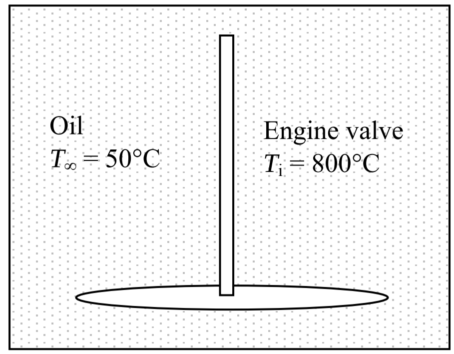
11-104 Internal combustion engine valves are quenched in a large oil bath. The time it takes for the valve temperature to drop to specified temperatures and the maximum heat transfer are to be determined.

Assumptions **1** The thermal properties of the valves are constant. **2** The heat transfer coefficient is constant and uniform over the entire surface. **3** Depending on the size of the oil bath, the oil bath temperature will increase during quenching. However, an average canstant temperature as specified in the problem will be used. **4** The Biot number is Bi < 0.1 so that the lumped system analysis is applicable (this assumption will be verified).

Properties The thermal conductivity, density, and specific heat of the balls are given to be $k = 48$ W/m.°C, $\rho = 7840$ kg/m^3, and $c_p = 440$ J/kg.°C.



Analysis (*a*) The characteristic length of the balls and the Biot number are

$$L_c = \frac{V}{A_s} = \frac{1.8(\pi D^2 L/4)}{2\pi DL} = \frac{1.8D}{8} = \frac{1.8(0.008\text{ m})}{8} = 0.0018\text{ m}$$

$$Bi = \frac{hL_c}{k} = \frac{(800\text{ W/m}^2.°\text{C})(0.0018\text{ m})}{48\text{ W/m.°C}} = 0.03 < 0.1$$

Therefore, we can use lumped system analysis. Then the time for a final valve temperature of 400°C becomes

$$b = \frac{hA_s}{\rho c_p V} = \frac{8h}{1.8\rho c_p D} = \frac{8(800\text{ W/m}^2.°\text{C})}{1.8(7840\text{ kg/m}^3)(440\text{ J/kg.°C})(0.008\text{ m})} = 0.1288\text{ s}^{-1}$$

$$\frac{T(t)-T_\infty}{T_i - T_\infty} = e^{-bt} \longrightarrow \frac{400-50}{800-50} = e^{-(0.1288\text{ s}^{-1})t} \longrightarrow t = \mathbf{5.9\text{ s}}$$

(*b*) The time for a final valve temperature of 200°C is

$$\frac{T(t)-T_\infty}{T_i - T_\infty} = e^{-bt} \longrightarrow \frac{200-50}{800-50} = e^{-(0.1288\text{ s}^{-1})t} \longrightarrow t = \mathbf{12.5\text{ s}}$$

(*c*) The time for a final valve temperature of 51°C is

$$\frac{T(t)-T_\infty}{T_i - T_\infty} = e^{-bt} \longrightarrow \frac{51-50}{800-50} = e^{-(0.1288\text{ s}^{-1})t} \longrightarrow t = \mathbf{51.4\text{ s}}$$

(*d*) The maximum amount of heat transfer from a single valve is determined from

$$m = \rho V = \rho\frac{1.8\pi D^2 L}{4} = (7840\text{ kg/m}^3)\frac{1.8\pi(0.008\text{ m})^2(0.10\text{ m})}{4} = 0.0709\text{ kg}$$

$$Q = mc_p[T_f - T_i] = (0.0709\text{ kg})(440\text{ J/kg.°C})(800-50)°\text{C} = 23{,}400\text{ J} = \mathbf{23.4\text{ kJ}}\ \text{(per valve)}$$