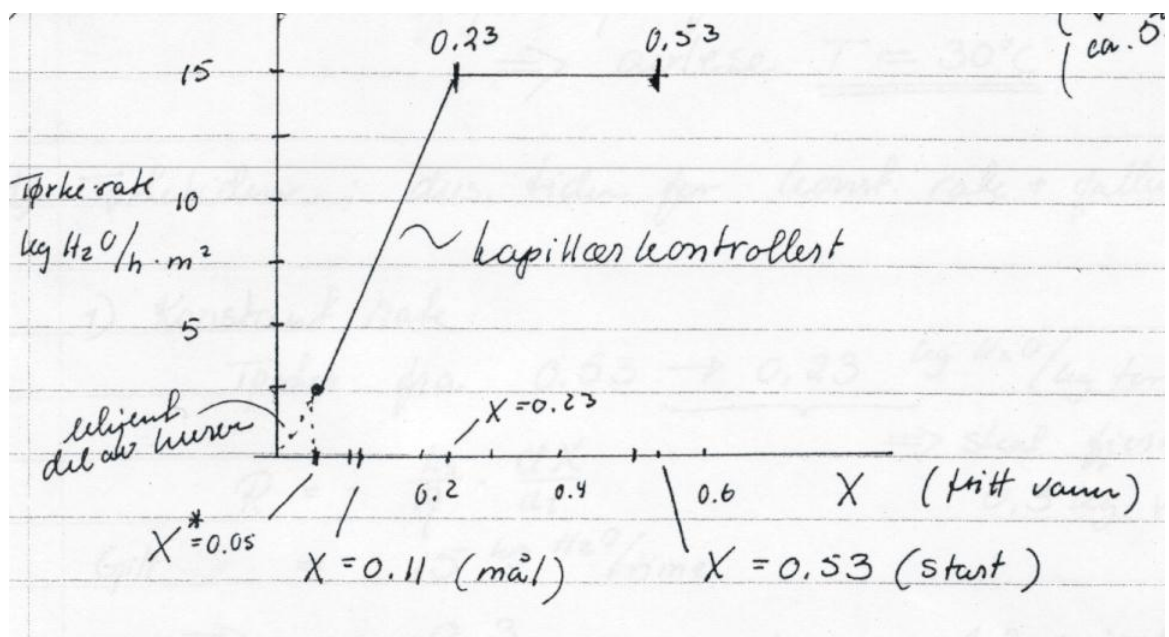
OPPGAVE 1 TØRKEPROSESS

100 kg bomullsgarn – (tørr vekt); tørkes fra $X = 0,53$ til $X = 0,11$ kg vann / kg tørt materiale

a)   Tørkeluft med $T = 62°C$, $H = 0,0134$ kg H_2O / tørr luft ; gitt $p_A = 1$ kPa

avleser Table A.2-9 (gitt): $p_{AS} = 19,94$ kPa

$\Rightarrow$ % relativ fuktighet; $\mathbf{H_R} = 100 (1/19,94) = \mathbf{5\%}$

b)   Skisse av tørkekurven:

c)   Temperaturen på garnet i perioden for konstant tørking;
$\Rightarrow$ Tørking som om vi er ved våtkuletemperatur; dvs. i diagrammet skal vi følge linjen for adiabatisk metning: ved $H = 0,0134$ kg H2O / tørr luft og temperatur $T = 62°C$;

Avleser da $\mathbf{T = 30°C}$

d)   Tørketiden for hver "batch"; dvs. tørketiden for I) konstant + II) fallende tørkerate:

I) Konstant rate; tørker fra $0,53 \rightarrow 0,23$ kg H_2O/kg tørt materiale; fjerner 0,3 kg H_2O

1) $R = - (L_s / A)^{\cdot}(dX / dt) = 15$ kg H_2O/time (gitt) $\Rightarrow t = (0,3/15) = 0,02$ time /kg tørt
Dvs. $100 \times 0,02 = 2$ timer

2) $t = (L_s/AR_c) (X_1 - X_2) = (100 / 15) (0,53 - 0,23)$ *= 2 timer*

II) Fallende tørkerate; $\Rightarrow$ lineær funksjon: $R = a X + b$

$\Rightarrow$ 3) t = (Ls/A) ((X_1 – X_2) / (R_1 – R_2)) ln (R_1 / R_2); vi må altså kjenne R_2
Antar lineær funksjon gjennom origo; $\Rightarrow$ R = aX = (R_c/X_c) X

$$R_2 = 15(0,05/0,23)$$
$$R_2 = 3,26 \text{ kg } H_2O \text{ / time m}^2$$

Denne verdien settes inn i likning 3); nå basert på en rett linje gjennom origo:

4) t = (-L_s/A)·(X_c/R_c)·(ln(X_2/X_c) = (100·0,23/15)·ln(0,23/0,11) = *1,13 timer*

Dvs. **total tørketid** blir: t = 2 + 1,13 = **3,13 timer eller 3 timer 10 minutter**

e)   Først noen kommentarer: Figur 1 i utlevert materiell (figur 9.4-1 i læreboka) skal for denne oppgaven benyttes til en viss sammenlikning av ull og bomull. Det avleses for eksempel for bomull (kurve 12) et likevekts vanninnhold på ~2 kg H_2O / 100 kg tørt ullgarn (= 0,02 kg H_2O / tørt materiale) ved Hr = 5%, og 25°C. "Worsted" Ull (kurve 2) har til sammenlikning ~ 3,5 kg H_2O / 100 kg tørt ullgarn (= 0,035 kg H_2O/kg tørt garn) ved disse betingelser. Dersom bomullen ved 25°C inneholdt like mye vann som ull ved likevekt 60°C, ville den altså inneholde 0,05 kg H_2O / tørt materiale (det er oppgitt i oppgaven). Den relative % fuktighet ved likevekt ville altså være forskjellig.

Går vi inn i tabellen, og avleser for bomull (kurve 12) 0,05 kg H_2O / tørt materiale, så vil *den relative fuktighet være så høy som ~35%* utfra likevekt vanninnhold.
(For ull (kurve 2) ville vi ligge på ~15% relativ fuktighet.)

Beregnet utfra H_R = 100 (p_A / p_{AS}) = 35%, så kan p_A finnes når p_{AS} er kjent.

Lufta med temperatur 25°C er mettet med damp.
Vi avleser av tabell A.2-9, et likevekts damptrykk *p_{AS} = 3,17 kPa* ved 25°C .

H_R = 100(p_A/3,17) = **35%** $\Rightarrow$ **p_A = 1,1kPa**

PROBLEM 2 – REVERS OSMOSIS

a)   Dette er forklart i pkt. 13.9 i læreboka. Det er da forventet at svaret skal forklare hva osmose er, og hvordan vi kan lage ferskvann ved å reversere denne prosessen ved å legge på et trykk som da må være høyere den det osmotiske trykk. Eksempel på osmotisk prosess («forward osmosis») kan utnyttes til kraftproduksjon.

b)   Beregn det osmotiske trykk (π) for sjøvann av 25°C som inneholder 0,5 mol NaCl

Benytter vant'Hoffs likning : $\pi = c_j RT / M = (n/V_m)RT$ og setter inn
(NB! Siden NaCl er et salt som er fullstendig dissosiert i vann, må vi gange med 2 fordi vi har like mange mol Na^+ som Cl^-
Vi har for enkelthets skyld antatt at tettheten for vann er 1000 kg/m^3 siden denne ikke er oppgitt.)

π = [(2·0,5·10^{-3}kmol)/10^{-3}m^3]·82,06·10·298,2 = **24,5 bar**

c) Beregn vannfluksen, N_w for den aktuelle membranen

Vi benytter likning 13.9-2 i vedlegget for fluksen, N_w. Vi kjenner ΔP, og vi løser for N_w:

$$N_w = A_w (\Delta P - \Delta \pi) = 2{,}04 \cdot 10^{-4}(50 - 24{,}5) = \mathbf{52{,}02 \cdot 10^{-4} \ [kg \ H_2O/s.m^2)}$$

d) Beregn nødvendig membrane areal for å produsere 2000 liter vann per 24 timer:

Siden tetthet vann ikke er gitt, antas tetthet for vann lik 1000 kg/m^3
Dvs 2000 liter vann veier 2000 kg

Arealet blir: $\mathbf{A} = (2000/24 \cdot 3600) / (52{,}04 \cdot 10^{-4}) = \mathbf{4{,}5 \ m^2}$

Gitt:
Vannets permeabilitetskonstant er $2{,}04 \times 10^{-4}$ kg $H_2O/(s \cdot m^2 \cdot bar)$

Van t'Hoff's likning for osmostisk trykk: $\pi = c_j RT / M = (n/V_m)RT$

hvor c_j = konsentrasjon løst stoff, M = molekylvekt av det løste stoff, T = temperatur, n = antall mol løst stoff, V_m = volum løsningsmiddel (vann)

Gasskonstanten, R, er gitt i tabell under
Molekylvekt NaCl = 58,45 g/mol

Ytterligere informasjon om RO-prosesser er gitt i vedlegg

Eksamen Sep-tek, des 2009.
Oppgaver av Sigurd Skogestad.

Oppgave/Oppgåve 3. Destillasjon (35%)

Føden til en destillasjonskolonne er 100 kmol/h med 20 mol-% metanol (A) og resten vann. Destillat-produktet skal inneholde 98 mol-% A og tapet av A i bunnproduktet skal være 0.1 % av A i føden.

- Føden er på mettet væske på kokepunktet
- Total kondensator med refluks på kokepunktet
- Oppvarming skjer ved direkte innblåsning av vanndamp (V), dvs. det er ingen koker.
- Trykket i kolonnen er 1 atm
- Refluksforhold R=L/D=2
- Angi ytterligere antagelser du gjør for å løse oppgaven

Damp/væske likevektsdata (molfraksjon A)

x	0.02	0.04	0.10	0.20	0.40	0.60	0.70	0.80	0.90	0.95
y	0.134	0.23	0.418	0.579	0.729	0.825	0.870	0.915	0.958	0.979

(a) Beregn mengde og sammensetninger av strømmene V (dampføde), D (topp-produkt) og B (bunnprodukt).

(b) Hvilken sammenheng er det driftslinjen uttrykker?
Utled ligningene for driftslinjene i kolonnen (med symboler).
Vis at driftslinjen i topp går gjennom punktet (x_D,x_D) og i bunn gjennom punktet $(x_B,0)$

(c) Bestem antall teoretiske trinn og fødetrinn når føden er optimalt plassert.

(d) Hva er kolonnediameteren dersom gasshastigheten er 1 m/s (anta V=100 kmol/h hvis du ikke fant den i delspørsmål a)?

(e) Hva er minimum dampmengde V_{min} (med uendelig antall trinn)? Hvor mye høyere er den virkelige dampmengden V?
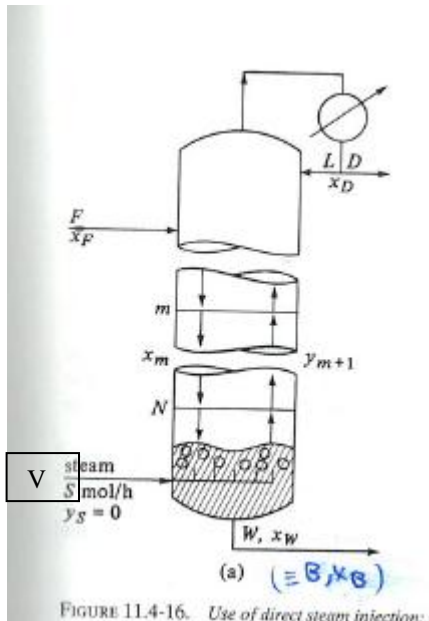
English text.
The feed to a distillation column is 100 kmol/h and contains 20 mol-% methanol (A) and 80% water. The distillate product is 98 mol% A and the loss of A in the bottom product should be 0.1% of the A in the feed.

- The feed is saturated liquid at the boiling point
- We use a total condenser with reflux at its boiling point
- The heat is supplied by direct steam (V) injection, that is, there is no reboiler.
- Column pressure is 1 atm
- Reflux ratio R=L/D=2
- Please give any additional assumptions you make
- VLE data is given above

(a) Find the amount and composition of the streams V (steam injection), D (top product) and B (bottom product).
(b) What relationship does the operating line express?
Derive the operating lines for the column (with symbols).
Show that the operating line for the top part goes through the point (x_D,x_D) and for the bottom goes through the point $(x_B,0)$.
(c) Find the number of theoretical stages and feed stage when the feed is optimally located.
(d) What is the diameter of the column if the gas velocity is 1 m/s (assume V=100 kmol/h if you could not solve part a)?
(e) What is the minimum steam required V_{min} (with infinite number of stages)? How much larger is the actual steam amount V?

Solution Oppgave/Oppgåve 3- Destillasjon (35%)

FIGURE 11.4-16. *Use of direct steam injection:*

Additional assumptions (2 points for any two of these):
>   Constant molar flows.
>   Ideal equilibrium stages (not a single student mentioned this important assumption for use of McCabe-Thiele….)
>   Ideal gas (for part d)
>   Temperature in bottom is 100 C (boiling point for water at 1 atm) (for part d)

(a) (10 points: 4 points for correctly understanding the problem (see flowsheet) and 6 points for setting up the balances given your understanding)

Mass balance methanol
>   (1) F zF = D xD + B xB
Total mass balance (methanol+water)
>   (2) F + V = D + B

Given (3) F=100 kmol/h, zF=0.2, xD=0.98
>   (4) BxB=0.001 FzF = 0.02 kmol/h   ("A in bottom is 0.1% of A in feed")
>   (5) L/D = 2

(1) and (4) gives: 20= D*0.98 20-0.02 [kmol/h] ->
>   D = 20.388 kmol/h
The reflux ratio is 2, i.e., L = 2D= 40.78 and the vapour at the top of the column is
>   VT = L + D = 3 D = 61.16 kmol/h
Since we assume constant molar flows and the feed is saturated liquid we then have:
>   V = VT = 61.16 kmol/h.
The total balance (2) gives:
>   B=F+V-D=100+61.16-20.39=140.78 kmol/h
and from (4):
>   xB = 0.001*20/140.78 = 0.000142

(b) (5 points) The operating lines give the vapor composition y as a function liquid composition x between the stages.

Top of column. Let x and y be mole fraction of A between two stages (actually, it should be x_n and $y_{n+1,}$ but I have dropped the subscripts).
Mass balance over the top (lower operating line):
>   Vy = Lx + D xD, i.e., y = L/V x + D/V xD

where L og V are flows in the top part.

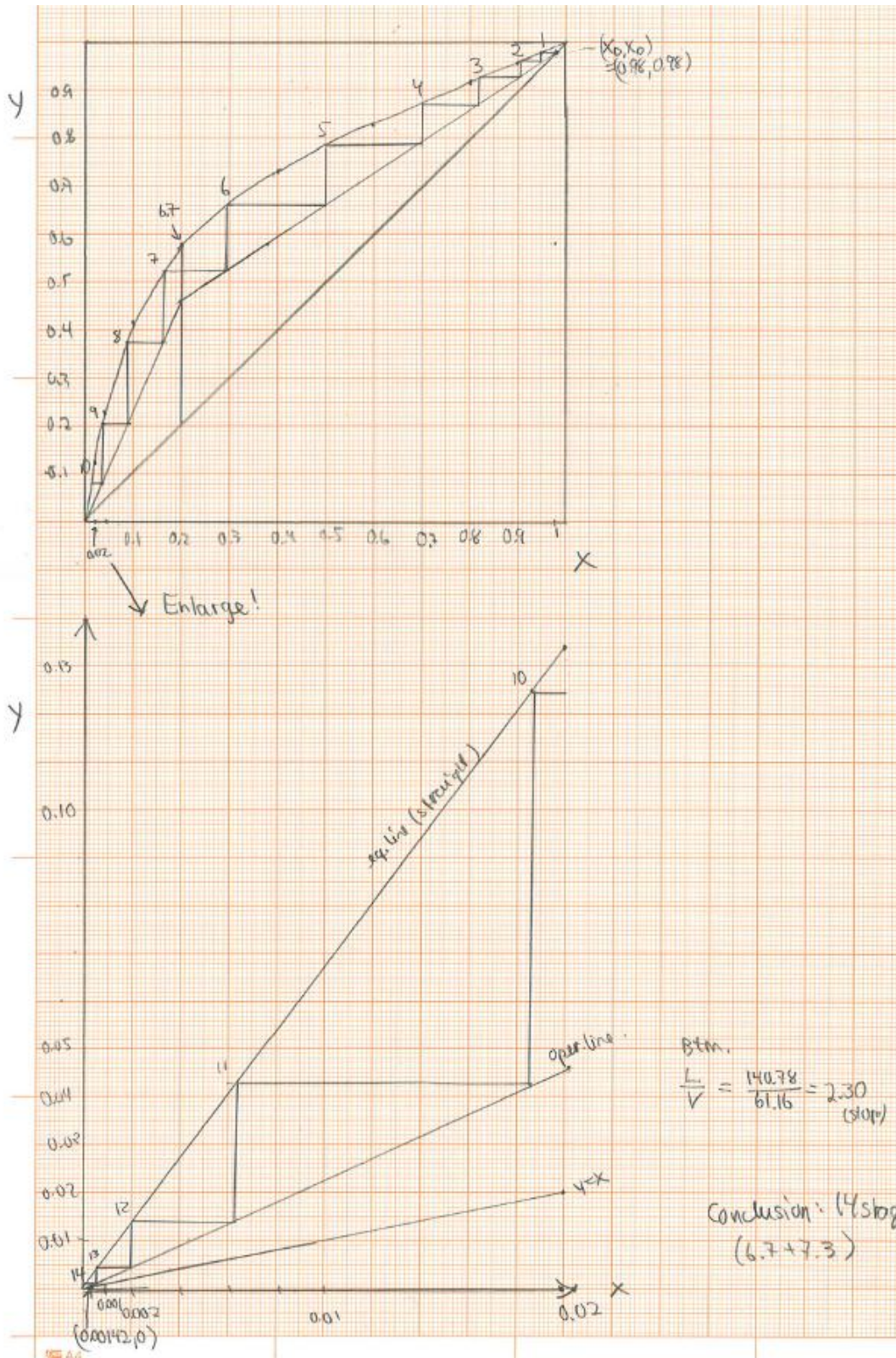Inserting x=xD gives: $y = (L+D)/V\ xD = xD$ since $L+D=V$

Bottom part. Let x and y be mole fraction of A between two stages (actually, it should be x_m and y_{m+1}, but I have dropped the subscripts).

Mass balance over the top (upper operating line):

$\quad\quad Lx = Vy + B\ xB$, i.e., $\ y = L/V\ x - B/V\ xB$

where L og V are flows in the top part.

Inserting x=xB gives $y = (L-B)/V\ xB = 0$ since $L=B$ in our case with direct steam injection.

(c) (10 points) Number of stages.

We use a graphical solution (McCabe-Thiele diagram) of the mass balance and equilibrium expressions on each stage. We make an enlarged diagram for the bottom of the column (x<0.02) and assume that the equilibrium line is straight in this region (we could have used the Kremser formula instead for the enlarged part and this would give the same result).

1. Draw equilibrium line

2. Draw upper operating line: Goes through (0.98,0.98) and has slope $L/V=L/(L+D)=2/3$

3. Draw lower operating line: goes through (0.000142,0) and through crossing with feed line (vertical feed line for liquid feed) and upper operating line. For the enlarged plot it is useful to know the slope for the bottom operating line; $L/V = 140.78/61.16 = 2.30$

4. Count stages using staircase (the staircase corresponds to a graphical solution of the mass balance (operating line) and equilibrium on each stage. The staircase changes between the operating line when they cross the feed line because this gives the fewest number of stages.

From the McCabe Thiele diagram we need 14 equilibrium stages and the feed stage is on stage 7 counted from the top. In summary, the column consists of (note: no reboiler!):
6 stages bottom + 7 stages top + Total condenser

Note: You would get almost the same solution with a regular column (with reboiler) if it had the same value of V. The only difference is that in our case (with direct steam injection) the bottom operating line is shifted slightly down, so direct injection requires fewer stages (but in our case the difference is very small since it is only shifted down by $x_B=0.000142$).

(d) (4 points) Want to find the column diameter given that we know v=1m/s. We have that
$$v \text{ [m/s]} = q \text{ [m3/s]} / S \text{ [m2]}$$
where S is the cross section area and q is the volumetric flow. Here
$$q \text{ [m3/s]} = n \text{ [mol/s]} * Vm \text{ [m3/mol]}$$
where
$$n = V = 61.16 \text{ kmol/h} = 17.0 \text{ mol/s}$$
and Vm is the molar volume which for an ideal gas is
$$Vm = RT/p \text{ [m3/mol]}$$
where p is 1 atm. What temperature T should we use? Note that V [mol/s] is assumed constant through the column (constant molar flows), but the volumetric vapor flow q is larger at the bottom where the temperature is highest, so to be "safe" we use the highest temperature. Since we have almost pure water in the bottom, we can assume that the temperature is 100C (boiling point of water).
$$T = 373 \text{ K}$$
We then get :
   $Vm = RT/p = 8.31*373 / 1.013e5 = 0.030 \text{ m3/mol}$.
   $q = V*Vm = 17*0.03 = 0.52 \text{ m3/s}$.
   $S = q \text{ [m3/s]} / v \text{ [m/s]} = 0.52 \text{ m3/s} (1 \text{ m/s} = 0.52 \text{ m2}$.
Diameter: $d = \text{sqrt}(S*4/pi) = 0.81 \text{ m}$

(e) (4 points) Minimum vapor needed.
The minimum reflux corresponds to the operating lines crossing the equilibrium line at xF=0.2. The corresponding slope of the operating line is
$$(L/V)min = (0.98-0.579)/(0.98-0.2) = 0.514.$$
which corresponds to
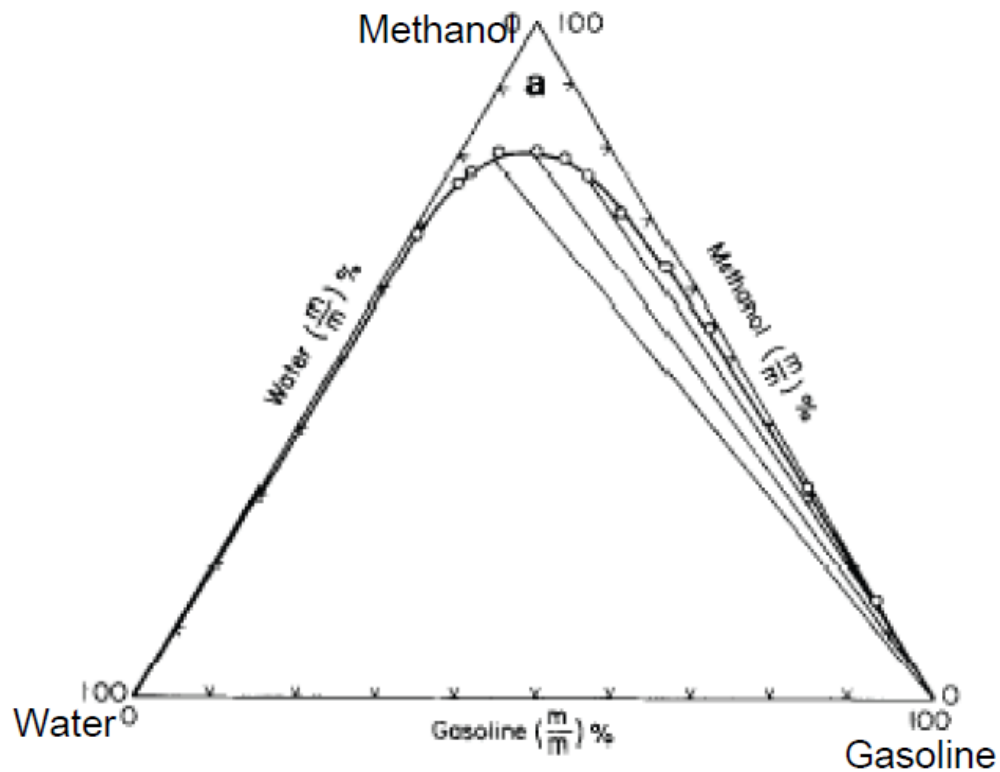$$Rmin = Lmin/D = Lmin /(Vmin-L) = (L/V)min/(1-(L/V)min) = 0.514/(1-0.514) = 1.058$$
So $Lmin = D*1.058$ and the minimum vapor flow at the top is
$$Vmin = Lmin + D = (1.058+1)*D = 2.058*20.39 \text{ kmol/h} = 41.95 \text{ kmol/h}$$
which is equal to the minimum vapor feed (at the bottom) since the feed is liquid.
The actual vapor feed is 61.16 kmol/h, which is 46% higher than the minimum.

Oppgave 4. Ekstraksjon (15%)

(a) Vi har en blanding med 500g vann og 500 g bensin som danner to væskefaser (se trekantdiagram). Hvor mye metanol må tilsettes for at vi skal få kun en væskefase?

(b) Vi har en blanding (V_0=10 t/h) av 50 vekt% metanol og 50% bensin som vi ønsker å separere for å få renere bensin. Noen har foreslått å tilsette vann (L_0=1 t/h) og bruke en ett-trinns ekstraksjonsprosess (mixer-settler). Tegn inn plasseringen på fødene L_0 og V_0 på trekantdiagrammet og bestem mengden og sammensetningen av produktene (L_1, V_1).

(c) Tegn flytskjema for en multi-trinns ekstraksjonsprosess. Vil du anbefale å vurdere multi-trinns ekstraksjon i dette tilfellet?

English text

(a) We have a mixture of 500 g water and 500 g gasoline that forms two liquid phases. How much methanol do you need to add to get only one liquid phase (use the diagram)?

(b) We have a mixture (V_0=10 t/h) of 50 wt% methanol and 50 wt% gasoline that we want to separate to make purer gasoline. It has been suggested to add water (L_0=1 t/h) and use a one-stage extraction process (mixer-settler). Plot in the feeds L_0 and V_0 on the diagram and find the amounts and compositions of the products (L_1, V_1).
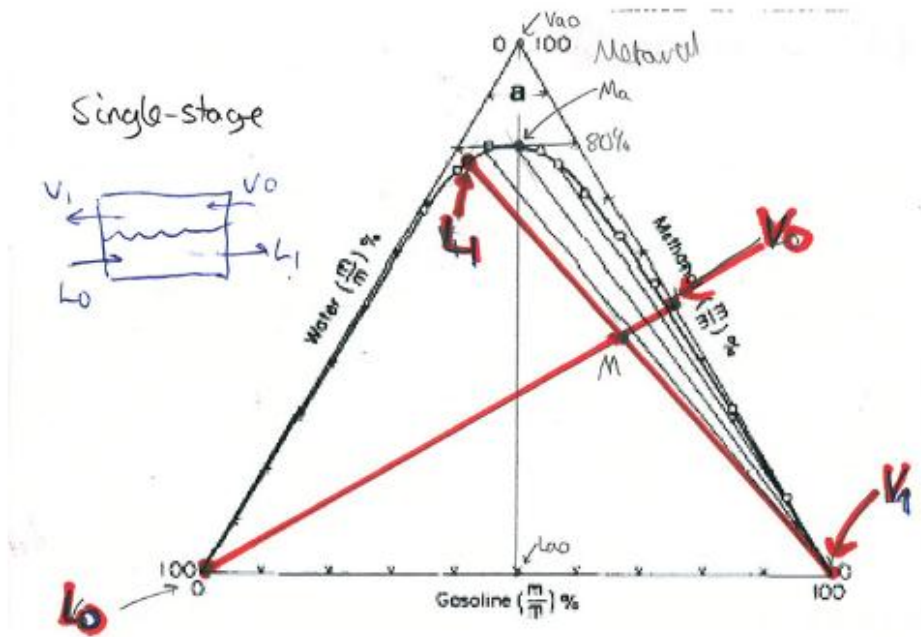
(c) Make a flow sheet of a multi-stage extraction process. Would you recommend considering multi-stage extraction in this case?

Solution. Oppgave 4. Ekstraksjon (15%)

(a) (4 points) The original mixture of water/gasoline is shown as point L_{a0} in the diagram. We want to add methanol (V_{a0}) so that we get into the single-phase region "a". From the diagram we see that the desired mixture point M_a contains about 80 wt% methanol. We then have

$$V_{a0} / (L_{a0} + V_{a0}) = 0.8$$

and since $L_{a0}=1$kg we get that the amount of methanol we must add to just be just on the phase boundary is $V_{a0} = 0.8/0.2 = 4$ kg.

(b) (8 points) The two feeds in this case are V_0 and L_0. We identify the mixing point M which contains 10% water (I found it from the 10% line on the diagram, but one could alternatively use the lever arm rule). The products (L_1, V_1) are at the end of the tie line through the point M (since M is not on one of the given tie lines, we need to estimate where the tie line through M goes).

From the diagram it seems that the gasoline product V_1 is almost pure gasoline while the other product (L_1) is about 78% methanol (read from point L1 in the diagram).

      Material balance for methanol: 0.78 L1 = 5 gives L1 = 6.41 t/h
      Total mass balance: V1 = 1 + 10 − 6.41 = 4.59 t/h

Could alternatively have used the lever arm rule:
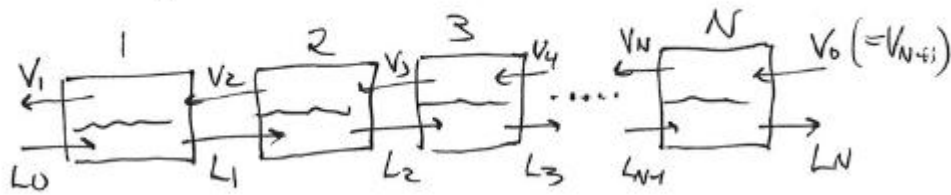 $L_1/V_1 = V_1M/L_1M = 5.4$cm/3.85cm = 1.40
      Total mass balance: L1+V1 = L0+V0 = 11 t/h -> 2.40 V1 = 11 t/h -> V1 = 4.58 t/h

The amount of gasoline in L1 (which can be a bit difficult to read exactly) can be found from the mass balances:
      Mass balance gasoline: V1 + xg L1 = 5 gives xg = 0.0296 (i.e. 3% gasoline in L1)
 The amount of water in L1 is then 100%-78%-3%=19%.

Multi-stage

(c) (3 points) Multi-stage extraction.

The figure shows countercurrent multi-stage extraction, which is generally the preferred solution.

In single-stage extraction, the products (V_1, $L_N=L_1$) must lie on the two-phase boundary and on a tie line through M.
In multi-stage extraction the products (V_1, L_N) must lie on the two-phase boundary on a line (not necessarily a tie line) through M.

It is better with multistage countercurrent extraction, but in our case, the gasoline product V_1 is already quite pure so with a <u>given overall feed</u> (V_0+L_0) there is really not much possibility for shifting L_N (because it lies on a line between the fixed point M and V_1 which is almost fixed).
Conclusion: Not much point in multistage extraction.

Comment: If we had another cases where we added much less water (L0) there would be some benefit because the gasoline product V1 from single-stage extraction would then not be very pure. However, adding a small amount of water (move M closer to V0) is not very smart, because the products (V1 and LN) must lie on the tie line through M, so we see from the diagram that the product LN then would contain more gasoline which is not desirable.