Øving 2

1 Distillation column for heptane-ethyl benzene

Design 1:

Rectification of a Heptane—Ethyl Benzene Mixture. A saturated liquid feed of 200 mol/h at the boiling point containing 42 mol % heptane and 58% ethylbenzene is to be fractionated at 101.32 kPa abs to give a distillate containing 97 mol % heptane and a bottom containing 1.1 mol % heptane. The reflux ratio used is 2.5: 1. Calculate the mol/h distillate, mol/h bottoms, theoretical number of trays, and the feed tray number. Equilibrium data are given below at 101.32 kPa abs pressure for the mole fraction n-heptane x_H and y_H:

Temperature K	Temperature °C	x_H	y_H	Temperature K	Temperature °C	x_H	y_H
409.3	136.1	0	0	383.8	110.6	0.485	0.730
402.6	129.4	0.08	0.230	376.0	102.8	0.790	0.904
392.6	119.4	0.250	0.514	371.5	98.3	1.000	1.000

$F = 200$ mol/h, $X_H^F = 0{,}42$, $X_E^F = 0{,}52$

$P = 101{,}32$ kPa

$R = \frac{L_T}{D} = 2{,}5$

$X_H^D = 0{,}97$, $X_E^D = 0{,}03$

$X_H^B = 0{,}011$, $X_E^B = 0{,}989$

Assume total condenser (seems that distillate is liquid)

$F = D + B \Rightarrow B = F - D$

$F x_H^F = D x_H^F + B x_H^B$

$F x_H^F = D x_H^D + (F-D) x_H^B$

$200 \cdot 0{,}42 = D \cdot 0{,}97 + (200 - D)\, 0{,}011$

$D(0{,}97 - 0{,}011) = 200(0{,}42 - 0{,}011)$

$D = \frac{200(0{,}42 - 0{,}011)}{0{,}97 - 0{,}011}$

$\underline{D = 85{,}297 \text{ mol/h}} \Rightarrow B = F - D = 200 - 85{,}297$

$\underline{B = 114{,}703 \text{ mol/h}}$

Theoretical number of trays

Want a Mccabe thiele diagram, heptane

$X_B = 0{,}011$

$X_F = 0{,}42$

$X_D = 0{,}97$

Saturated liquid ⇒ $q = 1$, vertical line

Upper operating line

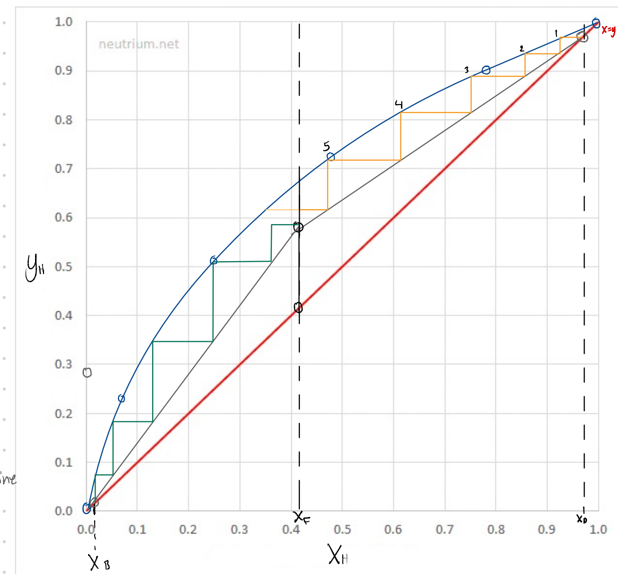
$$y = \frac{R}{R+1} x + \frac{X_D}{R+1}$$

$$y = 0{,}714x + 0{,}277$$

Gives $(0,\ 0{,}277)$ and $(0{,}97,\ 0{,}97)$

Bottom operating line

(X_B, X_B) and intersection X_F, upper o-line



Number of stages: $n_{top} \approx 5{,}4$

$n_{bottom} \approx 4{,}7$

⇒ <u>Theoretical number equilibrium stages = 10,1, including reboiler</u>

⇒ <u>Theoretical number of trays = 9,1</u>

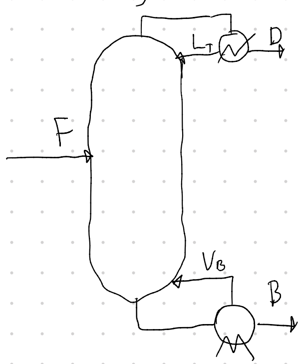
Feed tray number = n_{top} = 5,4

(i) Derive a general equation for V_{btm} as a function of F, $R = L/D$, and q for the case of constant molar flows.

(ii) Find the energy consumption Q (heat to the reboiler) given that the heat of vaporization at the normal boiling point (1 atm) is 31.8 kJ/mol for heptane and 35.6 kJ/mol for ethylbenzene.

(iii) Compute the minimum number of stages and the minimum reflux ratio and boil-up (R_{min}, V_{min}).

i)



$R = \frac{L_T}{D}$, $q = \frac{L_F}{F}$

Constant molar flows: $L_B = L_F + L_T = qF + L_T$

$V_T = V_B + V_F = V_B + (1-q)F \Rightarrow V_B = V_T - (1-q)F$

Mass balance

Top: $D = V_T - L_T \Rightarrow V_T = D + L_T$

$\Rightarrow V_B = V_T - (1-q)F$

$= D + L_T - (1-q)F$

$= D + DR - (1-q)F$

$V_B = D(1+R) + (q-1)F$

ii) Since $X_H^B = 0{,}011$ and $X_E^B = 0{,}989$, the liquid flowing into the reboiler will be mostly ethylbenzene

$V_B = D(1+R) + (q-1)F = 85{,}297(1+2{,}5) + 0$

$V_B = 298{,}5395$ mol/h

$Q = V_B \cdot \Delta_{vap}H = 298{,}5395 \frac{mol}{3600\,s} \cdot 35{,}6$ kJ/mol

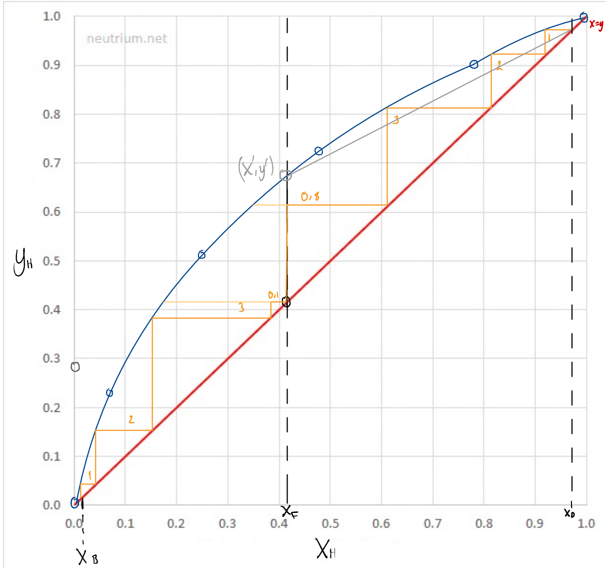
$Q = 2{,}952$ kW

iii) $n_{top} = 3,1$

$n_{bottom} = 3,8$

$n_{min} = 6,9$

Minimum number of stages = 6,9



$x' = 0,42$

$y' = 0,68$

$$\left(\frac{L}{V}\right)_{min} = \frac{x_D - y'}{x_D - x'} = \frac{0,97 - 0,68}{0,97 - 0,42} = 0,527$$

$$\left(\frac{L}{V}\right)_{min} = \frac{L_{min}}{L_{min} + D} = \frac{R_{min}}{R_{min} + 1}$$

$$\Rightarrow R_{min} = \frac{(L/V)_{min}}{1 - (L/V)_{min}} = \frac{0,527}{1 - 0,527}$$

$R_{min} = 1,11$

from ii): $V_{min} = (1+R)D + (1-q)F$

$V_{min} = 2,11 \cdot 85,297$

$V_{min} = 179,98$ mol/h

Design 2:

To save energy, consider another design where the reflux ratio is reduced to $R = 1.2R_{min}$. Show that this corresponds approximately to $V = 1.1V_{min}$ in this case. How many stages are required, and what is the energy consumption in this case? Compare and discuss the two designs.

Note: There are several ways to "start" the staircase when drawing the McCabe-Thiele diagram. In this case, when you are to design the column with both product compositions given, you are recommended to start at the top and go down to where the operating lines cross and then start from the bottom and go up to where the operating lines cross. You will then get a non-integer number of stages in each section.

$$V = (1+R)D = (1 + 1,2R_{min})D$$

$$\frac{V}{V_{min}} = \frac{(1 + 1,2R_{min})D}{(1 + R_{min})D} = \frac{1 + 1,2R_{min}}{1 + R_{min}} = 1,10 \approx 1,1$$

$\Rightarrow V = 1,1\, V_{min}$ ☐

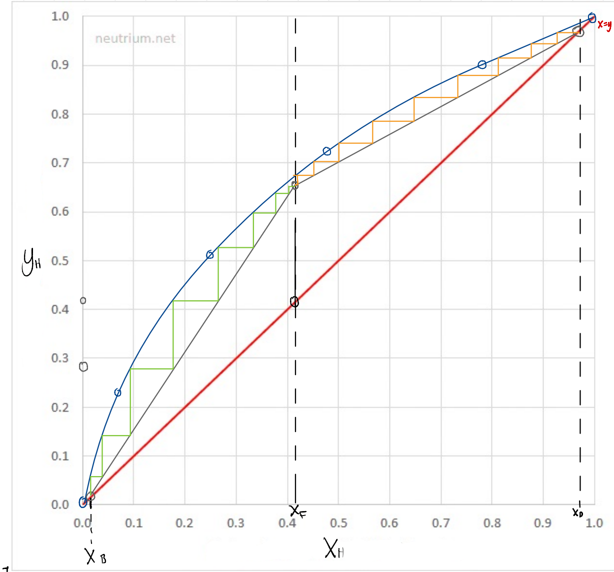
Upper operating line $R = 1{,}2\, R_{min} = 1{,}332$

$$y = \frac{R}{R+1} x + \frac{x_D}{R+1}$$

$$y = 0{,}5712\, x + 0{,}4160$$

Gives $(0,\ 0{,}416)$ and $(0.97,\ 0{,}97)$

Bottom operating line
(x_B, x_B) and intersection x_F, upper o-line



$n_{top} = 9{,}1$

$n_{bottom} = 7{,}6$

$n_{tot} = 16{,}7$

Total number of theoretical stages = 16,7

$$Q = V_B \cdot \Delta_{vap} H = (1 + 1{,}2 \cdot 1{,}11)\, 85{,}297 \frac{mol}{3600\,s} \cdot 35{,}6 \frac{kJ}{mol}$$

$Q = 1{,}967$ kW

- Design 1 uses more energy than design 2, in terms of cost during operation
- Design 2 demands more stages than design 1, therefore it will require a bigger area/height.

2 Enriching column for benzene-toluene

An enriching tower is fed 100 kg mol/h of a saturated vapor feed containing 40 mol % benzene (A) and 60 mol % toluene (B) at 101.32 kPa abs. The distillate is to contain 90 mol % benzene. The reflux ratio is set at 4.0: l.

a) Calculate the kg mol/h distillate D and bottoms W and their compositions.
b) Calculate the number of theoretical plates required.
c) What is the distillate composition if the feed composition drops to $x_F = 0.30$ (benzene) with the same reflux ratio and the same number of stages?

Comment: Note that a batch distillation column (like in the lab) behaves like an enriching column if we assume small holdups so that we have a steady-state in the column part. The "feed" is the vapor that leaves the boiler, and the bottom is returned to the boiler – but note that in a batch column, the fraction of light component in the "feed" drops as time goes because we remove light component in the distillate (top product).

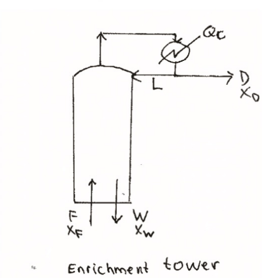
$F = 100$

$x_A^F = 0{,}4$

$x_B^F = 0{,}6$

$x_A^D = 0{,}9$

$R = 4$



a) We assume constant molar flows => $L = W$

$$F = D + W = D + L \qquad R = \frac{L}{D} = 4 \Rightarrow L = 4D$$

$$F = 5D$$

$$D = \frac{F}{5}$$

$$D = \frac{100 \text{ kg mol/h}}{5}$$

$$\underline{\underline{D = 20 \text{ kg mol/h}}} \Rightarrow W = F - D$$

$$\underline{\underline{W = 80 \text{ kg mol/h}}}$$

$$\underline{\underline{X_A^D = 0{,}9 \,,\, X_B^D = 0{,}1}}$$

Balance benzene (A)

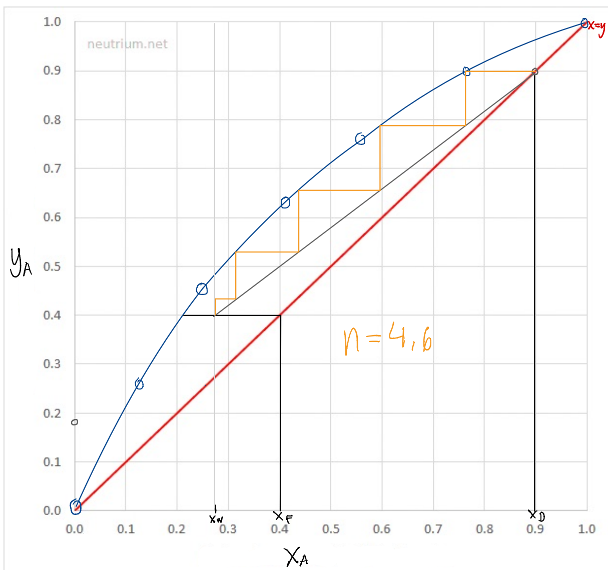
$$F \cdot X_A^F = D \cdot X_A^D + W \cdot X_A^W$$

$$100 \cdot 0{,}4 = 20 \cdot 0{,}9 + 80 \cdot X_A^W$$

$$\underline{\underline{x_A^W = 0{,}275 \Rightarrow X_B^W = 0{,}725}}$$

b)

Vapor Pressure							
Temperature		Benzene		Toluene		Mole Fraction Benzene at 101.325 kPa	
K	°C	kPa	mm Hg	kPa	mm Hg	x_A	y_A
353.3	80.1	101.32	760			1.000	1.000
358.2	85	116.9	877	46.0	345	0.780	0.900
363.2	90	135.5	1016	54.0	405	0.581	0.777
368.2	95	155.7	1168	63.3	475	0.411	0.632
373.2	100	179.2	1344	74.3	557	0.258	0.456
378.2	105	204.2	1532	86.0	645	0.130	0.261
383.8	110.6	240.0	1800	101.32	760	0	0



Saturated vapor => $q = 0$

q-line: horizontal

Upper operating line

$$y = \frac{R}{R+1} x + \frac{X_D}{R+1} \,,\, R = 4$$

$$y = 0{,}8x + 0{,}18$$

Gives (0, 0.18) and (0.9, 0.9)

Bottom operating line
(X_B, X_B) and intersection X_F, upper o-line

We do not have a reboiler, and we have a total condenser

=> <u>We need 4,6 theoretical plates</u>

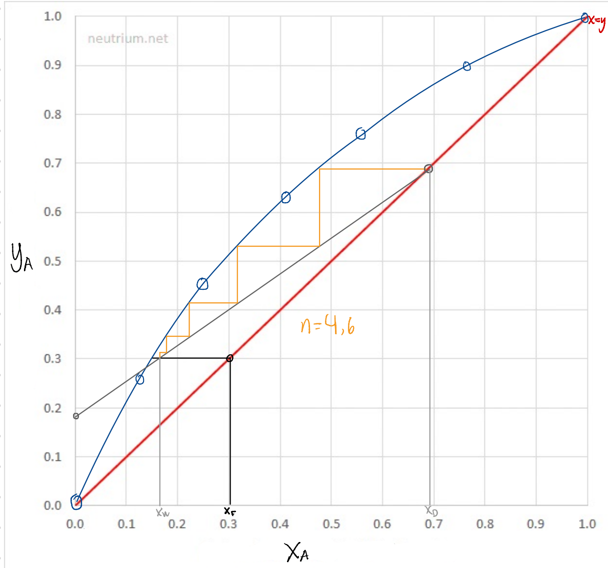
c) Changing the diagram

$x_F = 0{,}3$

- Attempt to draw a top line guess x_D

- Find x_W: Find the place where the first step up from the q-line $= 0{,}6$

- Check x_D: Take 4,6 steps from x_W, check if it hits x_D



$\Rightarrow \quad x_A^W = 0{,}17, \; x_B^W = 0{,}83, \; x_A^D = 0{,}69, \; x_B^D = 0{,}31$

$$F = W + D \Rightarrow D = F - W$$

$$F x_A^F = W x_A^W + D x_A^D$$

$$F x_A^F = W x_A^W + (F - W) x_A^D$$

$$W = \frac{F(x_A^F - x_A^D)}{x_A^W - x_A^D} = \frac{100(0{,}3 - 0{,}69)}{0{,}17 - 0{,}69} = 75, \quad D = F - W = 25$$

$W = 75$ kg mol/h, $D = 25$ kg mol/h