# Transport Phenomena

- **Closed-Book Examination**

1. For laminar flow in side a circular pipe, we know that $v_z = 2v_{av}\left[1-\left(\frac{r}{R}\right)^2\right]$ .

   (1) Find the wall shear stress $\tau_w$;

   (2) By defining the frictional factor f as $f = \frac{\tau_w}{\rho v_{av}^2/2}$ , find the relation between f and Reynolds number. (10%)

2. What is j-factor for heat tranfer $j_H$ and j-factor for mass tranfer $j_M$? What is *Chilton and Colburn* analogy? Specify the condition under which the analogy holds. (10%)

3. A steel wall separates hot water from cold air. There are N rectangular fins to be installed on the wall for increasing the heat transfer rate between water and air. The water side and air side heat transfer coefficient is 10 and 125 $W/m^2.K$, respectively. It is proposed to install (a) all N fins on the air side, (b) all N fins on the water side and (c) N/2 fins on water side and another N/2 fins on the air side. Which will give better heat transfer enhancement? Give reasons for your answer. (15%)

4. Explain film theory and penetration theory. The relation between mass transfer coefficient $k_c$ and diffusivity $D_{AB}$ can be expressed as $k_c \sim (D_{AB})^{\alpha}$, what are the value $\alpha$ for film theory and penetration theory? (15%)

5. A rod of radius $\kappa R$ moves upward with a constant velocity $v_0$ through a cylindrical container of inner radius $R$ containing a Newtonian liquid. The liquid circulates in the cylinder, moving upward along the moving center rod and moving downward along the fixed container wall. Find the velocity distribution in the annular region, far from the end disturbances. Please refer to Figure 1. Use the dimensionless variables $\phi = v_z / v_0$ and $\xi = r / R$; instead of the latter, it is more convenient to use $\zeta = (\xi - \kappa)/(1-\kappa)$ in this part of the problem.

   1. First consider the problem where the annular region is quite narrow – that is, where $\kappa$ is just slightly less than unity. In that case the annulus may be approximated by a thin plane slit and the curvature can be neglected. Please

calculate the velocity distribution in this limit.

2. Next work the problem without the thin-slit assumption. Please calculate the velocity distribution. (20%)

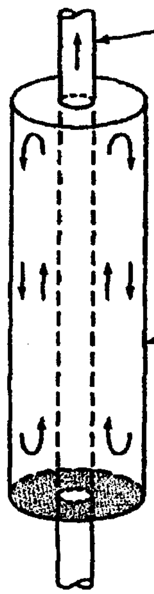


Figure 1: Circulating flow produced by an axially moving rod in a closed annular region.

6. Consider a long cylindrical nuclear fuel rod, surrounded by an annular layer of aluminum cladding as shown in Figure 2. Within the fuel rod heat is produced by fission; this heat source depends on position approximately as

$$S_n = S_{n0}\left[1 + b\left(\frac{r}{R_F}\right)^2\right]$$

Here $S_{n0}$ and $b$ are known constants, and $r$ is the radial coordinate measured from the axis of the cylindrical fuel rod. Calculate the maximum temperature in the fuel rod if the outer surface of the cladding is in contact with a liquid coolant at temperature $T_L$. The heat transfer coefficient at the cladding-coolant interface is $h_L$, and the thermal conductivities of the fuel rod and cladding are $k_F$ and $k_C$. (15%)

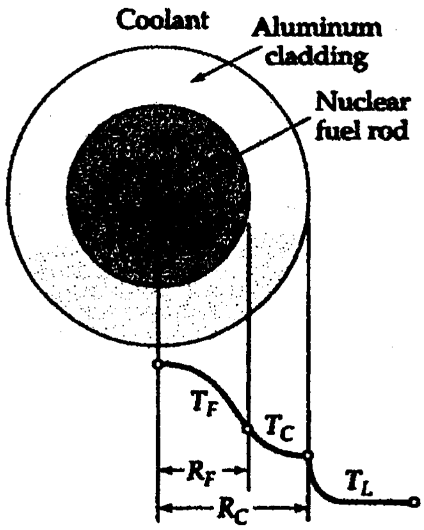


Figure 2 : Temperature distribution in a cylindrical fuel rod assembly.

7. A gas stream composed of a reactant $A$ and product $B$ is flowing past a spherical catalyst pellet in a reactor. The concentration $C_{As}$ of $A$ at the outer surface of the pellet is assumed constant. The reactant $A$ diffuses from the surface through the pores of catalyst and reacts in the pellet. Assuming a first-order reaction leads to $R_A = -k_R C_A$ where $k_R$ is called the specific rate constant. Product $B$ is formed and diffuses back to the outer surfaces and into the gas stream. Please find the concentration distribution in the pellet. (15%)

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1. For laminar tube flow with constant heat flux (q0) at the wall, the asymptotic solution for the entrance region can be found by the following steps:. (a) For small z the heat addition affects only a very thin region near the wall, so that curvature effects may be neglected. Show that $v_z(y) = 2v_{max}y/R$, where $y = R - r$ (5%); (b) Show that the energy equation $DT/dt = \alpha\nabla^2 T$ reduces to $v_{max}\frac{y}{R}\frac{\partial T}{\partial z} = \alpha\frac{\partial^2 T}{\partial y^2}$, state all your assumptions (10%); (c) Show that the PDE in (b) can be put into $\frac{\partial \Psi}{\partial \lambda} = \frac{\partial}{\partial \eta}\left(\frac{1}{\eta}\frac{\partial \Psi}{\partial \eta}\right)$ where $\Psi = q_y/q_0$, $\eta = y/R$, $\lambda = \alpha z/(v_{max}R^2)$ and $q_y = -k\frac{\partial T}{\partial y}$; write down the corresponding boundary conditions for this PDE (5%); (d) Show that by defining $\chi = \eta/(9\lambda)^{1/3}$, the solution for $\Psi$ is $\Psi = \frac{3}{\Gamma(2/3)}\int_{\chi}^{\infty} t\exp(-t^3)dt$ (10%)

2. What is Prandtl number (Pr)? For a fluid with Pr > 1 flowing over a flat plate, if $\delta$ and $\delta_T$ represent momentum boundary layer thickness and thermal boundary layer thickness, respectively; which is larger, $\delta$ or $\delta_T$? Explain why. (10%)

3. (a) A cup of water with the water level at a distance L from the top of the cup. As the water evaporates, the water level drops with time. Explain why we can treat this problem as steady state (called "pseudo-steady state") evaporation, even though the length of mass transfer path (L) increases with time? (5%); (b) Under pseudo-steady state assumption, prove that the time required for the water level to drop from L to $L_1$ is $t = \frac{\rho_w(L_1^2 - L^2)RTP_{aM}}{2M_w D_{AB}P(P_{w1} - P_{w2})}$ where the subscript w and a denote water and air, respectively; $P_{aM}$ is the log mean average of air partial pressure. (15%)

4. Explain the following terms (20 points)

A. D'Alembert's paradox
B. Bernoull's theorem for steady state motion
C. Darcy's law
D. Mach number
E. Oseen's approximation
F. Prandtl mixing length
G. Reynolds stress
H. Stokes law for a moving sphere

5. A semi-infinite body of liquid with constant density and viscosity is bounded below

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by a horizontal surface (the xz plane) as shown in the figure below. Initially the fluid and the solid are at rest. Then a time t=0, a constant force is applied to the fluid at the wall in the positive x direction, so the shear force $\tau_{yx}$ takes on a new constant value $\tau_o$ at y>0 for t> 0. Find out the stress and velocity profiles. (20 points)

The following relationship may be helpful.

$\int_x^\infty (1-erfu)du = \frac{1}{\sqrt{\pi}}e^{-x^2} - x(1-erfx)$ where *erf* is error function.