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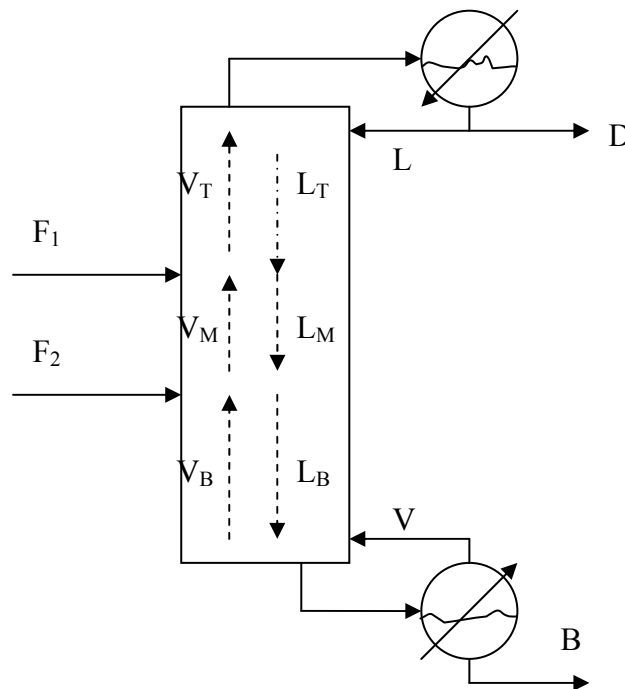> Nedre føde: $F_2 = 50$ mol/s, innholder 25 mol-% A og er mettet damp

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 2 / Oppgåve 2 :   Membranseparasjon – gasser (vekt 30%)

En miljøvennlig metode for å fjerne CO_2 fra en gasstrøm på, kan være å benytte skreddersydde membraner der CO_2 permeerer hurtigst gjennom membranen og andre gassene holdes tilbake på fødesiden. Utfordringene er forskjellig alt etter type gasstrøm som skal renses. For å illustrere dette, ser vi på tre forskjellige gassblandinger hvor CO_2 skal fjernes. For enkelhets skyld, betrakter vi gassblandingene som kun bestående av to komponenter; dette er illustrert i parentes. Prosessbetingelsene er gitt i hvert enkelt tilfelle.

1. CO_2 fra forbrenningsgass   (13 mol% CO_2 i blanding med 87 mol% N_2)
   Fødetrykk: 4 bar, permeattrykk: 0,1 bar, volumstrøm $5 \cdot 10^5$ m^3(STP)/time

2. CO_2 for oppgradering av biogass   (40 mol% CO_2 i blanding med 60 mol% CH_4)
   Fødetrykk: 7bar, permeattrykk: 1 bar, volumstrøm: 75 m^3(STP)/time

3. CO_2 fra naturgass   (10 mol% CO_2 i blanding med 90 mol% CH_4)
   Fødetrykk: 70 bar, permeattrykk: 1 bar, volumstrøm: 10^4 m^3(STP)/ time

Det er ønskelig å benytte en bestemt type polymer membran som er svært permeabel for CO_2 i alle tre tilfellene. Membranen er 2 μm tykk, og har følgende permeabiliteter, P':

$P'_{CO2} = 6 \cdot 10^{-7}$ m^3(STP)·m/m^2·bar·h
$P'_{N2} \;= 3 \cdot 10^{-9}$ m^3(STP)·m/m^2·bar·h
$P'_{CH4} = 1,2 \cdot 10^{-8}$ m^3(STP)·m/m^2·bar·h

a) Beregn minimum konsentrasjon som kan oppnås for CO_2 i retentatstrømmen, i de tre tilfellene over.

b) I tilfelle 1 (forbrenningsgass) skal den CO_2 som permeerer helst ha en renhet på 95 mol%, og 85% av all CO_2 skal fanges inn - er det mulig å oppnå ved de gitte betingelser og et permeatkutt (θ) lik 0,1?

c) I tilfelle 3 (naturgass) skal den rensede naturgassen selges til Europa. Da er kravet at fraksjonen av CO_2 ikke skal være høyere ennn 2,5 vol%. For å minske tapet av CH_4 settes dessuten permeatkuttet (θ) til 0,1. Beregn nødvendig membranareal.

d) Redegjør for hva slags konfigurasjon du vil velge på membranmodulen (flate, spiralrullet, hulfiber) og om det bør være medstrøm, motstrøm eller kryss-strøm.

Gitt: Likninger og informasjon i vedlegg 1

Oppgave 3 / Oppgåve 3: Absorpsjon (20%)

En pakket absorpsjonskolonne tilføres 2.13 kg/s av en gasstrøm 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.
.
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.

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

Oppgave 4 / Oppgåve 4   Litt diverse teori (20%)

a) I vedlegg 2 er gitt en figur som viser *to typer krystallisatorer*. Forklar virkemåten for disse, og bruk begreper fra krystallisasjonsteorien.

b) I samme vedlegg 2 er det vist en illustrasjon av *et adiabatisk metningskammer og måling av våtkuletemperatur.* Forklar eventuelle endringer i gassens temperatur og fuktighetsinnhold når den er i kontakt med vannet i disse to tilfellene. Sett opp en entalpibalanse for metningskammeret.
Hva er nytten av å måle en våtkuletemperatur? Hva er forskjellen på tørrkule-våtkuletemperatur?

For besvarelse av denne oppgaven kan det være nyttig å illustrere noe av forklaringen ved å skrive / tegne på figurene. Lever derfor inn arket med besvarelsen.

Gitt: Vedlegg 2

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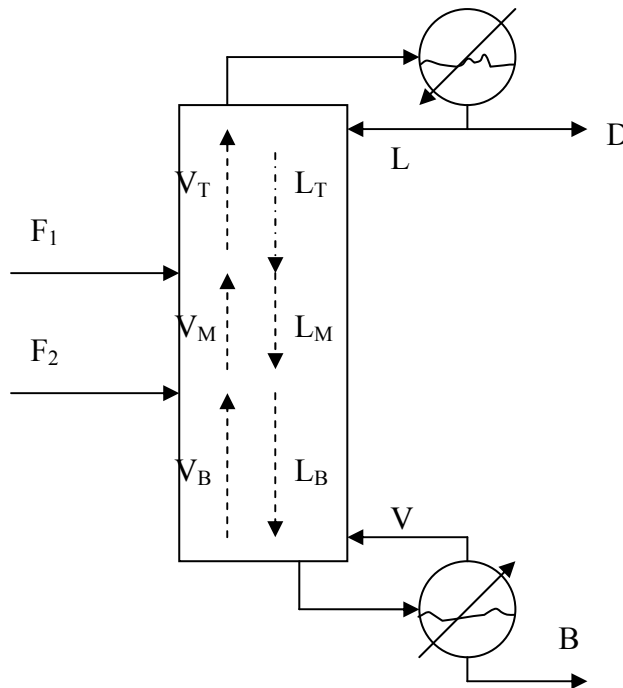Lower feed: $F_2 = 50$ mol/s, contains 25 mol-% A and is saturated vapour.

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 valances 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 2 – Membrane separation – Gases (Weight 30%)

An alternative environmentally friendly way of removing CO_2 from gas streams is under development – this method is using tailormade membranes where CO_2 is permeating very fast through the material and other gases are being retained on the feed side. The challenges are different depending on type of gas mixture. In order to illustrate this, three different gas streams containing CO_2 are given below. For the sake of simplicity, only two components are considered. Process conditions are given for each case.

1) CO_2 from flue gas   (13 mole% CO_2 in mixture with 87 mole% N_2)
   Feed pressure: 4 bar, permeate pressure 0,1 bar. Volume stream: $5 \cdot 10^5$ m^3(STP)/hour

2) CO_2 from biogas   (40 mole% CO_2 in mixture with 60 mole% CH_4)
   Feed pressure: 7 bar, permeate pressure: 1 bar. Volume stream: 75 m^3(STP)/hour

3) CO_2 from natural gas   (10 mole% CO_2 in mixture with 90 mole% CH_4)
   Feed pressure: 70 bar, permeate pressure: 1 bar. Volume stream: 10^4 m^3(STP)/hour

A polymeric membrane with high permeation for CO_2 is chosen for all three cases. The membrane is 2 μm thick, and has the following permeabilities, P':

$P'_{CO2} = 6 \cdot 10^{-7}$ m^3(STP)$\cdot$m/$m^2 \cdot$bar$\cdot$h
P'_{N2} = $3 \cdot 10^{-9}$ m^3(STP)$\cdot$m/$m^2 \cdot$bar$\cdot$h
$P'_{CH4} = 1,2 \cdot 10^{-8}$ m^3(STP)$\cdot$m/$m^2 \cdot$bar$\cdot$h

a. Calculate the minimum concentration of CO_2 which can be obtained in the retentate stream for all three cases

b. In case 1 (flue gas), the purity of permeated CO_2 should preferably be at least 95mol%, and 85% of all the CO2 should be captured. Is this possible to obtain at the given conditions and a permeate cut (θ) of 0,1?

c. Calculate the necessarry membrane area for case 3) by using the given equations and the following information: The fraction of CO_2 in the purified natural gas must not be higher than 2,5 vol% when it is sold to Europe. In order to minimize the loss of CH_4 in the permeate stream, the permeate cut (θ) is set to 0,1.

d. Explain which kind of configuration you will choose for the membrane module and why (flat sheets, spiral-wound, hollow fibres), and whether it should be cocurrent, counter current or cross flow.

Given: Equations and information in Attachment 1

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.
.
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: $K_y a$ [mol A/s,m3]= 39.2 $G_L^{0.5}$ where G_L[kg/(s,m2)] is the liquid load.

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

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

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.

Problem 4   Various theory   (20%)

a) In attachment 2, there are shown two crystallizers. Explain how they work, using also words/concepts from crystallization theory.

b) In the same attachment there are also illustrations of 1) an adiabatic saturation chamber and 2) a wet-bulb thermometer. Will there be any changes with respect to temperature and humidity of a gas in contact with the water in these two cases? Justify your answer.
Put up an enthalpy balance around the saturation chamber.
What is the use of measuring wet-bulb temperature? What is the difference between wetbulb- and drybulb temperature?

In answering this problem it may be useful to illustrate some of your explanation by writing and making notes directly on the figures. You should therefor turn in this sheet with your answer.

Given: Attachment 2

Please note that the units given here for P' and q can be neglected. Use the units given in the problem

13.4 COMPLETE-MIXING MODEL FOR GAS SEPARATION BY MEMBRANES

13.4A Basic Equations Used

In Fig. 13.4-1 a detailed process flow diagram is shown for complete mixing. When a separator element is operated at a low recovery (i.e., where the permeate flow rate is a small fraction of the entering feed rate), there is a minimal change in composition. Then the results derived using the complete-mixing model provide reasonable estimates of permeate purity. This case was derived by Weller and Steiner (W4).

The overall material balance (Fig. 13.4-1) is as follows:

$$q_f = q_o + q_p \qquad (13.4\text{-}1)$$

where q_f is total feed flow rate in cm^3(STP)/s; q_o is outlet reject flow rate, cm^3(STP)/s; and q_p is outlet permeate flow rate, cm^3(STP)/s. The cut or fraction of feed permeated, θ, is given as

$$\theta = \frac{q_p}{q_f} \qquad (13.4\text{-}2)$$

The rate of diffusion or permeation of species A (in a binary of A and B) is given below by an equation similar to Eq. (6.5-8) but which uses cm^3(STP)/s as rate of permeation rather than flux in kg mol/s · cm^2.

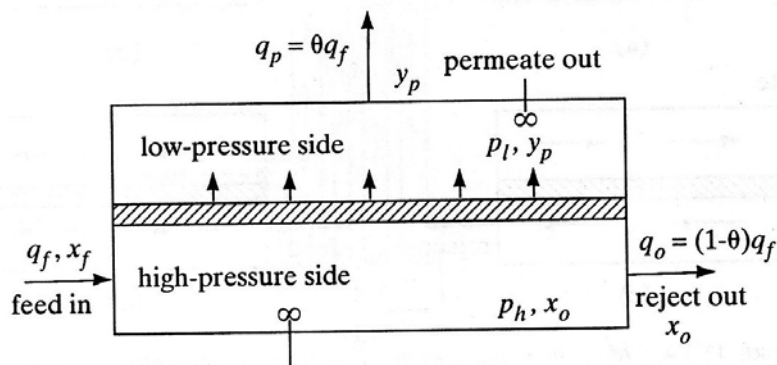$$\frac{q_A}{A_m} = \frac{q_p y_p}{A_m} = \left(\frac{P'_A}{t}\right)(p_h x_o - p_l y_p) \qquad (13.4\text{-}3)$$

FIGURE 13.4-1. *Process flow for complete mixing case.*

where P'_A is permeability of A in the membrane, cm³(STP)·cm/(s·cm²·cm Hg); q_A is flow rate of A in permeate, cm³(STP)/s; A_m is membrane area, cm²; t is membrane thickness, cm; p_h is total pressure in the high-pressure (feed) side, cm Hg; p_l is total pressure in the low-pressure or permeate side, cm Hg; x_o is mole fraction of A in reject side; x_f is mole fraction of A in feed; and y_p is mole fraction of A in permeate. Note that $p_h x_o$ is the partial pressure of A in the reject gas phase.

A similar equation can be written for component B.

$$\frac{q_B}{A_m} = \frac{q_p(1 - y_p)}{A_m} = \left(\frac{P'_B}{t}\right)[p_h(1 - x_o) - p_l(1 - y_p)] \qquad (13.4\text{-}4)$$

where P'_B is permeability of B, cm³(STP)·cm/(s·cm²·cm Hg). Dividing Eq. (13.4-3) by (13.4-4)

$$\frac{y_p}{1 - y_p} = \frac{\alpha^*[x_o - (p_l/p_h)y_p]}{(1 - x_o) - (p_l/p_h)(1 - y_p)} \qquad (13.4\text{-}5)$$

This equation relates y_p, the permeate composition, to x_o, the reject composition, and the ideal separation factor α^* is defined as

$$\alpha^* = \frac{P'_A}{P'_B} \qquad (13.4\text{-}6)$$

Making an overall material balance on component A

$$q_f x_f = q_o x_o + q_p y_p \qquad (13.4\text{-}7)$$

Dividing by q_f and solving for the outlet reject composition,

$$x_o = \frac{x_f - \theta y_p}{(1 - \theta)} \quad \text{or} \quad y_p = \frac{x_f - x_o(1 - \theta)}{\theta} \qquad (13.4\text{-}8)$$

Substituting $q_p = \theta q_f$ from Eq. (13.4-2) into Eq. (13.4-3) and solving for the membrane area, A_m,

$$A_m = \frac{\theta q_f y_p}{(P'_A/t)(p_h x_o - p_l y_p)} \qquad (13.4\text{-}9)$$
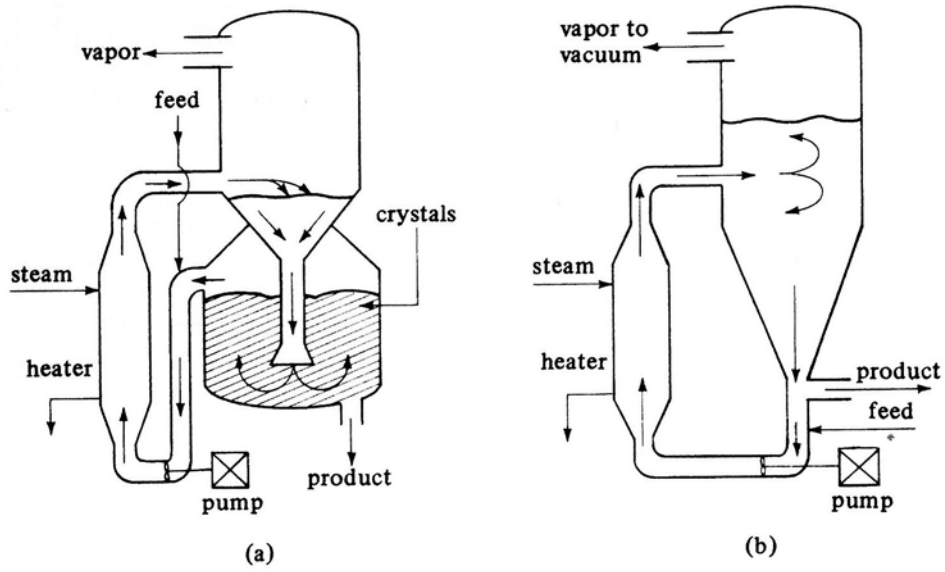
13.4C Minimum Concentration of Reject Stream

If all of the feed is permeated, then $\theta = 1$ and the feed composition $x_f = y_p$. For all values of $\theta < 1$, the permeate composition $y_p > x_f$ (H1). Substituting the value $x_f = y_p$ into Eq. (13.4-5) and solving, the minimum reject composition x_{oM} for a given x_f value is obtained as

$$x_{oM} = \frac{x_f\left[1 + (\alpha^* - 1)\dfrac{p_l}{p_h}(1 - x_f)\right]}{\alpha^*(1 - x_f) + x_f} \qquad (13.4\text{-}12)$$

Hence, a feed of x_f concentration cannot be stripped lower than a value of x_{oM} even with an infinitely large membrane area for a completely mixed system. To strip beyond this limiting value a cascade-type system could be used. However, a single unit could be used which is not completely mixed but is designed for plug flow.

PROBLEM 4, a)

steam

heater

vapor

feed

crystals

pump

product

(a)

vapor to vacuum

steam

heater

product

feed

pump

(b)

PROBLEM 4, b)

inlet gas

makeup H_2O
T_S

outlet gas

T_S

thermometer reads T_W

makeup water
T_W

gas

T_W

gas

wick