Mass Transfer – I (CH21202)

Solutions of Tutorial Sheet No.: MT-I/NCP/2023/4

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1. A liquid mixture containing 50 mol% benzene and 50 mol% toluene is to be continuously fractionated at 101.32 kPa at the rate of 8500 kg/h. A distillate containing 95 mol% benzene and a bottom product containing 10 mol% benzene are to be obtained. The feed is liquid at its bubble point. A total condenser will be used and the reflux will be returned at the bubble point. Determine (a) the product rates, kg/h; (b) the minimum reflux ratio, (c) the number of theoretical trays required for a reflux ratio 2.0 times the minimum, and (d) the optimum location of the feed tray. The benzene-toluene mixture is having an average relative volatility of 2.4.

Solution:

Basis : 1 hour operation

(a) The material balance equations can be written as:

$$F = W + D \qquad (1)$$

and

$$F\, z_F = W\, x_W + D\, x_D \qquad (2)$$

Given, $x_W = 0.10$, $x_D = 0.95$

Molecular weight benzene is 78 and that of toluene is 92.

Therefore, average molecular weight of the feed will be

0.5x78 + 0.5x92 = 85.0

$\therefore$ F = 8500/85.0 = 100 kmoles

Average molecular weight of the distillate, $M_{D,avg}$ = 0.95x78 + 0.05x92 = 78.7

Average molecular weight of the residue, $M_{W,avg}$ = 0.10x78 + 0.90x92 = 90.6

From equations (1) and (2), W = 52.94 kmoles and D = 47.06 kmoles.

Therefore, product rates will be 47.06 x 78.7 = 3704.0 kg/h of distillate and 52.94 x 90.6 = 4796.0 kg/h bottom product.

(b) From the given relative volatility, the equilibrium data were generated as follows:

$$y^* = \frac{\alpha_{av}\, x}{1 + (\alpha_{av} - 1)\, x}$$

x	0.0	0.2	0.4	0.6	0.8	1.0
y^*	0.0	0.375	0.615	0.783	0.905	1.0

The equilibrium data were plotted. As the feed is liquid at its bubble point, the q-line will be vertical. So, the q-line was drawn from $x = y = z_F$ on the 45° diagonal line. For minimum reflux ratio, the enriching section operating line should pass through the point of intersection of the q-line and the equilibrium curve. Its intercept on the y-axis is $x_D/(R_m + 1)$, which was found out from the graph to be 0.415.

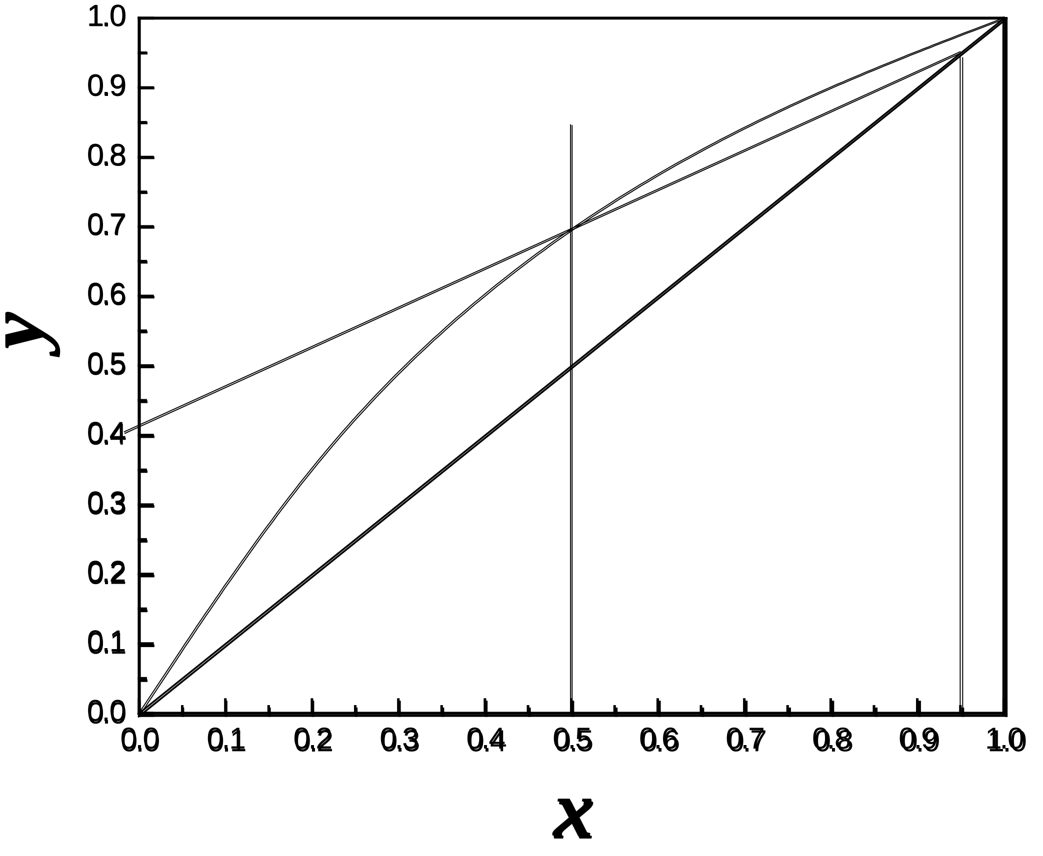
Therefore, minimum reflux ratio, R_m = 1.289

(c) Actual reflux ratio = 2.0 x R_m = 2.578

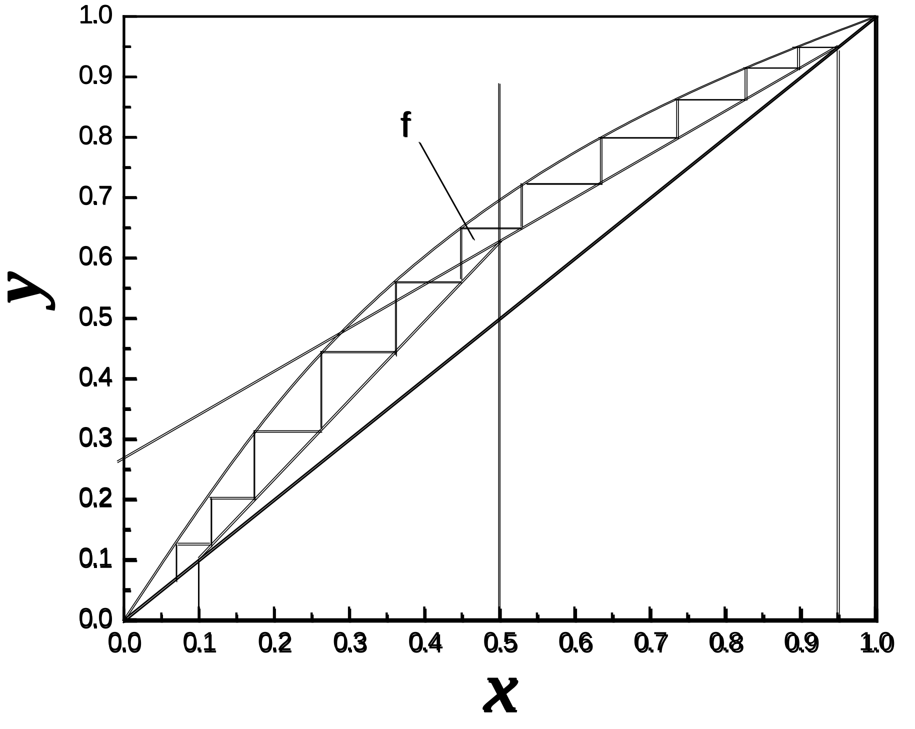
Intercept of enriching section actual operating line, $x_D/(R+1) = 0.95/(2.578+1) = 0.265$.

Now, the operating lines for both enriching as well as for stripping sections were drawn. The number of stages was determined by stage-wise construction to be 10.5, including the reboiler. Therefore, the total number of theoretical trays required is 9.5.

(d) The feed tray was located as the tray which straddles the operating-lines intersection. Therefore, the optimum location of the feed tray is the 6th tray from the top.



Determination of minimum reflux ratio



Determination of number of theoretical trays

2. A solution of *n*-heptane and ethylbenzene containing 42 mol% *n*-heptane is to be continuously fractionated at 101.3 kPa pressure at the rate of 20696 kg/h to give a distillate containing 97 mol% *n*-heptane and a bottom product containing 1.1 mol% *n*-heptane. The feed enters the tower partially vaporized so that 60 mol% is liquid and 40 mol% is vapour. A total condenser will be used and the reflux will be returned at the bubble point. Determine (a) the product rates, kg/h; (b) the minimum reflux ratio; (c) the number of theoretical trays required at a reflux ratio 75% more than the minimum and (d) the optimum location of the feed tray.

Equilibrium Data:

x	0.0	0.08	0.250	0.485	0.580	0.790	1.0
y	0.0	0.23	0.514	0.730	0.790	0.904	1.0

Solution:

Basis : 1 hour operation

(a) The material balance equations can be written as:

$$F = W + D \tag{1}$$

and

$$F\,z_F = W\,x_W + D\,x_D \tag{2}$$

Given, $z_F = 0.42$, $x_W = 0.011$, $x_D = 0.97$

Molecular weight *n*-heptane is 100 and that of ethylbenzene is 106.

Therefore, average molecular weight of the feed will be

$$0.42\text{x}100 + 0.58\text{x}106 = 103.48.$$

$$\therefore\ F = 20696/103.48 = 200 \text{ kmoles}$$

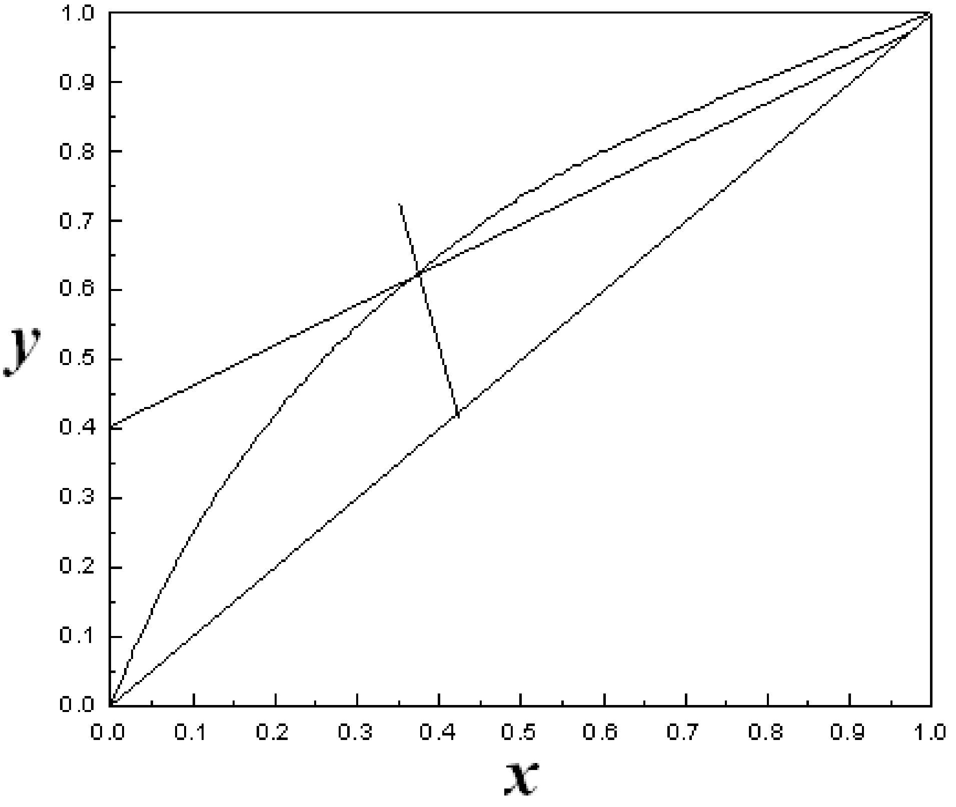
Average molecular weight of the distillate, $M_{D,avg} = 0.97\text{x}100 + 0.03\text{x}106 = 100.18$

From equations (1) and (2), $W = 114.7$ kmoles and $D = 85.3$ kmoles.

Therefore, product rates will be 85.3x100.18 = 8545.35 kg/h of distillate and (20696 – 8545.35) = 12150.65 kg/h bottom product.

(b) The equilibrium data were plotted. The feed is 40 mol% vaporized. Assuming molar latent heats of vaporization to be same, $q = 1 - 0.4 = 0.6$. Therefore, the slope of the q-line will be $q/(q-1) = -1.5$. The q-line was drawn from $x = y = z_F$ on the 45^{o} diagonal line. For minimum reflux ratio, the enriching section operating line should pass through the point of intersection of the q-line and the equilibrium curve. Its intercept on the y-axis is $x_D/(R_m + 1)$, which was found out from the graph to be 0.4

Therefore, minimum reflux ratio, $R_m = 1.425$



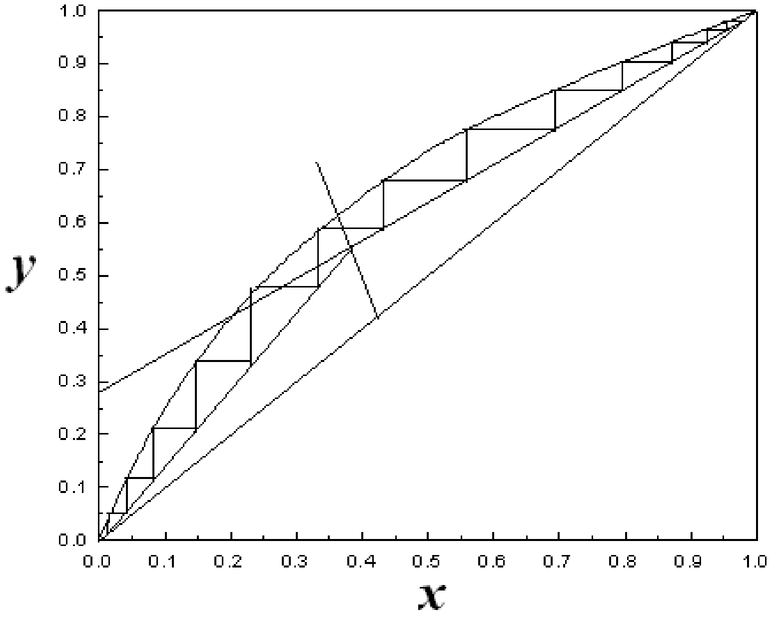
Determination of minimum reflux ratio

(c) Actual reflux ratio = 1.75 x R_m = 2.49375

Intercept of enriching section actual operating line, $x_D/(R+1) = 0.97/(2.49375+1) = 0.2776$.

Now, the operating lines for both enriching as well as for stripping sections were drawn. The number of stages was determined by stage-wise construction to be 13, including the reboiler. Therefore, the total number of theoretical trays required is 12.

(d) The feed tray was located as the tray which straddles the operating-lines intersection. Therefore, the optimum location of the feed tray is the 8th tray from the top.



Determination of number of theoretical trays

3. A solution of carbon tetrachloride (CCl_4) and carbon disulphide (CS_2) containing 50 mol% CCl_4 is to be continuously fractionated at standard atmospheric pressure at the rate of 23000 kg/h. The distillate product is to contain 95 mol% CS_2, the residue 1.0 mol% CS_2. The feed will be 50 mol% vaporized before it enters the tower. A total condenser will be used and the reflux will be returned at the bubble point. Determine (i) the product rates, kg/h; (ii) the minimum reflux ratio; (iii) the number of theoretical trays required at a reflux ratio 1.5 times the minimum and (iv) the location of the feed tray.

Equilibrium Data:

x	0.0	0.0296	0.0615	0.1106	0.1435	0.2585	0.3908	0.5318	0.6630	0.7574	0.8604	1.00
y	0.0	0.0823	0.1555	0.2660	0.3325	0.4950	0.6340	0.7470	0.8290	0.8780	0.9320	1.00

[2+3+4+1]

Solution:

Basis : 1 hour operation

(i) The material balance equations can be written as:

$$F = W + D \qquad (1)$$

and

$$F\, z_F = W\, x_W + D\, x_D \qquad (2)$$

Given, $z_F = 0.50$, $x_W = 0.01$, $x_D = 0.95$

Molecular weight CS_2 is 76 and that of CCl_4 is 154.

Therefore, average molecular weight of the feed will be

$$0.5\text{x}76 + 0.5\text{x}154 = 115$$

$$\therefore\ F = 23000/115 = 200 \text{ kmoles}$$

Average molecular weight of the distillate, $M_{D,avg} = 0.95\text{x}76 + 0.05\text{x}154 = 79.90$

From equations (1) and (2), $W = 94$ kmoles and $D = 104$ kmoles.

Therefore, product rates will be 104x79.90 = 8310 kg/h of distillate and (23000 – 8310) = 14690 kg/h bottom product.

(ii) The equilibrium data were plotted. The feed is 50 mol% vaporized. Assuming molar latent heats of vaporization to be same, q = 1 - 0.5 = 0.5. Therefore, the slope of the q-line will be q/(q-1) = -1.0 The q-line was drawn from $x = y = z_F$ on the 45^o diagonal line. For minimum reflux ratio, the enriching section operating line should pass through the point of intersection of the q-line and the equilibrium curve. Its intercept on the y-axis is $x_D/(R_m + 1)$, which was found out from the graph to be 0.4

Therefore, minimum reflux ratio, $R_m = 1.375$

(iii) Actual reflux ratio = 2.0 x R_m = 2.75

Intercept of enriching section actual operating line, $x_D/(R+1) = 0.95/(2.75+1) = 0.253$.

Now, the operating lines for both enriching as well as for stripping sections were drawn. The number of stages was determined by stage-wise construction to be 11.5, including the reboiler. Therefore, the total number of theoretical trays required is 10.5.

(iv) The feed tray was located as the tray which straddles the operating-lines intersection. Therefore, the optimum location of the feed tray is the 6^{th} tray from the top.