SECTION 10

Mass Transfer

PROBLEM 10.1

Ammonia gas is diffusing at a constant rate through a layer of stagnant air 1 mm thick. Conditions are fixed so that the gas contains 50% by volume of ammonia at one boundary of the stagnant layer. The ammonia diffusing to the other boundary is quickly absorbed and the concentration is negligible at that plane. The temperature is 295 K and the pressure atmospheric, and under these conditions the diffusivity of ammonia in air is 0.18 cm^2/s. Calculate the rate of diffusion of ammonia through the layer.

Solution

See Volume 1, Example 10.1.

PROBLEM 10.2

A simple rectifying column consists of a tube arranged vertically and supplied at the bottom with a mixture of benzene and toluene as vapour. At the top, a condenser returns some of the product as a reflux which flows in a thin film down the inner wall of the tube. The tube is insulated and heat losses can be neglected. At one point in the column, the vapour contains 70 mol% benzene and the adjacent liquid reflux contains 59 mol% benzene. The temperature at this point is 365 K. Assuming the diffusional resistance to vapour transfer to be equivalent to the diffusional resistance of a stagnant vapour layer 0.2 mm thick, calculate the rate of interchange of benzene and toluene between vapour and liquid. The molar latent heats of the two materials can be taken as equal. The vapour pressure of toluene at 365 K is 54.0 kN/m^2 and the diffusivity of the vapours is 0.051 cm^2/s.

Solution

In this solution, subscripts 1 and 2 refer to the liquid surface and vapour side of the stagnant layer respectively and subscripts B and T refer to benzene and toluene.

If the latent heats are equal and there are no heat losses, there is no net change of phase across the stagnant layer.

This is an example of equimolecular counter diffusion and:

$$N_A = -D(P_{A2} - P_{A1})/\mathbf{R}TL \qquad \text{(equation 10.23)}$$

where L = thickness of the stagnant layer = 0.2 mm = 0.0002 m.

As the vapour pressure of toluene = 54 kN/m^2, the partial pressure of toluene from Raoult's law = $(1 - 0.59) \times 54 = 22.14$ kN/m^2 = P_{T1} and:

$$P_{T2} = (1 - 0.70) \times 101.3 = 30.39 \text{ kN/m}^2$$

For toluene: $N_T = -(0.051 \times 10^{-4})(30.39 - 22.14)/(8.314 \times 365 \times 0.0002)$

$$= \underline{\underline{-6.93 \times 10^{-5} \text{ kmol/m}^2\text{s}}}$$

For benzene: $P_{B1} = 101.3 - 22.14 = 79.16$ kN/m^2

$$P_{B2} = 101.3 - 30.39 = 70.91 \text{ kN/m}^2$$

Hence, for benzene: $N_B = -(0.051 \times 10^{-4})(70.91 - 79.16)/(8.314 \times 365 \times 0.0002)$

$$= \underline{\underline{6.93 \times 10^{-5} \text{ kmol/m}^2\text{s}}}$$

Thus the rate of interchange of benzene and toluene is equal but opposite in direction.

PROBLEM 10.3

By what percentage would the rate of absorption be increased or decreased by increasing the total pressure from 100 to 200 kN/m^2 in the following cases?

(a) The absorption of ammonia from a mixture of ammonia and air containing 10% of ammonia by volume, using pure water as solvent. Assume that all the resistance to mass transfer lies within the gas phase.
(b) The same conditions as (a) but the absorbing solution exerts a partial vapour pressure of ammonia of 5 kN/m^2.

The diffusivity can be assumed to be inversely proportional to the absolute pressure.

Solution

(a) The rates of diffusion for the two pressures are given by:

$$N_A = -(D/\mathbf{R}TL)(P/P_{BM})(P_{A2} - P_{A1}) \qquad \text{(equation 10.34)}$$

where subscripts 1 and 2 refer to water and air side of the layer respectively and subscripts A and B refer to ammonia and air.

Thus: $P_{A2} = (0.10 \times 100) = 10$ kN/m^2 and $P_{A1} = 0$ kN/m^2

$$P_{B2} = (100 - 10) = 90 \text{ kN/m}^2 \text{ and } P_{B1} = 100 \text{ kN/m}^2$$

$$P_{BM} = (100 - 90)/\ln(100/90) = 94.91 \text{ kN/m}^2$$

$\therefore$ $P/P_{BM} = (100/94.91) = 1.054$

Hence: $N_A = -(D/\mathbf{R}TL)1.054(10 - 0) = -10.54D/\mathbf{R}TL$

If the pressure is doubled to 200 kN/m^2, the diffusivity is halved to $0.5D$ (from equation 10.18) and:

$$P_{A2} = (0.1 \times 200) = 20 \text{ kN/m}^2 \text{ and } P_{A1} = 0 \text{ kN/m}^2$$

$$P_{B2} = (200 - 20) = 180 \text{ kN/m}^2 \text{ and } P_{B1} = 200 \text{ kN/m}^2$$

$$\therefore \quad P_{BM} = (200 - 180)/\ln(200/180) = 189.82 \text{ kN/m}^2$$

$$P/P_{BM} = (200/189.82) = 1.054 \text{ i.e. unchanged}$$

Hence: $N_A = -(0.5D/\mathbf{R}TL)1.054(20 - 0) = -10.54D/\mathbf{R}TL$, that is the rate is unchanged

(b) If the absorbing solution now exerts a partial vapour pressure of ammonia of 5 kN/m^2, then at a total pressure of 100 kN/m^2:

$$P_{A2} = 10 \text{ kN/m}^2 \text{ and } P_{A1} = 5 \text{ kN/m}^2$$

$$P_{B2} = 90 \text{ kN/m}^2 \text{ and } P_{B1} = 95 \text{ kN/m}^2$$

$$P_{BM} = (95 - 90)/\ln(95/90) = 92.48 \text{ kN/m}^2$$

$$\therefore \quad P/P_{BM} = (100/92.48) = 1.081$$

$$N_A = -(D/\mathbf{R}TL) \times 1.081(10 - 5) = -5.406D/\mathbf{R}TL$$

At 200 kN/m^2, the diffusivity $= 0.5D$ and:

$$P_{A2} = 20 \text{ kN/m}^2 \text{ and } P_{A1} = 5 \text{ kN/m}^2$$

$$P_{B2} = 180 \text{ kN/m}^2 \text{ and } P_{B1} = 195 \text{ kN/m}^2$$

$$\therefore \quad P_{BM} = (195 - 180)/\ln(195/180) = 187.4 \text{ kN/m}^2$$

$$P/P_{BM} = 1.067$$

$$N_A = -(0.5D/\mathbf{R}TL)1.067(20 - 5) = -8.0D/\mathbf{R}TL$$

Thus the rate of diffusion has been increased by $100(8 - 5.406)/5.406 = \underline{\underline{48\%}}$.

PROBLEM 10.4

In the Danckwerts' model of mass transfer it is assumed that the fractional rate of surface renewal s is constant and independent of surface age. Under such conditions the expression for the surface age distribution function is se^{-st}.

If the fractional rate of surface renewal were proportional to surface age (say $s = bt$, where b is a constant), show that the surface age distribution function would then assume the form:

$$(2b/\pi)^{1/2}e^{-bt^2/2}$$

Solution

From equation 10.117: $\quad f'(t) = sf(t) = 0$