THERMAL/FLUID SYSTEMS

DOCTORAL QUALIFYING EXAMINATIONS

HEAT TRANSFER

September 3, 2003

READ THE FOLLOWING CAREFULLY BEFORE STARTING

1. This is a 3 1/2 hour, closed book exam. No reference material is allowed, other than that provided with this exam.

2. You will be graded on a total of five questions. You must work **both** problem 1 and problem 2. You are then to select any three (3) of the remaining five (5) problems. You are to turn in solutions to only the 5 problems you wish to be graded.

3. In addition to correctness, your answers will be judged for maturity and completeness. Show clearly any assumptions you make in order to complete a problem solution.

4. Start each problem on a new page. Put your student ID number on each page you hand in.

1) Consider the following convective flow problem with a low-speed approach velocity U_∞ and approach temperature T_∞.

CASE 1 — Consider a flat plate with a sharp leading edge, dimensions L in the flow direction by W in the span direction. The plate is held at a constant wall temperature $T_w > T_\infty$ and the flow remains laminar over the surface of the plate.

(a) sketch the distribution of heat transfer coefficient h over the range $0 \leq x \leq L$, where x is the flow direction.

(b) carefully explain the reason for the value for h at x=0. Use physical and mathematical arguments as appropriate.

(c) carefully explain the reason for how h behaves for small x. Use physical and mathematical arguments as appropriate.

CASE 2 - Consider a flat plate with a sharp leading edge, dimensions L in the flow direction by W in the span direction. The plate is heated using at a constant wall heat flux, and the flow remains laminar over the surface of the plate.

(c) sketch the distribution of heat transfer coefficient h over the range $0 \leq x \leq L$, where x is the flow direction.

(d) carefully explain the reason for the value for h at x=0. Use physical and mathematical arguments as appropriate.

(f) carefully explain the reason for how h behaves for small x. Use physical and mathematical arguments as appropriate.

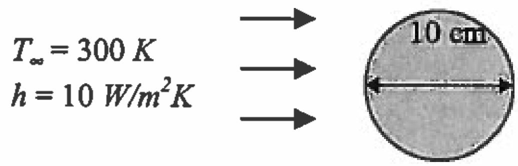
CASE 3 - Consider a cylinder of diameter D, perpendicular to the approach flow. The cylinder is held at a constant wall temperature Tw > T∞ and the flow remains laminar over the front half of the cylinder.

(g) sketch the distribution of heat transfer coefficient h over the range $0 \leq x \leq \pi D/4$, where x is the flow direction..

(h) carefully explain the reason for the value for h at x=0. Use physical and mathematical arguments as appropriate.

(i) carefully explain the reason for how h behaves for small x. Use physical and mathematical arguments as appropriate.

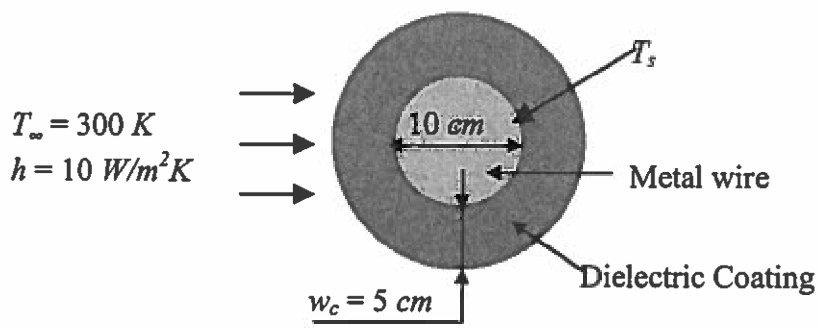
2) A power line can be treated as a long metal wire with a diameter $D = 10\ cm$. An electrical current passing through the wire results in Joule heat generation. The wire temperature is initially maintained at $T_i = 320\ K$ by losing heat to air with a temperature $T_\infty = 300\ K$ and convection heat transfer coefficient $h = 10\ W/m^2K$. The properties of the metal wire are: thermal conductivity $k = 400\ W/mk$, density $\rho = 8900\ kg/m^3$, specific heat $c = 390\ J/kgK$.



a) Due to a blackout accident, the electrical current through the metal wire suddenly drops to zero. Solve for the temperature T_0 at the center of the wire as a function of the time t after the current drops to zero, the given dimension, and the given properties.

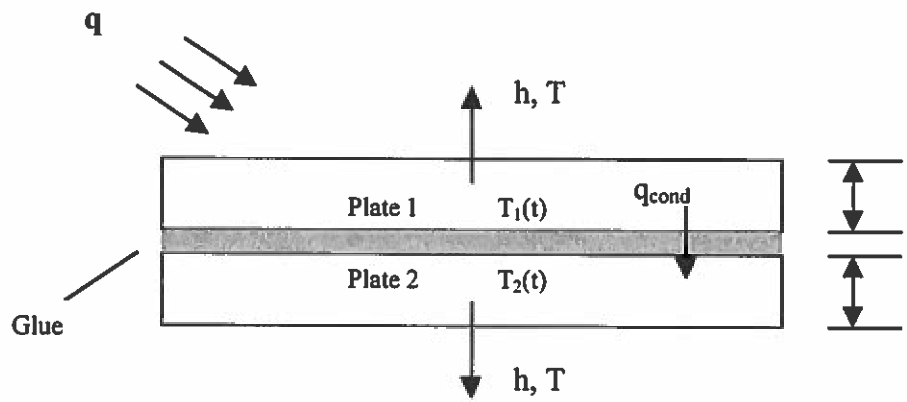
b) Before the power outage, what is the volumetric heat generation rate q in the metal wire?

c) If a dielectric coating with a wall thickness $w_c = 5\ cm$ is used to shield the wire from the air, what will be the steady-state temperature of the wire under the same volumetric heat generation rate q? The thermal conductivity of the coating is $k_c = 10\ W/mK$. The contact thermal resistance between the coating and the wire is negligible. Assume the same convective heat transfer coefficient $h = 10\ W/m^2K$.



3) Two identical square stainless steel plates are glued together in a thermal curing process that uses a radiant heat source **q** = 5000 W/m^2, directed at the top plate. The glue becomes effective at a temperature $\mathbf{T_0}$ = 100 °C. The ambient temperature is **T** = 25 °C, and the heat transfer coefficients are **h** = 10 W/m^2.K. It may be assumed that the thickness of the plates, _ = 1 mm, is small enough and the thermal conductivities of the plates are large enough so that lumped capacitance model is valid. i.e. The plates can be treated as lumped capacitors with temperatures $\mathbf{T_1}$ and $\mathbf{T_2}$. The thermal contact resistance of the glue is $\mathbf{R_c}$ = 10^{-4} m^2 K/W. The initial temperature of the plates is **T** .

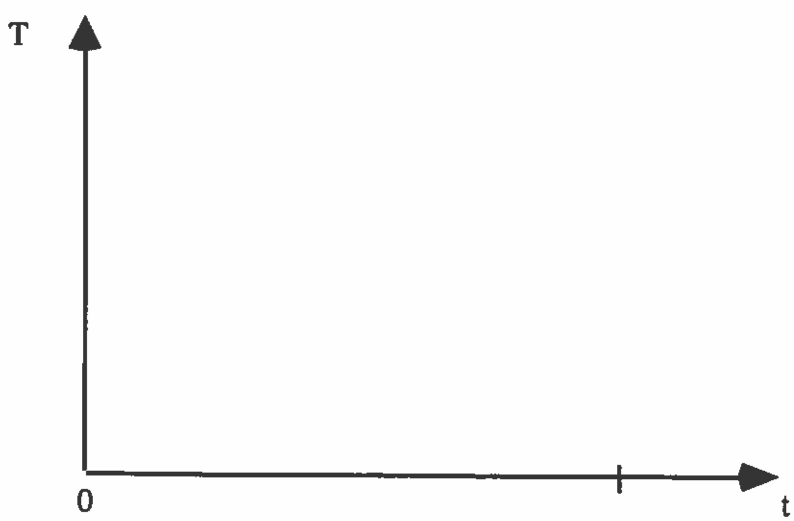
Note that the conduction heat flux across the glue is q_{cond} = $(T_1 - T_2)/R_c$. The thermal capacitance of the glue is much smaller than that of the plates and can be considered negligible. The density and specific heat of the stainless steel is 7854 kg/m^3 and 434 J/kg.K, respectively.



a) Provide the equation(s) governing the evolution of temperatures in this system.

b) Calculate the time required to obtain a bond between the plates (i.e. when the temperature of the glue is above T_0, which happens when the T_2 reaches T_0).

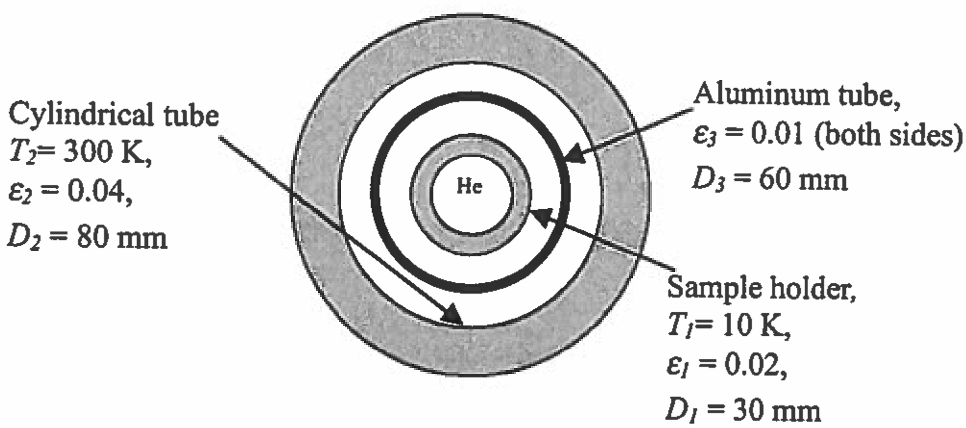
c) Sketch $T_1(t)$ and $T_2(t)$ below. Identify T_0 on the graph.



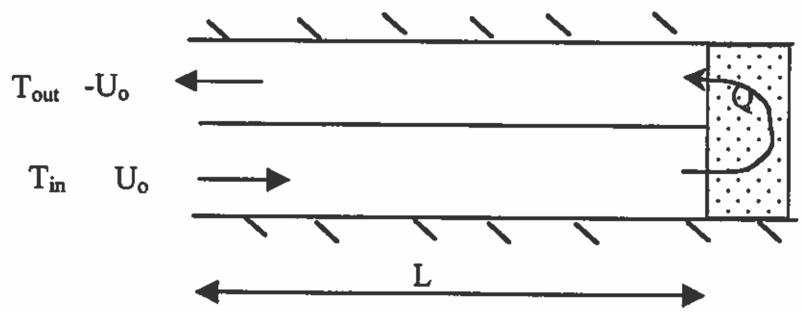
4) A cryostat consists of a long cylindrical sample holder that is enclosed in vacuum by a long concentric cylinder tube. The sample holder is cooled by liquid helium (He) flowing inside the holder to T_1 = 10 K. The emissivity and diameter of the sample holder are ε_1 = 0.02 and D_1 = 30 mm, respectively. The cylinder tube is at room temperature T_2 = 300 K, and its emissivity and diameter are ε_2 = 0.04 and D_2 = 80 mm, respectively.

(a) To reduce radiation heat transfer to the sample holder, a long thin aluminum tube is inserted between the sample holder and the outer tube. The aluminum tube has a diameter of D_3 = 60 mm and emissivity ε_3 = 0.01 for both sides. What is the rate of radiation heat transfer to the sample holder per unit length of the holder? All surfaces can be treated as diffuse and gray surfaces. The space between the sample holder and the cylindrical tube is vacuumed.

(b) In a different design of the cryostat, **transparent** helium vapor with a temperature of 5K and heat transfer coefficient h is introduced to the space between the sample holder and the aluminum tubing (in addition to the helium inside the sample holder). The temperatures of the sample holder and the cylindrical tube are the same as above. Is the temperature T_3 of the aluminum tube higher or lower than that in (a)? Draw a thermal circuit to describe the heat transfer process of this new design. You don t need to calculate.



5) A schematic of a recuperative heat exchanger is shown below. Low temperature fluid enters the bottom channel and is heated at the end of the heat exchanger by a volumetric source ($\dot{Q} = 1000\dot{m}$). The volumetric generation raises the temperature by 100°C for all flow rates. The heated fluid returns through the upper channel and exchanges heat with the cooler fluid below. A very thin plate separates the two flows. The other walls of the channel are insulated.

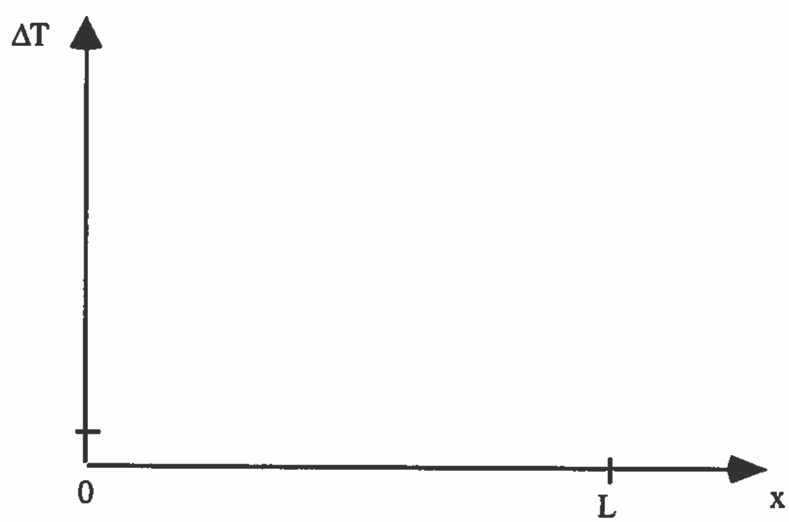


Assume that the temperature and flow fields are fully developed. Assume that Nu_D is constant and does not vary with mass flow rate. Assume that $Pe_D >> 1$. Assume that there is no axial conduction in the plate and no transverse resistance through the plate.

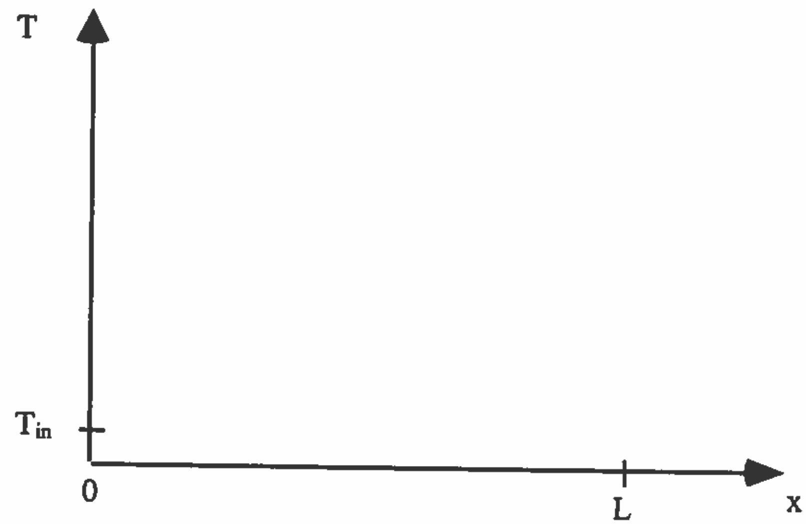
a) Write the bulk (or mean) temperature governing equations for the top and bottom channels.

b) Derive an equation for ΔT (the difference between the top and bottom bulk temperatures).

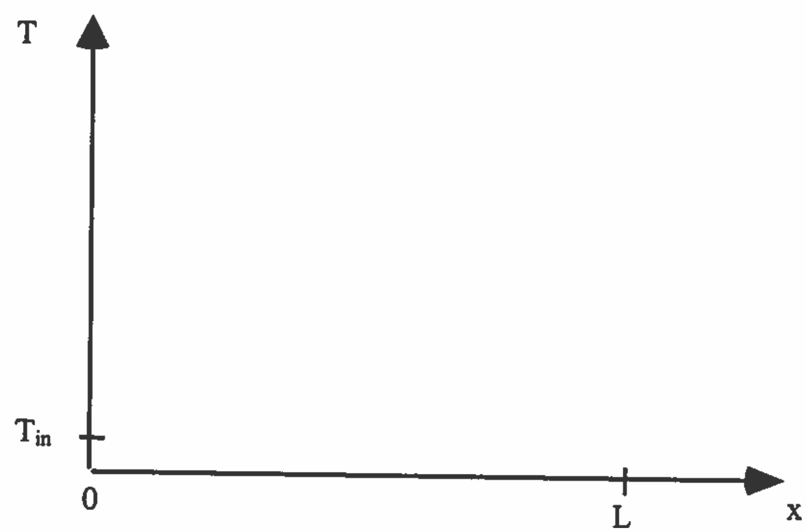
c) Sketch the variation of ΔT with respect to heat exchanger length.



d) Sketch the fluid bulk temperature variation (top and bottom) with respect to heat exchanger length for three values of the mass flow rate (high, medium and low). Sketch the plate temperature on the plot.



e) If the plate were perfectly conducting, sketch the bulk temperature variation (top and bottom) with respect to heat exchanger length for three values of the mass flow rate (high, medium and low). Sketch the plate temperature on the plot.



6) A 6-sided enclosure is created by two vertical plates whose dimensions are $H = 3$ m high by 1 m wide. The plates are spaced L = 10 cm apart. Each plate is isothermal, at temperatures of $T_1 =$ +20 °C and $T_2 =$ -10 °C. Assume the plates are opaque with an emissivity of 0.9. Assume also that the 4 sides that complete the enclosure are adiabatic.

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For convection, use the cavity correlation with all properties evaluated at a film temperature.

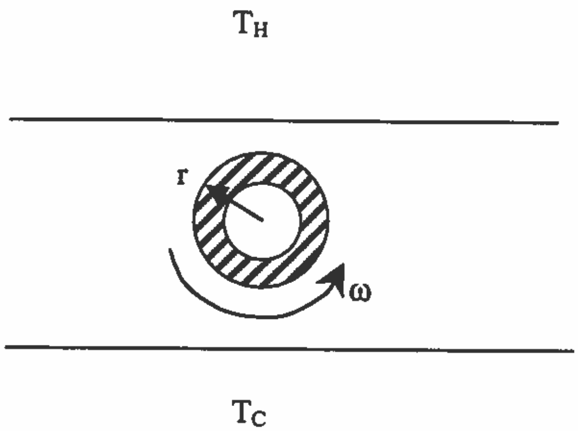
a) Determine the heat flux (W/m²) between the two vertical plates when air at one atmosphere is the fluid within the enclosure.

b) Determine the heat flux (W/m²) between the two vertical plates when the air within the enclosure is replaced by an opaque, solid material whose thermal conductivity is 0.03 W/m-K.

c) Determine the heat flux (W/m²) between the two vertical plates when the air within the enclosure is replaced by a transparent, solid material whose thermal conductivity is 10.0 W/m-K.

SUPPLEMENTAL REQUIRED INFORMATION: properties of air

7) A solid annular cylinder with thermal conductivity k rotates at an angular velocity of ω in a vacuum enclosure. The cylinder is located between two infinite plane walls. One wall is hot at a temperature T_H while the other is cold at a temperature T_C. Assume that the inner wall boundary condition for the cylinder is insulated (i.e., — |).



The following view factor relationship may prove useful.

Element of any length on cylinder to plane of infinite length and width.

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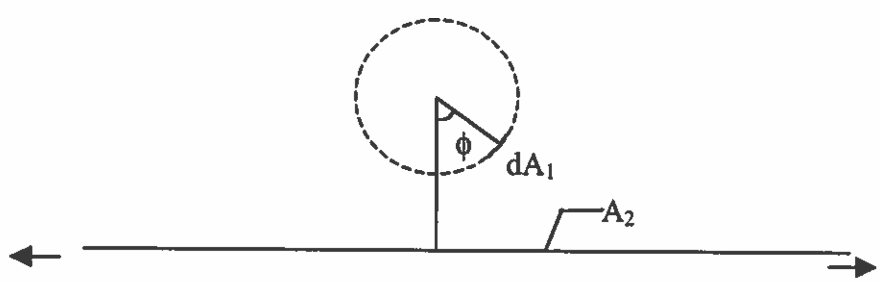

a) Write the complete differential equation and boundary conditions governing this problem.

b) Specify a scaling analysis which would clarify under what conditions the radial variation of the cylinder temperature can be neglected.

c) Derive the differential equation that governs the variation of the radially-lumped circumferential temperature.

d) State (in words and equations) under what condition the circumferential conduction term can be dropped.

SUPPORTING MATERIAL