Oppgave 1, ikke relevant

Oppgave 2

a) Explain with a sketch of the system what we mean when we say 1) the drying process is adiabatic, and 2) what is understood by wet bulb temperature

b) A typical drying curve is given in the figure below where drying rate (R) is a function of free water (X).
Explain how the drying takes place in the three different regions; B-C, C-D, D-E

c) The general drying equation is given below. Find from this the equations for time at constant drying rate and for falling drying rate.

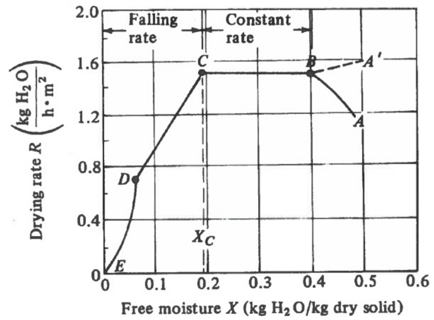
d) Air of temperature 65ºC (dry bulb temperature) has a dew point of 30ºC. We will use this air to dry some granulate (dog food). How much water (H) does this air contain at start? What is the percentage humidity?

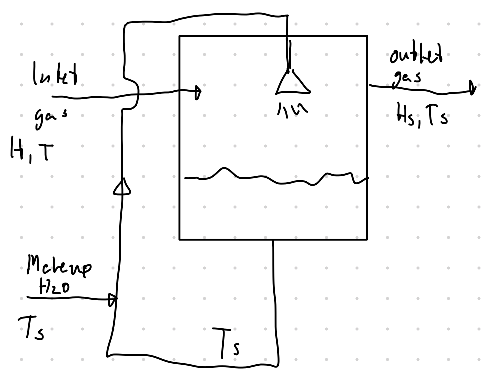
e) We dry adiabatic till 90% humidity in the air at exit. What is now the temperature of the air?
Show in the attached humidity chart how you find the answers for d) and e) – the diagram shall be turned in with your answers.

f) We will use a tray dryer with area 2 m², and we will produce 10 kg of the granulate. The granulate contains at start 0.4 kg H_2O/kg dried material. We will use the given diagram below, but assuming that the line C-E is straight and goes through origo. Find the time it will take to dry the granulates down to 0.05 kg H_2O/kg dried material which is the humidity content at equilibrium (X*). The critical water content (Xc) is 0.18 kg H_2O/kg dry material.

iven: $R = -\frac{L_S}{A}\frac{dX}{dt}$

Where L_S = kg dry material, A = drying area (m²), t = drying time (h)

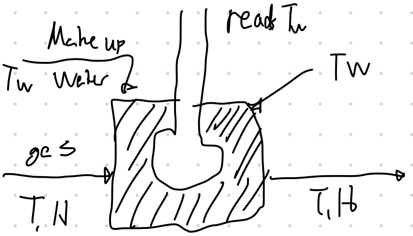




The air evaporates water, which releases its latent heat of evaporation, cooling the air.

Energy lost in air = energy gained by vapour

=> Adiabatic



Wet cloth covering bulb

=> Thermometer measures Tw, wet bulb termometer.

b)

B-C. Constant rate. Drying of liquid film on the outside of the material

C-D. Falling rate. The surface is no longer entirely covered by film, and the rate starts being limited by capillary forces drawing out the water.

D-E. At D, there is no longer a film, the evaporation is entirely limited by the movement of the liquid through the material (diffusion)

c) Constant rate:

$$R = -\frac{L_s}{A}\frac{dX}{dt}$$

$$R_c = -\frac{L_s}{A}\frac{\Delta X}{\underset{\underset{t-0}{\|}}{\Delta t}} \Rightarrow t = -\frac{L_s}{AR_c}\Delta X = -\frac{L_s}{AR_c}(X_2 - X_1)$$

$$= \frac{L_s}{AR_c}(X_1 - X_2)$$

Falling rate

$$R = -\frac{L_s}{A}\frac{dX}{dt}$$

$$dt = -\frac{L_s}{RA}dX \quad \Big/ \int_0^t , \int_{X_1}^{X_2}$$

$$t = -\frac{L_s}{A}\int_{X_1}^{X_2}\frac{dX}{R}$$

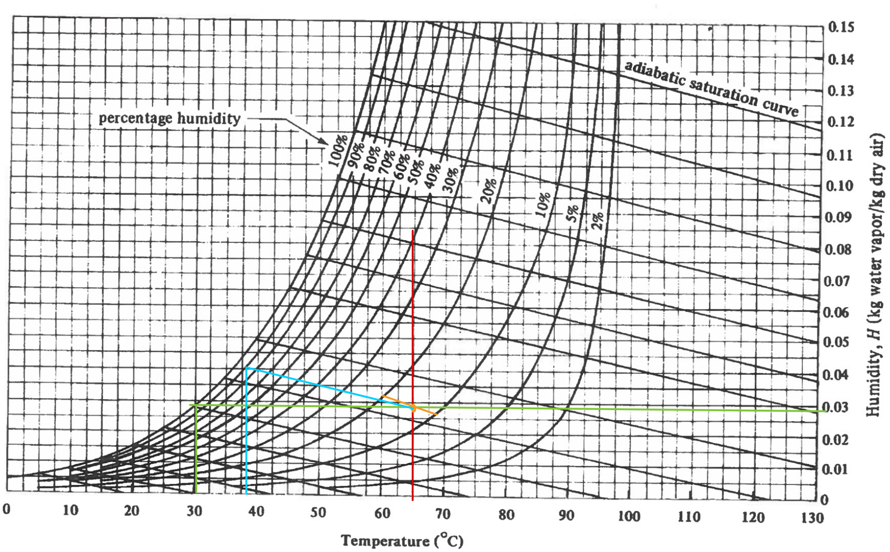
If $R = aX + b \Rightarrow a = \frac{R_2 - R_1}{X_2 - X_1}$

$\frac{dR}{dX} = a \Rightarrow dx = \frac{dR}{a}$

$$= -\frac{L_s}{Aa}\left(\ln R_2 - \ln R_1\right)$$

$$= \frac{L_s}{Aa}\ln\frac{R_1}{R_2}$$

d) $T_w = 65°C$, Dew point $30°C$



$H = 0{,}028$ kg H_2O/kg Air

$\%H \approx 14\%$

e) $T = 38°C$

f) $A = 2\ m^2$, 10 kg granulate, $H = 0{,}4$

$X_f = 0{,}05$

$X_c = 0{,}18$

$R_c = 1{,}5$

$B \rightarrow C$:

$$t = \frac{L_s}{A R_c}(X_1 - X_2) = \frac{10}{2 \cdot 1{,}5}(0{,}4 - 0{,}18) = 0{,}733\ h$$

$C \rightarrow D$:

$$a = \frac{1{,}5 - 0}{0{,}18 - 0} = 8{,}33,\quad t = \frac{L_s}{A a} \ln \frac{R_1}{R_2} = \frac{10}{2 \cdot 8{,}33} \ln \frac{1{,}5}{0{,}4166} = 0{,}769\ h$$

$R_1 = 8{,}33 \cdot 0{,}05 = 0{,}4166$

$t: 1{,}5\ h$

Problem 3 Membrane gas separation (20%)

(a) Make a sketch of a membrane with in- and out streams, and write the symbols on your sketch with respect to what is measured where. Use the same symbols as given in the equation below.

(b) Oxygen enriched air is used in several applications. Two examples are breathing machine at a hospital, another example is for more efficient combustion.
A hollow fibre membrane with selective thickness of 1 μm, is producing oxygen enriched air.
Permeability of O_2 (P_{O2}) is $1.109 \cdot 10^{-6}$ [m^3(STP)·m) / (m^2 bar h], and selectivity of O_2/N_2 is $\alpha = 5$. Pressure on feed side is 2 bar, while permeate pressure is 0,2 bar. The membrane module is going to produce 2 m^3(STP)/h of 45vol% O_2. Permeate cut ($\theta = q_p / q_f$) is 0,10. Calculate the composition of the retentate stream, the air flow into the membrane module and the necessarry permeation area.

Use the "complete mixing model" (equation given below) – indicate any assumptions made.

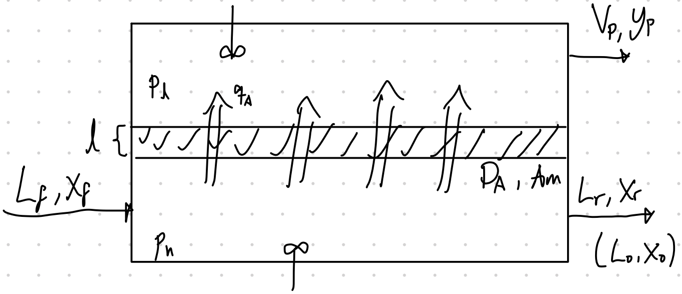
c) If you instead should produce high purity N_2 (95 vol%), how would you choose to arrange your membrane separation? (Comment on feed pressure, pressure ratio, permeate cut and calculation procedure.) Calculation is not needed.

Given: Equation gas separation, complete mixing model:

$$\frac{q_A}{A_m} = \frac{q_p \cdot y_p}{A_m} = \left(\frac{P_A}{l}\right)(p_h x_0 - p_l y_p)$$

where q_A = permeate flux of component A (m^3(STP)/h), P_A is permeability (units given in the text), l = membrane thickness (m), A_m = permeation area (m^2), p=trykk (bar), x_0 and y_p mol fractions of component A

a)



b) $l = 1\ \mu m$

$\mathbb{P}_A = 1{,}109 \cdot 10^{-6}\ \frac{m^3\,(STP)\,m}{m^2\ bar\ h}$

$\alpha = \frac{\mathbb{P}_A}{\mathbb{P}_B} = 5 \Rightarrow \mathbb{P}_B = \frac{\mathbb{P}_A}{5}$

$p_h = 2\ bar,\ p_l = 0{,}2\ bar$

$$\frac{q_p \cdot y_p}{A_m} = \frac{\mathbb{P}_A}{l}(p_h x_0 - p_l y_p)$$

$$\frac{1}{A_m} = \frac{1{,}109 \cdot \cancel{10^{-6}}\ \cancel{m^3(STP)}\cancel{m}/m^2\ \cancel{bar}\ \cancel{h}}{2\ \cancel{m^3(STP)}/\cancel{h} \cdot 0{,}45 \cdot \cancel{10^{-6}}\ \cancel{m}} \left(2\ \cancel{bar}\ x_0 - 0{,}2\ \cancel{bar}\ 0{,}45\right)$$

$$\frac{1}{A_m} = 2{,}4644\ x_0\ [m^{-2}] - 0{,}1109\ [m^{-2}]$$

Massebalanser

$$\theta = \frac{q_p}{q_f} = 0{,}1 \Rightarrow q_f = \frac{q_p}{0{,}1} = \frac{2}{0{,}1} = 20$$

$$q_f = q_p + q_r \Rightarrow 20 = 2 + q_r \Rightarrow q_r = 18$$

$$q_f x_f = q_p y_p + q_r x_r$$

$x_f = 0{,}21$

$$20 \cdot 0{,}21 = 2 \cdot 0{,}45 + 18 \cdot x_r \Rightarrow \underline{\underline{x_r = 0{,}1833}}$$

$$\Rightarrow \frac{1}{A_m} = 0{,}3409\ m^{-2} \Rightarrow \underline{\underline{A_m = 2{,}93\ m^2}}$$

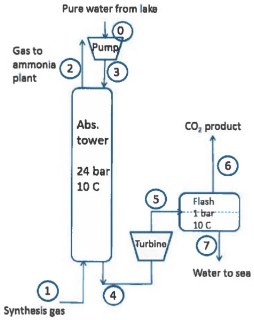
c) Increase pressure difference (product is retentate)

Feed – compressor, permeate – 1 atm

Calculate over 2 stages: x_0 0,21 → 0,10 → 0,05

Oppgave 4

We want to to look at CO2-absorption for ammonia production (this is the water wash tower («vannvask») mentioned in the lectures. The feed gas from the synthesis part of the plant is 6646 kmol/h and contains N_2 (approx. mol-20%) , H_2 (approx. mol-60%), other inert gases and 17 mol-% CO_2 (stream 1), og we want to reduce the CO_2-consentration in the gas which goes to ammonia production to 0.3 mol-% (stream 2). The water feed to the absorption column contains no CO2 (stream 3).



(a) Henry's law is given below, and it can alternatively be written in the form y=mx where x is the mole fraction of CO_2 in water. Find m at 0C, 10C and 20 C when p=24 bar and when p=1 bar (you can make a table).

(b) What is the definition of the absorption factor A? What assumptions are required for the Kremser equation? Do these assumptions hold in our case? Show that A can be written as a function of y_{N+1}, y_1, y^*_N og y^*_0 (see formula and figure).

(c) Find the minimum water flow (L_{min}, stream 3) in kmol/h and in m3/h (with an infinite number of equilibrium stages).

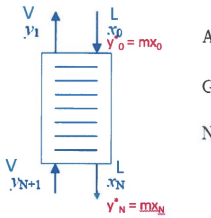
(d) We use 10% more than the minimum water flow ($L=1.1\ L_{min}$, stream 3). What is the fraction of CO2-fraksjonen in the water out (x_N, stream 4)? How many equilibrium stages (N) are needed? You can compute N using the Kremser equation, but who also your solution in the xy-diagram (McCabe-Thiele).
Comment: If you did not solve question (c) then use L=5000 m3/h (stream 3).

(e) What is the composition in the gas out (stream 2) if N=50. Use the same values for L (stream 3) og X_N (stream 4) as in question (d).

(f) Independent question: What are the CO_2-fractions (y,x) in the streams out of the flash tank (streams 6 and 7). How much (in percent) of the original CO2 ends up in the CO2-product (stream 6)?

Some data (you do not need all of this):
Henry's law for CO_2 in water: Partial pressure is $p_{co2} = H\ x_{co2}$ where H=719 bar at 0C, H=1027 bar at 10C, H=1402 bar at 20C, H=1835 bar at 30C, and H=2300 bar at 40C.
Vapor pressure for water: p^{sat}=0.012 bar at 10C and p^{sat}=1 bar at 100C.
Heat of vaporization for water at 100C: 40.7 kJ/mol
Heat capacity for water: 4.18 kJ/kg,K (liquid) and 1.87 kJ/kg,K (gas).
Heat capacity for CO_2: 37 J/K,mol (gas)
Molecular weights [g/mol]: 44 for CO_2 and 18 for water
Density water: 1000 kg/m^3
R = 8.31 J/K,mol

Kremser equations:



Book eq. (10.3-25):

$$\frac{y_{N+1}-y_1}{y_{N+1}-y_0^*} = \frac{A^{N+1}-A}{A^{N+1}-1}$$

Alternative simpler form (Sigurd):

$$\frac{y_{N+1}-y_N^*}{y_1-y_0^*} = A^N$$

Get:

$$N = ln\frac{y_{N+1}-y_N^*}{y_1-y_0^*}/lnA$$

Note. Can write:

$$A = \frac{y_{N+1}-y_1}{y_N^*-y_0^*}$$

- * = in equilibrium with other phase
  (could be imaginary composition, like y^*_0)

a) Hcr $P_{CO_2} = H x_{CO_2}$

$$yP = Hx$$

$$y = \frac{H}{P}x$$

$$y = mx$$

$$\Rightarrow m = \frac{H}{P}$$

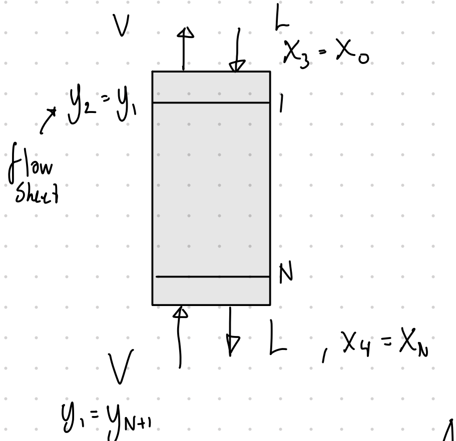
P_{bar} \ $T°C$	0	1	2
1	719	1027	1402
24	29,96	42,79	58,42

b) Definition: $A = \frac{L}{KV}$

Kremser equation: N adiabatic, equilibrium stages. Pure absorbent

constant m → straight eq line
constant $\frac{L}{V}$ → straight op. line.

- Constant p and T => m ≈ constent
- $y = 0{,}17 \Rightarrow$ not dilute => V will vary



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

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

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

c) L_{min} is when there is equilibrium in the bottom

$$X^*_{N+1} = X_N \Rightarrow \frac{y_{N+1}}{m} = X_N = \frac{0{,}17}{42{,}79} = 0{,}004$$

$$L_{min} = V \cdot \frac{y_{N+1} - y_1}{x_N - x_0} = 6646 \cdot \frac{0{,}17 - 0{,}003}{0{,}004 - 0}$$

$$\underline{L_{min} = 277470 \text{ kmol/h}} \left[\cdot 18 \cdot 10^{-3}\right] = \underline{\underline{4994 \ m^3/h}}$$

$\dot{n}$ to $\dot{\varphi}_v$

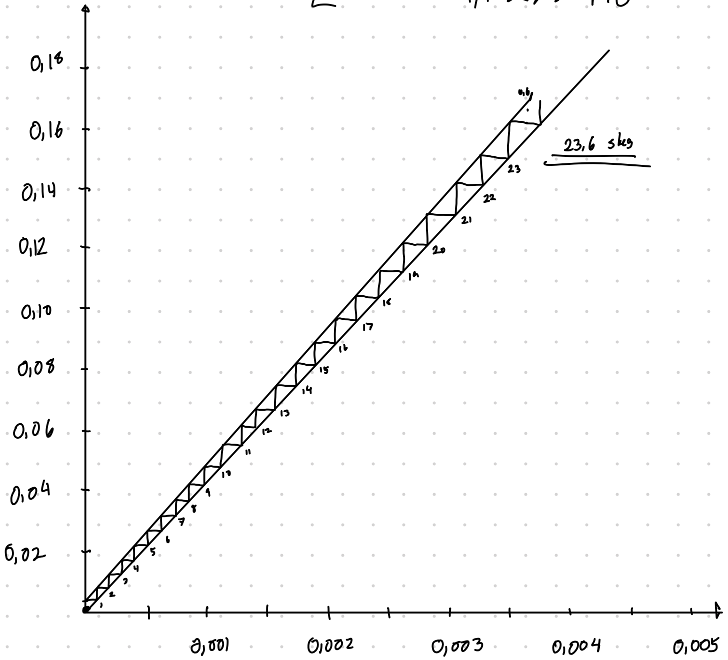
$$\cancel{kmol} \cdot \frac{1000\, \cancel{mol}}{1\, \cancel{kmol}} \cdot \frac{\cancel{g}}{\cancel{mol}} \cdot \frac{1\, \cancel{kg}}{1000\, \cancel{g}} \cdot \frac{1 m^3}{1000\, \cancel{kg}} = [m^3] =$$

$$\dot{n} \cdot M \cdot 10^{-3} \cdot \frac{1}{\rho} \quad [m^3]$$

d)

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

$$x_N = \frac{V(y_{N+1} - y_1)}{L} = \frac{6646\,(0{,}17 - 0{,}003)}{1{,}1 \cdot 277470} = \underline{\underline{0{,}00364}}$$



Eq-line: $y = 42{,}8x$

Op-line y_{inn}, x^* til y_{ut}, x_{inn}

Or $A = \frac{0{,}17 - 0{,}003}{42{,}8 \cdot 0{,}00364} = 1{,}072$

$$N = \frac{\ln \frac{y_{N+1} - y_N^*}{y_1 - y_0}}{\ln A} = \underline{\underline{22{,}4}}$$

e) Using sigurd's:

$$A^N = \frac{y_{N+1} - y_N^*}{y_1 - y_0^*} = 1{,}072^{50} = 32{,}34$$

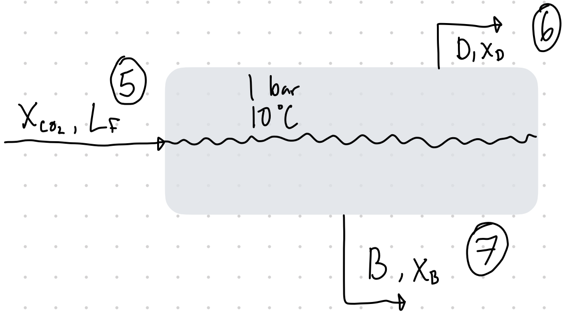
A is unchanged, $A = \frac{\overbrace{L/V}^{\text{kept constant}}}{\underset{\text{constant}}{K}}$

$$\frac{y_{N+1} - y_N^*}{32{,}34} = y_1 - y_0^*$$

$$y_1 = y_0^* + \frac{y_{N+1} - y_N^*}{32{,}34} = 0 + \frac{0{,}17 - 42{,}8 \cdot 0{,}00364}{32{,}34}$$

$$\underline{\underline{y_1 = 0{,}00044}}$$

f) $X_{CO_2} = 0{,}00364$, $L_F = 1{,}1 \cdot L_{min} = 305217$ kmol/h



L_F is almost pure water => Raout's law

$$P_{H_2O} = \underset{\substack{\shortparallel \\ 0{,}012 \text{ bar}}}{P^{sat}_{H_2O}} \cdot (1 - 0{,}00364) = 0{,}012 \text{ bar}$$

$$P_{CO_2} = P_{tot} - P_{H_2O} = 0{,}988 \text{ bar} \Rightarrow \underline{\underline{y_{CO_2} = 0{,}988}}$$

$$P_{CO_2} = H \cdot x_{CO_2} \Rightarrow x_{CO_2} = \frac{P_{CO_2}}{1027 \text{ bar}} = \frac{0{,}988 \cancel{\text{bar}}}{1027 \cancel{\text{bar}}} = \underline{\underline{0{,}00096}}$$

Mengde CO_2 ut:

$\overset{L_5}{SS}$

$$y_6 V_6 = L_5 X_5 - L_7 X_7 = L_5 (X_5 - X_7) = 305217\,(0{,}00364 - 0{,}00096)$$

$$\Rightarrow \dot{n}_{CO_2} = 818 \text{ kmol/h}$$

$$\text{Recovery\%} = \frac{\dot{n}_{CO_2,6}}{\dot{n}_{CO_2,1}} = \frac{818}{0{,}17 \cdot 6646} = \underline{\underline{72{,}4\%}}$$