Indian Institute of Technology Guwahati
Department of Biosciences and Bioengineering
End-Semester Examination (April 28, 2025)
Transport Phenomenon in Bioprocesses (BT 208)

- Any assumptions made MUST be explicitly defined with appropriate justifications
- Ambiguous answers WILL NOT be awarded ANY marks
- Question no(s) and respective answers should be written LEGIBLY

Duration: 3 h
Total Marks: 50

PART- A (15 Marks)

(Answer ALL the questions and each question carry EQUAL marks)

1. Streamlines in a fluid flow represents
    a. variation in density
    b. variation in viscosity
    c. variation in velocity
    d. variation in buoyancy
2. The typical value of Reynolds number for turbulent fluid flow in stirred tanks is
    a. above 4000
    b. above 10000
    c. above 2100
    d. above 10^3
3. Conceptually, Reynolds number represents the ratio of
    a. viscous forces to inertial forces
    b. buoyancy forces to viscous forces
    c. inertial forces to viscous forces
    d. inertial forces to shear forces
4. Eddies formed in the wake zone during boundary layer separation are kept in rotational motion by
    a. force of the bordering currents
    b. shear forces exerted by the fluid
    c. velocity gradient established in the fluid
    d. pressure drop of the fluid
5. Newton's law of viscosity for fluid flow is ONLY applicable under
    a. turbulent flow conditions
    b. transition flow conditions
    c. both laminar and turbulent conditions
    d. laminar flow conditions
6. Which ONE of the following is the unit of viscosity?
    a. $kg\ m^{-1}\ s^{-2}$
    b. $kg\ m^{-2}\ s^{-1}$
    c. $kg\ m^{-1}\ s^{-1}$
    d. $kg\ m^{-2}\ s^{-2}$

7. If the flow behaviour index (n) in the power law is less than 1, then the fluid is classified as
   a. Dilatant
   b. Pseudoplastic
   c. Casson-plastic
   d. Bingham-plastic
8. The primary function of baffle installed in a bioreactor is
   a. to create turbulence
   b. to provide mechanical strength
   c. to promote vortex formation
   d. to increase surface area
9. Which of the following is a NOT an axial flow impeller?
   a. Propeller
   b. Marine
   c. Pitched-blade
   d. Rushton turbine
10. In case of mixing at large-scale bioreactors, which ONE of the following is the slowest step?
   a. Dispersion
   b. Molecular Diffusion
   c. Distribution
   d. Eddy Diffusion
11. Based on heat, mass and momentum analogy, the rate is defined as ratio of
   a. driving force to coefficient
   b. driving force to flux
   c. driving force to surface area
   d. driving force to resistance
12. The major resistance for transport of oxygen from gas bubble to cell is
   a. gas film surrounding the bulk gas
   b. liquid film surrounding the gas bubble
   c. gas liquid interface
   d. liquid film surrounding the cell
13. A temperature cross occurs at some point in shell and tube heat exchanger where the
   a. temperature of cold fluid equals hot fluid temperature
   b. temperature of cold fluid exceeds hot fluid temperature
   c. temperature of cold fluid is independent of hot fluid temperature
   d. temperature of cold fluid changes inversely to hot fluid temperature
14. Conceptually, Nusselt number represents the ratio of
   a. rates of conductive and convective heat transfer
   b. rates of molecular diffusion and convective heat transfer
   c. rates of convective and conductive heat transfer
   d. rates of conductive heat transfer and molecular diffusion
15. A high value for Prandtl number indicates that
   a. hydrodynamic boundary layer is thinner than thermal boundary layer
   b. hydrodynamic boundary layer is equal to thermal boundary layer
   c. hydrodynamic boundary layer is only present
   d. hydrodynamic boundary layer is thicker than thermal boundary layer

PART- B

(Answer ALL the questions and each question carry EQUAL marks) (35 Marks)

16. A cylindrical bioreactor of diameter 3 m has four baffles. A Rushton turbine mounted in the reactor has a diameter one-third the tank diameter and is operated at a speed of 90 rpm. The density of the fluid is approximately 1 g cm^{-3}. The reactor is used to culture an anaerobic organism that does not require gas sparging. The broth can be assumed Newtonian. As the cells grow, the viscosity of the broth increases.

(a) Compare power requirements when the viscosity is:

(i) approximately that of water; (2)

(ii) 100 times greater than water; and (2)

(iii) 10^4 times greater than water. (2)

(b) When the viscosity is 1000 times greater than water, estimate the power required to achieve turbulence. Use viscosity of water at 20^0C as 1 cP. (1)

17. A cylindrical stirred bioreactor of diameter and height 2 m has a Rushton turbine one-third the tank diameter in size. The bioreactor contains Newtonian culture broth with the same density as water and with viscosity 4 cP.

(a) If the specific power consumption must not exceed 1.5 kW m^{-3}, determine the maximum allowable stirrer speed. What is the mixing time under these conditions? (5)

(b) If the tank is aerated. the approximate relationship between ungassed power number $(N_P)_0$ and gassed power number $(N_P)_g$ is: $(N_P)_g = 0.5\,(N_P)_0$. Calculate maximum stirrer speed possible and mixing time in the sparged reactor? (2)

18. A genetically-engineered strain of yeast is cultured in a bioreactor at 30^0C for production of heterologous protein. The oxygen requirement is 80 mmol L^{-1} h^{-1}; the critical oxygen concentration is 0.004 mM. The solubility of oxygen in the fermentation broth is estimated to be 10 % lower than in water due to solute effects.

(a) What is the minimum mass-transfer coefficient necessary to sustain this culture if the reactor is sparged with air at approximately 1 atm pressure? (5)

(b) What mass-transfer coefficient is required if pure oxygen is used instead of air? (2)

Note: Solubility of oxygen in water at 30^0C and 1 atm pressure is 8.05 x 10^{-3} kg/m^3;
Solubility of oxygen in water at 30^0C and 1 atm oxygen pressure is 3.84 x 10^{-2} kg/m^3

19. A fermenter is maintained at 35° C by water circulating at a rate of 0.5 kg s^{-1} in a cooling coil inside the vessel. The inlet and outlet temperatures of the water are 8°C and 15°C, respectively. The length of the cooling coil is increased by 50 %. In order to maintain the same fermentation temperature, the rate of heat removal must be kept the same. Determine the new cooling water flow rate and outlet temperature by carrying out the following calculations. The heat capacity of the cooling water can be taken as 4.18 kJ $kg^{-1}{}^oC^{-1}$. Rate of heat removal by cooling coil is $\overline{Q} = \overline{M}C_{Pc}(T_{Co} - T_{Ci})$.

(a) From a steady state energy balance on the cooling water, calculate the rate of cooling with the original coil. (1)

(b) Determine the mean temperature difference with the original coil. (2)

(c) Evaluate the UA for the original coil. (1)

(d) If the length of the original coil is increased by 50 %, the area available for heat transfer, A', also increases by 50 % so that $A' = 1.5A$. The value of overall heat transfer coefficient is not expected to change very much. For the new coil, what is the value of UA'? (1)

(e) Evaluate the new cooling water outlet temperature. (1)

(f) By how much the cooling water requirements reduced after the new coil is installed? (1)

20. A 100 m^3 fermenter of diameter 5 m is stirred using a turbine impeller 1.7 m in diameter at a speed of 80 rpm. The culture fluid inside the fermenter has the following properties:

$C_p = 4.2$ kJ kg^{-1} $°C^{-1}$

$K_{fb} = 0.6$ W m^{-1} $°C^{-1}$

$\rho = 10^3$ kg m^{-3}

$\mu_b = 1$ cP

Assume that the viscosity at the wall is equal to the bulk-fluid viscosity. Heat is generated by the fermentation at a rate of 2500 kW. This heat is removed to cooling water flowing in a helical stainless-steel coil inside the vessel. The coil wall thickness is 6 mm and the thermal conductivity of the metal is 20 W m^{-1} $°C^{-1}$. There are no fouling layers present, and the heat transfer coefficient for the cooling water can be neglected. The fermentation temperature is 30°C; cooling water enters the coil at 10°C.

(a) Calculate the fermentation-side heat transfer coefficient. (4)

(b) Calculate the overall heat transfer coefficient, U. What proportion of the total resistance to heat transfer is due to the pipe wall? (3)

Annexure

A1. Heat transfer coefficient for stirred liquids: $Nu = \overset{0.87}{\cancel{087}}\, Re_i^{0.62}\, Pr^{0.33} \left(\mu_b / \mu_w \right)^{0.14}$

A2. Correlation between Reynolds and Power number for Rushton turbine (1), pitched-blade turbine (2) and marine propeller (3) in fluids without gassing: