INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR

End-Autumn Semester 2019-20

Date of Examination: **21-11-2019** Session: **FN** Duration: **3 hrs** Full Marks: **100**

Subject No. : **ME30005** ____________________ Subject : **Heat Transfer**

Department/Center/School: **Mechanical Engineering**

Specific charts, graph paper, log book etc., required: **Nil**

Special Instructions (if any): **Answer all questions**

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1. Fill the blanks with an **appropriate expression/sentence or numerical value:**

a) Lumped capacitance model can be used to solve transient heat conduction problems when____________________________

b) Reynolds analogy between momentum and heat transfer is given by the expression ______________

c) A current carrying copper wire (**k = 385 W/m.K**) of **1 mm diameter** is covered with **1 mm thick** PVC insulation (**k = 0.17 W/m.K**). When the convective heat transfer coefficient between the wire and surrounding air is **5 W/m².K**, addition of insulation is seen to increase the electric current carrying capacity of the copper wire, this is because_______________________. The electrical resistivity may be assumed to remain constant.

d) For fluid flow and heat transfer through a circular tube, the flow is said to be thermally fully developed when____________________

e) The length of a fin is not optimized based on fin efficiency because______________

f) In a heat transfer problem when the ratio $\left({Gr}/{Re^2}\right) \approx 1$, it implies that ________________ (where Gr is the Grashof number and Re is the Reynolds number)

g) The LMTD of a heat exchanger in which the hot fluid condenses at T_h and the cold fluid boils at T_c is ________________

h) If the surface temperature of the filament of an incandescent lamp is **2000°C**, then the wavelength at which the spectral emissive power reaches a peak is approximately equal to________

i) In pool boiling, the primary mechanism(s) of heat transfer in the film boiling region is(are)________________

j) In Nusselt's laminar film condensation theory, the 2 basic assumptions made regarding the conditions at the liquid-vapour interface are__________________________

(2 x 10 = 20)

2a. For flow of fluid through a long circular tube, draw the temperature and velocity profiles in the developing (entrance) region. The Reynolds number calculated based on tube diameter is **1800** and the tube wall is maintained at a constant temperature that is lower than bulk fluid temperature. Also explain how the centreline velocity and temperature vary along length in the entrance region. **(5+5 = 10)**

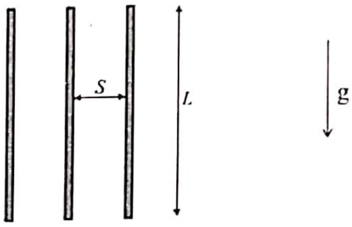
2b. In a power plant, the boiler feed water is heated by passing it through a circular tube that is exposed to the exhaust gases from the furnace. The feed water has to be heated from an inlet temperature of **30°C** to an outlet temperature of **120°C**. Assuming that the exhaust gases provide a near uniform tube wall of temperature of **150°C**, estimate the length of the tube required. The tube has an inner diameter of

4 cm and the feed water flow rate is **3 kg/s**. Assume that the feed water is pressurized such that it does not undergo any phase change as it flows through the tube. **(10)**

Properties of water at 75°C are:

ρ = 975 kg/m³, c_p = 4190 J/kg-K, μ = 37.79 X 10^{-5} kg/m-s, k_f = 0.6531 W/m-K

3a. As shown in the figure, a vertical array of printed circuit boards is immersed in quiescent ambient air at **17°C**. Although the components on the board protrude from their substrates on the circuit boards, it is reasonable, as a first approximation, to assume them as flat plates with uniform surface heat flux. Consider boards of length and width **L = W = 0.4m** and spacing **S = 25mm**. If the maximum allowable temperature of the board is **77°C**, what is the maximum allowable power dissipation per board? Assume ρ = *1.03 kg/m³*, *Pr = 0.7*, μ = *2. x 10^{-5} kg/m-s* and *k = 0.03 W/m-K.* **(15)**



3b. Under what conditions can natural convection from the outer surface of a vertically oriented cylinder be approximated as a vertical plate? **(5)**

4a. An opaque horizontal plate is perfectly insulated on its backside. The irradiation on the plate is **2500 W/m²** of which **500 W/m²** is reflected. The plate is at **227°C** and has an emissive power of **1200 W/m²**. Air at **127°C** flows over the plate leading to a convective heat transfer coefficient of **15 W/m²·K**. Estimate the following for the plate: a) Emissivity (ε), b) Absorptivity (α), c) Radiosity (J), and d) To maintain the plate at equilibrium under the stated conditions, what should be the net heat transfer rate from/to the plate per unit area of the plate (W/m²) and what is the direction of the net heat transfer. **(6+4 = 10)**

4b. The floor of an indoor stadium has to be maintained at a surface temperature of **21°C** while the surrounding walls and roof are at a mean surface temperature of **42°C**. The floor has an area of **5000 m²**, while the combined area of surrounding walls and roof is **15000 m²**. The emissivity of the floor is **0.85.** while the surrounding walls and roof may be assumed to be blackbodies. To maintain the floor at the required temperature, pipes are buried under the floor through which chilled water flows. A) Find the required flow rate of chilled water, if the chilled water temperature increases by **10 K** as it flows through buried pipes under the floor. The specific heat of chilled water is **4.2 kJ/kg.K**. B) How the flow rate of chilled water can be reduced without changing either the temperatures or the geometry? State clearly all the assumptions made. **(10+5=15)**

5a. A finned tube heat exchanger employs condensing steam at **100°C** inside the tubes to heat air from **30°C** to **70°C** as it flows across the fins. A total heat transfer of **50 kW** is to be accomplished and $U = 25\ \mathrm{W/m^2-K}$. Calculate the heat transfer area of the heat exchanger. Assume Cp of air to be 1.0 kJ/kg-K and latent heat of vaporization of water to be 2260 kJ/kg. **(10)**

5b. If the length of a counter flow heat exchanger is increased, will its effectiveness improve or deteriorate? Justify your answer with a short explanation/equation. (5)

End of the question paper

Useful data

Stefan Boltzmann constant: **5.667 x 10^{-8} W/m^2-K^4,**

Coefficient of Wien's law: **2900 μ-K**

Planck's Law: $e_{b\lambda} = \frac{2\pi C_1}{\lambda^5\left[e^{C_2/\lambda T}-1\right]}$ where C_1 = 5.96 x 10^{-17} W-m^2, C_2= 0.014387 m-K

Some useful Correlations

Forced Convection:

- Isothermal Flat Plate: $Nu_x = 0.332 Re_x^{1/2} Pr^{1/3}$ (laminar flow); $Nu_x = 0.0296 Re_x^{4/5} Pr^{1/3}$ (turbulent flow)
- Circular pipe – Laminar Flow: $\overline{Nu_D} = 3.66$ -> Isothermal wall $\overline{Nu_D} = 4.36$ -> Isoflux wall
- Circular pipe – Turbulent Flow
- Dittus-Boelter equation: $\overline{Nu_D} = 0.023 Re_D^{4/5} Pr^n$ *[n=0.3 for heated wall; n=0.4 for cold wall]*

Natural Convection:

- Vertical Flat Plate: Laminar Flow ($Ra_L < 10^9$) Turbulent Flow ($10^9 < Ra_L < 10^{12}$)

$$\overline{Nu_L} = 0.68 + \frac{0.670\, Ra_L^{1/4}}{\left[1+(0.492/\mathrm{Pr})^{9/16}\right]^{4/9}}$$

$$\overline{Nu_L} = \left\{0.825 + \frac{0.387\, Ra_L^{1/6}}{\left[1+(0.492/\mathrm{Pr})^{9/16}\right]^{8/27}}\right\}^2$$

- Horizontal cylinder:

$$\overline{Nu_D} = \left\{0.60 + \frac{0.387\, Ra_D^{1/6}}{\left[1+(0.559/\mathrm{Pr})^{9/16}\right]^{8/27}}\right\}^2 \qquad Ra_D < 10^{12}$$

- Natural convection through an array of vertical plates

$$\overline{Nu_S} = \left[\frac{C_1}{(Ra_S\, S/L)^2} + \frac{C_2}{(Ra_S\, S/L)^{1/2}}\right]^{-1/2}$$ Isothermal Surfaces

$$Nu_{S,L} = \left[\frac{C_1}{Ra_S^*\, S/L} + \frac{C_2}{(Ra_S^*\, S/L)^{2/5}}\right]^{-1/2}$$ Isoflux Surfaces

$$Nu_{S,L} = \left(\frac{q_s''}{T_{s,L} - T_\infty}\right)\frac{S}{k} \qquad Ra_S^* = \frac{g\beta q_s'' S^4}{k\alpha\nu}$$

Surface Condition	C_1	C_2	S_{opt}	S_{max}/S_{opt}
Symmetric isothermal plates ($T_{s,1} = T_{s,2}$)	576	2.87	$2.71(Ra_S/S^3L)^{-1/4}$	1.71
Symmetric isoflux plates ($q''_{s,1} = q''_{s,2}$)	48	2.51	$2.12(Ra_S^*/S^4L)^{-1/5}$	4.77
Isothermal/adiabatic plates ($T_{s,1}, q''_{s,2} = 0$)	144	2.87	$2.15(Ra_S/S^3L)^{-1/4}$	1.71
Isoflux/adiabatic plates ($q''_{s,1} = q''_{s,2} = 0$)	24	2.51	$1.69(Ra_S^*/S^4L)^{-1/5}$	4.77