11-116 An air conditioner operates on the vapor-compression refrigeration cycle. The rate of cooling provided to the space, the COP, the isentropic efficiency and the exergetic efficiency of the compressor, the exergy destruction in each component of the cycle, the total exergy destruction, the minimum power input, and the second-law efficiency of the cycle 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)

$$T_{sat@180\,kPa} = -12.7°C$$

$$\left.\begin{array}{l} P_1 = 180\,\text{kPa} \\ T_1 = -12.7 + 2.7 = 10°C \end{array}\right\} \begin{array}{l} h_1 = 245.14\text{ kJ/kg} \\ s_1 = 0.9483\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 1200\,\text{kPa} \\ s_1 = s_1 \end{array}\right\} h_{2s} = 285.32\text{ kJ/kg}$$

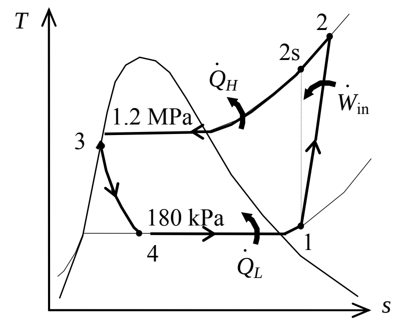
$$\left.\begin{array}{l} P_2 = 1200\,\text{kPa} \\ T_2 = 60°C \end{array}\right\} \begin{array}{l} h_2 = 289.64\text{ kJ/kg} \\ s_2 = 0.9614\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$T_{sat@1200\,kPa} = 46.3°C$$

$$\left.\begin{array}{l} P_3 = 1200\text{ kPa} \\ T_3 = 46.3 - 6.3 = 40°C \end{array}\right\} \begin{array}{l} h_3 \cong h_{f@40°C} = 108.26\text{ kJ/kg} \\ s_3 \cong s_{f@40°C} = 0.3948\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$h_4 = h_3 = 108.26\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 180\text{ kPa} \\ h_4 = 108.26\text{ kJ/kg} \end{array}\right\} s_4 = 0.4228\text{ kJ/kg}\cdot\text{K}$$



The cooling load and the COP are

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.06\text{ kg/s})(245.14 - 108.26)\text{kJ/kg} = 8.213\text{ kW}$$

$$= (8.213\text{ kW})\left(\frac{3412\text{ Btu/h}}{1\text{ kW}}\right) = \mathbf{28{,}020\ Btu/h}$$

$$\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.06\text{ kg/s})(289.64 - 108.26)\text{kJ/kg} = 10.88\text{ kW}$$

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = (0.06\text{ kg/s})(289.64 - 245.14)\text{kJ/kg} = 2.670\text{ kW}$$

$$\text{COP} = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{8.213\text{ kW}}{2.670\text{ kW}} = \mathbf{3.076}$$

(b) The isentropic efficiency of the compressor is

$$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{285.32 - 245.14}{289.64 - 245.14} = 0.9029 = \mathbf{90.3\%}$$

The reversible power and the exergy efficiency for the compressor are

$$\dot{W}_{rev} = \dot{m}\left[(h_2 - h_1) - T_0(s_2 - s_1)\right]$$
$$= (0.06\text{ kg/s})\left[(289.64 - 245.14)\text{kJ/kg} - (310\text{ K})(0.9614 - 0.9483)\text{kJ/kg}\cdot\text{K}\right]$$
$$= 2.428\text{ kW}$$

$$\eta_{ex,C} = \frac{\dot{W}_{rev}}{\dot{W}_{in}} = \frac{2.428\text{ kW}}{2.670\text{ kW}} = 0.9091 = \mathbf{90.9\%}$$

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

Compressor:

$$\dot{S}_{gen,1-2} = \dot{m}(s_2 - s_1) = (0.06\text{ kg/s})(0.9614 - 0.9483)\text{ kJ/kg}\cdot\text{K} = 0.0007827\text{ kW/K}$$

$$\dot{E}x_{dest,1\text{-}2} = T_0\dot{S}_{gen,1\text{-}2} = (310\text{ K})(0.0007827\text{ kW/K}) = \mathbf{0.2426\ kW}$$

Condenser:

$$\dot{S}_{\text{gen},2-3} = \dot{m}(s_3 - s_2) + \frac{\dot{Q}_H}{T_H} = (0.06\text{ kg/s})(0.3948 - 0.9614)\text{ kJ/kg}\cdot\text{K} + \frac{10.88\text{ kW}}{310\text{ K}} = 0.001114\text{ kW/K}$$

$$\dot{E}x_{\text{dest,2-3}} = T_0\dot{S}_{\text{gen,2-3}} = (310\text{ K})(0.001114\text{ kJ/kg}\cdot\text{K}) = \mathbf{0.3452\ kW}$$

Expansion valve:

$$\dot{S}_{\text{gen},3-4} = \dot{m}(s_4 - s_3) = (0.06\text{ kg/s})(0.4228 - 00.3948)\text{ kJ/kg}\cdot\text{K} = 0.001678\text{ kW/K}$$

$$\dot{E}x_{\text{dest,3-4}} = T_0\dot{S}_{\text{gen,3-4}} = (310\text{ K})(0.001678\text{ kJ/kg}\cdot\text{K}) = \mathbf{0.5203\ kJ/kg}$$

Evaporator:

$$\dot{S}_{\text{gen},4-1} = \dot{m}(s_1 - s_4) - \frac{\dot{Q}_L}{T_L} = (0.06\text{ kg/s})(0.9483 - 0.4228)\text{ kJ/kg}\cdot\text{K} - \frac{8.213\text{ kW}}{294\text{ K}} = 0.003597\text{ kW/K}$$

$$\dot{E}x_{\text{dest,4-1}} = T_0\dot{S}_{\text{gen,4-1}} = (310\text{ K})(0.003597\text{ kJ/kg}\cdot\text{K}) = \mathbf{1.115\ kW}$$

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

$$\begin{aligned}\dot{E}x_{\text{dest,total}} &= \dot{E}x_{\text{dest,1-2}} + \dot{E}x_{\text{dest,2-3}} + \dot{E}x_{\text{dest,3-4}} + \dot{E}x_{\text{dest,4-1}} \\ &= 0.2426 + 0.3452 + 0.5203 + 1.115 \\ &= \mathbf{2.223\ kW}\end{aligned}$$

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

$$\dot{E}x_{\dot{Q}_L} = -\dot{Q}_L\left(1 - \frac{T_0}{T_L}\right) = -(8.213\text{ kW})\left(1 - \frac{310}{294}\right) = 0.4470\text{ kW}$$

This is the minimum power input to the cycle:

$$\dot{W}_{\text{in,min}} = \dot{E}x_{\dot{Q}_L} = \mathbf{0.4470\ kW}$$

The second-law efficiency of the cycle is

$$\eta_{\text{II}} = \frac{\dot{W}_{\text{in,min}}}{\dot{W}_{\text{in}}} = \frac{0.4470}{2.670} = 0.1674 = \mathbf{16.7\%}$$

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

$$\dot{E}x_{\text{dest,total}} = \dot{W}_{\text{in}} - Ex_{\dot{Q}_L} = 2.670 - 0.4470 = 2.223\text{ kW}$$

The result is the same as expected.