Written Ph.D. Qualifying Examination (Heat Transfer)

Spring 2010

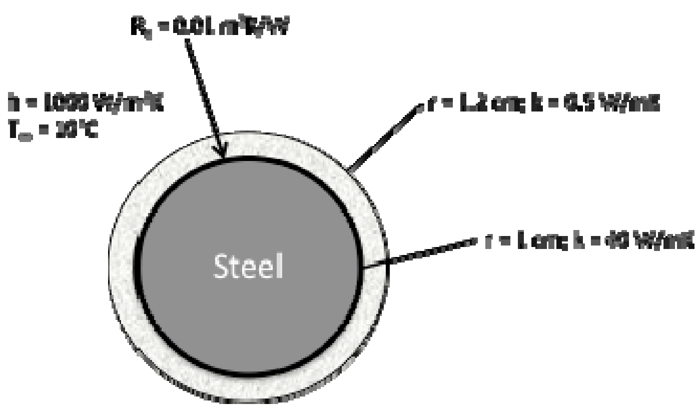
Problem 1. A cylindrical steel rod with a diameter of 2 cm is covered by a polymer material that is 0.2 cm thick as shown in the diagram. The rod is 0.5 m long and both ends are insulated. An interface resistance (R_c) of 0.01 m^2K/W exists between the rod and polymer coating. The entire system is exposed to a gas stream with a convective coefficient of h=1000 W/m^2K and T_∞ = 10˚C. Initially, the steel rod is heated (for example, by absorption of solar irradiation) until its surface reaches a uniform temperature of 175˚C, and at this point the heating is stopped.

(a) Determine the time required for the surface of the steel rod to cool to 100˚C.

(b) Calculate if the polymer coating is ‘safe to touch’ when the surface temperature of the steel rod is at 100˚C (assume that you can safely touch objects at T < 45˚C).

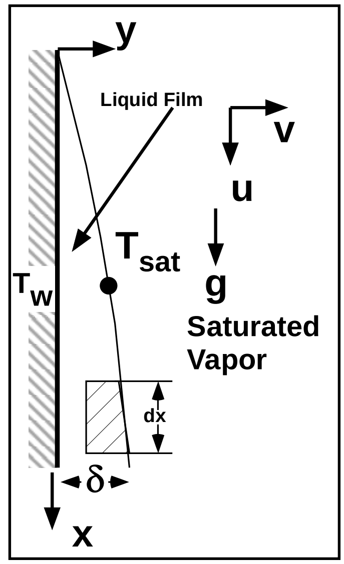
(c) If the radius of the steel rod is doubled when its surface temperature is at 100˚C what effect will this have on the temperature drop across the steel rod/polymer interface?

Please clearly state all assumptions



Steel: k=40 W/mK; c_p=434 J/kgK; density= 8131 kg/m^3

Problem 2. Consider a vertical flat plate maintained at temperature $T = T_w$, exposed on one side to a quiescent atmosphere of vapor at saturation temperature $T = T_{sat}$, such that $T_{sat} > T_w$, as shown in the Figure. The temperatures under consideration cause the vapor to condense on the plate and form a liquid film on the plate surface, growing in thickness as it flows down due to the influence of gravity.



1. Conduct a force balance on the liquid film, considering the effects of gravitational body forces and viscosity, and neglecting the effects of inertia, to develop an expression for the velocity profile u in the film at a location where the film has grown to thickness δ. The liquid and vapor phase densities are given by ρ_l and ρ_v, and the liquid phase viscosity is μ_l.

2. Use this velocity profile to obtain a relation for the mass flow rate of the liquid film per unit width, $\dot{m}'$, and also the corresponding differential mass flow rate $d\dot{m}'/d\delta$.

3. At low condensation rates, it can be assumed that the heat transfer in the film occurs only due to conduction; therefore, the heat flux to the interface to support this condensation rate can be expressed simply as $q'' = k_l\left(T_{sat} - T_w\right)/\delta$, where k_l is the liquid film conductivity. This can also be used to obtain the heat flow per unit width dq across differential width dx. From elementary thermodynamics, it is known that heat flow can be related to the condensate rate simply as $dq = h_{lv} d\dot{m}'$ where h_{lv} is the latent heat of condensation. Using these concepts, obtain an expression for the film thickness at location x in terms of $\Delta T = T_{sat} - T_w$, h_{lv}, g, and the relevant fluid properties, and location x.

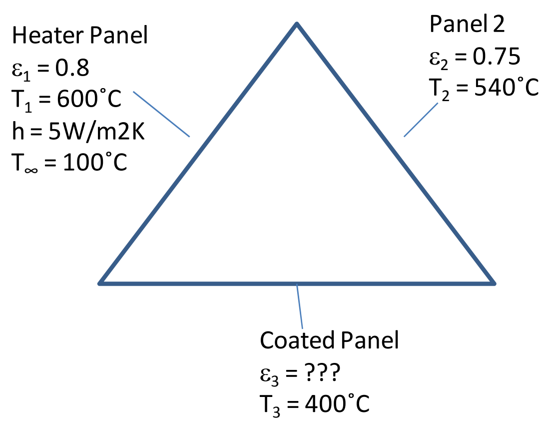
Recognizing, as above, that the heat transfer in the film is only due to conduction, use this film thickness to obtain an expression for the local film heat transfer coefficient h_l, and therefore, the local Nusselt number, $Nu_x = h_l x / k_l$

Problem 3. An oven used to anneal a coating on the surface of metal panels is fabricated by creating a triangular enclosure with heaters placed inside one of the walls. The second wall has some insulation which does not totally prevent heat loss through the wall. The third wall is made from the metal panel with the coating needing to be annealed. The cross section of the oven forms an equilateral triangle with each side measuring 1m in length. Thermocouples are used to show the steady state surface temperatures inside the oven. It is desired to analyze the radiation exchange in this system. Please provide a solution to the following questions and scenarios.

A) **Test to determine total emissivity.**

To determine the total emissivity of the coating on the metal panel, a colleague suggests that a sample of the coating be heated to 300°C and a photodetector be used to measure the normal reflectivity by illuminating the surface with a green laser (532 nm). Knowing that the coating is opaque and gray, the analysis of the test results determine that $\rho_n = 0.3$. Is this experiment sufficient to determine ε_T or what assumptions need to be made to determine the total hemispherical emissivity?

B) **Test to determine IR detector to measure panel temperature.** A colleague also suggests using an IR detector to verify the panel temperature is 300°C during the reflectivity experiment. One IR detector has a maximum sensitivity in the 3-5μm wavelength regime and 10% quantum efficiency, the other has a max sensitivity between 10-14 μm and a 40% quantum efficiency (q.e.~the amount of photons which are converted to electrons). Which detector is more sensitive for this application?



C) Assuming that the conditions needed in part A are met such that ε_T can be determined. Determine the heat per unit length required by the heaters and the cooling per unit length that must be supplied to the panel to maintain this furnace setup.

Note: There is convection with a convective heat transfer coefficient of 5 W/m^{2}K applied to the outside surface of just the heater panel exchanging energy with air at 100˚C.

D) If the insulation on surface 2 is replaced such that it becomes a perfect insulator and no heat generation takes place in this panel, what changes about the problem and how would you analyze it? What is the power required by the heaters and the cooling requirement for the panel?