Problem #1

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

Analysis (*a*) From refrigerant-134a tables (Tables A-11 through A-13)

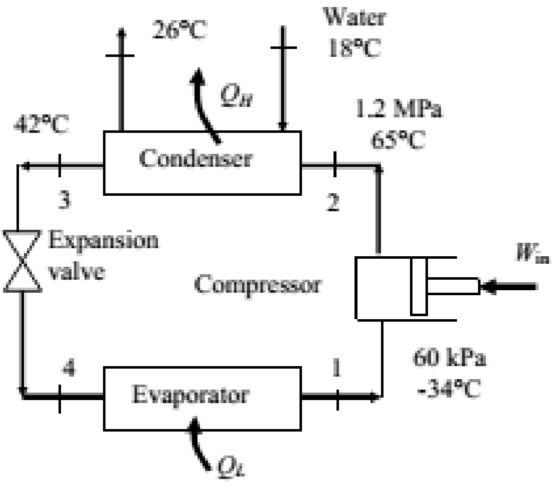
$$\left.\begin{array}{l} P_1 = 60\text{ kPa} \\ T_1 = -34°\text{C} \end{array}\right\} h_1 = 230.03\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 1200\text{ kPa} \\ T_2 = 65°\text{C} \end{array}\right\} h_2 = 295.16\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 1200\text{ kPa} \\ T_3 = 42°\text{C} \end{array}\right\} h_3 = 111.23\text{ kJ/kg}$$

$$h_4 = h_3 = 111.23\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 60\text{ kPa} \\ h_4 = 111.23\text{ kJ/kg} \end{array}\right\} x_4 = \mathbf{0.4795}$$



Using saturated liquid enthalpy at the given temperature, for water we have (Table A-4)

$$h_{w1} = h_{f@18°\text{C}} = 75.47\text{ kJ/kg}$$
$$h_{w2} = h_{f@26°\text{C}} = 108.94\text{ kJ/kg}$$

(*b*) The mass flow rate of the refrigerant may be determined from an energy balance on the compressor

$$\dot{m}_R(h_2 - h_3) = \dot{m}_w(h_{w2} - h_{w1})$$
$$\dot{m}_R(295.16 - 111.23)\text{kJ/kg} = (0.25\text{ kg/s})(108.94 - 75.47)\text{kJ/kg}$$
$$\longrightarrow \dot{m}_R = 0.0455\text{ kg/s}$$

The waste heat transferred from the refrigerant, the compressor power input, and the refrigeration load are

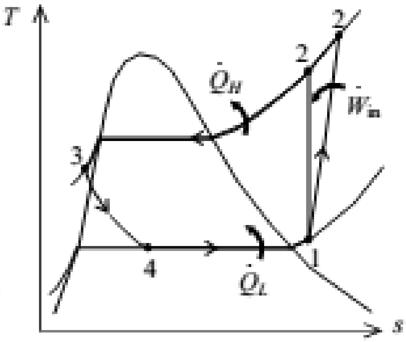
$$\dot{Q}_H = \dot{m}_R(h_2 - h_3) = (0.0455\text{ kg/s})(295.16 - 111.23)\text{kJ/kg} = 8.367\text{ kW}$$

$$\dot{W}_{in} = \dot{m}_R(h_2 - h_1) - \dot{Q}_{in} = (0.0455\text{ kg/s})(295.16 - 230.03)\text{kJ/kg} - 0.45\text{ kW} = 2.513\text{ kW}$$

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{in} = 8.367 - 2.513 = \mathbf{5.85\text{ kW}}$$

(*c*) The COP of the refrigerator is determined from its definition

$$\text{COP} = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{5.85}{2.513} = \mathbf{2.33}$$



(*d*) The reversible COP of the refrigerator for the same temperature limits is

$$\text{COP}_{\max} = \frac{1}{T_H/T_L - 1} = \frac{1}{(18+273)/(-30+273)-1} = 5.063$$

Then, the maximum refrigeration load becomes

$$\dot{Q}_{L,\max} = COP_{\max}\dot{W}_{in} = (5.063)(2.513\text{ kW}) = \mathbf{12.72\text{ kW}}$$

Problem #2

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

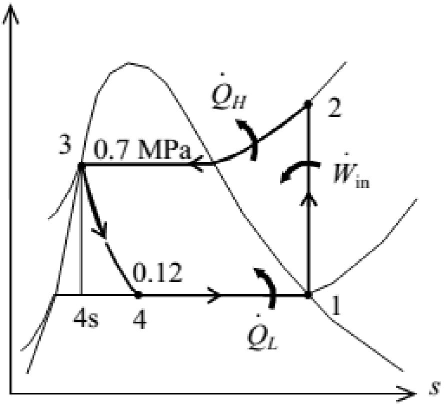
Analysis (*a*) In an ideal vapor-compression refrigeration cycle, the compression process is isentropic, the refrigerant enters the compressor as a saturated vapor at the evaporator pressure, and leaves the condenser as saturated liquid at the condenser pressure. From the refrigerant tables (Tables A-12 and A-13),

$$\left.\begin{array}{l} P_1 = 120\text{ kPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} h_1 = h_{g\ @\ 120\text{ kPa}} = 236.97\text{ kJ/kg} \\ s_1 = s_{g\ @\ 120\text{ kPa}} = 0.94779\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 0.7\text{ MPa} \\ s_2 = s_1 \end{array}\right\} h_2 = 273.50\text{ kJ/kg}\ (T_2 = 34.95°\text{C})$$

$$\left.\begin{array}{l} P_3 = 0.7\text{ MPa} \\ \text{sat. liquid} \end{array}\right\} h_3 = h_{f\ @\ 0.7\text{ MPa}} = 88.82\text{ kJ/kg}$$

$$h_4 \cong h_3 = 88.82\text{ kJ/kg (throttling)}$$



Then the rate of heat removal from the refrigerated space and the power input to the compressor are determined from

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.05\text{ kg/s})(236.97 - 88.82)\text{ kJ/kg} = \mathbf{7.41\ kW}$$

and

$$\dot{W}_{\text{in}} = \dot{m}(h_2 - h_1) = (0.05\text{ kg/s})(273.50 - 236.97)\text{ kJ/kg} = \mathbf{1.83\ kW}$$

(*b*) The rate of heat rejection to the environment is determined from

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{\text{in}} = 7.41 + 1.83 = \mathbf{9.23\ kW}$$

(*c*) The COP of the refrigerator is determined from its definition,

$$\text{COP}_\text{R} = \frac{\dot{Q}_L}{\dot{W}_{\text{in}}} = \frac{7.41\text{ kW}}{1.83\text{ kW}} = \mathbf{4.06}$$

Problem #3

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

Analysis (*a*) From the refrigerant tables (Tables A-12 and A-13),

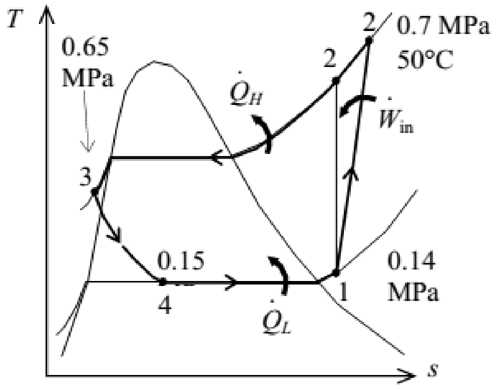
$$\left.\begin{array}{l} P_1 = 0.14 \text{ MPa} \\ T_1 = -10°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 246.36 \text{ kJ/kg} \\ s_1 = 0.97236 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 0.7 \text{ MPa} \\ T_2 = 50°\text{C} \end{array}\right\} h_2 = 288.53 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_{2s} = 0.7 \text{ MPa} \\ s_{2s} = s_1 \end{array}\right\} h_{2s} = 281.16 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 0.65 \text{ MPa} \\ T_3 = 24°\text{C} \end{array}\right\} h_3 = h_{f\,@\,24°\text{C}} = 84.98 \text{ kJ/kg}$$

$$h_4 \cong h_3 = 84.98 \text{ kJ/kg (throttling)}$$



Then the rate of heat removal from the refrigerated space and the power input to the compressor are determined from

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.12 \text{ kg/s})(246.36 - 84.98) \text{ kJ/kg} = \mathbf{19.4\ kW}$$

and

$$\dot{W}_{\text{in}} = \dot{m}(h_2 - h_1) = (0.12 \text{ kg/s})(288.53 - 246.36) \text{ kJ/kg} = \mathbf{5.06\ kW}$$

(*b*) The adiabatic efficiency of the compressor is determined from

$$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{281.16 - 246.36}{288.53 - 246.36} = \mathbf{82.5\%}$$

(*c*) The COP of the refrigerator is determined from its definition,

$$\text{COP}_\text{R} = \frac{\dot{Q}_L}{\dot{W}_{\text{in}}} = \frac{19.4 \text{ kW}}{5.06 \text{ kW}} = \mathbf{3.83}$$

Problem #4

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

Analysis (*a*) (*b*) From the refrigerant-134a tables (Tables A-11 through A-13)

$$\left.\begin{array}{l}P_4 = 120\text{ kPa}\\ x_4 = 0.30\end{array}\right\} h_4 = 86.83\text{ kJ/kg}$$

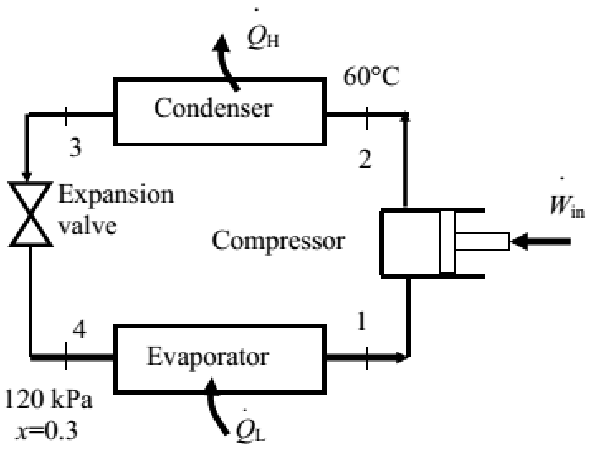
$$h_3 = h_4$$

$$\left.\begin{array}{l}h_3 = 86.83\text{ kJ/kg}\\ x_3 = 0\text{ (sat. liq.)}\end{array}\right\} P_3 = \mathbf{671.8\ kPa}$$

$$P_2 = P_3$$

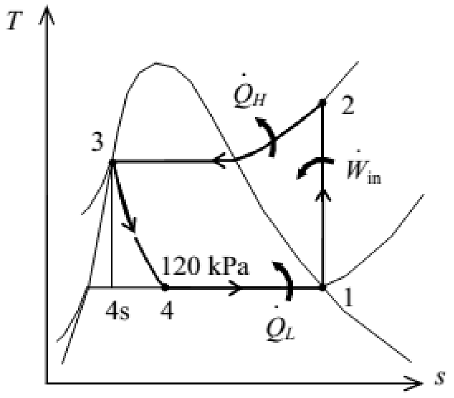
$$\left.\begin{array}{l}P_2 = 671.8\text{ kPa}\\ T_2 = 60°\text{C}\end{array}\right\} h_2 = 298.87\text{ kJ/kg}$$

$$\left.\begin{array}{l}P_1 = P_4 = 120\text{ kPa}\\ x_1 = 1\text{ (sat. vap.)}\end{array}\right\} h_1 = 236.97\text{ kJ/kg}$$



The mass flow rate of the refrigerant is determined from

$$\dot{m} = \frac{\dot{W}_{\text{in}}}{h_2 - h_1} = \frac{0.45\text{ kW}}{(298.87 - 236.97)\text{kJ/kg}} = \mathbf{0.00727\ kg/s}$$



(*c*) The refrigeration load and the COP are

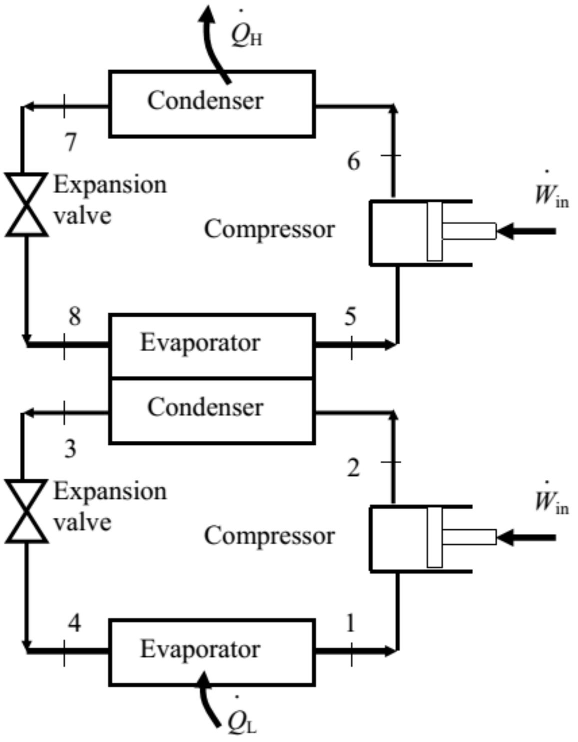
$$\begin{aligned}\dot{Q}_L &= \dot{m}(h_1 - h_4)\\ &= (0.0727\text{ kg/s})(236.97 - 86.83)\text{kJ/kg}\\ &= 1.091\text{ kW}\end{aligned}$$

$$\text{COP} = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{1.091\text{ kW}}{0.45\text{ kW}} = \mathbf{2.43}$$

Problem #5

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

Analysis (*a*) The properties are to be obtained from the refrigerant tables (Tables A-11 through A-13):



$$h_1 = h_{g@\,200\text{ kPa}} = 244.46 \text{ kJ/kg}$$
$$s_1 = s_{g@\,200\text{ kPa}} = 0.9377 \text{ kJ/kg.K}$$

$$\left.\begin{array}{l} P_2 = 500\text{ kPa} \\ s_2 = s_1 \end{array}\right\} h_{2s} = 263.30 \text{ kJ/kg}$$

$$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1}$$

$$0.80 = \frac{263.30 - 244.46}{h_2 - 244.46} \longrightarrow h_2 = 268.01 \text{ kJ/kg}$$

$$h_3 = h_{f@\,500\text{ kPa}} = 73.33 \text{ kJ/kg}$$
$$h_4 = h_3 = 73.33 \text{ kJ/kg}$$

$$h_5 = h_{g@\,400\text{ kPa}} = 255.55 \text{ kJ/kg}$$
$$s_5 = s_{g@\,400\text{ kPa}} = 0.9269 \text{ kJ/kg.K}$$

$$\left.\begin{array}{l} P_6 = 1200\text{ kPa} \\ s_6 = s_5 \end{array}\right\} h_{6s} = 278.33 \text{ kJ/kg}$$

$$\eta_C = \frac{h_{6s} - h_5}{h_6 - h_5}$$

$$0.80 = \frac{278.33 - 255.55}{h_6 - 255.55} \longrightarrow h_6 = 284.02 \text{ kJ/kg}$$

$$h_7 = h_{f@\,1200\text{ kPa}} = 117.77 \text{ kJ/kg}$$
$$h_8 = h_7 = 117.77 \text{ kJ/kg}$$

The mass flow rate of the refrigerant through the upper cycle is determined from an energy balance on the heat exchanger

$$\dot{m}_A (h_5 - h_8) = \dot{m}_B (h_2 - h_3)$$
$$\dot{m}_A (255.55 - 117.77)\text{kJ/kg} = (0.15 \text{ kg/s})(268.01 - 73.33)\text{kJ/kg} \longrightarrow \dot{m}_A = \mathbf{0.212 \text{ kg/s}}$$

(*b*) The rate of heat removal from the refrigerated space is

$$\dot{Q}_L = \dot{m}_B (h_1 - h_4) = (0.15 \text{ kg/s})(244.46 - 73.33)\text{kJ/kg} = \mathbf{25.67 \text{ kW}}$$

(*c*) The power input and the COP are

$$\dot{W}_{\text{in}} = \dot{m}_A (h_6 - h_5) + \dot{m}_B (h_2 - h_1)$$
$$= (0.15 \text{ kg/s})(284.02 - 255.55)\text{kJ/kg} + (0.212 \text{ kg/s})(268.01 - 244.46)\text{kJ/kg} = 9.566 \text{ kW}$$

$$\text{COP} = \frac{\dot{Q}_L}{\dot{W}_{\text{in}}} = \frac{25.67}{9.566} = \mathbf{2.68}$$