Eksamen 2013 - Sep-14

Forlag gisit MB Hägg

Oppgave 1 Membran-separasjon

a) Beregning av min reject.
   Using given information and eq. 13.4.12

\[ X_{on} = \frac{x_t \left[ 1 + (\alpha - 1) \frac{P_e}{P_h} (1 - x_t) \right]}{\alpha (1-x_t) + x_t} \]

\[ = \frac{0.5 \left[ 1 + (30 - 1) \frac{1}{10} (1 - 0.5) \right]}{30(1 - 0.5) + 0.5} \]

\[ X_{on,a} = 0.079 \approx 0.08 \text{ for } 900 \text{ A} \]

⇒ Gass B is thus \( X_{o,B} = 0.92 \)

b) Assuming 25% higher \( \Rightarrow X_{o,A} = 0.10 \)

⇒ using this value to calculate the stream:

\[ Q_t = 0.5 \]

\[ Q = 2 \frac{m^3}{min} \]

\[ Q_t = Q_r + Q_p \]

\[ Q_t \cdot X_t = Q_r \cdot X_r + Q_p \cdot X_p \]
b) \[ \frac{\theta}{Q} = 0.53 \Rightarrow Q = 0.53 \cdot 2 \]

\[ \frac{Q}{F} = 1.06 \text{ m}^3 \text{(STP)} \text{min}^{-1} \]

Thus, \[ Q = 0.94 \text{ m}^3 \text{(STP)} \text{min}^{-1} \]

Calculating composition \[ \frac{y_p}{x_p} \]

using 13.4-8: \[ \frac{y_p}{x_p} = \frac{x_4 - x_0}{\theta} \]

\[ = 0.5 - 0.1(1 - 0.53) \]

\[ = 0.855 \text{ (Gas A)} \]

How much of A are we losing? \[ \frac{0.855}{2} = 0.425 \text{ m}^3 \text{(STP) min}^{-1} \]

Gas A in \[ 2 \cdot 0.5 = 1 \text{ m}^3 \text{(STP) min}^{-1} \]

Hence, Gas B = \[ 1 \text{ m}^3 \text{(STP) min}^{-1} \]

Gas B in permeate: \[ 1.06 \cdot 0.145 = 0.154 \text{ m}^3 \text{(STP) min}^{-1} \]

Which is \[ \frac{0.154}{1} \cdot 100\% = 15.4\% \text{ loss} \]
1c) Calculating membrane area:

\[ \tilde{A}_m = \frac{\Theta q + \Delta P}{(P_a/10\text{bar}) (\frac{P_i}{X_o} - P_i Y_o)} \]

\[ = \frac{0.53 \cdot 2 \text{ m}^3 / \text{min} \cdot 0.86}{\frac{400 \text{ bar}}{10^{-6} \text{m}} \left( 10 \text{ bar} \cdot 0.86 - 1 \text{ bar} \cdot 0.86 \right)} \]

\[ = \frac{0.53 \cdot 2 \cdot 0.86 \cdot 10^6}{60 \cdot 400 \cdot 10^{-6} \cdot 0.14 \cdot 76} \]

\[ = \frac{0.9416 \cdot 10^6}{0.14 \cdot 76.2 \cdot 10^{-3}} \]

\[ = 357 \cdot 10^6 \text{ cm}^2 \]

Membrane area \( \Rightarrow \) \( = 357 \text{ m}^2 \)

d) Reduce the loss of B by:
- Make a cascade solution or two steps with reduced stage erl (\( \Theta \))
- Change pressure ratio
- Try to increase selectivity (new material)
Problem on Adsorption (4)

\[ H_I = 30 \text{ cm} \quad Q_p = 712.8 \text{ kg/m}^3 \]

Calculating \( C/C_0 \) \( \Rightarrow \) Table

<table>
<thead>
<tr>
<th>Time, h</th>
<th>( C/C_0 )</th>
<th>Time</th>
<th>( C/C_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) 0</td>
<td>0.10²</td>
<td>10.8</td>
<td>0.45</td>
</tr>
<tr>
<td>0.9</td>
<td>0.065</td>
<td>11.25</td>
<td>0.68</td>
</tr>
<tr>
<td>0.9.2</td>
<td>0.124</td>
<td>11.5</td>
<td>0.76</td>
</tr>
<tr>
<td>0.9.6</td>
<td>0.027</td>
<td>12.8</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>0.098</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.4</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ t_u = \int_0^{t_b} \left( 1 - \frac{C}{C_0} \right) dt \Rightarrow \text{from graph or Table} \]

b) Break point: \( t_b = 9.58 \text{ h} \)

\[
H_{\text{unused}} = \left( 1 - \frac{t_u}{t_c} \right) H_I
\]

\[
= \left( 1 - \frac{9.58}{12.8} \right) 0.36 \text{ m}
\]

\[
= 7.5 \text{ cm unused bed}
\]
c) The graph between $t = 9.58$ and $12.8$ h is 3.22 h.

$\Rightarrow$ additional bed in mass transfer zone is 1.61 h.

$\Rightarrow$ total capacity will be used after $9.58 + 1.61$ h $= 11.19$ h.

which is $\frac{t_u}{t_e} = \frac{9.58}{11.19} = 0.86 \Rightarrow 86\%$

d) Determine the capacity of the column for water uptake until break-point.

After 12.8 h the column is saturated.

$N_2$ flow rate: $4052 \text{ kg/m}^2\text{.h}$

Total water adsorbed:

$\frac{926 \times 10^{-6} \text{ kg H}_2\text{O}}{\text{kg N}_2}$

$926 \times 10^{-6} \times 4052 \times 9.58 \frac{\text{kg H}_2\text{O}}{\text{m}^3} \times 0.225 \text{m}$

$= \frac{35.95}{0.225} \frac{\text{kg H}_2\text{O}}{\text{m}^3} \approx 160 \frac{\text{kg H}_2\text{O}}{\text{m}^3}$

or:

$\frac{160 \text{ kg H}_2\text{O}}{712.8 \text{ kg particles}} = 0.22 \frac{\text{kg H}_2\text{O}}{\text{kg particles}}$
Solution Problem 1. Distillation

(a) **Upper operating line**: Mass balances over the top of the column give:

**Total**: \[ V = D + L \] (1)

**Component**: \[ V y = D yD + L x \] (2)

Inserting \( D = V - L \) gives the top operation line

\[ y = \left( \frac{L}{V} \right) x + \left( 1 - \frac{L}{V} \right) yD \]

Inserting \( \frac{L}{V} = 0.86 \) and \( yD = 0.90 \) this gives

\[ y = 0.86 x + 0.126. \]

This line goes through \((yD, yD) = (0.9, 0.9)\) and the point \((0, 0.126)\) and is plotted on the xy-diagram.

**Feed line.** The feed is liquid, and the feed line is therefore a vertical line through the point \((xF, xF) = (0.5, 0.5)\),

**Lower operating line.** The lower operating line starts from the intersection between the feed line and the upper operating line and ends in \((xB, xB)\), but we do not yet know \(xB\).

To find \(xB\), we need to do a "trial-and-error" approach, where we guess \(xB\) and keep changing it until we can fit \(7\) stages in the McCabe-Thiele staircase; see the plot.

(i) With \(2\) plates above the feed, we find that the feed is about optimally located, and by trial and error we find \(xB = 0.07\).

We can now find \(D\) and \(B\) from the overall material balances

\[ F = D + B \]

\[ Fx = DyD + BxB \]

We get:

\[ 10 \times 0.5 = D \times 0.9 + (10 - D) \times 0.07 \]

and \(D = 5.18 \text{ kmol/h}\) and \(B = 4.82 \text{ kmol/h}\)

(ii) With the feed moved down (three plates above the feed), the feed is no longer optimally located, so we get a slightly higher value for \(xB\), maybe around \(xB = 0.08\) (see figure).

(b) **Control.**

Inputs for control (MVs): \(L, V_B (QB), D, B, L_{cw} (Qc)\)

Controlled variables (CVs): \(L/V\) (said to fixed), \(yD, MD\) (level), \(MB\) (level), pressure
Main disturbances: F, xF

The pairing is not obvious, but one suggestion is given in the Figure:
First two rather obvious pairings:
L ↔ L/V (clearly the best option since V cannot be directly manipulated)
B ↔ MB
The other are less obvious, but one possibility is:
D ↔ p (since D is a vapor product it has a direct effect on pressure, but only an indirect
effect on level, so this is why we do not use D for controlling MB)
Lcw (QC) ↔ MD (this is reasonable since the liquid that condenses increases the level)
VB (QB) ↔ yD (this is a bit by elimination; but although VB seems a bit far away from yD its
effect is very fast)

There are also other possibilities for the last three, for example, using vB(QB), to control
pressure and D control composition, but this makes the composition control even more
indirect.

Solution Problem 2. Absorption

Flows: We have a dilute mixtures so we assume V = V1 = V2 (throughout column) and L = L1
= L2.

Equilibrium: From $p_{SO2} = Hx$ (which applies to dilute mixtures) we derive

$$y = (H/p) x = mx$$

where $y$ is the vapor mole fraction of SO2. At p=1 bar and 25°C, we get $m=46$bar/1bar = 46.

(a) The problem is that the liquid flow rate L is too low so that cannot absorb enough SO2 even
with equilibrium at the bottom of the column. Note also that the absorption factor is less
than 1: $A = (L/V)/m = (90000/3000)/46 = 0.652$.

Calculations: With equilibrium at the bottom (which requires an infinite number of stages)
we have that: $x_1 = x_1^*$ (approximately)
where $x_1^* = y_1/m = 0.002/46 = 0.0000435$.

From the mass balance we can then compute $y_2$:
In $SO2 = Out SO2$
$V y_1 + L x_2 = V y_2 + L x_1$
Here $x_2=0$ and $x_1=x_1^*=y_1/m$ so we derive
$y_2 = y_1 - (Ly_1/(V^*m)) = y_1 (1 - A) = 0.002 * 0.348 = 0.000696$
which is about 7 times too large.
(b) With another identical column we send \( y_2 \) as the feed to the second column (so \( y_1' = y_2 = 0.000696 \)). This helps a little, but still we have \( A = 0.652 < 1 \) so it is not enough. We get (similar to above):
\[
y_2' = y_1' (1 - A) = 0.000696 \times 0.348 = 0.000242,
\]
which is still a factor 2.5 too large.

(c) Instead of building a second column, the following modifications for the original design have been suggested:

a. Increase the sea water flow by a factor 2
b. Decrease the temperature from 25C to 5C.
c. Increase the pressure from 1 bar to 2 bar

All of these increase \( A = (L/V)/m \) by a factor of 2 and will remove SO2 effectively (see detailed calculation below).

a. \( L \) is increased by a factor 2, so \( A = 1.304 \)
b. \( m \) is decreased by a factor 2.09, so \( A = 1.363 \)
c. \( m = H/p \) is decreased by a factor 2, so \( A = 1.304 \)

**Detailed calculation for case a** (\( L = 90000 \times 2, A = 1.304 \)).

From the Kremser equation we have
\[
(y_1 - y_1^*)/(y_2 - y_2^*) = A^N = 1.304^{10} = 14.2
\]

In addition we have the mass balance
\[
V \cdot y_1 + L \cdot x_2 = V \cdot y_2 + L \cdot x_1
\]

And equilibrium relationships, \( y_1^* = m \cdot y_1, y_2^* = m \cdot y_2 \).

We have given \( y_1 = 0.002 \) and \( x_2 = 0 \) so we have enough information to find \( y_1 \) and \( x_2 \).

From the mass balance we get since \( x_2 = 0 \)
\[
x_1 = (V/L) \cdot (y_1 - y_2) \quad \text{or} \quad y_1^* = (y_1 - y_2)/A
\]

Putting this into the Kremser equation using \( y_2^* = 0 \) gives
\[
y_1/y_2 - (y_1/y_2 - 1)/A = A^N
\]
\[
y_1/y_2 (1 - 1/A) = A^N - A
\]

and we derive
\[
y_2 = y_1 (1 - 1/A)/(A^N - A) = 0.002^* (1 - 1/1.304)/(14.2 - 1.304) = 0.000036
\]

which is a factor 3 lower than the requirement of \( y_2 < 0.000100 \), so we are OK.

Which of the three modifications is the best?

All three give acceptable SO2-removal so practical issues is probably the main reason for choosing one. Increasing the pressure is expensive as it requires compressing the
feed gas, so I would suggest one of the other alternatives. If there is no cold sea water, then the best alternative is to increase the seawater flow.

(d) The Kremser equation (1) is on the form given in the lectures, but it is equivalent to what is given in the book.

a. The assumptions are dilute mixtures with $m$ constant (straight equilibrium line) and $L/V$ constant (straight operating line).

b. $y_1^* = mx_1$ and $y_2^* = mx_2$ are the “imaginary” vapor compositions in equilibrium with $x_1$ and $x_2$.

c. From the diagram you see easily that $(y_2-y_1)/(x_2-x_1) = L/V$ (operating line) and $(y_2^*-y_1^*)/(x_2-x_1) = m$ (equilibrium line); and it follows that $(y_2-y_1)/(y_2^*-y_1^*) = (L/V)/m = A$; See also lecture notes (slide).
Solution.

We have dilute mixtures so we use $V_1 = V_2 = V$ and $L_1 = L_2 = L$

(a)
(b) With another identical column we send $y_2$ as the feed to the second column (so $y_1' = y_2 = 0.000696$). This helps a little, but still we have $A=0.652 < 1$ so it is not enough. We get (similar to above): 
\[ y_2^* = y_1' (1-A) = 0.000696*0.348 = 0.000242, \] which is still a factor 2.5 too large.

(c) Instead of building a second column, the following modifications for the original design have been suggested:

a. Increase the sea water flow by a factor 2
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All of these increase $A=\frac{L}{V}/m$ by a factor of 2 and will remove SO2 effectively (see detailed calculation below).

a. L is increased by a factor 2, so $A=1.304$
b. $m$ is decreased by a factor 2.09, so $A = 1.363$
c. $m = H/p$ is decreased by a factor 2, so $A=1.304$

**Detailed calculation for case a ($L=90000*2$, $A=1.304$).**

From the Kremser equation we have

\[ \frac{(y_1-y_1^*)}{(y_2-y_2^*)} = A^N = 1.304^{10} = 14.2 \]

In addition we have the mass balance

\[ V \, y_1 + L \, x_2 = V \, y_2 + L \, x_1 \]

And equilibrium relationships, $y_1^* = m_1 \, y_1$, $y_2^* = m_2 \, y_2$.

We have given $y_1=0.002$ and $x_2=0$ so we have enough information to find $y_1$ and $x_2$.

From the mass balance we get since $x_2=0$

\[ x_1 = \frac{V}{L} \, (y_1 - y_2) \] or $y_1^* = (y_1-y_2)/A$

Putting this into the Kremser equation using $y_2^*=0$ gives

\[ y_1/y_2 - (y_1/y_2-1) = A^N \]

\[ y_1/y_2*(1-1/A) = A^N-A \]

and we derive

\[ y_2 = y_1 \, (1-1/A)/(A^N-A) = 0.002*\frac{(1-1/1.304)}{(14.2-1.304)} = 0.000036 \]

which is a factor 3 lower than the requirement of $y_2<0.000100$, so we are OK

Which of the three modifications is the best?

All three give acceptable SO2-removal so practical issues is probably the main reason for choosing one. Increasing the pressure is expensive as it requires compressing the
Figurer for oppgave 2
Oppgave 3 / Oppgåve 3 - Absorpsjon 25%

\[ \frac{y_1 - y_1^*}{y_2 - y_2^*} = A^n \]  \hspace{1cm} (1)

\[ A = \frac{LV}{m} \]  \hspace{1cm} (2)

\[ A = \frac{y_1 - y_2}{y_1^* - y_2^*} \]  \hspace{1cm} (3)

Figur for oppgave 3

Forbrenningsgassen \((y_1)\) fra et kullfyrte kraftverk er på 3000 mol/s (84 kg/s) ved 1 bar og inneholder 0.2 mol\% SO\(_2\) \((y_1=0.002)\). Vi ønsker å fjerne minst 95\% av SO\(_2\) en \((y_2<0.0001)\) ved absorpsjon med 90000 mol/s (1600 kg/s)sjøvann \((x_2=0)\) ved 25 C; se figur.

Likevektsgata (Henry’s konstant for SO\(_2\) i vann; \(p_{SO2} = Hx\) der \(x\) er molfraksjon SO\(_2\)): H=115 bar (50°C), H=46 bar (25°C), H=22 bar (5°C).

(a) Selv med en stor kolonne (med et stort antall teoretiske trinn, N) oppnås ikke ønsket spesifikasjon på SO\(_2\). Kan du forklare hvorfor? Hva er fraksjonen SO\(_2\) \((y_2)\) i utgassen dersom du antar en meget stor kolonne \((N \to \infty)\)?

(b) For å fjerne mer SO\(_2\) foreslår det å bygge en kolonne til, dvs. utgassen \((y_2)\) sendes til en annen identisk absorpsjonskolonne (som også har 90000 mol/s med sjøvann og mange trinn). Lag et flytsskjema av den foreslåtte prosessen med to kolonner. Hjelper dette? Hva er fraksjonen SO\(_2\) \((y_1')\) etter den andre absorpsjonskolonnen når du antar en meget stor kolonne \((N \to \infty)\)?

(c) I stedet for å bygge en kolonne til, er følgende modifikasjoner av den opprinnelige designen med en kolonne foreslått:
   a. Øke sjøvannsmengden med en faktor 2.
   b. Redusere temperaturen fra 25°C til 5°C.
   c. Øke trykket fra 1 bar til 2 bar.

Vil noen av disse endringene gi akseptabel SO\(_2\)-fjerning? Hvilken av endringene vil du anbefale?

(d) For beregningene i delspørsmålet (c) kan du om ønskelig bruke Kremser-ligningen (1) gitt i figuren med N=10.
   a. Hvilke antagelser ligger bak ligning (1)?
   b. Hvilken er \(y_1\) og \(y_2\) definert?
   c. A is definert i (2), men er også gitt av (3). Bruk et y-diagram med innegnet driftslinje og likevektsskurve (McCabe-Thiele) til å bevise at (3) er riktig.