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Ollscoil na hÉireann, Gaillimh
National University of Ireland, Galway
Semester II Examinations 2004 / 2005

Exam Code(s)	4BM1, 4BG1
Exam(s)	Fourth Mechanical Engineering Fourth Biomedical Engineering
Module Code(s)	ME404
Module(s)	Heat Transfer
Paper No.	
Repeat Paper	
External Examiner(s)	Prof. J. A. Fitzpatrick
Internal Examiner(s)	Prof. J. F. McNamara Dr. N. J. Quinlan

Instructions: **Answer Question 1 and any 4 other questions.**
All questions will be marked equally.

The following tables and charts from Incropera and DeWitt, "Fundamentals of Heat and Mass Transfer" (4^{th} 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

Useful equations are listed on page 8 of this paper.

Duration	3 hours
No. of Pages	8
Department(s)	Mechanical and Biomedical Engineering
Course Co-ordinator(s)	Dr. N. J. Quinlan

Requirements:

MCQ	
Handout	✓
Statistical Tables	mathematical tables
Graph Paper	
Log Graph Paper	
Other Material	

QUESTION 1 IS COMPULSORY

1

(a) A roof surface measures 8×11 m. Ambient air is at 5°C, the convection coefficient is 120 W/m^{2}K, the emissivity of the surface is 0.74, and the effective average temperature of the surroundings is –60°C. Calculate the rate of heat loss from the roof when its surface temperature is 13°C. **(6)**

(b) The liner of a combustion chamber consists of a large, 50 mm–thick wall of AISI 347 stainless steel. The inner surface of the wall is at 580°C and the outer surface is cooled by water at 80°C with a convection coefficient of 477 W/m^{2}K. Calculate the steady state temperature of the outer surface. **(6)**

(c) A drink can measuring 70 mm in diameter and 140 mm in height is removed from a fridge at 4°C. It stands upright, unopened, in ambient air at 25°C with a convection coefficient of 6.3 W/m^{2}K. Treat the can and contents as water, assume the contents are always at spatially uniform temperature, and neglect radiation effects. How long will it take for the can to warm to 10°C? **(8)**

ANSWER ANY 4 OF QUESTIONS 2–7

2

(a) Explain the meaning of *efficiency* (η) for a fin, in words and in an equation. Is there a maximum possible value for fin efficiency, and if so, what is it? **(3)**

(b) Explain the meaning of *effectiveness* (ε) for a fin, in words and in an equation. Is there a maximum possible value for fin effectiveness, and if so, what is it? **(3)**

(c) The temperature distribution in a fin with convection at the tip is given by the equation below.

$$\frac{T(x)-T_\infty}{T_b-T_\infty}=\frac{\left(\frac{km}{h}+1\right)e^{m(L-x)}+\left(\frac{km}{h}-1\right)e^{-m(L-x)}}{\left(\frac{km}{h}+1\right)e^{mL}+\left(\frac{km}{h}-1\right)e^{-mL}} \qquad \text{where} \qquad m^2=\frac{hP}{kA_c}$$

Derive an expression for total heat transfer from the fin, and hence show that the effectiveness of the fin is given by:

$$\varepsilon=\frac{km}{h}\frac{\left(\frac{km}{h}+1\right)e^{mL}-\left(\frac{km}{h}-1\right)e^{-mL}}{\left(\frac{km}{h}+1\right)e^{mL}+\left(\frac{km}{h}-1\right)e^{-mL}}$$ **(6)**

(d) A 200×75 mm surface on a motor casing is to be cooled with 25 fins of 2×60 mm rectangular cross-section and 40 mm length (perpendicular to the base surface). The base surface is at 60°C, the ambient air is at 20°C, and the convection coefficient is 8.8 W/m^{2}K. The fins are made of AISI 302 stainless steel. Calculate the effectiveness and efficiency of these fins, the heat transfer per fin, and the total heat transfer from base surface and fins. **(8)**

3 A pipe of outer diameter 15 mm is at a temperature of 80°C. It is covered in calcium silicate insulation ($k = 0.055$ W/mK) with an outer diameter of 60 mm. The convection coefficient for heat transfer between ambient air (which is at 20°C) and the insulation is 35 W/m^{2}K.

(a) Using a thermal resistance network, derive a general equation for heat loss from an insulated pipe, accounting for conduction through the insulation and convection at the outer surface of the insulation. The equation should give heat transfer rate as a function of pipe and ambient temperatures, conductivity of the insulation, convection coefficient, and inner and outer radii of the insulation. Make use of the equations on page 8. **(6)**

(b) Calculate the rate of heat loss from the above pipe, per unit length. **(2)**

(c) Calculate the temperature of the outer surface of the insulation. **(4)**

(d) It is required to reduce the heat loss from the pipe to 20 W/m. To achieve this, an electrical heating mat is wrapped around the insulation layer. Calculate the outer surface temperature required to satisfy the reduced heat loss criterion, and hence calculate the required heating power (per unit length). **(8)**

(Note that heat released from this heater may be conducted inwards through the insulation, or convected outwards. The heater is thin, so that temperature is the same on its inner and outer surfaces, and it presents no conduction resistance).

4

(a) Starting with the correlation for local Nusselt number Nu_x in laminar flow over a flat plate (Eq. 7.23 in the table provided), derive the correlation for average Nusselt number $\overline{Nu}_x$ over the region 0 to x (i.e. Eq. 7.31). Note the average heat transfer coefficient is defined as:

$$\overline{h} = \int_0^x h(x)dx$$

(One possible starting point is to rewrite the local correlation to give h as a function of x). **(8)**

(b) Write down the mass transfer correlations for average Sherwood number, for (i) laminar and (ii) mixed laminar/turbulent flow over a flat plate. **(2)**

(c) Dry air at atmospheric pressure and 40°C flows at 12 m/s over a plate which is wetted with a 0.2-mm thick film of water. The plate and the water are also at 40°C, and the plate is 1 m wide. Calculate the rate of mass transfer of water from the surface and the time required to dry out the plate completely if the plate is (i) 0.4 m and (ii) 1.2 m long in the direction of flow. **(8)**

(d) How and why would the results differ if the plate and water film were at 80°C (with the air remaining at 40°C)? **(2)**

5 Saline solution at 4°C is injected steadily into a vein of diameter 6 mm. Within a short distance downstream (distal) of the injection point, the injected liquid mixes thoroughly with the flowing blood to give a liquid mixture at a homogeneous temperature of 30°C, density of 999 kg/m^3, specific heat of 3940 J/kgK, thermal conductivity of 0.51 W/mK and dynamic viscosity of 0.0028 Ns/m^2. The flow rate of the mixture is 17 g/s. Consider a 400 mm length of vein downstream of the point at which the blood and saline become well-mixed. Assume that flow is steady, and that the temperature of the interior vein surface is uniform at 37°C.

(a) What is the Prandtl number of the mixture? **(2)**

(b) Is the flow from the injection point downstream laminar or turbulent? Is it hydrodynamically fully developed? Is it thermally fully developed? Justify your answers. **(4)**

(c) Calculate the average heat transfer coefficient for flow of the mixture through the 400 mm length of vein. **(6)**

(d) Based on your calculated heat transfer coefficient, estimate the vein length which would be required for blood mixture to reach 36°C. **(6)**

(e) Is the assumption of uniform vein wall temperature a reasonable one? Explain your answer, and suggest how a more realistic analysis could be made. **(2)**

6 A crossflow heat exchanger, used to cool air, consists of tubes arranged in staggered rows, as shown in Figure 6. Air flows over the tubes, perpendicular to the rows, which each contain 15 tubes. Air approaches the tube bank at 200°C, 100 kPa, and a velocity of 22 m/s. The tubes are arranged in a duct which is 195 mm wide. 1.02 kg/s of water in total flows through the tubes, entering at 27°C. The convection heat transfer coefficient for water flow in the tubes is 315 W/m^2K. The tubes are 200 mm long (perpendicular to the plane of the diagram), 6 mm in diameter, and spaced at centre-to-centre pitches of 12 mm in both the transverse and longitudinal directions. They are thin-walled and highly conductive. The heat exchanger must be designed to cool the air to 70°C.

(a) Calculate the mass flow rate of air, the total heat transfer, and hence outlet temperature of the water. **(4)**

(b) Estimate the convection coefficient for heat transfer from the air to the tube surfaces. **(8)**

(c) Hence, calculate the overall heat transfer coefficient (U) for heat transfer from air to water. **(1)**

(d) Using a heat exchanger analysis, determine the number of tube rows required. **(7)**

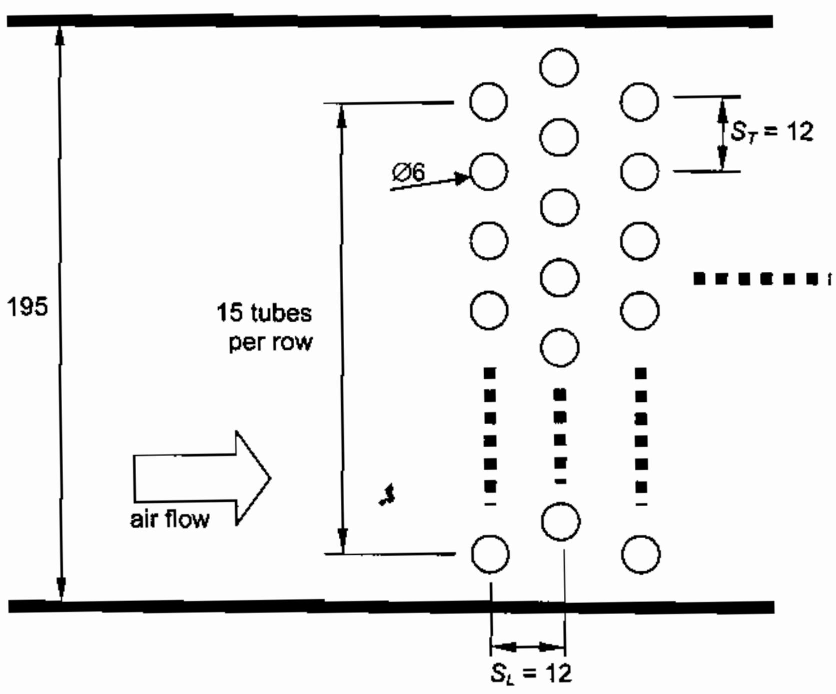

Figure 6 Schematic diagram of tubes in heat exchanger. Dimensions in mm, not to scale.

7 A cylindrical pipe of diameter 100 mm and length 25 m is suspended in a large room of dimensions 25×10×5 m, as shown in Figure 7. The pipe is aligned parallel with the longest sides of the room. The pipe conveys liquid oxygen and its outer surface (surface 1) is at a temperature of 120 K. The average temperature of the room's walls (surface 2) is 20°C. The pipe's surface is diffuse and grey, with an emissivity $\varepsilon_1 = 0.48$.

(a) Using a radiative resistance network, or otherwise, prove that the net radiation heat transfer rate from the walls to the pipe is given by:

$$q \cong \sigma\varepsilon_1 \frac{\pi}{4} d_1^2 L_1 \left(T_2^4 - T_1^4\right)$$ **(6)**

Hence, calculate the net radiation heat transfer rate from the walls to the pipe.

(b) To reduce radiant heating of the pipe, a radiation shield is installed around it. It consists of a thin-walled tube of diameter d_s = 200 mm and emissivity $\varepsilon_s = 0.15$. It is concentric with the pipe.

Draw a radiative resistance network for the arrangement. Calculate the net radiation heat transfer rate from the walls to the pipe in this arrangement, and the percentage reduction in heat transfer achieved by installation of the shield. **(12)**

(c) Explain briefly how the performance of the shield depends on its diameter, if at all. What other effects might be important in determining an optimum configuration of the shield? **(2)**

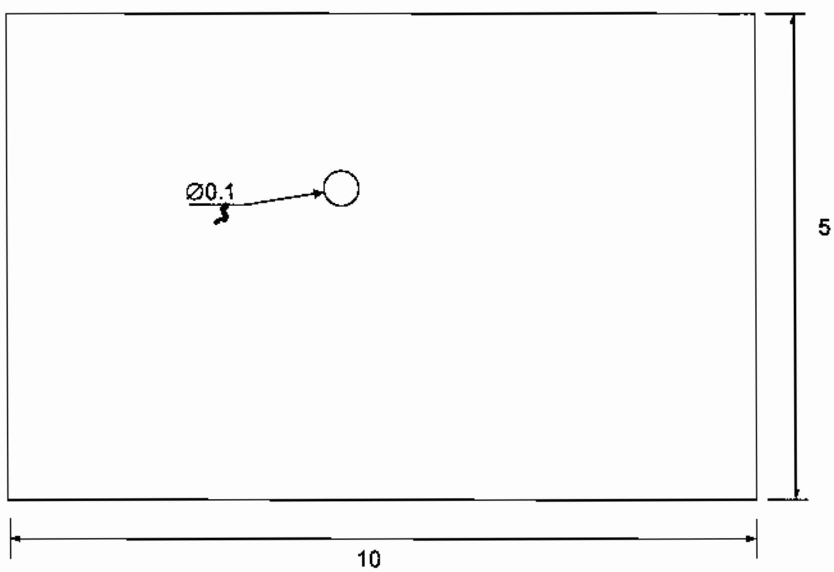

Figure 7 Schematic diagram of pipe suspended in a large room. Dimensions in m, not to scale.