–evaluating isentropic efficiencies for turbines, nozzles, compressors, and pumps from Eqs. 6.46, 6.47, and 6.48, respectively, including for ideal gases the appropriate use of Eqs. 6.41–6.42 for variable specific heats and Eqs. 6.43–6.45 for constant specific heats.

▶ apply Eq. 6.23 for closed systems and Eqs. 6.49 and 6.51 for one-inlet, one-exit control volumes at steady state, correctly observing the restriction to internally reversible processes.

▶ KEY ENGINEERING CONCEPTS

entropy change, p. 282	isentropic process, p. 292	entropy rate balance, pp. 301, 307
T–s diagram, p. 285	entropy transfer, pp. 292, 307	increase in entropy principle, p. 303
Mollier diagram, p. 286	entropy balance, p. 295	isentropic efficiencies, pp. 323, 325, 328
T ds equations, p. 287	entropy production, p. 296	

▶ KEY EQUATIONS

$$S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_b + \sigma$$

(6.24) p. 295 — Closed system entropy balance.

$$\frac{dS}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \dot{\sigma}$$

(6.28) p. 301 — Closed system entropy rate balance.

$$\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{\sigma}_{cv}$$

(6.34) p. 307 — Control volume entropy rate balance.

$$0 = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{\sigma}_{cv}$$

(6.36) p. 308 — Steady-state control volume entropy rate balance.

$$\eta_t = \frac{\dot{W}_{cv}/\dot{m}}{(\dot{W}_{cv}/\dot{m})_s} = \frac{h_1 - h_2}{h_1 - h_{2s}}$$

(6.46) p. 323 — Isentropic turbine efficiency.

$$\eta_{nozzle} = \frac{V_2^2/2}{(V_2^2/2)_s}$$

(6.47) p. 325 — Isentropic nozzle efficiency.

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

(6.48) p. 328 — Isentropic compressor (and pump) efficiency.

Ideal Gas Model Relations

$$s(T_2, v_2) - s(T_1, v_1) = \int_{T_1}^{T_2} c_v(T)\frac{dT}{T} + R \ln \frac{v_2}{v_1}$$

(6.17) p. 289 — Change in specific entropy; general form for T and v as independent properties.

$$s(T_2, v_2) - s(T_1, v_1) = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$

(6.21) p. 291 — Constant specific heat, c_v.

$$s(T_2, p_2) - s(T_1, p_1) = \int_{T_1}^{T_2} c_p(T)\frac{dT}{T} - R \ln \frac{p_2}{p_1}$$

(6.18) p. 289 — Change in specific entropy; general form for T and p as independent properties.

$$s(T_2, p_2) - s(T_1, p_1) = s°(T_2) - s°(T_1) - R \ln \frac{p_2}{p_1}$$

(6.20a) p. 290 — $s°$ for air from Table A-22. ($\bar{s}°$ for other gases from Table A-23).

$$s(T_2, p_2) - s(T_1, p_1) = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$

(6.22) p. 291 — Constant specific heat, c_p.

|		
$$\frac{p_2}{p_1} = \frac{p_{r2}}{p_{r1}}$$	**(6.41) p. 317**	
$$\frac{v_2}{v_1} = \frac{v_{r2}}{v_{r1}}$$	**(6.42) p. 318**	$s_1 = s_2$ (air only), p_r and v_r from Table A-22.
$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(k-1)/k}$$	**(6.43) p. 318**	
$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$$	**(6.44) p. 318**	$s_1 = s_2$, constant specific heat ratio k.
$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^{k}$$	**(6.45) p. 318**	

▶ EXERCISES: THINGS ENGINEERS THINK ABOUT

1. Is it possible for entropy *change* to be negative? For entropy *production* to be negative?

2. By what means can entropy be transferred across the boundary of a closed system? Across the boundary of a control volume?

3. Is it possible for the entropy of *both* a closed system and its surroundings to *decrease* during a process? Both to *increase* during a process?

4. What happens to the entropy produced within an insulated, one-inlet, one-exit control volume operating at steady state?

5. The two power cycles shown to the same scale in the figure are composed of internally reversible processes of a closed system. Compare the net work developed by these cycles. Which cycle has the greater thermal efficiency? Explain.

6. Can adiabatic mixing of two substances result in decreased entropy? Explain.

7. Is entropy produced within a system undergoing a *Carnot* cycle? Explain.

8. When a mixture of olive oil and vinegar *spontaneously* separates into two liquid phases, is the second law violated? Explain.

9. A magician claims that simply with a wave of her magic wand a cup of water, initially at room temperature, will be raised in temperature several degrees by quickly picking up energy from its surroundings. Is this possible? Explain.

10. How does the *Bernoulli* equation reduce to give the form used in the bat BIOCONNECTIONS discussion of Sec. 6.13.2?
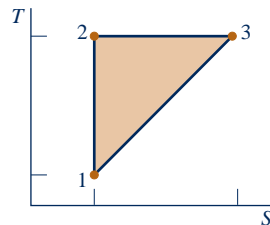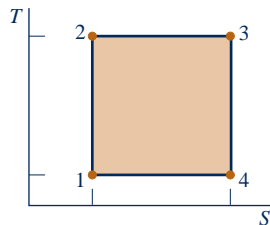
11. Is Eq. 6.51a restricted to adiabatic processes and thus to isentropic processes? Explain.

12. Using Eq. 6.51c, what data are required to determine the *actual* power input of a basement sump pump?

13. What *is* the ENERGY STAR® program?

▶ PROBLEMS: DEVELOPING ENGINEERING SKILLS

Using Entropy Data and Concepts

6.1 Using the tables for water, determine the specific entropy at the indicated states, in kJ/kg · K. In each case, locate the state by hand on a sketch of the *T–s* diagram.

(a) $p = 5.0$ MPa, $T = 400°C$.
(b) $p = 5.0$ MPa, $T = 100°C$.
(c) $p = 5.0$ MPa, $u = 1872.5$ kJ/kg.
(d) $p = 5.0$ MPa, saturated vapor.

6.2 Using the tables for water, determine the specific entropy at the indicated states, in Btu/lb · °R In each case, locate the state by hand on a sketch of the *T–s* diagram.

(a) $p = 1000$ lbf/in.^{2}, $T = 750°F$.
(b) $p = 1000$ lbf/in.^{2}, $T = 300°F$.
(c) $p = 1000$ lbf/in.^{2}, $h = 932.4$ Btu/lb.
(d) $p = 1000$ lbf/in.^{2}, saturated vapor.

6.3 Using the appropriate table, determine the indicated property. In each case, locate the state by hand on sketches of the T–v and T–s diagrams.

(a) water at $p = 0.20$ bar, $s = 4.3703$ kJ/kg · K. Find h, in kJ/kg.

(b) water at $p = 10$ bar, $u = 3124.4$ kJ/kg. Find s, in kJ/kg · K.

(c) Refrigerant 134a at $T = -28°C$, $x = 0.8$. Find s, in kJ/kg · K.

(d) ammonia at $T = 20°C$, $s = 5.0849$ kJ/kg · K. Find u, in kJ/kg.

6.4 Using the appropriate table, determine the change in specific entropy between the specified states, in Btu/lb · °R.

(a) water, $p_1 = 1000$ lbf/in.^{2}, $T_1 = 800°F$, $p_2 = 1000$ lbf/in.^{2}, $T_2 = 100°F$.

(b) Refrigerant 134a, $h_1 = 47.91$ Btu/lb, $T_1 = -40°F$, saturated vapor at $p_2 = 40$ lbf/in.^{2}

(c) air as an ideal gas, $T_1 = 40°F$, $p_1 = 2$ atm, $T_2 = 420°F$, $p_2 = 1$ atm.

(d) carbon dioxide as an ideal gas, $T_1 = 820°F$, $p_1 = 1$ atm, $T_2 = 77°F$, $p_2 = 3$ atm.

6.5 Using IT, determine the specific entropy of water at the indicated states. Compare with results obtained from the appropriate table.

(a) Specific entropy, in kJ/kg · K, for the cases of Problem 6.1.

(b) Specific entropy, in Btu/lb · °R, for the cases of Problem 6.2.

6.6 Using IT, repeat Prob. 6.4. Compare the results obtained using IT with those obtained using the appropriate table.

6.7 Using *steam table* data, determine the indicated property data for a process in which there is no change in specific entropy between state 1 and state 2. In each case, locate the states on a sketch of the T–s diagram.

(a) $T_1 = 40°C$, $x_1 = 100\%$, $p_2 = 150$ kPa. Find T_2, in °C, and Δh, in kJ/kg.

(b) $T_1 = 10°C$, $x_1 = 75\%$, $p_2 = 1$ MPa. Find T_2, in °C, and Δu, in kJ/kg.

6.8 Using the appropriate table, determine the indicated property for a process in which there is no change in specific entropy between state 1 and state 2.

(a) water, $p_1 = 14.7$ lbf/in.^{2}, $T_1 = 500°F$, $p_2 = 100$ lbf/in.^{2} Find T_2 in °F.

(b) water, $T_1 = 10°C$, $x_1 = 0.75$, saturated vapor at state 2. Find p_2 in bar.

(c) air as an ideal gas, $T_1 = 27°C$, $p_1 = 1.5$ bar, $T_2 = 127°C$. Find p_2 in bar.

(d) air as an ideal gas, $T_1 = 100°F$, $p_1 = 3$ atm, $p_2 = 2$ atm. Find T_2 in °F.

(e) Refrigerant 134a, $T_1 = 20°C$, $p_1 = 5$ bar, $p_2 = 1$ bar. Find v_2 in m^3/kg.

6.9 Using IT, obtain the property data requested in (a) Problem 6.7, (b) Problem 6.8, and compare with data obtained from the appropriate table.

6.10 Propane undergoes a process from state 1, where $p_1 = 1.4$ MPa, $T_1 = 60°C$, to state 2, where $p_2 = 1.0$ MPa, during which the change in specific entropy is $s_2 - s_1 = -0.035$ kJ/kg · K. At state 2, determine the temperature, in °C, and the specific enthalpy, in kJ/kg.

6.11 Air in a piston–cylinder assembly undergoes a process from state 1, where $T_1 = 300$ K, $p_1 = 100$ kPa, to state 2, where $T_2 = 500$ K, $p_2 = 650$ kPa. Using the ideal gas model for air, determine the change in specific entropy between these states, in kJ/kg · K, if the process occurs (a) without internal irreversibilities, (b) with internal irreversibilities.

6.12 Water contained in a closed, rigid tank, initially at 100 lbf/in.^{2}, 800°F, is cooled to a final state where the pressure is 20 lbf/in.^{2} Determine the change in specific entropy, in Btu/lb · °R, and show the process on sketches of the T–v and T–s diagrams.

6.13 One-quarter lbmol of nitrogen gas (N$_2$) undergoes a process from $p_1 = 20$ lbf/in.^{2}, $T_1 = 500°R$ to $p_2 = 150$ lbf/in.^{2} For the process $W = -500$ Btu and $Q = -125.9$ Btu. Employing the ideal gas model, determine

(a) T_2, in °R.

(b) the change in entropy, in Btu/°R.

Show the initial and final states on a T–s diagram.

6.14 One kilogram of water contained in a piston–cylinder assembly, initially at 160°C, 150 kPa, undergoes an isothermal compression process to saturated liquid. For the process, $W = -471.5$ kJ. Determine for the process,

(a) the heat transfer, in kJ.

(b) the change in entropy, in kJ/K.

Show the process on a sketch of the T–s diagram.

6.15 One-tenth kmol of carbon monoxide (CO) in a piston–cylinder assembly undergoes a process from $p_1 = 150$ kPa, $T_1 = 300$ K to $p_2 = 500$ kPa, $T_2 = 370$ K. For the process, $W = -300$ kJ. Employing the ideal gas model, determine

(a) the heat transfer, in kJ.

(b) the change in entropy, in kJ/K.

Show the process on a sketch of the T–s diagram.

6.16 Argon in a piston–cylinder assembly is compressed from state 1, where $T_1 = 300$ K, $V_1 = 1$ m^3, to state 2, where $T_2 = 200$ K. If the change in specific entropy is $s_2 - s_1 = -0.27$ kJ/kg · K, determine the final volume, in m^3. Assume the ideal gas model with $k = 1.67$.

6.17 Steam enters a turbine operating at steady state at 1 MPa, 200°C and exits at 40°C with a quality of 83%. Stray heat transfer and kinetic and potential energy effects are negligible. Determine (a) the power developed by the turbine, in kJ per kg of steam flowing, (b) the change in specific entropy from inlet to exit, in kJ/K per kg of steam flowing.

6.18 Answer the following true or false. Explain.

(a) The change of entropy of a closed system is the same for every process between two specified states.

(b) The entropy of a fixed amount of an ideal gas increases in every isothermal compression.

(c) The specific internal energy and enthalpy of an ideal gas are each functions of temperature alone but its specific entropy depends on two independent intensive properties.
(d) One of the $T\,ds$ equations has the form $T\,ds = du - p\,dv$.
(e) The entropy of a fixed amount of an incompressible substance increases in every process in which temperature decreases.

6.19 Showing all steps, derive Eqs. 6.43, 6.44, and 6.45.

Analyzing Internally Reversible Processes

6.20 One kilogram of water in a piston–cylinder assembly undergoes the two internally reversible processes in series shown in Fig. P6.20. For each process, determine, in kJ, the heat transfer and the work.

Fig. P6.20

6.21 One kilogram of water in a piston–cylinder assembly undergoes the two internally reversible processes in series shown in Fig. P6.21. For each process, determine, in kJ, the heat transfer and the work.
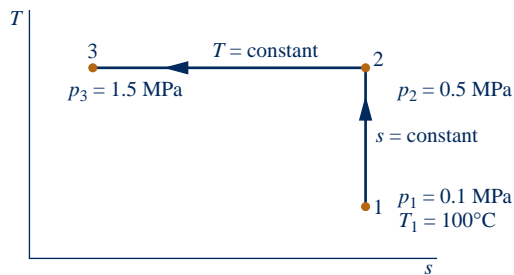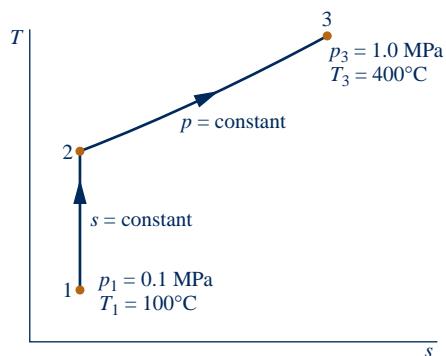

Fig. P6.21

6.22 One kilogram of water in a piston–cylinder assembly, initially at 160°C, 1.5 bar, undergoes an isothermal, internally reversible compression process to the saturated liquid state. Determine the work and heat transfer, each in kJ. Sketch the process on p–v and T–s coordinates. Associate the work and heat transfer with areas on these diagrams.

6.23 One pound mass of water in a piston–cylinder assembly, initially a saturated liquid at 1 atm, undergoes a constant-pressure, internally reversible expansion to $x = 90\%$. Determine the work and heat transfer, each in Btu. Sketch the process on p–v and T–s coordinates. Associate the work and heat transfer with areas on these diagrams.

6.24 A gas within a piston–cylinder assembly undergoes an isothermal process at 400 K during which the change in entropy is -0.3 kJ/K. Assuming the ideal gas model for the gas and negligible kinetic and potential energy effects, evaluate the work, in kJ.

6.25 Water within a piston–cylinder assembly, initially at 10 lbf/in.^{2}, 500°F, undergoes an internally reversible process to 80 lbf/in.^{2}, 800°F, during which the temperature varies linearly with specific entropy. For the water, determine the work and heat transfer, each in Btu/lb. Neglect kinetic and potential energy effects.

6.26 Nitrogen (N_2) initially occupying 0.1 m^3 at 6 bar, 247°C undergoes an internally reversible expansion during which $pV^{1.20} = constant$ to a final state where the temperature is 37°C. Assuming the ideal gas model, determine

(a) the pressure at the final state, in bar.
(b) the work and heat transfer, each in kJ.
(c) the entropy change, in kJ/K.

6.27 Air in a piston–cylinder assembly and modeled as an ideal gas undergoes two internally reversible processes in series from state 1, where $T_1 = 290$ K, $p_1 = 1$ bar.

Process 1–2: Compression to $p_2 = 5$ bar during which $pV^{1.19} = constant$.

Process 2–3: Isentropic expansion to $p_3 = 1$ bar.

(a) Sketch the two processes in series on T–s coordinates.
(b) Determine the temperature at state 2, in K.
(c) Determine the net work, in kJ/kg.

6.28 One lb of oxygen, O_2, in a piston–cylinder assembly undergoes a cycle consisting of the following processes:

Process 1–2: Constant-pressure expansion from $T_1 = 450$°R, $p_1 = 30$ lbf/in.^{2} to $T_2 = 1120$°R.

Process 2–3: Compression to $T_3 = 800$°R and $p_3 = 53.3$ lbf/in.^{2} with $Q_{23} = -60$ Btu.

Process 3–1: Constant-volume cooling to state 1.

Employing the ideal gas model with c_p evaluated at T_1, determine the change in specific entropy, in Btu/lb · °R, for each process. Sketch the cycle on p–v and T–s coordinates.

6.29 One-tenth kilogram of a gas in a piston–cylinder assembly undergoes a Carnot power cycle for which the isothermal expansion occurs at 800 K. The change in specific entropy of the gas during the isothermal compression, which occurs at 400 K, is -25 kJ/kg · K. Determine (a) the net work developed per cycle, in kJ, and (b) the thermal efficiency.

6.30 Figure P6.30 provides the T–s diagram of a Carnot refrigeration cycle for which the substance is Refrigerant 134a. Determine the coefficient of performance.
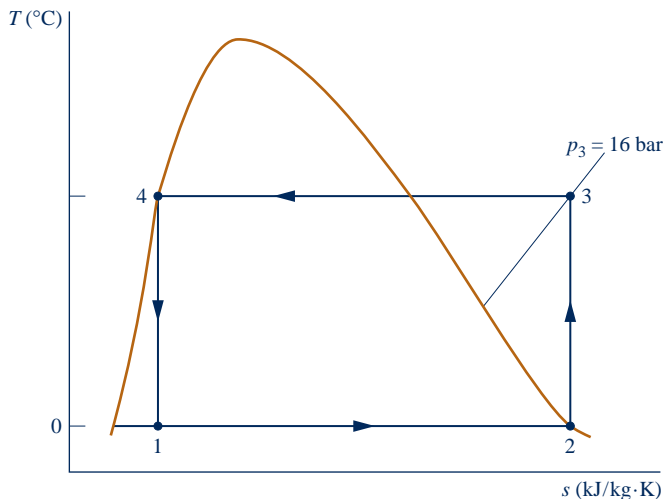

Fig. P6.30

6.31 Figure P6.31 provides the T–s diagram of a Carnot heat pump cycle for which the substance is ammonia. Determine the net work input required, in kJ, for 50 cycles of operation and 0.1 kg of substance.
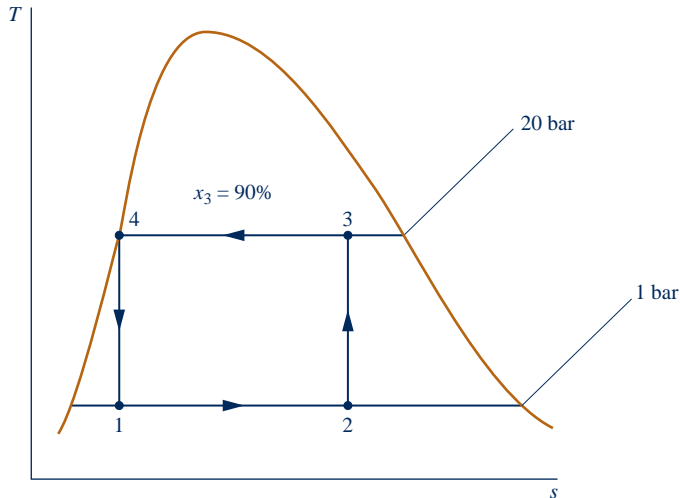

Fig. P6.31

6.32 Air in a piston–cylinder assembly undergoes a Carnot power cycle. The isothermal expansion and compression processes occur at 1400 K and 350 K, respectively. The pressures at the beginning and end of the isothermal compression are 100 kPa and 500 kPa, respectively. Assuming the ideal gas model with $c_p = 1.005$ kJ/kg · K, determine

(a) the pressures at the beginning and end of the isothermal expansion, each in kPa.
(b) the heat transfer and work, in kJ/kg, for each process.
(c) the thermal efficiency.

6.33 Water in a piston–cylinder assembly undergoes a Carnot power cycle. At the beginning of the isothermal expansion, the temperature is 250°C and the quality is 80%. The isothermal expansion continues until the pressure is 2 MPa. The adiabatic expansion then occurs to a final temperature of 175°C.

(a) Sketch the cycle on T–s coordinates.
(b) Determine the heat transfer and work, in kJ/kg, for each process.
(c) Evaluate the thermal efficiency.

6.34 A Carnot power cycle operates at steady state as shown in Fig. 5.15 with water as the working fluid. The boiler pressure is 200 lbf/in.^{2}, with saturated liquid entering and saturated vapor exiting. The condenser pressure is 20 lbf/in.^{2}
(a) Sketch the cycle on T–s coordinates.
(b) Determine the heat transfer and work for each process, in Btu per lb of water flowing.
(c) Evaluate the thermal efficiency.

6.35 Figure P6.35 shows a Carnot heat pump cycle operating at steady state with ammonia as the working fluid. The condenser temperature is 120°F, with saturated vapor entering and saturated liquid exiting. The evaporator temperature is 10°F.

(a) Determine the heat transfer and work for each process, in Btu per lb of ammonia flowing.
(b) Evaluate the coefficient of performance for the heat pump.
(c) Evaluate the coefficient of performance for a Carnot refrigeration cycle operating as shown in the figure.

Applying the Entropy Balance: Closed Systems

6.36 A closed system undergoes a process in which work is done on the system and the heat transfer Q occurs only at temperature T_b. For each case, determine whether the entropy change of the system is positive, negative, zero, or indeterminate.

(a) internally reversible process, $Q > 0$.
(b) internally reversible process, $Q = 0$.
(c) internally reversible process, $Q < 0$.
(d) internal irreversibilities present, $Q > 0$.
(e) internal irreversibilities present, $Q = 0$.
(f) internal irreversibilities present, $Q < 0$.

6.37 Answer the following true or false. Explain.

(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) One corollary of the second law of thermodynamics states that the change in entropy of a closed system must be greater than zero or equal to zero.
(d) A closed system can experience an increase in entropy only when irreversibilities are present within the system during the process.
(e) Entropy is produced in every internally reversible process of a closed system.
(f) In an adiabatic and internally reversible process of a closed system, the entropy remains constant.
(g) The energy of an isolated system must remain constant, but the entropy can only decrease.
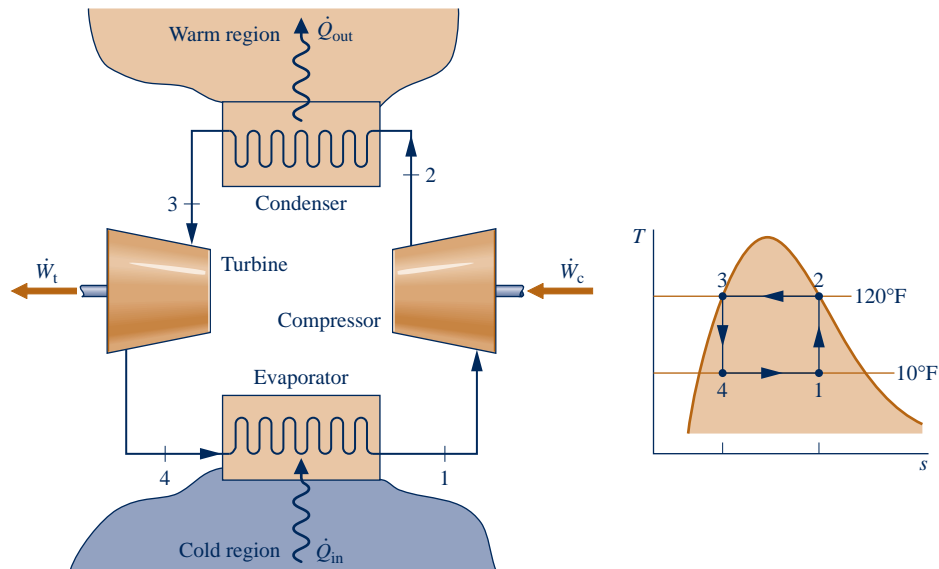
Fig. P6.35

6.38 One lb of water contained in a piston–cylinder assembly, initially saturated vapor at 1 atm, is condensed at constant pressure to saturated liquid. Evaluate the heat transfer, in Btu, and the entropy production, in Btu/°R, for

(a) the water as the system.
(b) an enlarged system consisting of the water and enough of the nearby surroundings that heat transfer occurs only at the ambient temperature, 80°F.

Assume the state of the nearby surroundings does not change during the process of the water, and ignore kinetic and potential energy.

6.39 Five kg of water contained in a piston–cylinder assembly expand from an initial state where $T_1 = 400$°C, $p_1 = 700$ kPa to a final state where $T_2 = 200$°C, $p_2 = 300$ kPa, with no significant effects of kinetic and potential energy. The accompanying table provides additional data at the two states. It is claimed that the water undergoes an adiabatic process between these states, while developing work. Evaluate this claim.

State	T(°C)	p(kPa)	v(m³/kg)	u(kJ/kg)	h(kJ/kg)	s(kJ/kg · K)
1	400	700	0.4397	2960.9	3268.7	7.6350
2	200	300	0.7160	2650.7	2865.5	7.3115

6.40 Two m³ of air in a rigid, insulated container fitted with a paddle wheel is initially at 293 K, 200 kPa. The air receives 710 kJ by work from the paddle wheel. Assuming the ideal gas model with $c_v = 0.72$ kJ/kg · K, determine for the air (a) the mass, in kg, (b) final temperature, in K, and (c) the amount of entropy produced, in kJ/K.

6.41 Air contained in a rigid, insulated tank fitted with a paddle wheel, initially at 1 bar, 330 K and a volume of 1.93 m³, receives an energy transfer by work from the paddle wheel in an amount of 400 kJ. Assuming the ideal gas model for the air, determine (a) the final temperature, in K, (b) the final

pressure, in bar, and (c) the amount of entropy produced, in kJ/K. Ignore kinetic and potential energy.

6.42 Air contained in a rigid, insulated tank fitted with a paddle wheel, initially at 4 bar, 40°C and a volume of 0.2 m³, is stirred until its temperature is 353°C. Assuming the ideal gas model with $k = 1.4$ for the air, determine (a) the final pressure, in bar, (b) the work, in kJ, and (c) the amount of entropy produced, in kJ/K. Ignore kinetic and potential energy.

6.43 Air contained in a rigid, insulated tank fitted with a paddle wheel, initially at 300 K, 2 bar, and a volume of 2 m³, is stirred until its temperature is 500 K. Assuming the ideal gas model for the air, and ignoring kinetic and potential energy, determine (a) the final pressure, in bar, (b) the work, in kJ, and (c) the amount of entropy produced, in kJ/K. Solve using

(a) data from Table A-22.
(b) constant c_v read from Table A-20 at 400 K.

Compare the results of parts (a) and (b).

6.44 A rigid, insulated container fitted with a paddle wheel contains 5 lb of water, initially at 260°F and a quality of 60%. The water is stirred until the temperature is 350°F. For the water, determine (a) the work, in Btu, and (b) the amount of entropy produced, in Btu/°R.

6.45 Two kilograms of air contained in a piston–cylinder assembly are initially at 1.5 bar and 400 K. Can a final state at 6 bar and 500 K be attained in an adiabatic process?

6.46 One pound mass of Refrigerant 134a contained within a piston–cylinder assembly undergoes a process from a state where the temperature is 60°F and the refrigerant is saturated liquid to a state where the pressure is 140 lbf/in.² and quality is 50%. Determine the change in specific entropy of the refrigerant, in Btu/lb · °R. Can this process be accomplished adiabatically?

6.47 Refrigerant 134a contained in a piston–cylinder assembly rapidly expands from an initial state where $T_1 = 140°F$, $p_1 = 200$ lbf/in.^{2} to a final state where $p_2 = 5$ lbf/in.^{2} and the quality, x_2, is (a) 99%, (b) 95%. In each case, determine if the process can occur adiabatically. If yes, determine the work, in Btu/lb, for an adiabatic expansion between these states. If no, determine the direction of the heat transfer.

6.48 One kg of air contained in a piston–cylinder assembly undergoes a process from an initial state where $T_1 = 300$ K, $v_1 = 0.8$ m^3/kg to a final state where $T_2 = 420$ K, $v_2 = 0.2$ m^3/kg. Can this process occur adiabatically? If yes, determine the work, in kJ, for an adiabatic process between these states. If no, determine the direction of the heat transfer. Assume the ideal gas model for air.

6.49 Air as an ideal gas contained within a piston–cylinder assembly is compressed between two specified states. In each of the following cases, can the process occur adiabatically? If yes, determine the work in appropriate units for an adiabatic process between these states. If no, determine the direction of the heat transfer.

(a) State 1: $p_1 = 0.1$ MPa, $T_1 = 27°C$. State 2: $p_2 = 0.5$ MPa, $T_2 = 207°C$. Use Table A-22 data.
(b) State 1: $p_1 = 3$ atm, $T_1 = 80°F$ State 2: $p_2 = 10$ atm, $T_2 = 240°F$. Assume $c_p = 0.241$ Btu/lb°R.

6.50 One kilogram of propane initially at 8 bar and 50°C undergoes a process to 3 bar, 20°C while being rapidly expanded in a piston–cylinder assembly. Heat transfer between the propane and its surroundings occurs at an average temperature of 35°C. The work done by the propane is measured as 42.4 kJ. Kinetic and potential energy effects can be ignored. Determine whether it is possible for the work measurement to be correct.

6.51 As shown in Fig. P6.51, a divider separates 1 lb mass of carbon monoxide (CO) from a thermal reservoir at 150°F. The carbon monoxide, initially at 60°F and 150 lbf/in.^{2}, expands isothermally to a final pressure of 10 lbf/in.^{2} while receiving heat transfer through the divider from the reservoir. The carbon monoxide can be modeled as an ideal gas.

(a) For the carbon monoxide as the system, evaluate the work and heat transfer, each in Btu, and the amount of entropy produced, in Btu/°R.

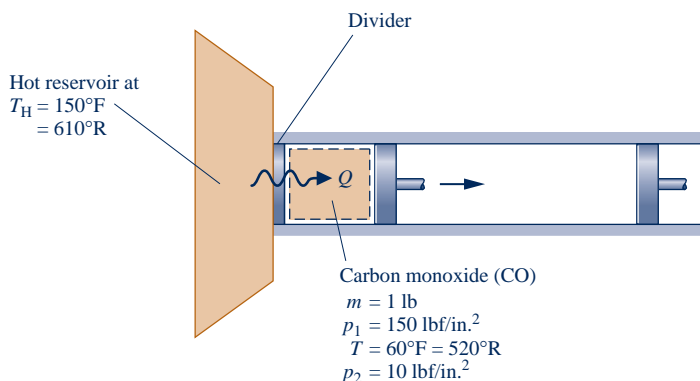(b) Evaluate the entropy production, in Btu/°R, for an enlarged system that includes the carbon monoxide and the divider, assuming the state of the divider remains unchanged. Compare with the entropy production of part (a) and comment on the difference.

6.52 Three kilograms of Refrigerant 134a initially a saturated vapor at 20°C expand to 3.2 bar, 20°C. During this process, the temperature of the refrigerant departs by no more than 0.01°C from 20°C. Determine the maximum theoretical heat transfer to the refrigerant during the process, in kJ.

6.53 An inventor claims that the device shown in Fig. P6.53 generates electricity while receiving a heat transfer at the rate of 250 Btu/s at a temperature of 500°R, a second heat transfer at the rate of 350 Btu/s at 700°R, and a third at the rate of 500 Btu/s at 1000°R. For operation at steady state, evaluate this claim.
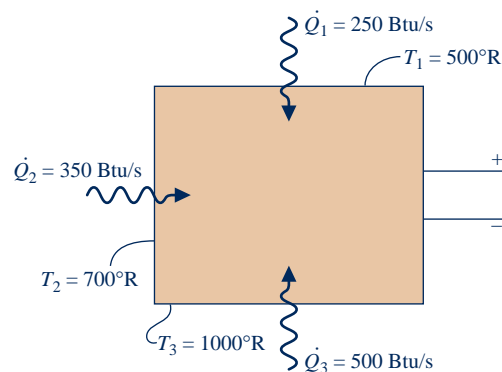

Fig. P6.53

6.54 For the silicon chip of Example 2.5, determine the rate of entropy production, in kW/K. What is the cause of entropy production in this case?

6.55 At steady state, the 20-W curling iron shown in Fig. P6.55 has an outer surface temperature of 180°F. For the curling iron, determine the rate of heat transfer, in Btu/h, and the rate of entropy production, in Btu/h · °R.

6.56 A rigid, insulated vessel is divided into two compartments connected by a valve. Initially, one compartment, occupying one-third of the total volume, contains air at 500°R, and the other is evacuated. The valve is opened and the air is allowed to fill the entire volume. Assuming the ideal gas model, determine the final temperature of the air, in °R, and the amount of entropy produced, in Btu/°R per lb of air.

6.57 A rigid, insulated vessel is divided into two equal-volume compartments connected by a valve. Initially, one compartment contains 1 m^3 of water at 20°C, $x = 50\%$, and the other is evacuated. The valve is opened and the water is allowed to fill the entire volume. For the water, determine the final temperature, in °C, and the amount of entropy produced, in kJ/K.

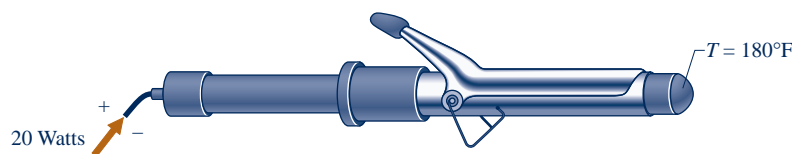**Fig. P6.51**

$T = 180°F$

20 Watts

Fig. P6.55

6.58 An electric motor at steady state draws a current of 10 amp with a voltage of 110 V. The output shaft develops a torque of 10.2 N · m and a rotational speed of 1000 RPM.

(a) If the outer surface of the motor is at 42°C, determine the rate of entropy production within the motor, in kW/K.
(b) Evaluate the rate of entropy production, in kW/K, for an enlarged system that includes the motor and enough of the nearby surroundings that heat transfer occurs at the ambient temperature, 22°C.

6.59 A power plant has a turbogenerator, shown in Fig. P6.59, operating at steady state with an input shaft rotating at 1800 RPM with a torque of 16,700 N · m. The turbogenerator produces current at 230 amp with a voltage of 13,000 V. The rate of heat transfer between the turbogenerator and its surroundings is related to the surface temperature T_b and the lower ambient temperature T_0, and is given by $\dot{Q} = -hA(T_b - T_0)$, where h = 110 W/m² · K, A = 32 m², and T_0 = 298 K.

(a) Determine the temperature T_b, in K.
(b) For the turbogenerator as the system, determine the rate of entropy production, in kW/K.
(c) If the system boundary is located to take in enough of the nearby surroundings for heat transfer to take place at temperature T_0, determine the rate of entropy production, in kW/K, for the enlarged system.

6.60 At steady state, work is done by a paddle wheel on a *slurry* contained within a closed, rigid tank whose outer surface temperature is 245°C. Heat transfer from the tank and its contents occurs at a rate of 50 kW to surroundings that, away from the immediate vicinity of the tank, are at 27°C. Determine the rate of entropy production, in kW/K,

(a) for the tank and its contents as the system.
(b) for an enlarged system including the tank and enough of the nearby surroundings for the heat transfer to occur at 27°C.

6.61 A 33.8-lb aluminum bar, initially at 200°F, is placed in a tank together with 249 lb of liquid water, initially at 70°F, and allowed to achieve thermal equilibrium. The aluminum bar and water can be modeled as incompressible with specific heats 0.216 Btu/lb · °R and 0.998 Btu/lb · °R, respectively. For the aluminum bar and water as the system, determine (a) the final temperature, in °F, and (b) the amount of entropy produced within the tank, in Btu/°R. Ignore heat transfer between the system and its surroundings.

6.62 In a heat-treating process, a 1-kg metal part, initially at 1075 K, is quenched in a tank containing 100 kg of water, initially at 295 K. There is negligible heat transfer between the contents of the tank and their surroundings. The metal part and water can be modeled as incompressible with specific heats 0.5 kJ/kg · K and 4.2 kJ/kg · K, respectively. Determine (a) the final equilibrium temperature after quenching, in K, and (b) the amount of entropy produced within the tank, in kJ/K.

6.63 A 50-lb iron casting, initially at 700°F, is quenched in a tank filled with 2121 lb of oil, initially at 80°F. The iron casting and oil can be modeled as incompressible with specific heats 0.10 Btu/lb · °R, and 0.45 Btu/lb · °R, respectively. For the iron casting and oil as the system, determine (a) the final equilibrium temperature, in °F, and (b) the amount of entropy produced within the tank, in Btu/°R. Ignore heat transfer between the system and its surroundings.

6.64 A 2.64-kg copper part, initially at 400 K, is plunged into a tank containing 4 kg of liquid water, initially at 300 K. The copper part and water can be modeled as incompressible with specific heats 0.385 kJ/kg · K and 4.2 kJ/kg · K, respectively. For the copper part and water as the system, determine (a) the final equilibrium temperature, in K, and (b) the amount of entropy produced within the tank, in kJ/K. Ignore heat transfer between the system and its surroundings.
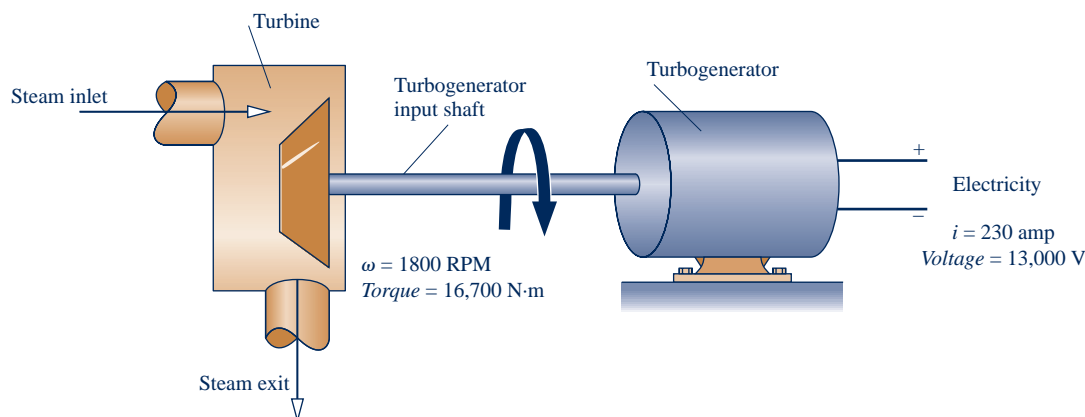

Turbine

Steam inlet

Turbogenerator input shaft

Turbogenerator

Electricity

$i = 230$ amp
Voltage = 13,000 V

$\omega = 1800$ RPM
Torque = 16,700 N·m

Steam exit

Fig. P6.59

6.65 Two insulated tanks are connected by a valve. One tank initially contains 1.2 lb of air at 240°F, 30 psia, and the other contains 1.5 lb of air at 60°F, 14.7 psia. The valve is opened and the two quantities of air are allowed to mix until equilibrium is attained. Employing the ideal gas model with $c_v = 0.18$ Btu/lb · °R determine

(a) the final temperature, in °F.
(b) the final pressure, in psia.
(c) the amount of entropy produced, in Btu/°R.

6.66 As shown in Fig. P6.66, an insulated box is initially divided into halves by a frictionless, thermally conducting piston. On one side of the piston is 1.5 m³ of air at 400 K, 4 bar. On the other side is 1.5 m³ of air at 400 K, 2 bar. The piston is released and equilibrium is attained, with the piston experiencing no change of state. Employing the ideal gas model for the air, determine

(a) the final temperature, in K.
(b) the final pressure, in bar.
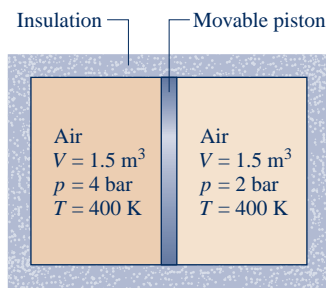(c) the amount of entropy produced, in kJ/kg.

Fig. P6.66

6.67 An insulated vessel is divided into two equal-sized compartments connected by a valve. Initially, one compartment contains steam at 50 lbf/in.² and 700°F, and the other is evacuated. The valve is opened and the steam is allowed to fill the entire volume. Determine

(a) the final temperature, in °F.
(b) the amount of entropy produced, in Btu/lb · °R.

6.68 An insulated, rigid tank is divided into two compartments by a frictionless, thermally conducting piston. One compartment initially contains 1 m³ of saturated water vapor at 4 MPa and the other compartment contains 1 m³ of water vapor at 20 MPa, 800°C. The piston is released and equilibrium is attained, with the piston experiencing no change of state. For the water as the system, determine

(a) the final pressure, in MPa.
(b) the final temperature, in °C.
(c) the amount of entropy produced, in kJ/K.

6.69 A system consisting of air initially at 300 K and 1 bar experiences the two different types of interactions described below. In each case, the system is brought from the initial

state to a state where the temperature is 500 K, while volume remains constant.

(a) The temperature rise is brought about adiabatically by stirring the air with a paddle wheel. Determine the amount of entropy produced, in kJ/kg · K.
(b) The temperature rise is brought about by heat transfer from a reservoir at temperature T. The temperature at the system boundary where heat transfer occurs is also T. Plot the amount of entropy produced, in kJ/kg · K, versus T for $T \geq 500$ K. Compare with the result of (a) and discuss.

6.70 A cylindrical copper rod of base area A and length L is insulated on its lateral surface. One end of the rod is in contact with a wall at temperature T_H. The other end is in contact with a wall at a lower temperature T_C. At steady state, the rate at which energy is conducted into the rod from the hot wall is

$$\dot{Q}_H = \frac{\kappa A(T_H - T_C)}{L}$$

where κ is the thermal conductivity of the copper rod.

(a) For the rod as the system, obtain an expression for the time rate of entropy production in terms of A, L, T_H, T_C, and κ.
(b) If $T_H = 327$°C, $T_C = 77$°C, $\kappa = 0.4$ kW/m · K, A $= 0.1$ m², plot the heat transfer rate $\dot{Q}_H$, in kW, and the time rate of entropy production, in kW/K, each versus L ranging from 0.01 to 1.0 m. Discuss.

6.71 Figure P6.71 shows a system consisting of air in a rigid container fitted with a paddle wheel and in contact with a thermal energy reservoir. By heating and/or stirring, the air can achieve a specified increase in temperature from T_1 to T_2 in alternative ways. Discuss how the temperature increase of the air might be achieved with (a) minimum entropy production, and (b) maximum entropy production. Assume that the temperature on the boundary where heat transfer to the air occurs, T_b, is the same as the reservoir temperature. Let $T_1 < T_b < T_2$. The ideal gas model applies to the air.
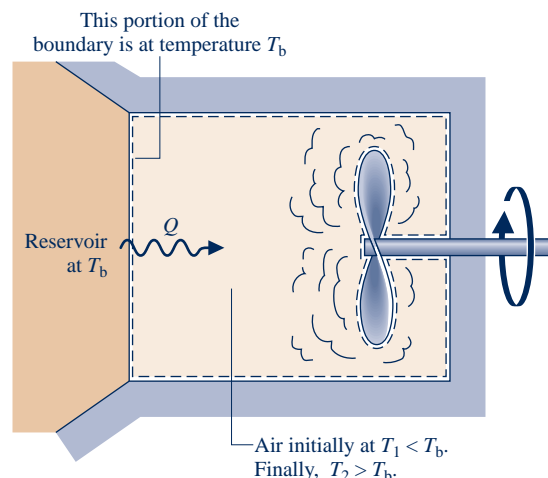

Fig. P6.71

6.72 An isolated system of total mass m is formed by mixing two equal masses of the same liquid initially at the temperatures T_1 and T_2. Eventually, the system attains an equilibrium state. Each mass is incompressible with constant specific heat c.

(a) Show that the amount of entropy produced is

$$\sigma = mc \ln\left[\frac{T_1 + T_2}{2(T_1 T_2)^{1/2}}\right]$$

(b) Demonstrate that σ must be positive.

6.73 A cylindrical rod of length L insulated on its lateral surface is initially in contact at one end with a wall at temperature T_H and at the other end with a wall at a lower temperature T_C. The temperature within the rod initially varies linearly with position z according to

$$T(z) = T_H - \left(\frac{T_H - T_C}{L}\right)z$$

The rod is then insulated on its ends and eventually comes to a final equilibrium state where the temperature is T_f. Evaluate T_f in terms of T_H and T_C and show that the amount of entropy produced is

$$\sigma = mc\left(1 + \ln T_f + \frac{T_C}{T_H - T_C}\ln T_C - \frac{T_H}{T_H - T_C}\ln T_H\right)$$

where c is the specific heat of the rod.

6.74 A system undergoing a thermodynamic cycle receives Q_H at temperature T'_H and discharges Q_C at temperature T'_C. There are no other heat transfers.

(a) Show that the net work developed per cycle is given by

$$W_{cycle} = Q_H\left(1 - \frac{T'_C}{T'_H}\right) - T'_C\sigma$$

where σ is the amount of entropy produced per cycle owing to irreversibilities within the system.
(b) If the heat transfers Q_H and Q_C are with hot and cold reservoirs, respectively, what is the relationship of T'_H to the temperature of the hot reservoir T_H and the relationship of T'_C to the temperature of the cold reservoir T_C?
(c) Obtain an expression for W_{cycle} if there are (i) no internal irreversibilities, (ii) no internal *or* external irreversibilities.

6.75 A thermodynamic power cycle receives energy by heat transfer from an incompressible body of mass m and specific heat c initially at temperature T_H. The cycle discharges energy by heat transfer to another incompressible body of mass m and specific heat c initially at a lower temperature T_C. There are no other heat transfers. Work is developed by the cycle until the temperature of each of the two bodies is the same. Develop an expression for the maximum theoretical amount of work that can be developed, W_{max}, in terms of m, c, T_H, and T_C.

6.76 At steady state, an insulated mixing chamber receives two liquid streams of the same substance at temperatures T_1 and T_2 and mass flow rates $\dot{m}_1$ and $\dot{m}_2$, respectively. A single stream exits at T_3 and $\dot{m}_3$. Using the incompressible substance model with constant specific heat c, obtain an expression for

(a) T_3 in terms of T_1, T_2, and the ratio of mass flow rates $\dot{m}_1/\dot{m}_3$.
(b) the rate of entropy production per unit of mass exiting the chamber in terms of c, T_1/T_2 and $\dot{m}_1/\dot{m}_3$.
(c) For fixed values of c and T_1/T_2, determine the value of $\dot{m}_1/\dot{m}_3$ for which the rate of entropy production is a maximum.

6.77 The temperature of an incompressible substance of mass m and specific heat c is reduced from T_0 to T $(< T_0)$ by a refrigeration cycle. The cycle receives energy by heat transfer at T from the substance and discharges energy by heat transfer at T_0 to the surroundings. There are no other heat transfers. Plot (W_{min}/mcT_0) versus T/T_0 ranging from 0.8 to 1.0, where W_{min} is the minimum theoretical work *input* required.

6.78 The temperature of a 12-oz (0.354-L) can of soft drink is reduced from 20 to 5°C by a refrigeration cycle. The cycle receives energy by heat transfer from the soft drink and discharges energy by heat transfer at 20°C to the surroundings. There are no other heat transfers. Determine the minimum theoretical work input required, in kJ, assuming the soft drink is an incompressible liquid with the properties of liquid water. Ignore the aluminum can.

6.79 As shown in Fig. P6.79, a turbine is located between two tanks. Initially, the smaller tank contains steam at 3.0 MPa, 280°C and the larger tank is evacuated. Steam is allowed to flow from the smaller tank, through the turbine, and into the larger tank until equilibrium is attained. If heat transfer with the surroundings is negligible, determine the maximum theoretical work that can be developed, in kJ.
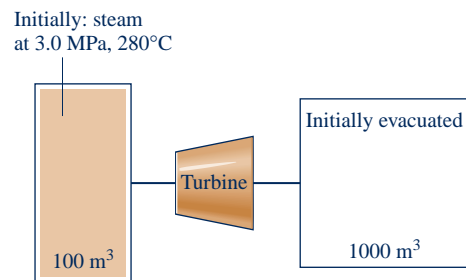

Initially: steam at 3.0 MPa, 280°C

Initially evacuated

Turbine

100 m³   1000 m³

Fig. P6.79

Applying the Entropy Balance: Control Volumes

6.80 A gas flows through a one-inlet, one-exit control volume operating at steady state. Heat transfer at the rate $\dot{Q}_{cv}$ takes place only at a location on the boundary where the temperature is T_b. For each of the following cases, determine whether the specific entropy of the gas at the exit is greater than, equal to, or less than the specific entropy of the gas at the inlet:

(a) no internal irreversibilities, $\dot{Q}_{cv} = 0$.
(b) no internal irreversibilities, $\dot{Q}_{cv} < 0$.
(c) no internal irreversibilities, $\dot{Q}_{cv} > 0$.
(d) internal irreversibilities, $\dot{Q}_{cv} \geq 0$.

6.81 Steam at 15 bar, 540°C, 60 m/s enters an insulated turbine operating at steady state and exits at 1.5 bar, 89.4 m/s. The work developed per kg of steam flowing is claimed to be (a) 606.0 kJ/kg, (b) 765.9 kJ/kg. Can either claim be correct? Explain.

6.82 Air enters an insulated turbine operating at steady state at 8 bar, 1127°C and exits at 1.5 bar, 347°C. Neglecting kinetic and potential energy changes and assuming the ideal gas model for the air, determine

(a) the work developed, in kJ per kg of air flowing through the turbine.
(b) whether the expansion is internally reversible, irreversible, or impossible.

6.83 Water at 20 bar, 400°C enters a turbine operating at steady state and exits at 1.5 bar. Stray heat transfer and kinetic and potential energy effects are negligible. A hard-to-read data sheet indicates that the quality at the turbine exit is 98%. Can this quality value be correct? If no, explain. If yes, determine the power developed by the turbine, in kJ per kg of water flowing.

6.84 Air enters a compressor operating at steady state at 15 lbf/in.^{2}, 80°F and exits at 400°F. Stray heat transfer and kinetic and potential energy effects are negligible. Assuming the ideal gas model for the air, determine the maximum theoretical pressure at the exit, in lbf/in.^{2}

6.85 Propane at 0.1 MPa, 20°C enters an insulated compressor operating at steady state and exits at 0.4 MPa, 90°C. Neglecting kinetic and potential energy effects, determine

(a) the power required by the compressor, in kJ per kg of propane flowing.
(b) the rate of entropy production within the compressor, in kJ/K per kg of propane flowing.

6.86 By injecting liquid water into superheated steam, the *desuperheater* shown in Fig. P6.86 has a saturated vapor stream at its exit. Steady-state operating data are provided in the accompanying table. Stray heat transfer and all kinetic and potential energy effects are negligible. (a) Locate states 1, 2, and 3 on a sketch of the *T–s* diagram. (b) Determine the rate of entropy production within the desuperheater, in kW/K.

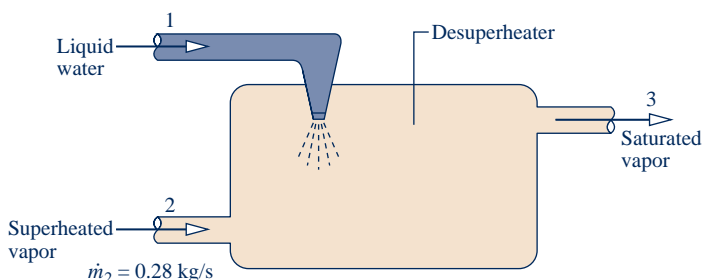| State	p(MPa)	T(°C)	v × 10³(m³/kg)	u(kJ/kg)	h(kJ/kg)	s(kJ/kg · K)
1	2.7	40	1.0066	167.2	169.9	0.5714
2	2.7	300	91.01	2757.0	3002.8	6.6001
3	2.5	sat. vap.	79.98	2603.1	2803.1	6.2575

Fig. P6.86

6.87 An inventor claims that at steady state the device shown in Fig. P6.87 develops power from entering and exiting streams of water at a rate of 1174.9 kW. The accompanying table provides data for inlet 1 and exits 3 and 4. The pressure at inlet 2 is 1 bar. Stray heat transfer and kinetic and potential energy effects are negligible. Evaluate the inventor's claim.

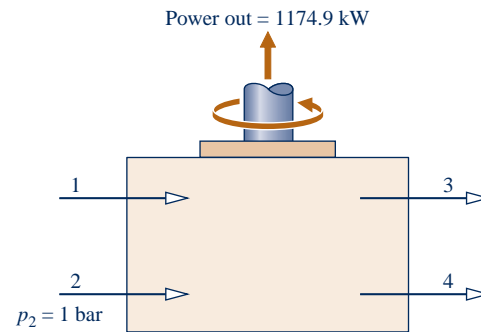| State	ṁ(kg/s)	p(bar)	T(°C)	v(m³/kg)	u(kJ/kg)	h(kJ/kg)	s(kJ/kg · K)
1	4	1	450	3.334	3049.0	3382.4	8.6926
3	5	2	200	1.080	2654.4	2870.5	7.5066
4	3	4	400	0.773	2964.4	3273.4	7.8985

Fig. P6.87

6.88 Figure P6.88 provides steady-state operating data for a well-insulated device having steam entering at one location and exiting at another. Neglecting kinetic and potential energy effects, determine (a) the direction of flow and (b) the power output or input, as appropriate, in kJ per kg of steam flowing.
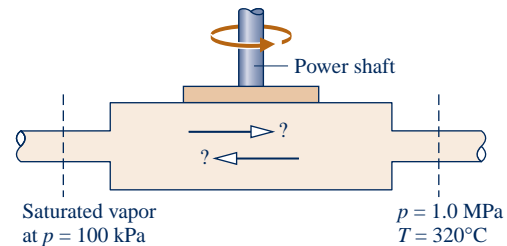

Fig. P6.88

6.89 Steam enters a well-insulated nozzle operating at steady state at 1000°F, 500 lbf/in.^{2} and a velocity of 10 ft/s. At the nozzle exit, the pressure is 14.7 lbf/in.^{2} and the velocity is 4055 ft/s. Determine the rate of entropy production, in Btu/°R per lb of steam flowing.

6.90 Air at 400 kPa, 970 K enters a turbine operating at steady state and exits at 100 kPa, 670 K. Heat transfer from the turbine occurs at an average outer surface temperature of 315 K at the rate of 30 kJ per kg of air flowing. Kinetic and potential energy effects are negligible. For air as an ideal gas with c_p = 1.1 kJ/kg · K, determine (a) the rate power is developed, in kJ per kg of air flowing, and (b) the rate of entropy production within the turbine, in kJ/K per kg of air flowing.

6.91 Steam at 240°C, 700 kPa enters an open feedwater heater operating at steady state with a mass flow rate of 0.5 kg/s. A separate stream of liquid water enters at 45°C, 700 kPa with a mass flow rate of 4 kg/s. A single mixed stream exits
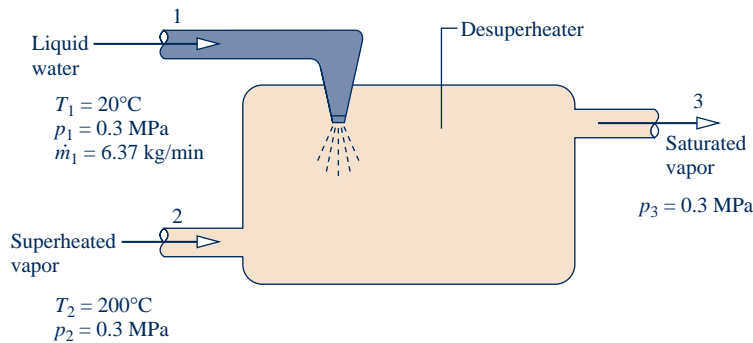
Fig. P6.92

at 700 kPa and temperature T. Stray heat transfer and kinetic and potential energy effects can be ignored. Determine (a) T, in °C, and (b) the rate of entropy production within the feedwater heater, in kW/K. (c) Locate the three principal states on a sketch of the T–s diagram.

6.92 By injecting liquid water into superheated vapor, the *desuperheater* shown in Fig. P6.92 has a saturated vapor stream at its exit. Steady-state operating data are shown on the figure. Ignoring stray heat transfer and kinetic and potential energy effects, determine (a) the mass flow rate of the superheated vapor stream, in kg/min, and (b) the rate of entropy production within the desuperheater, in kW/K.

6.93 Air at 600 kPa, 330 K enters a well-insulated, horizontal pipe having a diameter of 1.2 cm and exits at 120 kPa, 300 K. Applying the ideal gas model for air, determine at steady state (a) the inlet and exit velocities, each in m/s, (b) the mass flow rate, in kg/s, and (c) the rate of entropy production, in kW/K.

6.94 At steady state, air at 200 kPa, 52°C and a mass flow rate of 0.5 kg/s enters an insulated duct having differing inlet and exit cross-sectional areas. At the duct exit, the pressure of the air is 100 kPa, the velocity is 255 m/s, and the cross-sectional area is 2×10^{-3} m^2. Assuming the ideal gas model, determine

(a) the temperature of the air at the exit, in °C.
(b) the velocity of the air at the inlet, in m/s.
(c) the inlet cross-sectional area, in m^2.
(d) the rate of entropy production within the duct, in kW/K.

6.95 For the computer of Example 4.8, determine the rate of entropy production, in W/K, when air exits at 32°C. Ignore the change in pressure between the inlet and exit.

6.96 Electronic components are mounted on the inner surface of a horizontal cylindrical duct whose inner diameter is 0.2 m, as shown in Fig. P6.96. To prevent overheating of the electronics, the cylinder is cooled by a stream of air flowing through it and by convection from its outer surface. Air enters the duct at 25°C, 1 bar and a velocity of 0.3 m/s and exits at 40°C with negligible changes in kinetic energy and pressure. Convective cooling occurs on the outer surface to the surroundings, which are at 25°C, in accord with hA = 3.4 W/K, where h is the heat transfer coefficient and A is the surface area. The electronic components require 0.20 kW of electric power. For a control volume enclosing the cylinder, determine at steady state (a) the mass flow rate of the air, in kg/s, (b) the temperature on the outer surface of the duct, in °C, and (c) the rate of entropy production, in W/K. Assume the ideal gas model for air.
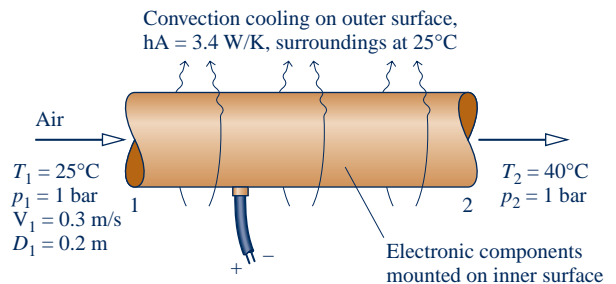

Fig. P6.96

6.97 Air enters a turbine operating at steady state at 500 kPa, 860 K and exits at 100 kPa. A temperature sensor indicates that the exit air temperature is 460 K. Stray heat transfer and kinetic and potential energy effects are negligible, and the air can be modeled as an ideal gas. Determine if the exit temperature reading can be correct. It yes, determine the power developed by the turbine for an expansion between these states, in kJ per kg of air flowing. If no, provide an explanation with supporting calculations.

6.98 Figure P6.98 provides steady-state test data for a control volume in which two entering streams of air mix to form a single exiting stream. Stray heat transfer and kinetic and potential energy effects are negligible. A hard-to-read photocopy of the data sheet indicates that the pressure of the exiting stream is either 1.0 MPa or 1.8 MPa. Assuming the ideal gas model for air with $c_p = 1.02$ kJ/kg · K, determine if either or both of these pressure values can be correct.
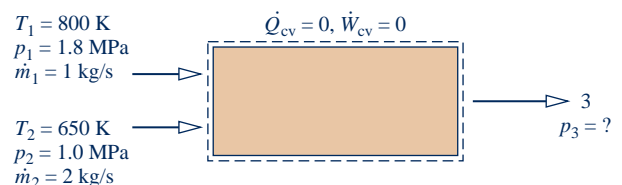
Fig. P6.98

6.99 Hydrogen gas (H_2) at 35°C and pressure p enters an insulated control volume operating at steady state for which $\dot{W}_{cv} = 0$. Half of the hydrogen exits the device at 2 bar and 90°C and the other half exits at 2 bar and -20°C. The effects of kinetic and potential energy are negligible. Employing the ideal gas model with constant $c_p = 14.3$ kJ/kg · K, determine the minimum possible value for the inlet pressure p, in bar.

$\dot{Q}_1 = 800$ kW

$T_1 = 1000$ K

$\dot{Q}_2 = 108$ kW

$T_2 = 540$ K

Power = 500 kW

4

Air
$T_4 = 500$ K
$\dot{m} = 2$ kg/s

5

Air
$T_5 = 600$ K
$p_5 = p_4$

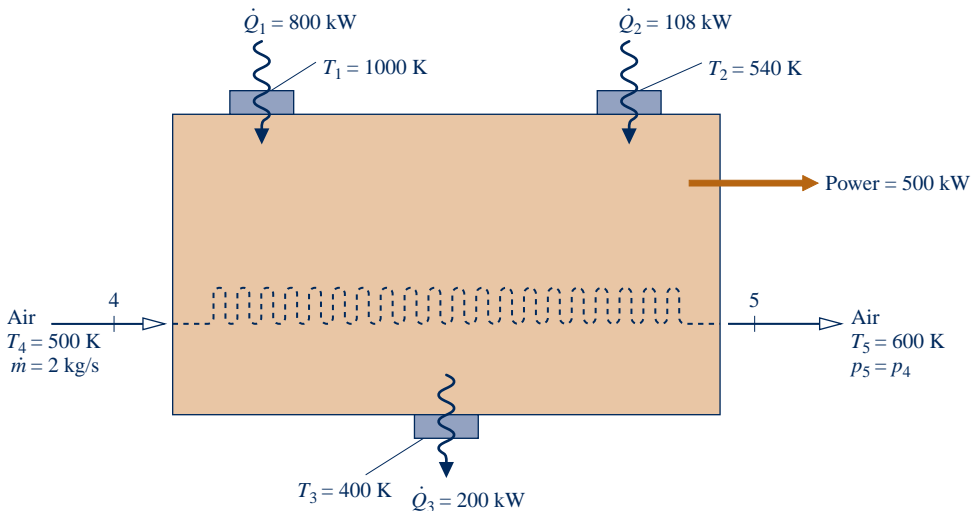$T_3 = 400$ K $\dot{Q}_3 = 200$ kW

Fig. P6.101

6.100 An engine takes in streams of water at 120°C, 5 bar and 240°C, 5 bar. The mass flow rate of the higher temperature stream is three times that of the other. A single stream exits at 5 bar with a mass flow rate of 4 kg/s. There is no significant heat transfer between the engine and its surroundings, and kinetic and potential energy effects are negligible. For operation at steady state, determine the rate at which power is developed in the absence of internal irreversibilities, in kW.

6.101 An inventor has provided the steady-state operating data shown in Fig. P6.101 for a *cogeneration* system producing power and increasing the temperature of a stream of air. The system receives and discharges energy by heat transfer at the rates and temperatures indicated on the figure. All heat transfers are in the directions of the accompanying arrows. The ideal gas model applies to the air. Kinetic and potential energy effects are negligible. Using energy and entropy rate balances, evaluate the thermodynamic performance of the system.

6.102 Steam at 550 lbf/in.², 700°F enters an insulated turbine operating at steady state with a mass flow rate of 1 lb/s. A two-phase liquid–vapor mixture exits the turbine at 14.7 lbf/in.² with quality x. Plot the power developed, in Btu/s, and the rate of entropy production, in Btu/°R · s, each versus x.

6.103 Refrigerant 134a at 30 lbf/in.², 40°F enters a compressor operating at steady state with a mass flow rate of 150 lb/h and exits as saturated vapor at 160 lbf/in.² Heat transfer occurs from the compressor to its surroundings, which are at 40°F. Changes in kinetic and potential energy can be ignored. A power input of 0.5 hp is claimed for the compressor. Determine whether this claim can be correct.

6.104 Ammonia enters a horizontal 0.2-m-diameter pipe at 2 bar with a quality of 90% and velocity of 5 m/s and exits at 1.75 bar as saturated vapor. Heat transfer to the pipe from the surroundings at 300 K takes place at an average outer surface temperature of 253 K. For operation at steady state, determine

(a) the velocity at the exit, in m/s.
(b) the rate of heat transfer to the pipe, in kW.
(c) the rate of entropy production, in kW/K, for a control volume comprising only the pipe and its contents.

(d) the rate of entropy production, in kW/K, for an enlarged control volume that includes the pipe and enough of its immediate surroundings so that heat transfer from the control volume occurs at 300 K.

6.105 Air at 500 kPa, 500 K and a mass flow of 600 kg/h enters a pipe passing overhead in a factory space. At the pipe exit, the pressure and temperature of the air are 475 kPa and 450 K, respectively. Air can be modeled as an ideal gas with $k = 1.39$. Kinetic and potential energy effects can be ignored. Determine at steady state, (a) the rate of heat transfer, in kW, for a control volume comprising the pipe and its contents, and (b) the rate of entropy production, in kW/K, for an enlarged control volume that includes the pipe and enough of its surroundings that heat transfer occurs at the ambient temperature, 300 K.

6.106 Steam enters a turbine operating at steady state at 6 MPa, 600°C with a mass flow rate of 125 kg/min and exits as saturated vapor at 20 kPa, producing power at a rate of 2 MW. Kinetic and potential energy effects can be ignored. Determine (a) the rate of heat transfer, in kW, for a control volume including the turbine and its contents, and (b) the rate of entropy production, in kW/K, for an enlarged control volume that includes the turbine and enough of its surroundings that heat transfer occurs at the ambient temperature, 27°C.

6.107 Air enters a compressor operating at steady state at 1 bar, 22°C with a volumetric flow rate of 1 m³/min and is compressed to 4 bar, 177°C. The power input is 3.5 kW. Employing the ideal gas model and ignoring kinetic and potential energy effects, obtain the following results:

(a) For a control volume enclosing the compressor only, determine the heat transfer rate, in kW, and the change in specific entropy from inlet to exit, in kJ/kg · K. What additional information would be required to evaluate the rate of entropy production?
(b) Calculate the rate of entropy production, in kW/K, for an enlarged control volume enclosing the compressor and a portion of its immediate surroundings so that heat transfer occurs at the ambient temperature, 22°C.

6.108 Carbon monoxide (CO) enters a nozzle operating at steady state at 25 bar, 257°C, and 45 m/s. At the nozzle exit, the conditions are 2 bar, 57°C, 560 m/s, respectively. The carbon monoxide can be modeled as an ideal gas.

(a) For a control volume enclosing the nozzle only, determine the heat transfer, in kJ, and the change in specific entropy, in kJ/K, each per kg of carbon monoxide flowing through the nozzle. What additional information would be required to evaluate the rate of entropy production?
(b) Evaluate the rate of entropy production, in kJ/K per kg of carbon monoxide flowing, for an enlarged control volume enclosing the nozzle and a portion of its immediate surroundings so that the heat transfer occurs at the ambient temperature, 27°C.

6.109 A counterflow heat exchanger operates at steady state with negligible kinetic and potential energy effects. In one stream, liquid water enters at 10°C and exits at 20°C with a negligible change in pressure. In the other stream, Refrigerant 134a enters at 10 bar, 80°C with a mass flow rate of 135 kg/h and exits at 10 bar, 20°C. The liquid water can be modeled as incompressible with c = 4.179 kJ/kg · K. Heat transfer from the outer surface of the heat exchanger can be ignored. Determine

(a) the mass flow rate of the liquid water, in kg/h.
(b) the rate of entropy production within the heat exchanger, in kW/K.

6.110 Saturated water vapor at 100 kPa enters a counterflow heat exchanger operating at steady state and exits at 20°C with a negligible change in pressure. Ambient air at 275 K, 1 atm enters in a separate stream and exits at 290 K, 1 atm. The air mass flow rate is 170 times that of the water. The air can be modeled as an ideal gas with c_p = 1.005 kJ/kg · K. Kinetic and potential energy effects can be ignored.

(a) For a control volume enclosing the heat exchanger, evaluate the rate of heat transfer, in kJ per kg of water flowing.
(b) For an enlarged control volume that includes the heat exchanger and enough of its immediate surroundings that heat transfer from the control volume occurs at the ambient temperature, 275 K, determine the rate of entropy production, in kJ/K per kg of water flowing.

6.111 Figure P6.111 shows data for a portion of the ducting in a ventilation system operating at steady state. The ducts are
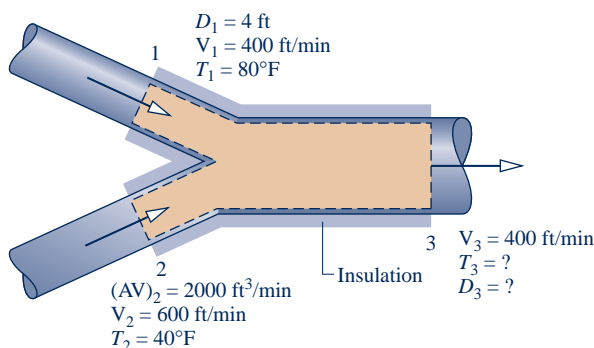
well insulated and the pressure is very nearly 1 atm throughout. Assuming the ideal gas model for air with c_p = 0.24 Btu/lb · °R, and ignoring kinetic and potential energy effects, determine (a) the temperature of the air at the exit, in °F, (b) the exit diameter, in ft, and (c) the rate of entropy production within the duct, in Btu/min · °R.

6.112 Air flows through an insulated circular duct having a diameter of 2 cm. Steady-state pressure and temperature data obtained by measurements at two locations, denoted as 1 and 2, are given in the accompanying table. Modeling air as an ideal gas with c_p = 1.005 kJ/kg · K, determine (a) the direction of the flow, (b) the velocity of the air, in m/s, at each of the two locations, and (c) the mass flow rate of the air, in kg/s.

Measurement location	1	2
Pressure (kPa)	100	500
Temperature (°C)	20	50

6.113 Determine the rates of entropy production, in Btu/min · °R, for the steam generator and turbine of Example 4.10. Identify the component that contributes more to inefficient operation of the overall system.

6.114 Air as an ideal gas flows through the compressor and heat exchanger shown in Fig. P6.114. A separate liquid water stream also flows through the heat exchanger. The data given are for operation at steady state. Stray heat transfer to the surroundings can be neglected, as can all kinetic and potential energy changes. Determine

(a) the compressor power, in kW, and the mass flow rate of the cooling water, in kg/s.
(b) the rates of entropy production, each in kW/K, for the compressor and heat exchanger.
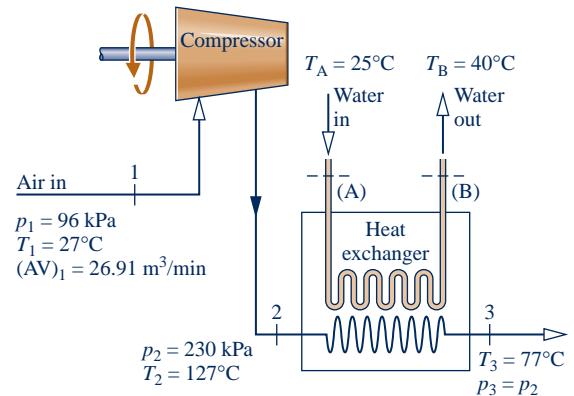
Fig. P6.114

6.115 Figure P6.115 shows several components in series, all operating at steady state. Liquid water enters the boiler at 60 bar. Steam exits the boiler at 60 bar, 540°C and undergoes a throttling process to 40 bar before entering the turbine. Steam expands adiabatically through the turbine to 5 bar, 240°C, and then undergoes a throttling process to 1 bar before entering the condenser. Kinetic and potential energy effects can be ignored.

(a) Locate each of the states 2–5 on a sketch of the T–s diagram.

Fig. P6.111

(b) Determine the power developed by the turbine, in kJ per kg of steam flowing.

(c) For the valves and the turbine, evaluate the rate of entropy production, each in kJ/K per kg of steam flowing.

(d) Using the result of part (c), place the components in rank order, beginning with the component contributing the most to inefficient operation of the overall system.

(e) If the goal is to increase the power developed per kg of steam flowing, which of the components (if any) might be eliminated? Explain.

Fig. P6.115

6.116 Air as an ideal gas flows through the turbine and heat exchanger arrangement shown in Fig. P6.116. Steady-state data are given on the figure. Stray heat transfer and kinetic and potential energy effects can be ignored. Determine

(a) temperature T_3, in K.

(b) the power output of the second turbine, in kW.

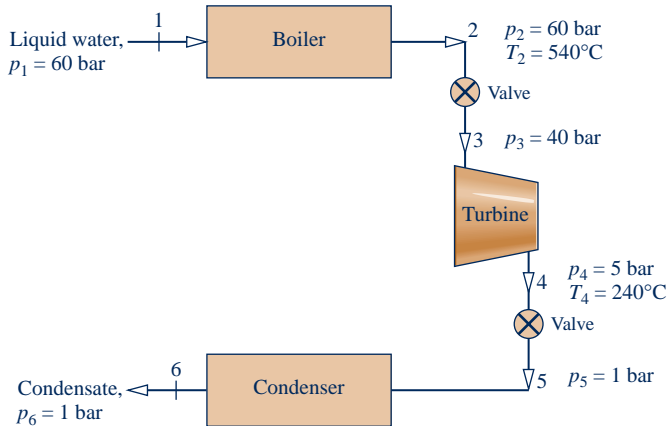(c) the rates of entropy production, each in kW/K, for the turbines and heat exchanger.

(d) Using the result of part (c), place the components in rank order, beginning with the component contributing most to inefficient operation of the overall system.

6.117 A rigid, insulated tank whose volume is 10 L is initially evacuated. A pinhole leak develops and air from the surroundings at 1 bar, 25°C enters the tank until the pressure in the tank becomes 1 bar. Assuming the ideal gas model

with $k = 1.4$ for the air, determine (a) the final temperature in the tank, in °C, (b) the amount of air that leaks into the tank, in g, and (c) the amount entropy produced, in J/K.

6.118 An insulated, rigid tank whose volume is 0.5 m³ is connected by a valve to a large vessel holding steam at 40 bar, 500°C. The tank is initially evacuated. The valve is opened only as long as required to fill the tank with steam to a pressure of 20 bar. Determine (a) the final temperature of the steam in the tank, in °C, (b) the final mass of the steam in the tank, in kg, and (c) the amount of entropy produced, in kJ/K.

6.119 For the control volume of Example 4.12, determine the amount of entropy produced during filling, in kJ/K. Repeat for the case where no work is developed by the turbine.

6.120 A well-insulated rigid tank of volume 10 m³ is connected by a valve to a large-diameter supply line carrying air at 227°C and 10 bar. The tank is initially evacuated. Air is allowed to flow into the tank until the tank pressure is p. Using the ideal gas model with constant specific heat ratio k, plot tank temperature, in K, the mass of air in the tank, in kg, and the amount of entropy produced, in kJ/K, versus p in bar.

6.121 A 180-ft³ tank initially filled with air at 1 atm and 70°F is evacuated by a device known as a *vacuum pump,* while the tank contents are maintained at 70°F by heat transfer through the tank walls. The vacuum pump discharges air to the surroundings at the temperature and pressure of the surroundings, which are 1 atm and 70°F, respectively. Determine the *minimum* theoretical work required, in Btu.

Using Isentropic Processes/Efficiencies

6.122 Air in a piston–cylinder assembly is compressed isentropically from $T_1 = 60°F$, $p_1 = 20$ lbf/in.² to $p_2 = 2000$ lbf/in.² Assuming the ideal gas model, determine the temperature at state 2, in °R using (a) data from Table A-22E, and (b) a constant specific heat ratio, $k = 1.4$. Compare the values obtained in parts (a) and (b) and comment.

6.123 Air in a piston–cylinder assembly is compressed isentropically from state 1, where $T_1 = 35°C$, to state 2, where the specific volume is one-tenth of the specific volume at state 1. Applying the ideal gas model with $k = 1.4$, determine (a) T_2, in °C and (b) the work, in kJ/kg.
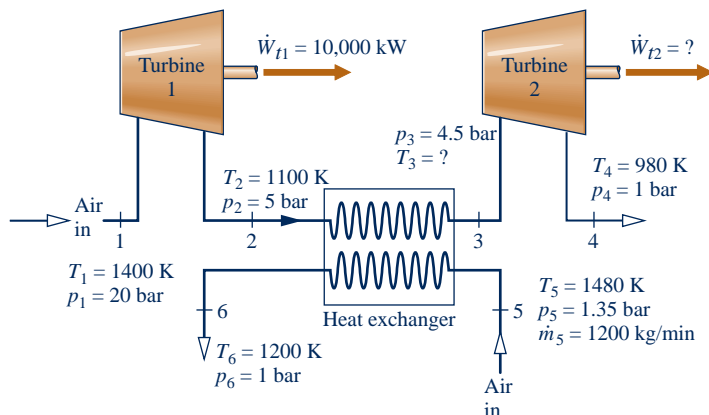

Fig. P6.116

6.124 Propane undergoes an isentropic expansion from an initial state where $T_1 = 40°C$, $p_1 = 1$ MPa to a final state where the temperature and pressure are T_2, p_2, respectively. Determine

(a) p_2, in kPa, when $T_2 = -40°C$.
(b) T_2, in °C, when $p_2 = 0.8$ MPa.

6.125 Argon in a piston–cylinder assembly is compressed isentropically from state 1, where $p_1 = 150$ kPa, $T_1 = 35°C$, to state 2, where $p_2 = 300$ kPa. Assuming the ideal gas model with $k = 1.67$, determine (a) T_2, in °C, and (b) the work, in kJ per kg of argon.

6.126 Air within a piston–cylinder assembly, initially at 12 bar, 620 K, undergoes an isentropic expansion to 1.4 bar. Assuming the ideal gas model for the air, determine the final temperature, in K, and the work, in kJ/kg. Solve two ways: using (a) data from Table A-22 and (b) $k = 1.4$.

6.127 Air within a piston–cylinder assembly, initially at 30 lbf/in.^{2}, 510°R, and a volume of 6 ft^3, is compressed isentropically to a final volume of 1.2 ft^3. Assuming the ideal gas model with $k = 1.4$ for the air, determine the (a) mass, in lb, (b) final pressure, in lbf/in.^{2}, (c) final temperature, in °R, and (d) work, in Btu.

6.128 Air contained in a piston–cylinder assembly, initially at 4 bar, 600 K and a volume of 0.43 m^3, expands isentropically to a pressure of 1.5 bar. Assuming the ideal gas model for the air, determine the (a) mass, in kg, (b) final temperature, in K, and (c) work, in kJ.

6.129 Air in a piston–cylinder assembly is compressed isentropically from an initial state where $T_1 = 340$ K to a final state where the pressure is 90% greater than at state 1. Assuming the ideal gas model, determine (a) T_2, in K, and (b) the work, in kJ/kg.

6.130 A rigid, insulated tank with a volume of 20 m^3 is filled initially with air at 10 bar, 500 K. A leak develops, and air slowly escapes until the pressure of the air remaining in the tank is 5 bar. Employing the ideal gas model with $k = 1.4$ for the air, determine the amount of mass remaining in the tank, in kg, and its temperature, in K.

6.131 A rigid, insulated tank with a volume of 21.61 ft^3 is filled initially with air at 110 lbf/in.^{2}, 535°R. A leak develops, and air slowly escapes until the pressure of the air remaining in the tank is 15 lbf/in.^{2} Employing the ideal gas model with $k = 1.4$ for the air, determine the amount of mass remaining in the tank, in lb, and its temperature, in °R.

6.132 The accompanying table provides steady-state data for an isentropic expansion of steam through a turbine. For a mass flow rate of 2.55 kg/s, determine the power developed by the turbine, in MW. Ignore the effects of potential energy.

	p(bar)	T(°C)	V(m/s)	h(kJ/kg)	s(kJ/kg · K)
Inlet	10	300	25	3051.1	7.1214
Exit	1.5	—	100		7.1214

6.133 Water vapor enters a turbine operating at steady state at 1000°F, 140 lbf/in.^{2}, with a volumetric flow rate of 21.6 ft^3/s, and expands isentropically to 2 lbf/in.^{2} Determine the power developed by the turbine, in hp. Ignore kinetic and potential energy effects.

6.134 Air enters a turbine operating at steady state at 6 bar and 1100 K and expands isentropically to a state where the temperature is 700 K. Employing the ideal gas model with data from Table A-22, and ignoring kinetic and potential energy changes, determine the pressure at the exit, in bar, and the work, in kJ per kg of air flowing.

6.135 Figure P6.135 shows a simple vapor power cycle operating at steady state with water as the working fluid. Data at key locations are given on the figure. Flow through the turbine and pump occurs isentropically. Flow through the steam generator and condenser occurs at constant pressure. Stray heat transfer and kinetic and potential energy effects are negligible. Sketch the four processes of this cycle in series on a T–s diagram. Determine the thermal efficiency.
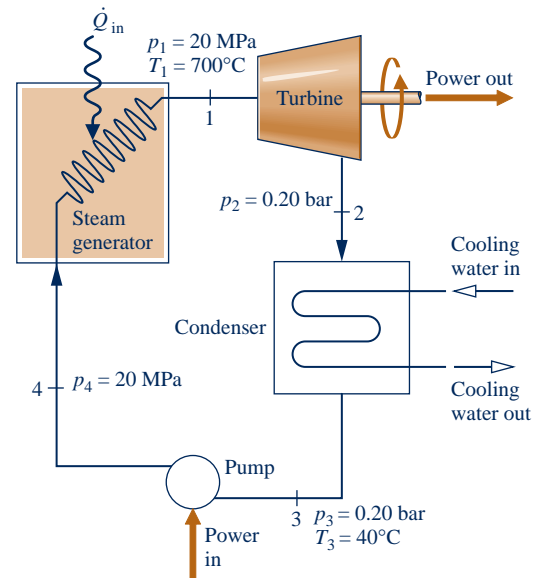

Fig. P6.135

6.136 The accompanying table provides steady-state data for steam expanding adiabatically though a turbine. The states are numbered as in Fig. 6.11. Kinetic and potential energy effects can be ignored. Determine for the turbine (a) the work developed per unit mass of steam flowing, in kJ/kg, (b) the amount of entropy produced per unit mass of steam flowing, in kJ/kg · K, and (c) the isentropic turbine efficiency.

State	p(bar)	T(°C)	x(%)	h(kJ/kg)	s(kJ/kg · K)
1	10	300	—	3051	7.121
2s	0.10	45.81	86.3	—	7.121
2	0.10	45.81	90.0	—	7.400

6.137 The accompanying table provides steady-state data for steam expanding adiabatically with a mass flow rate of 4 lb/s through a turbine. Kinetic and potential energy effects can be ignored. Determine for the turbine (a) the power developed, in hp, (b) the rate of entropy production, in hp/°R, and (c) the isentropic turbine efficiency.

	p(lbf/in.^{2})	T(°F)	u(Btu/lb)	h(Btu/lb)	s(Btu/lb · °R)
Inlet	140	1000	1371.0	1531.0	1.8827
Exit	2	270	1101.4	1181.7	2.0199

6.138 Water vapor at 800 lbf/in.^{2}, 1000°F enters a turbine operating at steady state and expands adiabatically to 2 lbf/in.^{2}, developing work at a rate of 490 Btu per lb of vapor flowing. Determine the condition at the turbine exit: two-phase liquid–vapor or superheated vapor? Also, evaluate the isentropic turbine efficiency. Kinetic and potential energy effects are negligible.

6.139 Air at 1600 K, 30 bar enters a turbine operating at steady state and expands adiabatically to the exit, where the temperature is 830 K. If the isentropic turbine efficiency is 90%, determine (a) the pressure at the exit, in bar, and (b) the work developed, in kJ per kg of air flowing. Assume ideal gas behavior for the air and ignore kinetic and potential energy effects.

6.140 Water vapor at 5 bar, 320°C enters a turbine operating at steady state with a volumetric flow rate of 0.65 m^3/s and expands adiabatically to an exit state of 1 bar, 160°C. Kinetic and potential energy effects are negligible. Determine for the turbine (a) the power developed, in kW, (b) the rate of entropy production, in kW/K, and (c) the isentropic turbine efficiency.

6.141 Air at 1175 K, 8 bar enters a turbine operating at steady state and expands adiabatically to 1 bar. The isentropic turbine efficiency is 92%. Employing the ideal gas model with $k = 1.4$ for the air, determine (a) the work developed by the turbine, in kJ per kg of air flowing, and (b) the temperature at the exit, in K. Ignore kinetic and potential energy effects.

6.142 Water vapor at 10 MPa, 600°C enters a turbine operating at steady state with a volumetric flow rate of 0.36 m^3 and exits at 0.1 bar and a quality of 92%. Stray heat transfer and kinetic and potential energy effects are negligible. Determine for the turbine (a) the mass flow rate, in kg/s, (b) the power developed by the turbine, in MW, (c) the rate at which entropy is produced, in kW/K, and (d) the isentropic turbine efficiency.

6.143 Air modeled as an ideal gas enters a turbine operating at steady state at 1040 K, 278 kPa and exits at 120 kPa. The mass flow rate is 5.5 kg/s, and the power developed is 1120 kW. Stray heat transfer and kinetic and potential energy effects are negligible. Determine (a) the temperature of the air at the turbine exit, in K, and (b) the isentropic turbine efficiency.

6.144 Water vapor at 1000°F, 140 lbf/in.^{2} enters a turbine operating at steady state and expands to 2 lbf/in.^{2} The mass flow rate is 4 lb/s and the power developed is 1600 Btu/s. Stray heat transfer and kinetic and potential energy effects are negligible. Determine the isentropic turbine efficiency.

6.145 Water vapor at 6 MPa, 600°C enters a turbine operating at steady state and expands to 10 kPa. The mass flow rate is 2 kg/s, and the power developed is 2626 kW. Stray heat transfer and kinetic and potential energy effects are negligible. Determine (a) the isentropic turbine efficiency and (b) the rate of entropy production within the turbine, in kW/K.

6.146 Water vapor at 800 lbf/in.^{2}, 1000°F enters a turbine operating at steady state and expands to 2 lbf/in.^{2} The mass flow rate is 5.56 lb/s, and the isentropic turbine efficiency is 92%. Stray heat transfer and kinetic and potential energy effects are negligible. Determine the power developed by the turbine, in hp.

6.147 Air enters the compressor of a gas turbine power plant operating at steady state at 290 K, 100 kPa and exits at 420 K, 330 kPa. Stray heat transfer and kinetic and potential energy effects are negligible. Using the ideal gas model for air, determine the isentropic compressor efficiency.

6.148 Air at 25°C, 100 kPa enters a compressor operating at steady state and exits at 260°C, 650 kPa. Stray heat transfer and kinetic and potential energy effects are negligible. Modeling air as an ideal gas with $k = 1.4$, determine the isentropic compressor efficiency.

6.149 Air at 290 K, 100 kPa enters a compressor operating at steady state and is compressed adiabatically to an exit state of 420 K, 330 kPa. The air is modeled as an ideal gas, and kinetic and potential energy effects are negligible. For the compressor, (a) determine the rate of entropy production, in kJ/K per kg of air flowing, and (b) the isentropic compressor efficiency.

6.150 Carbon dioxide (CO_2) at 1 bar, 300 K enters a compressor operating at steady state and is compressed adiabatically to an exit state of 10 bar, 520 K. The CO_2 is modeled as an ideal gas, and kinetic and potential energy effects are negligible. For the compressor, determine (a) the work input, in kJ per kg of CO_2 flowing, (b) the rate of entropy production, in kJ/K per kg of CO_2 flowing, and (c) the isentropic compressor efficiency.

6.151 Air at 300 K, 1 bar enters a compressor operating at steady state and is compressed adiabatically to 1.5 bar. The power input is 42 kJ per kg of air flowing. Employing the ideal gas model with $k = 1.4$ for the air, determine for the compressor (a) the rate of entropy production, in kJ/K per kg of air flowing, and (b) the isentropic compressor efficiency. Ignore kinetic and potential energy effects.

6.152 Air at 1 atm, 520°R enters a compressor operating at steady state and is compressed adiabatically to 3 atm. The isentropic compressor efficiency is 80%. Employing the ideal gas model with $k = 1.4$ for the air, determine for the compressor (a) the power input, in Btu per lb of air flowing, and (b) the amount of entropy produced, in Btu/°R per lb of air flowing. Ignore kinetic and potential energy effects.

6.153 Nitrogen (N_2) enters an insulated compressor operating at steady state at 1 bar, 37°C with a mass flow rate of 1000 kg/h and exits at 10 bar. Kinetic and potential energy effects are negligible. The nitrogen can be modeled as an ideal gas with $k = 1.391$.

(a) Determine the minimum theoretical power input required, in kW, and the corresponding exit temperature, in °C.
(b) If the exit temperature is 397°C, determine the power input, in kW, and the isentropic compressor efficiency.

6.154 Saturated water vapor at 300°F enters a compressor operating at steady state with a mass flow rate of 5 lb/s and is compressed adiabatically to 800 lbf/in.^{2} If the power input is 2150 hp, determine for the compressor (a) the isentropic

compressor efficiency and (b) the rate of entropy production, in hp/°R. Ignore kinetic and potential energy effects.

6.155 Refrigerant 134a at a rate of 0.8 lb/s enters a compressor operating at steady state as saturated vapor at 30 psia and exits at a pressure of 160 psia. There is no significant heat transfer with the surroundings, and kinetic and potential energy effects can be ignored.

(a) Determine the minimum theoretical power input required, in Btu/s, and the corresponding exit temperature, in °F.
(b) If the refrigerant exits at a temperature of 130°F, determine the actual power, in Btu/s, and the isentropic compressor efficiency.

6.156 Air at 1.3 bar, 423 K and a velocity of 40 m/s enters a nozzle operating at steady state and expands adiabatically to the exit, where the pressure is 0.85 bar and velocity is 307 m/s. For air modeled as an ideal gas with $k = 1.4$, determine for the nozzle (a) the temperature at the exit, in K, and (b) the isentropic nozzle efficiency.

6.157 Water vapor at 100 lbf/in.^{2}, 500°F and a velocity of 100 ft/s enters a nozzle operating at steady state and expands adiabatically to the exit, where the pressure is 40 lbf/in.^{2} If the isentropic nozzle efficiency is 95%, determine for the nozzle (a) the velocity of the steam at the exit, in ft/s, and (b) the amount of entropy produced, in Btu/°R per lb of steam flowing.

6.158 Helium gas at 810°R, 45 lbf/in.^{2}, and a velocity of 10 ft/s enters an insulated nozzle operating at steady state and exits at 670°R, 25 lbf/in.^{2} Modeling helium as an ideal gas with $k = 1.67$, determine (a) the velocity at the nozzle exit, in ft/s, (b) the isentropic nozzle efficiency, and (c) the rate of entropy production within the nozzle, in Btu/°R per lb of helium flowing.

6.159 Air modeled as an ideal gas enters a one-inlet, one-exit control volume operating at steady state at 100 lbf/in.^{2}, 900°R and expands adiabatically to 25 lbf/in.^{2} Kinetic and potential energy effects are negligible. Determine the rate of entropy production, in Btu/°R per lb of air flowing,

(a) if the control volume encloses a turbine having an isentropic turbine efficiency of 89.1%.
(b) if the control volume encloses a throttling valve.

6.160 Ammonia enters a valve as saturated liquid at 9 bar and undergoes a throttling process to a pressure of 2 bar. Determine the rate of entropy production per unit mass of ammonia flowing, in kJ/kg · K. If the valve were replaced by a power-recovery turbine operating at steady state, determine the maximum theoretical power that could be developed per unit mass of ammonia flowing, in kJ/kg, and comment. In each case, ignore heat transfer with the surroundings and changes in kinetic and potential energy.

6.161 Figure P6.161 provides the schematic of a heat pump using Refrigerant 134a as the working fluid, together with steady-state data at key points. The mass flow rate of the refrigerant is 7 kg/min, and the power input to the compressor is 5.17 kW. (a) Determine the coefficient of performance for the heat pump. (b) If the valve were replaced by a turbine, power could be produced, thereby reducing the power requirement of the heat pump system. Would you recommend this *power-saving* measure? Explain.
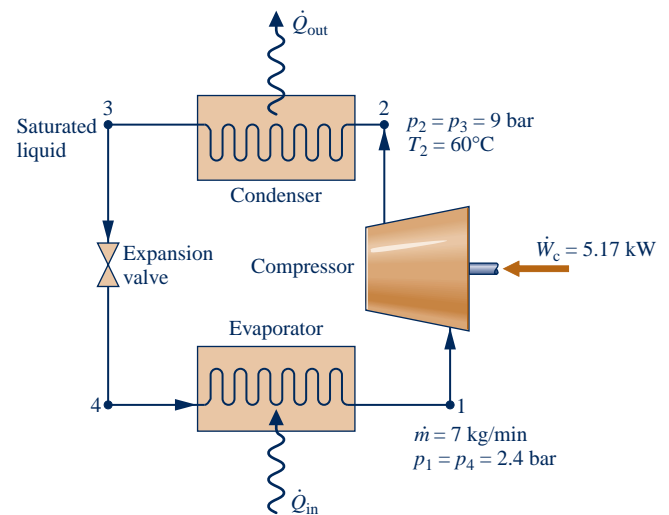

Fig. P6.161

6.162 Air enters an insulated diffuser operating at steady state at 1 bar, −3°C, and 260 m/s and exits with a velocity of 130 m/s. Employing the ideal gas model and ignoring potential energy, determine

(a) the temperature of the air at the exit, in °C.
(b) The maximum attainable exit pressure, in bar.

6.163 As shown in Fig. P6.163, air enters the diffuser of a jet engine at 18 kPa, 216 K with a velocity of 265 m/s, all data corresponding to high-altitude flight. The air flows adiabatically through the diffuser, decelerating to a velocity of 50 m/s at the diffuser exit. Assume steady-state operation, the ideal gas model for air, and negligible potential energy effects.

(a) Determine the temperature of the air at the exit of the diffuser, in K.
(b) If the air would undergo an isentropic process as it flows through the diffuser, determine the pressure of the air at the diffuser exit, in kPa.
(c) If friction were present, would the pressure of the air at the diffuser exit be greater than, less than, or equal to the value found in part (b)? Explain.
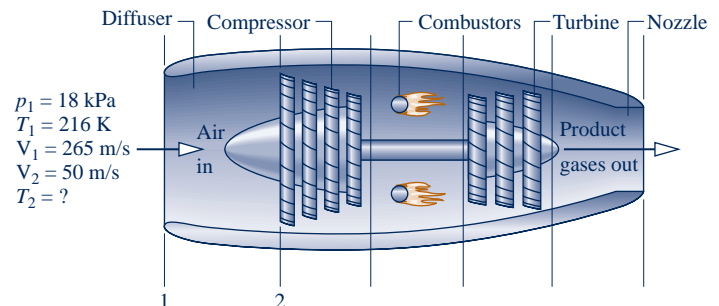

Fig. P6.163

6.164 As shown in Fig. P6.164, a steam turbine having an isentropic turbine efficiency of 90% drives an air compressor having an isentropic compressor efficiency of 85%. Steady-state operating data are provided on the figure. Assume the

ideal gas model for air, and ignore stray heat transfer and kinetic and potential energy effects.

(a) Determine the mass flow rate of the steam entering the turbine, in kg of steam per kg of air exiting the compressor.
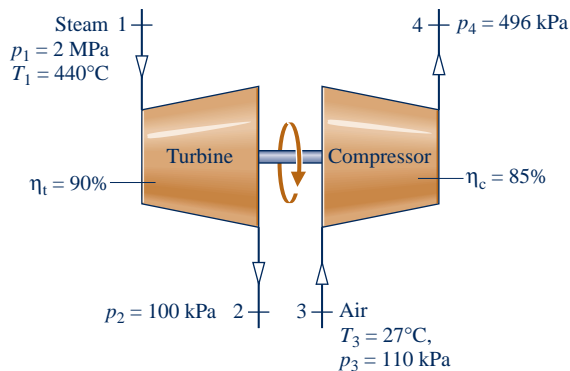(b) Repeat part (a) if $\eta_t = \eta_c = 100\%$

Steam 1
$p_1 = 2$ MPa
$T_1 = 440°C$

$\eta_t = 90\%$

Turbine   Compressor

4 + $p_4 = 496$ kPa

$\eta_c = 85\%$

$p_2 = 100$ kPa 2+   3 + Air
$T_3 = 27°C,$
$p_3 = 110$ kPa

Fig. P6.164

<mark>6.165</mark> Figure P6.165 shows a simple vapor power plant operating at steady state with water as the working fluid. Data at key locations are given on the figure. The mass flow rate of the water circulating through the components is 109 kg/s. Stray heat transfer and kinetic and potential energy effects can be ignored. Determine

(a) the net power developed, in MW.
(b) the thermal efficiency.
(c) the isentropic turbine efficiency.
(d) the isentropic pump efficiency.
(e) the mass flow rate of the cooling water, in kg/s.
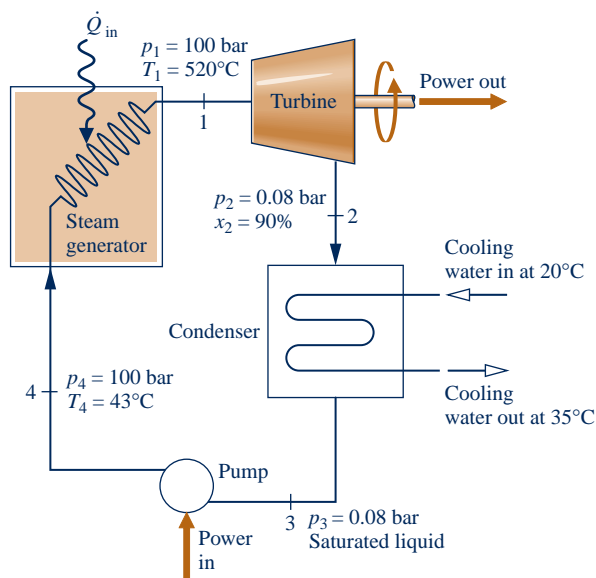(f) the rates of entropy production, each in kW/K, for the turbine, condenser, and pump.

$\dot{Q}_{in}$
$p_1 = 100$ bar
$T_1 = 520°C$

Turbine   Power out

1

$p_2 = 0.08$ bar
$x_2 = 90\%$ 2

Steam generator

Cooling water in at 20°C

Condenser

4 + $p_4 = 100$ bar
$T_4 = 43°C$

Cooling water out at 35°C

Pump

Power in

3 $p_3 = 0.08$ bar
Saturated liquid

Fig. P6.165

6.166 Figure P6.166 shows a power system operating at steady state consisting of three components in series: an air compressor having an isentropic compressor efficiency of 80%, a heat exchanger, and a turbine having an isentropic turbine efficiency of 90%. Air enters the compressor at 1 bar, 300 K with a mass flow rate of 5.8 kg/s and exits at a pressure of 10 bar. Air enters the turbine at 10 bar, 1400 K and exits at a pressure of 1 bar. Air can be modeled as an ideal gas. Stray heat transfer and kinetic and potential energy effects are negligible. Determine, in kW, (a) the power required by the compressor, (b) the power developed by the turbine, and (c) the *net* power output of the overall power system.
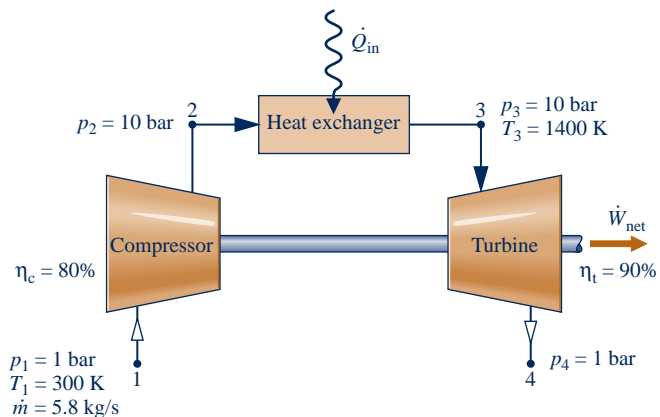

$\dot{Q}_{in}$

$p_2 = 10$ bar 2   Heat exchanger   3 $p_3 = 10$ bar
$T_3 = 1400$ K

$\eta_c = 80\%$

Compressor   Turbine $\dot{W}_{net}$

$\eta_t = 90\%$

$p_1 = 1$ bar
$T_1 = 300$ K   1
$\dot{m} = 5.8$ kg/s

$p_4 = 1$ bar
4

Fig. P6.166

6.167 As shown in Fig. P6.167, a well-insulated turbine operating at steady state has two stages in series. Steam enters the first stage at 800°F, 600 lbf/in.^{2} and exits at 250 lbf/in.^{2} The steam then enters the second stage and exits at 14.7 lbf/in.^{2} The isentropic efficiencies of the stages are 85% and 91%, respectively. Show the principal states on a *T–s* diagram. At the exit of the second stage, determine the temperature, in °F, if superheated vapor exits or the quality if a two-phase liquid–vapor mixture exits. Also determine the work developed by each stage, in Btu per lb of steam flowing.
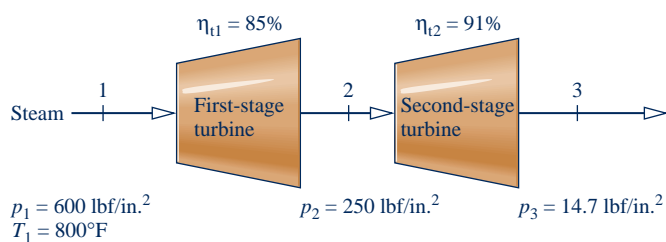

$\eta_{t1} = 85\%$ $\eta_{t2} = 91\%$

Steam   1   First-stage turbine   2   Second-stage turbine   3

$p_1 = 600$ lbf/in.^{2}
$T_1 = 800°F$

$p_2 = 250$ lbf/in.^{2}

$p_3 = 14.7$ lbf/in.^{2}

Fig. P6.167

6.168 A rigid tank is filled initially with 5.0 kg of air at a pressure of 0.5 MPa and a temperature of 500 K. The air is allowed to discharge through a turbine into the atmosphere, developing work until the pressure in the tank has fallen to the atmospheric level of 0.1 MPa. Employing the ideal gas model for the air, determine the *maximum* theoretical amount of work that could be developed, in kJ. Ignore heat transfer with the atmosphere and changes in kinetic and potential energy.

6.169 A tank initially containing air at 30 atm and 540°F is connected to a small turbine. Air discharges from the tank through the turbine, which produces work in the amount of 100 Btu. The pressure in the tank falls to 3 atm during the process and the turbine exhausts to the atmosphere at 1 atm. Employing the ideal gas model for the air and ignoring irreversibilities within the tank and the turbine, determine the volume of the tank, in ft^3. Heat transfer with the atmosphere and changes in kinetic and potential energy are negligible.

6.170 Air enters a 3600-kW turbine operating at steady state with a mass flow rate of 18 kg/s at 800°C, 3 bar and a velocity of 100 m/s. The air expands adiabatically through the turbine and exits at a velocity of 150 m/s. The air then enters a diffuser where it is decelerated isentropically to a velocity of 10 m/s and a pressure of 1 bar. Employing the ideal gas model, determine

(a) the pressure and temperature of the air at the turbine exit, in bar and °C, respectively.
(b) the rate of entropy production in the turbine, in kW/K.

Show the processes on a *T–s* diagram.

Analyzing Internally Reversible Flow Processes

6.171 Air enters a compressor operating at steady state with a volumetric flow rate of 0.2 m^3/s, at 20°C, 1 bar. The air is compressed isothermally without internal irreversibilities, exiting at 8 bar. The air is modeled as an ideal gas, and kinetic and potential energy effects can be ignored. Evaluate the power required and the heat transfer rate, each in kW.

6.172 Refrigerant 134a enters a compressor operating at steady state at 1 bar, -15°C with a volumetric flow rate of 3×10^{-2} m^3/s. The refrigerant is compressed to a pressure of 8 bar in an internally reversible process according to $pv^{1.06} = $ *constant*. Neglecting kinetic and potential energy effects, determine

(a) the power required, in kW.
(b) the rate of heat transfer, in kW.

6.173 An air compressor operates at steady state with air entering at $p_1 = 15$ lbf/in.^{2}, $T_1 = 60$°F. The air undergoes a polytropic process, and exits at $p_2 = 75$ lbf/in.^{2}, $T_2 = 294$°F. (a) Evaluate the work and heat transfer, each in Btu per lb of air flowing. (b) Sketch the process on *p–v* and *T–s* diagrams and associate areas on the diagrams with work and heat transfer, respectively. Assume the ideal gas model for air and neglect changes in kinetic and potential energy.

6.174 An air compressor operates at steady state with air entering at $p_1 = 1$ bar, $T_1 = 17$°C and exiting at $p_2 = 5$ bar. The air undergoes a polytropic process for which the compressor work input is 162.2 kJ per kg of air flowing. Determine (a) the temperature of the air at the compressor exit, in °C, and (b) the heat transfer, in kJ per kg of air flowing. (c) Sketch the process on *p–v* and *T–s* diagrams and associate areas on the diagrams with work and heat transfer, respectively. Assume the ideal gas model for air and neglect changes in kinetic and potential energy.

6.175 Water as saturated liquid at 1 bar enters a pump operating at steady state and is pumped isentropically to a

pressure of 50 bar. Kinetic and potential energy effects are negligible. Determine the pump work input, in kJ per kg of water flowing, using (a) Eq. 6.51c, (b) an energy balance. Obtain data from Table A-3 and A-5, as appropriate. Compare the results of parts (a) and (b), and comment.

6.176 Compare the work required at steady state to compress *water vapor* isentropically to 3 MPa from the saturated vapor state at 0.1 MPa to the work required to pump *liquid water* isentropically to 3 MPa from the saturated liquid state at 0.1 MPa, each in kJ per kg of water flowing through the device. Kinetic and potential energy effects can be ignored.

6.177 A pump operating at steady state receives saturated liquid water at 50°C with a mass flow rate of 20 kg/s. The pressure of the water at the pump exit is 1 MPa. If the pump operates with negligible internal irreversibilities and negligible changes in kinetic and potential energy, determine the power required in kW.

6.178 A pump operating at steady state receives liquid water at 20°C 100 kPa with a mass flow rate of 53 kg/min. The pressure of the water at the pump exit is 5 MPa. The isentropic pump efficiency is 70%. Stray heat transfer and changes in kinetic and potential energy are negligible. Determine the power required by the pump, in kW.

6.179 A pump operating at steady state receives liquid water at 50°C, 1.5 MPa. The pressure of the water at the pump exit is 15 MPa. The magnitude of the work required by the pump is 18 kJ per kg of water flowing. Stray heat transfer and changes in kinetic and potential energy are negligible. Determine the isentropic pump efficiency.

6.180 Liquid water at 70°F, 14.7 lbf/in.^{2} and a velocity of 30 ft/s enters a system at steady state consisting of a pump and attached piping and exits at a point 30 ft above the inlet at 250 lbf/in.^{2}, a velocity of 15 ft/s, and no significant change in temperature. (a) In the absence of internal irreversibilities, determine the power input required by the system, in Btu per lb of liquid water flowing. (b) For the same inlet and exit states, in the presence of friction would the power input be greater, or less, than determined in part (a)? Explain. Let $g = 32.2$ ft/s^2.

6.181 A 3-hp pump operating at steady state draws in liquid water at 1 atm, 60°F and delivers it at 5 atm at an elevation 20 ft above the inlet. There is no significant change in velocity between the inlet and exit, and the local acceleration of gravity is 32.2 ft/s^2. Would it be possible to pump 1000 gal in 10 min or less? Explain.

6.182 An electrically driven pump operating at steady state draws water from a pond at a pressure of 1 bar and a rate of 50 kg/s and delivers the water at a pressure of 4 bar. There is no significant heat transfer with the surroundings, and changes in kinetic and potential energy can be neglected. The isentropic pump efficiency is 75%. Evaluating electricity at 8.5 cents per kW · h, estimate the hourly cost of running the pump.

6.183 As shown in Fig. P6.183, water behind a dam enters an intake pipe at a pressure of 24 psia and velocity of 5 ft/s, flows through a hydraulic turbine-generator, and exits at a point 200 ft below the intake at 19 psia, 45 ft/s, and a specific
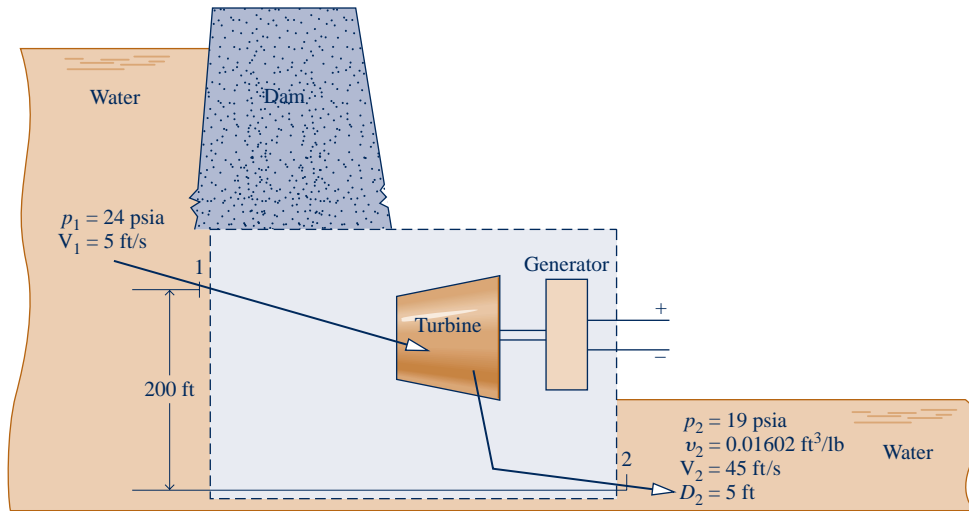
Fig. P6.183

volume of 0.01602 ft^3/lb. The diameter of the exit pipe is 5 ft and the local acceleration of gravity is 32.2 ft/s^2. Evaluating the electricity generated at 8.5 cents per kW · h, determine the value of the power produced, in $/day, for operation at steady state and in the absence of internal irreversibilities.

6.184 As shown in Figure P6.184, water flows from an elevated reservoir through a hydraulic turbine operating at steady state. Determine the maximum power output, in MW, associated with a mass flow rate of 950 kg/s. The inlet and exit diameters are equal. The water can be modeled as incompressible with $v = 10^{-3}$ m^3/kg. The local acceleration of gravity is 9.8 m/s^2.
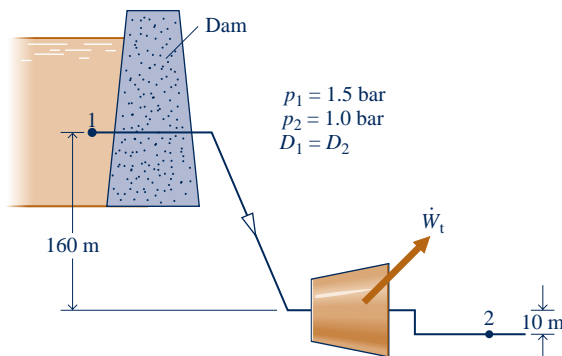

Fig. P6.184

6.185 Nitrogen (N$_2$) enters a nozzle operating at steady state at 0.2 MPa, 550 K with a velocity of 1 m/s and undergoes a polytropic expansion with $n = 1.3$ to 0.15 MPa. Using the ideal gas model with $k = 1.4$, and ignoring potential energy effects, determine (a) the exit velocity, in m/s, and (b) the rate of heat transfer, in kJ per kg of gas flowing.

6.186 Carbon monoxide enters a nozzle operating at steady state at 5 bar, 200°C with a velocity of 1 m/s and undergoes a polytropic expansion to 1 bar and an exit velocity of 630 m/s. Using the ideal gas model and ignoring potential energy effects, determine

(a) the exit temperature, in °C.
(b) the rate of heat transfer, in kJ per kg of gas flowing.

Reviewing Concepts

6.187 Answer the following true or false. Explain.

(a) For closed systems undergoing processes involving internal irreversibilities, both entropy change and entropy production are positive in value.
(b) The *Carnot* cycle is represented on a *Mollier* diagram by a rectangle.
(c) Entropy *change* of a closed system during a process can be greater than, equal to, or less than zero.
(d) For specified inlet state, exit pressure, and mass flow rate, the power *input* required by a compressor operating at steady state is less than that if compression occurred isentropically.
(e) The $T \, dS$ equations are fundamentally important in thermodynamics because of their use in deriving important property relations for pure, simple compressible systems.
(f) At liquid states, the following approximation is reasonable for many engineering applications $s(T, p) = s_f(T)$.

6.188 Answer the following true or false. Explain

(a) The steady-state form of the control volume entropy balance requires that the total rate at which entropy is transferred out of the control volume be *less* than the total rate at which entropy enters.
(b) In *statistical* thermodynamics, entropy is associated with the notion of microscopic *disorder*.
(c) For a gas modeled as an ideal gas, the specific internal energy, enthalpy, and entropy all depend on temperature only.
(d) The entropy change between two states of water can be read *directly* from the *steam tables*.
(e) The *increase of entropy principle* states that the only processes of an isolated system are those for which its entropy increases.
(f) Equation 6.52, the *Bernoulli* equation, applies generally to one-inlet, one-exit control volumes at steady state, whether internal irreversibilities are present or not.

6.189 Answer the following true or false. Explain

(a) The only entropy transfer to, or from, control volumes is that accompanying heat transfer.

(b) Heat transfer for internally reversible processes of closed systems can be represented on a temperature–entropy diagram as an area.

(c) For a specified inlet state, exit pressure, and mass flow rate, the power developed by a turbine operating at steady state is less than if expansion occurred isentropically.

(d) The entropy change between two states of air modeled as an ideal gas can be *directly* read from Table A-22 only when pressure at these states is the same.

(e) The term *isothermal* means constant temperature, whereas *isentropic* means constant specific volume.

(f) When a system undergoes a *Carnot* cycle, entropy is produced within the system.

▶ DESIGN & OPEN-ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE

6.1D Using the ENERGY STAR® home improvement tool box, obtain a rank-ordered list of the top three cost-effective improvements that would enhance the overall energy efficiency of your home. Develop a plan to implement the improvements. Write a report, including at least three references.

6.2D Ocean thermal energy conversion (OTEC) power plants generate electricity on ships or platforms at sea by exploiting the naturally occurring decrease of the temperature of ocean water with depth. One proposal for the use of OTEC-generated electricity is to produce and commercialize ammonia in three steps: Hydrogen (H_2) would first be obtained by electrolysis of desalted sea water. The hydrogen then would be reacted with nitrogen (N_2) from the atmosphere to obtain ammonia (NH_3). Finally, liquid ammonia would be shipped to shore, where it would be reprocessed into hydrogen or used as a feedstock. Some say a major drawback with the proposal is whether *current technology* can be integrated to provide cost-competitive end products. Investigate this issue and summarize your findings in a report with at least three references.

6.3D Natural gas is currently playing a significant role in meeting our energy needs and hydrogen may be just as important in years ahead. For natural gas *and* hydrogen, energy is required at every stage of distribution between production and end use: for storage, transportation by pipelines, trucks, trains and ships, and liquefaction, if needed. According to some observers, distribution energy requirements will weigh more heavily on hydrogen not only because it has special attributes but also because means for distributing it are less developed than for natural gas. Investigate the energy requirements for distributing hydrogen relative to that for natural gas. Write a report with at least three references.

6.4D For a compressor or pump located at your campus or workplace, take data sufficient for evaluating the isentropic compressor or pump efficiency. Compare the experimentally determined isentropic efficiency with data provided by the manufacturer. Rationalize any significant discrepancy between experimental and manufacturer values. Prepare a technical report including a full description of instrumentation, recorded data, results and conclusions, and at least three references.

6.5D Classical economics was developed largely in analogy to the notion of mechanical equilibrium. Some observers are now saying that a macroeconomic system is more like a thermodynamic system than a mechanical one. Further, they say the failure of traditional economic theories to account for recent economic behavior may be partially due to not recognizing the role of entropy in controlling economic change and equilibrium, similar to the role of entropy in thermodynamics. Write a report, including at least three references, on how the second law and entropy are used in economics.

6.6D Design and execute an experiment to obtain measured property data required to evaluate the change in entropy of a common gas, liquid, or solid undergoing a process of your choice. Compare the experimentally determined entropy change with a value obtained from published engineering data, including property software. Rationalize any significant discrepancy between values. Prepare a technical report including a full description of the experimental set-up and instrumentation, recorded data, sample calculations, results and conclusions, and at least three references.

6.7D The *maximum entropy method* is widely used in the field of astronomical data analysis. Over the last three decades, considerable work has been done using the method for data filtering and removing features in an image that are caused by the telescope itself rather than from light coming from the sky (called deconvolution). To further such aims, refinements of the method have evolved over the years. Investigate the maximum entropy method as it is used today in astronomy, and summarize the state-of-the-art in a memorandum.

6.8D The performance of turbines, compressors, and pumps decreases with use, reducing isentropic efficiency. Select one of these three types of components and develop a detailed understanding of how the component functions. Contact a manufacturer's representative to learn what measurements are typically recorded during operation, causes of degraded performance with use, and maintenance actions that can be taken to extend service life. Visit an industrial site where the selected component can be observed in operation and discuss the same points with personnel there. Prepare a poster presentation of your findings suitable for classroom use.

6.9D Elementary thermodynamic modeling, including the use of the temperature–entropy diagram for water and a form of the *Bernoulli equation* has been employed to study certain types of volcanic eruptions. (See L. G. Mastin, "Thermodynamics of Gas and Steam-Blast Eruptions," *Bull. Volcanol.*, 57, 85–98, 1995.) Write a report *critically evaluating* the underlying assumptions and application of thermodynamic principles, as reported in the article. Include at least three references.

6.10D In recent decades, many have written about the relationship between life in the biosphere and the second law of thermodynamics. Among these are Nobel Prize winners Erwin Schrodinger (Physics, 1933) and Ilya Prigogine (Chemistry, 1977). Contemporary observers such as Eric Schneider also have weighed in. Survey and *critically evaluate* such contributions to the literature. Summarize your conclusions in a report having at least three references.

6.11D Figure P6.11D shows an air compressor fitted with a water jacket fed from an existing water line accessible at a location 50 feet horizontally and 10 feet below the connection port on the water jacket. The compressor is a single-stage, double-acting, horizontal reciprocating compressor with a discharge pressure of 50 psig when compressing ambient air. Water at 45°F experiences a 10°F temperature rise as it flows through the jacket at a flow rate of 300 gal per hour. Design a cooling water piping system to meet these needs. Use standard pipe sizes and fittings and an appropriate off-the-shelf pump with a single-phase electric motor. Prepare a technical report including a diagram of the piping system, a full parts list, the pump specifications, an estimate of installed cost, and sample calculations.
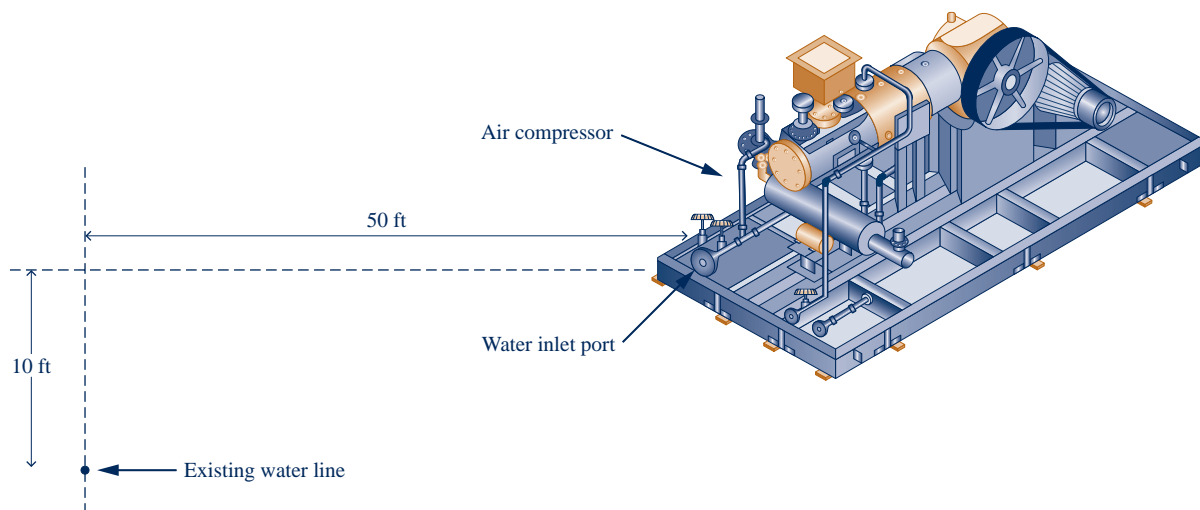

Fig. P6.11D