MASTERS IN BIOPROCESS ENGINEERING FIRST YEAR FIRST SEMESTER - 2024

1st Year, 1st Semester

TRANSPORT PHENOMENA IN BIOPROCESSES

Time: 3 Hours | Full Marks: 100

Answer Three (3) Questions taking at least One (1) from each Group

Group I

[Momentum Transport]

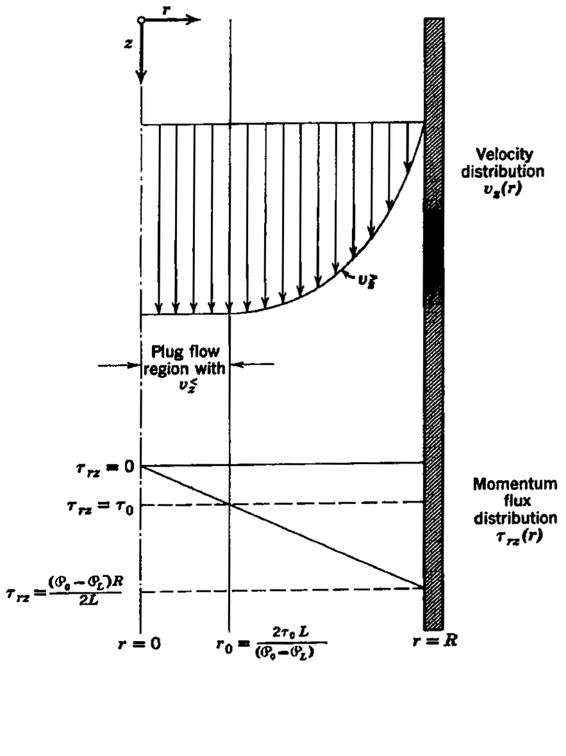
Q1. **[6+16+18=40]**

a) Explain 'velocity gradient for a flow of fluid past a solid surface' in the light of Newton's law of viscosity with the help of a diagram.

b) A sewage sludge, behaves like a *Bingham Plastic Fluid*. Model the flow velocity of a sewage sludge flowing through a circular conduit under laminar condition. Bingham plastic fluids exhibit Newtonian behaviour after the shear stress exceeds τ_o. Referring to the following diagram derive the following expressions of flow velocities at the

i) Unsheared Core: $r \le r_c$; $$u_z = u_c = \frac{\tau_0}{2\mu_\infty r_c}(R-r_c)^2$$

ii) Sheared Annular Region $r > r_c$; $$u_z = \frac{(R-r)}{\mu_\infty}\left[\frac{\tau_{rz}}{2}\left(1+\frac{r}{R}\right)-\tau_0\right]$$



[Turn over

c) A sewage sludge needs to be pumped down into a storage vessel that is 2440 m deep. The sludge is to be pumped at a rate of 0.15 m^3/min to the bottom of the storage vessel and back to the surface through a pipe having an effective diameter of 0.1 m. The pressure at the bottom of the well is 272 kg/cm^2. What pump head is required to pump the sludge to the bottom of the storage well? The sewage sludge has the properties of a Bingham plastic fluid with a yield stress of 100 dyne/cm^2, a limiting (plastic) viscosity of 35 cP, and a density of 1.2 g/cm^3. Atmospheric pressure is 1 kg/cm^2. Expressions for Friction Factors:

Laminar

$$f = \frac{16}{\mathrm{Re}_{BP}}\left[1 + \frac{He}{6\,\mathrm{Re}_{BP}} - \frac{He^4}{3f^3(\mathrm{Re}_{BP})^7}\right]$$ Non-Linear

$$He = \frac{D^2 \rho \tau_0}{\mu_\infty^2}$$ **Hedstrom Number**

$$\mathrm{Re}_{BP} = \frac{D\rho \overline{V}}{\mu_\infty}$$ Reynolds Number for Bingham Plastic Fluid

Turbulent

$$f = 10^a\,\mathrm{Re}_{BP}^{-0.193}$$
$$a = -1.378\left(1 + 0.146e^{-2.9x10^{-5}He}\right)$$

Q2. **[3+6+4+7+7+7+6=40]**

a) What is Newton's law of viscosity? Give an expression for the same, explaining different terms.

b) Explain the role of kinematic viscosity for a static and flowing fluid.

c) Explain the effects of temperature and pressure on fluid viscosity, specifically mentioning the reasons for differences in cases of gases and liquids.

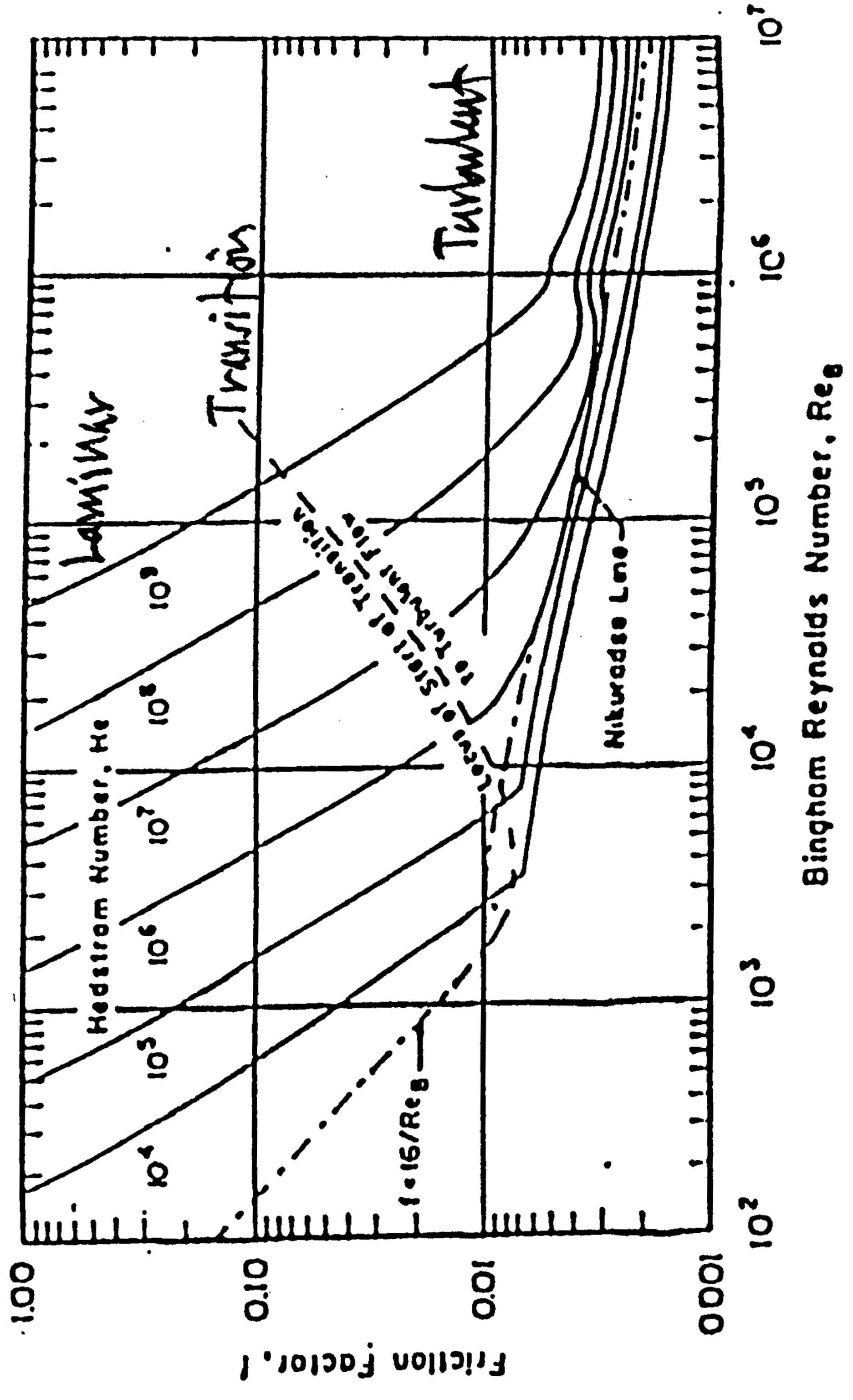
d) The space between two flat parallel plates is filled with oil. Each side of the plate is 70 cm. The thickness of the oil plate is 12.5 mm. The upper plate, moving at a speed of 3.15 m/s requires a force of 101.5 N to maintain the speed. Determine:

   i. Dynamic viscosity of oil in centipoise.
   ii. Kinematic viscosity of oil in Stokes if the specific gravity of the oil is 0.88.

e) The velocity distribution for a flow over a flat plate is given by: $u= 0.93y - y^2$, where, u = velocity (m/s); y = distance above the plate (m); Determine the shear stress at y = 0.35 m. Take the dynamic viscosity of the fluid as 8.6 Poise.

f) If the velocity profile over a flat plate is parabolic with the vortex being 20 cm away from the plate, where the velocity is 107 cm/s. Calculate the velocity gradient and shear stress at 0, 15, and 40 cm from the plate. Take the viscosity of oil as 8.8 Poise. (Hint: parabolic velocity profile $u = ay^2 + by + c$)

g) Two parallel flat plates, area 0.61m square, are spaced 0.24m apart. The lower plate is moving with a velocity of 1.22 m/s while the top plate is at rest. If the force required to move the plate is 70 dyne, find the viscosity of fluid between the plates in a suitable unit.


Friction Factor, f
Bingham Reynolds Number, Re_B
Hedstrom Number, He
Laminar
Transition
Turbulent
Locus of Start of Transition to Turbulent Flow
Nikuradse Line
$f = 16/Re_B$
1.00
0.10
0.01
0.001
10^2
10^3
10^4
10^5
10^6
10^7

Group II
[Heat Transport]

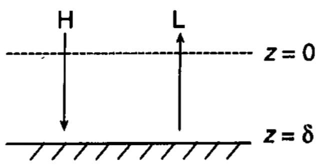
Q3. **[6+2+10+2+20=40]**

a) Considering the three basic mechanisms of heat transfer, explain the mode in each case and give examples for each.
b) State Fourier's Law of heat conduction.
c) Starting with Fourier's Law of heat conduction, derive the three-dimensional heat conduction equation using a differential control volume in rectilinear *Cartesian* coordinate. Also, write the special cases of the conduction equation and its transformation into cylindrical and spherical coordinates.
d) Under what conditions does Fourier's Equation of heat conduction transform into Poisson's equation and Laplace's equation?
e) Heat flows through the walls of an autoclave (annular), used to rejuvenate microbial strains, whose inside and outside radii are R_i and R_o respectively. The thermal conductivity of the material of construction of the autoclave is a function of temperature, given as: $k = aT^3+bT^2+c$. Derive the temperature profile of the wall and compute the heat loss through the walls of the Autoclave.

Group III
[Mass Transport]

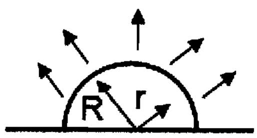
Q4. **[10+8+7+15=40]**

a) Starting with a differential control volume ($dx.dy.l$) for species conservation in two-dimensional flow of a viscous fluid with mass transfer, derive relevant convective-diffusive species continuity equation with or without generation/depletion.
b) The following sketch illustrates gas diffusion in the neighborhood of a catalytic surface.



Hot gases of heavy hydrocarbons diffuse to the catalytic surface where they are cracked into lighter compounds by the reaction: H $\rightarrow$ 2L, the light products diffuse back into the gas stream. *i)* Reduce the general differential equation for mass transfer to write the specific differential equation that will describe this steady-state transfer process if the catalyst is considered a flat surface. List all the assumptions you have made in simplifying the general differential equation. *ii)* Determine the Fick's law relationship in terms of only compound H and insert it into the differential equation you obtained in part *(i)*. *iii)* Repeat the solution for spherical catalyst surface.

c) A hemispherical droplet of liquid water, lying on a flat surface, evaporates by molecular diffusion through still air surrounding the droplet. The droplet initially has a radius R. As the liquid water slowly evaporates, the droplet shrinks slowly with time, but the flux of the water vapor is at a nominal steady state. The temperature of the droplet and the surrounding still air are kept constant. The air contains water vapor at an infinitely long distance from the droplet's surface. *i)* After drawing a picture of the physical process, select a coordinate system that will best describe this diffusion process, list at least five reasonable assumptions for the mass-transfer aspects of the water-evaporation process, and simplify the general differential equation for mass transfer in terms of the flux N_A. *ii)* What is the simplified differential form of Fick's equation for water vapor (species A)?



d) An encapsulated lyophilized microbial strain, of spherical shape, A of radius R_1, is suspended in a liquid fermentation media B. The encapsulation is porous. B diffuses through a stagnant liquid film of radius R_2. Derive an expression for the rate of diffusion of B.

Q5. **[15+10+15=40]**

a) Develop an algorithm that combines bioreactor design equations with reaction rates for the design of different bioreactors. Enumerate the steps to generate a scale-up model equation for a batch fermenter where a microbial reaction is taking place, following Monod kinetics. Estimate the expression to calculate the time required for a conversion of X_A in a constant volume (V) batch fermenter.

b) A large deep lake, which initially had a uniform oxygen concentration of 2 kg/m^3, has its surface concentration suddenly raised and maintained at 10 kg/m^3 concentration level. Reduce the general differential equation for mass transfer to write the specific differential equation for *i)* the transfer of oxygen into the lake without the presence of a chemical reaction; *ii)* the transfer of oxygen into the lake that occurs with the simultaneous disappearance of oxygen by a first-order biological reaction. Basic assumptions: 1. Chemical reaction occurs as per $-R_A = k_r C_A$ where k_r is the biological reaction rate constant. 2. For deep lake (stationary liquid) we can assume $v = 0$. 3. Unidirectional mass transfer.

c) Liquid flows over a thin, flat sheet of a slightly soluble solid. Over the region in which diffusion is occurring, the liquid velocity may be assumed to be parallel to the plate and to be given by $V_x = ay$, where y is the vertical distance from the plate and a is a constant. Show that the equation governing the mass transfer, with certain simplifying assumptions, is:

$$D_{AB}\left(\frac{\partial^2 c_A}{\partial x^2}+\frac{\partial^2 c_A}{\partial y^2}\right) = ay\frac{\partial c_A}{\partial x}$$

List the simplifying assumptions, and propose reasonable boundary conditions.

Species-continuity equation of A, written in rectangular coordinates is

$$\frac{\partial c_A}{\partial t} + \left[\frac{\partial N_{A,x}}{\partial x} + \frac{\partial N_{A,y}}{\partial y} + \frac{\partial N_{A,z}}{\partial z}\right] = R_A$$

in cylindrical coordinates is

$$\frac{\partial c_A}{\partial t} + \left[\frac{1}{r}\frac{\partial}{\partial r}(rN_{A,r}) + \frac{1}{r}\frac{\partial N_{A,\theta}}{\partial \theta} + \frac{\partial N_{A,z}}{\partial z}\right] = R_A$$

and in spherical coordinates is

$$\frac{\partial c_A}{\partial t} + \left[\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 N_{A,r}) + \frac{1}{r\sin\theta}\frac{\theta}{\partial \theta}(N_{A,\theta}\sin\theta) + \frac{1}{r\sin\theta}\frac{\partial N_{A,\phi}}{\partial \phi}\right] = R_A$$