2016 Heat Transfer Final Exam

When is the best time for you?

Wednesday June 8th 18:00 -- 21:00	0
Thursday June 9th 18:00 -- 21:00	1
Friday June 10th 9:00 -- 12:00	1
Friday June 10th 15:00 -- 18:00	2
Friday June 10th 18:00 -- 21:00	3
Saturday June 11th 9:00 -- 12:00	3
Sunday June 12th 18:00 -- 21:00	11
Monday June 13th 18:00 -- 21:00	0
Tuesday June 14th 18:00 -- 21:00	1
Wednesday June 15th 18:00 -- 21:00	5
Thursday June 16th 18:00 -- 21:00	9
Friday June 17th 9:00 -- 12:00	15
Friday June 17th 15:00 -- 18:00	13
Friday June 17th 18:00 -- 21:00	8

Poll ended at 6:40 pm on Tuesday May 31st 2016. Total votes: 72. Total voters: 28.

Please select the best time slots for you. You can select up to 5 choices. Please vote before Wednesday June 1st 9:00. We will choose then in class the most appropriate time based on your votes.

Some students had already some exams planned for Friday June 17th 9:00 — 12:00 and for Friday June 17th 15:00 — 18:00. So we chose the third option: Sunday June 12th 18:00 — 21:00. I'll announce soon the room number.

June 12th 2016
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 the wing of an aircraft as a flat plate of 2.5 m length in the flow direction. The plane is moving at 100 m/s in air that is at a pressure of 0.7 bar and a temperature of -10° C. If the top surface of the wing absorbs solar radiation at a rate of 800 $\mathrm{W/m^2}$, estimate its steady-state temperature with and without the effect of viscous dissipation. Assume the wing to be of solid construction and to have a single, uniform temperature. Ignore incident radiation on the bottom surface and take $\epsilon = 0.4$ on the top and bottom surfaces of the wing.

Question #2

Show that the fin efficiency of a fin with a rectangular cross-section and an insulated tip corresponds to:

$$\eta_{\mathrm{f}} = \frac{\tanh\left(\sqrt{2}\cdot L^{1.5}\cdot\left(\frac{h}{kA_{\mathrm{m}}}\right)^{0.5}\right)}{\sqrt{2}\cdot L^{1.5}\cdot\left(\frac{h}{kA_{\mathrm{m}}}\right)^{0.5}}$$

with $A_{\mathrm{m}} \equiv L \cdot t$ with L the length of the fin, t the thickness of the fin, k the thermal conductivity, and h the convective heat transfer coefficient. Outline all assumptions.

Question #3

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. A bonus of 10 points will be given to the students who can derive from basic principles that $\mathcal{P} = \rho u_{\rm b}^3 \pi f L D/8$.

Question #4

Consider liquid water flowing over a flat plate of length $L = 1$ m. The water has the following properties:

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

Midway through the plate at $x = 0.5$ m, you measure a heat flux to the surface of:

$$q''_{x=0.5\text{ m}} = 3181 \text{ W/m}^2$$

You also measure an average heat flux to the surface over the length of the plate of:

$$\overline{q''} = 4500 \text{ W/m}^2$$

Knowing the latter, and knowing that the plate temperature is equal to 20° C, do the following:

(a) Determine whether the flow is laminar or turbulent.

(b) Find a relationship between U_∞, the water speed far from the plate, and T_∞.

Question #5

You wish to cook some chicken optimally using a convection oven. A convection oven differs from standard ovens by blowing hot air at moderate speeds on the food. This results in the food being heated mostly through convective heat transfer rather than through radiation heat transfer. The chicken you wish to cook can be modeled as a solid sphere with a radius of 1 cm, a thermal conductivity of 0.5 W/m$^\circ$C, a density of 1000 kg/m^3, and a heat capacity of 3200 J/kg $^\circ$C. The convection oven blows hot air at atmospheric pressure, a temperature of 130° C and a speed of 5 m/s towards the chicken. The chicken is initially at a temperature of 5° C and stands on a grill through which the air can flow freely. You wish to cook the chicken optimally so that it is as tender as possible while being safe to eat. To be safe for eating, the temperature *at any location within the chicken* must have reached at least 70° C. To be as tender as possible, the chicken must not be overcooked and must therefore be taken out of the oven as soon as it is safe for eating. Knowing the latter, do the following:

(a) Find the most accurate possible average convective heat transfer coefficient over the chicken when in the oven.

(b) Using the average convective heat transfer coefficient found in (a), determine the amount of time the chicken should be left in the oven to be optimally cooked.

(c) Find the surface temperature of the chicken when it is taken out of the oven.

Question #6

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 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 $\Delta H_{\text{vap}} = 251$ kJ/kg and the saturation temperature of kerosene is of $T_{\text{sat}} = 200$°C, and given the following properties for the gases and the steel:

Matter	ρ, kg/m^3	c_p, J/kg°C	k, W/m°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.