Reference (J. P. Holman, **Heat Transfer, Tenth Edition,** McGraw-Hill Companies, Inc. 2010.

Ex//1) Air at 2 atm and 200◦C is heated as it flows through a tube with a diameter of 1 in (2.54 cm) at a velocity of 10 m/s. Calculate the heat transfer per unit length of tube if a constant-heat-flux condition is maintained at the wall and the wall temperature is 20◦C above the air temperature, all along the length of the tube. How much would the bulk temperature increase over a 3-m length of the tube?

$$\rho = \frac{p}{RT} = \frac{(2)(1.0132 \times 10^5)}{(287)(473)} = 1.493 \text{ kg/m}^3 \qquad [0.0932 \text{ lb}_m/\text{ft}^3]$$

$$\Pr = 0.681$$

$$\mu = 2.57 \times 10^{-5} \text{ kg/m} \cdot \text{s} \qquad [0.0622 \text{ lb}_m/\text{h} \cdot \text{ft}]$$

$$k = 0.0386 \text{ W/m} \cdot {}^\circ\text{C} \qquad [0.0223 \text{ Btu/h} \cdot \text{ft} \cdot {}^\circ\text{F}]$$

$$c_p = 1.025 \text{ kJ/kg} \cdot {}^\circ\text{C}$$

$$\text{Re}_d = \frac{\rho u_m d}{\mu} = \frac{(1.493)(10)(0.0254)}{2.57 \times 10^{-5}} = 14{,}756$$

so that the flow is turbulent. We therefore use Equation (6-4*a*) to calculate the heat-transfer coefficient.

$$\text{Nu}_d = \frac{hd}{k} = 0.023 \,\text{Re}_d^{0.8} \Pr^{0.4} = (0.023)(14{,}756)^{0.8}(0.681)^{0.4} = 42.67$$

$$h = \frac{k}{d}\text{Nu}_d = \frac{(0.0386)(42.67)}{0.0254} = 64.85 \text{ W/m}^2 \cdot {}^\circ\text{C} \qquad [11.42 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}]$$

The heat flow per unit length is then

$$\frac{q}{L} = h\pi d(T_w - T_b) = (64.85)\pi(0.0254)(20) = 103.5 \text{ W/m} \qquad [107.7 \text{ Btu/ft}]$$

$$q = \dot{m} c_p \Delta T_b = L\left(\frac{q}{L}\right)$$

We also have

$$\dot{m} = \rho u_m \frac{\pi d^2}{4} = (1.493)(10)\pi \frac{(0.0254)^2}{4}$$

$$= 7.565 \times 10^{-3} \text{ kg/s} \qquad [0.0167 \text{ lb}_m/\text{s}]$$

so that we insert the numerical values in the energy balance to obtain

$$(7.565 \times 10^{-3})(1025)\Delta T_b = (3.0)(103.5)$$

and

$$\Delta T_b = 40.04^\circ\text{C} \qquad [104.07^\circ\text{F}]$$

Ex//2) Water at 60◦C enters a tube of 1-in (2.54-cm) diameter at a mean flow velocity of 2 cm/s. Calculate the exit water temperature if the tube is 3.0 m long and the wall temperature is constant at 80◦C.

$$\rho = 985\ \text{kg/m}^3 \qquad c_p = 4.18\ \text{kJ/kg}\cdot{}^\circ\text{C}$$

$$\mu = 4.71 \times 10^{-4}\ \text{kg/m}\cdot\text{s} \qquad [1.139\ \text{lb}_m/\text{h}\cdot\text{ft}]$$

$$k = 0.651\ \text{W/m}\cdot{}^\circ\text{C} \qquad \text{Pr} = 3.02$$

$$\text{Re}_d = \frac{\rho u_m d}{\mu} = \frac{(985)(0.02)(0.0254)}{4.71 \times 10^{-4}} = 1062$$

so the flow is laminar. Calculating the additional parameter, we have

$$\text{Re}_d \text{Pr} \frac{d}{L} = \frac{(1062)(3.02)(0.0254)}{3} = 27.15 > 10$$

so Equation (6-10) is applicable. We do not yet know the mean bulk temperature to evaluate properties so we first make the calculation on the basis of 60°C, determine an exit bulk temperature, and then make a second iteration to obtain a more precise value. When inlet and outlet conditions are designated with the subscripts 1 and 2, respectively, the energy balance becomes

$$q = h\pi dL\left(T_w - \frac{T_{b_1} + T_{b_2}}{2}\right) = \dot{m}c_p(T_{b_2} - T_{b_1}) \qquad [a]$$

At the wall temperature of 80°C we have

$$\mu_w = 3.55 \times 10^{-4}\ \text{kg/m}\cdot\text{s}$$

From Equation (6-10)

$$\text{Nu}_d = (1.86)\left[\frac{(1062)(3.02)(0.0254)}{3}\right]^{1/3}\left(\frac{4.71}{3.55}\right)^{0.14} = 5.816$$

$$h = \frac{k\text{Nu}_d}{d} = \frac{(0.651)(5.816)}{0.0254} = 149.1\ \text{W/m}^2\cdot{}^\circ\text{C} \qquad [26.26\ \text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}]$$

The mass flow rate is

$$\dot{m} = \rho\frac{\pi d^2}{4}u_m = \frac{(985)\pi(0.0254)^2(0.02)}{4} = 9.982 \times 10^{-3}\ \text{kg/s}$$

Inserting the value for h into Equation (a) along with $\dot{m}$ and $T_{b_1} = 60°\text{C}$ and $T_w = 80°\text{C}$ gives

$$(149.1)\pi(0.0254)(3.0)\left(80 - \frac{T_{b_2} + 60}{2}\right) = (9.982 \times 10^{-3})(4180)(T_{b_2} - 60) \qquad [b]$$

This equation can be solved to give

$$T_{b_2} = 71.98°\text{C}$$

Thus, we should go back and evaluate properties at

$$T_{b,\text{mean}} = \frac{71.98 + 60}{2} = 66°\text{C}$$

We obtain

$$\rho = 982\ \text{kg/m}^3 \qquad c_p = 4185\ \text{J/kg}\cdot{}^\circ\text{C} \qquad \mu = 4.36 \times 10^{-4}\ \text{kg/m}\cdot\text{s}$$

$$k = 0.656\ \text{W/m}\cdot{}^\circ\text{C} \qquad \text{Pr} = 2.78$$

$$\text{Re}_d = \frac{(1062)(4.71)}{4.36} = 1147$$

$$\text{Re Pr}\frac{d}{L} = \frac{(1147)(2.78)(0.0254)}{3} = 27.00$$

$$\text{Nu}_d = (1.86)(27.00)^{1/3}\left(\frac{4.36}{3.55}\right)^{0.14} = 5.743$$

$$h = \frac{(0.656)(5.743)}{0.0254} = 148.3\ \text{W/m}^2\cdot{}^\circ\text{C}$$

We insert this value of h back into Equation (a) to obtain

$$T_{b_2} = 71.88°\text{C} \qquad [161.4°\text{F}]$$

H.W.

Q1//Air at 1 atm and 27◦C enters a 5.0-mm-diameter smooth tube with a velocity of 3.0 m/s. The length of the tube is 10 cm. A constant heat flux is imposed on the tube wall. Calculate the heat transfer if the exit bulk temperature is 77◦C. Also calculate the exit wall temperature and the value of *h* at exit.

Q2//A 2.0-cm-diameter tube having a relative roughness of 0.001 is maintained at a constant wall temperature of 90◦C.Water enters the tube at 40◦C and leaves at 60◦C. If the entering velocity is 3 m/s, calculate the length of tube necessary to accomplish the heating.

Q3//Air at 300 K and 1 atm enters a smooth tube having a diameter of 2 cm and length of 10 cm. The air velocity is 40 m/s. What constant heat flux must be applied at the tube surface to result in an air temperature rise of 5◦C? What average wall temperature would be necessary for this case?