Franklin W. Olin College of Engineering
ENGR 3310: Transport Phenomena

Problem Set 8

Assigned: 11/8/04 Fall 2004
Due: No due date

1. Parallel flow of atmospheric air over a flat plate of length $L = 3$ m is disrupted by an array of stationary rods placed in the flow path over the plate. Laboratory measurements of the local convection coefficient at the surface of the plate are made for a prescribed value of velocity, V, and a surface temperature $T_s > T_\infty$. The results are correlated by an expression of the form $h_x = 0.7 + 13.6x - 3.4x^2$ where h_x has units of W/m^2 K and x is in meters. Evaluate the average convection coefficient $\bar{h}_L$ for the entire plate and the ratio $\bar{h}_L / h_L$ at the trailing edge.

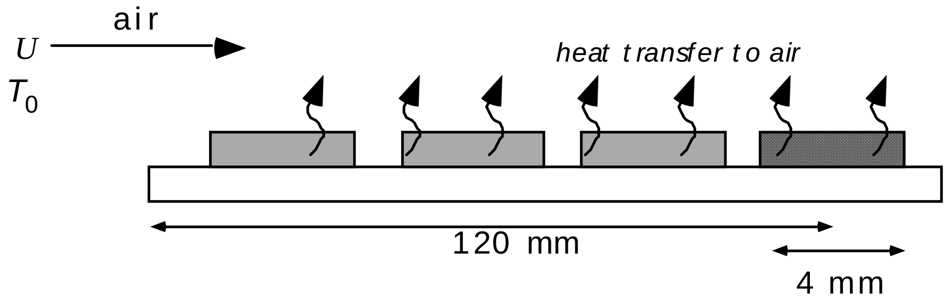
2. Consider conditions for which a fluid with a free stream velocity of $V = 1$ m/s flows over a surface with a characteristic length of $L = 1$ m, providing an average convection heat transfer coefficient of $\bar{h} = 100$ W/m^2 K. Calculate the dimensionless parameters $Nu_L, Re_L,$ and Pr for the following fluids: air, engine oil, mercury, and water. Assume the fluids to be at 300 K.

3. Consider a rectangular fin that is used to cool a motorcycle engine. The fin is 0.15 m long and at a constant temperature of 250 °C, while the motorcycle is moving at 80 km/h in air at 27 °C. The air is in parallel flow over both surfaces of the fin and turbulent flow conditions may be assumed to exist throughout.

a) What is the rate of heat removal per unit width of the fin?
b) Generate a plot of the heat removal rate per unit width of the fin for motorcycle speeds ranging from 10 to 100 km/h.

4. Inside any modern computer, you will have noticed that there are several fans which circulate air around the case to remove the heat generated in the silicon chips. For reliable and extended operation, it is critical that surface temperatures do not exceed preset values.

Consider the geometry shown below in which forced air at T_0 = 25˚C is blown by a fan at U = 10 m/s across the silicon components mounted on a circuit board. The component of interest is a sensitive logic chip of size 4 mm by 4mm located 120 mm from the leading edge of the board.



a) Assuming that the circuit board can be thought of as a flat plate, sketch the evolution of the thermal and velocity boundary layers along the plate direction *x*. For air, which boundary layer is thicker?

b) Briefly answer the following short questions:
   1. It is known that for air, the momentum (or velocity) boundary layer becomes turbulent at a critical Reynolds number of $Re_x = 3 \times 10^5$. What distance (x) down a flat plate such as the circuit board does a fluid particle travel before the boundary layer becomes turbulent?
   2. Given the nature of turbulent fluid motion you think that heat transfer is more or less effective after the boundary layer has become turbulent?
   3. Experiments show that in fact the presence of individual chips and other electronic components disrupt the momentum (or velocity) boundary layer. Do you think this will result in an earlier or later transition to turbulence?

c) Experiments have shown that the convective heat transfer for this circuit board design is correlated by an expression of the form:

$$Nu_x = 0.04(Re_x)^{0.85}(Pr)^{1/3} \qquad (3.1)$$

Evaluate the <u>average</u> heat transfer coefficient <u>for the particular 4mm chip being considered</u> (by integrating the *x-dependence* in eq. 3.1) and hence estimate the surface temperature of the chip if it is dissipating 30 mW of heat.

d) As clock rates of logic circuits continue to climb, the levels of power dissipation on circuit boards become increasingly problematic. To ensure reliable operation over extended periods, typical chip temperatures should not exceed 85˚C. If we assume we have an ample supply of air at T_0 = 25˚C (you should now see why it is important to keep fan/vent areas at the backs of computers clear, or keep them in air-conditioned environments), find a numerical expression for the maximum power dissipation $P_{\max}$ as a function of air velocity. Sketch the shape of this curve and evaluate the maximum power dissipation for air speeds of 1 m/s and 25 m/s.

5. In the final stages of production, a pharmaceutical is sterilized by heating it from 25 to 75 °C as moves at 0.2 m/s through a straight thin-walled stainless steel tube of 12.7 mm diameter. A uniform heat flux is maintained by an electric resistance heater wrapped around the outer surface of the tube. If the tube is 10 m long, what is the required heat flux? If fluid enters the tube with a fully developed velocity profile and a uniform temperature profile, what is the surface temperature at the tube exit and at a distance of 0.5 m from the entrance? Fluid properties may be approximated at ρ = 1000 kg/m^3, c_p = 4000 J/kg K, $\mu = 2\times10^{-3}$ kg/s$\cdot$m, k = 0.48 W/m K and Pr = 10.