Heat Transfer Design Problem Set 2

Instructions

ξ is a parameter related to your student ID, with ξ_1 corresponding to the last digit, ξ_2 to the last two digits, ξ_3 to the last three digits, etc. For instance, if your ID is 199225962, then $\xi_1 = 2$, $\xi_2 = 62$, $\xi_3 = 962$, $\xi_4 = 5962$, etc. Keep a copy of the assignment — the assignment will not be handed back to you. You must be capable of remembering the solutions you hand in.

Design Problem #1

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 1.6 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 $R_\circ = 15.4$ n$\Omega\cdot$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:

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

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

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

do the following:

(a) 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.

(b) For a power supply voltage of 3.5 Volts, find the cable resistance for an airspeed of 201 m/s when the aircraft is at an altitude of 30,000 feet ($\rho_\infty = 0.46\ \mathrm{kg/m^3}$ and $T_\infty = 229$ K).

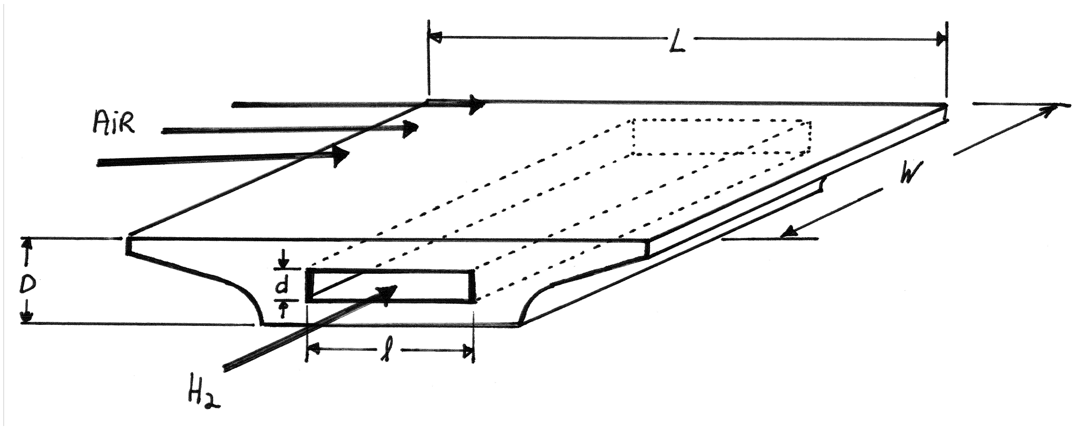
For part (a) and (b), assume that the copper cable is highly polished and that the radiation heat transfer is negligible.

Design Problem #2

You are working in the Hypersonic Branch at ADD (Korean Agency for Defense Development) in Daejeon and are the engineer in charge of installing the power generator on-board a ramjet flight vehicle. The power generator is needed to feed a megawatt-class energy weapon. Because of the high power requirements of the energy weapon and because of the necessity to minimize the weight of the power generating device, it is decided to use a MHD (magneto-hydro-dynamic) power generator rather than fuel cells or other alternatives. The MHD generator operates by converting some of the flow kinetic energy to electrical power through the Lorentz force. The Lorentz force appears when a magnetic field is present and when the airflow is sufficiently ionized to permit the flow of current. Your task is to design the cables linking the MHD generator located in the engine to the energy weapon located in the tail of the aircraft. When the energy weapon is activated, the power produced by the MHD generator is of 1 MW with a voltage difference of 300 Volts. Noting that the MHD generator is located 2 m away from the energy weapon, it is desired to find the optimal cable design that minimizes weight while keeping the temperature of the polyethylene insulator below melting point. The cable is located in an enclosed area in which there is stagnant air at a pressure of 0.05 atm and at a temperature of -10° 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 $16.8\ \mathrm{n\Omega \cdot m}$. The melting point and the thermal conductivity of polyethylene can be taken as 120° C and $0.5\ \mathrm{W/m^\circ C}$, 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 20° C.

Design Problem #3

Consider one of the panels making up the external surface of a hydrogen-fueled ramjet missile being tested at KARI (Korea Aerospace Research Institute):



The panel is made of steel, is located at the leading edge of the missile and has a length L of 1 m, a width W of 0.5 m, and a height D of 0.02 m. Air at a Mach number of 6, a speed of 6566 km/hour, a temperature of 230 K and a pressure of 0.05 atm flows on the top surface of the panel and forms a hot hypersonic boundary layer. Because of the high amount of viscous heating within the boundary layer at hypervelocities, the panel needs to be cooled or it would reach a temperature that could lead to meltdown and structural breakdown of the missile. To prevent structural failure, it is necessary to keep the temperature *anywhere* within the steel panel below 800 K. One of the main design challenges associated with hypersonic aircraft is how to achieve proper cooling of the surfaces while minimizing the weight of the cooling system. You are the one assigned this particularly challenging task. You propose to cool the panel using the hydrogen fuel that is stored in cryogenic tanks on-board. Prior to reaching the panel, however, the hydrogen has already been used to cool the combustor walls. As a consequence of this, the hydrogen underwent a phase change from liquid to gas and its temperature has increased to 250 K. As a first try, you fix the size of the hydrogen channel to $l = 80$ cm and $d = 1$ cm. Because the hydrogen flow is expected to be turbulent, you carefully measure the wall roughness within the channel and find that $e = 250\ \mu$m. To reduce as much as possible the weight of the pumps necessary to force the hydrogen flow through the channel, you then proceed to determine using Heat Transfer Theory the minimum amount of hydrogen that needs to be injected to maintain the steel temperature below 800 K. The design should be conservative and should take into consideration that the heat transfer coefficients (for the hydrogen and the air) could be off by as much as 30%.

Design Problem #4

After graduation, you are working for a natural gas power plant. In a natural gas power plant, the heat generated by burning the natural gas is used to produce high pressure steam. The high pressure steam then passes through a steam turbine generator, hence producing electrical power. One of the most important components of this type of power plant is the condenser located downstream of the turbine. The purpose of the condenser is to transform all of the steam coming out from the turbine into liquid water. The liquid water is afterwards directed to the burner, hence closing the cycle. Your first design project at the power plant consists of improving the performance of the condenser. The condenser is made of a multitude of pipes in which a cooling fluid is flowing. The cooling fluid temperature at the pipe entrance is of 50°C. To ensure that the cooling fluid flows rapidly enough, one pump is connected to each pipe. Each pipe has a length of 3 m, a diameter of 0.01 m, a relative wall roughness $e/D = 0.02$, and should condensate at least 0.03 kg/s of steam for the power plant to operate normally. Your task is to determine the minimum amount of power that should be given to each pump in order to obtain the desired amount of steam condensation. Your design should take into consideration the fact that the convective heat transfer coefficient of the cooling fluid may be off by as much as 30%. The saturation temperature and the latent heat of vaporization of the steam is of $T_{\rm sat} = 100^\circ$C and $\Delta H_{\rm vap} = 2260$ kJ/kg, respectively. The properties of the cooling fluid can be taken as $\rho = 1000$ kg/m^3, $\mu = 0.001$ kg/ms, $k = 0.6$ W/m$^\circ$C, $c_p = 4000$ J/kgK.

Hint: Assuming a pump efficiency of 100%, it can be shown that the pump power is related to the bulk velocity inside the pipe through the following expression:

$$\mathcal{P} = \frac{\rho u_{\rm b}^3 \pi f L D}{8}$$

where L is the length of the pipe, D is the diameter of the pipe, f the friction factor, and $u_{\rm b}$ the bulk velocity inside the pipe.

I will give a special bonus to the students who can derive from basic principles that

$$\mathcal{P} = \frac{\rho u_{\rm b}^3 \pi f L D}{8}$$

Question #5

Consider a combustor of a turbojet engine made of a 1 m long hollow steel cylinder, with the cylinder outer radius being of $r_{\rm o} = 0.3$ m and the cylinder inner radius being of $r_{\rm i} = 0.25$ m. Gases enter the combustor at a bulk temperature of 2000°C, a bulk velocity of 200 m/s and a mass flow rate of 400 kg/s. In order to prevent the combustor from melting, the inner surface of the combustor is film cooled. Film cooling consists of injecting liquid kerosene on all the inner surfaces of the combustor such that it evaporates when in contact with the hot gases and hence keeps the wall temperature to low values. For optimal design, it is here desired that the film cooling minimizes the amount of injected kerosene while keeping the inner combustor wall at a temperature not exceeding 200°C. Knowing that the latent heat of vaporization of kerosene is of $\Delta H_{\rm vap} = 251$ kJ/kg and the saturation temperature of kerosene is of $T_{\rm sat} = 200^\circ$C, and given the following properties for the gases and the steel:

Matter	ρ, kg/m^3	c_p, J/kg$^\circ$C	k, W/m$^\circ$C	μ, kg/ms
Gases	--	1200	0.1	$6 \cdot 10^{-5}$

Steel	7800	485	50	--

Do the following:

(a) Find the bulk temperature of the gases exiting the combustor.

(b) Find the optimal mass flow rate of kerosene needed for the film cooling of the combustor walls.

Hints: You can neglect radiation heat transfer and assume that the flow coming in the combustor is fully-developed.

Answers

1. 3.39 V, 15.6 mΩ.
2. 0.043 m.
3. 0.035 kg/s.
4. 100 W.
5. 1982.7°C, 33 kg/s.

Due on Monday June 10th at 9:00. Do Problems #2 and #5 only.

Note that only one question will be asked in the superquiz on Monday: I will ask you either 1 problem in the Design Project or 1 problem in Assignment #8. If you succeed this 1 problem, you will be given 6 points.