Eksamen 4. desember 2010. Problems 1 and 3

Oppgave / Oppgåve 1: Destillasjon (30%)

To komponenter (A og B) skal separeres i en destillasjonskolonne slik at topp-produktet (D) er 95 mol-% A og bunnproduktet (B) er 5 mol-% A. Kolonnen har to føder:

Øvre føde: $F_1 = 50$ mol/s, innholder 50 mol-% A og er mettet væske
Nedre føde: $F_2 = 50$ mol/s, innholder 25 mol-% A og er mettet damp

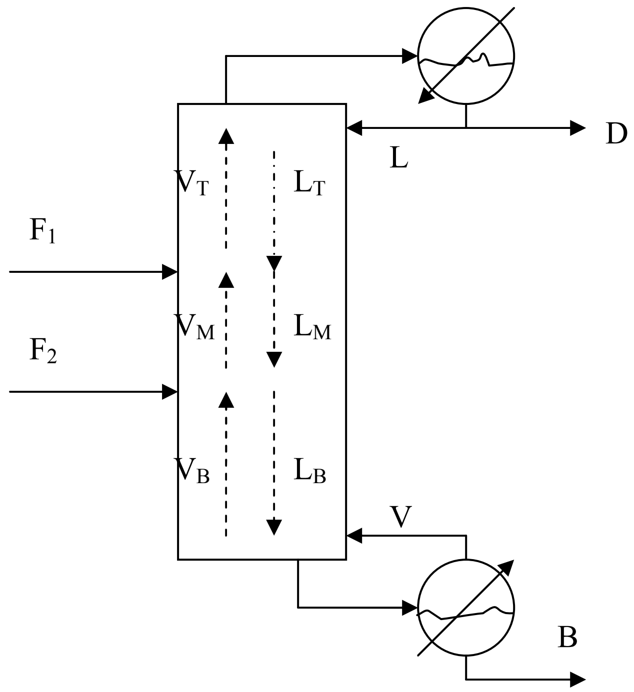
Refluksforholdet skal være R = L/D = 3.

Likevektsdata

x_A	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
y_A	0.12	0.25	0.42	0.56	0.67	0.75	0.83	0.88	0.94	0.97

Angi alle ytterligere antagelser du gjør.

(a) Beregn alle strømmene i kolonnen (D, B, L, LM, etc. [mol/s].), se figuren



(b) Bruk massebalanser til å utlede driftslinjen for de tre delene av kolonnen.

(c) Bestem nødvendig antall teoretiske trinn med den grafiske McCabe-Thiele metoden. F_1 og F_2 skal plasseres optimalt, dvs. slik at kolonnen får færrest mulig trinn

(d) Bestem minimum refluks (Lmin) og diskuter valg av refluks.

Oppgave / Oppgåve 3: Absorpsjon (20%)

En pakket absorpsjonskolonne tilføres 2.13 kg/s av en gassstrøm med 98 mol-% luft og 2 mol-% av en uønsket komponent A. 99.9% av komponent A skal fjernes ved absorpsjon i vann (som tilføres som rent vann i motstrøm). Gass- og væskebelastningen skal være henholdsvis 1.3 og 2.0 kg/(s,m2 tårntversnitt). Kolonnen opererer ved ca. 300K og 1 bar.
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Data:
Molvekter [kg/kmol] er 29 (luft), 18 (vann) og 70 (A).
Henry's lov: $p_A = H\ x_A$ der H = 0.2 bar.
Volumetrisk masseoverføringskoeffisient: $K_y a$ [mol A/s,m3]= $39.2\ G_L^{0.5}$ der G_L[kg/(s,m2)] er væskebelastningen.
R=8.31 J/K,mol

Angi ytterligere antagelser du gjør.

(a) Beregn tårntverrsnitt S [m2], gasshastigheten v [m/s] og væskeføden L [mol/s].

(b) Det er gitt at masseoverføringen i kolonnen kan beregnes fra uttrykket

$$N_A = (K_y\ a)\ S\ z\ (y-y^*)_{lm} \qquad \text{[mol A/s]}$$

Der "lm" angir logaritmisk midlere verdi, $\Delta y_{lm} = (\Delta y_1 - \Delta y_2)/\ln(\Delta y_1/\Delta y_2)$. Definer symbolene i uttrykket, og forklar kort hvordan det kan utledes og hvilke antagelser som må gjøres.

(c) Beregn nødvendig pakningshøyde.

(d) Ekstra poeng: Beregn minimum væskemengde Lmin og kommenter den valgte verdien.

ENGLISH

Problem 1: Distillation (30%)

Two components (A and B) are separated in a distillation column such that the top product (D) is 95 mol-% A and the bottom product (B) is 5 mol-% A. The column has two feeds:

Upper feed: F_1 = 50 mol/s, contains 50 mol-% A and is saturated liquid.
Lower feed: F_2 = 50 mol/s, contains 25 mol-% A and is saturated vapour.

The reflux ratio R = L/D = 3.

Equilibrium data

x_A	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
y_A	0.12	0.25	0.42	0.56	0.67	0.75	0.83	0.88	0.94	0.97

State any additional assumptions that you make.

(a) Find all the flows in the column (D, B, L, LM, etc. [mol/s].), see the figure.

(b) Use mass balances to derive the operating lines for the three parts of the column.

(c) Find the required number of theoretical stages using the graphical McCabe-Thiele method. The feeds F_1 are F_2 should be optimally located, that is, such that the number of stages in minimized.

(d) Find the minimum reflux (Lmin) and discuss the choice of the reflux. .

Problem 3: Absorption (20%)

A packed absorption column is fed 2.13 kg/s of a gas with 98 mol-% air og 2 mol-% of an undesirable component A. 99.9% of component A is to be removed by absorption in water (which is fed countercurrently as pure water. The gas and liquid loads are 1.3 og 2.0 kg/(s,m2 column cross-sectional area), respectively. The column operates at about 300K and1 bar.

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Data:
Mole weight [kg/kmol] are 29 (air), 18 (water) og 70 (A).
Henry's law: $p_A = H\, x_A$ where H = 0.2 bar.
Volumetric mass transfer coeffisient: K_ya [mol A/s,m3]= 39.2 $G_L^{0.5}$ where G_L[kg/(s,m2)] is the liquid load.
R=8.31 J/K,mol

State any additional assumptions that you make.

(a) Find the column cross-sectional area S [m2], gas velocity v [m/s] and the liquid feed L [mol/s].

(b) The overall mass transfer in the column can be calculated using the formula

$$N_A = (K_y\, a)\, S\, z\, (y-y^*)_{lm} \quad \text{[mol A/s]}$$

where "lm" denotes the log mean value, $\Delta y_{lm} = (\Delta y_1 - \Delta y_2) / \ln(\Delta y_1/\Delta y_2)$. Define the symbols in the fomula, explain briefly how it can be derived and state which assumptions that are needed.

(c) Find the required packing height.

(d) Extra points: Find the minimum liquid flow and comment on the chosen value.

SOLUTION

PROBLEM 1 Solution

(a) Balances over entire column

F1 + F2 = B + D
xF1 F1 + xF2 F2 = xB B + xD D

100=B+D
0.5*50+0.25*50 = B*0.05 + D*0.95

Get D=36.11 mol/s, B=63.89 mol/s

Given L/D=3, qF1=1 (liquid) and qF2 =0 (vapour) gives
L=LT = 108.33
LM=LB=LT+qF1*F1=158.33
VM=VT = L+D = 144.44
VB=V=LB-B=94.44

(b) Operating lines = Component material balance through section

Top:
y VT = x LT + D xD -> y = LT/VT x + DxD/VT = 0.75 x + 0.238

Middle :
y VM = x LM + D xD – F1 xF1-> y = 1.096 x + 0.064

Bottom :
y VB = x LB - BxB -> y = 1.677 x - 0.034

(c) Draw McThiele diagram.

- Draw upper feed line (liquid): Vertical line through (0.5, 0.5)
- Draw lower feed line (vapor): Horizontal line through (0.25, 0.25)
- Draw upper operating line through (0.95,0.95) and slope L/V=0.75
- Draw lower operating line through (0.05, 0.05) and slope L/V=1.677
- Draw middle operating line: Goes through crossing of lower operating line & lower feed line and upper operating line & upper feed line. Check: should go through (0, 0.064) and have slope L/V=1.096.

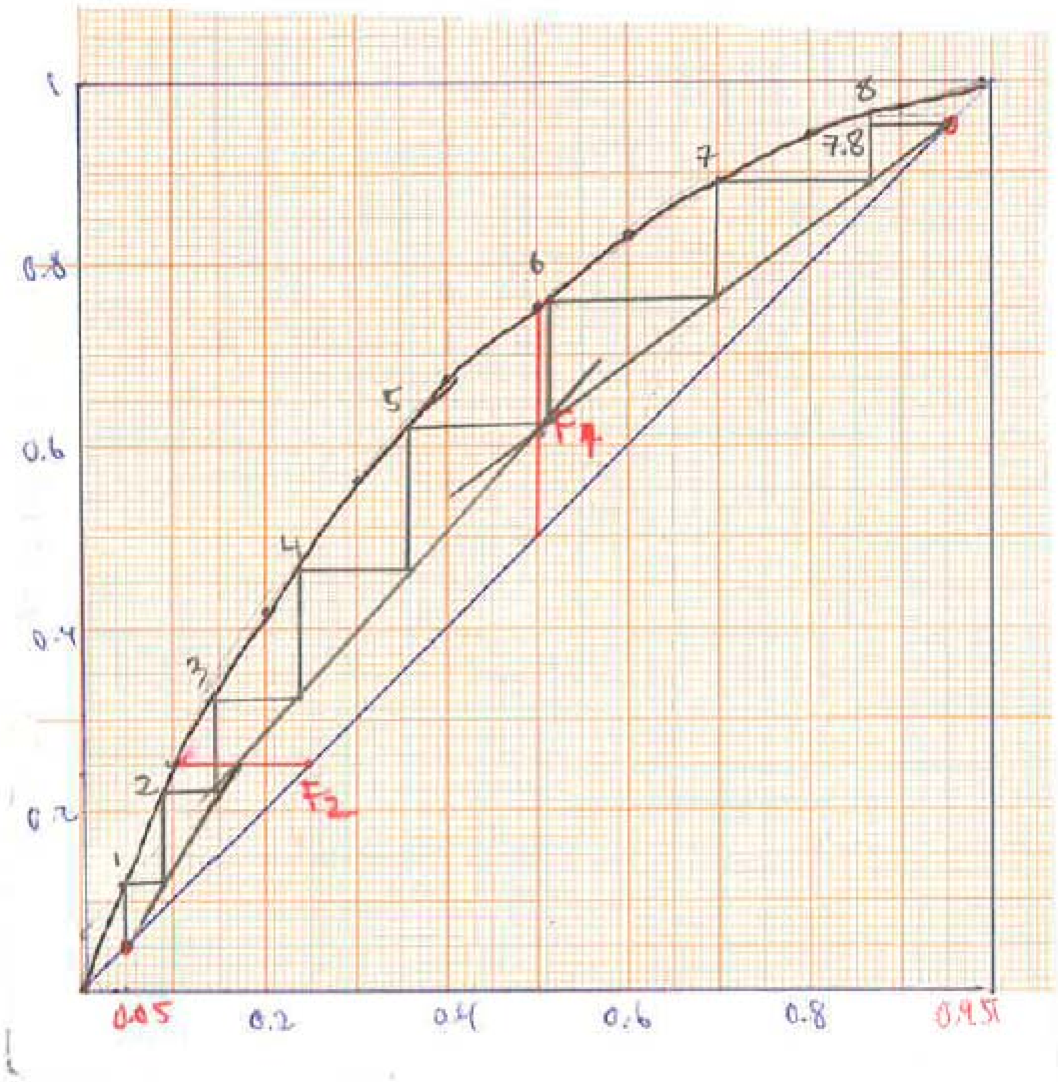
I started staircase from the bottom, but we could have started from the top instead.

From McCabe Thiele diagram, we need 7.8 theoretical stages.

Since reboiler gives 1 theor. stages we need:
reboiler (contributes 1 theor. stage)
6.8 theoretical trays inside column
Total condenser (contributes 0 stage)

Optimal feed location (counting stages from bottom):
Reboiler = stage 1
Feed 1: Above stage 2 (tray 1)
Feed 2: Above stage 5 (tray 4)

If we count from top, then feed 1 is below stage 3 and feed 2 is below stage 6, There are then 1.8 stages and finally the reboiler (1 stage).



(d) Minimum reflux. Have two feeds, so must consider possibility of pinch both places.

Upper feed: Upper feed line crosses eq. curve at (0.50, 0.75). Consider line through this point and (0.95, 0.95). Get Slope=$(L_{min}/V_{min})_T$ =(0.95-0.75)/(0.95-0.5)=0.44, or $(L_{min}/(L_{min}+D))$=0.44 or L_{min}=28.37 mol/s (at top).

Lower feed: Lower feed line crosses eq. curve at (0.10, 0.25). Consider line through this point and (0.05, 0.05). Get Slope=$(L_{min}/V_{min})_B$ =(0.25-0.05)/(0.10-0.05)=4, or $(L_{min}/(L_{min}-B))_B$=4 or LB_{min}/B=1.33 or LB_{min} = 84.97 mol/s, which corresponds top the following reflux flow at the top: $LT_{min}=Lb_{min}-F1$ = 34.97 mol/s.

So it is the bottom feed that gives the minimum reflux of Lmin=34.97 mol/s.

Discussion of choice of reflux L.
The actual reflux is L = 108.33 mol/s which is 3.1 Lmin, so this is very high-. Normally, we select L/Lmin about 1.2 to get a good tradeoff between capital costs (N) and energy (V).

Comment: Could alternative look at V. In bottom, Vmin = LBmin – B = 84.97 – 63.89 = 21.08 mol/s. Actual boilup is V = 94.44 mol/s =
+4.48 Vmin, which is way too large.

Problem 3
Solution:

(a) Column cross section area: S = 2.13 kg/s /1.3 kg/s,m2 = 1.64 m2.

The average mole weight is: 0.98*29+0.02*70 = 29.8 kg/kmol

Molar Gas feed rate: V = 2.13 kg/s / 29.8 kg/kmol = 0.07 kmol/s = 71.5 mol/s
(of this we have 71.5 * 0.98 = 70.07 mol air/s and NA=71.5*0.02 = 1.43 mol A/s)

Assume ideal gas. Then the molar volume is V = RT/p = 8.31*300/1.e5=0.0249 m3/mol.

Volumetric gas feed rate: V= 71.5 mol/s * 0.0249 m3/mol = 1.78 m3/s

Gas velocity, v = V[m3/s]/S = 1.78 m3/s / 1.64 m2 = 1.09 m/s

Liquid feed: 2 kg/s,m2*1.64 m2 = 3.28 kg/s.
This is water, so molar feed: L= 3.28 kg/s / 18 kg/kmol = 0.182 kmol/s = 182 mol/s

(b) S [m2] – column cross sectional area
y - gas phase mole fraction of component A
y* - (imaginary) gas mole fraction in equilibrium with liquid
1 – top of column
2 – btm of column

Derivation:
Assumptions: 1) Constant molar flows (straight equilibrium line).
2) Linear equilibrium curve (y = mx+b); Henry's law satisfies this.
Comment: These assumptions hold well for dilute mixtures as given in this problem.

(c)
Assumptions: Assume inert air (no condensation) and inert water (no evaporation of water).

Equilibrium for component A: y = mx where from Henry's law m = H/p = 0.2 bar/ 1 bar = 0.2

Mass transfer coefficient for component A: $K_ya = 39.2\ GL^{0.5} = 39.2*2^{0.5}$ = 55 mol A /s, m3

Mole fraction of A in gas feed:

$y2 = 0.02$

Amount of A in gas out = 1.43 mol/s *(1- 0.999) = 0.00143 mol/s

Mole fraction of A in gas leaving (assume air is inert)

$y1 = 0.00143/(70.07+0.00143) = 20.4\ e\text{-}6$ (ppm)

Mole fraction of A in liquid in (pure water) x1 = 0 -> $y1^* = 0$

Amount of A in liquid out = 1.43 mol/s * 0.999 = 1.429 mol/s

Mole fraction of A in liquid out, x2 = 1.429 / (1.429+182)= 0.0078 ->

$y2^* = 0.2\ x2 = 0.00156$

0.01844

Log mean mole fraction difference. dy1 = y1 – y1* = 20.4 e-6, dy2 = y2-y2*= ~~0.0027~~

dylm = (dy1-dy2)/ln(dy1/dy2)) = ~~0.00081~~

0.0027

Overall mass transfer of A;

$N_A = (K_y\ a)\ S\ z\ (y-y^*)_{lm}$

1.43 mol/s = 55 * 1.64 * z * 0.0027 -> z = 5.87 m

(d) Extra points for this: Minimum liquid load (corresponding to an infinite column height) occurs when we have equilibrium in the bottom of the column (that s, the equilibrium and operating lines cross), that is, when y2*=0.02, or x2=0.02/02=0.10. Here, x2 = 1.429/(Lmin+1.429), so Lmin = 12.86 mol/s (water).

Thus, we use 186/12.86 = 14.5 times the minimum, which is not a problem since water is so cheap and higher rates is good because it improves the mass transfer rate (see the given formula, where $K_y a$ increases by $G_L^{0.5}$).