Institutt for Kjemisk prosessteknologi

Eksamensoppgave i TKP4105 Separasjonsteknikk

Faglig kontakt under eksamen: Jana P. Jakobsen, Tlf.: 90847746
Sigurd Skogestad, Tlf.: 91371669

Eksamensdato: 14. desember 2017

Eksamenstid (fra-til): 09:00-13:00

Hjelpemiddelkode/Tillatte hjelpemidler:

Calculator
No printed or handwritten aids are allowed

Annen informasjon:

The text is in English however you may answer in Norwegian or English.
mm-paper must be available

Målform/språk: English

Antall sider (uten forside): 4

Antall sider vedlegg: -

Informasjon om trykking av eksamensoppgave

Originalen er:

1-sidig □ **2-sidig** □

sort/hvit □ **farger** □

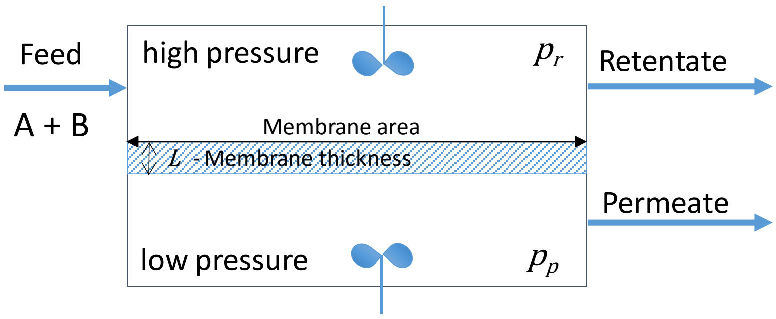
skal ha flervalgskjema □

Kontrollert av:

Dato Sign

Problem 1: Membrane gas separation (30%)

A gas mixture consisting of components A and B is to be separated by a membrane of the thickness L = 0,002 cm and permeability for component A - $P_A = 400 \cdot 10^{-10}$ cm^3(STP).cm/(s.cm^2.cm Hg). The gas mixture has a flow rate of $2 \cdot 10^3$ cm^3(STP)/s. The retentate side pressure is p_r =80 cm Hg and the permeate side pressure is p_p = 20 cm Hg. The fraction of the feed permeating the membrane is θ = 0,3, the volume fraction of component A in the feed is y_{Af} = 0,413 and the volume fraction of component A in the retentate is y_{Ar} = 0,3. Consider complete mixing model illustrated in the figure bellow.



a) Explain the underlying assumptions of a complete mixing model.
b) Formulate the overall material balance equation and the balance equation for component A. Calculate the volume fraction of component A in the permeate y_{Ap}.
c) The general expression for the overall flux of component A across the membrane (N_A = cm^3(STP)/(s.cm^2)) can be formulated as:

$$N_A = K\left(p_r y_{Ar} - p_p y_{Ap}\right)$$

where K is the overall mass transfer coefficient considering mass transfer resistance in the gas phases on both sides of the membrane:

$$K = \frac{1}{\left(\frac{1}{k_{gr}} + \frac{L}{P_A} + \frac{1}{k_{gp}}\right)}$$

Apply the principle of resistances in series and show how the relation for overall mass transfer coefficient is derived. Draw a sketch of partial pressure/concentration profiles and explain the assumptions made. Explain what membrane permeability is.
d) Simplify the expression for the flux of component A through the membrane assuming infinitely fast mass transfer in the gas phases on both sides of the membrane. Calculate the membrane area.
e) Formulate an analogous expressions for the flux and flow of component B through the membrane. Calculate the membrane selectivity. Explain what membrane selectivity is.
f) Name and explain with a sketch other alternative types of flow patterns in membrane modules and discuss briefly the implications it will have for model equations if the assumption of complete mixing is not valid. Sketch evt. the concentration profiles.

Problem 2 - Distillation (35%)
(You may need mm-paper to solve the problem)

F=100 mol/s of a mixture of water and 2-ethoxyethanol (cellusolve) is separated at atmospheric pressure in a distillation column with a total condenser. The feed is saturated liquid with composition x_F=0.3 mol water/ mol. During one period of operation the distillate product was x_D=0.85 and the bottom product was x_B=0.02 (both mole fraction water). The reflux ratio during this period was R=L/D=0.8.

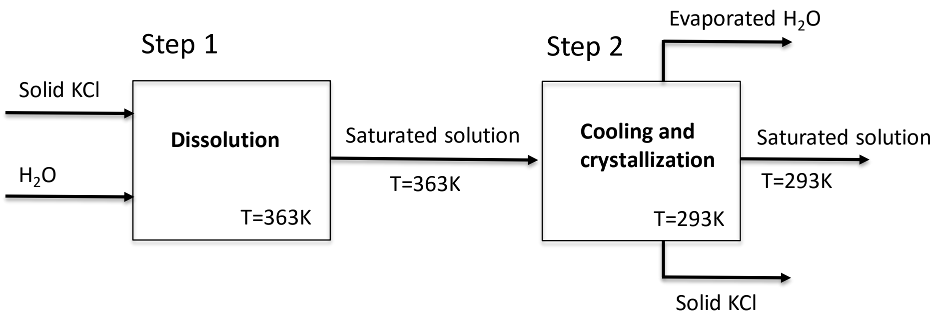
a) Make a flowsheet which includes the internal flows in the column. Find the product flows (D, B) and internal flows (L_T=L, V_T, L_B, V_B=V). What assumptions did you make?
b) It is given that the mixture at 1 atm has an azeotrope at 71 wt% water. What mole fraction of water does this correspond to?
c) Explain what we mean by the word «operating line». Explain briefly what equations we solve when we use the McCabe-Thiele method.
d) Find the equation for the upper operating line (both with symbols and with numbers). Show that it goes through the point (x,y)=(x_D,x_D).
e) How many theoretical stages does the column have if we assume that the feed is ideally located?
f) How does the answer change if it is given that the bottom section has 5 theoretical stages + reboiler?
g) Some months later, operation with the same feed and reflux ratio gave x_D=0.89 and x_B=0.02. The process engineer thought that such a high distillate purity was unlikely, because it is quite close to the azeotrope. She suspected that there was a leak of water (L_W) from the cooling water and into the reflux drum. To confirm this she measured the composition of the vapor overhead which was y_T=0.86. This confirmed here suspicion. (i) Why? (ii) Make a flowsheet of the top part of the column (with the leak). (iii) Set up the equations to compute L_W, L and D in this case. (iv) What is L_w [mol/s]?
h) What is the equation for the upper operating line in this case? Note that it no longer goes through the point (x,y)=(x_D,x_D). What point does it go through?

Data:
Mole weights: 18 g/mol for water and 90 g/mol for 2-ethoxyethanol.
Vapor-liquid equilibrium data at 1 atm (mole fraction water) :

x	0.01	0.05	0.1	0.2	0.3	0.5	0.7	0.8	0.9	0.95
y	0.12	0.38	0.49	0.61	0.68	0.8	0.86	0.88	0.91	0.935

Problem 3: Re-crystallization of KCl in a batch equilibrium crystallizer (20%)

A batch of 1000 kg KCl is first dissolved in water to make a saturated solution at 363K. The solution is then cooled to 293K and KCl is re-crystallized. The re-crystallization process in batch equilibrium crystallizer is illustrated in the sketch bellow:



The solubility data for KCl are given in the table below:

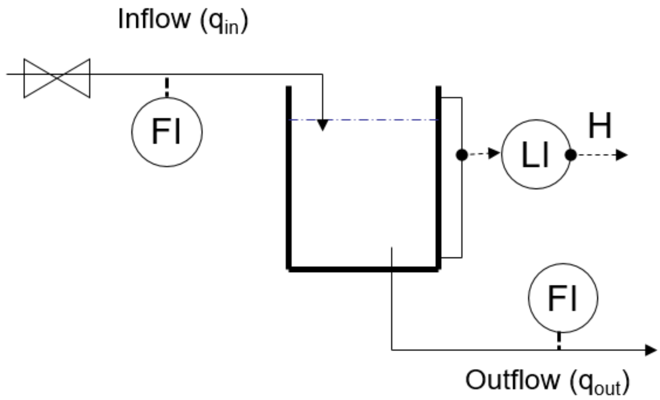
Temperature [K]	KCl solubility [wt %]
363	35,0
293	25,4

a) Explain and illustrate in the temperature – concentration diagram what is the driving force for crystallization. When does spontaneous crystallization occur and when has the crystallization process to be initiated?
b) Calculate the amount of water needed to prepare the saturated solution in step 1.
c) Formulate all the necessary mass balance equations and calculate the weight of obtained KCl crystals if no water evaporates on cooling in step 2.
d) Assume that 5% of the original water evaporates on cooling in step 2 and then calculate the weight of KCl crystals formed in step 2.
e) Explain and discuss your results in temperature – concentration diagram.
f) Describe qualitatively the process of crystal formation
g) The following equation describes the rate of crystal growth.

$$G = \frac{\Delta L}{\Delta \tau} = K \Delta c_A$$

Which assumptions have to apply for the equation to be valid?

Problem 4 - Level control (15%)



Consider level control using the inflow. We measure q_{in}, q_{out} [m^3/s] and H (level).

(a) Formulate the steady-state and dynamic material balance for the tank.

(b) Classify the variables with respect to control

(c) Suggest a control scheme based on feedforward control.

(d) Suggest a control scheme based on feedback control. What is the equation (algorithm) for a proportional controller?