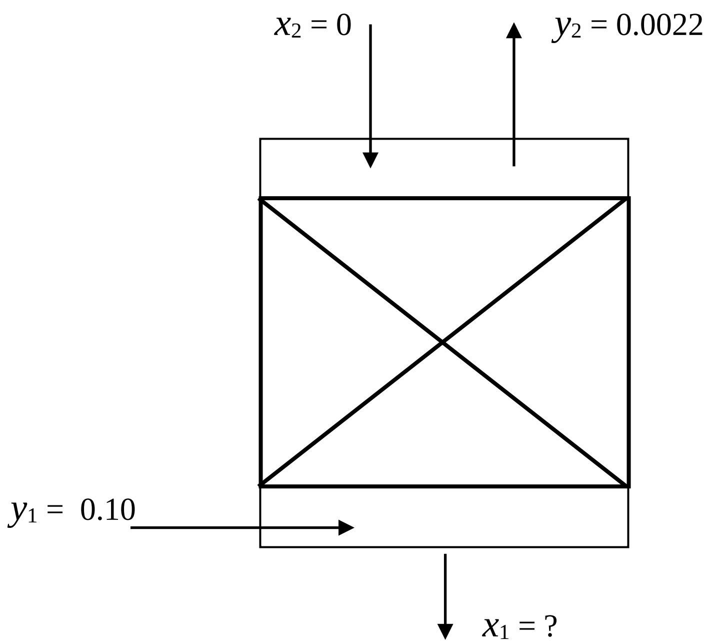
Mass Transfer – I (CH21202)
<u>Solutions of Tutorial Sheet No.: MT-I/NCP/2024/2</u>

1. Ammonia is to be removed from an ammonia-air mixture by water scrubbing in a 0.786 m diameter tower packed with 25 mm Raschig rings. The gas mixture is available at the rate of 600 m^3/h (at 25^{o}C and 1 atm) with 10% ammonia by volume. Pure water will be used as solvent at a rate twice the minimum. Film coefficients are $k_y a$ = 150 kmol/m^3 h Δy and $k_x a$ = 325 kmol/ m^3 h Δx. The equilibrium relation may be expressed y^* = 1.02 $x/(1 - x)$. Calculate the depth of the packing required for 98% removal of ammonia.

Solution:



$$M_{AV}\text{ (inlet)} = (0.10 \times 17) + (0.90 \times 29) = 27.80$$

$$\rho_{G1} = \frac{P.M_{AV}(inlet)}{R.T} = \frac{1\times 27.80}{82.1\times 10^{-3}\times 298} = 1.136 \quad kg/m^3$$

$$\text{Gas molar input rate} = G_1 = \frac{600\times 1.136}{27.80} = 24.52 \quad kmol/h$$

$$\text{Molar flow rate of the carrier} = G_S = 24.52\times 0.9 = 22.07 \quad kmol/h$$

$$G_2 = 22.07 + (24.52 - 22.07) \times 0.02 = 22.12 \; kmol/h$$

The operating line equation may be written in terms of <u>solute-free stream</u> as follows:

$$G_S\left(\frac{y}{1-y}-\frac{y_2}{1-y_2}\right)=L_S\left(\frac{x}{1-x}-\frac{x_2}{1-x_2}\right)$$

For minimum liquid rate, the operating line will cut the equilibrium line at $y = y_1$ (= 0.10), and the corresponding maximum liquid phase concentration will be (from the equilibrium relationship) $x_{max} = 0.089$. Putting $y = y_1$, and $x = x_{max}$, in the operating line equation, we get,

$$22.07\left(\frac{0.10}{1-0.10}-\frac{0.0022}{1-0.0022}\right)=L_{S,\min}\left(\frac{0.089}{1-0.089}\right)$$

$$\Rightarrow L_{S,\min}=24.60 \quad kmol/h \quad HN_3-free\ water$$

Designed liquid rate, L_S = 2 x 24.6 = 49.20 kmol/h

The actual NH_3 concentration in the outlet water can be calculated again from the material balance equation as,

$$22.07\left(\frac{0.10}{0.90}-\frac{0.0022}{0.9978}\right)=L_S\left(\frac{x_1}{1-x_1}\right)=49.20\left(\frac{x_1}{1-x_1}\right)$$

$$\Rightarrow x_1=0.046$$

The tower height can be calculated using the following equation:

$$Z=\frac{G'}{k_y a\,(1-y)_{iM}}\times\int_{y_2}^{y_1}\frac{(1-y)_{iM}}{(1-y)(y-y_i)}dy$$

$$=H_{tG} \quad \times \quad N_{tG}$$

The above equation can be simplified by replacing logarithmic average by arithmetic average. Thus,

$$(1-y)_{iM} \quad = \quad \frac{(1-y_i)-(1-y)}{\ln\left(\frac{1-y_i}{1-y}\right)} \quad \approx \quad \frac{(1-y_i)+(1-y)}{2}$$

$$\text{Therefore,}\ N_{tG}=\int_{y_2}^{y_1}\frac{dy}{y-y_i}+\frac{1}{2}\ln\frac{1-y_2}{1-y_1}$$

Evaluation of the first integral requires interfacial composition values. Now for any cross section of the tower, if we draw a line from any point on the operating line with a slope of - k_xa/k_ya, then this line will intersect the equilibrium curve at a point, whose coordinates will give the interfacial composition. Also, if $k_x a$ and $k_y a$ are assumed to remain constant throughout the tower, then the ratio ($k_x a/k_y a$) will remain constant, that is, all such lines will be parallel.

The x and y values of the operating line was obtained from the equation,

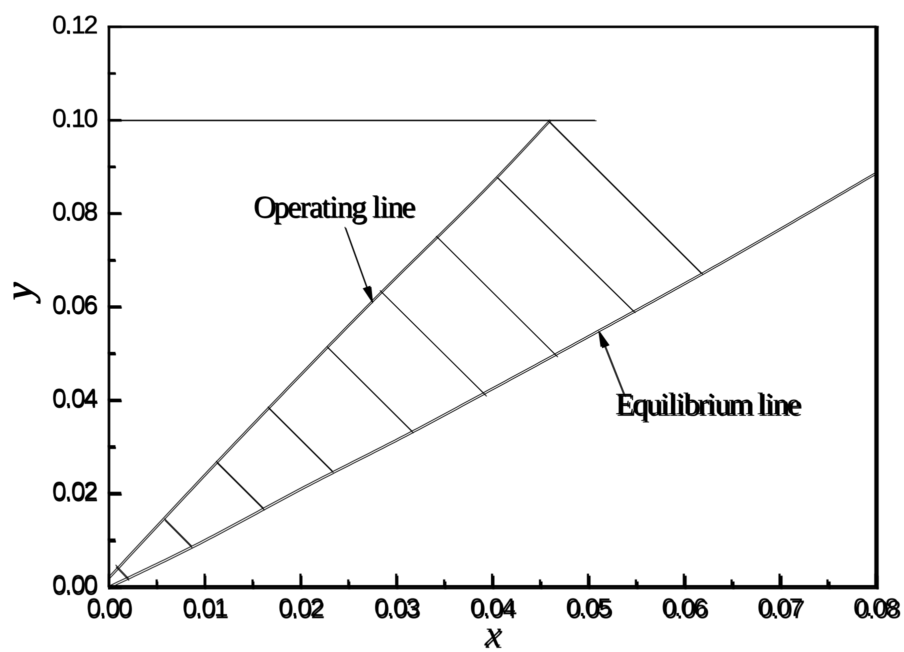
$$22.07\left(\frac{y}{1-y}-\frac{0.0022}{1-0.0022}\right)=49.20\left(\frac{x}{1-x}\right)$$

$$\text{Or, } \frac{y}{1-y} = 2.23\left(\frac{x}{1-x}\right) + 0.0022$$

x	0	0.01	0.02	0.03	0.04	0.046
y	0.002	0.024	0.0455	0.0664	0.0868	0.10

The interfacial concentrations were then found out as follows:

y	0.002	0.0142	0.0265	0.0387	0.051	0.063	0.075	0.0875	0.10
y_i	0.0005	0.008	0.017	0.024	0.033	0.041	0.0495	0.058	0.066
$\frac{1}{y-y_i}$	666.67	161.29	105.26	68.03	55.55	45.45	39.21	33.90	29.41



Determination of interfacial concentration

Therefore, the first integral value is given by,

$$I = \frac{0.01225}{3}\{666.67 + 4\times(161.29 + 68.03 + 45.45 + 33.90) + 2\times(105.26 + 55.55 + 39.21) + 29.41\}$$

$= 9.517$

$$N_{tG} = 9.517 + \frac{1}{2}\ln\frac{1-0.002}{1-0.1} = 9.568$$

$$H_{tG} = \frac{G'}{k_y.a.(1-y)_{iM}}$$

where $(1 - y)_{iM}$ can be taken as the arithmetic average of that at the bottom and at top of the tower.

At the inlet of gas: $(1-y)_{iM1} = \dfrac{(1-0.066)-(1-0.1)}{\ln\dfrac{(1-0.066)}{(1-0.1)}} = 0.9168$

At the outlet of gas: $(1-y)_{iM2} = \dfrac{(1-0.0005)-(1-0.002)}{\ln\dfrac{(1-0.0005)}{(1-0.002)}} = 0.9987$

Therefore, $(1 - y)_{iM} = (0.9168 + 0.9987)/2 = 0.9577$

$$H_{tG} = \frac{G'}{k_y.a.(1-y)_{iM}} = \frac{23.32/0.485}{150\times0.9577} = \frac{48.08}{143.655} = 0.335\,\text{m}$$

Total packed height = $Z = H_{tG} \times N_{tG}$ = 0.335 x 9.568 = **3.2 m**

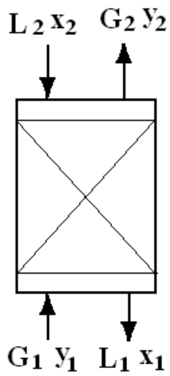
2. Benzene is to be removed from coke oven gas by scrubbing into a nonvolatile hydrocarbon oil in a 2.0 m diameter tower packed with 25 mm Berl saddles. The gas mixture is available at the rate of 100 kmol/h with 6% benzene by volume. Calculate the depth of the packing required to reduce the benzene content to 0.2% by volume. The scrubbing liquid, which is recycled from a stripper, contains 0.1 mol % benzene. The gas-liquid equilibrium may be expressed as $y^* = 0.65\ x$ where y^* is the equilibrium mole fraction of benzene in the gas phase at composition x mole fraction benzene in the oil. The oil rate is 160 kmol/h and $K_y a$ is given as 68 kmol/m^3 h (Δy^*).

Solution:

$G_1 =$ 100 kmol/h, $y_1 = 0.06$

$G_s = G_1(1 - y_1) = 100 \times 0.94 = 94$ kmol/h

$G_2 = G_s/(1 - y_2) = 94/0.998 = 94.2$ kmol/h



$G = (G_1 + G_2)/2 = 97.1$ kmol/h

$L_2 = 160$ kmol/h, $x_2 = 0.001$; $L_s = L_2\ (1\text{-}x_2)$

$= 160 \times 0.999 = 159.84$ kmol/h

From the equation of the operating line, we can write

$$159.84\left(\frac{x_1}{1-x_1}\right) = 94\left(\frac{0.06}{1-0.06} - \frac{0.002}{1-0.002}\right) = 5.8$$

$\Rightarrow x_1 = 0.035$

$y_1^* = m\ x_1 = 0.65 \times 0.035 = 0.0227;$

$y_2^* = m\ x_2 = 0.65 \times 0.001 = 0.00065$

$$(y^*_{BM})_1 = \frac{(1-y_1^*)-(1-y_1)}{\ln[(1-y_1^*)/(1-y_1)]} = \frac{0.06-0.0227}{\ln[(1-0.0227)/(1-0.06)]} = 0.958$$

$$(y^*_{BM})_2 = \frac{(1-y_2^*)-(1-y_2)}{\ln[(1-y_2^*)/(1-y_2)]} = \frac{0.002-0.00065}{\ln[(1-0.00065)/(1-0.002)]} = 0.998$$

$y_{BM}^* = (0.958 + 0.998)/2 = 0.978$

$G/A = 97.1/(\pi\ 2.0^2/4) = 30.92$ kmol/m^2 h

$$H_{tOG} = \frac{(G/A)}{K_y a\, y^*_{BM}} = \frac{30.92}{(68)(0.978)} = 0.465\,\text{m}$$

$$(y-y^*)_M = \frac{(y_1-y_1^*)-(y_2-y_2^*)}{\ln[(y_1-y_1^*)/(y_2-y_2^*)]} = \frac{(0.06-0.0227)-(0.002-0.00065)}{\ln[(0.06-0.0227)/(0.002-0.00065)]} = 0.01$$

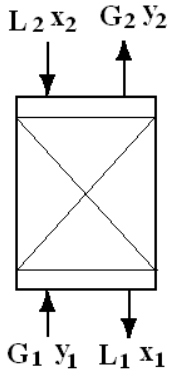
$$N_{tOG} = \frac{y_1-y_2}{(y-y^*)_M} = \frac{0.06-0.002}{0.01} = 5.8$$

Depth of the packing, Z = $H_{tOG} \times N_{tOG} = 0.465 \times 5.8 =$ **2.7 m**

3. Acetone is being absorbed by water in a packed tower having a cross-sectional area of 0.186 m^2 at 20^oC and 1 atm pressure. The inlet air contains 2.6 mol% acetone and the outlet air contains 0.5 mol% acetone. The gas flow rate is 14.0 kmol/h. The pure water flow rate is 820 kg/h. Film coefficients for the given flows in the tower are $k_y a$ = 0.0378 kmol/m^3 s Δy and $k_x a$ = 0.0616 kmol/ m^3 s Δx. The equilibrium relation may be expressed as $y = 1.186\ x$. Determine the height of the tower.

Solution:

For dilute systems as in the present case, the height of the packed tower can be expressed as:



$$Z = H_{tOG}\ X\ N_{tOG} = \frac{G^{/}}{K_y a}\ln\left[\frac{y_1 - m x_2}{y_2 - m x_2}(1-\frac{1}{A}) + \frac{1}{A}\right]/(1-\frac{1}{A})$$

For lean gas, $G' = G_1' =$ 14.0/0.186 = 75.268 kmol/m^2 h

L' = 820/(18 x 0.186) = 244.92 kmol/m^2 h

Given, $y_1 = 0.026$, $y_2 = 0.005$, $x_2 = 0.0$, $x_1 = ?$

By material balance: 75.268 x (0.026 – 0.005) = 244.92 x_1

$\Rightarrow x_1 = 0.00645$

Therefore, $y_1^* = m\ x_1$ = 1.186 x 0.00645 = 0.00765 and $y_2^* = 0.0$

Again,

$$\frac{1}{K_y a} = \frac{1}{k_y a} + \frac{m}{k_x a} = \frac{1}{0.0378} + \frac{1.186}{0.0616}$$

$$\Rightarrow K_y a = 0.02187\ \text{kmol/m}^3\ \text{s}\ (\Delta y^*)$$

Now, $H_{tOG} = \dfrac{G'}{K_y a} = \dfrac{75.268}{(0.02187)(3600)} = 0.956\ \text{m}$

$$N_{tOG} = \ln\left[\frac{y_1 - m x_2}{y_2 - m x_2}(1-\frac{1}{A}) + \frac{1}{A}\right]/(1-\frac{1}{A})$$

$A = L/m\ G = L'/m\ G'$ = 244.92/(1.186 x 76.268) = 2.7

$$N_{tOG} = \ln\left[\frac{0.026}{0.005}(1-\frac{1}{2.7}) + \frac{1}{2.7}\right]/(1-\frac{1}{2.7}) = 2.054$$

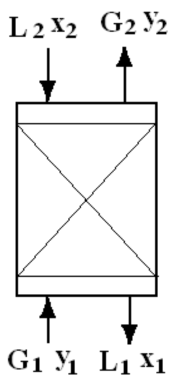
Depth of the packing, Z = H_{tOG} x N_{tOG} = 0.956 x 2.054 = **1.96 m**

4. A relatively nonvolatile hydrocarbon oil contains 2.5 mol% propane and is being stripped by direct superheated steam in a packed tower having a cross-sectional area of 0.86 m^2 to reduce the propane content to 0.2%. 25 kmol/h of direct steam is used for 250 kmol/h of entering liquid. The vapour-liquid equilibrium may be represented by $y = 25\,x$, where y is the mole fraction of propane in the steam and x is the mole fraction of propane in the oil. Steam can be considered as inert gas and will not condense. Film coefficients for the given flows in the tower are $k_y a$ = 0.04 kmol/m^3 s Δy and $k_x a$ = 0.06 kmol/ m^3 s Δx. Determine the height of the tower for the stripping operation.

[2+1+7]

Solution:

For dilute systems as in the present case, the height of the packed tower can be expressed as:



$$Z = \frac{L'}{K_x a}\int_{x_1}^{x_2}\frac{dx}{x-x^*} = \frac{L'}{K_x a}\frac{x_2-x_1}{(x-x^*)_M}$$

For dilute system, L' = L_2' = 250.0/0.86 = 290.7 kmol/m^2 h

G' = 25/0.86 = 29.07 kmol/m^2 h

Given, x_2 = 0.025, x_1 = 0.002, y_1 = 0.0, y_2 = ?

By material balance: 290.7 x (0.025 – 0.002) = 29.07 y_2

$\Rightarrow y_2 = 0.23$

Again, $$\frac{1}{K_x a} = \frac{1}{k_x a} + \frac{1}{m\,k_y a} = \frac{1}{0.06} + \frac{1}{25X\,0.04}$$

$\Rightarrow K_x a = 0.057$ kmol/m^3 s (Δx^*)

Now, $H_{toL} = L'/K_x a$ =290.7/(0.057x3600) = 1.416 m

For dilute systems, the number of transfer units may be expressed as

$$N_{tOL} = \frac{x_2 - x_1}{(x-x^*)_M}$$

In the present case, x_1^* = 0.0, $x_2^* = y_2$/m = 0.23/25 = 0.0092

$$\therefore (x-x^*)_M = \frac{(0.025-0.0092)-(0.002-0.0)}{\ln[(0.025-0.0092)/(0.002-0.0)]} = 6.67 \text{ x } 10^{-3}$$

$$N_{tOL} = \frac{(0.025-0.002)}{0.00667} = 3.45$$

Height of the tower = H_{toL} x N_{toL} = 1.416 x 3.45 = **4.88 m**

A = L/m G = L′/m G′ = 290.7/(25 x 29.07) = 0.4

$$N_{tOL} = \ln\left[\frac{x_2 - y_1/m}{x_1 - y_1/m}(1-A) + A\right]/(1-A)$$

$$N_{tOL} = \ln\left[\frac{0.025}{0.002}(1-0.4) + 0.4\right]/(1-0.4) = 3.44$$

5. Ammonia is to be removed from an ammonia-air mixture by water scrubbing in a 0.30 m diameter tower packed with 25 mm Berl saddles. The gas mixture is available at the rate of 6.0 kmol/h with 3% ammonia by volume. Calculate the depth of the packing required to reduce the ammonia content to 0.1% by volume. Laboratory data show that the Henry's law expression for solubility may be expressed as $y^* = 1.5\,x$ where y^* is the equilibrium mole fraction of ammonia over water at composition x mole fraction ammonia in the liquid. The water rate is 14 kmol/h and K_ya is given as 265 kmol/m^3 h (Δy^*).

Solution:

For dilute system, we can assume that the gas and liquid rates are remaining substantially constant. Therefore,

$A = L/m\,G = 14/(1.5 \text{ x } 6) = 1.5$

$$N_{tOG} = \ln\left[\frac{y_1 - m\,x_2}{y_2 - m\,x_2}(1-\frac{1}{A}) + \frac{1}{A}\right]/(1-\frac{1}{A})$$

$$N_{tOG} = \ln\left[\frac{0.03-0}{0.001-0}(1-\frac{1}{1.5}) + \frac{1}{1.5}\right]/(1-\frac{1}{1.5}) = 7.10$$

$$H_{tOG} = \frac{G'}{K_y a} = \frac{6/(3.14\,X\,0.3^2/4)}{265} = 0.32\,\text{m}$$

Depth of the packing = 0.32 x 7.10 = **2.27 m**