NTNU – Trondheim
Norwegian University of
Science and Technology

Department of chemical engineering

Examination paper for TKP4105 (Separation Technology)

Academic contact during examination:

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Examination date: 16.12.15

Examination time (from-to): 09:00 – 13:00

Permitted examination support material: No printed or handwritten material permitted. Simple calculator code D accepted.

Other information: Attachments to be turned inn with answers

Language: English

Number of pages: 5

Number of pages enclosed: 2

mm-paper may be needed for problem 1

Checked by:

12/12-2016 Tage Johannessen

Date Signature

Problem 1 (Ekstraksjon, 25%)

(Use the sheet in Attachment 1 to solve this problem or use mm-sheet)

We have 1 kg/s of a feed with 26.5 weight-% acetic acid and 73.5% water (L_0) which is difficult to separate using distillation. Instead we want use extraction with kg/s isopropyl ether (V_0).

(a) Use the data in the table to complete the drawing of the triangle diagram (write on legends on the axes, tie lines, two-phase region) for the system water – acetic acid – isopropyl ether (see separate sheet at the end which you can tear off and hand in with your solution)

(b) Draw a flowsheet of single-stage extraction. What are the amounts and compositions of the two products (L_1 and V_1)?

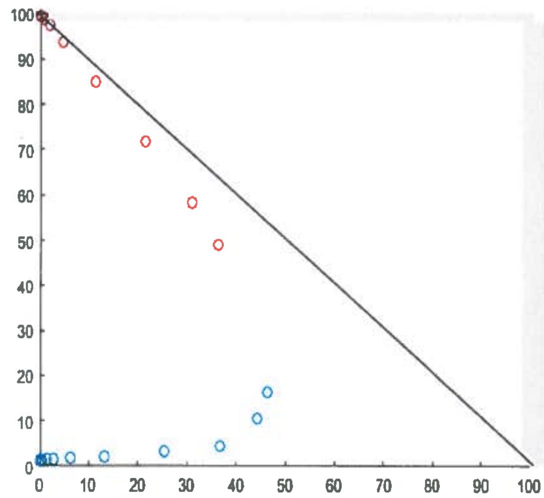
(c) Draw a flowsheet of 5-stage countercurrent extraction. We want an aqueous product (L_5) with 1% acetic acid. What is the definition of Δ and where is the Δ-point located for this separation (approximately)? Is the separation possible when we use 1 kg/s isopropyl ether and use 5 stages (see also the next question)?

(d) What is the minimum amount ($V_{0,min}$) of isopropyl ether required when we want the aqueous product to contain 1% acetic acid (with an infinite number of equilibrium stages)?

A.3-24 Acetic Acid–Water–Isopropyl Ether System, Liquid–Liquid Equilibria at 293 K or 20°C

Water Layer (wt %)			*Isopropyl Ether Layer (wt %)*		
Acetic Acid	*Water*	*Isopropyl Ether*	*Acetic Acid*	*Water*	*Isopropyl Ether*
0	98.8	1.2	0	0.6	99.4
0.69	98.1	1.2	0.18	0.5	99.3
1.41	97.1	1.5	0.37	0.7	98.9
2.89	95.5	1.6	0.79	0.8	98.4
6.42	91.7	1.9	1.93	1.0	97.1
13.30	84.4	2.3	4.82	1.9	93.3
25.50	71.1	3.4	11.40	3.9	84.7
36.70	58.9	4.4	21.60	6.9	71.5
44.30	45.1	10.6	31.10	10.8	58.1
46.40	37.1	16.5	36.20	15.1	48.7

Source: Trans. A.I.Ch.E., 36, 601, 628 (1940). With permission.



Problem 2 Drying (30%)

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.

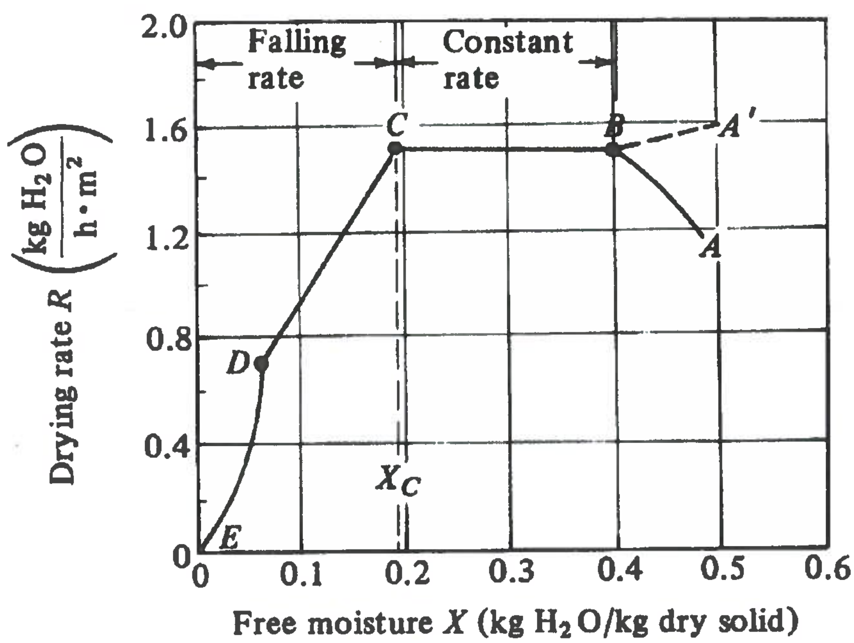
d) Air of temperature 65°C (dry bulb temperature) has a dew point of 30°C. We will use this air to dry some granulate (dog food). How much water (H) does this air contain at start? What is the percentage humidity?

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 m^2, 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 (X_c) is 0.18 kg H_2O/kg dry material.

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

Where L_s = kg dry material, A = drying area (m^2), t = drying time (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.

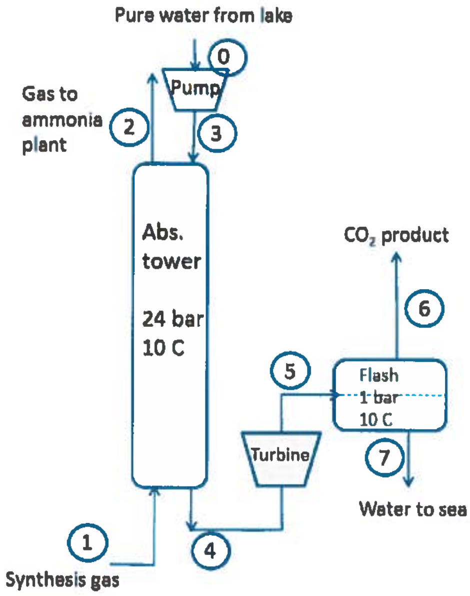
Given: Equation gas separation, complete mixing model:

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

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

Problem 2 (Absorption and equilibrium, 25%)

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)?

Date are given below and in the figure. State any additional assumptions you make.

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).

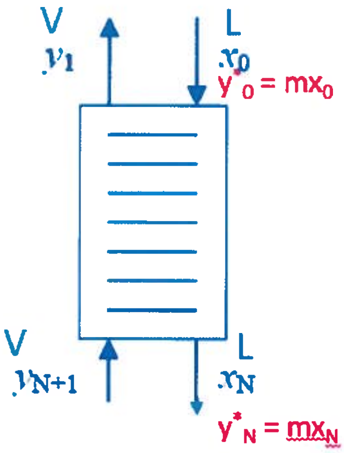
Heat capacity for CO_2: 37 J/K,mol (gas)

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):

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

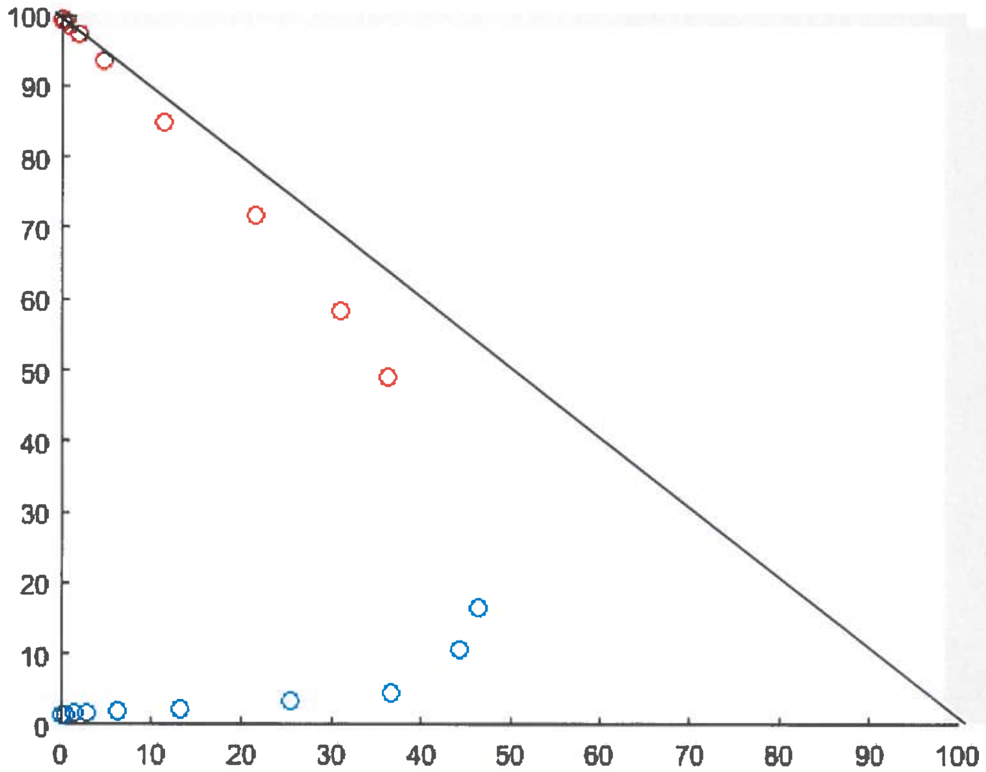
Get:

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

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)



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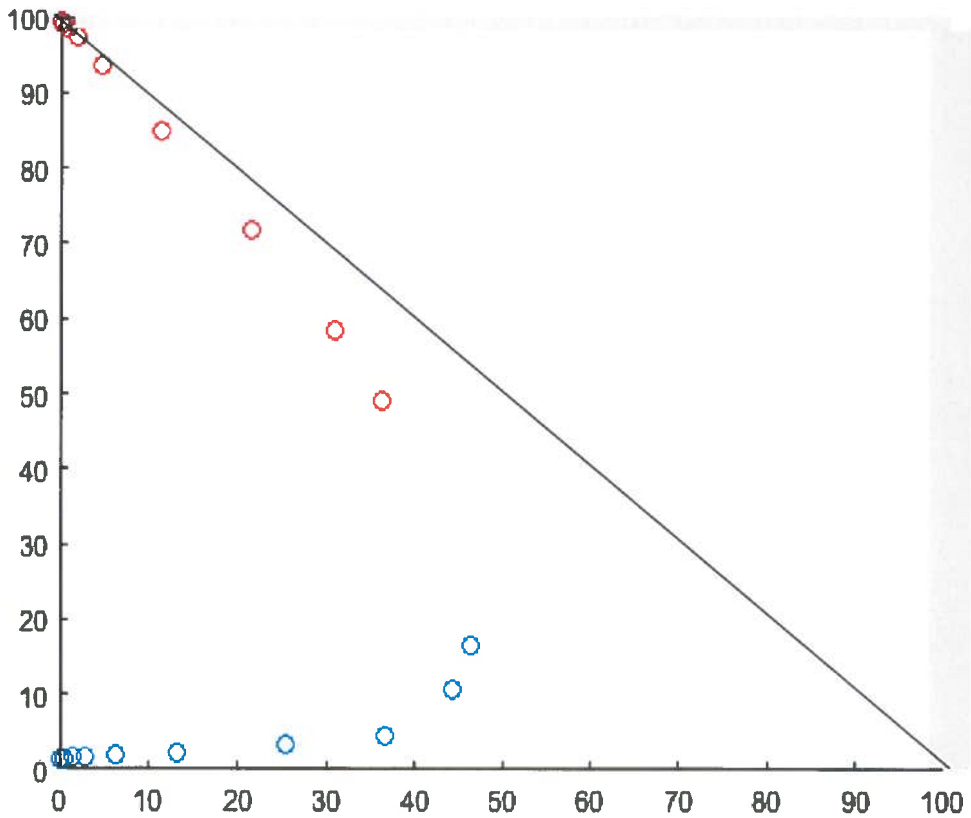

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Humidity Chart

APPENDIX 2

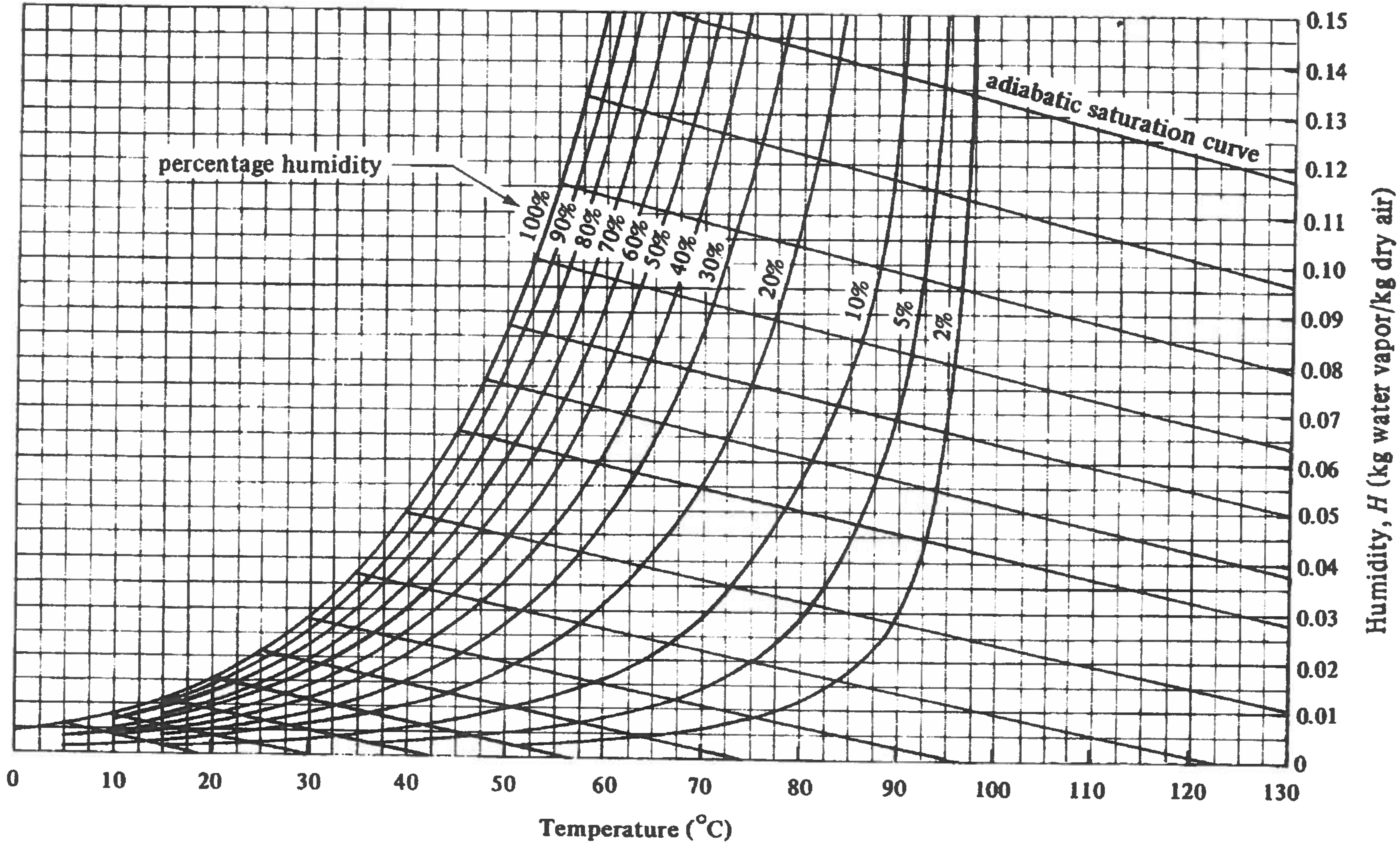

FIGURE 9.3-2. *Humidity chart for mixtures of air and water vapor at a total pressure of 101.325 kPa (760 mm Hg). (From R. E. Treybal, Mass-Transfer Operations, 3rd ed. New York: McGraw-Hill Book Company, 1980. With permission.)*