UNIVERSITY COLLEGE LONDON

University of London

EXAMINATION FOR INTERNAL STUDENTS

For The Following Qualification:-

M.Sc.

M9: Transport Processes

COURSE CODE	:	**CENG00M9**
DATE	:	**05-MAY-06**
TIME	:	**10.00**
TIME ALLOWED	:	**3 Hours**

06-N0012-3-30

TURN OVER

Full marks (80/80) may be obtained by correct answers to FOUR questions only.
Only the first four answers will be marked.
***ALL** questions carry a total of **20 MARKS** each, distributed as shown* [ ]

1. A long vertical drill shaft of radius R_1 is sheathed by a stationary coaxial cylindrical vessel forming a well of radius R_2 and contains a lubricating liquid. The shaft passes through the liquid free surface and rotates with angular velocity ω.

   Assuming that the liquid is Newtonian, derive expressions for the liquid velocity and pressure distributions respectively at a radial distance r from the shaft axis. [9]

   Hence show that the height of the free liquid surface relative to a datum $(h - h_o)$ as a function of radial distance, r, is given by:

$$h - h_o = \frac{C^2}{g}\left(2R_2^2 \ln\frac{R_2}{r} - \frac{R_2^4 - r^4}{2r^2}\right)$$

   where

$$C = R_1^2\omega/(R_2^2 - R_1^2).$$ [9]

   [Navier-Stokes and continuity equations are provided].

   Show what you would expect to happen if a viscoelastic polymer were added to the fluid. [2]

2. Discuss the concept of *penetration distance* in relation to the unsteady state transfer of heat into semi-infinite media. [5]

   Derive an expression for the contact temperature between two finite bodies brought together at initially different temperatures given that the temperature distribution in a semi-infinite slab is given by:

$$\frac{T - T_o}{T_s - T_o} = erfc\ \eta$$

   where

$$\eta = y/\sqrt{4\alpha t}$$

   and

$$erfc\ \eta = \frac{2}{\sqrt{\pi}}\int_\eta^\infty e^{-t^2}\,dt$$

   T_S is the surface temperature, T_O the initial temperature and T the temperature at distance y from the surface, α is the thermal diffusivity $(k/c_p\rho)$. [10]

   Thus explain which feels hotter to the touch: a hot insulator or a good conductor at the same temperature. [5]

TURN OVER

3. Discuss the conceptual differences between the film and penetration models of mass transfer respectively. State the appropriate boundary conditions and derive the corresponding transport equations. [5]

Using the film theory, show how the liquid phase concentration profiles and mass transfer enhancement may be estimated for a gas dissolving into water and undergoing a first order chemical reaction. Sketch the form of the concentration profiles for (a) no reaction, (b) slow reaction and (c) fast reaction. [5]

Explain the significance of the Hatta number, *Ha*, defined by:

$$Ha = \sqrt{D_A k_1} / k_L^o$$

where D_A is the liquid phase diffusivity of component *A*, k_1 is the pseudo first-order reaction rate constant, k_L^o is the physical mass transfer coefficient. [2]

Traces of CO_2 in a gas stream are absorbed by a 0.5M aqueous solution of $K_2CO_3/KHCO_3$. If the reaction rate constant k_1 is $1.5\times10\ s^{-1}$ and the mass transfer coefficient is $1\times10^{-1}\ m\ s^{-1}$:

(i) to what extent is the rate of absorption enhanced by the use of the reagents? [3]

(ii) to which case above (a, b or c) does the system correspond? [3]

(iii) what type of mass transfer device would you recommend for this duty, and why? [2]

(Take the diffusivity of the absorbent in water as $3\times10^{-9}\ m^2\ s^{-1}$).

4. Derive an expression for the Reynolds analogy between heat and momentum transfer in a pipe. [9]

State *briefly* how the Reynolds analogy may be modified to produce (i) the Prandtl analogy and (ii) the von Kármán analogy. [4]

Why are the Prandtl and von Kármán analogies likely to be superior to the Reynolds analogy? [3]

A gas flows through a straight pipe at $255\ kg\ m^{-2}\ s^{-1}$ and a Reynolds number of 150,000. At this Reynolds number $1/\sqrt{c_f} = 4.0 \log_{10}\left(Re\sqrt{c_f}\right) - 0.4$. Using the Reynolds analogy, estimate the corresponding value of the heat transfer coefficient. [4]

Data: gas property: $c_P = 1.8\ kJ\ kg^{-1}\ K^{-1}$.

CONTINUED

5. Discuss *briefly* Rushton's concept of shear and flow in a stirred tank. [6]

A bench scale stirred tank is to be scaled up to full-scale whilst retaining geometric similarity. The bench-scale tank is 0.15 m in diameter with multiple 0.05 m diameter impellers on a single shaft rotating at 12 Hz and consume, in total 5.3 W of power. The tank is filled to a depth equal to twice its diameter with a liquid of density 1080 kg m^{-3}. What is the mean energy dissipation rate? [3]

A geometrically similar prototype tank of 1.5 m diameter is to be built and scale up is to be performed at constant mean energy dissipation rate. How much power is required by the prototype impellers and what is their rate of rotation? [6]

By what factors would the shear and flow characteristics change in the full-scale tank if the diameter of the impellers were increased by 50% in diameter at constant power input? [5]

6. Show that the volumetric flow rate Q through a pipe of internal radius R for a Bingham plastic, $\dot{\gamma} = \frac{\tau_y - \tau}{\mu_p}$, are related to the wall shear stress τ_R by

$$\frac{4Q}{\pi R^3} = \frac{\tau_w}{\mu_p}\left[1 - \frac{4}{3}\left(\frac{\tau_y}{\tau_R}\right) + \frac{1}{3}\left(\frac{\tau_y}{\tau_R}\right)^4\right]$$

where $\dot{\gamma}$ is the shear rate, τ the shear stress, τ_y the fluid yield stress and μ_p the plastic viscosity. [10]

A Bingham plastic fluid is being pumped through a pipeline 0.20 m in diameter and 350 m long. If the pressure drop which is necessary to just start the flow is 600 kPa, calculate the yield stress of the fluid. [3]

At a pressure drop of 1.5 MPa the volumetric flow rate is found to be 0.05 $m^3 s^{-1}$. What is the plastic viscosity of the fluid? [5]

If the pressure drop were doubled to 3 MPa, what would be the new volumetric flow rate of the fluid? [2]

TURN OVER

Appendix

Equations of Change

Rectangular co-ordinates (*x*, *y*, *z*):

Continuity

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho v_x)+\frac{\partial}{\partial y}(\rho v_y)+\frac{\partial}{\partial z}(\rho v_z)=0$$

Motion

x-component

$$\rho\left(\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_x}{\partial y}+v_z\frac{\partial v_x}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left[\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_x}{\partial y^2}+\frac{\partial^2 v_x}{\partial z^2}\right]+\rho g_x$$

y-component

$$\rho\left(\frac{\partial v_y}{\partial t}+v_x\frac{\partial v_y}{\partial x}+v_y\frac{\partial v_y}{\partial y}+v_z\frac{\partial v_y}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left[\frac{\partial^2 v_y}{\partial x^2}+\frac{\partial^2 v_y}{\partial y^2}+\frac{\partial^2 v_y}{\partial z^2}\right]+\rho g_y$$

z-component

$$\rho\left(\frac{\partial v_z}{\partial t}+v_x\frac{\partial v_z}{\partial x}+v_y\frac{\partial v_z}{\partial y}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left[\frac{\partial^2 v_z}{\partial x^2}+\frac{\partial^2 v_z}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right]+\rho g_z$$

Cylindrical co-ordinates (*r*, θ, *z*):

Continuity

$$\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(\rho r v_r)+\frac{1}{r}\frac{\partial}{\partial \theta}(\rho v_\theta)+\frac{\partial}{\partial z}(\rho v_z)=0$$

Motion

r-component

$$\rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}-\frac{v_\theta^2}{r}+v_z\frac{\partial v_r}{\partial z}\right)=-\frac{\partial p}{\partial r}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(r v_r)\right)+\frac{1}{r^2}\frac{\partial^2 v_r}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta}+\frac{\partial^2 v_r}{\partial z^2}\right]+\rho g_r$$

θ-component

$$\rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{v_r v_\theta}{r}+v_z\frac{\partial v_\theta}{\partial z}\right)=-\frac{1}{r}\frac{\partial p}{\partial \theta}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(r v_\theta)\right)+\frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2}+\frac{2}{r^2}\frac{\partial v_r}{\partial \theta}+\frac{\partial^2 v_\theta}{\partial z^2}\right]+\rho g_\theta$$

z-component

$$\rho\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2}+\frac{\partial^2 v_z}{\partial z^2}\right]+\rho g_z$$

END OF PAPER