Problem 1 - Sigurd. Distillation (35%)

(You may 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?

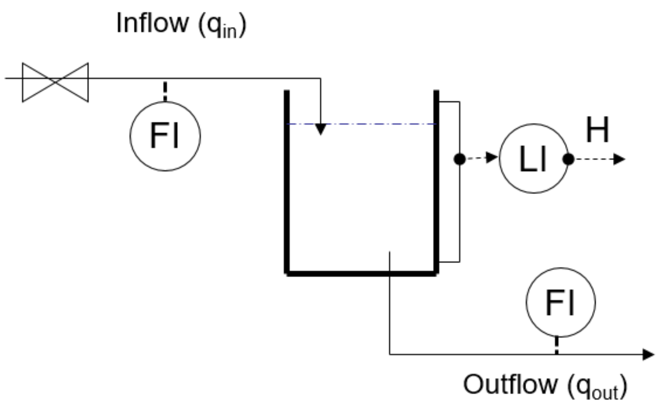
Data:

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 2 - Sigurd. 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?

Exam Dec. 2017

Solution.

(a) Overall mass balances.

$F = D + B$

$x_F F = x_D D + x_B B$

gives $0.3*100 = 0.85*D + 0.02*(100-D)$.

$D = (30 – 2)/0.83 = 33.73$, $B=66.26$

Internal flows

$L/D = 0.8$ gives $L=L_T=25.29$.

So $V_T = V_B = D+L_T = 59.02$, $L_B=L_T+q*F = 25.29+100=125.29$.

Assumption: Constant molar flows and saturated liquid feed corresponding to q=1.

(b) $x = 0.71/18 / (0.71/18 + 0.29/90) = 0.92$

(c) The operating lines is a mass balance relationship that gives the relationship between y and x between stages.
The McCabe Thiele method is a graphical method to solve the equations for the mass balance (operating line) and equilibrium on all stages in the column.

(d) Let y and x represent the vapor and liquid composition at a given cross section in the upper part of the column, and make a "control volume" to the top end of the column. The component balance (In=out) gives

$V_T\, y = L_T\, x + D\, x_D$

Upper operating line: $y = (L_T/V_T)\, x + (D/V_T)x_D$ (*)

Note that setting $x=x_D$ in (*) gives $y = (L_T+D)*x_D/V_T = V_T*x_D/V_T = x_D$ so (*) goes through the point $(x,y)=(x_D,x_D)$.

With numbers the upper operating line becomes

$y = 0.4285\, x + 0.4858$

(e) Stepping from each end gives; Ntop=2.9, Nbtm = 2.8 (including reboiler)

(f) The operating lines are the same but we don't switch at the feed. We start from the bottom and step upwards the column with Nbtm=6 (including reboiler). This gives a pinch around where the bottom operating crosses the equilibrium line (x about 0.35). We then switch to the upper operating line and need Ntop=1.6 to get to the top product.

(g) With leak Lw.
   (i) Without leak we would have $y_T=x_D$ because of total condenser.
   (ii) Flowsheet (not shown)
   (iii) Need to set up material balances.

Material balance for water around the condenser:

$V_T*y_T + L_w*x_w = (V_T+L_w)*x_D$

With numbers:

(1) Condenser water: $V_T*0.86 + L_w = (V_T+L_w)*0.89$

(2) Condenser total: VT + Lw = L + D = 1.8*D
(3) Overall water: 30 + Lw = D*0.89 + (100+Lw-D)*0.02

This gives 3 equations with 3 unknowns (VT, Lw, D).

(iv) Solution.

From (1) we we get: VT = ((1-0.89)/(0.89-0.86))*Lw = 3.667*Lw

Put into (2) gives: D = (4.667/1.8)*Lw = 2.593*Lw

Put into (3) gives: Lw = 28/(2.593*0.87+0.02-1) = 21.95 (so leak is more than 20% of feed)

Furthermore:
VT = 3.667*Lw = 80.47
D = 2.593*Lw = 56.92
L = LT = VT+Lw-D = 45.50 (Check: so L/D= 45.50/56.92 = 0.799. OK!)

(h) Upper operating line with leak.
Material balance for water over top part of column:

VT*y + Lw = LT*x + D*xD

or y = (LT/VT)*x + (D*xD – Lw)/VT

This line goes through (and starts from) the point (xD, yT) = (0.89, 0.86) because this point is on the material balance line at the top end of the column. This can be confirmed by putting in numbers.

y = 0.565*x + 0.357

We could use this upper operating line to compute the number of stages using McCabe-Thiele also in this case, but this is not asked for.

Problem 2 - Sigurd

(a) Assume constant liquid density.

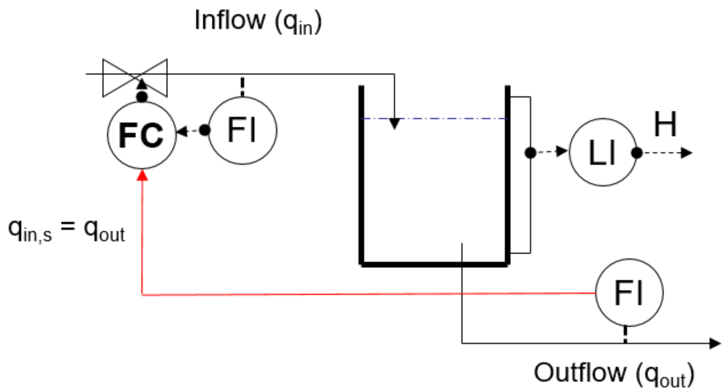
Steady-state mass balance: qin = qout [m3/3]

Dynamic mass balance: dV/dt = qin – qout [m3/s]

If we assume that the tank has constant area A [m2] then V=A*H, and dV/dt = A*dH/dt

(b) MV: qin, DV: qout, CV: H

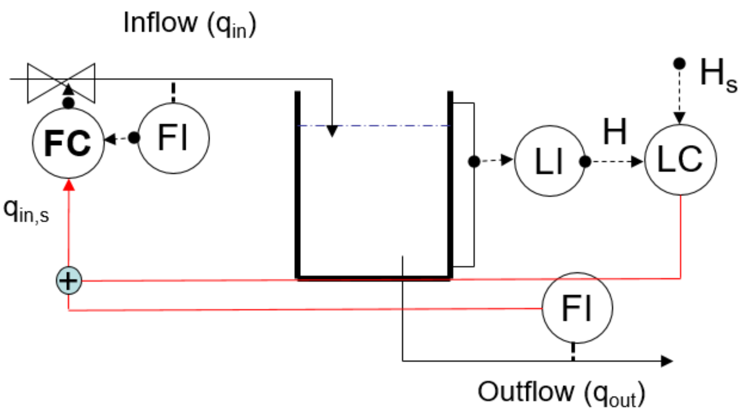
(c) Feedforward : Measure disturbance (qout) and change MV (qin).
Assume we want tight control of the level, then we want qin=quout because this makes dH/dt=0. To make qin=qout we may use a flow controller for qin with setpoint equal to qout. See Figure for feedforward



(d) Feedback: measure CV (H) and change MV (qin).

P-controller: u = Kc*(Hs-H) where u (=qin) is the output of the feedback controller

Comment (not asked for): We may also for the feedback use a flow controller, for example, to counteract disturbances in pin and linearize the valve. We may also combine feedback with feedforward control. See figure for combined feedback and feedforward:



More comments: 1) Actually, feedforward control cannot used alone for levels because otherwise the level will after some time drift away (integrating process). 2) This feedforward controller assumes that the objective is to have tight control of the level. In many cases the level should vary ("smooth" control") to avoid that the flow disturbance (here qout) propagates directly to the MV (here to qin).