MODULE 3: MASS TRANSFER COEFFICIENTS

LECTURE NO. 8

3.6.2 Overall mass transfer coefficients

Experimentally the mass transfer film coefficients k_y and k_x are difficult to measure except for cases where the concentration difference across one phase is small and can be neglected. Under these circumstances, the overall mass transfer coefficients K_y and K_x are measured on the basis of the gas phase or the liquid phase. The entire two-phase mass transfer effect can then be measured in terms of gas phase molar fraction driving force as:

$$N_A = K_y(y_{AG} - y_A^*) \qquad (3.76)$$

where, K_y is based on the overall driving force for the gas phase, in mole/m^2.s and y_A^* is the value of concentration in the gas phase that would be in the equilibrium with x_{AL}. Similarly, the entire two-phase mass transfer effect can then be measured in terms of liquid phase molar fraction driving force as:

$$N_A = K_x(x_A^* - x_{AL}) \qquad (3.77)$$

where K_x is based on the overall driving force for the liquid phase, in mole/m^2.s and x_A^* is the value of concentration in the liquid phase that would be in the equilibrium with y_{AG}. A relation between the overall coefficients and the individual mass transfer film coefficients can be obtained when the equilibrium relation is linear as $y_{Ai} = mx_{Ai}$. The linear equilibrium condition can be obtained at the low concentrations, where Henry's law is applicable. Here the proportionality constant m is defined as m= H/P. Utilizing the relationship, $y_{Ai} = mx_{Ai}$, gas and liquid phase concentrations can be related by

$$y_A^* = mx_{AL} \tag{3.78}$$

and

$$y_{AG} = mx_A^* \tag{3.79}$$

Rearranging Equation (3.76), one can get

$$\frac{1}{K_y} = \frac{y_{AG} - y_A^*}{N_A} \tag{3.80}$$

From geometry, $y_{AG} - y_A^*$ can be written as

$$y_{AG} - y_A^* = (y_{AG} - y_{Ai}) + (y_{Ai} - y_A^*) \tag{3.81}$$

Substituting Equation (3.81) in Equation (3.80)

$$\frac{1}{K_y} = \frac{y_{AG} - y_A^*}{N_A} = \frac{(y_{AG} - y_{Ai})}{N_A} + \frac{(y_{Ai} - y_A^*)}{N_A} = \frac{(y_{AG} - y_{Ai})}{N_A} + \frac{m(x_{Ai} - x_{AL})}{N_A} \tag{3.82}$$

The substitution of Equation (3.76) into the Equation (3.82) relates overall gas phase mass transfer coefficient (K_y) to the individual film coefficients by

$$\frac{1}{K_y} = \frac{1}{k_y} + \frac{m}{k_x} \tag{3.83}$$

Similarly the relation of overall liquid phase mass transfer coefficient (K_x) to the individual film coefficients can be derived as follows:

$$\frac{1}{K_x} = \frac{x_A^* - x_{AL}}{N_A} = \frac{y_{AG} - y_{Ai}}{mN_A} + \frac{x_{Ai} - x_{AL}}{N_A} \tag{3.84}$$

Or

$$\frac{1}{K_x} = \frac{1}{mk_y} + \frac{1}{k_x} \tag{3.85}$$

The following relationships between the mass transfer resistances can be made from the Equations (3.83) and (3.85):

$$\frac{\text{Resistance in gas phase}}{\text{Total resistance in both phases}} = \frac{1/k_y}{1/K_y} \tag{3.86}$$

$$\frac{\text{Resistance in liquid phase}}{\text{Total resistance in both phases}} = \frac{1/k_x}{1/K_x} \tag{3.87}$$

If solute A is very soluble in the liquid, m is very small. Then the term m/k_x in Equation (3.83) becomes minor and consequently the major resistance is represented by $1/k_y$. In this case, it is said that the rate of mass transfer is gas phase controlled. In the extreme it becomes:

$$\frac{1}{K_y} \approx \frac{1}{k_y} \qquad (3.88)$$

The total resistance equals the gas film resistance. The absorption of a very soluble gas, such as ammonia in water is an example of this kind. Conversely when solute A is relatively insoluble in the liquid, m is very large. Consequently the first term of Equation (3.85) becomes minor and the major resistance to the mass transfer resides within the liquid. The system becomes liquid film controlling. Finally this becomes:

$$\frac{1}{K_x} \approx \frac{1}{k_x} \qquad (3.89)$$

The total resistance equals the liquid film resistance. The absorption of a gas of low solubility, such as carbon dioxide or oxygen in water is of this type of system.

Example problem 3.3: In an experimental study of the absorption of ammonia by water in a wetted-wall column, the value of overall mass transfer coefficient, K_G was found to be 2.75×10^{-6} kmol/m^2-s-kPa. At one point in the column, the composition of the gas and liquid phases were 8.0 and 0.115 mole% NH_3, respectively. The temperature was 300K and the total pressure was 1 atm. Eighty five % of the total resistance to mass transfer was found to be in the gas phase. At 300 K, Ammonia –water solutions follows Henry's law upto 5 mole% ammonia in the liquid, with m = 1.64 when the total pressure is 1 atm. Calculate the individual film coefficients and the interfacial concentrations. Interfacial concentrations lie on the equilibrium line.

Solution 3.3:

The first step in the solution is to convert the given overall coefficient from K_G to K_y.

$K_y = K_G P$ = 2.75 × 10^{-6} × 101.3 = 2.786 × 10^{-4} kmol/m^2-s

For a gas-phase resistance that accounts for 85% of the total resistance,

$$k_y = \frac{K_y}{0.85} = 3.28 \times 10^{-4} \quad \text{kmol/m}^2\text{ - s}$$

From Equation, $\frac{1}{K_y} = \frac{1}{k_y} + \frac{m}{k_x}$, by substituting the values of K_y , k_y and m

k_x = 3.05 × 10^{-3} kmol/m^2-s

To estimate the ammonia flux and the interfacial concentrations at this particular point in the column use the equation, $y_A^* = mx_{A,L}$ to calculate

$$y_A^* = mx_{A,L} = 1.64 \times 1.15 \times 10^{-3} = 1.886 \times 10^{-3}$$

The flux is from equation

$$N_A = K_y (y_{AG} - y_A^*) = 2.768 \times 10^{-4} (0.080 - 1.866 \times 10^{-3}) = 2.18 \times 10^{-5} \quad kmol/m^2 - s$$

Calculate the gas-phase interfacial concentration from equation, $N_A = k_y (y_{AG} - y_{A,i})$ as

$$y_{A,i} = y_{AG} - \frac{N_A}{k_y} = 0.080 - \frac{2.18 \times 10^{-5}}{3.28 \times 10^{-4}} = 0.01362$$

Since the interfacial concentrations lie on the equilibrium line,

$$x_{A,i} = \frac{y_{A,i}}{m} = \frac{0.01362}{1.64} = 8.305 \times 10^{-3}$$

Nomenclature

a	Cross-sectional area [m^2]	s	Fraction of surface renewed/unit time [-]
C	Molar concentration [mol/m^3]	S_{av}	Average cross-sectional area for diffusion [m^2]
d	Diameter [m]	T	Temperature [K]
d_p	Diameter of a particle [m]	t	Time [s]
D_{AB}	Diffusivity of A in B [m^2/s]	u	Velocity [m/s]
D_E	Eddy diffusivity [m^2/s]	U	average velocity [m/s]
D_K	Knudsen diffusion coefficient [m^2/s]	U_α	Free stream velocity [m/s]
D_S	Surface diffusion coefficient [m^2/s]	V	Volume [m^3]
E_D	Activation energy [J/mol]	w	Mass fraction [-]
G_m	Molar mass velocity [$mol/m^2.s$]	W	Mass transfer rate [mol/s]
G_y	Mass velocity of gas [$kg/m^2.s$]	x	Mole fraction for liquid [-]
ΔH_A^V	Latent heat of vaporization of component A [J/mol]	y	Mole fraction for gas [-]
J	Flux based on arbitrary reference [$mol/m^2.s$]	X, Y, Z	Coordinates
K	Proportionality constant defined in Equation (1.79) [-]	x*,y*	Equilibrium mole fraction of solute in liquid and gas phase, respectively [-]
K	Overall mass transfer coefficient [m/s]	φ	Association factor [-]
$k^/$, k	Individual mass transfer coefficient [m/s]	ε	Porosity [-]

l	Length [m]	ν	Molar volume [mol/m^3]
m	Mass [kg]	ϕ	Packing fraction [-]
M	Molecular weight	σ_{AB}	Characteristic length parameter of binary mixture of A and B [m]
N	Flux [mol/m^2.s]	τ	Tortuosity [-]
p	Partial pressure [N/m^2]	Ω	collision integral [-]
P	Total pressure [N/m^2]	ρ	Density [kg/m^3]
P_A^V	Vapor pressure of A [N/m^2]	δ	Film thickness [m]
r	Radius [m]	μ	Viscosity [kg/m.s]
R	Universal gas constant [J/mol.K]		

References

1. Treybal, R. E., " Mass-Transfer Operations", 3rd Eddition, McGraw-Hill, 1981
2. Geankoplis, C.J., "Transport Processes and Separation Process Principles". 4th Edition, Prentice-Hall of India, New Delhi, 2005.
3. Dutta, B.K., "Principles of Mass transfer and Separation Processes". Prentice-Hall of India, New Delhi, 2007.