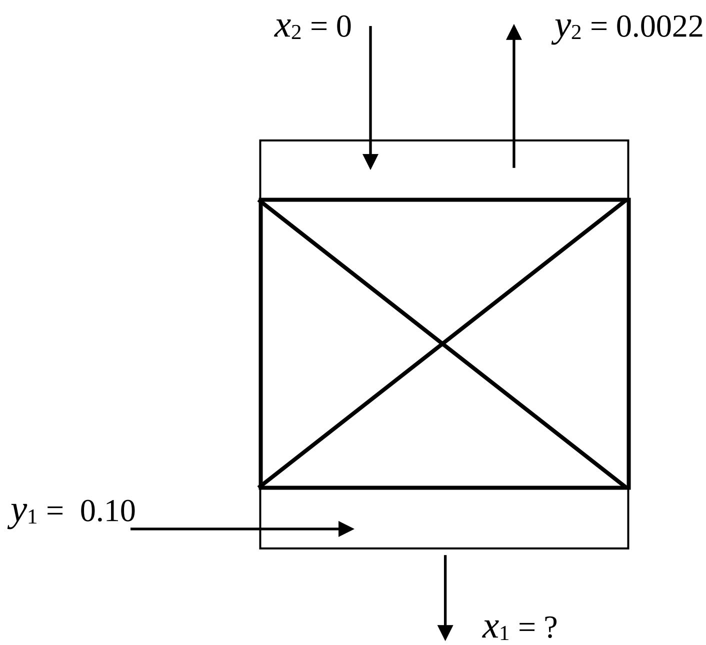
Solutions of 1st Problem of Tutorial Sheet #2 (2023)

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 25ºC 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_ya = 150 kmol/m^3 h Δy and k_xa = 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 solute-free stream 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,

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

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

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,

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

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

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

- $k_x a/k_y a$, 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,

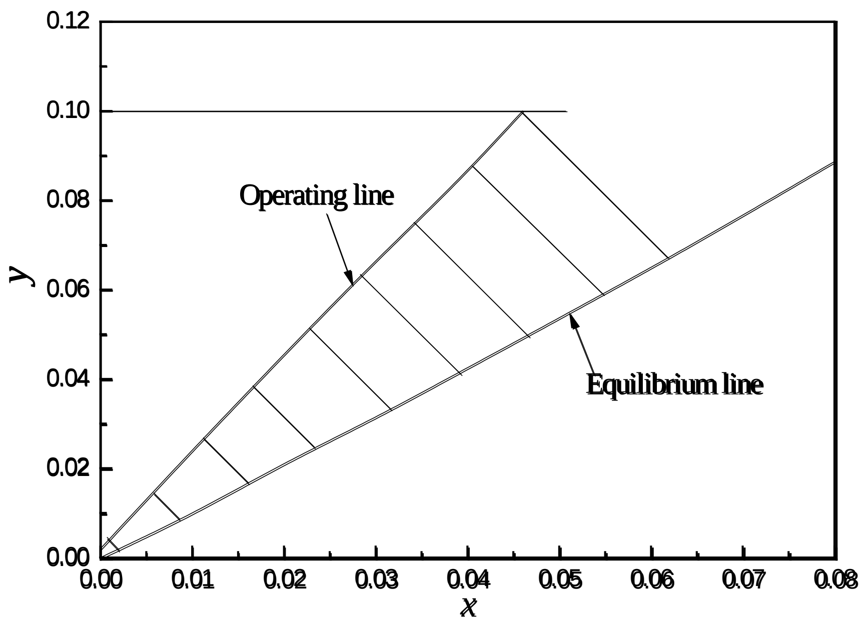
$$22.07\left(\frac{y}{1-y}-\frac{0.0022}{1-0.0022}\right)=49.20\left(\frac{x}{1-x}\right)$$

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

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
$\boldsymbol{y_i}$	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 is determined as

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

$$= \quad 9.517$$

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

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

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

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

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

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

$$H_{tG} = \frac{G'}{k_y.a.(1-y)_{iM}} = \frac{23.32/0.485}{150\times 0.9577} = \frac{48.08}{143.655} = 0.335\,\text{m}$$

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