2016 Heat Transfer Midterm Exam

When is the best time to have the midterm exam?

Wednesday April 27th 18:00 -- 20:00	3
Thursday April 28th 18:00 -- 20:00	3
Friday April 29th 10:00 -- 12:00	2
Friday April 29th 14:00 -- 16:00	9
Friday April 29th 16:00 -- 18:00	14
Friday April 29th 18:00 -- 20:00	20
Saturday April 30th 10:00 -- 12:00	2
Monday May 2nd 18:00 -- 20:00	2
Tuesday May 3rd 18:00 -- 20:00	1

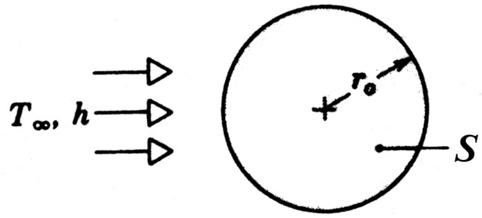
Poll ended at 6:28 pm on Sunday April 24th 2016. Total votes: 56. Total voters: 25.

Friday April 29th 2016
18:00 — 20:00

NO NOTES OR BOOKS; USE HEAT TRANSFER TABLES THAT WERE DISTRIBUTED; ANSWER ALL 4 QUESTIONS; ALL QUESTIONS HAVE EQUAL VALUE.

Question #1

Radioactive wastes are packed in a thin-walled spherical container. The wastes generate thermal energy nonuniformly according to the relation $S = S_0[1 + (r_0/r)^2] \times [1 - (r/r_0)^2]$, where S is the local rate of energy generation per unit volume, S_0 is a constant, and r_0 is the radius of the container. Steady-state conditions are maintained by submerging the container in a liquid which is at T_∞ and provides a uniform convection coefficient h.



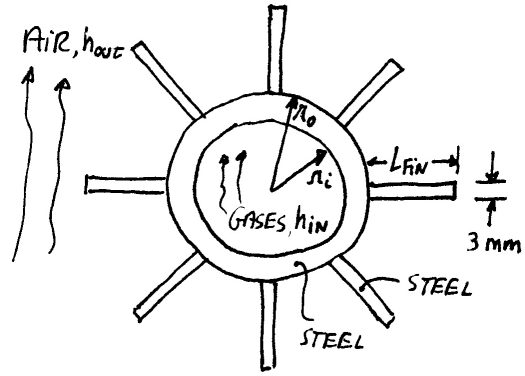
Obtain an expression for the total rate at which thermal energy is generated in the container. Use this result to obtain an expression for the temperature T_w of the container wall.

Question #2

The aircraft company you are working for is considering the use of plasma actuators to delay stall beyond the critical angle of attack. Plasma actuators can delay stall by injecting heat and applying electromagnetic forces on a region of the airflow that has been ionized. The heat injected and the applied forces alter the turbulent eddies within the boundary layer, and this can result in the flow remaining attached to the airfoil even when the angle of attack is increased beyond the critical point. In order to operate, the plasma actuators must be fed a power of 50 KiloWatts with a voltage difference of 200 Volts. You are assigned the task of designing the polyethylene-covered copper cable linking the power supply to the plasma actuators. Noting that the power supply is located 10 m away from the plasma actuators, it is desired to find the optimal cable design which minimizes weight while keeping the temperature of the polyethylene insulator below melting point. The cable is located inside the wing, where the air temperature is of -5° C and the convective heat transfer coefficient is known to be equal to $h = 10$ W/m$^2\cdot{}^\circ$C. For safe operation the polyethylene layer is given a thickness of 0.5 cm. The electrical resistivity of copper at 20° C can be taken as 16.8 n Ω·m. The melting point and the thermal conductivity of polyethylene can be taken as 120° C and 0.5 W/m°C, respectively. Design the cable with a safety margin: take into consideration that the convective heat transfer coefficient may have an error of 30% and do not let the maximum temperature within the polyethylene approach its melting point by less than 40° C.

Question #3

Consider a combustor of a turbojet engine made of a 1 m long hollow steel cylinder, with the cylinder outer radius being of $r_o = 0.3$ m and the cylinder inner radius being of $r_i = 0.25$ m. Gases flow within the combustor at a temperature of 2000° C with a convective heat transfer coefficient between the cylinder and the gases of $h_{in} = 4$ W/m$^2{}^\circ$C (including radiation). On the outside of the combustor, some cool air is flowing at a temperature of 10° C and a convective heat transfer of $h_{out} = 5$ W/m$^2{}^\circ$C (including radiation). You weld 8 steel fins on the outside of the combustor to cool it, as depicted below.



Each fin is 3 mm thick with a width of 1 m (spanning the length of the cylinder). You wish to minimize the length of the fins $L_{\rm fin}$ as much as possible to keep the weight of the combustor down while resulting in sufficient cooling so that the combustor temperature anywhere (i.e., anywhere within the steel) doesn't exceed 800 $^\circ$C. What would be the optimal fin length that would accomplish this? Specifically, given the following air, gases, and steel properties:

Matter	ρ, kg/m^3	c, J/kg$^\circ$C	k, W/m$^\circ$C
Gases	2	900	0.1
Steel	7800	485	50
Air	1	1000	0.03

Do the following:

1. Find the heat transfer at the base of one fin $q_{\rm fin}$ that will result in the combustor steel temperature not exceeding 800°C anywhere.
2. Find the fin length $L_{\rm fin}$ that yields the heat transfer found in part 1.

Hint: You can assume that the outer surface of the combustor is insulated except for the fins.

Question #4

Quenching is a heat treatment process in which a metal is first heated to a high temperature and rapidly cooled in a liquid bath. The rapid cooling changes the properties of the metal and makes it more stiff and more brittle. We here consider the quenching of an infinitely-long and infinitely-wide plate of steel with a thickness D, which is first heated to a temperature of 1000°C and then immersed in a bath of water for an amount of time Δt. The convective heat transfer coefficient within the bath can be taken as $h = 2500$ W/m$^{2\circ}$C and the water temperature far from the steel plate can be taken as 30° C. For the quenching to be successful, the steel plate should be removed out of the water when its minimum temperature reaches 100°C. Further, for the quenching not to introduce excessive stresses, the steel plate shouldn't be too thick so that the rate of change of temperature within the steel doesn't vary by more than 25% (that is, the change in temperature of the steel at one location shouldn't exceed the change in temperature of the steel at another location by more than 25%). Put in another way, we wish that the steel plate thickness D is low enough so that the following constraint is satisfied within the steel through the cooling process:

$$\frac{(T_{x,t=0} - T_{x,t=\Delta t})_{\text{min}}}{(T_{x,t=0} - T_{x,t=\Delta t})_{\text{max}}} \geq 0.75$$

Given the latter, determine:

1. The surface temperature of the steel plate after the cooling process is completed.
2. The temperature at the center of the steel plate after the cooling process is completed for a steel plate with the maximum possible thickness D_{max} that prevents excessive stresses from forming.
3. The maximum allowable thickness D_{max} of the steel plate that would prevent excessive stresses from forming.
4. The amount of time Δt in seconds that the steel plate with the thickness D_{max} needs to be immersed in the bath of water.

You can use the following steel properties:

$$\rho = 7800\ \text{kg/m}^3, \quad c = 465\ \text{J/kg}^\circ\text{C}, \quad k = 50\ \text{W/m}^\circ\text{C}$$

Hint: You don't need to know the value of D_{max} to determine the temperature at the center in part 2.

Answers

1. $\frac{16}{5}\pi S_0 r_0^3$, $T_\infty + \frac{4}{5} S_0 r_0 / h$.
2. 0.0034 m.
3. 942.5 W, 796°C, 0.274 m.
4. 100°C, 325°C, 0.22 m, 732 s.