14-93 Air is cooled and dehumidified at constant pressure. The cooling required is provided by a simple ideal vapor-compression refrigeration system using refrigerant-134a as the working fluid. The exergy destruction in the total system per 1000 m^3 of dry air is to be determined.

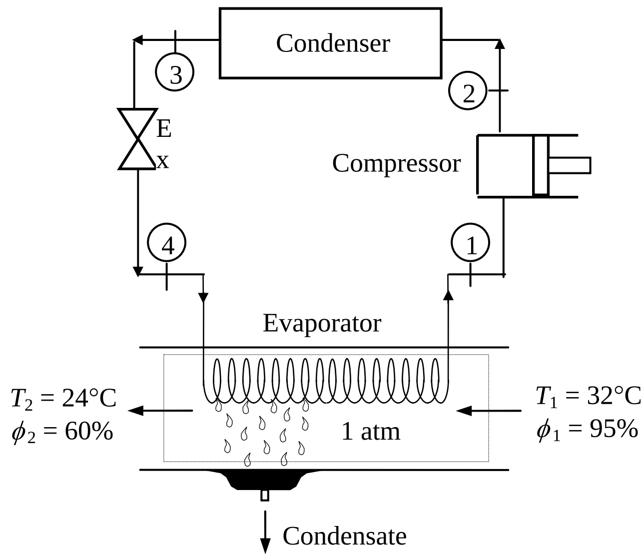
Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Properties The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. The properties of the air at various states are determined from the psychrometric chart (Figure A-31) to be

$$h_1 = 106.8 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0292 \text{ kg H}_2\text{O/kg dry air}$$
$$\boldsymbol{v}_1 = 0.905 \text{ m}^3\text{/kg dry air}$$

and

$$h_2 = 52.7 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.0112 \text{ kg H}_2\text{O/kg dry air}$$



We assume that the condensate leaves this system at the average temperature of the air inlet and exit. Then, from Table A-4,

$$h_w \cong h_{f\,@\,28°\text{C}} = 117.4 \text{ kJ/kg}$$

Analysis The amount of moisture in the air decreases due to dehumidification ($\omega_2 < \omega_1$). The mass of air is

$$m_a = \frac{\boldsymbol{V}_1}{\boldsymbol{v}_1} = \frac{1000 \text{ m}^3}{0.905 \text{ m}^3 \text{ / kg dry air}} = 1105 \text{ kg}$$

Applying the water mass balance and energy balance equations to the combined cooling and dehumidification section,

Water Mass Balance:

$$\sum \dot{m}_{w,i} = \sum \dot{m}_{w,e} \longrightarrow \dot{m}_{a1}\omega_1 = \dot{m}_{a2}\omega_2 + \dot{m}_w$$
$$m_w = m_a(\omega_1 - \omega_2) = (1105 \text{ kg})(0.0292 - 0.0112) = 19.89 \text{ kg}$$

Energy Balance:

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta\dot{E}_{\text{system}}^{\;\nearrow 0\text{ (steady)}} = 0$$
$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$
$$\sum \dot{m}_i h_i = \dot{Q}_{out} + \sum \dot{m}_e h_e$$
$$\dot{Q}_{\text{out}} = \dot{m}_{a1}h_1 - (\dot{m}_{a2}h_2 + \dot{m}_w h_w) = \dot{m}_a(h_1 - h_2) - \dot{m}_w h_w$$
$$Q_{\text{out}} = m_a(h_1 - h_2) - m_w h_w$$
$$Q_{\text{out}} = (1105 \text{ kg})(106.8 - 52.7)\text{kJ/kg} - (19.89 \text{ kg})(117.4 \text{ kJ/kg}) = 57{,}450 \text{ kJ}$$

We obtain the properties for the vapor-compression refrigeration cycle as follows (Tables A-11,through A-13):

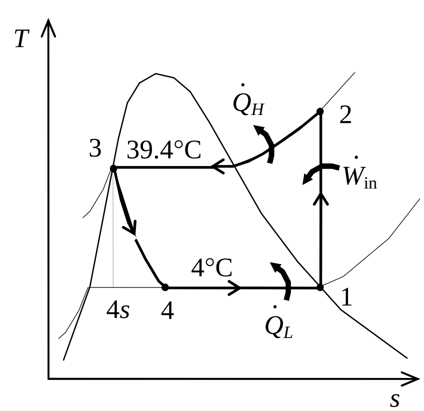
$$\left.\begin{array}{l} T_1 = 4°\text{C} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} h_1 = h_{g\,@\,4°\text{C}} = 252.77 \text{ kJ/kg} \\ s_1 = s_{g\,@\,4°\text{C}} = 0.92927 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = P_{\text{sat}\,@\,39.4°\text{C}} = 1 \text{ MPa} \\ s_2 = s_1 \end{array}\right\} h_2 = 275.29 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 1 \text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f\,@\,1\text{MPa}} = 107.32 \text{ kJ/kg} \\ s_3 = s_{f\,@\,1\text{MPa}} = 0.39189 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$h_4 \cong h_3 = 107.32 \text{ kJ/kg} \quad \text{(throttling)}$$

$$\left.\begin{array}{l} T_4 = 4°\text{C} \\ h_4 = 107.32 \text{ kJ/kg} \end{array}\right\} \begin{array}{l} x_4 = 0.2561 \\ s_4 = 0.4045 \text{ kJ/kg}\cdot\text{K} \end{array}$$



The mass flow rate of refrigerant-134a is

$$m_R = \frac{Q_L}{h_1 - h_4} = \frac{57{,}450\ \text{kJ}}{(252.77 - 107.32)\text{kJ/kg}} = 395.0\ \text{kg}$$

The amount of heat rejected from the condenser is

$$Q_H = m_R(h_2 - h_3) = (395.0\ \text{kg})(275.29 - 107.32)\ \text{kJ/kg} = 66{,}350\ \text{kg}$$

Next, we calculate the exergy destruction in the components of the refrigeration cycle:

$$X_{\text{destroyed,12}} = m_R T_0 (s_2 - s_1) = 0 \quad \text{(since the process is isentropic)}$$

$$X_{\text{destroyed,23}} = T_0\left(m_R(s_3 - s_2) + \frac{Q_H}{T_H}\right)$$

$$= (305\ \text{K})\left((395\ \text{kg})(0.39189 - 0.92927)\ \text{kJ/kg}\cdot\text{K} + \frac{66{,}350\ \text{kJ}}{305\ \text{K}}\right) = 1609\ \text{kJ}$$

$$X_{\text{destroyed,34}} = m_R T_0 (s_4 - s_3) = (395\ \text{kg})(305\ \text{K})(0.4045 - 0.39189)\ \text{kJ/kg}\cdot\text{K} = 1519\ \text{kJ}$$

The entropies of water vapor in the air stream are

$$s_{g1} = s_{g\,@\,32°\text{C}} = 8.4114\ \text{kJ/kg}\cdot\text{K}$$

$$s_{g2} = s_{g\,@\,24°\text{C}} = 8.5782\ \text{kJ/kg}\cdot\text{K}$$

The entropy change of water vapor in the air stream is

$$\Delta S_{\text{vapor}} = m_a(\omega_2 s_{g2} - \omega_1 s_{g1}) = (1105)(0.0112 \times 8.5782 - 0.0292 \times 8.4114) = -165.2\ \text{kJ/K}$$

The entropy of water leaving the cooling section is

$$S_w = m_w s_{f\,@\,28°\text{C}} = (19.89\ \text{kg})(0.4091\ \text{kJ/kg}\cdot\text{K}) = 8.14\ \text{kJ/K}$$

The partial pressures of water vapor and dry air for air streams are

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat}\,@\,32°\text{C}} = (0.95)(4.760\ \text{kPa}) = 4.522\ \text{kPa}$$

$$P_{a1} = P_1 - P_{v1} = 101.325 - 4.522 = 96.80\ \text{kPa}$$

$$P_{v2} = \phi_2 P_{g2} = \phi_2 P_{\text{sat}\,@\,24°\text{C}} = (0.60)(2.986\ \text{kPa}) = 1.792\ \text{kPa}$$

$$P_{a2} = P_2 - P_{v2} = 101.325 - 1.792 = 99.53\ \text{kPa}$$

The entropy change of dry air is

$$\Delta S_a = m_a(s_2 - s_1) = m_a\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_{a2}}{P_{a1}}\right)$$

$$= (1105)\left[(1.005)\ln\frac{297}{305} - (0.287)\ln\frac{99.53}{96.80}\right] = -38.34\ \text{kJ/kg dry air}$$

The entropy change of R-134a in the evaporator is

$$\Delta S_{R,\,41} = m_R(s_1 - s_4) = (395\ \text{kg})(0.92927 - 0.4045) = 207.3\ \text{kJ/K}$$

An entropy balance on the evaporator gives

$$S_{\text{gen,evaporator}} = \Delta S_{R,41} + \Delta S_{\text{vapor}} + \Delta S_a + S_w = 207.3 + (-165.2) + (-38.34) + 8.14 = 11.90\ \text{kJ/K}$$

Then, the exergy destruction in the evaporator is

$$X_{\text{dest}} = T_0 S_{\text{gen, evaporator}} = (305\ \text{K})(11.90\ \text{kJ/K}) = 3630\ \text{kJ}$$

Finally the total exergy destruction is

$$X_{\text{dest, total}} = X_{\text{dest, compressor}} + X_{\text{dest, condenser}} + X_{\text{dest, throttle}} + X_{\text{dest, evaporator}}$$

$$= 0 + 1609 + 1519 + 3630$$

$$= \mathbf{6758\ kJ}$$

The greatest exergy destruction occurs in the evaporator. Note that heat is absorbed from humid air and rejected to the ambient air at 32°C (305 K), which is also taken as the dead state temperature.