GX 807

OLLSCOIL NA hÉIREANN
The National University of Ireland

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Fourth Year (Mechanical, Biomedical) Engineering Examination

Heat Transfer (ME404)

Professor P.J. Mallon
Professor J.F. McNamara
Dr. N.J. Quinlan

Answer FIVE Questions
Time Allowed: 3 hours

The following tables and charts from Incropera and DeWitt, "Fundamentals of Heat and Mass Transfer" (4th ed.) are supplied:

Tables 6.2, 7.1–7.9, 8.4, 9.3, 12.1, A.1, A.4–A.6, A.8
Figures 7.11, 11.10–11.19, 12.15, 13.4-13.5, D.1-D.9

The Stefan-Boltzmann constant is $\sigma = 5.670\times10^{-8}$ W/m$^2\cdot$K^4

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(a) Define the terms fin effectiveness and fin efficiency. (4)

(b) In general, the temperature distribution in a fin of uniform cross-sectional area with uniform convection heat transfer coefficient is given by:

$$T(x)-T_{\infty} = C_1\, e^{mx} + C_2\, e^{-mx} \quad , \quad \text{where } m^2 = \frac{hP}{kA} .$$

What is the boundary condition at the tip (x=L) if the fin is very long (i.e. $L \rightarrow \infty$)? Derive expressions for the constants C_1 and C_2 in this case, and show that fin effectiveness is given by:

$$\varepsilon = \sqrt{\frac{kP}{hA}}$$

(8)

(c) The 40×60 mm surface of a chip operating at 80°C is exposed to an airflow at 25°C with a convection coefficient of 68 $\mathrm{Wm^{-2}K^{-1}}$. The surface must dissipate heat at a rate of 45 kW per square metre of base surface. Aluminium 2024-T6 fins of square 1.2×1.2 mm cross-section are attached to the surface, and there is no restriction on the length of the fins. The convection coefficient is the same for the base surface as for the fin surface. How many fins are required? (8)

2 Air at a free-stream temperature of 33°C flows at 12 m/s over the exterior of a pipe of 22 mm diameter with a surface temperature of 75°C. The direction of flow is perpendicular to the pipe centreline.

(a) Calculate the heat loss from the pipe per unit length. (7)

(b) A similar pipe is located deep inside a staggered tube bundle in which the tube spacing (centre to centre) is 60 mm in both the longitudinal and transverse directions. The air velocity measured upstream of the tube bundle is again 12 m/s, average air temperature in the tube bundle is 33°C, and pipe surface temperature is 75°C. Calculate the heat loss from the pipe per unit length in this case. (9)

(c) Explain the difference between the two results. (4)

3 A flat surface measuring 1.2 × 0.5 m is coated with a 0.1 mm thick layer of water. A heater maintains the temperature of the surface (and the water film) at 12°C. Air at a temperature of 6°C and a relative humidity of 35% flows over the surface at 1.1 m/s, parallel to its short side.

(a) If these conditions are maintained in steady state, how long will it take for all the water to evaporate? **(14)**

(b) What power must be supplied to the heater to maintain the surface temperature during the drying process? **(6)**

Note: The saturation pressure of water vapour is 943 Pa at 6°C and 1419 Pa at 12°C. The enthalpy of evaporation (h_{fg}) of water at 6°C is 2487.2 kJ/kg.

4 Consider a small volume of living tissue perfused by capillary blood flow at a rate ω (blood volume per unit time per unit tissue volume). Blood is delivered to tissue at arterial temperature T_a and metabolic heat is generated at a rate q'''_m per unit volume.

(a) Derive the Pennes bioheat transfer equation:

$$(\rho c)_t \frac{\partial T}{\partial t} = k_t \nabla^2 T + (\rho c)_b \omega_b (T_a - T) + q'''_m$$ **(8)**

(b) Explain the main assumption on which this equation is based and discuss its validity. **(6)**

(c) Heat is to be delivered ultrasonically to a region of the liver for a therapeutic procedure requiring steady temperature of 42°C. Before the procedure, tissue perfusion is measured as 0.0445 ml $s^{-1}ml^{-1}$, tissue conductivity is measured as 0.49 $Wm^{-1}K^{-1}$ and arterial temperature as 37.1°C. Assuming (as a first approximation) that temperature is uniform in the heated region, and that metabolic heat generation is negligible compared with the artificially delivered heat, estimate the steady state power delivery required (in W/m^3). **(6)**

Take the density and specific heat of blood as 1050 kg/m^3 and 3880 $Jkg^{-1}K^{-1}$ and derive any equations used.

5 An AISI 304 stainless steel sphere of 60 mm diameter emerges from a heat-treatment process at a uniform temperature of 680°C. It is immersed in water at a temperature of 20°C with a convection coefficient of 334 $Wm^{-1}K^{-1}$. It is required to calculate the time taken for the surface of the sphere to cool to 50°C.

(a) Would you expect a lumped capacitance analysis to be valid for this problem? Why? **(4)**

(b) Assuming that a lumped capacitance model is applicable, estimate the time taken for the surface to cool to 50°C. **(6)**

(c) Use Heisler and Grobler charts (provided) to carry out the same calculation. **(6)**

(d) Compare the two results. In your answer, comment on the reasons for any discrepancy and the reliability of each result. **(4)**

6 A condenser consists of a shell-and-tube heat exchanger with steam flowing in the shell and cold water in the single tube. Steam enters in a saturated condition at 100°C and remains saturated throughout the heat exchanger. Water enters the tube at 20°C and 1.2 m/s. The tube consists of copper pipe of length 5 m, inner diameter 15 mm and outer diameter 20 mm. The convection coefficient for heat transfer between the steam and the outer surface of the tube is 422 $Wm^{-2}K^{-1}$.

(a) Calculate the convection coefficient for heat transfer between the inner surface of the pipe and the water inside the pipe. **(8)**

(b) Calculate the overall heat transfer coefficient between water and steam. **(3)**

(c) How is analysis of the heat exchanger simplified by the fact that the steam is saturated? **(1)**

(d) Calculate the total heat transfer from the steam and the outlet temperature of the water.

(8)

Note: the conductive thermal resistance of a thick-walled tube is given by $\dfrac{\ln(r_o/r_i)}{2\pi kL}$.

7 A radiant heater consists of a cylindrical heated element and a reflector. A cross-sectional view of the assembly is shown in ***Figure 7*** with a graph of the spectral hemispherical emissivity of the element surface as a function of wavelength. The geometry is long and uniform in the direction perpendicular to the drawing. The reflector is a cylindrical surface of radius 1 m and subtends 60° as shown. The back of the reflector is insulated. The heater element has a diameter of 40 mm and is offset by 60 mm from a plane passing through the edges of the reflector. The temperatures of the element, reflector and surroundings are 1100 K, 380 K and 300 K respectively. The emissivity of the reflector is 0.1. The view factor from the element to the reflector is 0.538. The reflector surface is diffuse and grey and the element surface is diffuse.

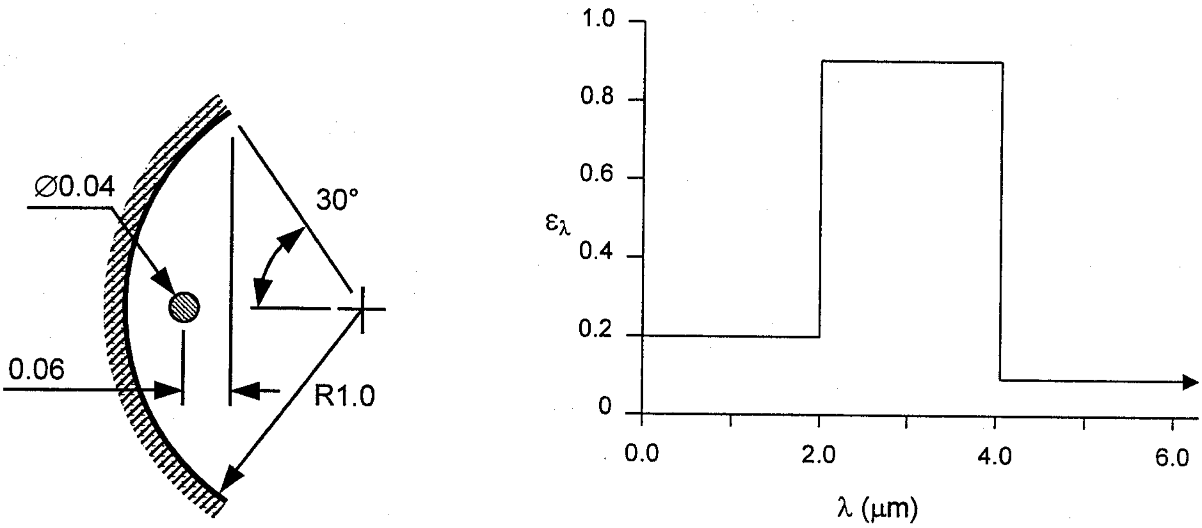

Figure 7 Cross-section of a radiant heater (dimensions in m, not to scale), and variation of the spectral hemispherical emissivity of the element with wavelength.

(a) Determine the total, hemispherical emissivity of the element. **(6)**

(b) What is the simplest way to incorporate the surroundings in an analysis of radiation exchange in this problem? **(2)**

(c) Labelling the element as surface 1 and the reflector as surface 2, calculate F_{22}, the view factor for radiation from the reflector surface to itself. **(8)**

(d) The element surface can be approximated as a grey surface with emissivity equal to the value determined in part (a) above. Construct a radiative resistance network for this arrangement. Label the network diagram, showing the quantities represented by each node and expressions for each resistance.

Write an expression for the power supplied to the element in terms of the surface's blackbody emission and radiosity. **(4)**