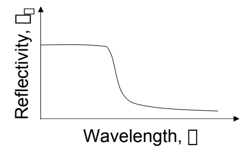
ME109 – Heat Transfer

Final Exam; Instructor: Prof. A. Majumdar

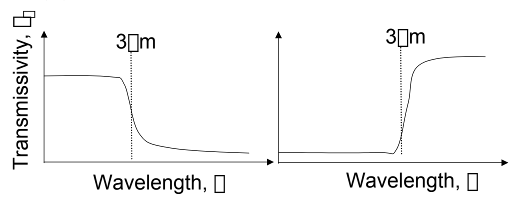
December 18, 2004; Time: 12:30-3:30 pm; Maximum Points = 100

NOTE: This is an open book, open notes exam.

1. Give brief answers with explanation and reasoning.
   (i) Show that the Biot number, $Bi = hL/k$, is the ratio of two thermal resistances; internal conduction resistance and external thermal resistances. (4)
   (ii) The spectral reflectivity of a diffuse opaque surface has the following spectral distribution. If the temperature increases, will the total-hemispherical emissivity increase or decrease with temperature. (4)



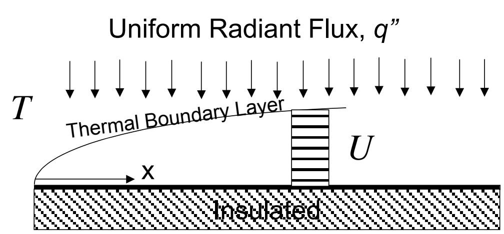
   (iii) The resistance network analysis used for conduction can be combined with the radiation network analysis used radiation, when both conduction and radiation are relevant. True or False. Explain. (4)
   (iv) It is widely believed that greenhouse gases in the atmosphere lead to global warming. Which of the following spectral transmissivity does the atmosphere have to produce greenhouse effect. (4)



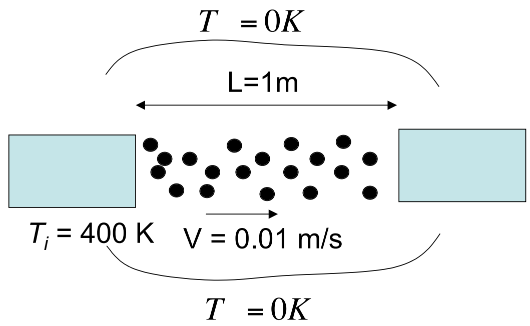
   (v) At a surface, the velocity of a fluid is zero, such that only conduction leads to heat transfer between a solid and a fluid. What, then, is the role of convection, i.e. when you increase the velocity, why does the heat transfer increase? (4)

2. A silicon chip of thickness, d = 0.5 mm, has a surface area, A = 2 cm x 2 cm. It is packaged in a way that the heat transfer coefficient between the chip and ambient air is h = 500 [W/m^2-K] on both the 2 cm x 2 cm surfaces of the chip. At t = 0, the power input to the chip is turned on to P_o = 100 W. Properties of silicon are: thermal conductivity, k = 150 W/m-K; density, ρ= 2300 kg/; and heat capacity, C_p = 700 J/kg-K.
   (i) Based on 1st law of thermodynamics, develop an equation for the temperature of the silicon chip as a function of time. (5)
   (ii) Develop an expression and calculate the thermal time constant, τ, for the chip. (5)
   (iii) Calculate the steady state temperature rise, $\theta_{ss} = T_{ss} - T_\infty$. (10)

3. A flat opaque plate exchanges radiative heat transfer with its surroundings such that a net uniform q'' (see figure) is absorbed. The bottom surface the plate is insulated, whereas on the top surface a transparent fluid at temperature T_∞ and velocity U_∞ flows over the plate. The convection is such that the thermal boundary layer is much thicker than the velocity boundary layer. In fact, the velocity can be assumed to be U_∞ across the thermal boundary layer. Using the integral method, determine the temperature of the plate surface along the flow direction, i.e. x direction, in terms of U_∞, T_∞, q'', and thermal diffusivity, α. (Note: the heat flux is uniform, but not the surface temperature) Integral energy equation: $\frac{d}{dx}\int_0^{\delta_t} u(T - T_\infty)dy = -\alpha \left.\frac{\partial T}{\partial y}\right|_{y=0}$ (20)

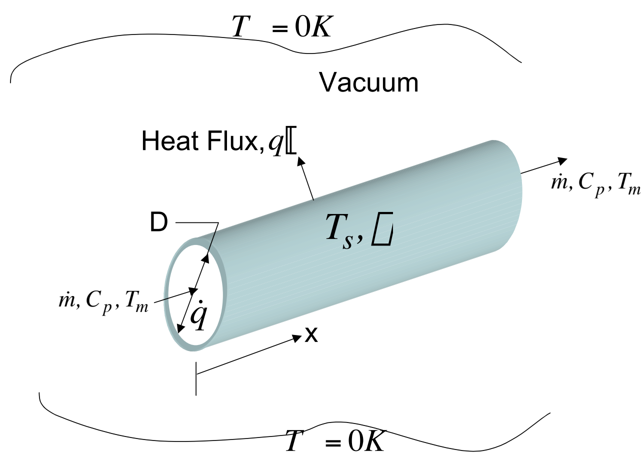


4. A radiative heat exchanger used in space uses small aluminum balls of, $\rho C = 2 \times 10^6$ J/m^3-K, diameter D = 0.1 mm to flow through a region that is fully enclosed by space, which is assumed to be a temperature of 0 K. The balls enter the heat exchanger at 400 K and move at a speed of 0.01 m/s. The heat exchanger length is 1 m. The emissivity of the outer surface of the ball is 1. Assume that lumped capacitance can be used and that neighboring balls and the tubes at either end do not influence the heat transfer of an individual ball.



   (i) Using first law of thermodynamics, derive an equation for the time variation of the temperature of the ball? (5)
   (ii) Solve the equation to find the temperature of a ball at the exit of the heat exchanger.(5)
   (iii) What is the energy transferred by a single ball during its passage through the heat exchanger? (5)
   (iv) What is the effectiveness of the heat exchanger? (5)

5. Consider an opaque tube of diameter D = 0.01 m through which there is a thermally and hydrodynamically fully developed flow of reacting gases at a mass flow rate of $\dot{m}$ = 0.001 kg/s and heat capacity of C_p = 1 kJ/kg-K. The fluid enters the tube at a mean temperature of T_{mi} = 600 K. As the gases flow through the tube, the reaction produces an energy generation rate of $\dot{q} = 10^6$ W/m^3 per unit volume inside the tube. Because the fluid inside the tube is hotter than the tube surface temperature, T_s, heat is transferred from the fluid to the tube walls, with a heat transfer coefficient, h = 25 W/m^2-K, which remains constant along x. The heat transfer conditions are such that both the mean fluid temperature, T_m, and the heat flux, q'', remain unchanged along the x-direction. Assume the outer and inner surfaces of the tube to be at the same temperature, i.e., the tube poses no thermal resistance. The tube is used in a spacecraft such that the outer surface of the tube is completely surrounded by space (T_∞ = 0 K) and transfers heat by radiation.



   (i) Using first law of thermodynamics, derive an equation for the variation of the mean fluid temperature, T_m, as a function of x inside the tube in terms of $\dot{q}$, $\dot{m}$, C_p, T_{mi}, T_s.(5)
   (ii) Given the fact that T_m does not change with x, derive a relation for the surface temperature, T_s, in terms the parameters given above. What is the value of T_s? (5)
   (iii) What is the heat flux q''? (3)
   (iv) What is the total-hemispherical emissivity, ε, of the outer tube surface? (7)