2014 Heat Transfer Final Exam

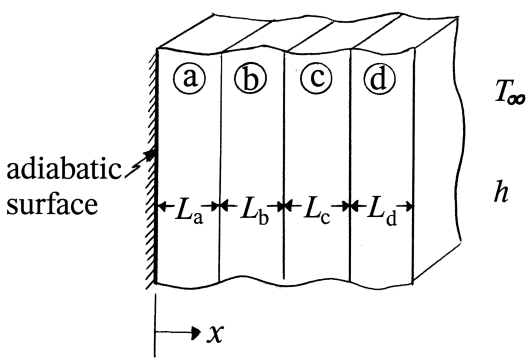
June 15th 2014

18:00 — 21:00

NO NOTES OR BOOKS; USE HEAT TRANSFER TABLES THAT WERE DISTRIBUTED; ALL QUESTIONS HAVE EQUAL VALUE; ANSWER ALL 6 QUESTIONS.

Question #1

Consider steady-state one-dimensional heat conduction through a composite wall:



with the lengths $L_a = 0.1$ m, $L_b = 0.1$ m, $L_c = 0.1$ m, $L_d = 0.1$ m, the thermal conductivities $k_a = 20$ W/m·°C, $k_b = 50$ W/m·°C, $k_c = 10$ W/m·°C, $k_d = 5$ W/m ·°C, the heat generation per unit volume $S_a = 0$, $S_b = 10^4$ W/m^3, $S_c = 0$, $S_d = 0$, the convection heat transfer coefficient $h = 50$ W/m^2·°C, and the temperature of the environment $T_\infty = 20$°C. Do the following tasks:

(a) Sketch a qualitatively accurate temperature profile for this composite wall

(b) Find the maximum temperature in the wall.

Question #2

A thin rod of length L and constant cross section area has its two ends connected to two walls which are maintained at temperatures T_1 and T_2, respectively. The rod loses heat to the environment at T_∞ by convection. Derive an expression (i) for the temperature distribution in the rod and (ii) for the total heat lost by the rod through convection.

Question #3

On the T-50 fighter jet developed by KAI (Korea Aerospace Industries), airspeed is continuously measured during flight using a Pitot tube. The Pitot tube can yield the speed of the aircraft with respect to the air by measuring the difference between the static pressure and the stagnation pressure of the incoming airflow. Because airspeed calculation is crucial to the safe operation of the T-50, and because Pitot tubes can sometimes be prone to failure due to icing interfering with the pressure measurements, it is desired to install onboard a backup airspeed measuring system. Recalling the external convection heat transfer theory you learned while studying Heat Transfer at PNU, you propose to determine the airspeed by measuring the temperature of a heated copper cable positioned transverse to the incoming airflow. In order to minimize the heat loss to the environment as well as to minimize the drag, it is decided to use a fairly thin copper cable with a diameter of 2.0 mm and a length of 1 m. The temperature of the copper cable is to be measured through a resistance meter (a.k.a. ohmmeter) knowing that the electrical resistivity of copper varies as a function of the temperature according to the following relationship:

$$R_c = R_\circ(1 + \alpha(T - T_\circ))$$

where $R_\circ = 15.4$ nΩ·m, $T_\circ = 273$ K, and $\alpha = 0.00451$ K^{-1}. Because it is desired to measure the airspeed with high precision, the design should be such that the temperature of the cable varies as much as possible when exposed to changes in flow speed. Noting that the airspeed must be measured accurately over the range of flow conditions:

$$150 \text{ km/hour} < U_\infty < 1300 \text{ km/hour},$$

$$0.3 \text{ kg/m}^3 < \rho_\infty < 1.3 \text{ kg/m}^3,$$

$$220 \text{ K} < T_\infty < 320 \text{ K},$$

Determine the power supply voltage resulting in optimal design. For optimal design, the temperature of the cable must vary as much as possible over the range of flow conditions while not exceeding 700 K. Beyond 700 K, there is a risk of structural failure of the cable due to the tensile strength of copper reaching too low values. You can assume that the copper cable is highly polished and that the radiation heat transfer is negligible.

Question #4

The first design project given to you after you join a water distribution company is to prevent water flowing in an underground pipe from freezing. Consider a long 100 m pipe with a 0.15 m radius buried 2 m under ground (the center of the pipe is 2 m below the earth surface). Water flows in the pipe with the following properties:

$$\rho = 1000 \text{ kg/m}^3, \quad c_p = 4000 \text{ J/kgK}, \quad k = 0.6 \text{ W/m°C}, \quad \mu = 10^{-3} \text{ kg/ms}$$

On a cold winter day, the surface of the ground is measured to be -10°C. Water enters the pipe at a bulk temperature of 20° C. To prevent freezing (with a safety margin), the water temperature should not drop below 3.3° C at any location.

The ground conductivity can be taken as 1.5 W/m°C, and the pipe walls can be assumed smooth and to oppose negligible resistance to heat flow. Do the following:

(a) Determine the minimum water mass flow rate through the pipe that prevents the water temperature to fall below 3.3°C *anywhere* within the pipe; make your design safe by taking into consideration that the ground surface temperature varies by as much as ±2.4°C and that the ground conductivity varies by as much as ±0.5 W/m°C.

(b) Determine the wall temperature of the pipe for the mass flow rate found in (a)

(c) Determine the bulk temperature of the water exiting the pipe for the mass flow rate found in (a)

Question #5

A boat in the antarctic is towing a small iceberg. The iceberg is at a temperature of −30° C and is 10 m long, 10 m wide, and 2 m high. The iceberg has to be towed over a distance of 30 km. Knowing that the water temperature in the antarctic ocean is of 3° C, that the latent heat of melting for water is of 334 kJ/kg, that the water properties correspond to:

$$\rho_{\rm w} = 1000\ {\rm kg/m^3}, \quad (c_p)_{\rm w} = 4000\ {\rm J/kgK}, \quad k_{\rm w} = 0.6\ {\rm W/m^\circ C}, \quad \mu_{\rm w} = 10^{-3}\ {\rm kg/ms}$$

and that the iceberg properties correspond to:

$$\rho_{\rm ice} = 920\ {\rm kg/m^3}, \quad (c_p)_{\rm ice} = 1900\ {\rm J/kgK}, \quad k_{\rm ice} = 2.5\ {\rm W/m^\circ C}$$

find out the percentage of the iceberg that would melt for the following two scenarios:

(a) The boat speed is of 1.944 knots

(b) The boat speed is of 0.1944 knot

Hints: (i) you can assume that there is no heat transfer between the iceberg and the air; (ii) 1 knot is equal to 1.852 km/hour.

Question #6

You wish to determine the surface emissivity of a sphere through a simple experiment. You place the sphere in a large vacuum chamber, and heat the sphere with an electric heater that generates heat *evenly* throughout the sphere. In one experiment, the power given to the electric heater is of 8.54 W, and the temperature at the *center* of the sphere is measured to be 107° C. Knowing that the radius of the sphere is of 0.1 m, that the walls of the vacuum chamber are at a temperature of 20° C and that the thermal conductivity of the sphere corresponds to $k = k_0(1 + \beta_0 T)$ with $k_0 = 0.1\ {\rm W/m^\circ C}$ and $\beta_0 = 0.01\ \frac{1}{\rm K}$, determine the surface emissivity of the sphere, ϵ. *Hint:* the heat generation per unit volume S is constant throughout the sphere.

Answers

1. 71° C.
2. $q = kAm \times (\sinh(mL))^{-1} \times (\cosh(mL) - 1) \times (T_2 + T_1 - 2T_\infty)$.
3. 2.86 V.
4. 0.12 kg/s, 3.3° C, 7° C.
5. 23.8%, 32.9%.
6. 0.1.