UNIVERSITY OF RUHUNA

Faculty of Engineering

End-Semester 8 Examination in Engineering: February 2020

Module Number: ME8301 **Module Name: Heat Transfer**

[Three Hours]

[Answer **all questions**, each question carries **12** marks]

Q1. a) One-dimensional heat conduction through a cylindrical layer of inner radius r_1, outer radius r_2, length L, and average thermal conductivity k with no heat generation can be expressed as,

$$\dot{Q}_{cond,cyl} = \frac{T_1 - T_2}{R_{cyl}}$$

Where

$$R_{cyl} = \frac{\ln(r_2/r_1)}{2\pi Lk}$$

The two surfaces of the cylindrical layer are maintained at constant temperatures T_1 and T_2.

Consider heat convective heat transfer from a solid surface of area A_s and temperature T_s to a fluid whose temperature is sufficiently far from the surface is T_α, with a convection heat transfer coefficient h. Convection heat transfer rate can be expressed as,

$$\dot{Q}_{conv} = \frac{T_s - T_\alpha}{R_{conv}}$$

Where

$$R_{conv} = \frac{1}{hA_s}$$

Figure Q1 shows a two-layered composite cylinder of Length L with convective boundary conditions on both sides. Show that steady heat transfer rate through this composite cylinder can be expressed as,

$$\dot{Q} = \frac{\Delta T}{\sum R_{th}}$$

Where, $\Delta T_{overall} = T_{hf} - T_{cf}$ and

$$\sum R_{th} = \frac{1}{2\pi L}\left[\frac{1}{h_{hf}r_1} + \frac{1}{k_1}ln\left[\frac{r_2}{r_1}\right] + \frac{1}{k_2}ln\left[\frac{r_3}{r_2}\right] + \frac{1}{h_{cf}r_3}\right]$$

$k_1 = Thermal\ conductivity\ of\ inner\ cylinder\ 1$
$k_2 = Thermal\ conductivity\ of\ outer\ cylinder\ 2$
$r_1 = Inner\ radius\ of\ cylinder\ 1$
$r_2 = Outer\ radius\ of\ cylinder\ 1$
$r_3 = Inner\ radius\ of\ cylinder\ 2$
$T_1 = Temperature\ at\ inner\ surface\ of\ cylinder\ 1$
$T_2 = Temperature\ at\ outer\ surface\ of\ cylinder\ 1$
$T_3 = Temperature\ at\ outer\ surface\ of\ cylinder\ 2$

[4.0 Marks]

b) A 10m long steel tube has 5 cm inner diameter, 7.6 cm outer diameter and thermal conductivity, k =15W/m°C. It is covered with 2cm thickness insulation material with thermal conductivity, k = 0.2 W/m°C. A hot gas at 330 °C flow inside the steel tube. The outer surface of the insulation is exposed to cooler air at 30 °C with h_{cf} = 60 W/m²°C. Taking the heat transfer coefficient inside the steel tube as h_{hf} = 60 W/m²°C, determine,

i) The overall heat transfer coefficient (U) for the system.

ii) Rate of heat loss from the hot gas.

iii) Temperature drops across the steel tube and the insulation.

[8.0 Marks]

Q2. a) Explain why is a counter-flow heat exchanger more effective than a parallel-flow heat exchanger?

[4.0 Marks]

b) A Shell and tube heat exchanger is to be designed to condense an organic vapor using water. Organic vapor flow at a rate of 500 kg/min and is enters the heat exchanger at 82 °C which is its saturation temperature. Cooling water flow at a rate of 60 kg/s and is enters the heat exchanger at 13 °C. The overall heat transfer coefficient is 475 W/m²C. Latent heat of condensation of the organic vapor is 600 kJ/kg.

i) Draw temperature profiles for each fluid.

ii) Calculate the number of tubes required, if tubes have 25 mm outer diameter and 2 mm thickness and average water velocity in tubes is 2 m/s.

iii) Calculate the number of tube passes, the number of tubes per pass, and the length of the tubes, if the tube length must not be longer than 4.5m (The correction factor for a condenser or boiler is F = 1).

[8.0 Marks]

Q3. a) What is the physical significance of the Reynolds number? How is it defined for external flow over a plate of length L?

[2.0 Marks]

b) What does the friction coefficient represent in flow over a flat plate? How is it related to the drag force acting on the plate?

[2.0 Marks]

c) Air at 25 °C flows over a flat plate at 2.5 m/s. The size of the plate is measured to be 600 mm X 300 mm and a uniform temperature of 95 °C is maintained at the plate.

If Properties of air at 60°C,

$Pr = 0.696$

$\nu = 1897 * 10^{-6}\ m^2/s$

$k = 0.02896$

Determine the total drag force and the rate of heat transfer per unit width of the entire plate.

The *average Nusselt number* over an entire flate plate,

$$Laminar: Nu = \frac{hL}{k} = 0.664 Re_L^{0.5} Pr^{1/3} \quad Re_L < 5 * 10^5$$

$$Turbulent: Nu = \frac{hL}{k} = 0.037 Re_L^{0.8} Pr^{1/3} \quad 5 * 10^5 \leq Re_L \leq 10^7$$

The *average friction coefficient* over an entire flat plate,

$$Laminar: C_f = \frac{1.33}{Re_L^{1/2}} \quad Re_L < 5 * 10^5$$

$$Turbulent: C_f = \frac{0.074}{Re_L^{1/5}} \quad 5 * 10^5 \leq Re_L \leq 10^7$$

Drag force exerted by a fluid on a body,

$$F_D = C_D \frac{1}{2} \rho V^2 A$$

[8.0 Marks]

Q4. a) Draw the boiling curve and identify the different boiling regimes. Also, explain the characteristics of each regime.

[5.0 Marks]

b) Water is to be boiled at atmospheric pressure in a polished copper pan by means of an electric heater. The diameter of the pan is 0.38m and its inner surface of the bottom is maintained at 115 °C. Determine,

i) Surface heat flux.
ii) Power required to boil the water.
iii) The rate of evaporation of water.
iv) Maximum heat flux that can be attained in the nucleate boiling regime.

$Density\ of\ the\ water, \rho_l = 961\ kg/m^2$
$Prandtl\ Number\ of\ water, Pr = 1.740$
$Specific\ heat\ of\ the\ water, C_{pl} = 4216 J/kgK$
$Dynamic\ viscosity\ of\ water, \mu_l = 281.6\ Ns/m^2$
$Density\ of\ water, \rho_l = 961\ kg/m^2$
$Density\ of\ vapor, \rho_v = 0.597\ kg/m^2$
$Enthalpy\ of\ vaporization, h_{fg} = 2256.9 kJ/kg$
$Gravitational\ acceleration, g = 9.81\ m/s^2$

For the boiling of water on a copper surface,
$C_{sf} = 0.013$
$n = 1$

Surface tension of liquid-vapor interface for water at 100 °C,
$\sigma = 0.5888\ N/m$

$$Heat\ flux\ in\ nucleate\ boiling, \frac{Q}{A} = \mu_l * h_{fg} * \left[\frac{g * (\rho_l - \rho_v)}{\sigma}\right]^{0.5} * \left[\frac{C_{pl} * \Delta T}{C_{sf} h_{fg} Pr^n}\right]^3$$

$$Critical\ heat\ flux\ in\ nucleate\ boiling, \frac{Q}{A} = 0.18 h_{fg} * \rho_v \left[\frac{\sigma * g * (\rho_l - \rho_v}{\rho_v^2}\right]$$

[7.0 Marks]

Q5. a. Calculate the following for an industrial furnace in the form of blackbody emitting radiation at 2500 °C.

i) Spectral emissive power at 1.2 μm length.
ii) Wavelength at which the emission is maximum.
iii) Total emissive power.

iv) Total emissive power of the furnace if it is assumed as a real surface with emissivity equal to 0.9.

Plank Law,

$$(E_\lambda)_b = \frac{C_1 \lambda^{-5}}{\exp\left(\frac{C_2}{\lambda T}\right) - 1}$$

Where

$C_1 = 0.3742 * 10^{-15}\ W.m^4/m^2$
$C_2 = 1.4388 * 10^{-2}\ mK$

Wien's displacement law,

$$\lambda_{max} T = 2898$$

[4.0 Marks]

b. An experiment is conducted to determine the emissivity of a certain material. A long cylindrical rod of 0.01 m diameter is coated with this new material and is placed in an evacuated long cylindrical enclosure of diameter 0.1 m and emissivity 0.95, which is cooled externally and maintained at a temperature of 200 K at all times. The rod is heated by passing electric current through it. When steady operating conditions are reached, it is observed that the rod is dissipating electric power at a rate of 8 W per unit of its length and its surface temperature is 500 K. Based on these measurements, determine the emissivity of the coating on the rod.

Radiation heat transfer between concentric cylinders is given by,

$$\dot{Q}_{12} = \frac{A_1 \sigma (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1 - \epsilon_2}{\epsilon_2}\left(\frac{r_1}{r_2}\right)}$$

$\epsilon_1 = Emisivity\ of\ cylinder\ 1\ surface$
$\epsilon_2 = Emisivity\ of\ cylinder\ 2\ surface$
$r_1 = radius\ of\ cylinder\ 1$
$r_2 = radius\ of\ cylinder\ 2$
$T_1 = Temperature\ at\ surface\ of\ cylinder\ 1$
$T_2 = Temperature\ at\ surface\ of\ cylinder\ 2$
$\sigma = Stefan\ Boltzman\ constant = 5.670 * 10^{-8} W/m^2 K^4$

[8.0 Marks]

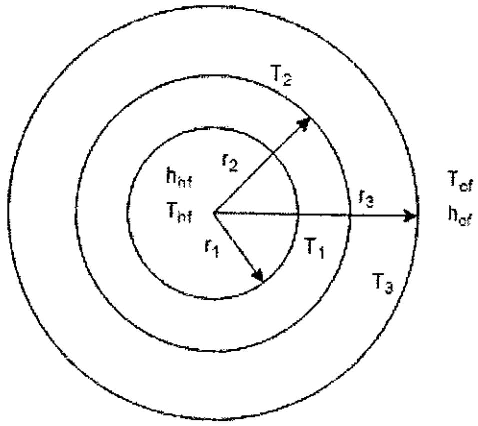

Figure Q1