

3. What irreversibilities are found in living things?
4. In what ways are irreversibilities associated with the operation of an automobile beneficial?
5. Use the *second law* to explain which species coexisting in a wilderness will be *least* numerous—foxes or rabbits?
6. Is the power generated by fuel cells limited by the Carnot efficiency? Explain.
7. Does the second law impose performance limits on elite athletes seeking world records in events such as track and field and swimming? Explain.
8. Which method of heating is better in terms of operating cost: electric-resistance baseboard heating or a heat pump? Explain.
9. What options exist for effectively using energy discharged by heat transfer from electricity-generating power plants?
10. When would the power input to a basement sump pump be greater—in the presence or absence of internal irreversibilities? Explain.
11. One automobile make recommends 5W20 motor oil while another make specifies 5W30 oil. What do these designations mean and why might they differ for the two makes?
12. What factors influence the *actual* coefficient of performance achieved by refrigerators in family residences?
13. What is the SEER rating labeled on refrigerators seen in appliance showrooms?
14. How does the *thermal glider* (Sec. 5.4) sustain underwater motion for scientific missions lasting weeks?

► PROBLEMS: DEVELOPING ENGINEERING SKILLS

Exploring the Second Law

- 5.1 Complete the demonstration of the equivalence of the Clausius and Kelvin–Planck statements of the second law given in Sec. 5.2.2 by showing that a violation of the Kelvin–Planck statement implies a violation of the Clausius statement.
- 5.2 An inventor claims to have developed a device that undergoes a thermodynamic cycle while communicating thermally with two reservoirs. The system receives energy  $Q_C$  from the cold reservoir and discharges energy  $Q_H$  to the hot reservoir while delivering a net amount of work to its surroundings. There are no other energy transfers between the device and its surroundings. Evaluate the inventor's claim using (a) the Clausius statement of the second law, and (b) the Kelvin–Planck statement of the second law.
- 5.3 Classify the following processes of a closed system as *possible*, *impossible*, or *indeterminate*.

	Entropy Change	Entropy Transfer	Entropy Production
(a)	$>0$	$0$	
(b)	$<0$		$>0$
(c)	$0$	$>0$	
(d)	$>0$	$>0$	
(e)	$0$	$<0$	
(f)	$>0$		$<0$
(g)	$<0$	$<0$	

5.4 As shown in Fig. P5.4, a hot thermal reservoir is separated from a cold thermal reservoir by a cylindrical rod insulated on its lateral surface. Energy transfer by conduction between the two reservoirs takes place through the rod, which remains at steady state. Using the Kelvin–Planck statement of the second law, demonstrate that such a process is irreversible.

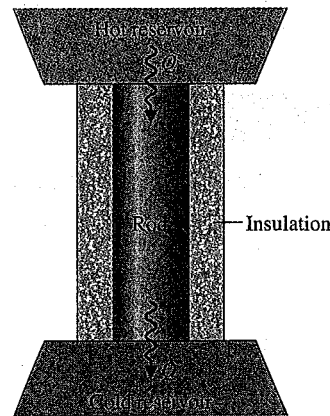


Fig. P5.4

5.5 As shown in Fig. P5.5, a rigid insulated tank is divided into halves by a partition. On one side of the partition is a gas. The other side is initially evacuated. A valve in the partition is opened and the gas expands to fill the entire volume. Using the Kelvin–Planck statement of the second law, demonstrate that this process is irreversible.

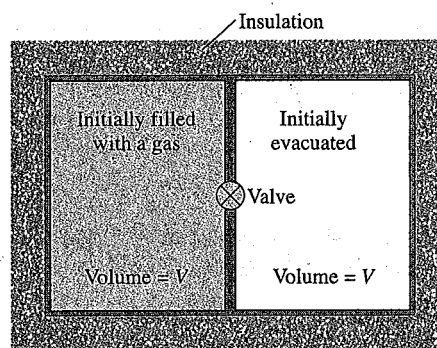


Fig. P5.5

5.6 Answer the following true or false.

- (a) A process that violates the second law of thermodynamics violates the first law of thermodynamics.
- (b) When a net amount of work is done on a closed system undergoing an *internally reversible* process, a net heat transfer of energy from the system also occurs.
- (c) A closed system can experience an increase in entropy only when a net amount of entropy is transferred into the system.
- (d) The change in entropy of a closed system is the same for every process between two specified end states.

5.7 Complete the discussion of the Kelvin-Planck statement of the second law in the box of Sec. 5.4 by showing that if a system undergoes a thermodynamic cycle reversibly while communicating thermally with a single reservoir, the equality in Eq. 5.3 applies.

5.8 A reversible power cycle R and an irreversible power cycle I operate between the same two reservoirs.

- (a) If each cycle receives the same amount of energy  $Q_H$  from the hot reservoir, show that cycle I necessarily discharges more energy  $Q_C$  to the cold reservoir than cycle R. Discuss the implications of this for actual power cycles.
- (b) If each cycle develops the same net work, show that cycle I necessarily receives more energy  $Q_H$  from the hot reservoir than cycle R. Discuss the implications of this for actual power cycles.

5.9 A power cycle I and a reversible power cycle R operate between the same two reservoirs, as shown in Fig. 5.6. Cycle I has a thermal efficiency equal to two-thirds of that for cycle R. Using the Kelvin-Planck statement of the second law, prove that cycle I must be irreversible.

5.10 Provide the details left to the reader in the demonstration of the second Carnot corollary given in the box of Sec. 5.6.2.

5.11 Using the Kelvin-Planck statement of the second law of thermodynamics, demonstrate the following corollaries:

- (a) The coefficient of performance of an irreversible refrigeration cycle is always less than the coefficient of performance of a reversible refrigeration cycle when both exchange energy by heat transfer with the same two reservoirs.
- (b) All reversible refrigeration cycles operating between the same two reservoirs have the same coefficient of performance.
- (c) The coefficient of performance of an irreversible heat pump cycle is always less than the coefficient of performance of a reversible heat pump cycle when both exchange energy by heat transfer with the same two reservoirs.
- (d) All reversible heat pump cycles operating between the same two reservoirs have the same coefficient of performance.

5.12 Before introducing the temperature scale now known as the Kelvin scale, Kelvin suggested a *logarithmic* scale in which the function  $\psi$  of Sec. 5.8.1 takes the form

$$\psi = \exp \theta_C / \exp \theta_H$$

where  $\theta_H$  and  $\theta_C$  denote, respectively, the temperatures of the hot and cold reservoirs on this scale.

(a) Show that the relation between the Kelvin temperature  $T$  and the temperature  $\theta$  on the logarithmic scale is

$$\theta = \ln T + C$$

where  $C$  is a constant.

(b) On the Kelvin scale, temperatures vary from 0 to  $+\infty$ . Determine the range of temperature values on the logarithmic scale.

(c) Obtain an expression for the thermal efficiency of any system undergoing a reversible power cycle while operating between reservoirs at temperatures  $\theta_H$  and  $\theta_C$  on the logarithmic scale.

5.13 Demonstrate that the *gas temperature scale* (Sec. 5.8.2) is identical to the *Kelvin temperature scale* (Sec. 5.8.1).

5.14 The platinum resistance thermometer is said to be the most important of the three thermometers specified in ITS-90 because it covers the broad, practically significant interval from 13.8 K to 1234.93 K. What is the operating principle of resistance thermometry and why is platinum specified for use in ITS-90?

5.15 The relation between resistance  $R$  and temperature  $T$  for a *thermistor* closely follows

$$R = R_0 \exp \left[ \beta \left( \frac{1}{T} - \frac{1}{T_0} \right) \right]$$

where  $R_0$  is the resistance, in ohms ( $\Omega$ ), measured at temperature  $T_0$  (K) and  $\beta$  is a material constant with units of K. For a particular thermistor  $R_0 = 2.2 \Omega$  at  $T_0 = 310$  K. From a calibration test, it is found that  $R = 0.31 \Omega$  at  $T = 422$  K. Determine the value of  $\beta$  for the thermistor and make a plot of resistance versus temperature.

5.16 Over a limited temperature range, the relation between electrical resistance  $R$  and temperature  $T$  for a *resistance temperature detector* is

$$R = R_0 [1 + \alpha(T - T_0)]$$

where  $R_0$  is the resistance, in ohms ( $\Omega$ ), measured at reference temperature  $T_0$  (in  $^{\circ}\text{F}$ ) and  $\alpha$  is a material constant with units of  $(^{\circ}\text{F})^{-1}$ . The following data are obtained for a particular resistance thermometer:

	$T$ ( $^{\circ}\text{F}$ )	$R$ ( $\Omega$ )
Test 1	32	51.39
Test 2	196	51.72

What temperature would correspond to a resistance of 51.47  $\Omega$  on this thermometer?

### Power Cycle Applications

5.17 The data listed below are claimed for a power cycle operating between hot and cold reservoirs at 1000 K and 300 K, respectively. For each case, determine whether the cycle operates *reversibly*, *irreversibly*, or is *impossible*.

- (a)  $Q_H = 600$  kJ,  $W_{\text{cycle}} = 300$  kJ,  $Q_C = 300$  kJ
- (b)  $Q_H = 400$  kJ,  $W_{\text{cycle}} = 280$  kJ,  $Q_C = 120$  kJ
- (c)  $Q_H = 700$  kJ,  $W_{\text{cycle}} = 300$  kJ,  $Q_C = 500$  kJ
- (d)  $Q_H = 800$  kJ,  $W_{\text{cycle}} = 600$  kJ,  $Q_C = 200$  kJ

5.18 A power cycle receives energy  $Q_H$  by heat transfer from a hot reservoir at  $T_H = 1500^\circ\text{R}$  and rejects energy  $Q_C$  by heat transfer to a cold reservoir at  $T_C = 500^\circ\text{R}$ . For each of the following cases, determine whether the cycle operates *reversibly*, operates *irreversibly*, or is *impossible*.

- $Q_H = 900 \text{ Btu}$ ,  $W_{\text{cycle}} = 450 \text{ Btu}$
- $Q_H = 900 \text{ Btu}$ ,  $Q_C = 300 \text{ Btu}$
- $W_{\text{cycle}} = 600 \text{ Btu}$ ,  $Q_C = 400 \text{ Btu}$
- $\eta = 70\%$

5.19 A power cycle operating at steady state receives energy by heat transfer at a rate  $\dot{Q}_H$  at  $T_H = 1000 \text{ K}$  and rejects energy by heat transfer to a cold reservoir at a rate  $\dot{Q}_C$  at  $T_C = 300 \text{ K}$ . For each of the following cases, determine whether the cycle operates *reversibly*, operates *irreversibly*, or is *impossible*.

- $\dot{Q}_H = 500 \text{ kW}$ ,  $\dot{Q}_C = 100 \text{ kW}$
- $\dot{Q}_H = 500 \text{ kW}$ ,  $W_{\text{cycle}} = 250 \text{ kW}$ ,  $\dot{Q}_C = 200 \text{ kW}$
- $W_{\text{cycle}} = 350 \text{ kW}$ ,  $\dot{Q}_C = 150 \text{ kW}$
- $\dot{Q}_H = 500 \text{ kW}$ ,  $\dot{Q}_C = 200 \text{ kW}$

5.20 As shown in Fig. P5.20, a reversible power cycle receives energy  $Q_H$  by heat transfer from a hot reservoir at  $T_H$  and rejects energy  $Q_C$  by heat transfer to a cold reservoir at  $T_C$ .

- If  $T_H = 1200 \text{ K}$  and  $T_C = 300 \text{ K}$ , what is the thermal efficiency?
- If  $T_H = 500^\circ\text{C}$ ,  $T_C = 20^\circ\text{C}$ , and  $W_{\text{cycle}} = 1000 \text{ kJ}$ , what are  $Q_H$  and  $Q_C$ , each in kJ?
- If  $\eta = 60\%$  and  $T_C = 40^\circ\text{F}$ , what is  $T_H$ , in  $^\circ\text{F}$ ?
- If  $\eta = 40\%$  and  $T_H = 727^\circ\text{C}$ , what is  $T_C$ , in  $^\circ\text{C}$ ?

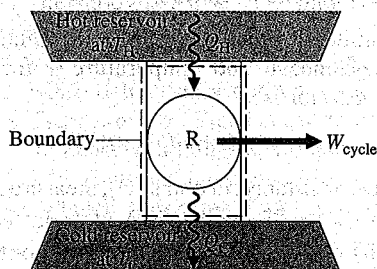


Fig. P5.20

5.21 A reversible power cycle whose thermal efficiency is 40% receives 50 kJ by heat transfer from a hot reservoir at 600 K and rejects energy by heat transfer to a cold reservoir at temperature  $T_C$ . Determine the energy rejected, in kJ, and  $T_C$ , in K.

5.22 Determine the maximum theoretical thermal efficiency for *any* power cycle operating between hot and cold reservoirs at  $602^\circ\text{C}$  and  $112^\circ\text{C}$ , respectively.

5.23 A reversible power cycle operating as in Fig. 5.5 receives energy  $Q_H$  by heat transfer from a hot reservoir at  $T_H$  and rejects energy  $Q_C$  by heat transfer to a cold reservoir at  $40^\circ\text{F}$ . If  $W_{\text{cycle}} = 3 Q_C$ , determine (a) the thermal efficiency and (b)  $T_H$ , in  $^\circ\text{F}$ .

5.24 A reversible power cycle has the same thermal efficiency for hot and cold reservoirs at temperature  $T$  and 500 K,

respectively, as for hot and cold reservoirs at 2000 and 1000 K, respectively. Determine  $T$ , in K.

5.25 As shown in Fig. P5.25, two reversible cycles arranged in series each produce the same net work,  $W_{\text{cycle}}$ . The first cycle receives energy  $Q_H$  by heat transfer from a hot reservoir at  $1000^\circ\text{R}$  and rejects energy  $Q$  by heat transfer to a reservoir at an intermediate temperature,  $T$ . The second cycle receives energy  $Q$  by heat transfer from the reservoir at temperature  $T$  and rejects energy  $Q_C$  by heat transfer to a reservoir at  $400^\circ\text{R}$ . All energy transfers are positive in the directions of the arrows. Determine

- the intermediate temperature  $T$ , in  $^\circ\text{R}$ , and the thermal efficiency for each of the two power cycles.
- the thermal efficiency of a *single* reversible power cycle operating between hot and cold reservoirs at  $1000^\circ\text{R}$  and  $400^\circ\text{R}$ , respectively. Also, determine the net work developed by the single cycle, expressed in terms of the net work developed by each of the two cycles,  $W_{\text{cycle}}$ .

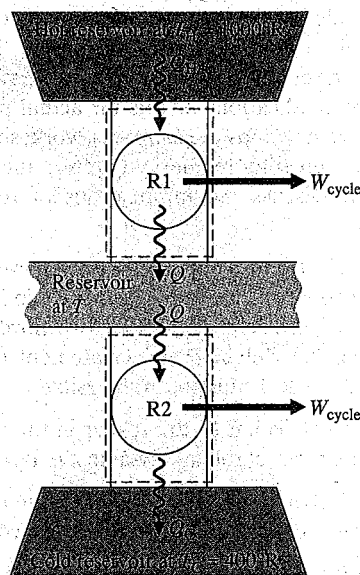


Fig. P5.25

5.26 Two reversible power cycles are arranged in series. The first cycle receives energy by heat transfer from a hot reservoir at  $1000^\circ\text{R}$  and rejects energy by heat transfer to a reservoir at temperature  $T (< 1000^\circ\text{R})$ . The second cycle receives energy by heat transfer from the reservoir at temperature  $T$  and rejects energy by heat transfer to a cold reservoir at  $500^\circ\text{R} (< T)$ . The thermal efficiency of the first cycle is 50% greater than that of the second cycle. Determine

- the intermediate temperature  $T$ , in  $^\circ\text{R}$ , and the thermal efficiency for each of the two power cycles.
- the thermal efficiency of a *single* reversible power cycle operating between hot and cold reservoirs at  $1000^\circ\text{R}$  and  $500^\circ\text{R}$ , respectively.

5.27 A reversible power cycle operating between hot and cold reservoirs at 1000 K and 300 K, respectively, receives 100 kJ by heat transfer from the hot reservoir for each cycle of operation. Determine the net work developed in 10 cycles of operation, in kJ.

- 5.28 A reversible power cycle operating between hot and cold reservoirs at  $1040^{\circ}\text{F}$  and  $40^{\circ}\text{F}$ , respectively, develops net work in the amount of 600 Btu for each cycle of operation. For three cycles of operation, determine the energy received by heat transfer from the hot reservoir, in Btu.
- 5.29 A power cycle operates between a lake's surface water at a temperature of 300 K and water at a depth whose temperature is 285 K. At steady state the cycle develops a power output of 10 kW, while rejecting energy by heat transfer to the lower-temperature water at the rate 14,400 kJ/min. Determine (a) the thermal efficiency of the power cycle and (b) the maximum thermal efficiency for any such power cycle.
- 5.30 An inventor claims to have developed a power cycle having a thermal efficiency of 40%, while operating between hot and cold reservoirs at temperature  $T_H$  and  $T_C = 300$  K, respectively, where  $T_H$  is (a) 600 K, (b) 500 K, (c) 400 K. Evaluate the claim for each case.
- 5.31 Referring to the cycle of Fig. 5.13, if  $p_1 = 2$  bar,  $v_1 = 0.31$  m<sup>3</sup>/kg,  $T_H = 475$  K,  $Q_H = 150$  kJ, and the gas is air obeying the ideal gas model, determine  $T_C$ , in K, the net work of the cycle, in kJ, and the thermal efficiency.
- 5.32 An inventor claims to have developed a power cycle operating between hot and cold reservoirs at 1000 K and 250 K, respectively, that develops net work equal to a multiple of the amount of energy,  $Q_C$ , rejected to the cold reservoir—that is  $W_{\text{cycle}} = NQ_C$ , where all quantities are positive. What is the maximum theoretical value of the number  $N$  for any such cycle?
- 5.33 A power cycle operates between hot and cold reservoirs at 500 K and 310 K, respectively. At steady state the cycle develops a power output of 0.1 MW. Determine the minimum theoretical rate at which energy is rejected by heat transfer to the cold reservoir, in MW.
- 5.34 At steady state, a new power cycle is claimed by its inventor to develop power at a rate of 100 hp for a heat addition rate of  $5.1 \times 10^5$  Btu/h, while operating between hot and cold reservoirs at 1000 and 500 K, respectively. Evaluate this claim.
- 5.35 An inventor claims to have developed a power cycle operating between hot and cold reservoirs at 1175 K and 295 K, respectively, that provides a steady-state power output of 32 kW while receiving energy by heat transfer from the hot reservoir at the rate 150,000 kJ/h. Evaluate this claim.
- 5.36 At steady state, a power cycle develops a power output of 10 kW while receiving energy by heat transfer at the rate of 10 kJ per cycle of operation from a source at temperature  $T$ . The cycle rejects energy by heat transfer to cooling water at a lower temperature of 300 K. If there are 100 cycles per minute, what is the minimum theoretical value for  $T$ , in K?
- 5.37 A power cycle operates between hot and cold reservoirs at 600 K and 300 K, respectively. At steady state the cycle develops a power output of 0.45 MW while receiving energy by heat transfer from the hot reservoir at the rate of 1 MW.  
 (a) Determine the thermal efficiency and the rate at which energy is rejected by heat transfer to the cold reservoir, in MW.  
 (b) Compare the results of part (a) with those of a reversible power cycle operating between these reservoirs and receiving the same rate of heat transfer from the hot reservoir.
- 5.38 As shown in Fig. P5.38, a system undergoing a power cycle develops a net power output of 1 MW while receiving energy by heat transfer from steam condensing from saturated vapor to saturated liquid at a pressure of 100 kPa. Energy is discharged from the cycle by heat transfer to a nearby lake at  $17^{\circ}\text{C}$ . These are the only significant heat transfers. Kinetic and potential energy effects can be ignored. For operation at steady state, determine the minimum theoretical steam mass flow rate, in kg/s, required by any such cycle.
- 5.39 A power cycle operating at steady state receives energy by heat transfer from the combustion of fuel at an average temperature of 1000 K. Owing to environmental considerations, the cycle discharges energy by heat transfer to the atmosphere at 300 K at a rate no greater than 60 MW. Based on the cost of fuel, the cost to supply the heat transfer is \$4.50 per GJ. The power developed by the cycle is valued at \$0.08 per kW · h. For 8000 hours of operation annually, determine for any such cycle, in \$ per year, (a) the maximum value of the power generated and (b) the corresponding fuel cost.
- 5.40 At steady state, a 750-MW power plant receives energy by heat transfer from the combustion of fuel at an average temperature of  $317^{\circ}\text{C}$ . As shown in Fig. P5.40, the plant discharges energy by heat transfer to a river whose mass flow rate is  $1.65 \times 10^5$  kg/s. Upstream of the power plant the river is at  $17^{\circ}\text{C}$ . Determine the increase in the temperature of the river,  $\Delta T$ , traceable to such heat transfer, in  $^{\circ}\text{C}$ , if the thermal efficiency of the power plant is (a) the Carnot

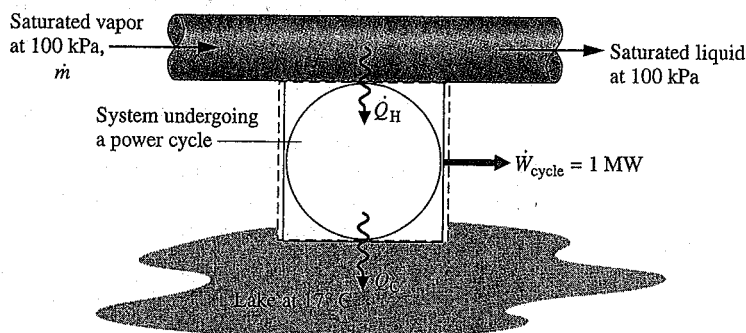


Fig. P5.38

efficiency of a power cycle operating between hot and cold reservoirs at  $317^\circ\text{C}$  and  $17^\circ\text{C}$ , respectively, (b) two-thirds of the Carnot efficiency found in part (a). Comment.

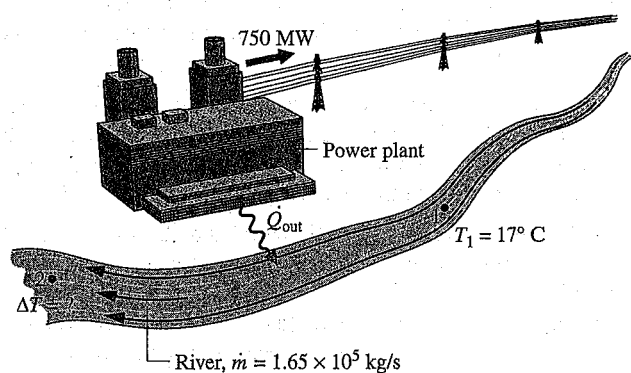


Fig. P5.40

5.41 To increase the thermal efficiency of a reversible power cycle operating between reservoirs at  $T_H$  and  $T_C$ , would you increase  $T_H$  while keeping  $T_C$  constant, or decrease  $T_C$  while keeping  $T_H$  constant? Are there any *natural* limits on the increase in thermal efficiency that might be achieved by such means?

5.42 Two reversible power cycles are arranged in series. The first cycle receives energy by heat transfer from a hot reservoir at temperature  $T_H$  and rejects energy by heat transfer to a reservoir at an intermediate temperature  $T < T_H$ . The second cycle receives energy by heat transfer from the reservoir at temperature  $T$  and rejects energy by heat transfer to a cold reservoir at temperature  $T_C < T$ .

(a) Obtain an expression for the thermal efficiency of a *single* reversible power cycle operating between hot and cold reservoirs at  $T_H$  and  $T_C$ , respectively, in terms of the thermal efficiencies of the two cycles.

(b) Obtain an expression for the intermediate temperature  $T$  in terms of  $T_H$  and  $T_C$  for the *special case* where the thermal efficiencies of the two cycles are equal.

### Refrigeration and Heat Pump Cycle Applications

5.43 A refrigeration cycle operating between two reservoirs receives energy  $Q_C$  from a cold reservoir at  $T_C = 275\text{ K}$  and rejects energy  $Q_H$  to a hot reservoir at  $T_H = 315\text{ K}$ . For each of the following cases, determine whether the cycle operates *reversibly*, operates *irreversibly*, or is *impossible*:

- $Q_C = 1000\text{ kJ}$ ,  $W_{\text{cycle}} = 80\text{ kJ}$ .
- $Q_C = 1200\text{ kJ}$ ,  $Q_H = 2000\text{ kJ}$ .
- $Q_H = 1575\text{ kJ}$ ,  $W_{\text{cycle}} = 200\text{ kJ}$ .
- $\beta = 6$ .

5.44 A reversible refrigeration cycle operates between cold and hot reservoirs at temperatures  $T_C$  and  $T_H$ , respectively.

- If the coefficient of performance is 3.5 and  $T_H = 80^\circ\text{F}$ , determine  $T_C$ , in  $^\circ\text{F}$ .
- If  $T_C = -30^\circ\text{C}$  and  $T_H = 30^\circ\text{C}$ , determine the coefficient of performance.

(c) If  $Q_C = 500\text{ Btu}$ ,  $Q_H = 800\text{ Btu}$ , and  $T_C = 20^\circ\text{F}$ , determine  $T_H$ , in  $^\circ\text{F}$ .

(d) If  $T_C = 30^\circ\text{F}$  and  $T_H = 100^\circ\text{F}$ , determine the coefficient of performance.

(e) If the coefficient of performance is 8.9 and  $T_C = -5^\circ\text{C}$ , find  $T_H$ , in  $^\circ\text{C}$ .

5.45 At steady state, a reversible heat pump cycle discharges energy at the rate  $\dot{Q}_H$  to a hot reservoir at temperature  $T_H$ , while receiving energy at the rate  $\dot{Q}_C$  from a cold reservoir at temperature  $T_C$ .

(a) If  $T_H = 21^\circ\text{C}$  and  $T_C = 7^\circ\text{C}$ , determine the coefficient of performance.

(b) If  $\dot{Q}_H = 10.5\text{ kW}$ ,  $\dot{Q}_C = 8.75\text{ kW}$ , and  $T_C = 0^\circ\text{C}$ , determine  $T_H$ , in  $^\circ\text{C}$ .

(c) If the coefficient of performance is 10 and  $T_H = 27^\circ\text{C}$ , determine  $T_C$ , in  $^\circ\text{C}$ .

5.46 Two reversible cycles operate between hot and cold reservoirs at temperature  $T_H$  and  $T_C$ , respectively.

(a) If one is a power cycle and the other is a heat pump cycle, what is the relation between the coefficient of performance of the heat pump cycle and the thermal efficiency of the power cycle?

(b) If one is a refrigeration cycle and the other is a heat pump cycle, what is the relation between their coefficients of performance?

5.47 A refrigeration cycle rejects  $Q_H = 500\text{ Btu}$  per cycle to a hot reservoir at  $T_H = 540^\circ\text{R}$ , while receiving  $Q_C = 375\text{ Btu}$  per cycle from a cold reservoir at temperature  $T_C$ . For 10 cycles of operation, determine (a) the net work input, in Btu, and (b) the minimum theoretical temperature  $T_C$ , in  $^\circ\text{R}$ .

5.48 A reversible heat pump cycle operates as in Fig. 5.7 between hot and cold reservoirs at  $T_H = 27^\circ\text{C}$  and  $T_C = -3^\circ\text{C}$ , respectively. Determine the fraction of the heat transfer  $Q_H$  discharged at  $T_H$  provided by (a) the net work input, (b) the heat transfer  $Q_C$  from the cold reservoir  $T_C$ .

5.49 A reversible power cycle and a reversible heat pump cycle operate between hot and cold reservoirs at temperature  $T_H = 1000^\circ\text{R}$  and  $T_C$ , respectively. If the thermal efficiency of the power cycle is 60%, determine (a)  $T_C$ , in  $^\circ\text{R}$ , and (b) the coefficient of performance of the heat pump.

5.50 An inventor has developed a refrigerator capable of maintaining its freezer compartment at  $20^\circ\text{F}$  while operating in a kitchen at  $70^\circ\text{F}$ , and claims the device has a coefficient of performance of (a) 10, (b) 9.6, (c) 4. Evaluate the claim in each of the three cases.

5.51 An inventor claims to have developed a food freezer that at steady state requires a power input of  $0.6\text{ kW}$  to extract energy by heat transfer at a rate of  $3000\text{ J/s}$  from freezer contents at  $270\text{ K}$ . Evaluate this claim for an ambient temperature of  $293\text{ K}$ .

5.52 An inventor claims to have developed a refrigerator that at steady state requires a net power input of  $0.7\text{ horsepower}$  to remove  $12,000\text{ Btu/h}$  of energy by heat transfer from the



freezer compartment at  $0^{\circ}\text{F}$  and discharge energy by heat transfer to a kitchen at  $70^{\circ}\text{F}$ . Evaluate this claim.

- 5.53 An inventor claims to have devised a refrigeration cycle operating between hot and cold reservoirs at 300 K and 250 K, respectively, that removes an amount of energy  $Q_C$  by heat transfer from the cold reservoir that is a multiple of the net work input—that is,  $Q_C = N\dot{W}_{\text{cycle}}$ , where all quantities are positive. Determine the maximum theoretical value of the number  $N$  for any such cycle.
- 5.54 Data are provided for two reversible refrigeration cycles. One cycle operates between hot and cold reservoirs at  $27^{\circ}\text{C}$  and  $-8^{\circ}\text{C}$ , respectively. The other cycle operates between the same hot reservoir at  $27^{\circ}\text{C}$  and a cold reservoir at  $-28^{\circ}\text{C}$ . If each refrigerator removes the same amount of energy by heat transfer from its cold reservoir, determine the ratio of the net work input values of the two cycles.
- 5.55 By removing energy by heat transfer from its freezer compartment at a rate of 1.25 kW, a refrigerator maintains the freezer at  $-26^{\circ}\text{C}$  on a day when the temperature of the surroundings is  $22^{\circ}\text{C}$ . Determine the minimum theoretical power, in kW, required by the refrigerator at steady state.
- 5.56 At steady state, a refrigeration cycle maintains a *clean room* at  $55^{\circ}\text{F}$  by removing energy entering the room by heat transfer from adjacent spaces at the rate of 0.12 Btu/s. The cycle rejects energy by heat transfer to the outdoors where the temperature is  $80^{\circ}\text{F}$ .
- (a) If the rate at which the cycle rejects energy by heat transfer to the outdoors is 0.16 Btu/s, determine the power required, in Btu/s.
- (b) Determine the power required to maintain the clean room's temperature by a reversible refrigeration cycle operating between cold and hot reservoirs at  $55^{\circ}\text{F}$  and  $80^{\circ}\text{F}$ , respectively, and the corresponding rate at which energy is rejected by heat transfer to the outdoors, each in Btu/s.
- 5.57 For each kW of power input to an ice maker at steady state, determine the maximum rate that ice can be produced, in lb/h, from liquid water at  $32^{\circ}\text{F}$ . Assume that 144 Btu/lb of energy must be removed by heat transfer to freeze water at  $32^{\circ}\text{F}$ , and that the surroundings are at  $78^{\circ}\text{F}$ .
- 5.58 At steady state, a refrigeration cycle operates between hot and cold reservoirs at 300 K and 270 K, respectively. Determine the minimum theoretical net power input required, in kW per kW of heat transfer from the cold reservoir.
- 5.59 At steady state, a refrigeration cycle operating between hot and cold reservoirs at 300 K and 275 K, respectively, removes energy by heat transfer from the cold reservoir at a rate of 600 kW.
- (a) If the cycle's coefficient of performance is 4, determine the power input required, in kW.
- (b) Determine the minimum theoretical power required, in kW, for any such cycle.
- 5.60 An air conditioner operating at steady state maintains a dwelling at  $20^{\circ}\text{C}$  on a day when the outside temperature is  $35^{\circ}\text{C}$ . Energy is removed by heat transfer from the dwelling at a rate of 2800 J/s while the air conditioner's power input is 0.8 kW. Determine (a) the coefficient of performance of the air conditioner and (b) the power input required by a reversible refrigeration cycle providing the same cooling effect while operating between hot and cold reservoirs at  $35^{\circ}\text{C}$  and  $20^{\circ}\text{C}$ , respectively.
- 5.61 As shown in Fig P5.61, an air conditioner operating at steady state maintains a dwelling at  $70^{\circ}\text{F}$  on a day when the outside temperature is  $90^{\circ}\text{F}$ . If the rate of heat transfer into the dwelling through the walls and roof is 30,000 Btu/h, might a net power input to the air conditioner compressor of 3 hp be sufficient? If yes, determine the coefficient of performance. If no, determine the minimum theoretical power input, in hp.
- 5.62 A heat pump cycle is used to maintain the interior of a building at  $20^{\circ}\text{C}$ . At steady state, the heat pump receives energy by heat transfer from well water at  $10^{\circ}\text{C}$  and discharges energy by heat transfer to the building at a rate

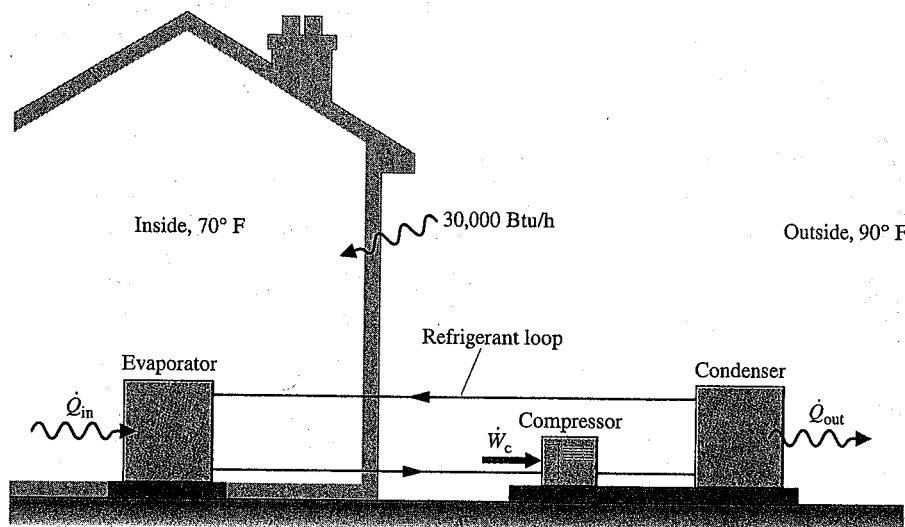


Fig. P5.61

of 120,000 kJ/h. Over a period of 14 days, an electric meter records that 1490 kW · h of electricity is provided to the heat pump. Determine

- (a) the amount of energy that the heat pump receives over the 14-day period from the well water by heat transfer, in kJ.
- (b) the heat pump's coefficient of performance.
- (c) the coefficient of performance of a reversible heat pump cycle operating between hot and cold reservoirs at 20°C and 10°C.

**5.63** A refrigeration cycle has a coefficient of performance equal to 75% of the value for a reversible refrigeration cycle operating between cold and hot reservoirs at -5°C and 40°C, respectively. For operation at steady state, determine the net power input, in kW per kW of cooling, required by

- (a) the actual refrigeration cycle and (b) the reversible refrigeration cycle. Compare values.

**5.64** By removing energy by heat transfer from a room, a window air conditioner maintains the room at 22°C on a day when the outside temperature is 32°C.

- (a) Determine, in kW per kW of cooling, the *minimum* theoretical power required by the air conditioner.
- (b) To achieve required rates of heat transfer with practical-sized units, air conditioners typically receive energy by heat transfer at a temperature *below* that of the room being cooled and discharge energy by heat transfer at a temperature *above* that of the surroundings. Consider the effect of this by determining the *minimum* theoretical power, in kW per kW of cooling, required when  $T_C = 18^\circ\text{C}$  and  $T_H = 36^\circ\text{C}$ , and compare with the value found in part (a).

**5.65** The refrigerator shown in Fig. P5.65 operates at steady state with a coefficient of performance of 5.0 within a kitchen at 23°C. The refrigerator rejects 4.8 kW by heat transfer to its surroundings from metal coils located on its exterior. Determine

- (a) the power input, in kW.
- (b) the lowest theoretical temperature *inside* the refrigerator, in K.

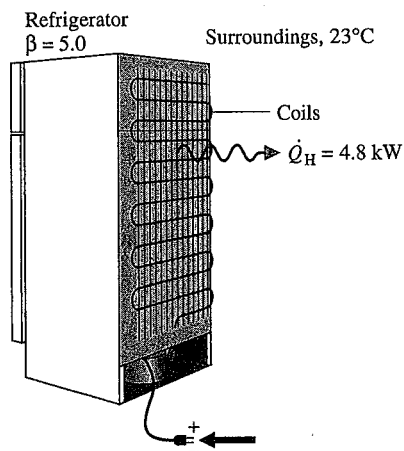


Fig. P5.65

**5.66** At steady state, a heat pump provides energy by heat transfer at the rate of 25,000 Btu/h to maintain a dwelling at 70°F on a day when the outside temperature is 30°F. The power input to the heat pump is 4.5 hp. Determine

- (a) the coefficient of performance of the heat pump.
- (b) the coefficient of performance of a reversible heat pump operating between hot and cold reservoirs at 70°F and 30°F, respectively, and the corresponding rate at which energy would be provided by heat transfer to the dwelling for a power input of 4.5 hp.

**5.67** By supplying energy at an average rate of 24,000 kJ/h, a heat pump maintains the temperature of a dwelling at 20°C. If electricity costs 8.5 cents per kW · h, determine the minimum theoretical operating cost for each day of operation if the heat pump receives energy by heat transfer from

- (a) the outdoor air at -7°C.
- (b) the ground at 5°C.

**5.68** A heat pump with a coefficient of performance of 3.5 provides energy at an average rate of 70,000 kJ/h to maintain a building at 20°C on a day when the outside temperature is -5°C. If electricity costs 8.5 cents per kW · h,

- (a) determine the actual operating cost and the minimum theoretical operating cost, each in \$/day.
- (b) compare the results of part (a) with the cost of electrical-resistance heating.

**5.69** A heat pump is under consideration for heating a research station located on an Antarctica ice shelf. The interior of the station is to be kept at 15°C. Determine the maximum theoretical rate of heating provided by a heat pump, in kW per kW of power input, in each of two cases: The role of the cold reservoir is played by (a) the atmosphere at -20°C, (b) ocean water at 5°C.

**5.70** As shown in Fig. P5.70, a heat pump provides energy by heat transfer to water vaporizing from saturated liquid to saturated vapor at a pressure of 2 bar and a mass flow rate of 0.05 kg/s. The heat pump receives energy by heat transfer from a pond at 16°C. These are the only significant heat transfers. Kinetic and potential energy effects can be ignored. A faded, hard-to-read data sheet indicates the power required by the pump is 35 kW. Can this value be correct? Explain.

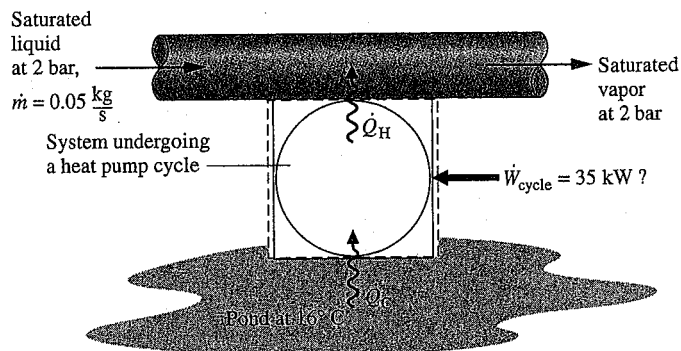


Fig. P5.70

5.71 To maintain a dwelling steadily at 68°F on a day when the outside temperature is 32°F, heating must be provided at an average rate of 700 Btu/min. Compare the electrical power required, in kW, to deliver the heating using (a) electrical-resistance heating, (b) a heat pump whose coefficient of performance is 3.5, (c) a reversible heat pump.

5.72 Referring to the heat pump cycle of Fig. 5.16, if  $p_1 = 14.7$  and  $p_4 = 18.7$ , each in lbf/in.<sup>2</sup>,  $v_1 = 12.6$  and  $v_4 = 10.6$ , each in ft<sup>3</sup>/lb, and the gas is air obeying the ideal gas model, determine  $T_H$  and  $T_C$ , each in °R, and the coefficient of performance.

5.73 Two reversible refrigeration cycles operate in series. The first cycle receives energy by heat transfer from a cold reservoir at 300 K and rejects energy by heat transfer to a reservoir at an intermediate temperature  $T$  greater than 300 K. The second cycle receives energy by heat transfer from the reservoir at temperature  $T$  and rejects energy by heat transfer to a higher-temperature reservoir at 883 K. If the refrigeration cycles have the same coefficient of performance, determine (a)  $T$ , in K, and (b) the value of each coefficient of performance.

5.74 Two reversible heat pump cycles operate in series. The first cycle receives energy by heat transfer from a cold reservoir at 250 K and rejects energy by heat transfer to a reservoir at an intermediate temperature  $T$  greater than 250 K. The second cycle receives energy by heat transfer from the reservoir at temperature  $T$  and rejects energy by heat transfer to a higher-temperature reservoir at 1440 K. If the heat pump cycles have the same coefficient of performance, determine (a)  $T$ , in K, and (b) the value of each coefficient of performance.

5.75 Two reversible refrigeration cycles are arranged in series. The first cycle receives energy by heat transfer from a cold reservoir at temperature  $T_C$  and rejects energy by heat transfer to a reservoir at an intermediate temperature  $T$  greater than  $T_C$ . The second cycle receives energy by heat transfer from the reservoir at temperature  $T$  and rejects energy by heat transfer to a higher-temperature reservoir at  $T_H$ . Obtain an expression for the coefficient of performance of a single reversible refrigeration cycle operating directly between cold and hot reservoirs at  $T_C$  and  $T_H$ , respectively, in terms of the coefficients of performance of the two cycles.

5.76 Repeat Problem 5.75 for the case of two reversible heat pump cycles.

### Carnot Cycle Applications

5.77 A quantity of water within a piston-cylinder assembly executes a Carnot power cycle. During isothermal expansion, the water is heated from saturated liquid at 50 bar until it is a saturated vapor. The vapor then expands adiabatically to a pressure of 5 bar while doing 364.31 kJ/kg of work.

- Sketch the cycle on  $p$ - $v$  coordinates.
- Evaluate the heat transfer per unit mass and work per unit mass for each process, in kJ/kg.
- Evaluate the thermal efficiency.

5.78 One and one-half pounds of water within a piston-cylinder assembly execute a Carnot power cycle. During isothermal

expansion, the water is heated at 500°F from saturated liquid to saturated vapor. The vapor then expands adiabatically to a temperature of 100°F and a quality of 70.38%.

- Sketch the cycle on  $p$ - $v$  coordinates.
- Evaluate the heat transfer and work for each process, in Btu.
- Evaluate the thermal efficiency.

5.79 Two kilograms of air within a piston-cylinder assembly execute a Carnot power cycle with maximum and minimum temperatures of 750 K and 300 K, respectively. The heat transfer to the air during the isothermal expansion is 60 kJ. At the end of the isothermal expansion, the pressure is 600 kPa and the volume is 0.4 m<sup>3</sup>. Assuming the ideal gas model for the air, determine

- the thermal efficiency.
- the pressure and volume at the beginning of the isothermal expansion, in kPa and m<sup>3</sup>, respectively.
- the work and heat transfer for each of the four processes, in kJ.
- Sketch the cycle on  $p$ - $V$  coordinates.

5.80 The pressure-volume diagram of a Carnot power cycle executed by an ideal gas with constant specific heat ratio  $k$  is shown in Fig. P5.80. Demonstrate that

- $V_4V_2 = V_1V_3$ .
- $T_2/T_3 = (p_2/p_3)^{(k-1)/k}$ .
- $T_2/T_3 = (V_3/V_2)^{(k-1)}$ .

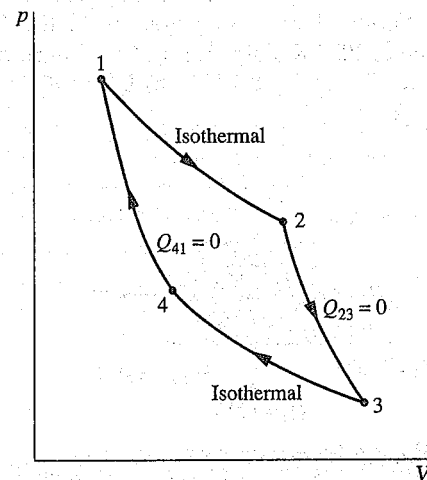


Fig. P5.80

5.81 Carbon dioxide (CO<sub>2</sub>) as an ideal gas executes a Carnot power cycle while operating between thermal reservoirs at 450 and 100°F. The pressures at the initial and final states of the isothermal expansion are 400 and 200 lbf/in.<sup>2</sup>, respectively. The specific heat ratio is  $k = 1.24$ . Using the results of Problem 5.80 as needed, determine

- the work and heat transfer for each of the four processes, in Btu/lb.
- the thermal efficiency.
- the pressures at the initial and final states of the isothermal compression, in lbf/in.<sup>2</sup>