EXAMPLE 9.1 | Analyzing the Otto Cycle

The temperature at the beginning of the compression process of an air-standard Otto cycle with a compression ratio of 8 is 540°R, the pressure is 1 atm, and the cylinder volume is 0.02 ft^3. The maximum temperature during the cycle is 3600°R. Determine **(a)** the temperature and pressure at the end of each process of the cycle, **(b)** the thermal efficiency, and **(c)** the mean effective pressure, in atm.

Solution

Known An air-standard Otto cycle with a given value of compression ratio is executed with specified conditions at the beginning of the compression stroke and a specified maximum temperature during the cycle.

Find Determine the temperature and pressure at the end of each process, the thermal efficiency, and mean effective pressure, in atm.

Schematic and Given Data:

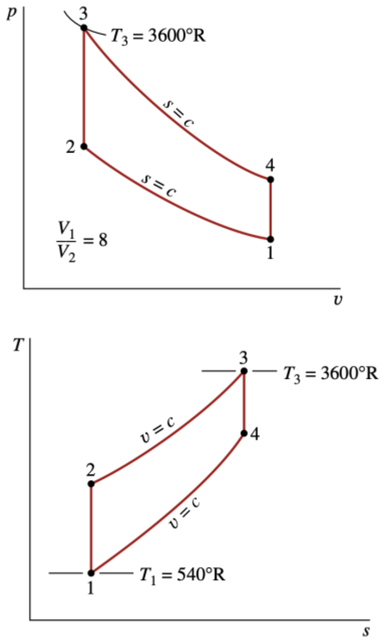


FIG. E9.1

Engineering Model

1. The air in the piston–cylinder assembly is the closed system.
2. The compression and expansion processes are adiabatic.
3. All processes are internally reversible.
4. The air is modeled as an ideal gas.
5. Kinetic and potential energy effects are negligible.

Analysis

a. The analysis begins by determining the temperature, pressure, and specific internal energy at each principal state of the cycle. At $T_1 = 540°R$, Table A-22E gives $u_1 = 92.04$ Btu/lb and $v_{r1} = 144.32$.

For the isentropic compression process 1–2

$$v_{r2} = \frac{V_2}{V_1} v_{r1} = \frac{v_{r1}}{r} = \frac{144.32}{8} = 18.04$$

Interpolating with v_{r2} in Table A-22E, we get $T_2 = 1212°R$ and $u_2 = 211.3$ Btu/lb. With the ideal gas equation of state

$$p_2 = p_1 \frac{T_2}{T_1}\frac{V_1}{V_2} = (1 \text{ atm})\left(\frac{1212°R}{540°R}\right)8 = 17.96 \text{ atm}$$

The pressure at state 2 can be evaluated alternatively by using the

At $T_3 = 3600°R$, Table A-22E gives $u_3 = 721.44$ Btu/lb and $v_{r3} = 0.6449$.

For the isentropic expansion process 3–4

$$v_{r4} = v_{r3}\frac{V_4}{V_3} = v_{r3}\frac{V_1}{V_2} = 0.6449(8) = 5.16$$

Interpolating in Table A-22E with v_{r4} gives $T_4 = 1878°R$, $u_4 = 342.2$ Btu/lb. The pressure at state 4 can be found using the isentropic relationship $p_4 = p_3(p_{r4}/p_{r3})$ or the ideal gas equation of state applied at states 1 and 4. With $V_4 = V_1$, the ideal gas equation of state gives

$$p_4 = p_1\frac{T_4}{T_1} = (1 \text{ atm})\left(\frac{1878°R}{540°R}\right) = 3.48 \text{ atm}$$

b. The thermal efficiency is

$$\eta = 1 - \frac{Q_{41}/m}{Q_{23}/m} = 1 - \frac{u_4 - u_1}{u_3 - u_2}$$
$$= 1 - \frac{342.2 - 92.04}{721.44 - 211.3} = 0.51 \; (51\%)$$

c. To evaluate the mean effective pressure requires the net work per cycle. That is,

$$W_{\text{cycle}} = m[(u_3 - u_4) - (u_2 - u_1)]$$

where m is the mass of the air, evaluated from the ideal gas equation of state as follows:

$$m = \frac{p_1 V_1}{(\bar{R}/M)T_1}$$
$$= \frac{(14.696 \text{ lbf/in.}^2)|144 \text{ in.}^2/\text{ft}^2|(0.02 \text{ ft}^3)}{\left(\frac{1545}{28.97}\frac{\text{ft}\cdot\text{lbf}}{\text{lb}\cdot°R}\right)(540°R)}$$
$$= 1.47 \times 10^{-3} \text{ lb}$$

Inserting values into the expression for W_{cycle}

$$W_{\text{cycle}} = (1.47 \times 10^{-3} \text{ lb})[(721.44 - 342.2) - (211.3 - 92.04)] \text{ Btu/lb}$$
$$= 0.382 \text{ Btu}$$

The displacement volume is $V_1 - V_2$, so the mean effective pressure is given by

$$\text{mep} = \frac{W_{\text{cycle}}}{V_1 - V_2} = \frac{W_{\text{cycle}}}{V_1(1 - V_2/V_1)}$$

1
$$= \frac{0.382 \text{ Btu}}{(0.02 \text{ ft}^3)(1 - 1/8)}\left|\frac{778 \text{ ft}\cdot\text{lbf}}{1 \text{ Btu}}\right|\left|\frac{1 \text{ ft}^2}{144 \text{ in.}^2}\right|$$
$$= 118 \text{ lbf/in.}^2 = 8.03 \text{ atm}$$

isentropic relationship, $p_2 = p_1(p_{r2}/p_{r1})$.

Since Process 2–3 occurs at constant volume, the ideal gas equation of state gives

$$p_3 = p_2 \frac{T_3}{T_2} = (17.96 \text{ atm})\left(\frac{3600°\text{R}}{1212°\text{R}}\right) = 53.3 \text{ atm}$$

1 This solution utilizes Table A-22E for air, which accounts explicitly for the variation of the specific heats with temperature. A solution also can be developed on a cold air-standard basis in which constant specific heats are assumed. This solution is left as an exercise, but for comparison the results are presented for the case $k = 1.4$ in the following table:

Parameter	Air-Standard Analysis	Cold Air-Standard Analysis, $k = 1.4$
T_2	1212°R	1241°R
T_3	3600°R	3600°R
T_4	1878°R	1567°R
η	0.51 (51%)	0.565 (56.5%)
mep	8.03 atm	7.05 atm

SKILLS DEVELOPED

Ability to…

- sketch the Otto cycle p–v and T–s diagrams.
- evaluate temperatures and pressures at each principal state and retrieve necessary property data.
- calculate thermal efficiency and mean effective pressure.

Quick Quiz

Determine the heat addition and the heat rejection for the cycle, each in Btu. Ans. $Q_{23} = 0.750$ Btu, $Q_{41} = 0.368$ Btu.

EXAMPLE 9.2 | Analyzing the Diesel Cycle

At the beginning of the compression process of an air-standard Diesel cycle operating with a compression ratio of 18, the temperature is 300 K and the pressure is 0.1 MPa. The cutoff ratio for the cycle is 2. Determine **(a)** the temperature and pressure at the end of each process of the cycle, **(b)** the thermal efficiency, **(c)** the mean effective pressure, in MPa.

Solution

Known An air-standard Diesel cycle is executed with specified conditions at the beginning of the compression stroke. The compression and cutoff ratios are given.

Find Determine the temperature and pressure at the end of each process, the thermal efficiency, and mean effective pressure.

Schematic and Given Data:

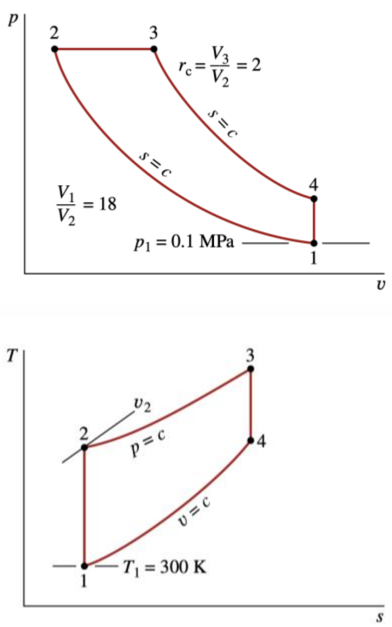


FIG. E9.2

Engineering Model

1. The air in the piston–cylinder assembly is the closed system.
2. The compression and expansion 3–4 are adiabatic.
3. All processes are internally reversible.
4. The air is modeled as an ideal gas.
5. Kinetic and potential energy effects are negligible.

Analysis

a. The analysis begins by determining properties at each principal state of the cycle. With $T_1 = 300$ K, Table A-22 gives $u_1 = 214.07$ kJ/kg and $v_{r1} = 621.2$. For the isentropic compression process 1–2

$$v_{r2} = \frac{V_2}{V_1} v_{r1} = \frac{v_{r1}}{r} = \frac{621.2}{18} = 34.51$$

Interpolating in Table A-22, we get $T_2 = 898.3$ K and $h_2 = 930.98$ kJ/kg. With the ideal gas equation of state

$$p_2 = p_1 \frac{T_2}{T_1} \frac{V_1}{V_2} = (0.1)\left(\frac{898.3}{300}\right)(18) = 5.39 \text{ MPa}$$

The pressure at state 2 can be evaluated alternatively using the isentropic relationship, $p_2 = p_1 (p_{r2}/p_{r1})$.

Since Process 2–3 occurs at constant pressure, the ideal gas equation of state gives

$$T_3 = \frac{V_3}{V_2} T_2$$

Introducing the cutoff ratio, $r_c = V_3/V_2$

$$T_3 = r_c T_2 = 2(898.3) = 1796.6 \text{ K}$$

From Table A-22, $h_3 = 1999.1$ kJ/kg and $v_{r3} = 3.97$.

For the isentropic expansion process 3–4

$$v_{r4} = \frac{V_4}{V_3} v_{r3} = \frac{V_4}{V_2} \frac{V_2}{V_3} v_{r3}$$

Introducing $V_4 = V_1$, the compression ratio r, and the cutoff ratio r_c, we have

$$v_{r4} = \frac{r}{r_c} v_{r3} = \frac{18}{2}(3.97) = 35.73$$

Interpolating in Table A-22 with v_{r4}, we get $u_4 = 664.3$ kJ/kg and $T_4 = 887.7$ K. The pressure at state 4 can be found using the isentropic relationship $p_4 = p_3(p_{r4}/p_{r3})$ or the ideal gas equation of state applied at states 1 and 4. With $V_4 = V_1$, the ideal gas equation of state gives

$$p_4 = p_1 \frac{T_4}{T_1} = (0.1 \text{ MPa})\left(\frac{887.7 \text{ K}}{300 \text{ K}}\right) = 0.3 \text{ MPa}$$

b. The thermal efficiency is found using

$$\eta = 1 - \frac{Q_{41}/m}{Q_{23}/m} = 1 - \frac{u_4 - u_1}{h_3 - h_2}$$

❶ $$= 1 - \frac{664.3 - 214.07}{1999.1 - 930.98} = 0.578(57.8\%)$$

c. The mean effective pressure written in terms of specific volumes is

$$\text{mep} = \frac{W_{\text{cycle}}/m}{v_1 - v_2} = \frac{W_{\text{cycle}}/m}{v_1(1 - 1/r)}$$

The net work of the cycle equals the net heat added

$$\frac{W_{\text{cycle}}}{m} = \frac{Q_{23}}{m} - \frac{Q_{41}}{m} = (h_3 - h_2) - (u_4 - u_1)$$
$$= (1999.1 - 930.98) - (664.3 - 214.07)$$
$$= 617.9 \text{ kJ/kg}$$

The specific volume at state 1 is

$$v_1 = \frac{(\bar{R}/M)T_1}{p_1} = \frac{\left(\frac{8314}{28.97} \frac{\text{N} \cdot \text{m}}{\text{kg} \cdot \text{K}}\right)(300 \text{ K})}{10^5 \text{ N/m}^2} = 0.861 \text{ m}^3/\text{kg}$$

Inserting values

$$\text{mep} = \frac{617.9 \text{ kJ/kg}}{0.861(1 - 1/18) \text{ m}^3/\text{kg}} \left|\frac{10^3 \text{ N} \cdot \text{m}}{1 \text{ kJ}}\right| \left|\frac{1 \text{ MPa}}{10^6 \text{ N/m}^2}\right|$$
$$= 0.76 \text{ MPa}$$

❶ This solution uses the air tables, which account explicitly for the variation of the specific heats with temperature. Note that Eq. 9.13 based on the assumption of *constant* specific heats has not been used to determine the thermal efficiency. The cold air-standard solution of this example is left as an exercise.

SKILLS DEVELOPED

Ability to…

- sketch the Diesel cycle p–v and T–s diagrams.
- evaluate temperatures and pressures at each principal state and retrieve necessary property data.
- calculate the thermal efficiency and mean effective pressure.

Quick Quiz

If the mass of air is 0.0123 kg, what is the *displacement volume*, in L? Ans. 10 L.

EXAMPLE 9.4 | Analyzing the Ideal Brayton Cycle

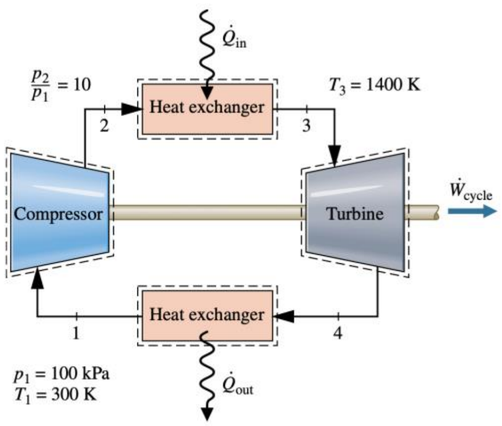
Air enters the compressor of an ideal air-standard Brayton cycle at 100 kPa, 300 K, with a volumetric flow rate of 5 m³/s. The compressor pressure ratio is 10. The turbine inlet temperature is 1400 K. Determine **(a)** the thermal efficiency of the cycle, **(b)** the back work ratio, **(c)** the *net* power developed, in kW.

Solution

Known An ideal air-standard Brayton cycle operates with given compressor inlet conditions, given turbine inlet temperature, and a known compressor pressure ratio.

Find Determine the thermal efficiency, the back work ratio, and the *net* power developed, in kW.

Schematic and Given Data:



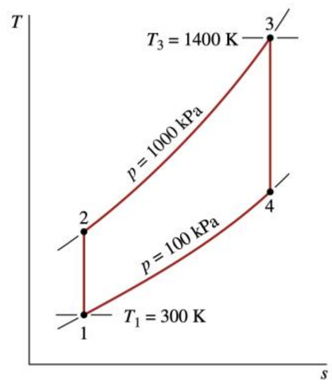


FIG. E9.4

Engineering Model

1. Each component is analyzed as a control volume at steady state. The control volumes are shown on the accompanying sketch by dashed lines.
2. The turbine and compressor processes are isentropic.
3. There are no pressure drops for flow through the heat exchangers.
4. Kinetic and potential energy effects are negligible.
5. The working fluid is air modeled as an ideal gas.

❶ **Analysis** The analysis begins by determining the specific enthalpy at each numbered state of the cycle. At state 1, the temperature is 300 K. From Table A-22, $h_1 = 300.19$ kJ/kg and $p_{r1} = 1.386$.

Since the compressor process is isentropic, the following relationship can be used to determine h_2:

$$p_{r2} = \frac{p_2}{p_1} p_{r1} = (10)(1.386) = 13.86$$

Then, interpolating in Table A-22, we obtain $h_2 = 579.9$ kJ/kg.

The temperature at state 3 is given as $T_3 = 1400$ K. With this temperature, the specific enthalpy at state 3 from Table A-22 is $h_3 = 1515.4$ kJ/kg. Also, $p_{r3} = 450.5$.

The specific enthalpy at state 4 is found by using the isentropic relationship

$$p_{r4} = p_{r3}\frac{p_4}{p_3} = (450.5)(1/10) = 45.05$$

Interpolating in Table A-22, we get $h_4 = 808.5$ kJ/kg.

a. The thermal efficiency is

$$\eta = \frac{(\dot{W}_t/\dot{m}) - (\dot{W}_c/\dot{m})}{\dot{Q}_{in}/\dot{m}}$$

$$= \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2} = \frac{(1515.4 - 808.5) - (579.9 - 300.19)}{1515.4 - 579.9}$$

$$= \frac{706.9 - 279.7}{935.5} = 0.457\ (45.7\%)$$

b. The back work ratio is

❷ $$\text{bwr} = \frac{\dot{W}_c/\dot{m}}{\dot{W}_t/\dot{m}} = \frac{h_2 - h_1}{h_3 - h_4} = \frac{279.7}{706.9} = 0.396\ (39.6\%)$$

c. The net power developed is

$$\dot{W}_{cycle} = \dot{m}[(h_3 - h_4) - (h_2 - h_1)]$$

To evaluate the net power requires the mass flow rate $\dot{m}$, which can be determined from the volumetric flow rate and specific volume at the compressor inlet as follows:

$$\dot{m} = \frac{(AV)_1}{\upsilon_1}$$

Since $\upsilon_1 = (\bar{R}/M)T_1/p_1$, this becomes

$$\dot{m} = \frac{(AV)_1 p_1}{(\bar{R}/M)T_1} = \frac{(5\ m^3/s)(100 \times 10^3\ N/m^2)}{\left(\frac{8314}{28.97}\frac{N \cdot m}{kg \cdot k}\right)(300\ K)}$$

$$= 5.807\ kg/s$$

Finally,

$$\dot{W}_{cycle} = (5.807\ kg/s)(706.9 - 279.7)\left(\frac{kJ}{kg}\right)\left|\frac{1\ kW}{1\ kJ/s}\right| = 2481\ kW$$

❶ The use of the ideal gas table for air is featured in this solution. A solution also can be developed on a cold air-standard basis in which constant specific heats are assumed. The details are left as an exercise, but for comparison the results are presented for the case $k = 1.4$ in the following table:

Parameter	Air-Standard Analysis	Cold Air-Standard Analysis, $k = 1.4$
T_2	574.1 K	579.2 K
T_4	787.7 K	725.1 K
η	0.457	0.482
bwr	0.396	0.414
$\dot{W}_{cycle}$	2481 kW	2308 kW

❷ The value of the back work ratio in the present gas turbine case is significantly greater than the back work ratio of the simple vapor power cycle of Example 8.1.

SKILLS DEVELOPED

Ability to…

- sketch the schematic of the basic air-standard gas turbine and the T–s diagram for the corresponding ideal Brayton cycle.
- evaluate temperatures and pressures at each principal state and retrieve necessary property data.
- calculate the thermal efficiency and back work ratio.

Quick Quiz

Determine the rate of heat transfer to the air passing through the combustor, in kW. Ans. 5432 kW.

EXAMPLE 10.1 | Analyzing an Ideal Vapor-Compression Refrigeration Cycle

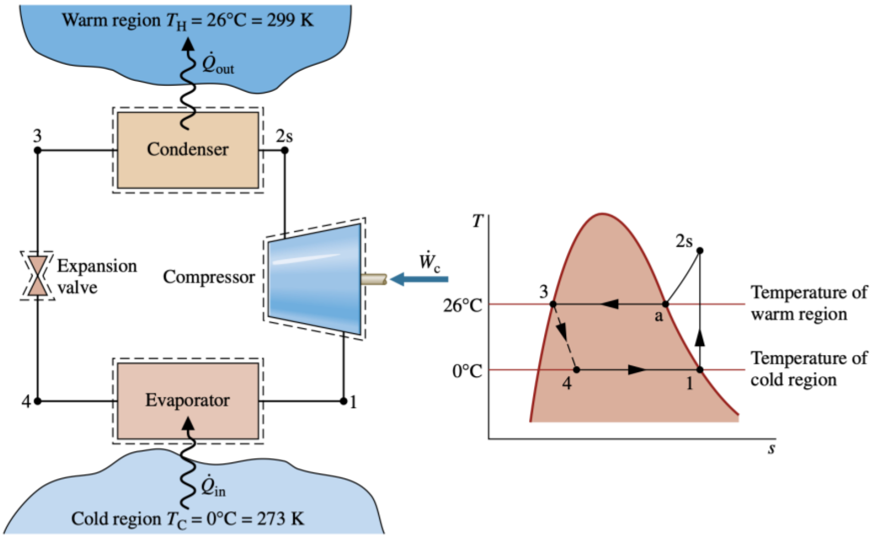
Refrigerant 134a is the working fluid in an ideal vapor-compression refrigeration cycle that communicates thermally with a cold region at 0°C and a warm region at 26°C. Saturated vapor enters the compressor at 0°C and saturated liquid leaves the condenser at 26°C. The mass flow rate of the refrigerant is 0.08 kg/s. Determine **(a)** the compressor power, in kW, **(b)** the refrigeration capacity, in tons, **(c)** the coefficient of performance, and **(d)** the coefficient of performance of a Carnot refrigeration cycle operating between warm and cold regions at 26 and 0°C, respectively.

Solution

Known An ideal vapor-compression refrigeration cycle operates with Refrigerant 134a. The states of the refrigerant entering the compressor and leaving the condenser are specified, and the mass flow rate is given.

Find Determine the compressor power, in kW, the refrigeration capacity, in tons, coefficient of performance, and the coefficient of performance of a Carnot vapor refrigeration cycle operating between warm and cold regions at the specified temperatures.

Schematic and Given Data:



Engineering Model

1. Each component of the cycle is analyzed as a control volume at steady state. The control volumes are indicated by dashed lines on the accompanying sketch.
2. Except for the expansion through the valve, which is a throttling process, all processes of the refrigerant are internally reversible.
3. The compressor and expansion valve operate adiabatically.
4. Kinetic and potential energy effects are negligible.
5. Saturated vapor enters the compressor, and saturated liquid leaves the condenser.

Analysis Let us begin by fixing each of the principal states located on the accompanying schematic and T–s diagrams. At the inlet to the compressor, the refrigerant is a saturated vapor at 0°C, so from Table A-10, $h_1 = 247.23$ kJ/kg and $s_1 = 0.9190$ kJ/kg · K.

The pressure at state 2s is the saturation pressure corresponding to 26°C, or $p_2 = 6.853$ bar. State 2s is fixed by p_2 and the fact that the specific entropy is constant for the adiabatic, internally reversible compression process. The refrigerant at state 2s is a superheated vapor with $h_{2s} = 264.7$ kJ/kg. State 3 is saturated liquid at 26°C, so $h_3 = 85.75$ kJ/kg. The expansion through the valve is a throttling process (assumption 2), so $h_4 = h_3$. (1)

a. The compressor work input is

$$\dot{W}_c = \dot{m}(h_{2s} - h_1)$$

where $\dot{m}$ is the mass flow rate of refrigerant. Inserting values

$$\dot{W}_c = (0.08 \text{ kg/s})(264.7 - 247.23) \text{ kJ/kg} \left|\frac{1 \text{ kW}}{1 \text{ kJ/s}}\right|$$

$$= 1.4 \text{ kW}$$

b. The refrigeration capacity is the heat transfer rate to the refrigerant passing through the evaporator. This is given by

$$\dot{Q}_{in} = \dot{m}(h_1 - h_4)$$

$$= (0.08 \text{ kg/s})|60 \text{ s/min}|(247.23 - 85.75) \text{ kJ/kg} \left|\frac{1 \text{ ton}}{211 \text{ kJ/min}}\right|$$

$$= 3.67 \text{ ton}$$

c. The coefficient of performance β is

$$\beta = \frac{\dot{Q}_{in}}{\dot{W}_c} = \frac{h_1 - h_4}{h_{2s} - h_1} = \frac{247.23 - 85.75}{264.7 - 247.23} = 9.24$$

d. For a Carnot vapor refrigeration cycle operating at $T_H = 299$ K and $T_C = 273$ K, the coefficient of performance determined from Eq. 10.1 is

(2) $$\beta_{max} = \frac{T_C}{T_H - T_C} = 10.5$$

(1) The value for h_{2s} can be obtained by double interpolation in Table A-12 or by using *Interactive Thermodynamics: IT*.

(2) As expected, the ideal vapor-compression cycle has a lower coefficient of performance than a Carnot cycle operating between the temperatures of the warm and cold regions. The smaller value can be attributed to the effects of the external irreversibility associated with desuperheating the refrigerant in the condenser (Process 2s–a on the T–s diagram) and the internal irreversibility of the throttling process.

SKILLS DEVELOPED

Ability to…

- sketch the T–s diagram of the ideal vapor-compression refrigeration cycle.
- fix each of the principal states and retrieve necessary property data.
- calculate refrigeration capacity and coefficient of performance.
- compare with the corresponding Carnot refrigeration cycle.

Quick Quiz

Keeping all other given data the same, determine the mass flow rate of refrigerant, in kg/s, for a 10-ton refrigeration capacity. Ans. 0.218 kg/s.

EXAMPLE 10.4 | Analyzing an Actual Vapor-Compression Heat Pump Cycle

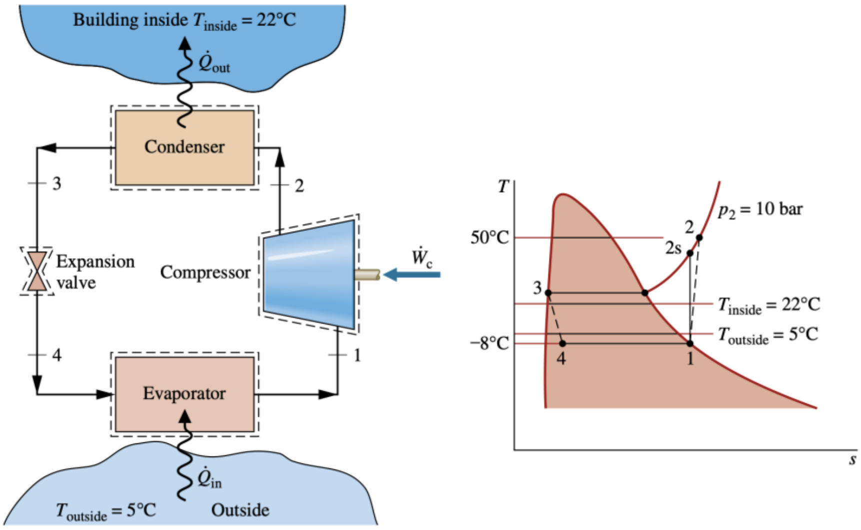
Refrigerant 134a is the working fluid in an electric-powered, air-source heat pump that maintains the inside temperature of a building at 22°C for a week when the average outside temperature is 5°C. Saturated vapor enters the compressor at −8°C and exits at 50°C, 10 bar. Saturated liquid exits the condenser at 10 bar. The refrigerant mass flow rate is 0.2 kg/s for steady-state operation. Determine **(a)** the compressor power, in kW, **(b)** the isentropic compressor efficiency, **(c)** the heat transfer rate provided to the building, in kW, **(d)** the coefficient of performance, and **(e)** the total cost of electricity, in $, for 80 hours of operation during that week, evaluating electricity at 15 cents per kW · h.

Solution

Known A heat pump cycle operates with Refrigerant 134a. The states of the refrigerant entering and exiting the compressor and leaving the condenser are specified. The refrigerant mass flow rate and interior and exterior temperatures are given.

Find Determine the compressor power, the isentropic compressor efficiency, the heat transfer rate to the building, the coefficient of performance, and the cost to operate the electric heat pump for 80 hours of operation.

Schematic and Given Data:



Engineering Model

1. Each component of the cycle is analyzed as a control volume at steady state.
2. There are no pressure drops through the evaporator and condenser.
3. The compressor operates adiabatically. The expansion through the valve is a throttling process.
4. Kinetic and potential energy effects are negligible.
5. Saturated vapor enters the compressor and saturated liquid exits the condenser.
6. For costing purposes, conditions provided are representative of the entire week of operation and the value of electricity is 15 cents per kW · h.

Analysis Let us begin by fixing the principal states located on the accompanying schematic and T–s diagram. State 1 is saturated vapor at −8°C; thus h_1 and s_1 are obtained directly from Table A-10. State 2 is superheated vapor; knowing T_2 and p_2, h_2 is obtained from Table A-12. State 3 is saturated liquid at 10 bar and h_3 is obtained from Table A-11. Finally, expansion through the valve is a throttling process; therefore, $h_4 = h_3$. A summary of property values at these states is provided in the following table:

State	T(°C)	p(bar)	h(kJ/kg)	s(kJ/kg · K)
1	−8	2.1704	242.54	0.9239
2	50	10	280.19	—
3	—	10	105.29	—
4	—	2.1704	105.29	—

a. The compressor power is

$$\dot{W}_c = \dot{m}(h_2 - h_1) = 0.2\frac{\text{kg}}{\text{s}}(280.19 - 242.54)\frac{\text{kJ}}{\text{kg}}\left|\frac{1\text{ kW}}{1\text{ kJ/s}}\right| = 7.53\text{ kW}$$

b. The isentropic compressor efficiency is

$$\eta_c = \frac{(\dot{W}_c/\dot{m})_s}{(\dot{W}_c/\dot{m})} = \frac{(h_{2s} - h_1)}{(h_2 - h_1)}$$

where h_{2s} is the specific entropy at state 2s, as indicated on the accompanying T–s diagram. State 2s is fixed using p_2 and $s_{2s} = s_1$.

Interpolating in Table A-12, $h_{2s} = 274.18$ kJ/kg. Solving for compressor efficiency

$$\eta_c = \frac{(h_{2s} - h_1)}{(h_2 - h_1)} = \frac{(274.18 - 242.54)}{(280.19 - 242.54)} = 0.84\ (84\%)$$

c. The heat transfer rate provided to the building is

$$\dot{Q}_{out} = \dot{m}(h_2 - h_3) = \left(0.2\frac{\text{kg}}{\text{s}}\right)(280.19 - 105.29)\frac{\text{kJ}}{\text{kg}}\left|\frac{1\text{ kW}}{1\text{ kJ/s}}\right|$$

$$= 34.98\text{ kW}$$

d. The heat pump coefficient of performance is

$$\gamma = \frac{\dot{Q}_{out}}{\dot{W}_c} = \frac{34.98\text{ kW}}{7.53\text{ kW}} = 4.65$$

e. Using the result from part (a) together with the given cost and use data

[electricity cost for 80 hours of operation]

$$= (7.53\text{ kW})(80\text{ h})\left(0.15\frac{\$}{\text{kW}\cdot\text{h}}\right) = \$90.36$$

SKILLS DEVELOPED

Ability to…

- sketch the *T–s* diagram of the vapor-compression heat pump cycle with irreversibilities in the compressor.
- fix each of the principal states and retrieve necessary property data.
- calculate the compressor power, heat transfer rate delivered, and coefficient of performance.
- calculate isentropic compressor efficiency.
- conduct an elementary economic evaluation.

Quick Quiz

If the cost of electricity is 10 cents per kW · h, which is the U.S. average for the period under consideration, evaluate the cost to operate the heat pump, in \$, keeping all other data the same. Ans. \$60.24.