FDE 307
Mass Transfer and Unit Operations

- What is mass transfer????

- Many of daily experiences involve mass transfer.
- A lump of sugar added to a cup of tea eventually dissolves and then diffuses uniformly throughout the tea.
- You can smell the perfume, sprayed by a friend who is far away, due to diffusion of perfume molecules in air.

- Mass transfer has an important role in many areas of science and engineering.
- leaching of sugar from sugar cane,
- distillation of alcoholic beverages,
- drying of apricots
- absorption and desorption,
- solvent extraction,
- humidification,
- oxygenation of foods,
- distillation columns to separate components in a mixture.

PRINCIPLES OF DIFFUSION AND MASS TRANSFER

- Diffusion describes the spread of particles through random motion from regions of higher concentration to regions of lower concentration.

- The concentration gradient tends to move the component in such a direction to equalize the concentrations.
- The concentration gradient is considered as the driving force for movement of a component.

- INTRODUCTION TO MASS TRANSFER

- There are three modes of mass transfer; such as
  - molecular mass diffusion,
  - convective mass transfer and
  - mass transfer by change of phase.

- *Molecular mass diffusion* occurs as a result of concentration gradient in a fluid at rest.

It is similar to heat transfer by conduction due to temperature gradient.

- *Convective mass transfer* occurs when the fluid is in motion. Mass transfer may be between a fluid in motion and a surface or between two immiscible moving fluids. In this case the mass transfer by molecular mass diffusion is enhanced by motion of the fluid.

- It is analogous to convective heat transfer.

- Some common examples to *mass transfer by change of phase* can be given as;

- boiling of water in an open pan,
- evaporation of a cryogenic liquid from its container,
- diffusion of smoke from its chimney, etc.

The analogy of mass, heat and momentum transfer for molecular diffusion

$$Rateoftransfer = (\frac{Drivingforce}{resista\eta ce})$$

In general, molecular flux is defined as;

$$Molecular\ \ flux = (Diffusivity)(\frac{Quantity/Volume}{Length})$$

$$Molecular\ \ flux = (Transport\ \ property)(Potential\ \ gradient)$$

For mass $$J_B = -D_{BC}\frac{dC_B}{dx}$$

For heat energy $$\frac{\dot{Q}_x}{A} = -\alpha\frac{d(\rho c_p T)}{dx}$$

For momentum $$\tau_{xz} = -\upsilon\frac{d(\upsilon_z \rho)}{dx}$$

- where *x* is the measure of distance in the direction of flow. These equations state that mass transport occurs because of a gradient in mass concentration, energy transport because of a gradient in energy and momentum transport because of a gradient in momentum.

The analogy of mass and heat transfer for convective transfer

For heat; $$q = h(\Delta T)$$

For mass; $$N_A = k_c(\Delta C_A)$$

DEFINITION OF CONCENTRATION, VELOCITY AND FLUX

- In order to understand diffusion theory, three interrelated quantity should be defined. These concepts can be listed as
  - concentration,
  - velocity and
  - flux.

Concentrations

- Concentration can be expressed in different forms such as mass concentration, molar concentration, mass fraction and mole fraction.
- *Mass concentration* (*Mass density*) (ρ_A) (kg/m^3) of a species A in a mixture is defined as mass of component A per unit volume of the mixture.

- *Molar concentration* (*Molar density*) (c_A) (*kg moles/m³*) of a species A in a mixture is defined as the number of moles of component A per unit volume of the mixture.

- The relation between these concentrations can be given as;

$$C_A = \frac{\rho_A}{M_A}$$

- where M_A is the molecular weight of species A.

- *Mass fraction* (w_A) is the ratio of mass concentration of species A to the total mass density of the mixture.

$$w_A = \frac{\rho_A}{\rho}$$

- *Mole fraction* (X_A) is the ratio of molar density of species A to the total molar density of the mixture.

$$X_A = \frac{C_A}{C}$$

- For a binary mixture which is composed of species A and B, the following equations can be derived by definition of the terms.

$$\rho_A + \rho_B = \rho$$

$$C_A + C_B = C$$

$$w_A + w_B = 1$$

$$X_A + X_B = 1$$

Velocities

- Mass diffusion may occur in a stationary medium or moving medium. In a stationary medium, the components in a mixture move just because of the concentration gradients and the velocity of each species is equal to the *diffusion velocity* (υ_{diff}) only. On the other hand, if the medium is also in motion, the absolute velocity of a species can be calculated by the addition of the bulk flow velocity and the diffusion velocity.

- For a binary mixture of two components A and B the following relations can be derived for *mass average velocity of flow* (υ_{mass}).

$$\dot{m} = \dot{m}_A + \dot{m}_B$$

$$\rho \upsilon_{mass} A = \rho_A \upsilon_A A + \rho_B \upsilon_B A$$

$$\upsilon_{mass} = \frac{\rho_A \upsilon_A + \rho_B \upsilon_B}{\rho} = w_A \upsilon_A + w_B \upsilon_B$$

- It should be mentioned that for a stationary medium the mass average velocity (υ_{mass}) is equal to zero.
- If there is no concentration gradient, velocity of all species is equal to the mass average velocity of flow.
- Additionally, in the presence of concentration gradient, *average velocity* (υ_i) of each component can be calculated by the following equation.
- For A;

$$\upsilon_A = \upsilon_{mass} + \upsilon_{diff\_A}$$

- For B;

$$\upsilon_B = \upsilon_{mass} + \upsilon_{diff\_B}$$

- Similarly, *molar average velocity* (υ_{molar}) is defined by:

$$\upsilon_{molar} = \frac{n_A \upsilon_A + n_B \upsilon_B}{n} = X_A \upsilon_A + X_B \upsilon_B$$

- Molar average velocity of each component can be calculated by:

$$\upsilon_A = \upsilon_{molar} + \upsilon_{diff\_A}$$

$$\upsilon_B = \upsilon_{molar} + \upsilon_{diff\_B}$$

Flux

For species A, the absolute flux can be calculated by the addition of diffusion flux and convective flux that is flux due to bulk motion.

$$Absolute\ \ flux = Molecular\ \ flux + Convective\ \ flux$$

$$N_A = J_A + \rho_A \upsilon_{mass}$$

Diffusion flux (molecular flux) can be defined as mass flow per unit time per unit area.

Bulk motion flux (convective flux) is calculated by the multiplication of density and mass average velocity of the component.

- Example A cubic volume which is 1 cm on each side is moving to the right in the +z direction with a bulk velocity of 1 cm/s. In the volume at steady state there are 2 moles of A (M=2 g/mol), 3 moles of B (M=3 g/mol) and 4 moles of C (M=4 g/mol). Molecule A diffuses in +z direction with a diffusion rate of 2 mol/s and molecule B diffuses in the opposite direction with a diffusion rate of 1 mol/s. Molecule C is under the effect of convective flow only. Calculate:
- a) Molar average velocity
- b) Mass average velocity