UNIVERSITY COLLEGE LONDON

University of London

EXAMINATION FOR INTERNAL STUDENTS

For the following qualifications :-

M.Sc.

M9: Transport Processes

COURSE CODE	:	**CENG00M9**
DATE	:	**30-APR-02**
TIME	:	**10.00**
TIME ALLOWED	:	**3 hours**

02-N0021-3-30

TURN OVER

*Answer **FOUR** questions only.*

Each question carries a total of 20 marks distributed as shown [ ].

The Equations of Change are appended.

1. A long horizontal pipe of circular cross-section and radius R is filled with a Newtonian liquid of viscosity μ and density ρ. A continuous wire, radius xR ($x < 1$) is drawn along the pipe axis at a steady velocity V.

Using the continuity and Navier-Stokes equations in the appended equations of change, derive an equation describing the velocity profile in the liquid. Neglect any end effects. [10]

If the pipe is 20 m long, $\mu = 10^{-1}$ Pa s, $x = 2\times10^{-1}$ and $V = 2$ m s^{-1}, calculate the force required to draw the wire through the liquid. [10]

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2. Describe, with the aid of a sketch, the phenomenon of the boundary layer with reference to the two dimensional flow of a Newtonian fluid along a horizontal, flat plate. [5]

The differential describing equations describing the flow within the boundary layer along a flat plate can be written as:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0$$

$$v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} = \vartheta \frac{\partial^2 v_x}{\partial y^2}$$

where v_x and v_y are the fluid velocities parallel to and perpendicular to the flat plate respectively, and ϑ is the momentum diffusivity of the fluid.

Write down the boundary conditions for this flow situation given that the bulk fluid velocity far from the plate is V. [5]

A numerical solution to the boundary layer equations for fluid flowing over a flat plate is given by:

η	0	0.1	0.2	0.3	1	2.5	5
v_x/V	0	0.0665	0.133	0.195	0.630	0.990	1.00

where η is a dimensionless variable given by:

$$\eta = y\left(\frac{V}{4\vartheta x}\right)^{0.5}$$

where x is the distance along the plate from the leading edge, y is the distance perpendicular to the plate, V is the velocity of the bulk flow far from the plate and ϑ is the momentum diffusivity of the fluid.

Use this numerical solution to find

(i) An expression for the boundary layer thickness, δ, and [5]

(ii) The local surface shear stress, τ_0, [5]

both as functions of distance x from the leading edge.

TURN OVER

3. A soluble gas component S is to be absorbed into a liquid containing soluble component R which it reacts instantaneously and irreversibly according to $S + qR \rightarrow SR_q$.

(i) Derive describing equations for the *mass flux* and *critical concentration*. [6]

(ii) Sketch how the rate of absorption of gas varies *quantitatively* with the concentration of R in the liquid within the range $0 < [R] < 10$ kmol m^{-3}. [10]

(iii) Calculate the maximum absorption enhancement factor. [2]

(iv) Specify suitable types of contacting device over the range $0 < [R] < 10$ kmol m^{-3}, with reasons. [2]

Data:

Diffusion coefficients of S and R in the liquid phase	$= 1.0\times10^{-8}$ m^2 s^{-1}
Gas phase film mass transfer coefficient	$= 2.0\times10^{-3}$ kmol m^{-2} s^{-1} bar^{-1}
Liquid phase mass transfer coefficient	$= 1.0\times10^{-4}$ m s^{-1}
Partial pressure of S in the bulk gas phase	$= 0.15$ bar
Henry's Law coefficient for the solubility of gas in liquid	$= 1.2\times10^{2}$ bar m^3 kmol^{-1}
Stoichiometric ratio	$= 2$

TURN OVER

4. 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_w by

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

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 slurry is to be pumped through a 130 m long, straight horizontal, 180 mm diameter pipe. Calculate:

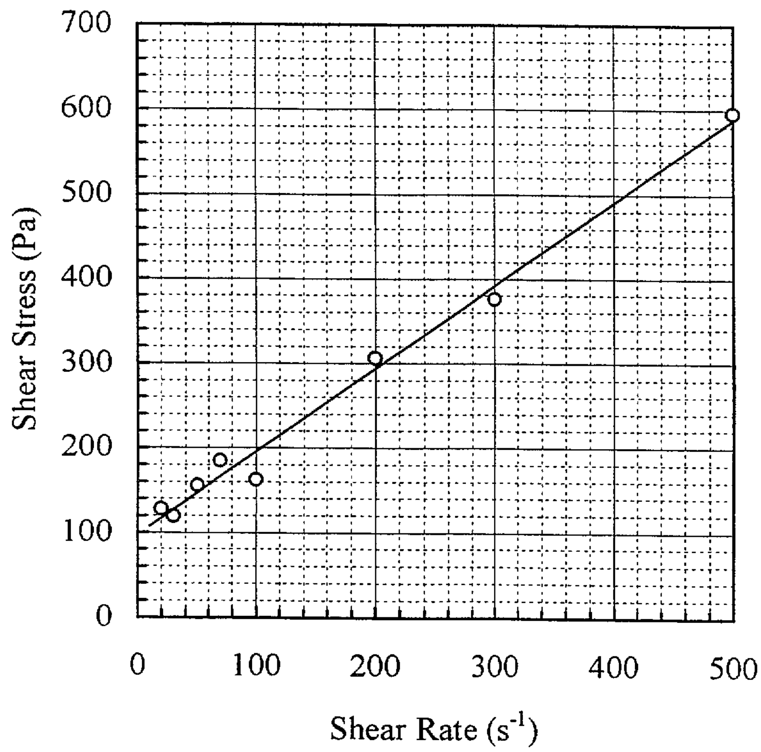
(i) the pressure drop required to just start the slurry flowing; [2]

(ii) the mass flowrate when a pressure difference of 6 bar is applied across the pipe length; and [6]

(iii) the fraction of the pipe cross-sectional area occupied by the "solid" central plug at the flowrate given in (ii). [2]

Data: Slurry properties: density 1250 kg m^{-3}; "flow curve" below.

Slurry Flow Curve

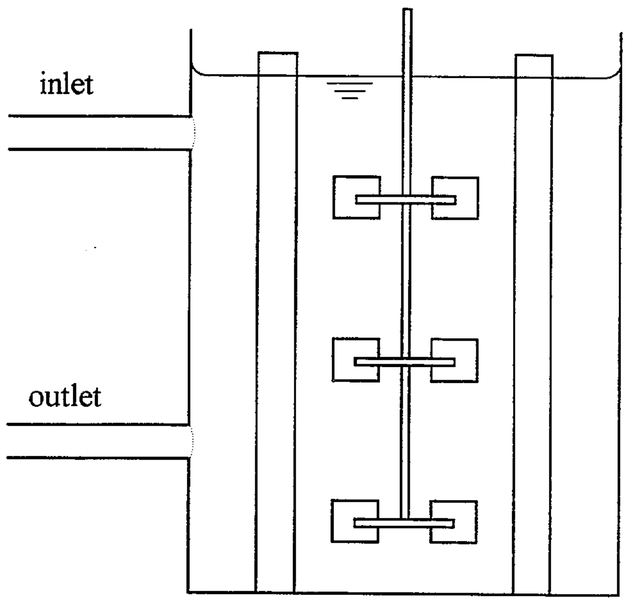


TURN OVER

5. It is proposed to scale-up a continuous stirred tank reactor to maintain the same product yield per unit volume per unit time. To do this, it has been recommended that scale-up be at constant residence time distribution and at constant mean residence time.

(i) Derive an appropriate scale-up criterion to achieve this under geometric similarity. [6]

A pilot plant continuous stirred tank reactor (illustrated below) has an internal diameter of 300 mm and is filled to a depth of 500 mm. It is fitted with three Rushton (disk) turbines, each with a diameter one third of that of the tank, mounted one half of a tank diameter apart on a single impeller shaft. This impeller shaft rotates at 600 rpm and is centrally mounted in the vessel, which is fully baffled.



Pilot scale stirred tank reactor

Experiments indicate that a mean residence time of 15 minutes achieves the required product yield.

(ii) Calculate the mass flowrate of reactants into the pilot scale vessel. [2]

(iii) Using the scale-up criterion derived in (i) above, calculate the diameter of a geometrically similar production-scale reactor to handle 2 kg s^{-1} feed. [3]

(iv) What are the power and torque required from a motor drive to the impellers for your production-scale reactor sized in (iii)? [6]

(v) Comment upon any drawbacks of this scale-up criterion. [3]

Data: Reaction mixture density = 1150 kg m^{-3}, viscosity = 0.56×10^{-3} Pa s.
The power number for a single Rushton (disk) turbine is 0.5 .

TURN OVER

6. Outline the bases of:

(i) the *Prandtl Mixing Length* theory of turbulence, and [5]

(ii) the *Kolmogorov* theory of turbulence. [5]

An ideal gas at 5 bar and 270 °C flows through a pipe 600 mm internal diameter. If the mass flow rate of gas is 50 kg min^{-1}, estimate:-

(iii) the Prandtl scale of eddies on the pipe centre-line; [2]

(iv) the Kolmogorov dissipation scale of turbulence; and [6]

(v) the smallest scale of eddies present. [2]

Data: gas properties: molecular mass = 17, viscosity = 1.9×10^{-5} Pa s.
$c_f = 0.079Re^{-0.25}$. $R = 8.314$ kJ kg^{-1} K^{-1}.

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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

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

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