

Mass Transfer – I (CH21202)
Solutions of Tutorial Sheet No.: MT-I/NCP/2024/4

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:

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

and $F z_F = W x_W + D x_D \quad (2)$

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

$$0.5 \times 78 + 0.5 \times 92 = 85.0$$

$$\therefore F = 8500/85.0 = 100 \text{ kmoles}$$

$$\text{Average molecular weight of the distillate, } M_{D,avg} = 0.95 \times 78 + 0.05 \times 92 = 78.7$$

$$\text{Average molecular weight of the residue, } M_{W,avg} = 0.10 \times 78 + 0.90 \times 92 = 90.6$$

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

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

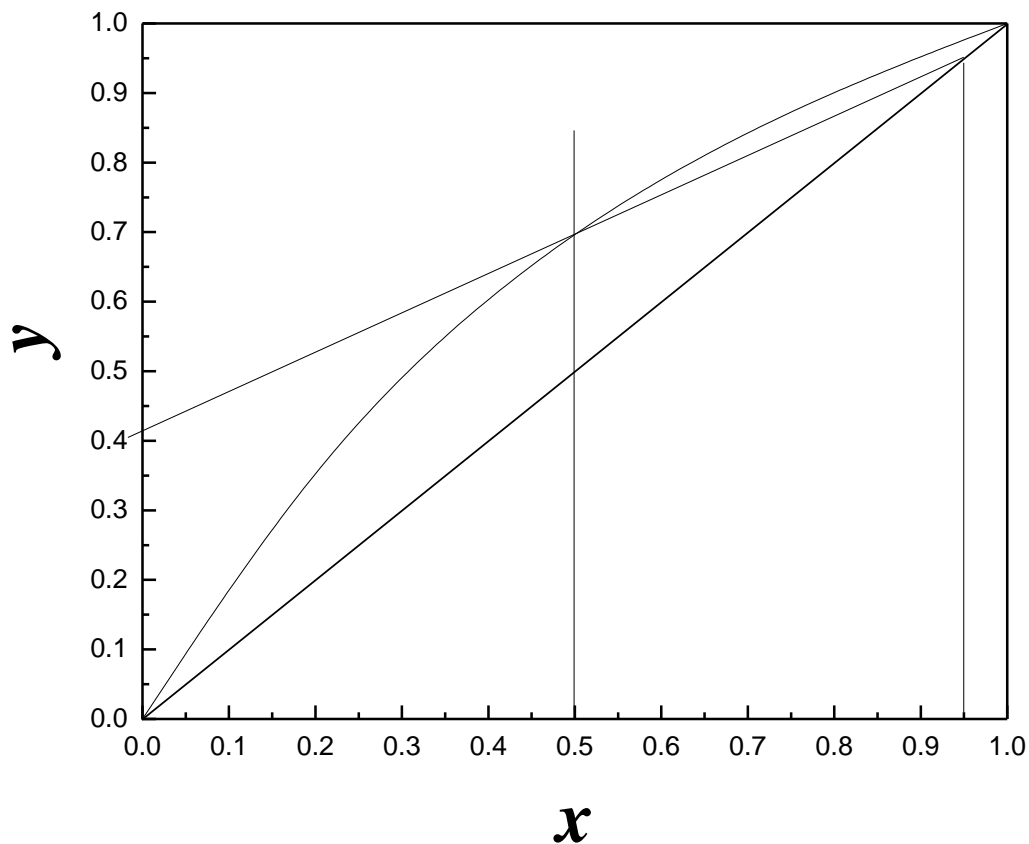
Therefore, minimum reflux ratio, $R_m = 1.289$

(c) Actual reflux ratio = $2.0 \times R_m = 2.578$

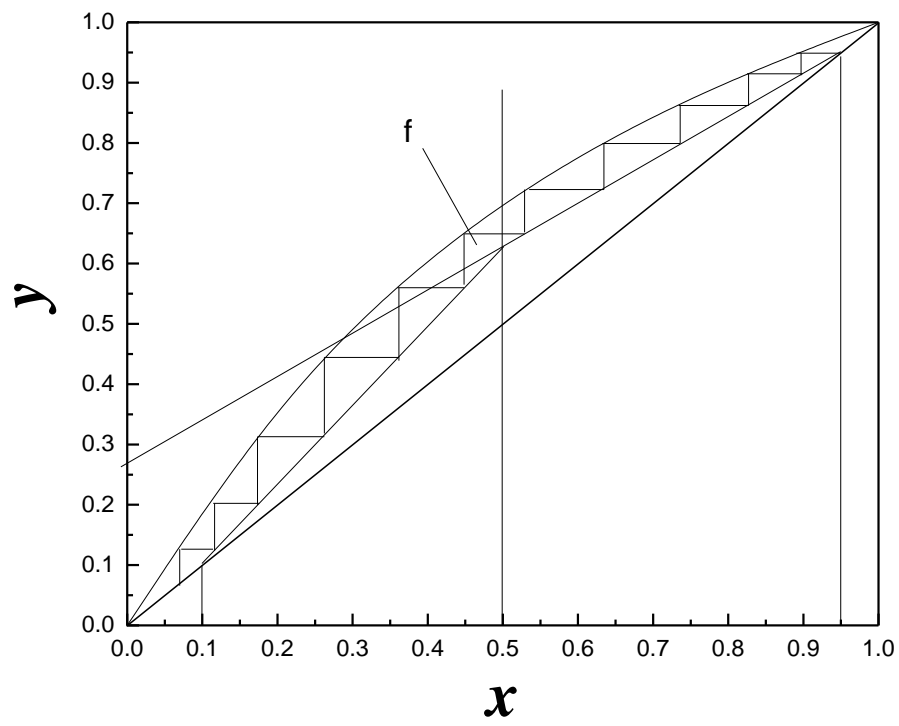
Intercept of enriching section actual operating line, $x_D/(R+1) = 0.95/(2.578+1) = 0.265$.

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:

<i>x</i>	0.0	0.08	0.250	0.485	0.580	0.790	1.0
<i>y</i>	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:

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

and $F z_F = W x_W + D x_D \quad (2)$

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

$$0.42 \times 100 + 0.58 \times 106 = 103.48.$$

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

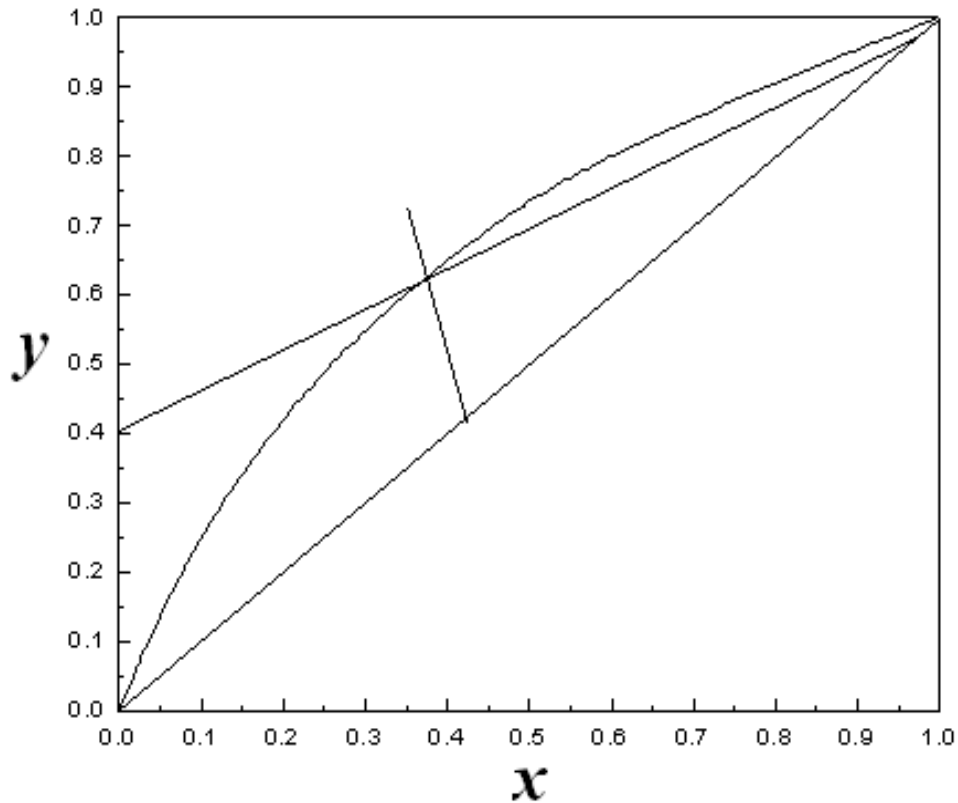
Average molecular weight of the distillate, $M_{D,avg} = 0.97 \times 100 + 0.03 \times 106 = 100.18$

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

Therefore, product rates will be $85.3 \times 100.18 = 8545.35$ 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° 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, $R_m = 1.425$



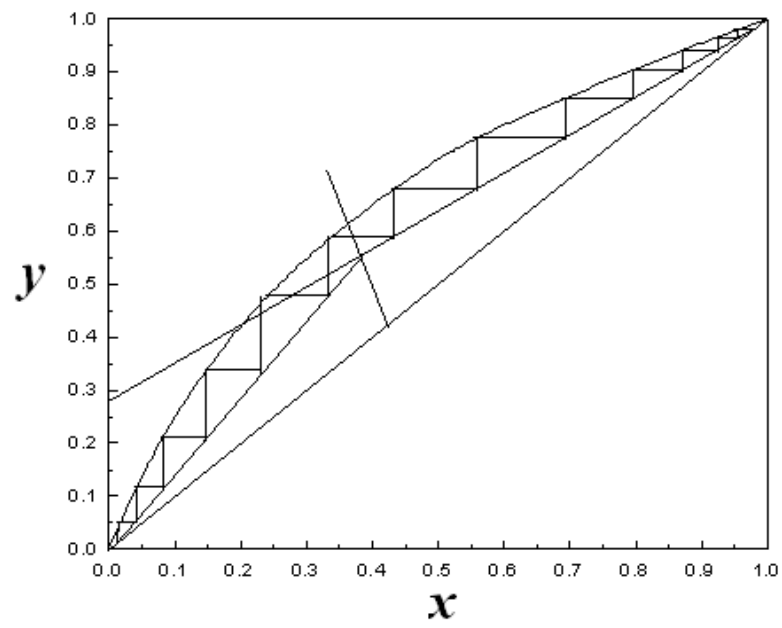
Determination of minimum reflux ratio

(c) Actual reflux ratio = $1.75 \times R_m = 2.49375$

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

1. A mixture of diethyl amine (DEA) and triethyl amine (TEA) containing 50 mol% of DEA is to be continuously fractionated at a rate of 8700 kg/h and at a total pressure of 113.3 kPa. The top product should have 98% more volatile component and the bottom product 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.

The equilibrium data for the system at the given pressure are given below:

x	0.0	0.02	0.104	0.227	0.34	0.428	0.52	0.65	0.79	0.90	0.95	1.0
y	0.0	0.052	0.231	0.45	0.6	0.694	0.765	0.845	0.915	0.963	0.982	1.0

Solution:

Basis : 1 hour operation

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

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

and $F z_F = W x_W + D x_D \quad (2)$

Given, $x_W = 0.02$, $x_D = 0.98$

Molecular weight DEA is 73 and that of TEA is 101.

Therefore, average molecular weight of the feed will be

$$0.5 \times 73 + 0.5 \times 101 = 87.0.$$

$$\therefore F = 8700/87 = 100 \text{ kmoles}$$

$$\text{Average molecular weight of the distillate, } M_{D,avg} = 0.98 \times 73 + 0.02 \times 101 = 73.56$$

$$\text{Average molecular weight of the residue, } M_{W,avg} = 0.02 \times 73 + 0.98 \times 101 = 100.44$$

From equations (1) and (2), $W = 50$ kmoles and $D = 50$ kmoles.

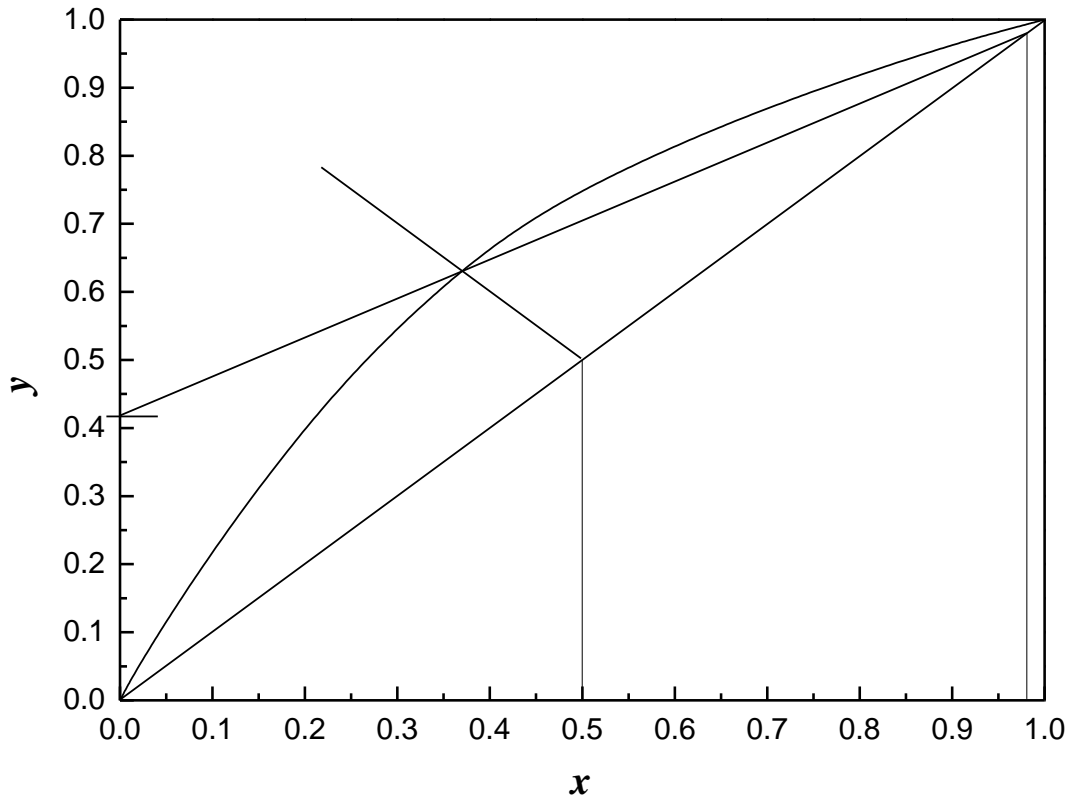
Therefore, product rates will be $50 \times 73.56 = 3678$ kg/h of distillate and $50 \times 100.44 = 5022$ kg/h bottom product.

(b) The equilibrium data were plotted. The feed is 50 mol% vaporized. Assuming molar latent heats of vaporization of the amines 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° 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 0.418

Therefore, minimum reflux ratio, $R_m = 1.34$

(c) Actual reflux ratio, $R = 1.5 \times R_m = 2.01$

$$\text{Intercept of enriching section actual operating line, } x_D/(R+1) = 0.98/(2.01+1) = 0.325.$$



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 15, including the reboiler. Therefore, the total number of theoretical trays required is 14.

(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 7th tray from the top.

