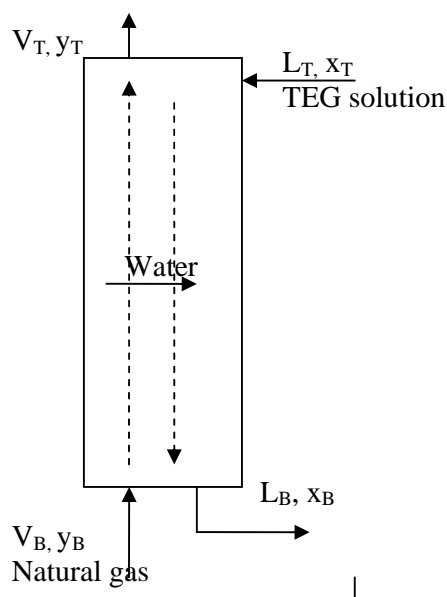


Eksamen 15. august 2011. SOLUTIONS TO PROBLEMS 1 and 3.

Oppgave / Oppgave 1: Tørring av naturgass ved absorpsjon (35%)



Vi skal fjerne vann fra 10290 kmol/h naturgass ved absorpsjon med TEG (tri-etylenglykol)-løsning i motstrøm i et platetårn. Naturgassen holder 30C og 60 bar og er mettet ved vann i denne tilstanden, noe som tilsvarer en molbrøk av vann på $y_B=0.87 \cdot 10^{-3}$. Når den forlater tårnet skal den tørkede naturgassen ha en molbrøk vann på $y_T=0.046 \cdot 10^{-3}$ (noe som tilsvarer et vandduggpunkt på ca. -15C ved 60 bar). Temperaturen i hele tårnet kan antas 30C og trykket er 60 bar.

Data: Molvekt for tørr naturgass er 23.58 kg/kmol, molvekt for TEG er 150.2 kg/kmol, molvekt for vann er 18 kg/kmol. Du kan anta ideell gass.

Likevekten for vann i TEG-løsning antas å være gitt ved følgende enkle Henry's lov-uttrykk (ved 30C).

$$\begin{aligned} \text{For } x < 0.2: & \quad p[\text{bar}] = 0.03 x \\ \text{For } 0.2 < x < 1: & \quad p[\text{bar}] = 0.006 + 0.05 (x-0.2) \end{aligned}$$

(merk at linjene krysser hverandre i $x=0.2$) Her er p partialtrykket av vann i gassfasen (som er vann + naturgass), og x er molfraksjon av vann i væskefasen (som er vann + TEG).

(a) Hva er høyeste teoretiske mulige fraksjonen av vann i innkommende TEG for å oppnå renskravet. Oppgi svaret både i molbrøk vann (x_T) og i vektprosent TEG.

(b) Anta at den innkommende TEG-løsningen er 99.5 vekt-% TEG, og regn ut den tilhørende molbrøken ned vann (x_T). Anta videre at vi bruker 30 kg TEG-løsning pr. kg fjernet vann. Beregn molbrøk vann i væsken ut av tårnet (x_B).

(c) Bestem antall teoretiske trinn i tårnet.

Kommentar: Du kan bruke McCabe-Thiele's grafiske metode (yx-diagram), men merk at driftslinjen vil være krum, noe du kan ta hensyn til ved å bestemme et par punkter ekstra på driftslinjen, for eksempel, ved å dele opp kolonnen i tenkte deler). Hvis du ikke får til å bruke krum driftslinje kan du bruke rett driftslinje, men det vil ikke være fullgodt svar.

English

Problem 1: Drying of natural gas by absorption (35%).

The task is to remove water from 10290 kmol/h of natural gas by contacting in with TEG (tri-ethylene glycol) solution in a plate tower; see figure. The natural gas is at 30C and 60 bar, and is saturated with water in this state, which corresponds to a mole fraction of water of $y_B=0.87 \cdot 10^{-3}$. When leaving the tower, the mole fraction of water in the dried gas should be $y_T=0.046 \cdot 10^{-3}$ (which corresponds to a water dew point of about -15C at 60 bar). The tower is operating at 30C and 60 bar.

Data: The mole weight for dry natural gas is 23.58 kg/kmol, for TEG is 150.2 kg/kmol and for water is 18 kg/kmol. You can assume ideal gas.

The equilibrium for water above a TEG solution is assumed to be given by the following simple Henry's law expression (at 30C):

$$\begin{array}{ll} \text{For } x < 0.2: & p[\text{bar}] = 0.03 x \\ \text{For } 0.2 < x < 1: & p[\text{bar}] = 0.006 + 0.05 (x-0.2) \end{array}$$

(note that the two lines cross at $x=0.2$). Here p is the partial pressure of water in the gas phase (which is water + natural gas) and x is the mole fraction of water in the liquid phase (which is water + TEG).

(a) What is the highest possible fraction of water in the incoming TEG liquid solution, if one is to satisfy the drying specifications. Please give your answer both as mole fraction water (x_T) as well as weight percent TEG.

(b) Assume that the incoming TEG solution is 99.5 weight-% TEG. Find the corresponding mole fraction of water (x_T). Assume further that we use 30 kg TEG solution for each kg water removed. Find the mole fraction of water in the liquid leaving the tower (x_B).

(c) Find the number of theoretical stages in the tower.

Comment: You may use McCabe Thiele's graphical method (yx-diagram), but note that the operating line is not quite straight. This is something you may take into account by finding one or two extra points on the operating line, for example, by dividing up the column. If you are not able to find the non-straight line, then you may use a straight line, but note that this will not be a complete answer.

Solution Problem 1

Assumption: The fraction of water in the vapor is small so we will assume for simplicity that the vapor flow (natural gas) through the column is constant, $V=V' = 10290$ kmol/h.

(However, the assumption $L=L'$ is a bit inaccurate since the water content in the liquid reaches $x_B=0.243$ in the bottom; this gives a slightly curved operating line, see below).

(a) The limiting case for this is when we have equilibrium between the gas out and the liquid inlet (at the top of the column¹).

Let y be the mole fraction of water in the gas phase. From the definition of partial pressure, we have that $p = y p_{\text{tot}}$ where $p_{\text{tot}}=60$ bar, so we have $y = p/60\text{bar}$ and the equilibrium relationship becomes

$$\begin{array}{ll} \text{For } x < 0.2: & y = 0.5 \cdot 10^{-3} x \\ \text{For } 0.2 < x < 1: & y = 0.1 \cdot 10^{-3} + 0.833 \cdot 10^{-3} (x-0.2) \end{array}$$

¹ If the question had been to find the minimum flow of TEG solution, then the limiting case would be to have equilibrium at the bottom of the column (and assuming no water in the inlet TEG at the top),

For $y=0.046 \cdot 10^{-3}$ the liquid equilibrium mole fraction is given by the first expression ($y = 0.5 \cdot 10^{-3} x$), so we find $x^*_T = 0.046/0.5 = 0.092$ (water).

The corresponding fraction of TEG is $x_{TEG} = 1 - x^* = 0.908$, which is **98.9 weight-% TEG** solution.

Proof: Basis = 1 kmol total with avg. mole weight: $0.092 \cdot 18 + 0.908 \cdot 150.2 = 138.04$ kg/kmol. Weight fraction TEG: $0.908 \cdot 150.2 / 138.04 = 0.988$ (98.8 wt%).

(b) Top (in): $x_T = (0.5/18)/(0.5/18 + 99.5/150.2) = 0.0402$

Water removed from gas: $10290 \text{ kmol/h} \cdot (0.87 - 0.046) \cdot 10^{-3} = 8.479 \text{ kmol/h} = 152.6 \text{ kg/h}$

Amount of feed TEG solution required: $152.6 \text{ kg/h} \cdot 30 = 4578 \text{ kg/h} = 31.59 \text{ kmol/h} = LT$
(using MW 99.5 wt% TEG = $0.9598 \cdot 150.2 + 0.0402 \cdot 18 = 144.9 \text{ kg/kmol}$).

Mass balances: $L' = \text{TEG out} = \text{TEG in} = 31.59 \text{ kmol/h} \cdot 0.9598 = 30.32 \text{ kmol/h}$

Water out = Water in TEG in + Water removed = $31.59 \cdot 0.0402 + 8.479 = 1.270 + 8.479 = 9.749 \text{ kmol/h}$

Mole fraction of water in liquid out: $x_B = 9.749/(9.749 + 30.32) = 0.243$.

Check water balance for entire column (assuming $V=V'$ constant, but this is not really necessary):

Water in = Water out

$$x_T L T + y_B V B = x_B L B + y_T V T$$

$$x_T L' / (1 - x_T) + y_B V' = x_B L' / (1 - x_B) + y_T V'$$

$$0.0402 \cdot 30.32 / (1 - 0.0402) + 0.87e-3 \cdot 10290 = 0.243 \cdot 30.32 / (1 - 0.243) + 0.046e-3 \cdot 10290$$

$$1.27 + 8.95 = 9.73 + 0.473 \text{ (OK!)}$$

(c) **Operating line.** It goes through the following points

Btm: $x_B = 0.243$, $y_B = 0.87 \cdot 10^{-3}$

Top: $x_T = 0.0402$, $y_T = 0.046 \cdot 10^{-3}$

To get an extra point, consider the place in the column where $x=0.14$.

A water mass balance at this place and around the bottom gives (would get same if we took the balance around the top):

$$x L + y_B V B = y V + x_B L B$$

Here $x L = x L' / (1 - x) = 0.14 \cdot 30.32 / (1 - 0.14) = 4.94 \text{ kmol/h}$

$$y_B V B = y_B \cdot V' = 0.87e-3 \cdot 10290 = 8.95 \text{ kmol/h}$$

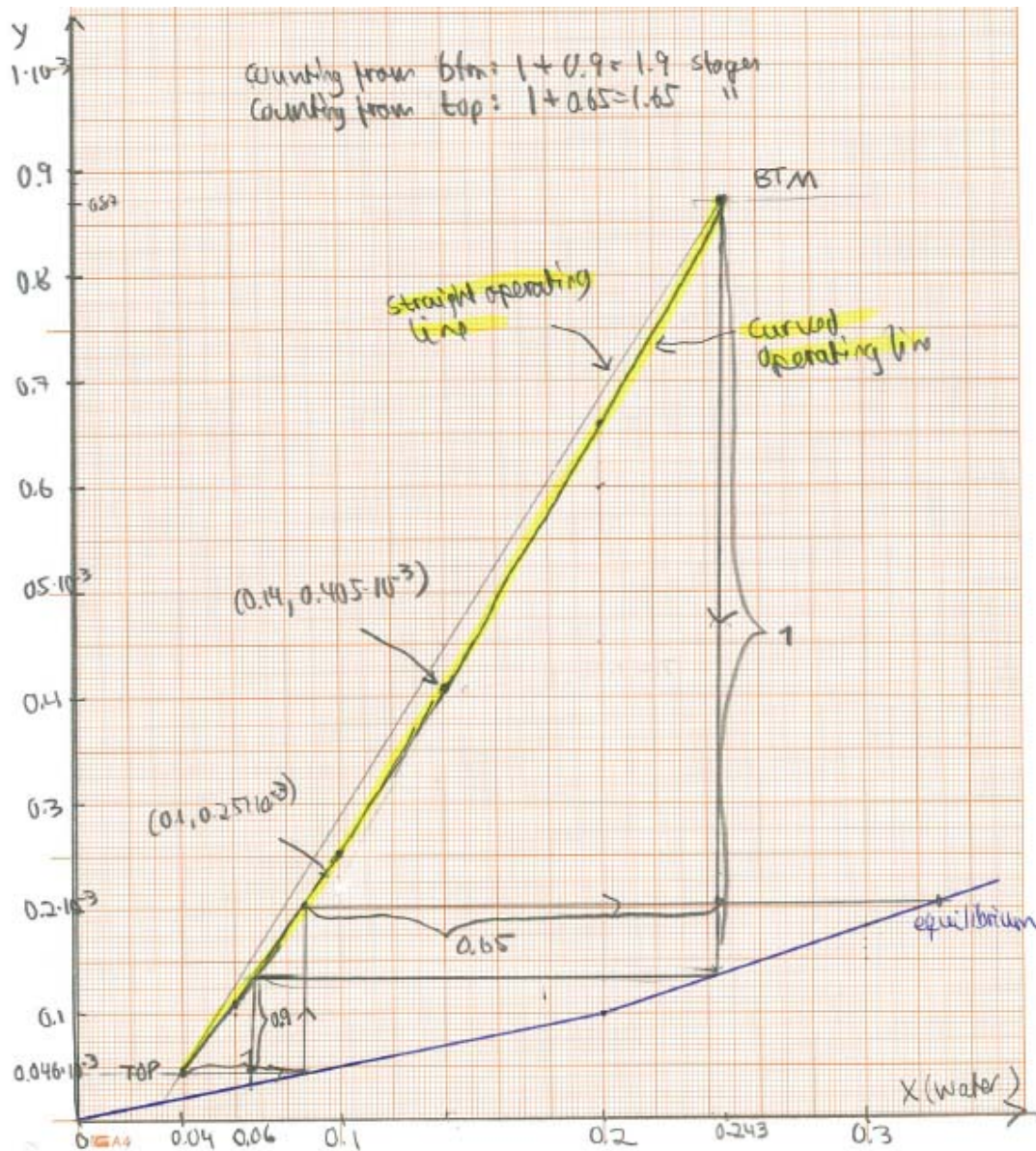
$$x_B L B = x_B L' / (1 - x_B) = 0.243 \cdot 30.32 / (1 - 0.243) = 9.73 \text{ kmol/h}$$

So for $x=0.14$ we get at the operating line: $y = (4.94 + 8.95 - 9.73) / 10290 = 0.405 e-3$.

A couple more points

$$\text{For } x=0.1: y = (3.37 + 8.95 - 9.73) / 10290 = 0.252e-3$$

$$\text{For } x=0.2: y = (7.58 + 8.95 - 9.73) / 10290 = 0.661e-3$$



The real operating line is slightly curved (see Figure).

From the figure we need between 1.65 and 1.9 theoretical stages:

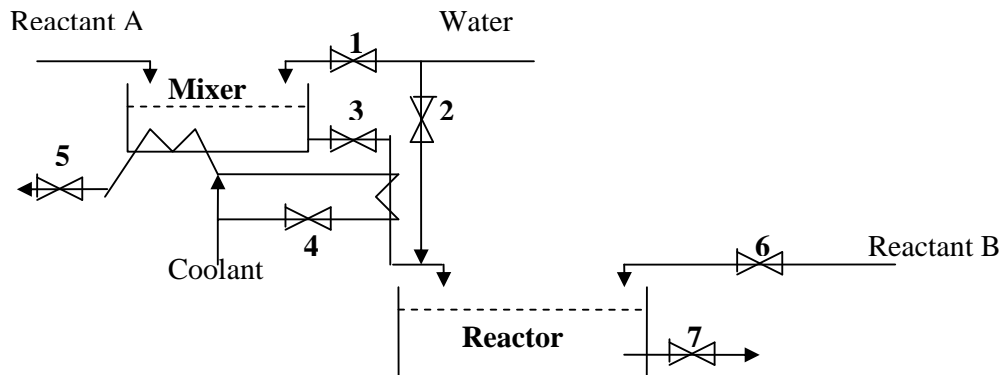
Counting from the btm: 1.9 theoretical stages

Counting from the top: 1.65 theoretical stages.

Oppgave / Oppgave 3. Regulering av reaktor (25%)

Før tilsats til en reaktor skal reaktant A fortynnes med vann til en nøyaktig konsentrasjon, se figur. Fortynningen medfører en kraftig varmetutvikling. Prosessen som skal brukes er vist i figuren. Konsentrasjonen grovjusteres i et blandekar med kjøling. Forholdene gjør det vanskelig å installere en konsentrasjonsmåler her. Blandingen avkjøles videre i en varmeveksler og konsentrasjonen finjusteres før reaktoren. Strøm-mengden av reaktant A kan

måles men settes for øvrig konstant av operatøren. Forholdet B/A bør holds konstant. Sett opp et forslag til reguleringsopplegg, gjerne basert på klassifisering av variable og prosessmatrise.



Problem 3. Control of reactor (25%)

Before feeding to the reactor, reactant A needs to be diluted with water to a specified concentration; see Figure. The mixing with water releases a lot of heat. The process flow sheet is shown in the figure. The main dilution is done in the mixing tank which is also cooled. The conditions in the mixing tank make it difficult to install a concentration sensor here. The mixture is further cooled in a heat exchanger before the concentration is “fine tuned” before entering the reactor. The flow of reactant A is measured, but it set a constant rate by the operator. Suggest a control structure, preferably based on classification of variables and a process matrix.

Problem 3. Reactor control. Solution

Classification of variables.

Inputs (MVs): There are 7 MVs (q_1, \dots, q_7) as shown in the flowsheet. Note that the feedrates of water (q_1, q_2) and reactant B (q_6) are inputs,.

Disturbances: The main disturbance is most likely in the flowrate of stream A (q_A). In addition, there may be disturbances in the concentrations of feedstreams A

Selection of controlled variables (CVs).

Based on the given description we select the following:

1. Level mixer: L_{mix}
2. Level reactor: L_{rx}
3. Temperature mixer: T_{mix}
4. Temperature Reactor: T_{rx}
5. Concentration in feed to reactor (we assume that it is measured after the point where q_2 (water) is added) : c_A
6. Ratio A/B (given that it should be constant)

In addition, we would like to control the concentration of A in the mixing tank, but it is given that it is difficult to measure. This probably means that we should set q_1 (main water dilutant in ratio to the flow of reactant A).

Proposed control structure (see Figure)

The pairing etc. seems quite obvious in this case, so no process matrix has been used.

Feedback controllers (5 of these)

LC: $L_{mix} - q_3$

LC: $L_{rx} - q_7$

TC: $T_{mix} - q_5$

TC: $T_{rx} - q_4$

CC: $c_A - q_2$

Feedforward (ratio) controllers (2 of these):

Ratio control: q_1/q_A constant (the ratio setpoint should be adjusted so that the flow q_2 has a reasonable value: it must at least be positive)

Ratio control of A/B: q_6/q_A constant (the ratio setpoint should be adjusted so that there is no excess of A or B in the product stream)

