

**8-158** Stainless steel ball bearings leaving the oven at a uniform temperature of  $900^{\circ}\text{C}$  at a rate of 1400 /min are exposed to air and are cooled to  $850^{\circ}\text{C}$  before they are dropped into the water for quenching. The rate of heat transfer from the ball to the air and the rate of entropy generation due to this heat transfer are to be determined.

**Assumptions** **1** The thermal properties of the bearing balls are constant. **2** The kinetic and potential energy changes of the balls are negligible. **3** The balls are at a uniform temperature at the end of the process

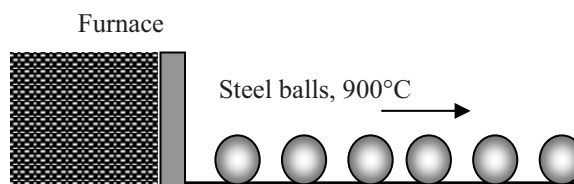
**Properties** The density and specific heat of the ball bearings are given to be  $\rho = 8085 \text{ kg/m}^3$  and  $c_p = 0.480 \text{ kJ/kg}\cdot^{\circ}\text{C}$ .

**Analysis** (a) We take a single bearing ball as the system. The energy balance for this closed system can be expressed as

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$-Q_{\text{out}} = \Delta U_{\text{ball}} = m(u_2 - u_1)$$

$$Q_{\text{out}} = mc(T_1 - T_2)$$



The total amount of heat transfer from a ball is

$$m = \rho V = \rho \frac{\pi D^3}{6} = (8085 \text{ kg/m}^3) \frac{\pi (0.012 \text{ m})^3}{6} = 0.007315 \text{ kg}$$

$$Q_{\text{out}} = mc(T_1 - T_2) = (0.007315 \text{ kg})(0.480 \text{ kJ/kg}\cdot^{\circ}\text{C})(900 - 850)^{\circ}\text{C} = 0.1756 \text{ kJ/ball}$$

Then the rate of heat transfer from the balls to the air becomes

$$\dot{Q}_{\text{total}} = \dot{n}_{\text{ball}} Q_{\text{out (per ball)}} = (1400 \text{ balls/min}) \times (0.1756 \text{ kJ/ball}) = \mathbf{245.8 \text{ kJ/min} = 4.10 \text{ kW}}$$

Therefore, heat is lost to the air at a rate of 4.10 kW.

(b) We again take a single bearing ball as the system. The entropy generated during this process can be determined by applying an entropy balance on an *extended system* that includes the ball and its immediate surroundings so that the boundary temperature of the extended system is at  $30^{\circ}\text{C}$  at all times:

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$-\frac{Q_{\text{out}}}{T_b} + S_{\text{gen}} = \Delta S_{\text{system}} \rightarrow S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}}$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = mc_{\text{avg}} \ln \frac{T_2}{T_1} = (0.007315 \text{ kg})(0.480 \text{ kJ/kg}\cdot\text{K}) \ln \frac{850 + 273}{900 + 273} = -0.0001530 \text{ kJ/K}$$

Substituting,

$$S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}} = \frac{0.1756 \text{ kJ}}{303 \text{ K}} - 0.0001530 \text{ kJ/K} = 0.0004265 \text{ kJ/K (per ball)}$$

Then the rate of entropy generation becomes

$$\dot{S}_{\text{gen}} = S_{\text{gen}} \dot{n}_{\text{ball}} = (0.0004265 \text{ kJ/K} \cdot \text{ball})(1400 \text{ balls/min}) = 0.597 \text{ kJ/min}\cdot\text{K} = \mathbf{0.00995 \text{ kW/K}}$$