CHE 260: THERMODYNAMICS AND HEAT TRANSFER

FINAL FOR HEAT TRANSFER

12th DECEMBER 2014

NAME:

STUDENT ID NUMBER:

Q1	Q2	Q3	Q4	Q5	Q6	Total
15	10	20	15	15	15	90

INSTRUCTIONS

1. This examination is open textbook (the custom textbook for this course) along with one 8.5” x 11” aid sheet (both sides), closed internet, closed all communication devices.
2. All non-communicating calculators are permissible.
3. Please write legibly. If your handwriting is unreadable, your answers will not be assessed.
4. Answers written in pencil will NOT be re-marked. This is University policy.
5. For all problems, you must present the solution process in a step by step fashion for partial marks.
6. **ANSWERS WRITTEN ON THE BLANK, LEFT SIDES OF THE ANSWER BOOK WILL NOT BE ASSESSED. USE THE LEFT SIDES FOR ROUGH WORK ONLY. THIS WILL BE IMPLEMENTED STRICTLY THIS TIME.**

Q.1. [15 points] DEEP-FRIED ICE-CREAM

I recently went to a Thai restaurant, where, on the dessert menu, they had an item called deep-fried ice-cream. It was described as "A combination of hot and cold. The hot crispy crust and creamy filling cold make this dessert a delight!" I ordered it and dissected it, only to discover that deep-fried ice cream is essentially a spherical scoop of ice-cream, coated with a thick layer of batter, and deep fried in hot oil.

I decided to make some deep-fried ice-cream at home for my wife. The initial temperature of the ice-cream was -18ºC. The oil was maintained at a temperature of 185ºC. The ice-cream scoop I took was initially a sphere of 2.0 cm radius, and I coated it with a 0.5 cm thick layer of batter, and immersed it in oil. To ensure that the batter was completely cooked, I allowed the ice-cream to be deep-fried for 20 min.

Use the one-term approximation to solve parts (b), (c) and (d). Comment on the validity of the one-term approximation for these parts. For your calculations, assume the batter to also be at an initial temperature of -18ºC. The convective heat transfer coefficient is 450 W/m^2-K, and the thermal conductivities of the batter and ice-cream are both 1 W/m-K. The density and the specific heat capacity of the batter and ice-cream are 980 kg/m^3 and 4000 J/kg-K respectively.

(a) **[3 points]** What is the rate-controlling step in this heat transfer problem, conduction within the solid, or convection past the solid surface?

(b) **[4 points]** After my deep fry experiment, did the ice-cream inside melt completely (this would classify as a fried-ice-cream 'fail')? Assume that the ice-cream melts at $0^{o}C$.

(c) **[4 points]** What is the maximum duration of deep fry over which at least some fraction of the ice-cream would have been in a solid state?

(d) **[4 points]** What is the maximum duration of deep fry over which all the ice-cream remains frozen?

Q.2. [10 points] DRAG ON A PLATE

For flow over a flat plate with an extremely rough surface, convection heat transfer effects are known to be correlated by the expression: $\mathrm{Nu}_x = 0.04\,\mathrm{Re}_x^{0.9}\,\mathrm{Pr}^{1/3}$, where Nu_x is the local Nusselt number at a distance x from the leading edge of the plate, Re_x is a Reynolds number based on the length x, and Pr is the Prandtl number. For flow of a fluid over the plate at 10 m/s, what is the surface shear stress at $x = 1$ m from the plate's leading edge? Take the fluid density and viscosity to be 1000 kg/m^3 and 10^{-3} Pa-s respectively.

Q. 3. [20 points] HEAT LOSSES FROM A STEAM PIPE

An uninsulated steam pipe is used to transport high temperature steam from one building to another. The pipe is 0.5 m in diameter, has a surface temperature of 150ºC, and is exposed to ambient air at -10ºC. The air moves in cross-flow fashion over the pipe with a velocity of 5 m/s.

(a) **[10 points]** What is the heat loss per unit length of pipe?

(b) **[10 points]** What is the heat loss per unit length after the pipe is insulated with a rigid urethane foam (k = 0.026 W/mºC) of 10 cm thickness?

Use an appropriate correlation from the textbook to determine the heat transfer coefficient. Get air properties from table A-22.

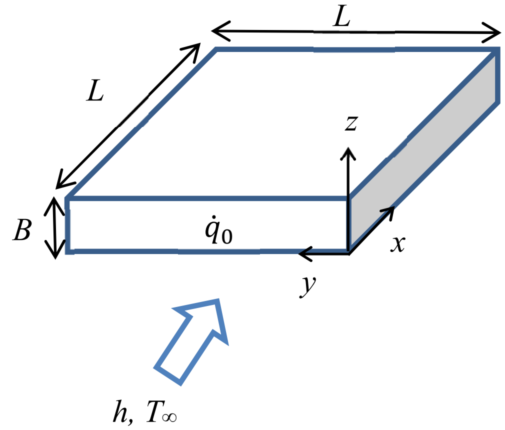
Q.4. [15 points] THERMOCOUPLE JUNCTION

A thermocouple junction, which may be approximated as a sphere, is to be used for a temperature measurement in a fluid stream. The convection coefficient between the junction surface and the gas is h = 500 W/m^2°C. The junction thermophysical properties are k = 10 W/m°C, C_p = 400 J/kg°C, ρ = 8500 kg/m^3.

(a) **[8 points]** Determine the junction diameter required for the thermocouple to have a time constant of 0.5 seconds in response to temperature changes. [If F is a variable of interest that decays exponentially with time t as $F = F_0 \exp\left(-t/\tau\right)$, then τ is called its time constant.] **Hint**: What Bi regime would you want a 'fast' thermocouple to work in?

(b) **[7 points]** The junction, initially at 25ºC, is suddenly placed in a fluid at 150ºC. How long does it take for the temperature to reach 149ºC?

Q.5 [15 points] TEMPERATURE DISTRIBUTION IN A SQUARE-SHAPED SOLID



Consider a square-shaped solid (thermal conductivity k) of side L in the x and y directions, and thickness B in the z direction. A constant source of heat $\dot{q}_0$ (W/m^3) is present everywhere within the solid. The solid is placed in an ambient fluid at a temperature T_∞. The heat transfer coefficient corresponding to convective heat transfer past the surface of the plate is h. Answer the following questions:

(a) **[4 points]** Write down the governing equation for the temperature distribution under steady state conditions for a constant thermal conductivity. Specify the boundary conditions of each face. Note that the temperature will be, in general, a function of x, y and z co-ordinates.

(b) **[5 points]** Render the governing equations and the boundary conditions dimensionless. The spatial scales are given; keep the scale for the temperature undetermined as ΔT_c . Identify the spatial scales and the scale for temperature. There should be three dimensionless parameters appearing in the dimensionless equations: the Biot number $\mathrm{Bi} = \dfrac{hB}{k}$, the geometric aspect ratio, $\varepsilon = \dfrac{B}{L}$, and another parameter that involves the unknown temperature scale. Write the equations in terms of these parameters.

(c) **[2 points]** When the geometric aspect ratio $\varepsilon = \dfrac{B}{L}$ is much less than 1, i.e. when the solid is basically a plate, the governing equation simplifies to just two terms. Write this equation down. Hence identify the temperature scale.

(d) **[4 points]** Integrate the equation from (c), apply suitable boundary conditions, and get the temperature distribution. In which regions of the plate is this solution likely to fail?

Q. 6. [15 points] THERMAL AND MOMENTUM BOUNDARY LAYERS FOR FLOW PAST A WEDGE

Consider a fluid at a temperature T_∞ that impinges against a stationary wedge of angle θ, as shown in the figure below. The wedge is maintained at a constant temperature $T_S > T_\infty$. As the fluid flows past the wedge, momentum and thermal boundary layers of thicknesses δ and δ_t respectively, are developed near the surface of the wedge. These thicknesses are functions of the position *x* measured along the surface of the wedge.

Above the wedge, outside the momentum boundary layer, the velocity, u_e, is not constant as in the flat plate problem, but a function of the position *x*:

$$u_e = c\,x^m, \quad \text{where } c \text{ is a constant, and } m = \theta/(2\pi - \theta).$$

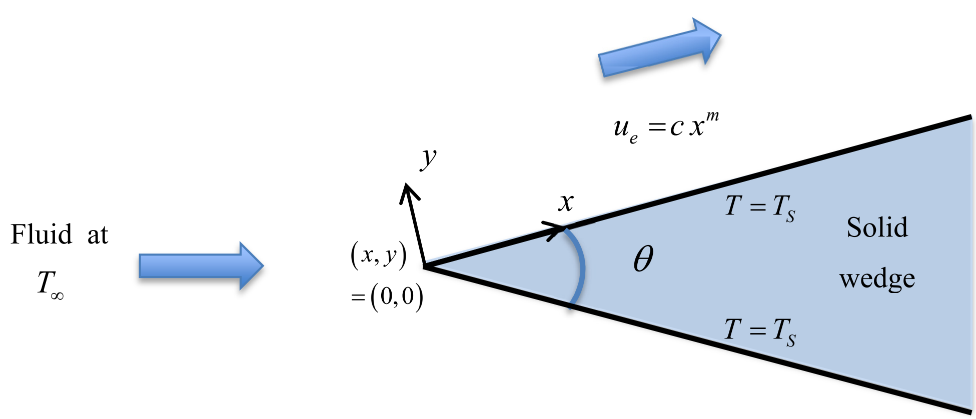
If the fluid properties are such that <u>the thermal boundary layer is much thicker than the momentum boundary layer</u>, determine, up to an undetermined prefactor,

(a) **[5 points]** the thickness of the momentum boundary layer, $\delta(x)$,

(b) **[5 points]** the thickness of the thermal boundary layer, $\delta_t(x)$, and

(c) **[3 points]** the Nusselt number for heat transfer, $Nu_x = hx/k_f$,

in terms of the flow conditions and the fluid properties: density ρ, specific heat capacity = C_p, viscosity = μ, and thermal conductivity k_f. Derive the answers for a general *m*, but write the solutions specifically for the case of the flow past a flat plate $\left[m = 0 \ (\theta = 0)\right]$ and the flow against a perpendicular flat plate $\left[m = 1 \ (\theta = \pi)\right]$. Assume that the flow is laminar and that the fluid properties are constant. Sketch the momentum and thermal boundary layers **[2 points].**



(Note that while the boundary layers have been shown only on the upper side of the wedge, identical boundary layers will exist on the bottom surface).