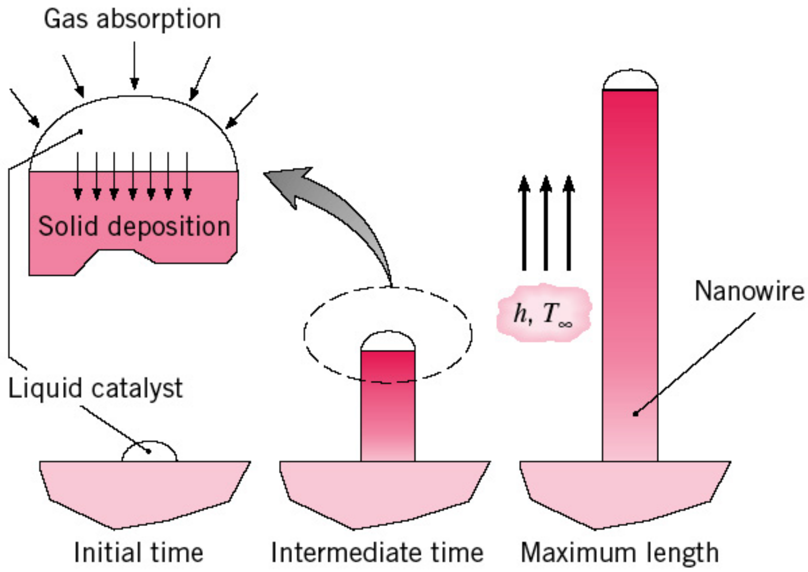
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
2.005 Thermal-Fluids Engineering I

PROBLEM SET #6, Fall Term 2008
Issued: Thursday, October 9, 2008 Due: Thursday, October 16, 2008, 9:30am

Problem 0: Please read the course notes through chapter 6.6.

Problem 1 (I&D 3.109 mod)



One method that is used to grow nanowires is to initially deposit a small droplet of a liquid catalyst onto a flat surface. The surface and catalyst are heated and simultaneously exposed to a higher temperature, low pressure gas that contains a mixture of chemical species from which the nanowires are to be formed. The catalytic liquid *slowly* absorbs the species from the gas through its top surface and converts these to a solid material that is deposited onto the underlying liquid-solid interface, resulting in a construction of the nanowires. The liquid catalyst remains suspended at the tip of the nanowires.

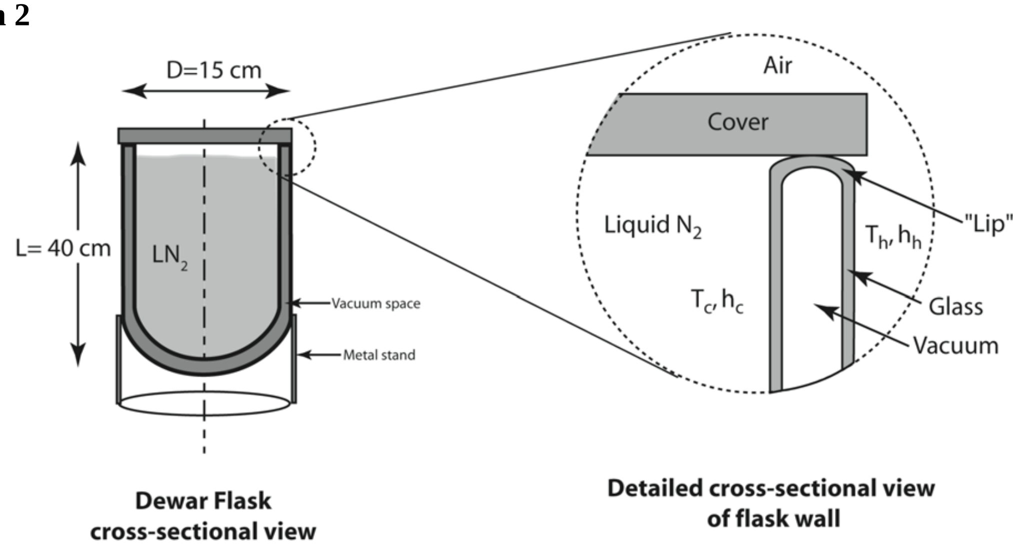
Consider the growth of a 15 nm diameter silicon nanowire onto a silicon surface. The surface is maintained at a temperature of T_s=1100 K, and the particular liquid catalyst that is used must be maintained in the range of 1100 K $\leq T_c \leq$ 1150 K in order to perform its function.

a) Determine the maximum length of a nanowire that may be grown for conditions characterized by h= 10^5 W/m^{2}K and T_∞=1200 K. Assume that the nanowire has a thermal conductivity 20 W/mK and assume that radiation effects can be neglected.

b) If radiation cannot be neglected, determine the maximum length of a nanowire. Assume that the emissivity of the nanowire is 1 and that the radiation equation can be linearized ($T_s \sim T_\infty$).

V1

Problem 2

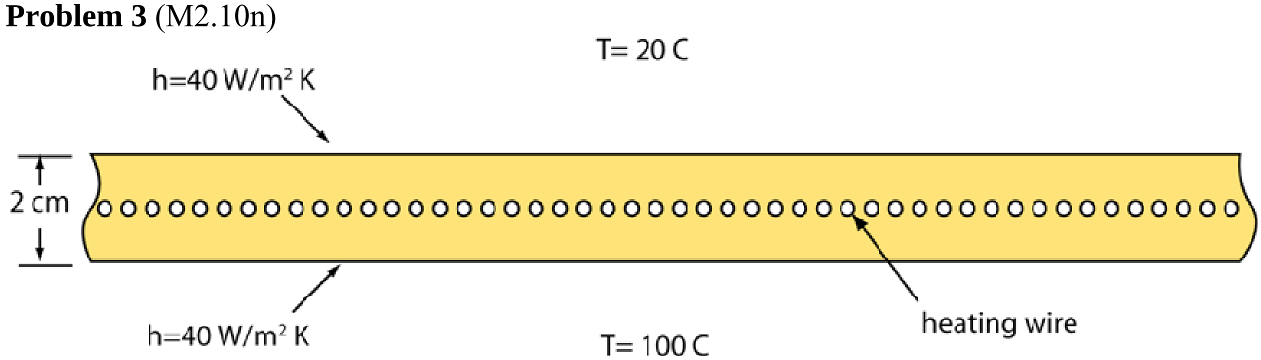


A Dewar flask, shown in the figure above, is a double-walled glass container that has a vacuum between its inner and outer walls. The vacuum eliminates heat conduction from the inner to the outer wall. The inner and outer walls are also coated with a low emissivity material to minimize thermal radiation. Dewar flasks are typically used to hold low-temperature liquids. It may be assumed that no heat is conducted or radiated through the space between the walls. A low conductivity foam lid has been placed across the top of the Dewar to prevent air flow into the flask; the lid may be regarded as adiabatic. The Dewar is 40 cm tall and each glass wall is 2 mm thick. The lip has a length of 2 cm. The glass has a conductivity of k_{glass} = 0.9 W/mK.
The inside of the Dewar is filled to the top with liquid nitrogen at 77 K and a heat transfer coefficient h_c= 25 W/m^{2}K. The outside of the Dewar is surrounded by air at 20 C with h_h= 5 W/m^2 K.

a) Explain how heat is transferred from the air outside to the liquid nitrogen inside.

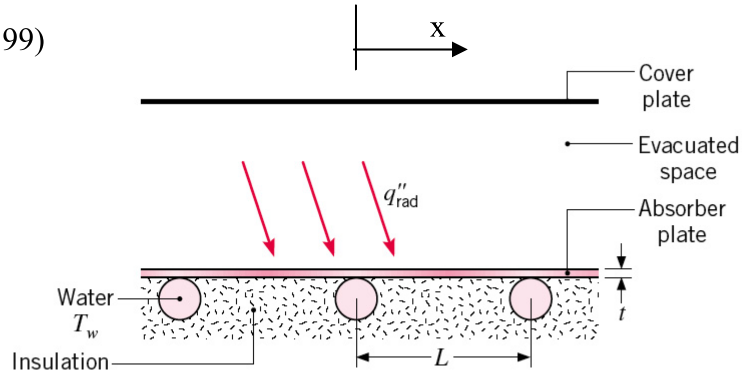
b) Calculate the rate of heat flow into the nitrogen. Assume the Dewar has an outer diameter of 15 cm and neglect curvature effects.

Problem 3 (M2.10n)



A 2 cm thick composite plate has electrical heating wires arranged in a fine grid on its center plane. On one side there is air at 20 C and on the other side there is air at 100 C.
The composite material has a thermal conductivity of 0.45 W/m K. If the heat transfer coefficient on both sides is 40 W/m^{2}K, what is the maximum allowable rate of heat generation per unit area if the composite temperature should not exceed 300 C?

Problem 4 (I&D 3.99)

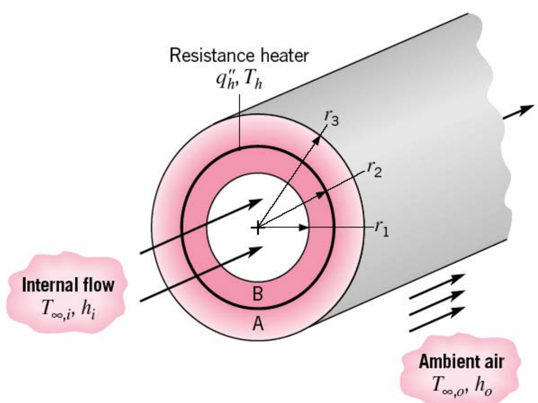


Copper tubing is joined to the absorber of a flat-plate solar collector. The aluminum alloy absorber with a k=180 W/mK is 6 mm thick and well insulated on its bottom. The top surface of the plate is separated from a transparent cover plate by an evacuated space. The tubes are spaced a distance L=0.20 m from each other and water is circulated through the tubes to remove the collected energy. The water may be assumed to be at a uniform temperature of T_w=60 ^oC. Assume that the temperature of the absorber plate directly above a tube is equal to that of the water.

a) Under steady-state operating conditions for which the net radiation heat flux to the surface is q''_{rad}=800 W/m^2, determine the temperature distribution as a function of the distance x. The q''_{rad} represents the net effect of solar radiation absorption by the absorber plate and radiation exchange between the absorber and cover plates.

b) What is the maximum temperature on the plate?

Problem 5 (I&D 3.46)



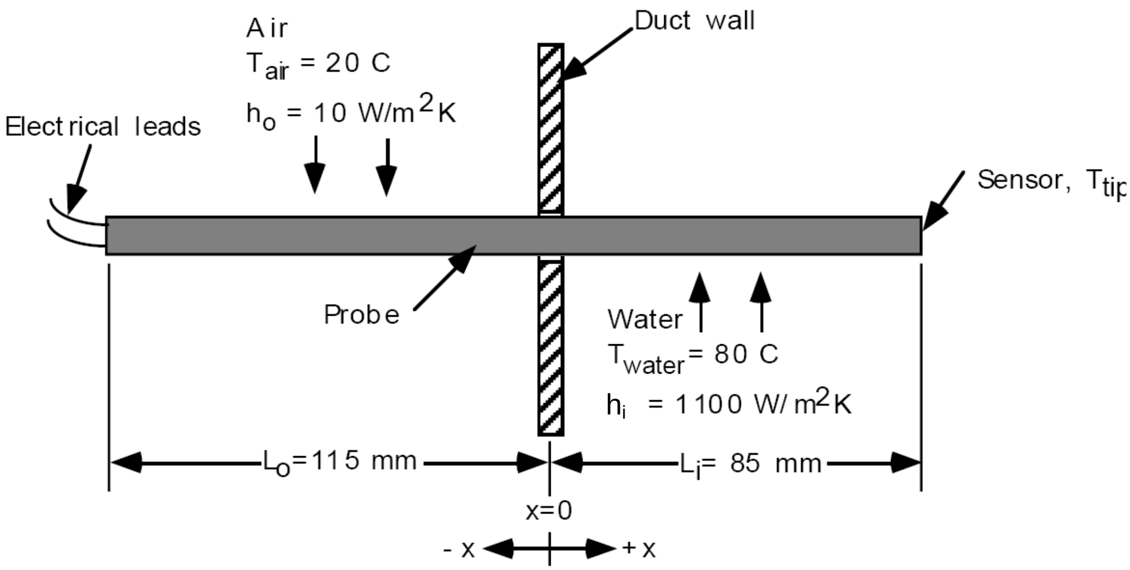
A composite cylindrical wall is composed of two materials of thermal conductivity k_A and k_B which are separated by a very thin, electric resistance heater (for which interface contact resistances are negligible) at r_2. Liquid pumped through the tube is at a temperature $T_{\infty,i}$ and provides a convection coefficient h_i, at the inner surface, r_1, of the composite. The outer surface, r_3, is exposed to ambient air, which is at $T_{\infty,o}$ and provides a convection coefficient of h_o. Under steady-state conditions, a uniform heat flux of q_h" is dissipated by the heater. L is the total length of the composite cylinder.

a) Develop a model for the system using thermal resistances.

b) Obtain an expression that can be used to determine T_h.

c) Obtain an expression for the ratio of heat transfer rates to the outer and inner fluids, $\dot{Q}_o / \dot{Q}_i$. How can the variables be adjusted to minimize this ratio?

Problem 6



As shown in the sketch, a solid cylindrical probe (diameter = 12.5 mm) is used to measure fluid temperature with a temperature sensor buried in its tip. The probe is inserted through the wall of a duct into a water stream that has a uniform temperature of 80 C. The overall length of the probe is 200 mm and 85 mm of this length is exposed to the water stream, while the remaining length is exposed to ambient air whose temperature is 20 C. The convection heat transfer coefficient between the surface of the probe and the water is h_i (= 1100 W/m^{2}K) while that between the probe surface and the air is h_o (= 10 W/m^2 K). The thermal conductivity of the probe material is k_{probe}= 177 W/mK. The probe is thermally isolated from the duct wall, but there is a water tight seal to prevent water from leaking out of the duct.

a) Describe a one-dimensional heat transfer model that will enable you to determine the temperature at the tip of the portion of the probe immersed in the water while the other portion of the probe is exposed to air.
b) For a geometry in which the origin of the x-axis is in the middle of the duct wall, sketch the distribution T=T(x) in the probe. Pay careful attention to the slope, dT/dx, at each end of the probe and at the origin and the values of T at these locations.
c) Estimate the error in the measured temperature $\Delta T_{error}=T_{tip}-T_{water}$ for this probe configuration. Does the error increase or decrease as the immersion length increases? Why?
d) Suppose the same probe and geometry is used to measure the temperature outside a house. The indoor temperature is 20 C and the ambient outside temperature is -10 C. What is the temperature measured by the sensor at the probe tip? You may assume h_{in}= h_{out} = 3 W/m^{2}K.