# 2018 Heat Transfer Final Exam

Sunday June 10th 2018
19:00 — 22:00

NO NOTES OR BOOKS; USE HEAT TRANSFER TABLES THAT WERE DISTRIBUTED; ALL QUESTIONS HAVE EQUAL VALUE; FOR EACH PROBLEM STATE ALL ASSUMPTIONS; ANSWER ALL 6 QUESTIONS; LEAVING THE EXAMINATION ROOM ENDS YOUR EXAM.

### Question #1

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

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

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

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

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

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

Knowing the latter, and knowing that the plate temperature is equal to $20^\circ$ C do the following:

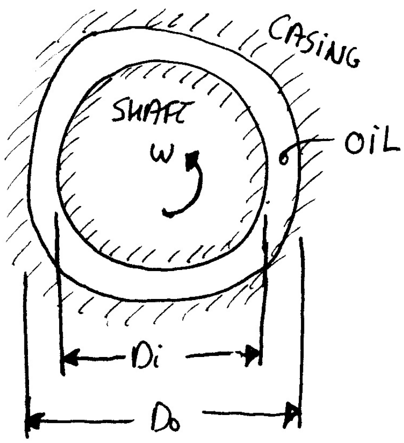
(a) Is the flow laminar or turbulent, or a mix of both? You must provide proof of this using the data provided.

(b) What is the possible range of the freestream velocity $U_\infty$?

(c) Find a relationship between $T_\infty$ and $U_\infty$

## Question #2

Consider a journal bearing with a shaft diameter $D_i$ and a casing diameter $D_o$ as follows:




The shaft rotates at a speed $\omega$ (in rad/s), and the oil has a density $\rho$ (in kg/m$^3$), a viscosity $\mu$ (in kg/ms), and a thermal conductivity $k$ in (W/mK). Knowing that there is heat generation *inside the shaft* of $S$ (in W/m$^3$) and that the temperature of the casing is of $T_o$ (in °C), do the following:

(a) From the momentum equation, derive the velocity distribution within the oil as a function of $D_i$, $D_o$, $\omega$ and the distance from the casing, $y$.

(b) From the energy equation, derive the temperature distribution within the oil as a function of $D_i$, $D_o$, $\omega$, $y$, $T_o$, $S$, $\mu$, and $k$.

## 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 $T_{\text{sat}} = 100^\circ\text{C}$ and $\Delta H_{\text{vap}} = 2260$ 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:

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

where $L$ is the length of the pipe, $D$ is the diameter of the pipe, $f$ the friction factor, and $u_{\text{b}}$ the bulk velocity inside the pipe. I will give a bonus to the those who can prove the latter from basic principles.

## Question #4

Consider a 0.01 m diameter sphere made of magnesium initially at a uniform temperature of 80$^\circ$C. The sphere is then immersed in a large pool of water with the water being still and at an initial temperature of 20$^\circ$C. Because of the gravitational force, the sphere accelerates towards the bottom of the pool and quickly reaches a constant velocity. Knowing that the drag coefficient of the sphere is of 1.1, do the following:

(a) When the sphere velocity becomes constant, find the velocity of the sphere with respect to the water.

(b) Find the temperature at the center of the sphere after a time of 2 seconds.

(c) Find the temperature on the surface of the sphere after a time of 2 seconds.

(d) Find the amount of energy (in Joules) lost by the sphere to the water after a time of 2 seconds.

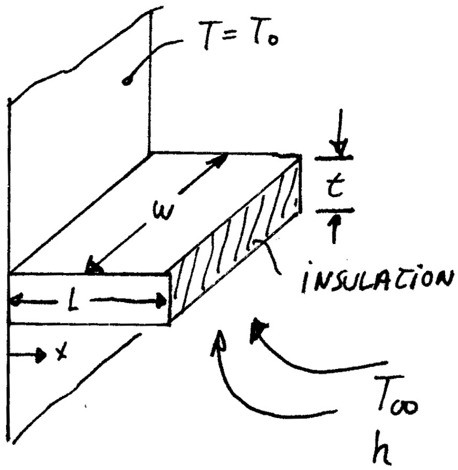
Hints: (i) the buoyancy force is equal to the weight of the displaced fluid; (ii) the drag coefficient is equal to $C_D = F_{\text{drag}}/(\frac{1}{2}\rho_\infty u_\infty^2 A)$ with the frontal area $A = \pi R^2$ and $R$ the radius of the sphere.

Use the following data for magnesium and water:

| Property | Water | Magnesium |
|---|---|---|
| $\rho$, kg/m$^3$ | 1000 | 1700 |
| $c$, kJ/kgK | 4 | 1 |
| $k$, W/m$^\circ$C | 0.6 | 171 |
| $\mu$, kg/ms | 0.001 | -- |

## Question #5

Consider a rectangular fin with an insulated tip attached to a wall as follows:




The fin is made of aluminum with a length $L = 0.1$ m, a width $W = 1$ m, and a thickness $t = 0.03$ m. The wall temperature $T_0$ is fixed to 20° C. Some water vapor at a temperature $T_\infty = 200°$C is blown towards the fin. Because the fin temperature is less than the water vapor saturation temperature ($T_{\text{sat}} = 100°$C), a thin layer of condensate forms all around the fin. Knowing that $h_{\text{condensate}}$ can be assumed constant and equal to 500 W/m$^2$°C, do the following:

(a) Find the temperature of the fin at $x = L$.

(b) Find $h$ (the convective heat transfer coefficient of the incoming water vapor) at $x = 0$.

(c) Find $h$ at $x = L$.

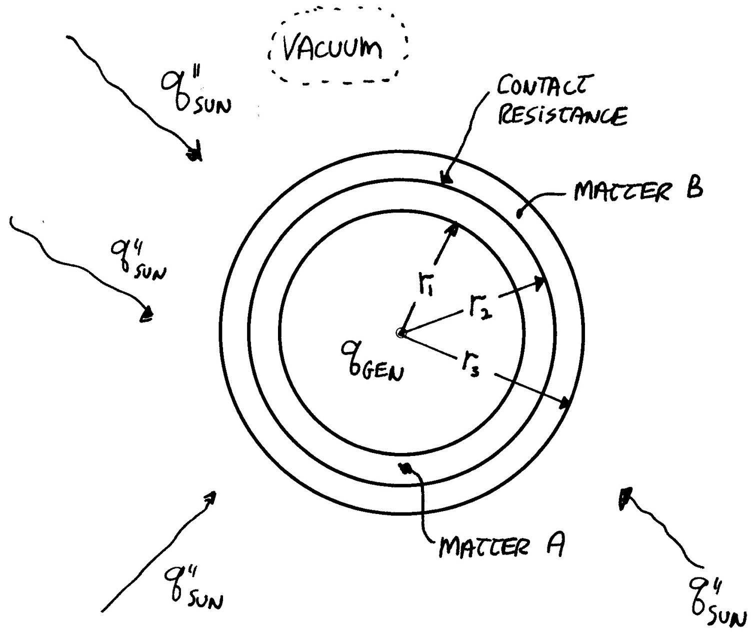
Use the following data for liquid water, water vapor, and aluminum:

| Property | Liquid water | Water vapor | Aluminum |
|---|---|---|---|
| $\rho$, kg/m$^3$ | 1000 | 0.5 | 2700 |
| $c_p$, kJ/kgK | 4 | 2 | 0.9 |
| $k$, W/m°C | 0.6 | 0.04 | 200 |
| $\mu$, kg/ms | 0.001 | $2 \times 10^{-5}$ | -- |

*Hint:* $h$ can not be assumed constant.

**Question #6**

Consider a micro satellite in the shape of a hollow sphere orbiting around the earth in space as follows:




Electrical circuits located within the satellite generate power with the amount $q_{\text{gen}}$ (in Watts). The temperature within either matter A or matter B can not exceed 600 K for safety reasons. The incoming radiation heat flux from the sun varies between being 0 and being $q''_{\text{sun}} = 1200$ W/m$^2$. The radiation heat flux from the sun may reflect on adjacent solar panels and may thus englobe the micro satellite from all directions. The thermal conductivities are of $k_{\text{A}} = 0.5$ W/mK and of $k_{\text{B}} = 0.2$ W/mK, while the contact conductance between matter A and matter B is of $h_{\text{c}} = 24.68$ W/m$^2$K. Knowing that the outer surface of the micro-satellite is a black body, and that the dimensions are of $r_1 = 8$ cm, $r_2 = 9$ cm, $r_3 = 10$ cm, do the following:

(a) Indicate where the maximum temperature will occur (i.e. the precise location within either matter A or matter B).

(b) Find the maximum allowable $q_{\text{gen}}$ that maintains the temperature within both matter A and matter B to less than 600 K.

(c) Find the temperature on the outer surface of the satellite when the maximum temperature within either matter A or B is of 600 K.