

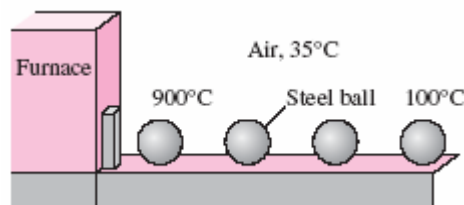
**8-49** Carbon steel balls are to be annealed at a rate of 2500/h by heating them first and then allowing them to cool slowly in ambient air at a specified rate. The total rate of heat transfer from the balls to the ambient air and the rate of exergy destruction due to this heat transfer are to be determined.

**Assumptions** 1 The thermal properties of the balls are constant. 2 There are no changes in kinetic and potential energies. 3 The balls are at a uniform temperature at the end of the process.

**Properties** The density and specific heat of the balls are given to be  $\rho = 7833 \text{ kg/m}^3$  and  $c_p = 0.465 \text{ kJ/kg} \cdot ^\circ\text{C}$ .

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

$$\begin{aligned} \underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} &= \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc. energies}} \\ -Q_{\text{out}} &= \Delta U_{\text{ball}} = m(u_2 - u_1) \\ Q_{\text{out}} &= mc_p(T_1 - T_2) \end{aligned}$$



The amount of heat transfer from a single ball is

$$\begin{aligned} m &= \rho V = \rho \frac{\pi D^3}{6} = (7833 \text{ kg/m}^3) \frac{\pi (0.008 \text{ m})^3}{6} = 0.00210 \text{ kg} \\ Q_{\text{out}} &= mc_p(T_1 - T_2) = (0.0021 \text{ kg})(0.465 \text{ kJ/kg} \cdot ^\circ\text{C})(900 - 100)^\circ\text{C} = 781 \text{ J} = 0.781 \text{ kJ (per ball)} \end{aligned}$$

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

$$\dot{Q}_{\text{out}} = \dot{n}_{\text{ball}} Q_{\text{out}} = (1200 \text{ balls/h}) \times (0.781 \text{ kJ/ball}) = 936 \text{ kJ/h} = \mathbf{260 \text{ W}}$$

(b) The exergy destruction (or irreversibility) can be determined from its definition  $X_{\text{destroyed}} = T_0 S_{\text{gen}}$ . 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 35°C at all times:

$$\begin{aligned} \underbrace{S_{\text{in}} - S_{\text{out}}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{\text{gen}}}_{\text{Entropy generation}} &= \underbrace{\Delta S_{\text{system}}}_{\text{Change in entropy}} \\ -\frac{Q_{\text{out}}}{T_b} + S_{\text{gen}} &= \Delta S_{\text{system}} \rightarrow S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}} \end{aligned}$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = mc_p \ln \frac{T_2}{T_1} = (0.00210 \text{ kg})(0.465 \text{ kJ/kg} \cdot \text{K}) \ln \frac{100 + 273}{900 + 273} = -0.00112 \text{ kJ/K}$$

Substituting,

$$S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}} = \frac{0.781 \text{ kJ}}{308 \text{ K}} - 0.00112 \text{ kJ/K} = 0.00142 \text{ kJ/K (per ball)}$$

Then the rate of entropy generation becomes

$$\dot{S}_{\text{gen}} = S_{\text{gen}} \dot{n}_{\text{ball}} = (0.00142 \text{ kJ/K} \cdot \text{ball})(1200 \text{ balls/h}) = 1.704 \text{ kJ/h} \cdot \text{K} = 0.000473 \text{ kW/K}$$

Finally,

$$\dot{X}_{\text{destroyed}} = T_0 \dot{S}_{\text{gen}} = (308 \text{ K})(0.000473 \text{ kW/K}) = 0.146 \text{ kW} = \mathbf{146 \text{ W}}$$