MANICALAND STATE UNIVERSITY OF APPLIED SCIENCES

FACULTY OF ENGINEERING, SCIENCE AND TECHNOLOGY

DEPARTMENT: CHEMICAL AND PROCESSING ENGINEERING

MODULE: TRANSPORT PHENOMENA

CODE: CHEP 211

SESSIONAL EXAMINATIONS
APRIL 2023

DURATION: 3 HOURS

EXAMINER: MISS N. T. MADZIWA

INSTRUCTIONS

1. *Answer **all** questions.*
2. *Start a new question on a fresh page*
3. *Total marks 100*
4. *Formulae sheet is given at the end of the paper.*

Additional material(s): *Calculator and Lennard-Jones Constants Tables*

QUESTION 1

a) State Newton's law of viscosity. [2]

b) Show that for diffusion in gases, the diffusivities of species **A** and **B**, D_{AB} and D_{BA} are equal. [6]

c) Explain how heat transfer by natural convection occurs when the surface is hotter than the surrounding fluid. [4]

d) Give ***two*** differences between forced convection and free convection in heat transfer. [2]

e) How does the viscosity of low density gases depend on temperature and pressure? [2]

f) Calculate the diffusivity of CO_2 in air at 85°C and 2.1×10^5 Pa., using the Chapman-Enskog theory and Lennard-Jones constants, which result in the following equation:

$$D_{AB} = \frac{1.858 \times 10^{-3}\, T^{3/2} \left[\frac{1}{M_A} + \frac{1}{M_B}\right]^{1/2}}{P \Omega_D {\sigma_{AB}}^2}$$

where D_{AB} is diffusivity in cm^2/s; T is absolute temperature in K; M_A is the molecular weight of A; M_B is the molecular weight of B; P is total pressure in atm; Ω_D is a function of $\kappa T/\varepsilon_{AB}$; κ is the Boltzmann constant (1.38×10^{-16}) ergs/K; $\varepsilon_{AB} = \sqrt{\varepsilon_A \varepsilon_B}$ which is energy of molecular interaction in ergs; $\sigma_{AB} = \frac{\sigma_A + \sigma_B}{2}$ which is collision diameter in Å [9]

QUESTION 2

a. Determine the diffusivity of CO_2 in SO_2 at 57°C and 3.3 atm. [8]

b. Ethanol, C_2H_5OH, flows in a thin film down the outside surface of an inclined plane, 2 m wide and 4 m long. The liquid temperature is 289K. Ethanol-free air at 303K and 1 atm flows across the length of the plate parallel to the surface. At the average temperature of the gas film, the diffusivity of ethanol vapour in air is 1.32×10^{-5} m²/s. The vapour pressure of ethanol at 289K is 6.45×10^{-2} atm. If the air velocity is 2.5 m/s, determine the rate at which the ethanol should be supplied to the top of the plate to compensate for evaporation, which will otherwise prevent it from reaching the very bottom of the plate. The heat transfer coefficient is estimated using the following correlation:

$$Sh_L = 0.0365\, Re_L^{\frac{4}{5}}\, Sc^{\frac{1}{3}}$$

The properties of air, evaluated at film temperature of 296 K are:

$\rho = 1.194$ kg/m³; $\mu = 1.827 \times 10^{-5}$ Pa·s [13]

c. State Fick's law of molecular diffusion and define each term. [4]

QUESTION 3

a) Compute the thermal conductivity of argon (Ar) at 94℃ and atmospheric pressure, using the Chapman-Enskog theory and Lennard-Jones constants, which results in the following equation:

$$k = 0.0829 \frac{\sqrt{T/M}}{\sigma^2 \Omega_k}$$

where k is in W/m·K; σ is characteristic diameter in Å; T is in K; M is the molecular weight; Ω_k is the Lennard-Jones collision integral which is a function of $\kappa T/\varepsilon$. [8]

b) A furnace wall consists of 30 cm of fire brick (k = 1 W/m·K), 25 cm of insulating brick (k = 0.12 W/m·K) and a 35 cm of red brick (k = 0.75 W/m·K).

The inner wall of fire brick is exposed to furnace gas at 1200K whilst air at 310 K is adjacent to the outside wall of red brick. The inside and outside convective heat transfer coefficients are 95 and 20 $W/m^2 \cdot K$, respectively. Determine:

i. The heat loss per square metre of the composite wall. [9]

ii. The temperature of the innermost wall surface. [3]

a. Estimate the viscosity of NO at 450K using Lennard-Jones parameters. [5]

QUESTION 4

a) Gas A diffuses from point 1 at a partial pressure of 20.26 kPa to point 2, a distance 2.0 mm away. At point 2 it undergoes the following instantaneous chemical reaction at the catalyst surface: $A \longrightarrow 2B$. Component B diffuses in counter-flow at steady state. The total pressure is 101.32 kPa, temperature is 300 K and $D_{AB} = 0.15 \times 10^{-4}$ m^2/s. Determine the rate of diffusion of A per square meter. [11]

b) Spherical pellets of 1.0 cm diameter are spray painted with a very thin coat of paint. The paint contains a volatile solvent. The vapour pressure of the solvent at 298 K is 1.17×10^4 Pa. The amount of solvent in the wet paint on the pellet is 0.12 g solvent per cm^2 of pellet surface area. The molecular weight of the solvent is 78 kg/kg mol. Determine the minimum time to dry the painted pellet if air at 298 K and 1.0 atm pressure flows around the pellet at a bulk velocity of 1.0 m/s. The mass transfer coefficient is estimated using the following correlation:

$$Sh_D = 2 + 0.552\, Re_D^{\frac{1}{2}}\, Sc^{\frac{1}{3}}$$

The properties of air, evaluated at 298 K are:

$\rho = 1.18 \times 10^{-3}$ g/cm^3; $D_{AB} = 0.0962$ cm^2/s; $\mu = 1.85 \times 10^{-4}$ $g/cm \cdot s$ [14]

END OF EXAMINATION

FORMULAE SHEET

Diffusional molar flux in the z-direction: $N_{A_z} = -cD_{AB}\frac{\partial y_A}{\partial z} + y_A N_{total}$

Diffusional molar flux of A in the *z*-direction: $N_{A_z} = -CD_{AB}\frac{\partial y_A}{\partial z} + y_A\left(N_{A_z} + N_{B_z}\right)$

Navier-Stokes equation: $\rho\frac{Dv}{Dt} = -\nabla \boldsymbol{P} + \mu\nabla^2\boldsymbol{v} + \rho\boldsymbol{g}$

Navier-Stokes equation in the *x*-direction:

$$-\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 \mathrm{v}_x}{\partial x^2} + \frac{\partial^2 \mathrm{v}_x}{\partial y^2} + \frac{\partial^2 \mathrm{v}_x}{\partial z^2}\right) + \rho g_x = \rho\left[\frac{\partial \mathrm{v}_x}{\partial t} + \mathrm{v}_x\frac{\partial \mathrm{v}_x}{\partial x} + \mathrm{v}_y\frac{\partial \mathrm{v}_x}{\partial y} + \mathrm{v}_z\frac{\partial \mathrm{v}_x}{\partial z}\right]$$

Equation of Continuity: $\frac{\partial \mathrm{v}_x}{\partial x} + \frac{\partial \mathrm{v}_y}{\partial y} + \frac{\partial \mathrm{v}_z}{\partial z} = 0$

Stoke's flow or Creeping flow: $-\nabla \boldsymbol{P} + \mu\nabla^2\boldsymbol{v} + \rho\boldsymbol{g} = 0$

Euler equation: $\rho\frac{Dv}{Dt} = -\nabla \boldsymbol{P} + \rho\boldsymbol{g}$

Grad function: $\nabla = \frac{\partial}{\partial x}i + \frac{\partial}{\partial y}j + \frac{\partial}{\partial z}k$

Velocity in vector notation: $\boldsymbol{v} = v_x i + v_y j + v_z k$

Gravitational acceleration in vector notation: $\boldsymbol{g} = g_x i + g_y j + g_z k$

z-component of momentum flux in x-direction: $\phi_{xz} = \tau_{xz} + \rho v_x v_z$

z-component of momentum flux in y-direction: $\phi_{yz} = \tau_{yz} + \rho v_y v_z$

z-component of momentum flux in z-direction: $\phi_{zz} = P + \tau_{zz} + \rho v_z v_z$

General formula for viscous stress tensors: $\tau_{ij} = -\mu\left(\frac{\partial v_i}{\partial j} + \frac{\partial v_j}{\partial i}\right)$ where *i,j* = *x, y, z*