10.27E A heat pump that operates on the ideal vapor-compression cycle with refrigerant-134a is used to heat a house and maintain it at 75°F by using underground water at 50°F as the heat source. The house is losing heat at a rate of 90,000 Btu/h. The evaporator and condenser pressures are 50 and 120 psia, respectively. Determine the power input to the heat pump and the electric power saved by using a heat pump instead of a resistance heater.

Answers: 3.68 hp, 31.69 hp

10.28 A heat pump that operates on the ideal vapor-compression cycle with refrigerant-134a is used to heat water from 15 to 54°C at a rate of 0.18 kg/s. The condenser and evaporator pressures are 1.4 and 0.32 MPa, respectively. Determine the power input to the heat pump.

10.29 A heat pump using refrigerant-134a heats a house by using underground water at 8°C as the heat source. The house is losing heat at a rate of 60,000 kJ/h. The refrigerant enters the compressor at 280 kPa and 0°C, and it leaves at 1 MPa and 60°C. The refrigerant exits the condenser at 30°C. Determine (a) the power input to the heat pump, (b) the rate of heat absorption from the water, and (c) the increase in electric power input if an electric resistance heater is used instead of a heat pump.

Answers: (a) 3.65 kW, (b) 13.02 kW, (c) 13.02 kW

Innovative Refrigeration Systems

10.30C What is cascade refrigeration? What are the advantages and disadvantages of cascade refrigeration?

10.31C How does the COP of a cascade refrigeration system compare to the COP of a simple vapor-compression cycle operating between the same pressure limits?

10.32C A certain application requires maintaining the refrigerated space at -32°C. Would you recommend a simple refrigeration cycle with refrigerant-134a or a two-stage cascade refrigeration cycle with a different refrigerant at the bottoming cycle? Why?

10.33C Consider a two-stage cascade refrigeration cycle and a two-stage compression refrigeration cycle with a flash chamber. Both cycles operate between the same pressure limits and use the same refrigerant. Which system would you favor? Why?

10.34C Can a vapor-compression refrigeration system with a single compressor handle several evaporators operating at different pressures? How?

10.35C Is it possible to have liquid helium at room temperature?

10.36C In the liquefaction process, why are gases compressed to very high pressures?

10.37 Consider a two-stage cascade refrigeration system operating between the pressure limits of 0.8 and 0.14 MPa. Each stage operates on the ideal vapor-compression refrigeration cycle with refrigerant-134a as

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\[ \dot{m} = 0.12 \text{ kg/s} \]
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a) What is the heat rate of the first stage?

b) the rate of heat removal from the refrigerated space to the compressor

c) COP of the cascade ref.
A two-stage cascade refrigeration system is considered. Each stage operates on the ideal vapor-compression cycle with refrigerant-134a as the working fluid. The mass flow rate of refrigerant through the lower cycle, the rate of heat removal from the refrigerated space, the power input to the compressor, and the COP of this cascade refrigerator are to be determined.

**Assumptions**
1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.
3. The heat exchanger is adiabatic.

**Analysis**
(a) Each stage of the cascade refrigeration cycle is said to operate on the ideal vapor compression refrigeration cycle. Thus the compression process is isentropic, and the refrigerant enters the compressor as a saturated vapor at the evaporator pressure. Also, the refrigerant leaves the condenser as a saturated liquid at the condenser pressure. The enthalpies of the refrigerant at all 8 states are determined from the refrigerant tables (Tables A-11, A-12, and A-13) to be

\[
\begin{align*}
  h_1 &= 236.04 \text{ kJ/kg}, \\
  h_2 &= 257.39 \text{ kJ/kg} \\
  h_3 &= 62.00 \text{ kJ/kg}, \\
  h_4 &= 62.00 \text{ kJ/kg} \\
  h_5 &= 252.32 \text{ kJ/kg}, \\
  h_6 &= 266.59 \text{ kJ/kg} \\
  h_7 &= 93.42 \text{ kJ/kg}, \\
  h_8 &= 93.42 \text{ kJ/kg}
\end{align*}
\]

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

\[
\begin{align*}
  \dot{E}_{\text{in}} - \dot{E}_{\text{out}} &= \Delta \dot{E}_{\text{system}} \\
  \dot{E}_{\text{in}} &= \dot{E}_{\text{out}} \\
  \sum \dot{m}_i h_i &= \sum \dot{m}_j h_j \\
  \dot{m}_A (h_3 - h_5) &= \dot{m}_B (h_2 - h_3) \\
  \dot{m}_B &= \frac{h_5 - h_8}{h_2 - h_3}, \quad \dot{m}_A = \frac{252.32 - 93.42}{257.39 - 62.00} (0.12 \text{ kg/s}) = 0.0966 \text{ kg/s}
\end{align*}
\]

(b) The rate of heat removed by a cascade cycle is the rate of heat absorption in the evaporator of the lowest stage. The power input to a cascade cycle is the sum of the power inputs to all of the compressors:

\[
\begin{align*}
  \dot{Q}_\text{L} &= \dot{m}_A (h_1 - h_4) = (0.0966 \text{ kg/s})(236.04 - 62.00) \text{ kJ/kg} = 16.8 \text{ kW} \\
  \dot{W}_\text{in} &= \dot{W}_{\text{compl.1}} + \dot{W}_{\text{compl.2}} = \dot{m}_A (h_6 - h_5) + \dot{m}_B (h_2 - h_1) \\
  &= (0.12 \text{ kg/s})(266.59 - 252.32) \text{ kJ/kg} + (0.0966 \text{ kg/s})(257.39 - 236.04) \text{ kJ/kg} \\
  &= 3.77 \text{ kW}
\end{align*}
\]

(c) The COP of this refrigeration system is determined from its definition,

\[
\text{COP}_R = \frac{\dot{Q}_\text{L}}{\dot{W}_{\text{net.in}}} = \frac{16.8 \text{ kW}}{3.77 \text{ kW}} = 4.46
\]
working fluid. Heat rejection from the lower cycle to the upper cycle takes place in an adiabatic counterflow heat exchanger where both streams enter at about 0.4 MPa. If the mass flow rate of the refrigerant through the upper cycle is 0.12 kg/s, determine (a) the mass flow rate of the refrigerant through the lower cycle, (b) the rate of heat removal from the refrigerated space and the power input to the compressor, and (c) the coefficient of performance of this cascade refrigerator.

*Answers:* (a) 0.0966 kg/s; (b) 16.8 kW, 3.77 kW; (c) 4.46

10-38 Repeat Prob. 10-37 for a heat exchanger pressure of 0.5 MPa.

10-39 A two-stage compression refrigeration system operates with refrigerant-134a between the pressure limits of 1 and 0.14 MPa. The refrigerant leaves the condenser as a saturated liquid and is throttled to a flash chamber operating at 0.5 MPa. The refrigerant leaving the low-pressure compressor at 0.5 MPa is also routed to the flash chamber. The vapor in the flash chamber is then compressed to the condenser pressure by the high-pressure compressor, and the liquid is throttled to the evaporator pressure. Assuming the refrigerant leaves the evaporator as saturated vapor and both compressors are isentropic, determine (a) the fraction of the refrigerant that evaporates as it is throttled to the flash chamber, (b) the amount of heat removed from the refrigerated space for a mass flow rate of 0.25 kg/s through the condenser, and (c) the coefficient of performance.

10-40 Repeat Prob. 10-39 for a flash chamber pressure of 0.32 MPa.

**Gas Refrigeration Cycle**

10-41 C How does the ideal-gas refrigeration cycle differ from the Brayton cycle?

10-42 C Devise a refrigeration cycle that works on the reversed Stirling cycle. Also, determine the COP for this cycle.

10-43 C How does the ideal-gas refrigeration cycle differ from the Carnot refrigeration cycle?

10-44 C How is the ideal-gas refrigeration cycle modified for aircraft cooling?

10-45 C In gas refrigeration cycles, can we replace the turbine by an expansion valve as we did in vapor-compression refrigeration cycles? Why?

10-46 C How do we achieve very low temperatures with gas refrigeration cycles?

10-47 An ideal-gas refrigeration cycle using air as the working fluid is to maintain a refrigerated space at −23°C while rejecting heat to the surrounding medium at 27°C. If the pressure ratio of the compressor is 3, determine (a) the maximum and minimum temperatures in the cycle, (b) the coefficient of performance, and (c) the rate of refrigeration for a mass flow rate of 0.15 kg/s.
10.39 A two-stage compression refrigeration system with refrigerant-134a as the working fluid is considered. The fraction of the refrigerant that evaporates as it is throttled to the flash chamber, the amount of heat removed from the refrigerated space, and the COP are to be determined.

**Assumptions** 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible. 3 The flash chamber is adiabatic.

**Analysis** (a) The enthalpies of the refrigerant at several states are determined from the refrigerant tables (Tables A-11, A-12, and A-13) to be

\[ h_1 = 236.04 \text{ kJ/kg}, \quad h_2 = 262.07 \text{ kJ/kg} \]
\[ h_3 = 256.07 \text{ kJ/kg}, \quad h_5 = 105.29 \text{ kJ/kg} \]
\[ h_6 = 71.33 \text{ kJ/kg}, \quad h_7 = 71.33 \text{ kJ/kg} \]

The fraction of the refrigerant which evaporates as it is throttled to the flash chamber is simply the quality at state 6,

\[ x_6 = \frac{h_6 - h_f}{h_f - h_g} = \frac{105.29 - 71.33}{184.74 - 71.33} = 0.1838 \]

(b) The enthalpy at state 9 is determined from an energy balance on the mixing chamber:

\[ E_{in} - E_{out} = \Delta E_{system} \quad \text{(steady)} = 0 \]
\[ E_{in} = E_{out} \]

\[ \sum m_i h_i = \sum m_i h_i \]

\[ (1) h_9 = x_6 h_3 + (1 - x_6) h_2 \]

\[ h_9 = (0.1838)(256.07) + (1 - 0.1838)(260.07) = 260.97 \text{ kJ/kg} \]

also,

\[ P_4 = 1 \text{ MPa} \]
\[ s_4 = 0.9285 \text{ kJ/kg} \cdot \text{K} \]

\[ h_4 = 275.64 \text{ kJ/kg} \]

Then the amount of heat removed from the refrigerated space and the compressor work input per unit mass of refrigerant flowing through the condenser are

\[ \dot{m}_B = (1 - x_6) \dot{m}_A = (1 - 0.1838)(0.25 \text{ kg/s}) = 0.20405 \text{ kg/s} \]

\[ \dot{Q}_c = \dot{m}_B (h_1 - h_6) = (0.20405 \text{ kg/s})(236.04 - 71.33) \text{ kJ/kg} = 33.61 \text{ kW} \]

\[ \dot{W}_{in} = \dot{W}_{compl, in} + \dot{W}_{compl, in} = \dot{m}_A (h_4 - h_9) + \dot{m}_B (h_2 - h_1) \]

\[ = (0.25 \text{ kg/s})(275.64 - 260.97) \text{ kJ/kg} + (0.20405 \text{ kg/s})(262.07 - 236.04) \text{ kJ/kg} \]

\[ = 8.98 \text{ kW} \]

(c) The coefficient of performance is determined from

\[ \text{COP}_R = \frac{\dot{Q}_c}{\dot{W}_{net, in}} = \frac{33.61 \text{ kW}}{8.98 \text{ kW}} = 3.74 \]

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