

undergoing cycles while interacting with thermal reservoirs. The irreversibility concept is introduced and the related notions of irreversible, reversible, and internally reversible processes are discussed. The Kelvin temperature scale is defined and used to obtain expressions for maximum performance measures of power, refrigeration, and heat pump cycles operating between two thermal reservoirs. The Carnot cycle is introduced to provide a specific example of a reversible cycle operating between two thermal reservoirs. Finally, the Clausius inequality providing a bridge from Chap. 5 to Chap. 6 is presented and discussed.

The following checklist provides a study guide for this chapter. When your study of the text and end-of-chapter exercises has been completed you should be able to

- ▶ write out the meanings of the terms listed in the margins throughout the chapter and understand each of the related concepts. The subset of key concepts listed below is particularly important in subsequent chapters.
- ▶ give the Kelvin–Planck statement of the second law, correctly interpreting the “less than” and “equal to” signs in Eq. 5.3.
- ▶ list several important irreversibilities.
- ▶ apply the corollaries of Secs. 5.6.2 and 5.7.2 together with Eqs. 5.9, 5.10, and 5.11 to assess the performance of power cycles and refrigeration and heat pump cycles.
- ▶ describe the Carnot cycle.
- ▶ interpret the Clausius inequality.

▶ KEY ENGINEERING CONCEPTS

second law statements, p. 239
 thermal reservoir, p. 239
 irreversible process, p. 242
 reversible process, p. 242
 irreversibilities, p. 243

internal and external irreversibilities, p. 243
 internally reversible process, p. 246
 Carnot corollaries, p. 249
 Kelvin scale, p. 253

Carnot efficiency, p. 257
 Carnot cycle, p. 262
 Clausius inequality, p. 265

▶ KEY EQUATIONS

$W_{\text{cycle}} \leq 0 \begin{cases} < 0: & \text{Internal irreversibilities present.} \\ = 0: & \text{No internal irreversibilities.} \end{cases} \quad (\text{single reservoir})$	(5.3) p. 247	Analytical form of the Kelvin–Planck statement.
$\eta_{\text{max}} = 1 - \frac{T_C}{T_H}$	(5.9) p. 257	Maximum thermal efficiency: power cycle operating between two reservoirs.
$\beta_{\text{max}} = \frac{T_C}{T_H - T_C}$ $\gamma_{\text{max}} = \frac{T_H}{T_H - T_C}$	(5.10) p. 259 (5.11) p. 259	Maximum coefficient of performance: refrigeration cycle operating between two reservoirs. Maximum coefficient of performance: heat pump cycle operating between two reservoirs.
$\oint \left(\frac{\delta Q}{T} \right)_b = -\sigma_{\text{cycle}}$	(5.13) p. 265	Clausius inequality.

▶ EXERCISES: THINGS ENGINEERS THINK ABOUT

1. Extending the discussion of Sec. 5.1.2, how might work be developed when (a) T_i is less than T_0 in Fig. 5.1a, (b) p_i is less than p_0 in Fig. 5.1b?
2. Are health risks associated with consuming tomatoes induced to ripen by an ethylene spray? Explain.

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.

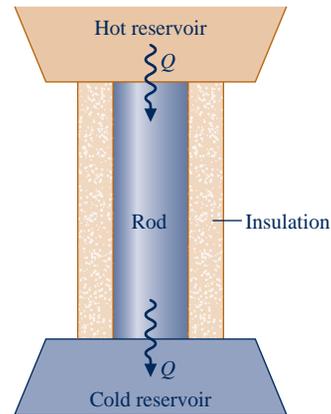


Fig. P5.4

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.

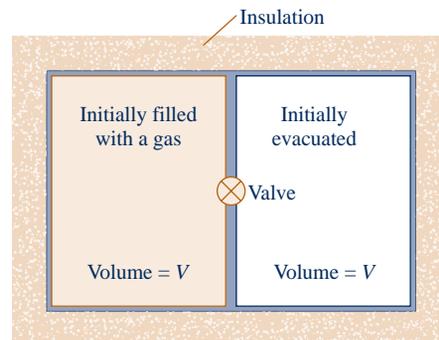


Fig. P5.5

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 ψ of Sec. 5.8.1 takes the form

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

where θ_H and θ_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 θ 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 θ_H and θ_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 (Ω), measured at temperature T_0 (K) and β 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 β 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 (Ω), measured at reference temperature T_0 (in $^{\circ}\text{F}$) and α 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 51.47Ω 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*, operates *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*.

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

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 $^\circ\text{C}$?

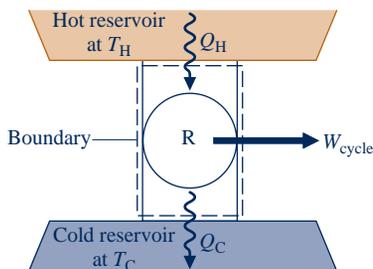


Fig. P5.20

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°C and 112°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°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_{cycle} . The first cycle receives energy Q_H by heat transfer from a hot reservoir at 1000°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°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°R and 400°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_{cycle} .

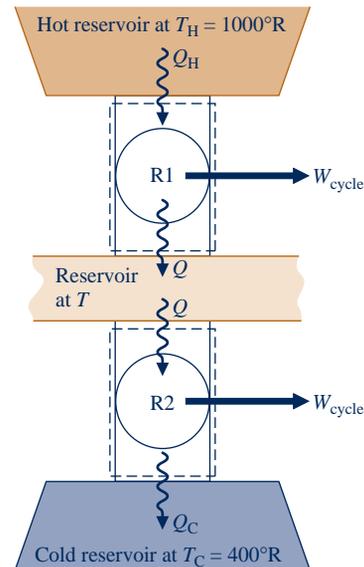


Fig. P5.25

5.26 Two reversible power cycles are arranged in series. The first cycle receives energy by heat transfer from a hot reservoir at 1000°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°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°R and 500°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°F and 40°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, $v_1 = 0.31$ m³/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 5.1×10^5 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°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°C. As shown in Fig. P5.40, the plant discharges energy by heat transfer to a river whose mass flow rate is 1.65×10^5 kg/s. Upstream of the power plant the river is at 17°C. Determine the increase in the temperature of the river, ΔT , traceable to such heat transfer, in °C, if the thermal efficiency of the power plant is (a) the Carnot

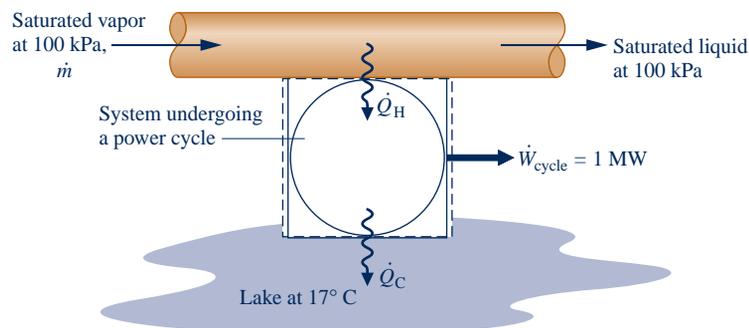


Fig. P5.38

efficiency of a power cycle operating between hot and cold reservoirs at 317°C and 17°C , respectively, (b) two-thirds of the Carnot efficiency found in part (a). Comment.

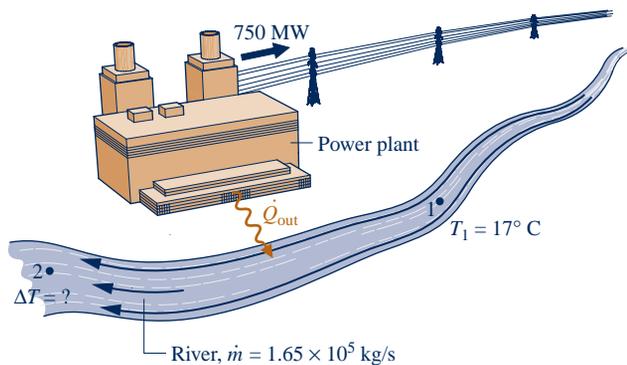


Fig. P5.40

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°F while operating in a kitchen at 70°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 kW to extract energy by heat transfer at a rate of 3000 J/s from freezer contents at 270 K . Evaluate this claim for an ambient temperature of 293 K .

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

freezer compartment at 0°F and discharge energy by heat transfer to a kitchen at 70°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°C and -8°C , respectively. The other cycle operates between the same hot reservoir at 27°C and a cold reservoir at -28°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°C on a day when the temperature of the surroundings is 22°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°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°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°F and 80°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°F . Assume that 144 Btu/lb of energy must be removed by heat transfer to freeze water at 32°F , and that the surroundings are at 78°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°C on a day when the outside temperature is 35°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°C and 20°C , respectively.
- 5.61** As shown in Fig P5.61, an air conditioner operating at steady state maintains a dwelling at 70°F on a day when the outside temperature is 90°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°C . At steady state, the heat pump receives energy by heat transfer from well water at 10°C and discharges energy by heat transfer to the building at a rate

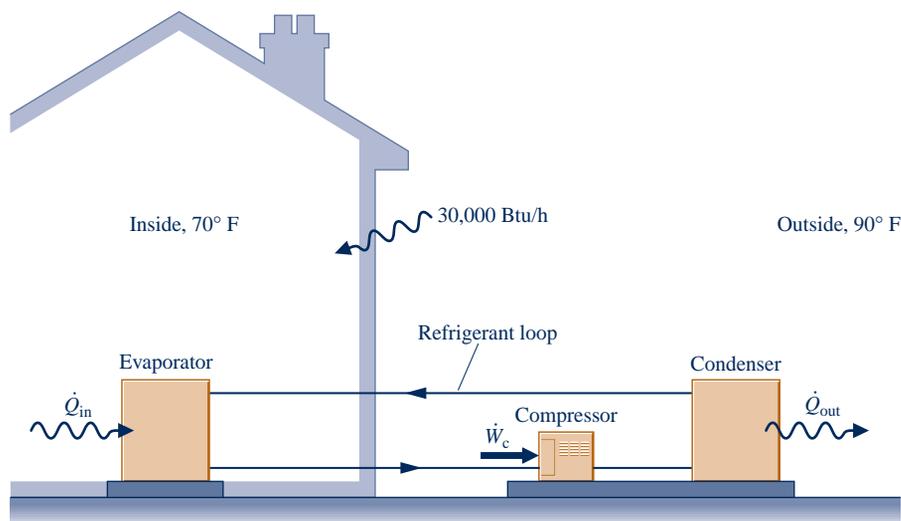


Fig. P5.61

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

- the amount of energy that the heat pump receives over the 14-day period from the well water by heat transfer, in kJ.
- the heat pump's coefficient of performance.
- 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

- the actual refrigeration cycle and
- 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 .

- Determine, in kW per kW of cooling, the *minimum* theoretical power required by the air conditioner.
- 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

- the power input, in kW.
- the lowest theoretical temperature *inside* the refrigerator, in K.

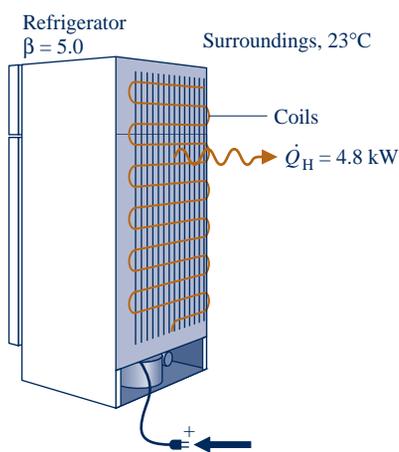


Fig. P5.65

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

- the coefficient of performance of the heat pump.
- 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

- the outdoor air at -7°C .
- 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,

- determine the actual operating cost and the minimum theoretical operating cost, each in \$/day.
- 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.

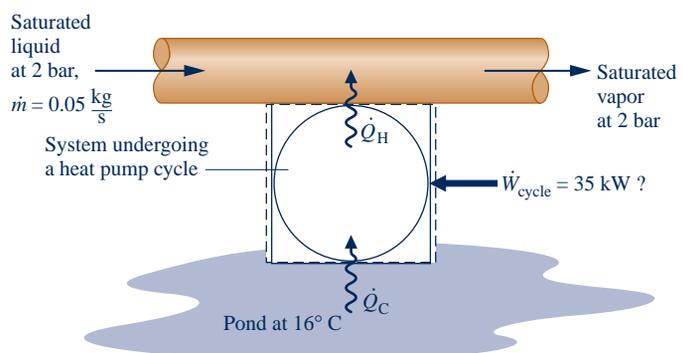


Fig. P5.70

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.², $v_1 = 12.6$ and $v_4 = 10.6$, each in ft³/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 m³. 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 m³, 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

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

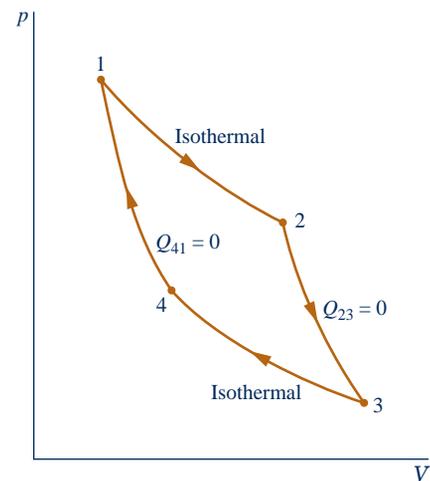


Fig. P5.80

5.81 Carbon dioxide (CO₂) 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.², 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.²

5.82 One-tenth kilogram of air as an ideal gas with $k = 1.4$ executes a Carnot refrigeration cycle, as shown in Fig. 5.16. The isothermal expansion occurs at -23°C with a heat transfer to the air of 3.4 kJ. The isothermal compression occurs at 27°C to a final volume of 0.01 m^3 . Using the results of Prob. 5.80 adapted to the present case, determine

- (a) the pressure, in kPa, at each of the four principal states.
- (b) the work, in kJ, for each of the four processes.
- (c) the coefficient of performance.

Clausius Inequality Applications

5.83 A system executes a power cycle while receiving 1000 kJ by heat transfer at a temperature of 500 K and discharging energy by heat transfer at a temperature of 300 K. There are no other heat transfers. Applying Eq. 5.13, determine σ_{cycle} if the thermal efficiency is (a) 100%, (b) 40%, (c) 30%. Identify cases (if any) that are internally reversible or impossible.

5.84 A system executes a power cycle while receiving 1050 kJ by heat transfer at a temperature of 525 K and discharging 700 kJ by heat transfer at 350 K. There are no other heat transfers.

- (a) Using Eq. 5.13, determine whether the cycle is *internally reversible, irreversible, or impossible*.
- (b) Determine the thermal efficiency using Eq. 5.4 and the given heat transfer data. Compare this value with the *Carnot efficiency* calculated using Eq. 5.9 and comment.

5.85 As shown in Fig. P5.85, a system executes a power cycle while receiving 750 kJ by heat transfer at a temperature of 1500 K and discharging 100 kJ by heat transfer at a temperature of 500 K. Another heat transfer from the system occurs at a temperature of 1000 K. Using Eq. 5.13, determine the thermal efficiency if σ_{cycle} is (a) 0 kJ/K, (b) 0.1 kJ/K, (c) 0.2 kJ/K, (d) 0.35 kJ/K.

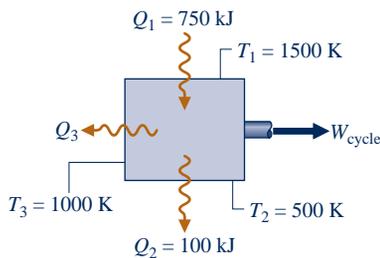


Fig. P5.85

5.86 Figure P5.86 gives the schematic of a vapor power plant in which water steadily circulates through the four components shown. The water flows through the boiler and condenser at constant pressure and through the turbine and pump adiabatically. Kinetic and potential energy effects can be ignored. Process data follow:

Process 4–1: constant-pressure at 1 MPa from saturated liquid to saturated vapor

Process 2–3: constant-pressure at 20 kPa from $x_2 = 88\%$ to $x_3 = 18\%$

- (a) Using Eq. 5.13 expressed on a time-rate basis, determine if the cycle is *internally reversible, irreversible, or impossible*.

- (b) Determine the thermal efficiency using Eq. 5.4 expressed on a time-rate basis and steam table data.
- (c) Compare the result of part (b) with the *Carnot efficiency* calculated using Eq. 5.9 with the boiler and condenser temperatures and comment.

5.87 Repeat Problem 5.86 for the following case:

Process 4–1: constant-pressure at 8 MPa from saturated liquid to saturated vapor

Process 2–3: constant-pressure at 8 kPa from $x_2 = 67.5\%$ to $x_3 = 34.2\%$

5.88 Repeat Problem 5.86 for the following case:

Process 4–1: constant-pressure at 0.15 MPa from saturated liquid to saturated vapor

Process 2–3: constant-pressure at 20 kPa from $x_2 = 90\%$ to $x_3 = 10\%$

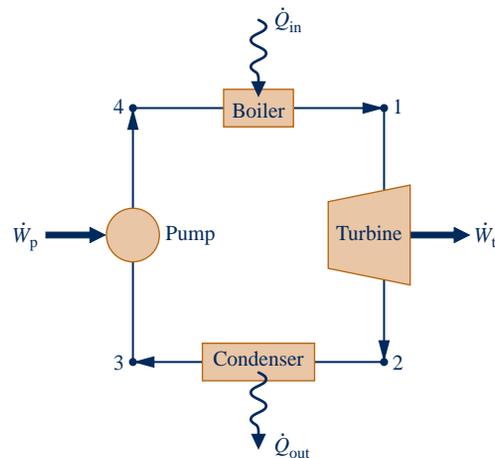


Fig. P5.86–88

5.89 A reversible power cycle R and an irreversible power cycle I operate between the same two reservoirs. Each receives Q_H from the hot reservoir. The reversible cycle develops work W_R , while the irreversible cycle develops work W_I . The reversible cycle discharges Q_C to the cold reservoir, while the irreversible cycle discharges Q'_C .

- (a) Using Eq. 5.13, evaluate σ_{cycle} for cycle I in terms of W_I , W_R , and temperature T_C of the cold reservoir only.
- (b) Demonstrate that $W_I < W_R$ and $Q'_C > Q_C$.

5.90 A reversible refrigeration cycle R and an irreversible refrigeration cycle I operate between the same two reservoirs and each removes Q_C from the cold reservoir. The net work input required by R is W_R , while the net work input for I is W_I . The reversible cycle discharges Q_H to the hot reservoir, while the irreversible cycle discharges Q'_H . Using Eq. 5.13, show that $W_I > W_R$ and $Q'_H > Q_H$.

5.91 Using Eq. 5.13, complete the following involving reversible and irreversible cycles:

- (a) Reversible and irreversible *power cycles* each discharge energy Q_C to a cold reservoir at temperature T_C and receive energy Q_H from hot reservoirs at temperatures T_H and T'_H ,

respectively. There are no other heat transfers. Show that $T'_H > T_H$.

(b) Reversible and irreversible *refrigeration* cycles each discharge energy Q_H to a hot reservoir at temperature T_H and receive energy Q_C from cold reservoirs at temperatures T_C and T'_C , respectively. There are no other heat transfers. Show that $T'_C > T_C$.

(c) Reversible and irreversible *heat pump* cycles each receive energy Q_C from a cold reservoir at temperature T_C and discharge energy Q_H to hot reservoirs at temperatures T_H and T'_H , respectively. There are no other heat transfers. Show that $T'_H < T_H$.

- 5.92** Figure P5.92 shows a system consisting of a power cycle driving a heat pump. At steady state, the power cycle receives \dot{Q}_s by heat transfer at T_s from the high-temperature source and delivers \dot{Q}_1 to a dwelling at T_d . The heat pump receives \dot{Q}_0 from the outdoors at T_0 , and delivers \dot{Q}_2 to the dwelling. Using Eq. 5.13 on a time rate basis, obtain an expression for the maximum theoretical value of the performance parameter $(\dot{Q}_1 + \dot{Q}_2)/\dot{Q}_s$ in terms of the temperature ratios T_s/T_d and T_0/T_d .

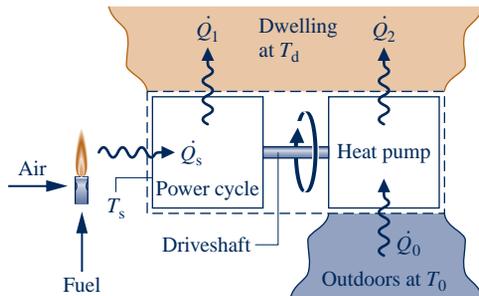


Fig. P5.92

Reviewing Concepts

- 5.93** Answer the following true or false. Explain.

(a) The maximum thermal efficiency of *any* power cycle operating between hot and cold thermal reservoirs at 1000°C and 500°C , respectively, is 50%.

(b) A process of a closed system that violates the second law of thermodynamics necessarily violates the first law of thermodynamics.

(c) One statement of the second law of thermodynamics recognizes that the extensive property entropy is *produced* within systems whenever friction and other nonidealities are present there.

(d) In principle, the *Clausius inequality* is applicable to *any* thermodynamic cycle.

(e) When a net amount of work is done on a system undergoing an internally reversible process, a net heat transfer from the system necessarily occurs.

- 5.94** Answer the following true or false. Explain.

(a) The Kelvin scale is the only absolute temperature scale.

(b) In certain instances, domestic refrigerators violate the *Clausius* statement of the second law of thermodynamics.

(c) Friction associated with flow of fluids through channels and around objects is one type of *irreversibility*.

(d) A product website claims that a heat pump capable of maintaining a dwelling at 70°F on a day when the outside temperature is 32°F has a coefficient of performance of 3.5. Still, such a claim is *not* in accord the second law of thermodynamics.

(e) There are no irreversibilities within a system undergoing an *internally reversible process*.

- 5.95** Answer the following true or false. Explain.

(a) The *second Carnot corollary* states that all power cycles operating between the same two thermal reservoirs have the same thermal efficiency.

(b) When left alone, systems tend to undergo spontaneous changes until equilibrium is attained, both internally and with their surroundings.

(c) Internally reversible processes do not actually occur but serve as hypothetical limiting cases as internal irreversibilities are reduced further and further.

(d) The energy of an *isolated* system remains constant, but its entropy can only decrease.

(e) The maximum coefficient of performance of *any* refrigeration cycle operating between cold and hot reservoirs at 40°F and 80°F , respectively, is closely 12.5.

► DESIGN & OPEN-ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE

5.1D The second law of thermodynamics is sometimes cited in publications of disciplines far removed from engineering and science, including but not limited to philosophy, economics, and sociology. Investigate use of the second law in peer-reviewed nontechnical publications. For three such publications, each in different disciplines, write a three-page critique. For each publication, identify and comment on the key objectives and conclusions. Clearly explain how the second law is used to inform the reader and propel the presentation. Score each publication on a 10-point scale, with 10 denoting a highly effective use of the second law and 1 denoting an ineffective use. Provide a rationale for each score.

5.2D The U.S. Food and Drug Administration (FDA) has long permitted the application of citric acid, ascorbic acid, and other substances to keep fresh meat looking red longer. In 2002, the FDA began allowing meat to be treated with carbon monoxide. Carbon monoxide reacts with *myoglobin* in the meat to produce a substance that resists the natural browning of meat, thereby giving meat a longer shelf life. Investigate the use of carbon monoxide for this purpose. Identify the nature of myoglobin and explain its role in the reactions that cause meat to brown or, when treated with carbon monoxide, allows the meat to appear red longer. Consider the hazards, if any, that may accompany this practice for consumers and for meat industry workers. Report your findings in a memorandum.

5.3D Investigate adverse health conditions that might be exacerbated for persons living in urban *heat islands*. Write a report including at least three references.

5.4D For a refrigerator in your home, dormitory, or workplace, use a plug-in appliance load tester (Fig. P5.4D) to determine the appliance's power requirements, in kW. Estimate *annual* electrical usage for the refrigerator, in kW · h. Compare your estimate of annual electricity use with that for the same or a similar refrigerator posted on the ENERGY STAR® website. Rationalize any significant discrepancy between these values. Prepare a poster presentation detailing your methodologies and findings.

5.5D The objective of this project is to identify a commercially available heat pump system that will meet annual heating and cooling needs of an existing dwelling in a locale of your choice. Consider each of two types of heat pump: air source and ground source. Estimate installation costs, operating costs, and other pertinent costs for each type of heat pump. Assuming a 12-year life, specify the more economical heat pump system. What if electricity were to cost twice its current cost? Prepare a poster presentation of your findings.

5.6D Insulin and several other pharmaceuticals required daily by those suffering from diabetes and other medical conditions have relatively low thermal stability. Those living and traveling in hot climates are especially at risk by heat-induced loss of potency of their pharmaceuticals. Design a wearable, lightweight, and reliable cooler for transporting temperature-sensitive pharmaceuticals. The cooler also must be solely powered by human motion. While the long-term goal is a moderately-priced consumer product, the final project report need only provide the costing of a single prototype.

5.7D Over the years, claimed *perpetual motion* machines have been rejected because they violate physical laws, primarily the first or second laws of thermodynamics, or both. Yet, while skepticism is deeply ingrained about perpetual motion, the *ATMOS* clock is said to enjoy a nearly unlimited operational service life, and advertisements characterize it as a *perpetual motion clock*. Investigate how the *ATMOS* operates. Provide a complete explanation of its operation, including sketches and references to the first and second laws, as appropriate. Clearly establish whether the *ATMOS* can justifiably be called a perpetual motion machine, closely approximates one, or only appears to be one. Prepare a memorandum summarizing your findings.

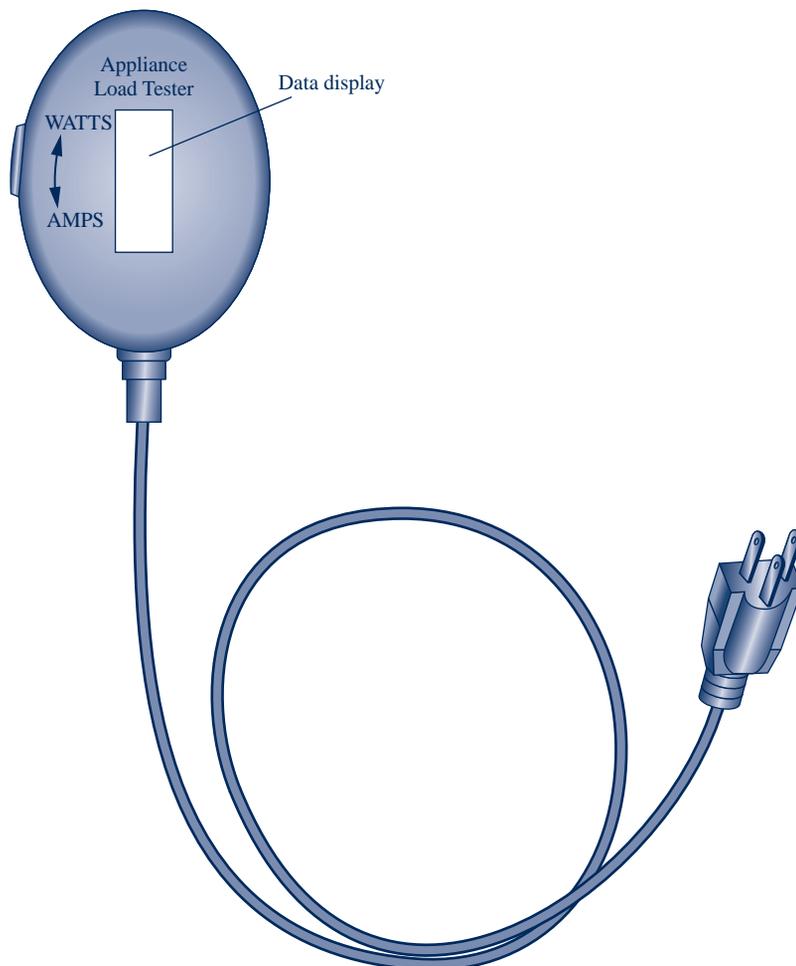


Fig. P5.4D