Indian Institute of Technology, Kharagpur
Mechanical Engineering Department

Heat Transfer (ME 30005) – Autumn Semester 2016
End-Semester Exam

1. A porous medium consists of a solid and fluid with thermal conductivities of k_s and k_f respectively. Show that for a porosity ε, the effective thermal conductivity (k_e) of the porous medium in the direction of heat flow will lie between $\varepsilon k_f + (1-\varepsilon)k_s$ and $\left(\varepsilon/k_f + (1-\varepsilon)/k_s\right)^{-1}$. 8

2. Air is heated passing through a circular pipe of 5 cm diameter at a mass flow rate of 0.06 kg/s. It is decided to replace the circular tube with a square one of identical cross section. What will be the effect on rate of heat transfer due to this change? You may consider the following properties of the air at an average bulk temperature of 40°C. Assume fully developed flow, smooth surface and ρ_{air} = 1.13 kg/m3, k_{air} = 0.03 W/m-K, C_p = 1005 J/kg-K, ν_{air} = 1.7 x 10^{-5} m^2/s. 6

3. The cooling of fruits and vegetables, in refrigerated air at temperature 4°C, pressure 1 atm and velocity 0.3 m/s, is modeled as a combination of convection, radiation and evaporation of air. The heat coefficient for the combination of convection, radiation and evaporation of air, in the velocity range 0.1 < V < 0.3 m/s is, determined experimentally and expressed as

$$h = 5k\frac{\mathrm{Re}^{\frac{1}{3}}}{D}$$

where k is the thermal conductivity of air (=0.03 W/m-K) and D is the characteristic length.

   a. Calculate the initial rate of heat transfer from the surface of the fruit, whose area is equivalent to the surface area of a 5 mm diameter sphere, if the initial temperature of the fruit is 20°C and its thermal conductivity is 0.8 W/m-K. Assume ν_{air} = 1.7 x 10^{-5} m^2/s.
   b. Determine the initial temperature gradient at the inner surface of the fruit and the Nusselt number corresponding to that. 4+4 = 8

4. Two parallel plates of size 1 m × 2 m are spaced 1 m apart. One plate is maintained at 1500 K and the other at 1000 K. The emissivities of the plates are 0.3 and 0.7 respectively. The plates are placed in a large room whose walls are at 300 K. The plates exchange heat with each other and with the room, but only the plate surfaces facing each other are to be considered in the analysis. *Assume* F_{12} = 0.285 and σ = 5.67 x 10^{-8} W/m^2-K^4.
   a. Draw the equivalent network for this radiation problem
   b. Calculate shape factors between the plates and the room
   c. Calculate the blackbody emissive power and the radiosity of the plates and the room
   d. Calculate the heat lost by plate at 1500 K. 4+2+6+4 = 16

5. A shell and tube heat exchanger with a total heat transfer requirement of 200 kW is used as an ammonia condenser with ammonia entering the shell at 50°C as saturated vapour. Water enters the single pass tube arrangement at a mass flow rate and inlet temperature of 2.39 kg/s and 20°C respectively. The overall heat transfer coefficient is calculated to be 1000 W/m^2-K.
   a. Determine the area to achieve heat exchanger effectiveness of 60%, Take C_p of water = 4.18 kJ/kg-K.
   b. Calculate the reduction in heat transfer if the water flow rate is reduced to half without altering the exchanger area and overall heat transfer coefficient. 5+3 = 8

6. A horizontal thin walled tube of diameter D is cooled by an internal fluid at T_w. The tube is immersed in a stagnant atmosphere of saturated vapour at T_{sat} (> T_w) which condenses as a laminar film on the outer surface.
   a. Sketch the variation of condensation heat transfer coefficient as T_w is increased from room temperature to T_{sat} and explain the trend(s).

b. It is proposed to increase total condensation rate by flattening the tube into rectangular cross section with negligible thickness. Calculate the percentage increase in condensation rate, if any assuming the same conditions for both.

4+7 = 10

7. Answer the following short questions:

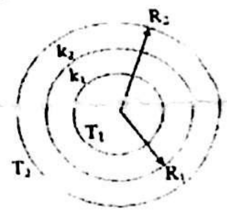
a. Sub-cooled water enters a steam generator and leaves it as a superheated steam. It exchanges heat with a hot stream of gas which is cooled down. Considering a counter current flow arrangement, sketch the temperature change of the two fluid streams along the length of the steam generator.

b. In a counter flow heat exchanger, cold water is heated from 20°C to 50°C exchanging heat with a stream of hot water entering at 65°C. The mass flow rate and specific heat of the two streams are same. Show the variation of temperature of the two streams along the length of heat exchanger.

c. If the overall heat transfer coefficient of the heat exchanger is 800 W/m^2K and the area for heat exchange is 0.1 m^2 for the above counter flow heat exchanger, what is the rate of heat transfer?

d. A horizontal isothermal flat plate loses heat to a uniform stream of fluid with a constant free stream temperature. Consider two cases Pr >> 1 and Pr << 1. Sketch the variation of the thickness of thermal and hydrodynamic boundary layers along the length of the plate in the laminar region. Also sketch the velocity and temperature profiles in the boundary layer at a particular location.

e. Two long concentric cylinders of radius R_1 and R_2 are as shown in the accompanying figure. The inner cylinder generates heat at a constant volumetric rate. For steady state show the radial temperature variation for $T_1 > T_2$, $k_1 < k_2$, where T is the temperature and k is the thermal conductivity.



5 x 4=20

Forced Convection – Internal Flow Correlations

- Circular pipe – Laminar Flow

$$\overline{Nu_D} = 3.66 \text{ -> Isothermal wall}$$
$$\overline{Nu_D} = 4.36 \text{ -> Isoflux wall}$$

- Circular pipe – Turbulent Flow

Dittus-Boelter correlation for smooth walls ($Re_D > 10{,}000$)

$$\overline{Nu_D} = 0.023 Re_L^{4/5} Pr^n \quad \textit{[n=0.3 for heated wall; n=0.4 for cold wall]}$$

Laminar film condensation

$$\overline{Nu_L} = 0.943 \left[\frac{\rho_l g(\rho_l-\rho_v)h'_{fg}L^3}{\mu_l k_l(T_{sat}-T_w)}\right]^{1/4} \rightarrow \text{Vertical plate}$$

$$\overline{Nu_D} = C \left[\frac{\rho_l g(\rho_l-\rho_v)h'_{fg}D^3}{\mu_l k_l(T_{sat}-T_w)}\right]^{1/4} \rightarrow C = 0.826 \text{ for sphere; } C = 0.729 \text{ for horizontal cylinder}$$