Heat and Mass Transfer (DI05019071)

Complete Lecture Deck

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Fick's Law of Diffusion

- Course: Heat and Mass Transfer (DI05019071)
- Unit 5: Mass Transfer
- Lecture 43: Fick's Law

Lecture Agenda

- 1. Introduction to Fick's First Law
- 2. The Mathematical Equation
- 3. Diffusion Coefficient (Diffusivity)
- 4. Characteristics of Diffusivity in different phases
- 5. Fick's Law: Mass vs. Molar Basis
- 6. General Mass Diffusion Equation

Introduction to Fick's First Law

- Proposed by Adolf Fick in 1855.
- It states that the mass diffusion flux of a constituent in a mixture is proportional to the concentration gradient.
- Diffusion always occurs in the direction of decreasing concentration.
- It perfectly mirrors Fourier's Law of heat conduction.

Fick's First Law (Mass Basis)

- The equation for mass diffusion flux (j_A) in the x-direction:
- j_A = - D_AB * (d(ρ_A) / dx)
- Where:
- - j_A = Mass diffusion flux of species A (kg/m^2·s)
- - D_AB = Diffusion coefficient (or mass diffusivity) of species A in species B (m^2/s)
- - d(ρ_A) / dx = Concentration gradient of species A (kg/m^4)

Diffusion Coefficient (Diffusivity)

- Denoted as D_AB (diffusion of A into B).
- Unit: m^2/s (Same unit as thermal diffusivity, α, and kinematic viscosity, ν).
- It is a property of the specific binary mixture (A and B), the temperature, and the pressure.
- A higher D_AB means mass diffuses more rapidly.

Characteristics of Diffusivity

- **In Gases**: Diffusion is rapid. D_AB is relatively high (approx. 10^-5 m^2/s). D_AB increases with temperature and decreases with pressure.
- **In Liquids**: Diffusion is much slower due to close molecular packing (approx. 10^-9 m^2/s).
- **In Solids**: Diffusion is extremely slow (approx. 10^-14 m^2/s). Depends heavily on the solid structure (crystalline, amorphous).

Fick's Law (Molar Basis)

- Chemical engineers often prefer the molar basis.
- Molar diffusion flux (J_A):
- J_A = - D_AB * (dC_A / dx)
- Where:
- - J_A = Molar diffusion flux (kmol/m^2·s)
- - C_A = Molar concentration (kmol/m^3)
- - dC_A / dx = Molar concentration gradient (kmol/m^4)

Fick's Law using Mass/Mole Fractions

- If total mixture density (ρ) is constant:
- j_A = - ρ * D_AB * (dm_A / dx)
- If total molar concentration (C) is constant (typical for ideal gas mixtures at constant T and P):
- J_A = - C * D_AB * (dx_A / dx)
- This form is highly useful in derivation and problem solving.

Total Absolute Flux Equation

- Recall from last lecture: Total Absolute Flux = Diffusion Flux + Bulk Flux
- $n_A = j_A + \rho_A * v$
- Substituting Fick's Law for j_A:
- $n_A = - D_{AB} * (d\rho_A / dx) + \rho_A * v$
- Similarly for Molar Flux:
- $N_A = - D_{AB} * (dC_A / dx) + x_A * (N_A + N_B)$

General Mass Diffusion Equation

- Analogous to the general heat conduction equation (Heat Equation).
- Derived from species conservation over a control volume.
- Governing Equation (1D, stationary medium, no bulk flow):
- ∂C_A / ∂t = D_AB * (∂^2 C_A / ∂x^2) + R_A
- (Where R_A is the rate of generation of species A due to chemical reactions).

Summary

- Fick's First Law relates diffusion flux linearly to the concentration gradient.
- The negative sign indicates mass moves from high to low concentration.
- Diffusivity (D_AB) depends on the mixture, temperature, and pressure, and is highest in gases.
- The total absolute mass flux includes both Fickian diffusion and bulk fluid motion.

Next Lecture Preview

- Topic: Steady state diffusion through a plain membrane
- Key questions to ponder:
- - How do we apply Fick's law to a solid membrane?
- - What happens to the concentration profile across a membrane in steady state?
- - How can we use the concept of 'mass transfer resistance' to solve problems quickly?