Birla Institute of Technology and Science Pilani

K. K. Birla Goa Campus

Comprehensive Examination 2022-23

Heat Transfer (ME F220)

Date: 13-05-2023 Time: 2.00 PM - 5.00 PM Total Marks: 80

Instruction:

- All questions are compulsory.
- Answer all parts of the question in the same place and start each question in a new page.
- Symbols have their usual meaning.
- Make suitable assumptions whenever necessary. Please state your assumptions clearly.

Q 1. A metal steam pipe ($k = 45\,\text{W/m}\cdot\text{K}$) of 5 cm inner diameter and 6.5 cm outer diameter is lagged with 2.75 cm radial thickness of high-temperature insulation having a thermal conductivity of $1.1\,\text{W/m}\cdot\text{K}$. The convective heat transfer coefficients on the inside and outside surfaces are $h_i = 4650\,\text{W/m}^2\cdot\text{K}$ and $h_o = 11.5\,\text{W/m}^2\cdot\text{K}$, respectively. If the steam temperature is 200 °C and the ambient temperature is 25 °C, calculate: [10]

(a) Heat loss per meter length of pipe

(b) Temperature of the interface of pipe and insulation

(c) Overall heat transfer coefficients based on inside area U_i.

Q 2. A plane wall of thickness $L = 0.1\,\text{m}$ and thermal conductivity $k = 25\,\text{W/m}\cdot\text{K}$ having uniform volumetric heat generation of $\dot{q} = 0.3\,\text{MW/m}^3$ is insulated on one side, while the other side is exposed to a fluid at $T_\infty = 92\,°\text{C}$. The convection heat transfer coefficient between the wall and the fluid is $h = 500\,\text{W/m}^2\cdot\text{K}$. Obtain an equation for the maximum temperature T_0 in the wall in terms of T_∞, $\dot{q}$, k, L, and h and compute it. [10]

The steady-state heat conduction equation with heat generation is given as

$$\frac{d^2T}{dx^2} + \frac{\dot{q}}{k} = 0$$

Q 3. The hydrodynamic and thermal boundary layer equations are given as [10]

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{dP}{dx} + \nu\frac{\partial^2 u}{\partial y^2} \quad (2)$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} \quad (3)$$

Express the Eqs. (1) to (3) in dimensionless form using suitable reference scales.

Q 4. A metallic airfoil of elliptical cross section has a mass of 50 kg, surface area of $12\,\text{m}^2$, and a specific heat of $0.50\,\text{kJ/kg}\cdot\text{K}$. The airfoil is subjected to airflow at 1 atm, 25 °C, and 5 m/s along its 3 m long side. The average temperature of the airfoil is observed to drop from 160 °C to 150 °C within 2 min of cooling. Assuming the surface temperature of the airfoil to be equal to its average temperature and using the momentum–heat transfer analogy, determine the average friction coefficient of the airfoil surface. Properties of air are: $\rho = 1.1614\,\text{kg/m}^3$, $\nu = 15.89 \times 10^{-6}\ \text{m}^2\text{/s}$, $k = 26.3 \times 10^{-3}\ \text{W/m}\cdot\text{K}$, and $Pr = 0.707$. [10]

Q 5. Water entering at 20 °C is to be heated to 60 °C while flowing through a tube of 4 cm diameter and 9 m length. The tube surface is maintained at 90 °C. Determine the mass flow rate $\dot{m}$ of the water. Take properties of water at mean bulk temperature of 40 °C as: $\rho = 993\,\text{kg/m}^3$, $c_p = 4170\,\text{J/kg}\cdot\text{K}$, $k = 0.64\,\text{W/m}\cdot\text{K}$, $\nu = 0.65 \times 10^{-6}\ \text{m}^2/\text{s}$, and $Pr = 4.206$. [10]

Q 6. Consider a steady and laminar flow of fluid through a constant cross-sectional pipe. The fluid enters the pipe at a mean temperature of $T_{m,i}$.

(a) Assuming heat transfer from the pipe surface to the fluid, obtain a governing differential equation to predict the variation of mean fluid temperature T_m with the flow direction x as given below. [3]

$$\frac{dT_m}{dx} = \frac{q_s'' p}{\dot{m} c_p}$$

where $q_s'', p, \dot{m}$, and c_p denote the surface heat flux, perimeter, mass flow rate, and specific heat, respectively.

(b) The surface temperature of the pipe T_s is maintained constant. Solve the differential equation obtained in part (a) and obtain an expression for the variation of mean fluid temperature T_m with x. [7]

Q 7. Steam is to be condensed on the shell side of a 1-shell-pass and 8-tube-passes condenser, with 50 tubes in each pass, at 30 °C ($h_{fg} = 2431\,\text{kJ/kg}$). Cooling water ($c_p = 4180\,\text{J/kg}\cdot\text{K}$) enters the tubes at 15 °C at a rate of 1800 kg/h. The tubes are thin-walled, and have a diameter of 1.5 cm and length of 2 m per pass. The overall heat transfer coefficient is $3000\,\text{W/m}^2\cdot\text{K}$. Determine (a) the rate of heat transfer and (b) the rate of condensation of steam for counter-flow arrangement. [10]

Q 8. Answer the following

(a) Sketch the velocity and thermal boundary layers, and illustrate their relative thickness for $Pr \ll 1$ and $Pr \gg 1$. [2]

(b) The local Nusselt number Nu_x for laminar flow along a flat plate is given by [3]

$$Nu_x = 0.332\ Re_x^{1/2}\ Pr^{1/3}$$

Develop a relation for the average heat transfer coefficient $\overline{h}$ from $x = 0$ to $x = L$.

(c) A double-pipe parallel-flow heat exchanger is to heat water ($c_p = 4180\,\text{J/kg}\cdot\text{K}$) from 25 °C to 60 °C at a rate of 0.2 kg/s. The heating is to be accomplished by geothermal water ($c_p = 4310\,\text{J/kg}\cdot\text{K}$) available at 140 °C at a mass flow rate of 0.3 kg/s. The inner tube is thin-walled and has a diameter of 0.8 cm. If the overall heat transfer coefficient of the heat exchanger is $550\,\text{W/m}^2\cdot\text{K}$, determine the length of the tube required to achieve the desired heating. [5]

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If needed, use the following information.

Dittus–Boelter correlation for the internal flow is given as

$$Nu_D = 0.023\ Re_D^{4/5}\ Pr^{0.4}$$

Effectiveness ε of a counter-flow heat exchanger when $C_r = 0$ is given by

$$\varepsilon = 1 - \exp[-\text{NTU}]$$