11-35 An ideal vapor-compression refrigeration cycle is used to keep a space at a low temperature. The cooling load, the COP, the exergy destruction in each component, the total exergy destruction, and the second-law efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis (a) The properties of R-134a are (Tables A-11 through A-13)

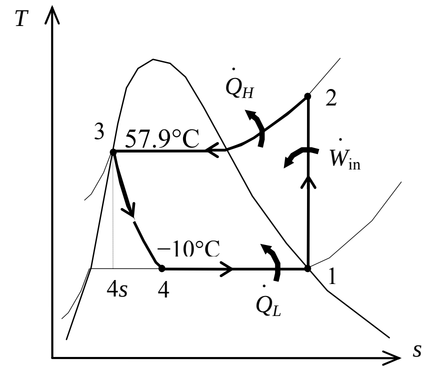
$$\left.\begin{array}{l} T_1 = -10°\text{C} \\ x_1 = 1 \end{array}\right\} \begin{array}{l} h_1 = 244.51 \text{ kJ/kg} \\ s_1 = 0.9377 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = P_{\text{sat@57.9°C}} = 1600 \text{ kPa} \\ s_2 = s_1 \end{array}\right\} h_2 = 287.85 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 1600 \text{ kPa} \\ x_3 = 0 \end{array}\right\} \begin{array}{l} h_3 = 135.93 \text{ kJ/kg} \\ s_3 = 0.4791 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$h_4 = h_3 = 135.93 \text{ kJ/kg}$$

$$\left.\begin{array}{l} T_4 = -10°\text{C} \\ h_4 = 135.93 \text{ kJ/kg} \end{array}\right\} s_4 = 0.5251 \text{ kJ/kg}\cdot\text{K}$$



The energy interactions in the components and the COP are

$$q_L = h_1 - h_4 = 244.51 - 135.93 = \mathbf{108.6 \text{ kJ/kg}}$$

$$q_H = h_2 - h_3 = 287.85 - 135.93 = 151.9 \text{ kJ/kg}$$

$$w_{\text{in}} = h_2 - h_1 = 287.85 - 244.51 = 43.33 \text{ kJ/kg}$$

$$\text{COP} = \frac{q_L}{w_{\text{in}}} = \frac{108.6 \text{ kJ/kg}}{43.33 \text{ kJ/kg}} = \mathbf{2.506}$$

(b) The exergy destruction in each component of the cycle is determined as follows

Compressor:

$$s_{\text{gen},1-2} = s_2 - s_1 = 0$$

$$Ex_{\text{dest,1-2}} = T_0 s_{\text{gen,1-2}} = \mathbf{0}$$

Condenser:

$$s_{\text{gen},2-3} = s_3 - s_2 + \frac{q_H}{T_H} = (0.4791 - 0.9377) \text{ kJ/kg}\cdot\text{K} + \frac{151.9 \text{ kJ/kg}}{298 \text{ K}} = 0.05124 \text{ kJ/kg}\cdot\text{K}$$

$$Ex_{\text{dest,2-3}} = T_0 s_{\text{gen,2-3}} = (298 \text{ K})(0.05124 \text{ kJ/kg}\cdot\text{K}) = \mathbf{15.27 \text{ kJ/kg}}$$

Expansion valve:

$$s_{\text{gen},3-4} = s_4 - s_3 = 0.5251 - 0.4791 = 0.04595 \text{ kJ/kg}\cdot\text{K}$$

$$Ex_{\text{dest,3-4}} = T_0 s_{\text{gen,3-4}} = (298 \text{ K})(0.04595 \text{ kJ/kg}\cdot\text{K}) = \mathbf{13.69 \text{ kJ/kg}}$$

Evaporator:

$$s_{\text{gen},4-1} = s_1 - s_4 - \frac{q_L}{T_L} = (0.9377 - 0.5251) \text{ kJ/kg}\cdot\text{K} - \frac{108.6 \text{ kJ/kg}}{278 \text{ K}} = 0.02201 \text{ kJ/kg}\cdot\text{K}$$

$$Ex_{\text{dest,4-1}} = T_0 s_{\text{gen,4-1}} = (298 \text{ K})(0.02201 \text{ kJ/kg}\cdot\text{K}) = \mathbf{6.56 \text{ kJ/kg}}$$

The total exergy destruction can be determined by adding exergy destructions in each component:

$$\begin{aligned} \dot{E}x_{\text{dest,total}} &= \dot{E}x_{\text{dest,1-2}} + \dot{E}x_{\text{dest,2-3}} + \dot{E}x_{\text{dest,3-4}} + \dot{E}x_{\text{dest,4-1}} \\ &= 0 + 15.27 + 13.69 + 6.56 = \mathbf{35.52 \text{ kJ/kg}} \end{aligned}$$

(c) The exergy of the heat transferred from the low-temperature medium is

$$Ex_{q_L} = -q_L\left(1-\frac{T_0}{T_L}\right) = -(108.6\text{ kJ/kg})\left(1-\frac{298}{278}\right) = 7.812\text{ kJ/kg}$$

The second-law efficiency of the cycle is

$$\eta_{\text{II}} = \frac{Ex_{q_L}}{w_{\text{in}}} = \frac{7.812}{43.33} = 0.1803 = \mathbf{18.0\%}$$

The total exergy destruction in the cycle can also be determined from

$$Ex_{\text{dest,total}} = w_{\text{in}} - Ex_{q_L} = 43.33 - 7.812 = 35.52\text{ kJ/kg}$$

The result is identical as expected.

The second-law efficiency of the compressor is determined from

$$\eta_{\text{II,Comp}} = \frac{\dot{X}_{\text{recovered}}}{\dot{X}_{\text{expended}}} = \frac{\dot{W}_{\text{rev}}}{\dot{W}_{\text{act, in}}} = \frac{\dot{m}[h_2 - h_1 - T_0(s_2 - s_1)]}{\dot{m}(h_2 - h_1)}$$

since the compression through the compressor is isentropic ($s_2 = s_1$), the second-law efficiency is

$$\eta_{\text{II,Comp}} = 1 = \mathbf{100\%}$$

The second-law efficiency of the evaporator is determined from

$$\eta_{\text{II, Evap}} = \frac{\dot{X}_{\text{recovered}}}{\dot{X}_{\text{expended}}} = \frac{\dot{Q}_L(T_0 - T_L)/T_L}{\dot{m}[h_4 - h_1 - T_0(s_4 - s_1)]} = 1 - \frac{\dot{X}_{\text{dest,4-1}}}{\dot{X}_4 - \dot{X}_1}$$

where

$$\begin{aligned} x_4 - x_1 &= h_4 - h_1 - T_0(s_4 - s_1) \\ &= (135.93 - 244.51)\text{ kJ/kg} - (298\text{ K})(0.5251 - 0.9377)\text{ kJ/kg}\cdot\text{K} \\ &= 14.37\text{ kJ/kg} \end{aligned}$$

Substituting,

$$\eta_{\text{II, Evap}} = 1 - \frac{x_{\text{dest,4-1}}}{x_4 - x_1} = 1 - \frac{6.56\text{ kJ/kg}}{14.37\text{ kJ/kg}} = 0.544 = \mathbf{54.4\%}$$