The use of mass and energy balances for control volumes at steady state is illustrated for nozzles and diffusers, turbines, compressors and pumps, heat exchangers, throttling devices, and integrated systems. An essential aspect of all such applications is the careful and explicit listing of appropriate assumptions. Such model-building skills are stressed throughout the chapter.

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

- write out the meanings of the terms listed in the margins throughout the chapter and explain each of the related concepts. The subset of key concepts listed below is particularly important in subsequent chapters.
- list the typical modeling assumptions for nozzles and diffusers, turbines, compressors and pumps, heat exchangers, and throttling devices.
- apply Eqs. 4.6, 4.18, and 4.20 to control volumes at steady state, using appropriate assumptions and property data for the case at hand.
- apply mass and energy balances for the transient analysis of control volumes, using appropriate assumptions and property data for the case at hand.

▶ KEY ENGINEERING CONCEPTS

conservation of mass, p. 170
mass flow rates, p. 170
mass rate balance, p. 170
one-dimensional flow, p. 172
volumetric flow rate, p. 173
steady state, p. 173
mass flux, p. 173
flow work, p. 179
energy rate balance, p. 180
nozzle, p. 183
diffuser, p. 183
turbine, p. 186
compressor, p. 190
pump, p. 190
heat exchanger, p. 195
throttling calorimeter, p. 200
throttling process, p. 201
system integration, p. 202
transient operation, p. 205

▶ KEY EQUATIONS

$\dot{m} = \dfrac{\text{AV}}{v}$	**(4.4b) p. 172**	**Mass flow rate, one-dimensional flow. (See Fig. 4.3.)**
$\dfrac{dm_{\text{cv}}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$	**(4.2) p. 170**	**Mass rate balance.**
$\underset{\text{(mass rate in)}}{\sum_i \dot{m}_i} = \underset{\text{(mass rate out)}}{\sum_e \dot{m}_e}$	**(4.6) p. 173**	**Mass rate balance at steady state.**
$\dfrac{dE_{\text{cv}}}{dt} = \dot{Q}_{\text{cv}} - \dot{W}_{\text{cv}} + \sum_i \dot{m}_i\left(h_i + \dfrac{\text{V}_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(h_e + \dfrac{\text{V}_e^2}{2} + gz_e\right)$	**(4.15) p. 180**	**Energy rate balance.**
$0 = \dot{Q}_{\text{cv}} - \dot{W}_{\text{cv}} + \sum_i \dot{m}_i\left(h_i + \dfrac{\text{V}_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(h_e + \dfrac{\text{V}_e^2}{2} + gz_e\right)$	**(4.18) p. 181**	**Energy rate balance at steady state.**
$0 = \dot{Q}_{\text{cv}} - \dot{W}_{\text{cv}} + \dot{m}\left[(h_1 - h_2) + \dfrac{(\text{V}_1^2 - \text{V}_2^2)}{2} + g(z_1 - z_2)\right]$	**(4.20a) p. 181**	**Energy rate balance for one-inlet, one-exit control volumes at steady state.**
$0 = \dfrac{\dot{Q}_{\text{cv}}}{\dot{m}} - \dfrac{\dot{W}_{\text{cv}}}{\dot{m}} + (h_1 - h_2) + \dfrac{(\text{V}_1^2 - \text{V}_2^2)}{2} + g(z_1 - z_2)$	**(4.20b) p. 181**	
$h_2 = h_1 \quad (p_2 < p_1)$	**(4.22) p. 201**	**Throttling process. (See Fig. 4.15.)**

▶ EXERCISES: THINGS ENGINEERS THINK ABOUT

1. How does the control volume energy rate balance account for work where mass flows across the boundary?
2. When a drip coffeemaker on-off switch is turned to the *on* position, how is cold water in the water reservoir converted to hot water and sent upward to drip down into the coffee grounds in the filter?
3. When a hair dryer on-off switch is turned to the *on* position, is the hair dryer in steady-state operation, transient operation, or both?
4. As a tree grows, its mass increases. Does this violate the conservation of mass principle? Explain.
5. Wind turbines and hydraulic turbines develop mechanical power from moving streams of air and water, respectively. In each case, what aspect of the stream is tapped for power?
6. When selecting a pump to remove water from a flooded basement, how does one size the pump to ensure that it is suitable?
7. How does a heart-lung machine maintain blood circulation and oxygen content during surgery?
8. Where do you encounter *microelectromechanical* systems in daily life?
9. Where are compressors found within households?
10. How does the operator of a pumper-tanker fire engine control water flow to all the hoses in use?
11. For air flowing through a converging-diverging channel, sketch the variation of the air pressure as air accelerates in the converging section and decelerates in the diverging section.
12. In what subsystems are pumps found in automobiles?
13. If the expansion valve of a refrigerator becomes ice encased, does the *throttling process* model still apply? Explain.
14. For a home heating or cooling system commonly used in your locale, what types of heat exchangers and working fluids are employed?
15. What are intra-articular pain pumps?

▶ CHECKING UNDERSTANDING

For problems 1–5, match the appropriate definition in the right column with each term in the left column.

1. __ Compressor	**A.** A device in which power is developed as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate
2. __ Diffuser	**B.** A device in which work is done on a gas to increase the pressure and/or elevation
3. __ Nozzle	**C.** A device in which work is done on a liquid to increase the pressure and/or elevation
4. __ Pump	**D.** A flow passage of varying cross-sectional area in which the velocity of a gas or liquid increases in the direction of flow
5. __ Turbine	**E.** A flow passage of varying cross-sectional area in which the velocity of a gas or liquid decreases in the direction of flow

6. Liquid flows at steady state at a rate of 2 lb/s through a pump, which operates to raise the elevation of the liquid 100 ft from control volume inlet to exit. The liquid specific enthalpy at the inlet is 40.09 Btu/lb and at the exit is 40.94 Btu/lb. The pump requires 3 Btu/s of power to operate. If kinetic energy effects are negligible and gravitational acceleration is 32.174 ft/s^2, the heat transfer rate associated with this steady-state process is most closely

   (a) 1.04 Btu/s from the liquid to the surroundings
   (b) 2.02 Btu/s from the liquid to the surroundings
   (c) 3.98 Btu/s from the surroundings to the liquid
   (d) 4.96 Btu/s from the surroundings to the liquid

7. A flow idealized as a throttling process through a device has

   (a) $h_2 > h_1$ and $p_2 > p_1$
   (b) $h_2 = h_1$ and $p_2 > p_1$
   (c) $h_2 > h_1$ and $p_2 < p_1$
   (d) $h_2 = h_1$ and $p_2 < p_1$

8. ____________ is the work associated with the fluid pressure as mass is introduced at inlets and removed at exits.

9. Steady flow devices that result in a drop in working fluid pressure from inlet to exit are

   (a) Nozzle, pump, throttling device
   (b) Diffuser, turbine, throttling device
   (c) Nozzle, turbine, throttling device
   (d) Diffuser, pump, throttling device

10. Steam enters a horizontal pipe operating at steady state with a specific enthalpy of 3000 kJ/kg and a mass flow rate of 0.5 kg/s. At the exit, the specific enthalpy is 1700 kJ/kg. If there is no significant change in kinetic energy from inlet to exit, the rate of heat transfer between the pipe and its surroundings is

    (a) 650 kW from the pipe to the surroundings
    (b) 650 kW from the surroundings to the pipe
    (c) 2600 kW from the pipe to the surroundings
    (d) 2600 kW from the surroundings to the pipe

11. A ____________ is a device that introduces a restriction into a line to reduce the pressure of a gas or liquid.

12. The time rate of change of the energy contained within a one-inlet, one-exit control volume at time t equals

(a) $\dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$

(b) $\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$

(c) $\dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_i\left(u_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_e\left(u_e + \frac{V_e^2}{2} + gz_e\right)$

(d) $\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i\left(u_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_e\left(u_e + \frac{V_e^2}{2} + gz_e\right)$

13. The time rate of mass flow per unit area is called

(a) Mass flow rate
(b) Volumetric flow rate
(c) Velocity
(d) Mass flux

14. ____________ means all properties are unchanging in time.

15. Steam enters a turbine operating at steady state with a specific enthalpy of 1407.6 Btu/lb and expands to the turbine exit where the specific enthalpy is 1236.4 Btu/lb. The mass flow rate is 5 lb/s. During this process, heat transfer to the surroundings occurs at a rate of 40 Btu/s. Neglecting kinetic and potential energy effects, the power developed by the turbine is

(a) 896 Btu/s (c) 656 Btu/s
(b) 816 Btu/s (d) 74.2 Btu/s

16. Air enters a compressor operating at steady state at 1 atm with a specific enthalpy of 290 kJ/kg and exits at a higher pressure with a specific enthalpy of 1023 kJ/kg. The mass flow rate is 0.1 kg/s. Kinetic and potential energy effects are negligible and the air can be modeled as an ideal gas. If the compressor power input is 77 kW, the rate of heat transfer between the air and its surroundings is

(a) 150.3 kW from the surroundings to the air
(b) 150.3 kW from the air to the surroundings
(c) 3.7 kW from the surroundings to the air
(d) 3.7 kW from the air to the surroundings

17. ____________ operation involves state changes with time.

18. Water vapor enters an insulated nozzle operating at steady state with a velocity of 100 m/s and specific enthalpy of 3445.3 kJ/kg, and exits with specific enthalpy of 3051.1 kJ/kg. The velocity at the exit is most closely

(a) 104 m/s (c) 888 m/s
(b) 636 m/s (d) 894 m/s

19. A horizontal air diffuser operates with inlet velocity and specific enthalpy of 250 m/s and 270.11 kJ/kg, respectively, and exit specific enthalpy of 297.31 kJ/kg. For negligible heat transfer with the surroundings, the exit velocity is

(a) 223 m/s (c) 90 m/s
(b) 196 m/s (d) 70 m/s

20. Mass flow rate for a flow modeled as one-dimensional depends on all except

(a) Density of working fluid
(b) Cross-sectional area through which flow passes
(c) Velocity of working fluid
(d) Total volume of working fluid

21. As velocity increases in a nozzle, pressure ____________.

22. Why does the relative velocity *normal* to the flow boundary, V_n, appear in Eqs. 4.3 and 4.8?

23. The mass flow rate of steam with pressure of 800 lbf/in.^{2}, temperature of 900°F, and velocity of 30 ft/s flowing through a 6-in.-diameter pipe is most closely.

(a) 5.68 lb/s (c) 6.11 lb/s
(b) 5.89 lb/s (d) 7.63 lb/s

24. The mechanisms of energy transfer for a control volume are ____________, ____________, and ____________.

Indicate whether the following statements are true or false. Explain.

25. For one-dimensional flow, mass flow rate is the product of density, area, and velocity.

26. At steady state, conservation of mass asserts the total rate at which mass enters the control volume equals the total rate at which mass exits.

27. At steady state, conservation of energy asserts the total rate at which energy is transferred into the control volume equals the total rate at which energy is transferred out.

28. Hydropower is a nonrenewable means for producing electricity.

29. As velocity decreases in a diffuser, pressure decreases.

30. Compressor types include reciprocating, axial flow, centrifugal, and Roots type.

31. Common heat exchanger types include direct-contact, counterflow, parallel-flow, and cross-flow heat exchangers.

32. A mixing chamber is a direct-contact heat exchanger.

33. A significant increase in pressure can be achieved by introducing a restriction into a line through which a gas or liquid flows.

34. Volumetric flow rate is expressed in units of m^3/s or ft^3/s.

35. System integration is the practice of combining components to achieve an overall objective.

36. For a control volume at steady state, mass can accumulate within the control volume.

37. Factors that may allow one to model a control volume as having negligible (zero) heat transfer include (1) the outer surface of the control volume is well insulated, (2) the outer surface area of the control volume is too small to permit effective heat transfer, (3) the temperature difference between the control volume and its surroundings is so small that the heat transfer can be ignored, and (4) the working fluid passes through the control volume so quickly that there is not enough time for significant heat transfer to occur.

38. For a one-inlet, one-exit control volume at steady state, the mass flow rates at the inlet and exit are equal but the inlet and exit *volumetric* flow rates may not be equal.

39. *Flow work* is the work done on a flowing stream by a paddle wheel or piston.

40. *Transient* operation denotes a change in state with time.

41. In this book the flow at control volume inlets and exits is normally taken as *one-dimensional*.

42. Where mass crosses the boundary of a control volume, the accompanying energy transfer is accounted for by the internal energy of the mass only.

43. A *diffuser* is a flow passage of varying cross-sectional area in which the velocity of a gas or liquid increases in the direction of flow.

44. The human body is an example of an *integrated* system.

45. When a substance undergoes a *throttling process* through a valve, the specific enthalpies of the substance at the valve inlet and valve exit are equal.

46. The hot and cold streams of *cross-flow* heat exchangers flow in the same direction.

47. The thermodynamic performance of a device such as a turbine through which mass flows is best analyzed by studying the flowing mass alone.

48. For *every* control volume at steady state, the total of the entering rates of mass flow equals the total of the exiting rates of mass flow.

49. An *open feedwater* heater is a special type of a counterflow heat exchanger.

50. A key step in thermodynamic analysis is the careful listing of modeling assumptions.

51. An automobile's radiator is an example of a cross-flow heat exchanger.

52. At steady state, identical electric fans discharging air at the same temperature in New York City and Denver will deliver the same volumetric flow rate of air.

▶ PROBLEMS: DEVELOPING ENGINEERING SKILLS

Evaluating Mass Flow Rate

4.1 A *laser Doppler velocimeter* measures a velocity of 8 m/s as water flows in an open channel. The channel has a rectangular cross section of 0.5 m by 0.2 m in the flow direction. If the water density is a constant 998 kg/m^3, determine the mass flow rate, in kg/s.

4.2 Refrigerant 134a exits a heat exchanger through 0.75-in.-diameter tubing with a mass flow rate of 0.9 lb/s. The temperature and quality of the refrigerant are –15°F and 0.05, respectively. Determine the velocity of the refrigerant, in m/s.

4.3 Steam enters a 1.6-cm-diameter pipe at 80 bar and 600°C with a velocity of 150 m/s. Determine the mass flow rate, in kg/s.

4.4 Air modeled as an ideal gas enters a combustion chamber at 20 lbf/in.^{2} and 70°F through a rectangular duct, 5 ft by 4 ft. If the mass flow rate of the air is 830,000 lb/h, determine the velocity, in ft/s.

4.5 Air exits a turbine at 200 kPa and 150°C with a volumetric flow rate of 7000 liters/s. Modeling air as an ideal gas, determine the mass flow rate, in kg/s.

4.6 If a kitchen-sink water tap leaks one drop per second, how many gallons of water are wasted annually? What is the mass of the wasted water, in lb? Assume that there are 46,000 drops per gallon and that the density of water is 62.3 lb/ft^3.

Applying Conservation of Mass

4.7 Figure P4.7 provides data for water entering and exiting a tank. At the inlet and exit of the tank, determine the mass flow rate, each in kg/s. Also find the time rate of change of mass contained within the tank, in kg/s.

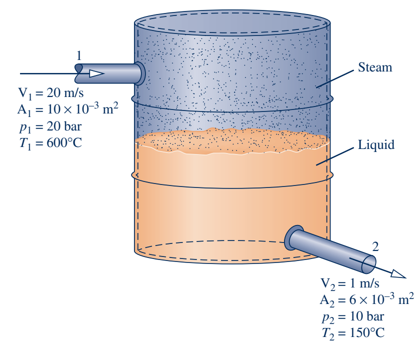


Fig. P4.7

4.8 Figure P4.8 shows a mixing tank initially containing 2000 lb of liquid water. The tank is fitted with two inlet pipes, one delivering hot water at a mass flow rate of 0.8 lb/s and the other delivering cold water at a mass flow rate of 1.2 lb/s. Water exits through a single exit pipe at a mass flow rate of 2.5 lb/s. Determine the amount of water, in lb, in the tank after one hour.

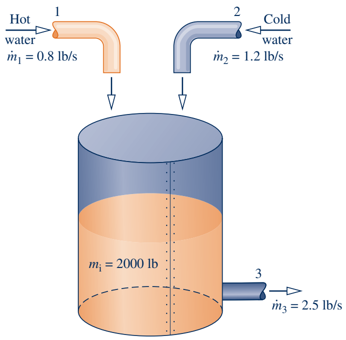


Fig. P4.8

4.9 A 380-L tank contains steam, initially at 400°C, 3 bar. A valve is opened, and steam flows out of the tank at a constant mass flow rate of 0.005 kg/s. During steam removal, a heater maintains the temperature within the tank constant. Determine the time, in s, at which 75% of the initial mass remains in the tank; also determine the specific volume, in m^3/kg, and pressure, in bar, in the tank at that time.

4.10 Data are provided for the crude oil storage tank shown in Fig. P4.10. The tank initially contains 1000 m^3 of crude oil. Oil is pumped into the tank through a pipe at a rate of 2 m^3/min and out of the tank at a velocity of 1.5 m/s through another pipe having a diameter of 0.15 m. The crude oil has a specific volume of 0.0015 m^3/kg. Determine

(a) the mass of oil in the tank, in kg, after 24 hours, and
(b) the volume of oil in the tank, in m^3, at that time.

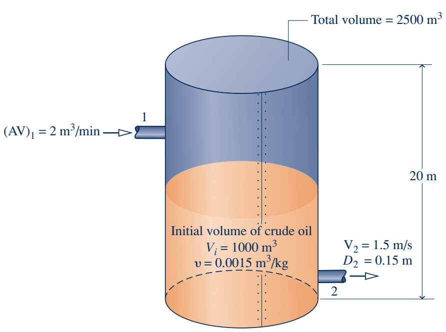


Fig. P4.10

4.11 An 8-ft^3 tank contains air at an initial temperature of 80°F and initial pressure of 100 lbf/in.^{2} The tank develops a small hole, and air leaks from the tank at a constant rate of 0.03 lb/s for 90 s until the pressure of the air remaining in the tank is 30 lbf/in.^{2} Employing the ideal gas model, determine the final temperature, in °F, of the air remaining in the tank.

4.12 Liquid propane enters an initially empty cylindrical storage tank at a mass flow rate of 10 kg/s. Flow continues until the tank is filled with propane at 20°C, 9 bar. The tank is 25 m long and has a 4-m diameter. Determine the time, in minutes, to fill the tank.

4.13 As shown in Fig. P4.13, river water used to irrigate a field is controlled by a gate. When the gate is raised, water flows steadily with a velocity of 75 ft/s through an opening 8 ft by 3 ft. If the gate is raised for 24 hours, determine the volume of water, in gallons, provided for irrigation. Assume the density of river water is 62.3 lb/ft^3.

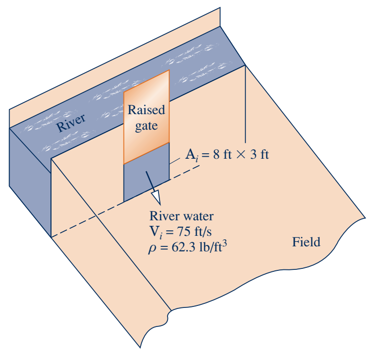


Fig. P4.13

4.14 Figure P4.14 shows a two-tier fountain operating with basins A and B. Both basins are initially empty. When the fountain is turned on, water flows with a constant mass flow rate of 10 kg/s into basin A. Water overflows from basin A into basin B. Thereafter, water drains from basin B at a rate of $5L_B$ kg/s, where L_B is the height of the water in basin B, in m. Dimensions of the basins are indicated on the figure. Determine the variation of water height in each basin as a function of time. The density of water is constant at 1000 kg/m^3.

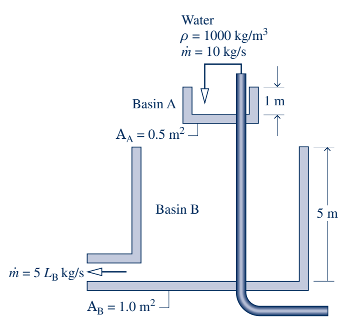


Fig. P4.14

4.15 Liquid water flows isothermally at 20°C through a one-inlet, one-exit duct operating at steady state. The duct's inlet and exit diameters are 0.02 m and 0.04 m, respectively. At the inlet, the velocity is 40 m/s and pressure is 1 bar. At the exit, determine the mass flow rate, in kg/s, and velocity, in m/s.

4.16 Air enters a one-inlet, one-exit control volume at 6 bar, 500 K, and 30 m/s through a flow area of 28 cm^2. At the exit, the pressure is 3 bar, the temperature is 456.5 K, and the velocity is 300 m/s. The air behaves as an ideal gas. For steady-state operation, determine

(a) the mass flow rate, in kg/s.
(b) the exit flow area, in cm^2.

4.17 As shown in Fig. P4.17, air with a volumetric flow rate of 15,000 ft^3/min enters an air-handling unit at 35°F, 1 atm. The air-handling unit delivers air at 80°F, 1 atm to a duct system with three branches consisting of two 26-in.-diameter ducts and one 50-in. duct. The velocity in each 26-in. duct is 10 ft/s. Assuming ideal gas behavior for the air, determine at steady state

(a) the mass flow rate of air entering the air-handling unit, in lb/s.
(b) the volumetric flow rate in each 26-in. duct, in ft^3/min.
(c) the velocity in the 50-in. duct, in ft/s.

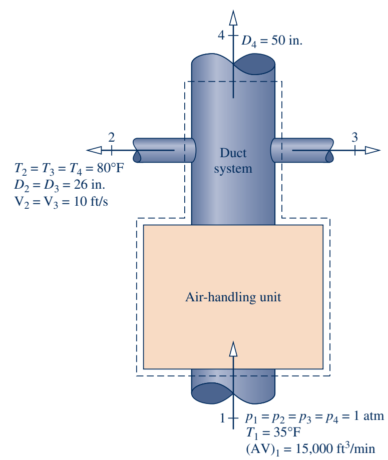


Fig. P4.17

4.18 Refrigerant 134a enters the evaporator of a refrigeration system operating at steady state at −4°C and quality of 20% at a velocity of 7 m/s. At the exit, the refrigerant is a saturated vapor at a temperature of −4°C. The evaporator flow channel has constant diameter. If the mass flow rate of the entering refrigerant is 0.1 kg/s, determine

(a) the diameter of the evaporator flow channel, in cm.
(b) the velocity at the exit, in m/s.

4.19 As shown in Fig. P4.19, steam at 80 bar, 440°C, enters a turbine operating at steady state with a volumetric flow rate of 236 m^3/min. Twenty percent of the entering mass flow exits through a diameter of 0.25 m at 60 bar, 400°C. The rest exits through a diameter of 1.5 m with a pressure of 0.7 bar and a quality of 90%. Determine the velocity at each exit duct, in m/s.

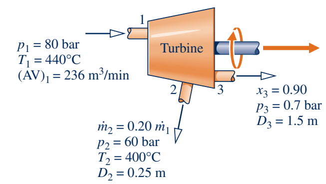


Fig. P4.19

4.20 Figure P4.20 provides steady-state data for water vapor flowing through a piping configuration. At each exit, the volumetric flow rate, pressure, and temperature are equal. Determine the mass flow rate at the inlet and exits, each in kg/s.

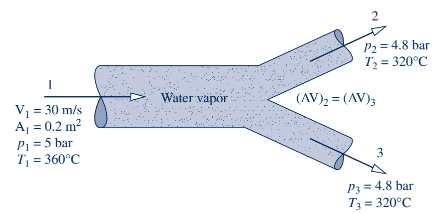


Fig. P4.20

4.21 Air enters a compressor operating at steady state with a pressure of 14.7 lbf/in.^{2} and a volumetric flow rate of 8 ft^3/s. The air velocity in the exit pipe is 225 ft/s and the exit pressure is 150 lbf/in.^{2} If each unit mass of air passing from inlet to exit undergoes a process described by $pv^{1.3}$ = *constant*, determine the diameter of the exit pipe, in inches.

4.22 Ammonia enters a control volume operating at steady state at p_1 = 16 bar, T_1 = 32°C, with a mass flow rate of 1.5 kg/s. Saturated vapor at 6 bar leaves through one exit and saturated liquid at 6 bar leaves through a second exit with a volumetric flow rate of 0.10 m^3/min. Determine

(a) the minimum diameter of the inlet pipe, in cm, so the ammonia velocity at the inlet does not exceed 18 m/s.
(b) the volumetric flow rate of the exiting saturated vapor, in m^3/min.

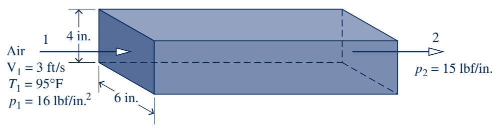


Fig. P4.23

4.23 Figure P4.23 provides steady-state data for air flowing through a rectangular duct. Assuming ideal gas behavior for the air, determine the inlet volumetric flow rate, in ft^3/s, and inlet mass flow rate, in kg/s. If you can determine the volumetric flow rate and mass flow rate at the exit, evaluate them. If not, explain.

Energy Analysis of Control Volumes at Steady State

4.24 Refrigerant 134a enters a horizontal pipe operating at steady state at 40°C, 300 kPa, and a velocity of 40 m/s. At the exit, the temperature is 50°C and the pressure is 240 kPa. The pipe diameter is 0.04 m. Determine (a) the mass flow rate of the refrigerant, in kg/s, (b) the velocity at the exit, in m/s, and (c) the rate of heat transfer between the pipe and its surroundings, in kW.

4.25 As shown in Fig. P4.25, air enters a pipe at 25°C, 100 kPa with a volumetric flow rate of 23 m^3/h. On the outer pipe surface is an electrical resistor covered with insulation. With a voltage of 120 V, the resistor draws a current of 4 amps. Assuming the ideal gas model with c_p = 1.005 kJ/kg · K for air and ignoring kinetic and potential energy effects, determine (a) the mass flow rate of the air, in kg/h, and (b) the temperature of the air at the exit, in °C.

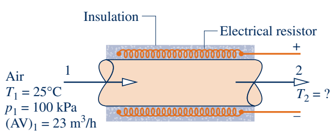


Fig. P4.25

4.26 Air enters a horizontal, constant-diameter heating duct operating at steady state at 290 K, 1 bar, with a volumetric flow rate of 0.25 m^3/s, and exits at 325 K, 0.95 bar. The flow area is 0.04 m^2. Assuming the ideal gas model with k = 1.4 for the air, determine (a) the mass flow rate, in kg/s, (b) the velocity at the inlet and exit, each in m/s, and (c) the rate of heat transfer, in kW.

4.27 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, and (b) the mass flow rate, in kg/s.

4.28 At steady state, air at 200 kPa, 325 K, and mass flow rate of 0.5 kg/s enters an insulated duct having differing inlet and exit cross-sectional areas. The inlet cross-sectional area is 6 cm^2. At the duct exit, the pressure of the air is 100 kPa and the velocity is 250 m/s. Neglecting potential energy effects and modeling air as an ideal gas with constant c_p = 1.008 kJ/kg · K, determine

(a) the velocity of the air at the inlet, in m/s.
(b) the temperature of the air at the exit, in K.
(c) the exit cross-sectional area, in cm^2.

4.29 Refrigerant 134a flows at steady state through a horizontal tube having an inside diameter of 0.05 m. The refrigerant enters the tube with a quality of 0.1, temperature of 36°C, and velocity of 10 m/s. The refrigerant exits the tube at 9 bar as a saturated liquid. Determine

(a) the mass flow rate of the refrigerant, in kg/s.
(b) the velocity of the refrigerant at the exit, in m/s.
(c) the rate of heat transfer, in kW, and its associated direction with respect to the refrigerant.

4.30 As shown in Fig. P4.30, electronic components mounted on a flat plate are cooled by convection to the surroundings and by liquid water circulating through a U-tube bonded to the plate. At steady state, water enters the tube at 20°C and a velocity of 0.4 m/s and exits at 24°C with a negligible change in pressure. The electrical components receive 0.5 kW of electrical power. The rate of energy transfer by convection from the plate-mounted electronics is estimated to be 0.08 kW. Kinetic and potential energy effects can be ignored. Determine the tube diameter, in cm.

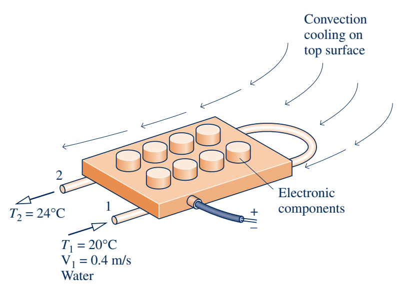


Fig. P4.30

4.31 Steam enters a nozzle operating at steady state at 20 bar, 280°C, with a velocity of 80 m/s. The exit pressure and temperature are 7 bar and 180°C, respectively. The mass flow rate is 1.5 kg/s. Neglecting heat transfer and potential energy, determine

(a) the exit velocity, in m/s.
(b) the inlet and exit flow areas, in cm^2.

4.32 Refrigerant 134a enters a well-insulated nozzle at 200 lbf/in.^{2}, 220°F, with a velocity of 120 ft/s and exits at 20 lbf/in.^{2} with a velocity of 1500 ft/s. For steady-state operation, and neglecting potential energy effects, determine the exit temperature, in °F.

4.33 Air enters a nozzle operating at steady state at 720°R with negligible velocity and exits the nozzle at 500°R with a velocity of 1450 ft/s. Assuming ideal gas behavior and neglecting potential energy effects, determine the heat transfer in Btu per lb of air flowing.

4.34 Air with a mass flow rate of 2.3 kg/s enters a horizontal nozzle operating at steady state at 450 K, 350 kPa, and velocity of 3 m/s. At the exit, the temperature is 300 K and the velocity is 460 m/s. Using the ideal gas model for air with constant c_p = 1.011 kJ/kg · K, determine

(a) the area at the inlet, in m^2.
(b) the heat transfer between the nozzle at its surroundings, in kW. Specify whether the heat transfer is to or from the air.

4.35 Helium gas flows through a well-insulated nozzle at steady state. The temperature and velocity at the inlet are 550°R and 150 ft/s, respectively. At the exit, the temperature is 400°R and the pressure is 40 lbf/in.^{2} The area of the exit is 0.0085 ft^2. Using the ideal gas model with k = 1.67, and neglecting potential energy effects, determine the mass flow rate, in lb/s, through the nozzle.

4.36 Nitrogen, modeled as an ideal gas, flows at a rate of 3 kg/s through a well-insulated horizontal nozzle operating at steady state. The nitrogen enters the nozzle with a velocity of 20 m/s at 340 K, 400 kPa and exits the nozzle at 100 kPa. To achieve an exit velocity of 478.8 m/s, determine

(a) the exit temperature, in K.
(b) the exit area, in m^2.

4.37 As shown in Fig. P4.37, air enters the diffuser of a jet engine operating at steady state at 18 kPa, 216 K and a velocity of 265 m/s, all data corresponding to high-altitude flight. The air flows adiabatically through the diffuser and achieves a temperature of 250 K at the diffuser exit. Using the ideal gas model for air, determine the velocity of the air at the diffuser exit, in m/s.

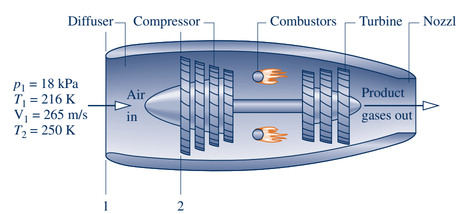


Fig. P4.37

4.38 Air enters a diffuser operating at steady state at 540°R, 15 lbf/in.^{2}, with a velocity of 600 ft/s, and exits with a velocity of 60 ft/s. The ratio of the exit area to the inlet area is 8. Assuming the ideal gas model for the air and ignoring heat transfer, determine the temperature, in °R, and pressure, in lbf/in.^{2}, at the exit.

4.39 Refrigerant 134a enters an insulated diffuser as a saturated vapor at 80°F with a velocity of 1453.4 ft/s. At the exit, the temperature is 280°F and the velocity is negligible. The diffuser operates at steady state and potential energy effects can be neglected. Determine the exit pressure, in lbf/in.^{2}

4.40 Oxygen gas enters a well-insulated diffuser at 30 lbf/in.^{2}, 440°R, with a velocity of 950 ft/s through a flow area of 2.0 in.^{2} At the exit, the flow area is 15 times the inlet area, and the velocity is 25 ft/s. The potential energy change from inlet to exit is negligible. Assuming ideal gas behavior for the oxygen and steady-state operation of the diffuser, determine the exit temperature, in °R, the exit pressure, in lbf/in.^{2}, and the mass flow rate, in lb/s.

4.41 Air modeled as an ideal gas enters a well-insulated diffuser operating at steady state at 270 K with a velocity of 180 m/s and exits with a velocity of 48.4 m/s. For negligible potential energy effects, determine the exit temperature, in K.

4.42 Steam enters a well-insulated turbine operating at steady state at 4 MPa with a specific enthalpy of 3015.4 kJ/kg and a velocity of 10 m/s. The steam expands to the turbine exit where the pressure is 0.07 MPa, specific enthalpy is 2431.7 kJ/kg, and the velocity is 90 m/s. The mass flow rate is 11.95 kg/s. Neglecting potential energy effects, determine the power developed by the turbine, in kW.

4.43 Air expands through a turbine from 8 bar, 960 K to 1 bar, 450 K. The inlet velocity is small compared to the exit velocity of 90 m/s. The turbine operates at steady state and develops a power output of 2500 kW. Heat transfer between the turbine and its surroundings and potential energy effects are negligible. Modeling air as an ideal gas, calculate the mass flow rate of air, in kg/s, and the exit area, in m^2.

4.44 Air expands through a turbine operating at steady state. At the inlet, p_1 = 150 lbf/in.^{2}, T_1 = 1400°R, and at the exit, p_2 = 14.8 lbf/in.^{2}, T_2 = 700°R. The mass flow rate of air entering the turbine is 11 lb/s, and 65,000 Btu/h of energy is rejected by heat transfer. Neglecting kinetic and potential energy effects, determine the power developed, in hp.

4.45 Steam enters a turbine operating at steady state at 700°F and 450 lbf/in.^{2} and leaves as a saturated vapor at 1.2 lbf/in.^{2} The turbine develops 12,000 hp, and heat transfer from the turbine to the surroundings occurs at a rate of 2×10^6 Btu/h. Neglecting kinetic and potential energy changes from inlet to exit, determine the volumetric flow rate of the steam at the inlet, in ft^3/s.

4.46 A well-insulated turbine operating at steady state develops 28.75 MW of power for a steam flow rate of 50 kg/s. The steam enters at 25 bar with a velocity of 61 m/s and exits as saturated vapor at 0.06 bar with a velocity of 130 m/s. Neglecting potential energy effects, determine the inlet temperature, in °C.

4.47 Steam enters a turbine operating at steady state with a mass flow of 10 kg/min, a specific enthalpy of 3100 kJ/kg, and a velocity of 30 m/s. At the exit, the specific enthalpy is 2300 kJ/kg and the velocity is 45 m/s. The elevation of the inlet is 3 m higher than at the exit. Heat transfer from the turbine to its surroundings occurs at a rate of 1.1 kJ per kg of steam flowing. Let $g = 9.81$ m/s^2. Determine the power developed by the turbine, in kW.

4.48 Steam enters a turbine operating at steady state at 2 MPa, 360°C with a velocity of 100 m/s. Saturated vapor exits at 0.1 MPa and a velocity of 50 m/s. The elevation of the inlet is 3 m higher than at the exit. The mass flow rate of the steam is 15 kg/s, and the power developed is 7 MW. Let $g = 9.81$ m/s^2. Determine (a) the area at the inlet, in m^2, and (b) the rate of heat transfer between the turbine and its surroundings, in kW.

4.49 Water vapor enters a turbine operating at steady state at 500°C, 40 bar, with a velocity of 200 m/s, and expands adiabatically to the exit, where it is saturated vapor at 0.8 bar, with a velocity of 150 m/s and a volumetric flow rate of 9.48 m^3/s. The power developed by the turbine, in kW, is approximately

(a) 3500, (c) 3580,
(b) 3540, (d) 7470.

4.50 Steam enters the first-stage turbine shown in Fig. P4.50 at 40 bar and 500°C with a volumetric flow rate of 90 m^3/min. Steam exits the turbine at 20 bar and 400°C. The steam is then reheated at constant pressure to 500°C before entering the second-stage turbine. Steam leaves the second stage as saturated vapor at 0.6 bar. For operation at steady state, and ignoring stray heat transfer and kinetic and potential energy effects, determine the

(a) mass flow rate of the steam, in kg/h.
(b) total power produced by the two stages of the turbine, in kW.
(c) rate of heat transfer to the steam flowing through the reheater, in kW.

4.51 Steam at 1800 lbf/in.^{2} and 1100°F enters a turbine operating at steady state. As shown in Fig. P4.51, 20% of the entering mass flow is extracted at 600 lbf/in.^{2} and 500°F. The rest of the steam exits as a saturated vapor at 1 lbf/in.^{2} The turbine develops a power output of 6.8×10^6 Btu/h. Heat transfer from the turbine to the surroundings occurs at a rate of 5×10^4 Btu/h. Neglecting kinetic and potential energy effects, determine the mass flow rate of the steam entering the turbine, in lb/s.

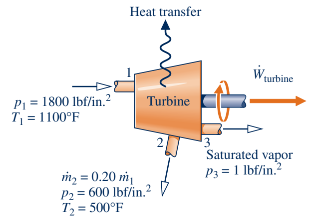


Fig. P4.51

4.52 Hot combustion gases, modeled as air behaving as an ideal gas, enter a turbine at 145 lbf/in.^{2}, 2700°R with a mass flow rate of 0.22 lb/s and exit at 29 lbf/in.^{2} and 1620°R. If heat transfer from the turbine to its surroundings occurs at a rate of 14 Btu/s, determine the power output of the turbine, in hp.

4.53 Air enters a compressor operating at steady state at 1.05 bar, 300 K, with a volumetric flow rate of 12 m^3/min and exits at 12 bar, 400 K. Heat transfer occurs at a rate of 2 kW from the compressor to its surroundings. Assuming the ideal gas model for air and neglecting kinetic and potential energy effects, determine the power input, in kW.

4.54 Nitrogen is compressed in an axial-flow compressor operating at steady state from a pressure of 15 lbf/in.^{2} and a temperature of 50°F to a pressure 60 lbf/in.^{2} The gas enters the compressor through a 6-in.-diameter duct with a velocity of 30 ft/s and exits at 198°F with a velocity of 80 ft/s. Using the ideal gas model, and neglecting stray heat transfer and potential energy effects, determine the compressor power input, in hp.

4.55 Refrigerant 134a enters a compressor operating at steady state as saturated vapor at 0.12 MPa and exits at 1.2 MPa and 70°C at a mass flow rate of 0.108 kg/s. As the refrigerant passes through the compressor, heat transfer to the surroundings occurs at a rate of 0.32 kJ/s. Determine at steady state the power input to the compressor, in kW.

4.56 Carbon dioxide gas is compressed at steady state from a pressure of 20 lbf/in.^{2} and a temperature of 32°F to a pressure of 50 lbf/in.^{2} and a temperature of 120°F. The gas enters the

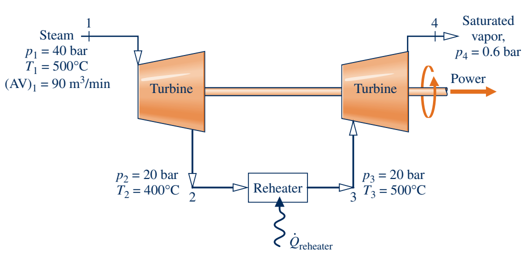


Fig. P4.50

compressor with a velocity of 30 ft/s and exits with a velocity of 80 ft/s. The mass flow rate is 0.98 lb/s. The magnitude of the heat transfer rate from the compressor to its surroundings is 5% of the compressor power input. Using the ideal gas model with $c_p = 0.21$ Btu/lb · °R and neglecting potential energy effects, determine the compressor power input, in horsepower.

4.57 At steady state, a well-insulated compressor takes in nitrogen at 60°F, 14.2 lbf/in.^{2}, with a volumetric flow rate of 1200 ft^3/min. Compressed nitrogen exits at 500°F, 120 lbf/in.^{2} Kinetic and potential energy changes from inlet to exit can be neglected. Determine the compressor power, in hp, and the volumetric flow rate at the exit, in ft^3/min.

4.58 Air enters a compressor operating at steady state with a pressure of 14.7 lbf/in.^{2}, a temperature of 80°F, and a volumetric flow rate of 18 ft^3/s. The air exits the compressor at a pressure of 90 lbf/in.^{2} Heat transfer from the compressor to its surroundings occurs at a rate of 9.7 Btu per lb of air flowing. The compressor power input is 90 hp. Neglecting kinetic and potential energy effects and modeling air as an ideal gas, determine the exit temperature, in °F.

4.59 Refrigerant 134a enters an air conditioner compressor at 4 bar, 20°C, and is compressed at steady state to 12 bar, 80°C. The volumetric flow rate of the refrigerant entering is 4 m^3/min. The work input to the compressor is 60 kJ per kg of refrigerant flowing. Neglecting kinetic and potential energy effects, determine the heat transfer rate, in kW.

4.60 Refrigerant 134a enters an insulated compressor operating at steady state as saturated vapor at −20°C with a mass flow rate of 1.2 kg/s. Refrigerant exits at 7 bar, 70°C. Changes in kinetic and potential energy from inlet to exit can be ignored. Determine (a) the volumetric flow rates at the inlet and exit, each in m^3/s, and (b) the power input to the compressor, in kW.

4.61 Refrigerant 134a enters a water-jacketed compressor operating at steady state at −10°C, 1.4 bar, with a mass flow rate of 4.2 kg/s, and exits at 50°C, 12 bar. The compressor power required is 150 kW. Neglecting kinetic and potential energy effects, determine the rate of heat transfer to the cooling water circulating through the water jacket.

4.62 Air, modeled as an ideal gas, is compressed at steady state from 1 bar, 300 K, to 5 bar, 500 K, with 150 kW of power input. Heat transfer occurs at a rate of 20 kW from the air to cooling water circulating in a water jacket enclosing the compressor. Neglecting kinetic and potential energy effects, determine the mass flow rate of the air, in kg/s.

4.63 Air enters a compressor operating at steady state with a pressure of 14.7 lbf/in.^{2} and a temperature of 70°F. The volumetric flow rate at the inlet is 16.6 ft^3/s, and the flow area is 0.26 ft^2. At the exit, the pressure is 35 lbf/in.^{2}, the temperature is 280°F, and the velocity is 50 ft/s. Heat transfer from the compressor to its surroundings is 1.0 Btu per lb of air flowing. Potential energy effects are negligible, and the ideal gas model can be assumed for the air. Determine (a) the velocity of the air at the inlet, in ft/s, (b) the mass flow rate, in lb/s, and (c) the compressor power, in Btu/s and hp.

4.64 Air enters a compressor operating at steady state at 14.7 lbf/in.^{2} and 60°F and is compressed to a pressure of 150 lbf/in.^{2} As the air passes through the compressor, it is cooled at a rate of 10 Btu per lb of air flowing by water circulated through the compressor casing. The volumetric flow rate of the air at the inlet is 5000 ft^3/min, and the power input to the compressor is 700 hp. The air behaves as an ideal gas, there is no stray heat transfer, and kinetic and potential effects are negligible. Determine (a) the mass flow rate of the air, lb/s, and (b) the temperature of the air at the compressor exit, in °F.

4.65 As shown in Fig. P4.65, a pump operating at steady state draws water from a pond and delivers it though a pipe whose exit is 90 ft above the inlet. At the exit, the mass flow rate is 10 lb/s. There is no significant change in water temperature, pressure, or kinetic energy from inlet to exit. If the power required by the pump is 1.68 hp, determine the rate of heat transfer between the pump and its surroundings, in hp and Btu/min. Let $g = 32.0$ ft/s^2.

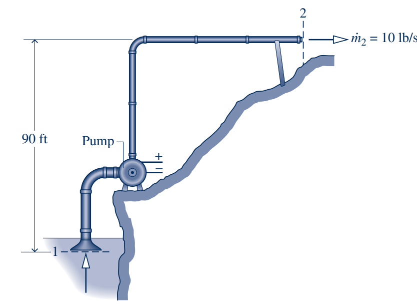


Fig. P4.65

4.66 Figure P4.66 provides steady-state operating data for a pump drawing water from a reservoir and delivering it at a pressure of 3 bar to a storage tank perched above the

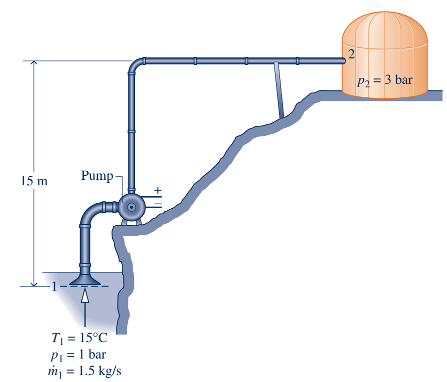


Fig. P4.66

reservoir. The mass flow rate of the water is 1.5 kg/s. The water temperature remains nearly constant at 15°C, there is no significant change in kinetic energy from inlet to exit, and heat transfer between the pump and its surroundings is negligible. Determine the power required by the pump, in kW. Let $g = 9.81$ m/s^2.

4.67 Figure P4.67 provides steady-state operating data for a submerged pump and an attached delivery pipe. At the inlet, the volumetric flow rate is 0.75 m^3/min and the temperature is 15°C. At the exit, the pressure is 1 atm. There is no significant change in water temperature or kinetic energy from inlet to exit. Heat transfer between the pump and its surroundings is negligible. Determine the power required by the pump, in kW. Let $g = 9.81$ m/s^2.

4.68 As shown in Fig. P4.68, a power washer used to clean the siding of a house has water entering through a hose at 20°C, 1 atm and a velocity of 0.2 m/s. A jet of water exits with a velocity of 20 m/s at an average elevation of 5 m with no significant change in temperature or pressure. At steady state, the magnitude of the heat transfer rate *from* the power washer to the surroundings is 10% of the electrical power *input*. Evaluating electricity at 8 cents per kW · h, determine the cost of the power required, in cents per liter of water delivered. Compare with the cost of water, assuming 0.05 cent per liter, and comment.

4.69 During cardiac surgery, a heart-lung machine achieves *extracorporeal circulation* of the patient's blood using a pump operating at steady state. Blood enters the well-insulated pump at a rate of 5 liters/min. The temperature change of the blood is negligible as it flows through the pump. The pump requires 20 W of power input. Modeling the blood as an incompressible substance with negligible kinetic and potential energy effects, determine the pressure change, in kPa, of the blood as it flows through the pump.

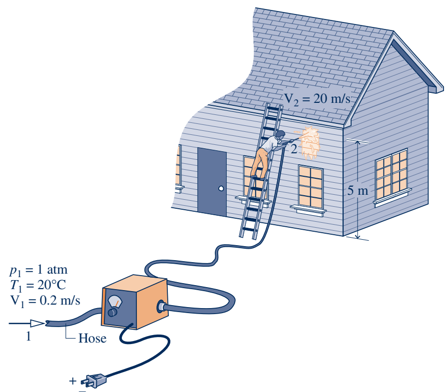


Fig. P4.68

4.70 A pump is used to circulate hot water in a home heating system. Water enters the well-insulated pump operating at steady state at a rate of 0.42 gal/min. The inlet pressure and temperature are 14.7 lbf/in.^{2}, and 180°F, respectively; at the exit the pressure is 120 lbf/in.^{2} The pump requires 1/35 hp of power input. Water can be modeled as an incompressible substance with constant density of 60.58 lb/ft^3 and constant specific heat of 1 Btu/lb · °R. Neglecting kinetic and potential energy effects, determine the temperature change, in °R, as the water flows through the pump. Comment on this change.

4.71 Refrigerant 134a at a flow rate of 0.5 lb/s enters a heat exchanger in a refrigeration system operating at steady state

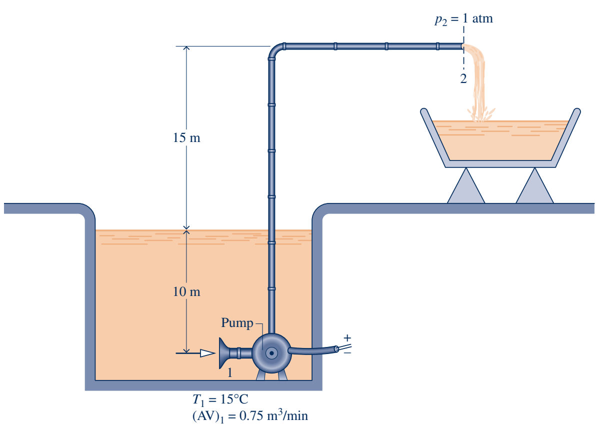


Fig. P4.67

as saturated liquid at 0°F and exits at 20°F at a pressure of 20 lbf/in.^{2} A separate air stream passes in counterflow to the Refrigerant 134a stream, entering at 120°F and exiting at 77°F. The outside of the heat exchanger is well insulated. Neglecting kinetic and potential energy effects and modeling the air as an ideal gas, determine the mass flow rate of air, in lb/s.

4.72 Oil enters a counterflow heat exchanger at 450 K with a mass flow rate of 10 kg/s and exits at 350 K. A separate stream of liquid water enters at 20°C, 5 bar. Each stream experiences no significant change in pressure. Stray heat transfer with the surroundings of the heat exchanger and kinetic and potential energy effects can be ignored. The specific heat of the oil is constant, c = 2 kJ/kg · K. If the designer wants to ensure no water vapor is present in the exiting water stream, what is the allowed range of mass flow rates for the water, in kg/s?

4.73 As shown in Fig. P4.73, Refrigerant 134a enters a condenser operating at steady state at 70 lbf/in.^{2}, 160°F and is condensed to saturated liquid at 60 lbf/in.^{2} on the outside of tubes through which cooling water flows. In passing through the tubes, the cooling water increases in temperature by 20°F and experiences no significant pressure drop. Cooling water can be modeled as incompressible with v = 0.0161 ft^3/lb and c = 1 Btu/lb · °R. The mass flow rate of the refrigerant is 3100 lb/h. Neglecting kinetic and potential energy effects and ignoring heat transfer from the outside of the condenser, determine

(a) the volumetric flow rate of the entering cooling water, in gal/min.
(b) the rate of heat transfer, in Btu/h, to the cooling water from the condensing refrigerant.

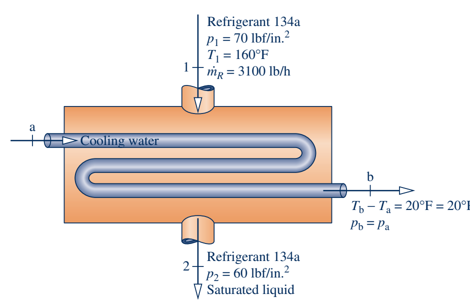


Fig. P4.73

4.74 Steam at a pressure of 0.08 bar and a quality of 93.2% enters a shell-and-tube heat exchanger where it condenses on the outside of tubes through which cooling water flows, exiting as saturated liquid at 0.08 bar. The mass flow rate of the condensing steam is 3.4 × 10^5 kg/h. Cooling water enters the tubes at 15°C and exits at 35°C with negligible change in pressure. Neglecting stray heat transfer and ignoring kinetic and potential energy effects, determine the mass flow rate of the cooling water, in kg/h, for steady-state operation.

4.75 An air-conditioning system is shown in Fig. P4.75 in which air flows over tubes carrying Refrigerant 134a. Air enters with a volumetric flow rate of 50 m^3/min at 32°C, 1 bar, and exits at 22°C, 0.95 bar. Refrigerant enters the tubes at 5 bar with a quality of 20% and exits at 5 bar, 20°C. Ignoring heat transfer at the outer surface of the air conditioner, and neglecting kinetic and potential energy effects, determine at steady state

(a) the mass flow rate of the refrigerant, in kg/min.
(b) the rate of heat transfer, in kJ/min, between the air and refrigerant.

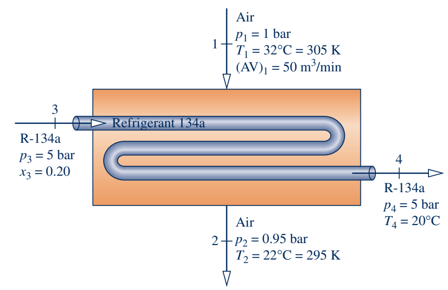


Fig. P4.75

4.76 Steam enters a heat exchanger operating at steady state at 250 kPa and a quality of 90% and exits as saturated liquid at the same pressure. A separate stream of oil with a mass flow rate of 29 kg/s enters at 20°C and exits at 100°C with no significant change in pressure. The specific heat of the oil is c = 2.0 kJ/kg · K. Kinetic and potential energy effects are negligible. If heat transfer from the heat exchanger to its surroundings is 10% of the energy required to increase the temperature of the oil, determine the steam mass flow rate, in kg/s.

4.77 Refrigerant 134a enters a heat exchanger at −12°C and a quality of 42% and exits as saturated vapor at the same temperature with a volumetric flow rate of 0.85 m^3/min. A separate stream of air enters at 22°C with a mass flow rate of 188 kg/min and exits at 17°C. Assuming the ideal gas model for air and ignoring kinetic and potential energy effects, determine (a) the mass flow rate of the Refrigerant 134a, in kg/min, and (b) the heat transfer between the heat exchanger and its surroundings, in kJ/min.

4.78 As sketched in Fig. P4.78, a condenser using river water to condense steam with a mass flow rate of 2 × 10^5 kg/h from saturated vapor to saturated liquid at a pressure of 0.1 bar is proposed for an industrial plant. Measurements indicate that several hundred meters upstream of the plant, the river has a volumetric flow rate of 2 × 10^5 m^3/h and a temperature of 15°C. For operation at steady state and ignoring changes in kinetic and potential energy, determine the river-water temperature rise, in °C, downstream of the plant traceable to use of such a condenser, and comment.

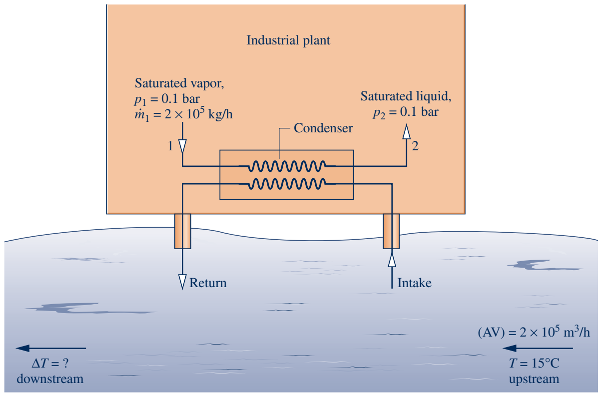


Fig. P4.78

4.79 Figure P4.79 shows a solar collector panel embedded in a roof. The panel, which has a surface area of 24 ft^2, receives energy from the sun at a rate of 200 Btu/h per ft^2 of collector surface. Twenty-five percent of the incoming energy is lost to the surroundings. The remaining energy is used to heat domestic hot water from 90 to 120°F. The water passes through the solar collector with a negligible pressure drop. Neglecting kinetic and potential effects, determine at steady state how many gallons of water at 120°F the collector generates per hour.

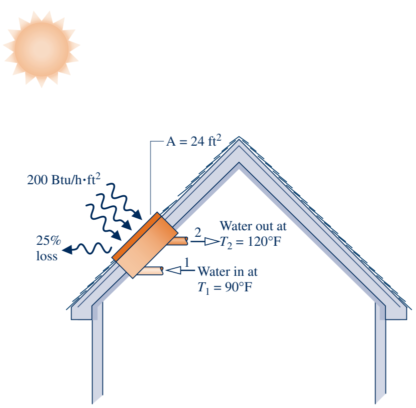


Fig. P4.79

4.80 Steam enters a counterflow heat exchanger operating at steady state at 0.07 MPa with a specific enthalpy of 2431.6 kJ/kg and exits at the same pressure as saturated liquid. The steam mass flow rate is 1.5 kg/min. A separate stream of air with a mass flow rate of 100 kg/min enters at 30°C and exits at 60°C. The ideal gas model with c_p = 1.005 kJ/kg · K can be assumed for air. Kinetic and potential energy effects are negligible. Determine (a) the quality of the entering steam and (b) the rate of heat transfer between the heat exchanger and its surroundings, in kW.

4.81 Figure P4.81 provides steady-state operating data for a *parallel flow* heat exchanger in which there are separate streams of air and water. Each stream experiences no significant change in pressure. Stray heat transfer with the surroundings of the heat exchanger and kinetic and potential energy effects can be ignored. The ideal gas model applies to the air. If each stream exits at the same temperature, determine the value of that temperature, in K.

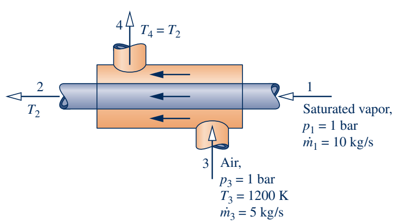


Fig. P4.81

4.82 Figure P4.82 provides steady-state operating data for a *parallel flow* heat exchanger in which there are separate streams of air and carbon dioxide (CO_2). Stray heat transfer with the surroundings of the heat exchanger and kinetic and potential energy effects can be ignored. The ideal gas model applies to each gas. A constraint on heat exchanger size requires the temperature of the exiting air to be 20 degrees greater than the temperature of the exiting CO_2. Determine the exit temperature of each stream, in °R.

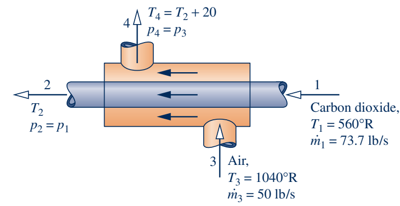


Fig. P4.82

4.83 An open feedwater heater operates at steady state with liquid water entering inlet 1 at 10 bar, 50°C, and a mass flow rate of 60 kg/s. A separate stream of steam enters inlet 2 at 10 bar and 200°C. Saturated liquid at 10 bar exits the feedwater heater at exit 3. Ignoring heat transfer with the surroundings and neglecting kinetic and potential energy effects, determine the mass flow rate, in kg/s, of the steam at inlet 2.

4.84 Figure P4.84 provides steady-state data for the ducting ahead of the chiller coils in an air-conditioning system. Outside air at 90°F is mixed with return air at 75°F. Stray heat transfer is negligible, kinetic and potential energy effects can be ignored, and the pressure throughout is 1 atm. Modeling the air as an ideal gas with c_p = 0.24 Btu/lb · °R, determine (a) the mixed-air temperature, in °F, and (b) the diameter of the mixed-air duct, in ft.

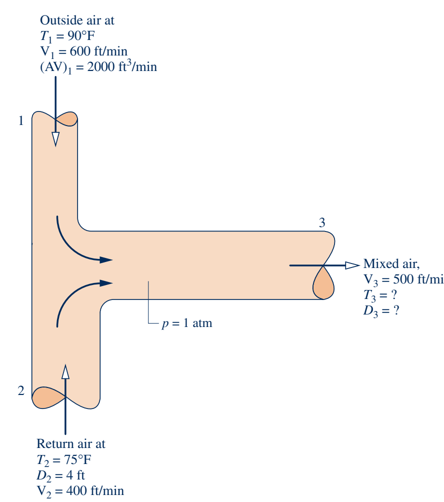


Fig. P4.84

4.85 For the *desuperheater* shown in Fig. P4.85, liquid water at state 1 is injected into a stream of superheated vapor entering at state 2. As a result, saturated vapor exits at state 3. Data for steady state operation are shown on the figure. Ignoring stray heat transfer and kinetic and potential energy effects, determine the mass flow rate of the incoming superheated vapor, in kg/min.

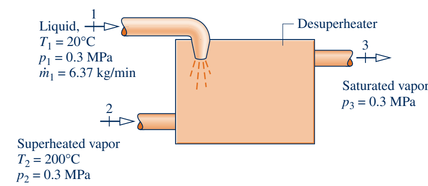


Fig. P4.85

4.86 Three return steam lines in a chemical processing plant enter a collection tank operating at steady state at 1 bar. Steam enters inlet 1 with flow rate of 0.8 kg/s and quality of 0.9. Steam enters inlet 2 with flow rate of 2 kg/s at 200°C. Steam enters inlet 3 with flow rate of 1.2 kg/s at 95°C. Steam exits the tank at 1 bar. The rate of heat transfer from the collection tank is 40 kW. Neglecting kinetic and potential energy effects, determine for the steam exiting the tank

(a) the mass flow rate, in kg/s.
(b) the temperature, in °C.

4.87 A well-insulated tank in a vapor power plant operates at steady state. Water enters at inlet 1 at a rate of 125 lb/s at 14.7 lbf/in.^{2} Make-up water to replenish steam losses from the plant enters at inlet 2 at a rate of 10 lb/s at 14.7 lbf/in.^{2} and 60°F. Water exits the tank at 14.7 lbf/in.^{2} Neglecting kinetic and potential energy effects, determine for the water exiting the tank

(a) the mass flow rate, in lb/s.
(b) the specific enthalpy, in Btu/lb.
(c) the temperature, in °F.

4.88 Steam with a quality of 0.7, pressure of 1.5 bar, and flow rate of 10 kg/s enters a steam separator operating at steady state. Saturated vapor at 1.5 bar exits the separator at state 2 at a rate of 6.9 kg/s while saturated liquid at 1.5 bar exits the separator at state 3. Neglecting kinetic and potential energy effects, determine the rate of heat transfer, in kW, and its associated direction.

4.89 Ammonia enters the expansion valve of a refrigeration system at a pressure of 10 bar and a temperature of 24°C and exits at 1 bar. If the refrigerant undergoes a throttling process, what is the quality of the refrigerant exiting the expansion valve?

4.90 Propane vapor enters a valve at 1.0 MPa, 60°C, and leaves at 0.3 MPa. If the propane undergoes a throttling process, what is the temperature of the propane leaving the valve, in °C?

4.91 Steam enters a partially open valve operating at steady state as saturated liquid at 300°F and exits at 60 lbf/in.^{2}

Neglecting kinetic and potential energy effects and any stray heat transfer with the surroundings, determine the temperature, in °F, and the quality of the steam exiting the valve.

4.92 At steady state, a valve and steam turbine operate in series. The steam flowing through the valve undergoes a throttling process. At the valve inlet, the conditions are 600 lbf/in.^{2}, 800°F. At the valve exit, corresponding to the turbine inlet, the pressure is 300 lbf/in.^{2} At the turbine exit, the pressure is 5 lbf/in.^{2} The work developed by the turbine is 350 Btu per lb of steam flowing. Stray heat transfer and kinetic and potential energy effects can be ignored. Fix the state at the turbine exit: If the state is superheated vapor, determine the temperature, in °F. If the state is a two-phase liquid–vapor mixture, determine the quality.

4.93 A horizontal constant-diameter pipe with a build-up of debris is shown in Fig. P4.93. Air modeled as an ideal gas enters at 320 K, 900 kPa, with a velocity of 30 m/s and exits at 305 K. Assuming steady state and neglecting stray heat transfer, determine for the air exiting the pipe

(a) the velocity, in m/s.
(b) the pressure, in kPa.

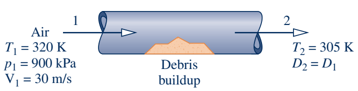


Fig. P4.93

4.94 Liquid water enters a valve at 300 kPa and exits at 275 kPa. As water flows through the valve, the change in its temperature, stray heat transfer with the surroundings, and potential energy effects are negligible. Operation is at steady state. Modeling the water as incompressible with constant ρ = 1000 kg/m^3, determine the change in kinetic energy per unit mass of water flowing through the valve, in kJ/kg.

Advanced Energy Systems at Steady State

4.95 Figure P4.95 shows a turbine operating at a steady state that provides power to an air compressor and an electric generator. Air enters the turbine with a mass flow rate of 5.4 kg/s at 527°C and exits the turbine at 107°C, 1 bar. The turbine provides power at a rate of 900 kW to the compressor and at a rate of 1400 kW to the generator. Air can be modeled as an ideal gas, and kinetic and potential energy changes are negligible. Determine (a) the volumetric flow rate of the air at the turbine exit, in m^3/s, and (b) the rate of heat transfer between the turbine and its surroundings, in kW.

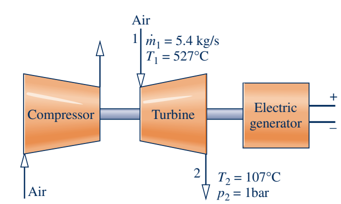


Fig. P4.95

4.96 Figure P4.96 provides steady-state data for a throttling valve in series with a heat exchanger. Saturated liquid Refrigerant 134a enters the valve at a pressure of 9 bar and is throttled to a pressure of 2 bar. The refrigerant then enters the heat exchanger, exiting at a temperature of 10°C with no significant decrease in pressure. In a separate stream, liquid water at 1 bar enters the heat exchanger at a temperature of 25°C with a mass flow rate of 2 kg/s and exits at 1 bar as liquid at a temperature of 15°C. Stray heat transfer and kinetic and potential energy effects can be ignored. Determine

(a) the temperature, in °C, of the refrigerant at the exit of the valve.
(b) the mass flow rate of the refrigerant, in kg/s.

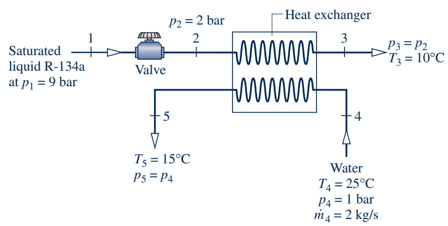


Fig. P4.96

4.97 As shown in Fig. P4.97, Refrigerant 22 enters the compressor of an air-conditioning unit operating at steady state at 40°F, 80 lbf/in.^{2} and is compressed to 140°F, 200 lbf/in.^{2} The refrigerant exiting the compressor enters a condenser where energy transfer to air as a separate stream occurs and the refrigerant exits as a liquid at 200 lbf/in.^{2}, 90°F. Air enters the condenser at 80°F, 14.7 lbf/in.^{2} with a volumetric flow rate of 750 ft^3/min and exits at 110°F. Neglecting stray heat transfer and kinetic and potential energy effects, and assuming ideal gas behavior for the air, determine (a) the mass flow rate of refrigerant, in lb/min, and (b) the compressor power, in horsepower.

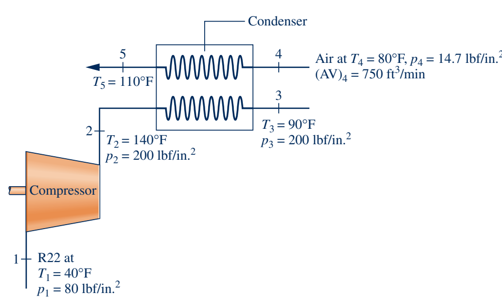


Fig. P4.97

4.98 Figure P4.98 shows three components of an air-conditioning system. Refrigerant 134a flows through a throttling valve and a heat exchanger while air flows through a fan and the same heat exchanger. Data for steady-state operation are given on the figure. There is no significant heat transfer between any of the components and the surroundings. Kinetic and potential energy effects are negligible. Modeling air as an ideal gas with constant c_p = 0.240 Btu/lb · °R, determine the mass flow rate of the air, in lb/s.

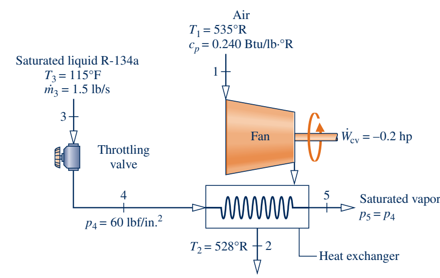


Fig. P4.98

4.99 Figure P4.99 shows a turbine-driven pump that provides water to a mixing chamber located 25 m higher than the pump. Steady-state operating data for the turbine and pump are labeled on the figure. Heat transfer from the water to its surroundings occurs at a rate of 2 kW. For the turbine, heat transfer with the surroundings and potential energy effects are negligible. Kinetic energy effects at all numbered states can be ignored. Determine

(a) the power required by the pump, in kW, to supply water to the inlet of the mixing chamber.
(b) the mass flow rate of steam, in kg/s, that flows through the turbine.

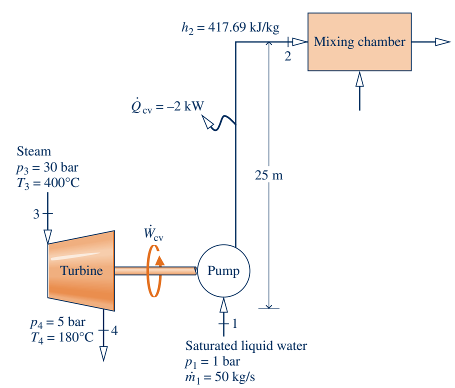


Fig. P4.99

4.100 Separate streams of air and water flow through the compressor and heat exchanger arrangement shown in Fig. P4.100. Steady-state operating data are provided on the figure. Heat transfer with the surroundings can be neglected, as can all kinetic and potential energy effects. The air is modeled as an ideal gas. Determine

(a) the total power required by both compressors, in kW.
(b) the mass flow rate of the water, in kg/s.

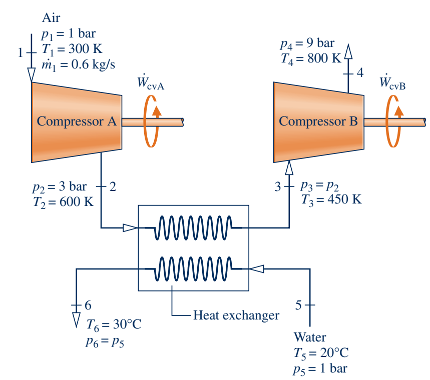


Fig. P4.100

4.101 Figure P4.101 shows a *pumped-hydro* energy storage system delivering water at steady state from a lower reservoir to an upper reservoir using *off-peak* electricity (see Sec. 4.8.3). Water is delivered to the upper reservoir at a volumetric flow rate of 150 m^3/s with an increase in elevation of 20 m. There is no significant change in temperature, pressure, or kinetic energy from inlet to exit. Heat transfer from the pump to its surroundings occurs at a rate of 0.6 MW and g = 9.81 m/s^2. Determine the pump power required, in MW. Assuming the same volumetric flow rate when the system generates *on-peak* electricity using this water, will the power be greater, less, or the same as the pump power? Explain.

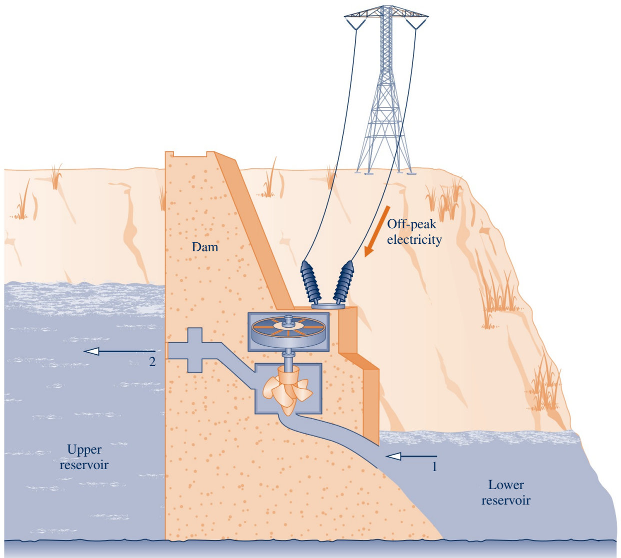


Fig. P4.101

4.102 Steady-state operating data for a simple steam power plant are provided in Fig. P4.102. Stray heat transfer and kinetic and potential energy effects can be ignored. Determine the (a) thermal efficiency and (b) the mass flow rate of the cooling water, in kg per kg of steam flowing.

4.103 Steady-state operating data are provided for a compressor and heat exchanger in Fig. P4.103. The power input to the compressor is 50 kW. As shown in the figure, nitrogen (N_2) flows through the compressor and heat exchanger with a mass flow rate of 0.25 kg/s. The nitrogen is modeled as an ideal gas. A separate cooling stream of helium, modeled as an ideal gas with $k = 1.67$, also flows through the heat exchanger. Stray heat transfer and kinetic and potential energy effects are negligible. Determine the mass flow rate of the helium, in kg/s.

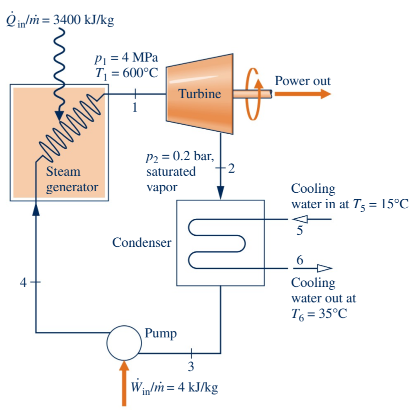


Fig. P4.102

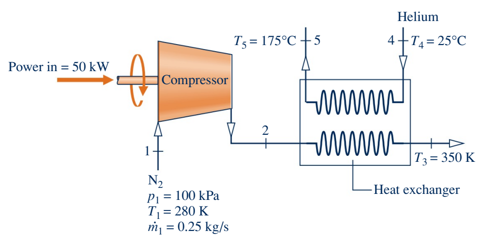


Fig. P4.103

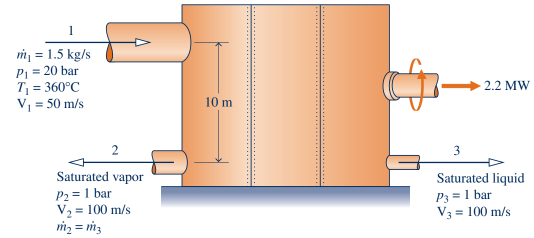


Fig. P4.104

4.104 Figure P4.104 provides steady-state operating data for a *cogeneration system* with water vapor at 20 bar, 360°C entering at location 1. Power is developed by the system at a rate of 2.2 MW. Process steam leaves at location 2, and hot water for other process uses leaves at location 3. Evaluate the rate of heat transfer, in MW, between the system and its surroundings. Let $g = 9.81$ m/s^2.

4.105 As shown in Fig. P4.105, hot industrial waste water at 15 bar, 180°C with a mass flow rate of 5 kg/s enters a *flash chamber* via a valve. Saturated vapor and saturated liquid streams, each at 4 bar, exit the flash chamber. The saturated vapor enters the turbine and expands to 0.08 bar, $x = 90\%$. Stray heat transfer and kinetic and potential energy effects are negligible. For operation at steady state, determine the power, in hp, developed by the turbine.

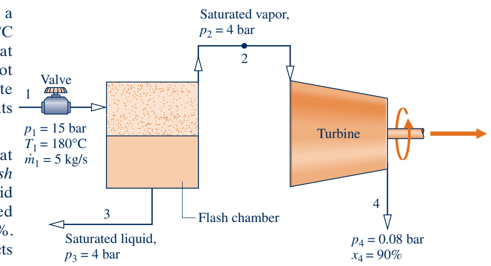


Fig. P4.105

4.106 A simple gas turbine power cycle operating at steady state with air as the working substance is shown in Fig. P4.106. The cycle components include an air compressor mounted on the same shaft as the turbine. The air is heated in the high-pressure heat exchanger before entering the turbine. The air exiting the turbine is cooled in the low-pressure heat exchanger before returning to the compressor. Kinetic and potential effects are negligible. The compressor and turbine are adiabatic. Using the ideal gas model for air, determine the (a) power required for the compressor, in hp, (b) power output of the turbine, in hp, and (c) thermal efficiency of the cycle.

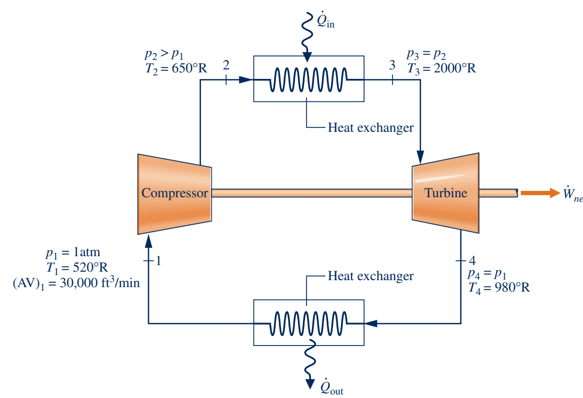


Fig. P4.106

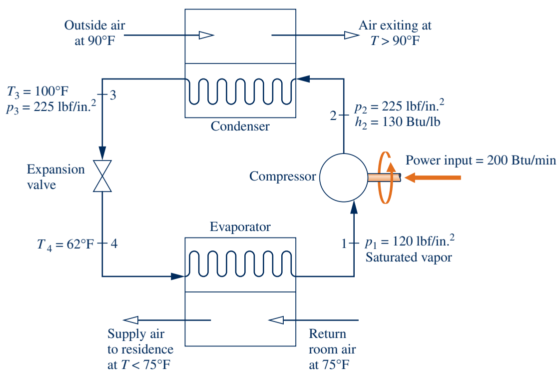


Fig. P4.107

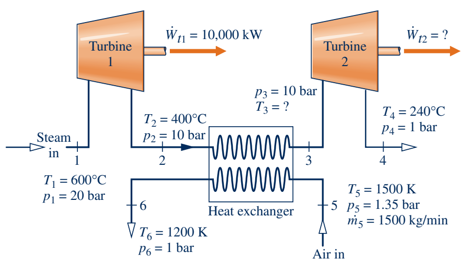


Fig. P4.108

4.107 A residential air-conditioning system operates at steady state, as shown in Fig. P4.107. Refrigerant 22 circulates through the components of the system. Property data at key locations are given on the figure. If the evaporator removes energy by heat transfer from the room air at a rate of 600 Btu/min, determine (a) the rate of heat transfer between the compressor and the surroundings, in Btu/min, and (b) the coefficient of performance.

4.108 Separate streams of steam and air flow through the turbine and heat exchanger arrangement shown in Fig. P4.108. Steady-state operating data are provided on the figure. Heat transfer with the surroundings can be neglected, as can all kinetic and potential energy effects. Determine (a) T_3, in K, and (b) the power output of the second turbine, in kW.

Transient Analysis

4.109 A rigid tank whose volume is 10 L is initially evacuated. A pinhole develops in the wall, and air from the surroundings at 1 bar, 25°C enters until the pressure in the tank becomes 1 bar. No significant heat transfer between the contents of the tank and the surroundings occurs. Assuming the ideal gas model with $k = 1.4$ for the air, determine (a) the final temperature in the tank, in °C, and (b) the amount of air that leaks into the tank, in g.

4.110 A tank whose volume is 0.01 m^3 is initially evacuated. A pinhole develops in the wall, and air from the surroundings at 21°C, 1 bar enters until the pressure in the tank is 1 bar. If the final temperature of the air in the tank is 21°C, determine (a) the final mass in the tank, in g, and (b) the heat transfer between the tank contents and the surroundings, in kJ.

4.111 A rigid tank whose volume is 2 m^3, initially containing air at 1 bar, 295 K, is connected by a valve to a large vessel holding air at 6 bar, 295 K. The valve is opened only as long as required to fill the tank with air to a pressure of 6 bar and a temperature of 350 K. Assuming the ideal gas model for the air, determine the heat transfer between the tank contents and the surroundings, in kJ.

4.112 An insulated, rigid tank whose volume is 0.5 m^3 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 the final temperature of the steam in the tank, in °C, and the final mass of the steam in the tank, in kg.

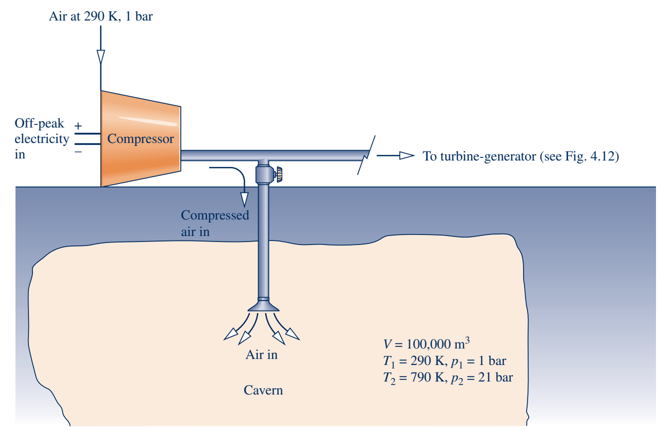


Fig. P4.114

4.113 An insulated, rigid tank whose volume is 10 ft^3 is connected by a valve to a large steam line through which steam flows at 500 lbf/in.^{2}, 800°F. The tank is initially evacuated. The valve is opened only as long as required to fill the tank with steam to a pressure of 500 lbf/in.^{2} Determine the final temperature of the steam in the tank, in °F, and the final mass of steam in the tank, in lb.

4.114 Figure P4.114 provides operating data for a *compressed-air* energy storage system using *off-peak* electricity to power a compressor that fills a cavern with pressurized air (see Sec. 4.8.3). The cavern shown in the figure has a volume of 10^5 m^3 and initially holds air at 290 K, 1 bar, which corresponds to ambient air. After filling, the air in the cavern is at 790 K, 21 bar. Assuming ideal gas behavior for the air, determine (a) the initial and final mass of air in the cavern, each in kg, and (b) the work required by the compressor, in GJ. Ignore heat transfer and kinetic and potential energy effects.

4.115 A rigid tank whose volume is 0.5 m^3, initially containing ammonia at 20°C, 1.5 bar, is connected by a valve to a large supply line carrying ammonia at 12 bar, 60°C. The valve is opened only as long as required to fill the tank with additional ammonia, bringing the total mass of ammonia in the tank to 143.36 kg. Finally, the tank holds a two-phase liquid–vapor mixture at 20°C. Determine the heat transfer between the tank contents and the surroundings, in kJ, ignoring kinetic and potential energy effects.

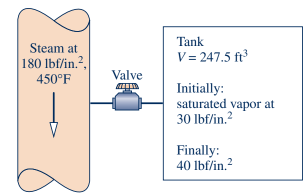


Fig. P4.116

4.116 As shown in Fig. P4.116, a 247.5-ft^3 tank contains saturated vapor water initially at 30 lbf/in.^{2} The tank is connected to a large line carrying steam at 180 lbf/in.^{2}, 450°F. Steam flows into the tank through a valve until 2.9 lb of steam have been added to the tank. The valve is then closed and the pressure in the tank is 40 lbf/in.^{2} Determine the specific volume, in ft^3/lb, at the final state of the control volume and the magnitude and direction of the heat transfer between the tank and its surroundings, in Btu.

4.117 A rigid copper tank, initially containing 1 m^3 of air at 295 K, 5 bar, is connected by a valve to a large supply line carrying air at 295 K, 15 bar. The valve is opened only as long as required to fill the tank with air to a pressure of 15 bar. Finally, the air in the tank is at 310 K. The copper tank, which has a mass of 20 kg, is at the same temperature as the air in the tank, initially and finally. The specific heat of the copper is $c = 0.385$ kJ/kg · K. Assuming ideal gas behavior for the air, determine (a) the initial and final mass of air within the tank, each in kg, and (b) the heat transfer to the surroundings from the tank and its contents, in kJ, ignoring kinetic and potential energy effects.

4.118 A rigid, insulated tank, initially containing 0.4 m^3 of saturated water vapor at 3.5 bar, is connected by a valve to a large vessel holding steam at 15 bar, 320°C. The valve is opened only as long as required to bring the tank pressure to 15 bar. For the tank contents, determine the final temperature, in °C, and final mass, in kg.

4.119 A rigid, well-insulated tank of volume 0.9 m^3 is initially evacuated. At time $t = 0$, air from the surroundings at 1 bar, 27°C begins to flow into the tank. An electric resistor transfers energy to the air in the tank at a constant rate for 5 minutes, after which time the pressure in the tank is 1 bar and the temperature is 457°C. Modeling air as an ideal gas, determine the power input to the tank, in kW.

4.120 A well-insulated rigid tank of volume 15 m^3 is connected to a large steam line through which steam flows at 1 MPa and 320°C. The tank is initially evacuated. Steam is allowed to flow into the tank until the pressure inside is p.

(a) Determine the amount of mass in the tank, in kg, and the temperature in the tank, in °C, when $p = 500$ kPa.
(b) Plot the quantities of part (a) versus p ranging from 0 kPa to 500 kPa.

4.121 A 50-gallon-capacity hot-water heater is shown in Fig. P4.121. Water in the tank of the water heater initially has a temperature of 120°F. When someone turns on the shower faucet, water flows from the tank at a rate of 0.47 lb/s, and replenishment water at 40°F flows into the tank from the municipal water distribution system. Water in the tank receives an energy input at a rate of 40,000 Btu/h from electrical resistors. If the water within the tank is well mixed, the temperature at any time can be taken as uniform throughout. The tank is well insulated so stray heat transfer with the surroundings is negligible. Neglecting kinetic and potential energy effects, assuming negligible change in pressure from inlet to exit of the tank, and modeling water as an incompressible substance with density of 62.28 lb/ft^3 and specific heat of 1.0 Btu/lb·°R, plot the temperature, in °F, of the water in the tank versus time from $t = 0$ to 20 min.

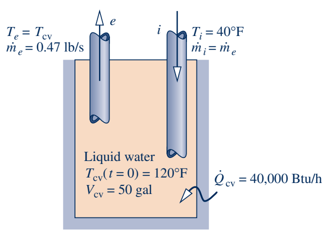


Fig. P4.121

4.122 A rigid tank having a volume of 0.1 m^3 initially contains water as a two-phase liquid–vapor mixture at 1 bar and a quality of 1%. The water is heated in two stages:

Stage 1: Constant-volume heating until the pressure is 20 bar.
Stage 2: Continued heating while saturated water vapor is slowly withdrawn from the tank at a constant pressure of 20 bar. Heating ceases when all the water remaining in the tank is saturated vapor at 20 bar.

For the water, evaluate the heat transfer, in kJ, for each stage of heating. Ignore kinetic and potential energy effects.

4.123 A rigid, insulated tank having a volume of 50 ft^3 initially contains a two-phase liquid–vapor mixture of ammonia at 100°F and a quality of 1.9%. Saturated vapor is slowly withdrawn from the tank until a two-phase liquid–vapor mixture at 80°F remains. Determine the mass of ammonia in the tank initially and finally, each in lb.

4.124 A pressure cooker has a volume of 0.011 m^3 and initially contains a two-phase liquid–vapor mixture of H_2O at a temperature of 100°C and a quality of 10%. As the water is heated at constant volume, the pressure rises to 2 bar and the quality becomes 18.9%. With further heating a pressure-regulating valve keeps the pressure constant in the cooker at 2 bar by allowing saturated vapor at 2 bar to escape. Neglecting kinetic and potential energy effects,

(a) determine the quality of the H_2O at the initial onset of vapor escape (state 2) and the amount of heat transfer, in kJ, to reach this state.
(b) determine the final mass in the cooker, in kg, and the additional amount of heat transfer, in kJ, if heating continues from state 2 until the final quality is 1.0.
(c) plot the quantities of part (b) versus quality increasing from the value at state 2 to 100%.

4.125 A well-insulated rigid tank of volume 8 ft^3 initially contains carbon dioxide at 180°F and 40 lbf/in.^{2} A valve connected to the tank is opened, and carbon dioxide is withdrawn slowly until the pressure within the tank drops to p. An electrical resistor inside the tank maintains the temperature at 180°F. Modeling carbon dioxide as an ideal gas and neglecting kinectic and potential energy effects,

(a) determine the mass of carbon dioxide withdrawn, in lb, and the energy input to the resistor, in Btu, when $p = 22$ lbf/in.^{2}
(b) plot the quantities of part (a) versus p ranging from 15 to 40 lbf/in.^{2}

4.126 A tank of volume 1.2 m^3 initially contains steam at 8 MPa and 400°C. Steam is withdrawn slowly from the tank until the pressure drops to p. Heat transfer to the tank contents maintains the temperature constant at 400°C. Neglecting all kinetic and potential energy effects and assuming specific enthalpy of the exiting steam is linear with the mass in the tank,

(a) determine the heat transfer, in kJ, if $p = 2$ MPa.
(b) plot the heat transfer, in kJ, versus p ranging from 0.5 to 8 MPa.

4.127 An open cooking pot containing 0.5 liter of water at 20°C, 1 bar sits on a stove burner. Once the burner is turned on, the water is gradually heated at a rate of 0.85 kW while pressure remains constant. After a period of time, the water starts boiling and continues to do so until all of the water has evaporated. Determine

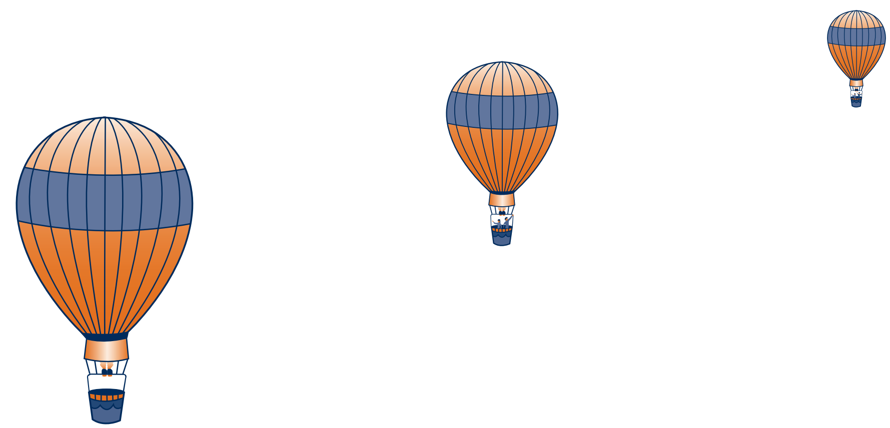
(a) the time required for the onset of evaporation, in s.
(b) the time required for all of the water to evaporate, in s, once evaporation starts.

4.128 Nitrogen gas is contained in a rigid 1-m tank, initially at 10 bar, 300 K. Heat transfer to the contents of the tank occurs until the temperature has increased to 400 K. During the process, a pressure-relief valve allows nitrogen to escape, maintaining constant pressure in the tank. Neglecting kinetic and potential energy effects, and using the ideal gas model with constant specific heats evaluated at 350 K, determine the mass of nitrogen that escapes, in kg, and the amount of energy transfer by heat, in kJ.

4.129 The air supply to a 2000-ft^3 office has been shut off overnight to conserve utilities, and the room temperature has dropped to 40°F. In the morning, a worker resets the thermostat to 70°F, and 200 ft^3/min of air at 120°F begins to flow in through a supply duct. The air is well mixed within the room, and an equal mass flow of air at room temperature is withdrawn through a return duct. The air pressure is nearly 1 atm everywhere. Ignoring heat transfer with the surroundings and kinetic and potential energy effects, estimate how long it takes for the room temperature to reach 70°F. Plot the room temperature as a function of time.

4.130 The procedure to inflate a hot-air balloon requires a fan to move an initial amount of air into the balloon envelope followed by heat transfer from a propane burner to complete the inflation process. After a fan operates for 10 minutes with negligible heat transfer with the surroundings, the air in an initially deflated balloon achieves a temperature of 80°F and a volume of 49,100 ft^3. Next the propane burner provides heat transfer as air continues to flow into the balloon without use of the fan until the air in the balloon reaches a volume of 65,425 ft^3 and a temperature of 210°F. Air at 77°F and 14.7 lbf/in.^{2} surrounds the balloon. The net rate of heat transfer is 7×10^6 Btu/h. Ignoring effects due to kinetic and potential energy, modeling the air as an ideal gas, and assuming the pressure of the air inside the balloon remains the same as that of the surrounding air, determine

(a) the power required by the fan, in hp.
(b) the time required for full inflation of the balloon, in min.



▶ DESIGN & OPEN-ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE

4.1D Using the Internet, identify at least five medical applications of *MEMS* technology. In each case, explain the scientific and technological basis for the application, discuss the state of current research, and determine how close the technology is in terms of commercialization. Write a report of your findings, including at least three references.

4.2D A group of cells called the *sinus node* is the natural pacemaker of the heart and controls the heartbeat. Sinus node dysfunction is one source of the medical condition known as heart *arrhythmia:* irregular heartbeat. Significant arrhythmias are treated in several ways, including the use of an artificial pacemaker, which is an electrical device that sends the signals needed to make the heart beat properly. Research how both natural and artificial pacemakers operate to achieve their goal of maintaining a regular heartbeat. Place your findings in a memorandum that includes annotated sketches of each type of pacemaker.

4.3D Conduct a term-length project centered on using a *low-wind* turbine to meet the electricity needs of a small business, farm, or neighborhood selected by, or assigned to, your project group. Take several days to research the project and then prepare a brief written plan having a statement of purpose, a list of objectives, and several references. As part of your plan, schedule on-site wind-speed measurements for at least three different days to achieve a good match between the requirements of candidate low-wind turbines and local conditions. Your plan also should recognize the need for compliance with applicable zoning codes. During the project,

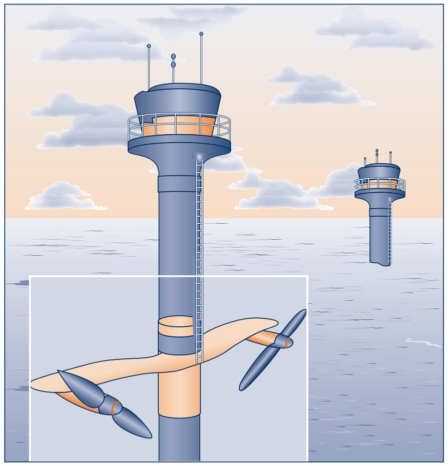


Fig. P4.4D

observe good practices such as discussed in Sec. 1.3 of *Thermal Design and Optimization,* John Wiley & Sons Inc., New York, 1996, by A. Bejan, G. Tsatsaronis, and M.J. Moran. Provide a well-documented report, including an assessment of the economic viability of the selected turbine for the application considered.

4.4D Generation of electricity by harnessing currents, waves, and tides is being studied across the globe. Electricity can be generated from currents using underwater turbines, as illustrated in Fig. P4.4D. Electricity also can be generated from the *undulating motion* of waves using tethered buoys. Like means can be used to generate power from tidal movements. Although currents and waves have long been used to meet relatively modest power needs, many observers today are thinking of large-scale power generation systems. Some see the oceans as providing a nearly unlimited renewable source of power. For a site in U.S. coastal waters, estuaries, or rivers, critically evaluate the viability of currents and/or waves for large-scale power generation by 2025. Consider technical and economic factors and effects on the ecosystem. Write a report including at least three references.

4.5D Owing to their relatively compact size, simple construction, and modest power requirement, centrifugal-type blood pumps are under consideration for several medical applications. Still, centrifugal pumps have met with limited success thus far for blood flow because they can cause damage to blood cells and are subject to mechanical failure. The goal of current development efforts is a device having sufficient long-term biocompatibility, performance, and reliability for widespread deployment. Investigate the status of centrifugal blood pump development, including identifying key technical challenges and prospects for overcoming them. Summarize your findings in a report, including at least three references.

4.6D Design an experiment to determine the energy, in kW-h, required to completely evaporate a fixed quantity of water. For the experiment develop written procedures that include identification of all equipment needed and specification of all required calculations. Conduct the experiment, and communicate your results in an executive summary.

4.7D Investigate the water system for your local municipality. Prepare a diagram that traces the water from its original source through municipal treatment, storage, and distribution systems to wastewater collection, treatment, and disposal systems. Identify steady-flow and transient-flow devices incorporated in these systems to achieve the necessary flow, storage, and treatment. Summarize your findings in a PowerPoint presentation.

4.8D The technical literature contains discussions of ways for using tethered kite-mounted wind turbine systems to harvest power from high-altitude winds, including jet streams at elevations from 6 to 15 kilometers (4 to 9 miles). Analysts estimate that if such systems were deployed in sufficient numbers, they could meet a significant share of total U.S. demand for electricity. Critically evaluate the feasibility of such a kite system, selected from the existing literature, to be fully operational by 2025. Consider means for deploying the system to the proper altitude, how the power developed is transferred to earth, infrastructure requirements, environmental impact, cost, and other pertinent issues. Write a report including at least three references.

4.9D *Reverse engineer* a handheld hair dryer by disassembling the dryer into its individual parts. Mount each part onto a presentation board to illustrate how the parts are connected when assembled. Label each part with its name. Next to each part identify its purpose and describe its fundamental operating principle (if applicable). Include a visual trace of the mass and energy flows through the hair dryer during operation. Display the presentation board where others can learn from it.

4.10D Residential *integrated systems* capable of generating electricity *and* providing space heating and water heating will reduce reliance on electricity supplied from central power plants. For a 2500-ft^2 dwelling in your locale, evaluate two alternative technologies for combined power and heating: a solar energy-based system and a natural gas fuel cell system. For each alternative, specify equipment and evaluate costs, including the initial system cost, installation cost, and operating cost. Compare total cost with that for conventional means for powering and heating the dwelling. Write a report summarizing your analysis and recommending either or both of the options if they are preferable to conventional means.

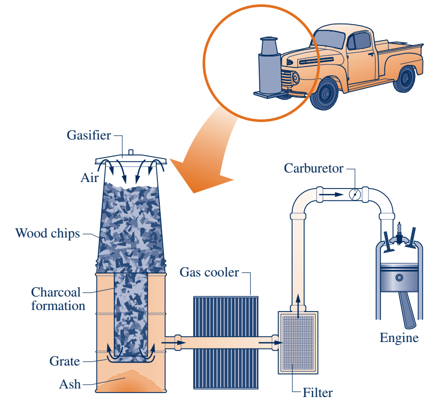


Fig. P4.11D

4.11D Figure P4.11D provides the schematic of a device for producing a combustible fuel gas for transportation from biomass. While several types of solid biomass can be employed in current gasifier designs, wood chips are commonly used. Wood chips are introduced at the top of the gasifier unit. Just below this level, the chips react with oxygen in the combustion air to produce charcoal. At the next depth, the charcoal reacts with hot combustion gases from the charcoal-formation stage to produce a fuel gas consisting mainly of hydrogen, carbon monoxide, and nitrogen from the combustion air. The fuel gas is then cooled, filtered, and ducted to the internal combustion engine served by the gasifier. Critically evaluate the suitability of this technology for transportation use today in the event of a prolonged petroleum shortage in your locale. Document your conclusions in a memorandum.

▶ KEY EQUATIONS

$W_{cycle} \leq 0 \begin{cases} < 0\text{: Internal irreversibilities present.} \\ = 0\text{: No internal irreversibilities.} \end{cases}$ (single reservoir)	(5.3) p. 254	**Analytical form of the Kelvin–Planck statement.**
$\eta_{max} = 1 - \dfrac{T_C}{T_H}$	(5.9) p. 265	**Maximum thermal efficiency: power cycle operating between two reservoirs.**
$\beta_{max} = \dfrac{T_C}{T_H - T_C}$	(5.10) p. 267	**Maximum coefficient of performance: refrigeration cycle operating between two reservoirs.**
$\gamma_{max} = \dfrac{T_H}{T_H - T_C}$	(5.11) p. 267	**Maximum coefficient of performance: heat pump cycle operating between two reservoirs.**
$\oint \left(\dfrac{\delta Q}{T}\right)_b = -\sigma_{cycle}$	(5.13) p. 273	**Clausius inequality.**

▶ EXERCISES: THINGS ENGINEERS THINK ABOUT

1. What is an example of a process that would satisfy the conservation of energy principle but not actually be observed in nature?
2. Are health risks associated with consuming tomatoes induced to ripen by an ethylene spray? Explain.
3. What is the cost, per lb, of the refrigerant used in the air conditioner of the car you drive?
4. Are irreversibilities found in living things? Explain.
5. Is the power generated by fuel cells limited by the Carnot efficiency? Explain.
6. Does the second law impose performance limits on elite athletes seeking world records in events such as track and field and swimming? Explain.
7. Which method of heating is better in terms of operating cost: electric-resistance baseboard heating or a heat pump? Explain.
8. What is delaying the appearance in new car showrooms of automobiles powered by hydrogen fuel cells?
9. What options exist for effectively using energy discharged by heat transfer from electricity-generating power plants?
10. How significant is the roughness at a pipe's inner surface in determining the friction factor? Explain.
11. One automobile engine requires 5W20 motor oil while another engine requires 5W30 oil. What do these designations mean and why might they differ for the two engines?
12. What factors influence the *actual* coefficient of performance achieved by refrigerators in family residences?
13. What is the SEER rating labeled on refrigerators seen in appliance showrooms?
14. How does the *thermal glider* (Sec. 5.4) sustain underwater motion for missions lasting weeks?

▶ CHECKING UNDERSTANDING

1. A reversible heat pump cycle operates between cold and hot thermal reservoirs at 300 °C and 500 °C, respectively. The coefficient of performance is closely (a) 1.5, (b) 3.87, (c) 2.87, (d) 2.5.
2. Referring to the list of Sec. 5.3.1, irreversibilities present during operation of an internal combustion automobile engine include (a) friction, (b) heat transfer, (c) chemical reaction, (d) all of the above.

3. Referring to the list of Sec. 5.3.1, irreversibilities present during operation of a forced-air, natural gas-fueled furnace include all of the following except (a) chemical reaction, (b) fluid friction, (c) polarization, (d) heat transfer.
4. Uses of the second law of thermodynamics include (a) defining the Kelvin scale, (b) predicting the direction of processes, (c) developing means for evaluating internal energy in terms of more readily measured properties, (d) all of the above.
5. For heating a home, does electrical-resistance baseboard heating or a heat pump use less electricity? Explain.
6. A power cycle operates between hot and cold thermal reservoirs at 2000 °F and 1000 °F, respectively. If the thermal efficiency of the power cycle were 45%, its mode of operation (a) is reversible, (b) is irreversible, (c) is impossible, (d) cannot be determined with the data provided.
7. When placed outside and exposed to the atmosphere, an ice cube melts, forming a thin film of liquid on the ground. Overnight, the liquid freezes, returning to the initial temperature of the ice cube. The water making up the cube undergoes (a) a thermodynamic cycle, (b) a reversible process, (c) an irreversible process, (d) none of the above.
8. Extending the discussion of Fig. 5.1a, how might work be developed when T_i is less than T_0?
9. Extending the discussion of Fig. 5.1b, how might work be developed when p_i is less than p_0?
10. An ideal gas in a piston-cylinder assembly expands isothermally, doing work and receiving an equivalent amount of energy by heat transfer from the surrounding atmosphere. Is this process of the gas in violation of the Kelvin–Planck statement of the second law? Explain.
11. The maximum coefficient of performance of *any* heat pump cycle operating between cold and hot reservoirs at 40°F and 80°F, respectively, is ___________.
12. A *throttling process* is (a) reversible, (b) internally reversible, (c) irreversible, (d) isobaric.
13. Absolute temperature scales include the (a) Rankine scale, (b) Centigrade scale, (c) Fahrenheit scale, (d) Kelvin scale.
14. The energy of an isolated system remains constant, but change in entropy must satisfy (a) $\Delta S \leq 0$, (b) $\Delta S > 0$, (c) $\Delta S \geq 0$, (d) $\Delta S < 0$.
15. The maximum thermal efficiency of *any* power cycle operating between hot and cold reservoirs at 1000°C and 500°C, respectively, is __________.
16. A power cycle operating between hot and cold reservoirs at 500 K and 300 K, respectively, receives 1000 kJ by heat transfer from the hot reservoir. The magnitude of the energy discharged by heat transfer to the cold reservoir must satisfy (a) $Q_C > 600$ kJ, (b) $Q_C \geq 600$ kJ, (c) $Q_C = 600$ kJ, (d) $Q_C \leq 600$ kJ.
17. Referring to Fig. 5.13, if the gas obeys the ideal gas model, and $p_1 = 3$ atm, $v_1 = 4.2$ ft^3/lb, $p_4 = 1$ atm, the specific volume at state 4 is _____ ft^3/lb.
18. Referring to Fig. 5.15, if the boiler and condenser pressures are 50 bar and 0.5 bar, respectively, the thermal efficiency of the power cycle is ______________.
19. An internal irreversibility within a gearbox is (a) chemical reaction, (b) unrestrained expansion of a gas, (c) mixing, (d) friction.
20. The coefficient of performance of a reversible refrigeration cycle is always (a) greater than, (b) less than, (c) equal to the coefficient of performance of an irreversible refrigeration cycle when each operates between the same two thermal reservoirs.
21. When hot and cold gas streams pass in counterflow through a heat exchanger, each at constant pressure, the principal internal irreversibility for the heat exchanger is __________.
22. A cell phone initially has a fully charged battery. After a period of cell phone use, the battery is recharged to its initial state. The quantity of electricity to recharge the battery is (a) less than, (b) equal to, (c) greater than the quantity required to operate the phone. Explain.
23. Referring to Fig. 5.12, if the temperature corresponding to point b is 1225°C, the Carnot efficiency is _________%.
24. The thermal efficiency of a system that undergoes a power cycle while receiving 1000 kJ of energy by heat transfer from a hot reservoir at 1000 K and discharging 500 kJ of energy by heat transfer to a cold reservoir at 400 K is _________.
25. The coefficient of performance of an irreversible heat pump cycle is always (a) equal to, (b) greater than, (c) less than the coefficient of performance of a reversible heat pump cycle when each operates between the same two thermal reservoirs.
26. For a closed system, entropy (a) may be produced within the system, (b) may be transferred across its boundary, (c) may remain constant throughout the system, (d) all of the above.
27. Referring to the list of Sec. 5.3.1, significant irreversibilities present during operation of a household refrigerator include (a) inelastic deformation, (b) chemical reaction, (c) heat transfer through a finite temperature difference, (d) none of the above.
28. As shown in Fig. P5.28C, energy transfer between hot and cold reservoirs takes place through a rod insulated on its outer surface and at steady state. The principal source of irreversibility is _____________________________.

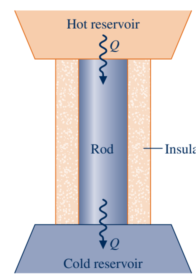


Fig. P5.28C

29. As shown in Fig. P5.29C, a rigid, insulated tank is divided into halves by a partition that has gas on one side and an evacuated space on the other side. When the valve is opened, the gas expands to all fill the entire volume. The principal source of irreversibility is ____________________.

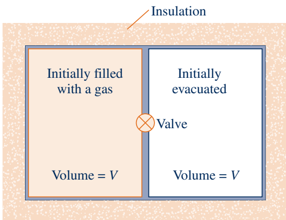


Fig. P5.29C

30. As shown in Fig. P5.30C, when the steam in the piston–cylinder assembly expands, the transmission converts the piston motion to rotary motion of a paddlewheel that stirs a viscous liquid. Later the steam is returned to its initial state. Does the steam undergo a reversible process? Explain.

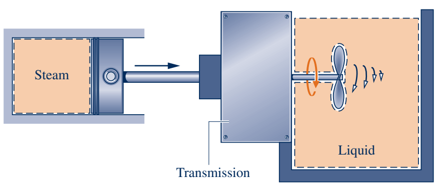


Fig. P5.30C

Indicate whether the following statements are true or false. Explain.

31. The change in entropy of a closed system is the same for every process between two specified end states.

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

33. A process of a closed system that violates the second law of thermodynamics necessarily violates the first law of thermodynamics.

34. One statement of the second law of thermodynamics recognizes that the extensive property entropy is *produced* within systems whenever internal irreversibilities are present.

35. In principle, the *Clausius inequality* applies to any cycle.

36. The Kelvin scale is the only absolute temperature scale.

37. Friction associated with flow of fluids through pipes and around objects is one type of *irreversibility*.

38. There are no irreversibilities within a system undergoing an *internally reversible* process.

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

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

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

42. For reversible refrigeration and heat pump cycles operating between the same hot and cold reservoirs, the relation between their coefficients of performance is $\gamma_{max} = \beta_{max} + 1$.

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

44. Mass, energy, entropy, and temperature are examples of extensive properties.

45 Every process consistent with the conservation of energy and conservation of mass principles can actually occur in nature.

46. The Clausius statement of the second law denies the possibility of transferring energy by heat from a cooler to a hotter body.

47. When an *isolated* system undergoes a process, the values of its energy and entropy can only increase or remain the same.

48. The Kelvin–Planck and Clausius statements of the second law of thermodynamics are equivalent because a violation of one statement implies the violation of the other.

49. The Carnot efficiency also limits the efficiency of wind turbines in generating electricity.

50. When $\sigma_{cycle} = 0$ in Eq. 5.13, the corresponding cycle is one that you will never encounter on the job.

▶ PROBLEMS: DEVELOPING ENGINEERING SKILLS

Exploring the Second Law

5.1 Complete the demonstration of the equivalence of the Clausius and Kelvin–Planck statements of the second law given in Sec. 5.2.2 by showing that a violation of the Kelvin–Planck statement implies a violation of the Clausius statement.

5.2 Shown in Fig. P5.2 is a proposed system that undergoes a cycle while operating between cold and hot reservoirs. The system receives 500 kJ from the cold reservoir and discharges 400 kJ to the hot reservoir while delivering net work to its surroundings in the amount of 100 kJ. There are no other energy transfers between the system and its surroundings. Evaluate the performance of the system using

(a) the Clausius statement of the second law.
(b) the Kelvin-Planck statement of the second law.

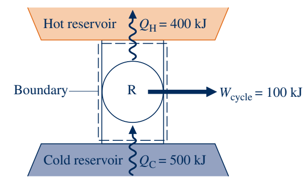


Fig. P5.2

5.3 Classify the following processes of a closed system as *possible, impossible,* or *indeterminate*.

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

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

5.5 As shown in Fig. P5.5, a reversible power cycle R and an irreversible power cycle I operate between the same hot and cold thermal reservoirs. Cycle I has a thermal efficiency equal to one-third of the thermal efficiency of cycle R.

(a) If each cycle receives the same amount of energy by heat transfer from the hot reservoir, determine which cycle (i) develops greater net work, (ii) discharges greater energy by heat transfer to the cold reservoir.
(b) If each cycle develops the same net work, determine which cycle (i) receives greater energy by heat transfer from the hot reservoir, (ii) discharges greater energy by heat transfer to the cold reservoir.

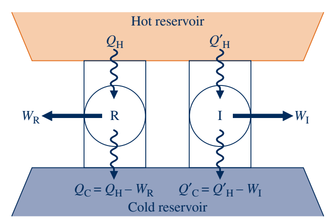


Fig. P5.5

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

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

5.8 Using the Kelvin–Planck statement of the second law of thermodynamics, demonstrate the following corollaries:

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

5.9. Use the Kelvin–Planck statement of the second law to show that the specified process is irreversible.

(a) As shown in Fig. P5.9*a*, a hot thermal reservoir is separated from a cold thermal reservoir by a cylindrical rod insulated on its lateral surface. Energy transfer by conduction between the two reservoirs takes place through the rod, which remains at steady state.

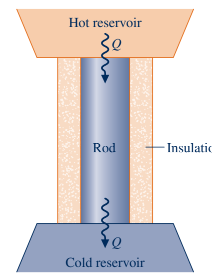


Fig. P5.9a

(b) As shown in Fig. P5.9*b*, a rigid insulated tank is divided into halves by a partition. On one side of the partition is a

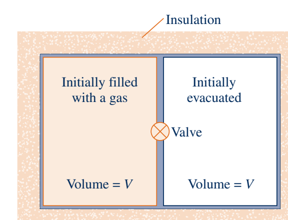


Fig. P5.9b

gas. The other side is initially evacuated. A valve in the partition is opened and the gas expands to fill the entire volume.

5.10 Figure P5.10 shows two power cycles, denoted 1 and 2, operating in series, together with three thermal reservoirs. The energy transfer by heat into cycle 2 is equal in magnitude to the energy transfer by heat from cycle 1. All energy transfers are positive in the directions of the arrows.

(a) Determine an expression for the thermal efficiency of an overall cycle consisting of cycles 1 and 2 expressed in terms of their individual thermal efficiencies.
(b) If cycles 1 and 2 are each reversible, use the result of part (a) to obtain an expression for the thermal efficiency of the overall cycle in terms of the temperatures of the three reservoirs, T_H, T, and T_C, as required. Comment.
(c) If cycles 1 and 2 are each reversible and have the same thermal efficiency, obtain an expression for the intermediate temperature T in terms of T_H and T_C.

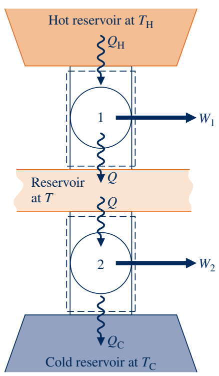


Fig.P5.10

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

5.12 Repeat Problem 5.11 for the case of two reversible heat pump cycles.

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

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

5.14 Figure P5.14 shows a system consisting of a reversible power cycle driving a reversible heat pump. The power cycle receives Q_s by heat transfer at T_s from a high-temperature source and delivers Q_1 to a dwelling at T_d. The heat pump receives Q_0 from the outdoors at T_0 and delivers Q_2 to the dwelling. Obtain an expression for the ratio of the total heating provided to the dwelling to the heat transfer supplied from the high-temperature source: $(Q_1 + Q_2)/ Q_s$ in terms of the temperatures T_s, T_d, and T_0.

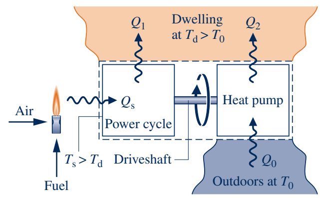


Fig. P5.14

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

5.16 Before introducing the temperature scale now known as the Kelvin scale, Kelvin suggested a *logarithmic* scale in which the function ψ of Sec. 5.8.1 takes the form

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

where θ_H and θ_C denote, respectively, the temperatures of the hot and cold reservoirs on this scale.

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

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

where C is a constant.

(b) On the Kelvin scale, temperatures vary from 0 to $+\infty$. Determine the range of temperature values on the logarithmic scale.
(c) Obtain an expression for the thermal efficiency of any system undergoing a reversible power cycle while operating between reservoirs at temperatures θ_H and θ_C on the logarithmic scale.

Power Cycle Applications

5.17 The data listed below are claimed for a power cycle operating between hot and cold reservoirs at 1500 K and 450 K, respectively. For each case, determine whether the cycle operates *reversibly,* operates *irreversibly,* or is *impossible*.

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

5.18 A power cycle receives energy Q_H by heat transfer from a hot reservoir at $T_H = 1200$°R and rejects energy Q_C by heat transfer to a cold reservoir at $T_C = 400$°R. For each of the following cases, determine whether the cycle operates *reversibly,* operates *irreversibly,* or is *impossible*.

(a) $Q_H = 900$ Btu, $W_{cycle} = 450$ Btu
(b) $Q_H = 900$ Btu, $Q_C = 300$ Btu
(c) $W_{cycle} = 600$ Btu, $Q_C = 400$ Btu
(d) $\eta = 70\%$

5.19 A power cycle operating at steady state receives energy by heat transfer at a rate $\dot{Q}_H$ at $T_H = 1800$ K and rejects energy by heat transfer to a cold reservoir at a rate $\dot{Q}_C$ at $T_C = 600$ K. For each of the following cases, determine whether the cycle operates *reversibly,* operates *irreversibly,* or is *impossible*.

(a) $\dot{Q}_H = 500$ kW, $\dot{Q}_C = 100$ kW
(b) $\dot{Q}_H = 500$ kW, $\dot{W}_{cycle} = 250$ kW, $\dot{Q}_C = 200$ kW
(c) $\dot{W}_{cycle} = 350$ kW, $\dot{Q}_C = 150$ kW
(d) $\dot{Q}_H = 500$ kW, $\dot{Q}_C = 200$ kW

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

(a) If $T_H = 1600$ K and $T_C = 400$ K, what is the thermal efficiency?
(b) If $T_H = 500$°C, $T_C = 20$°C, and $W_{cycle} = 1000$ kJ, what are Q_H and Q_C, each in kJ?
(c) If $\eta = 60\%$ and $T_C = 40$°F, what is T_H, in °F?
(d) If $\eta = 40\%$ and $T_H = 727$°C, what is T_C, in °C?

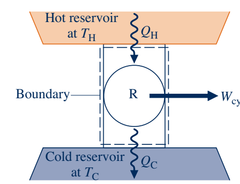


Fig.P5.20

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

5.22 At a particular location, magma exists several kilometers below Earth's surface at a temperature of 1100°C, while the average temperature of the atmosphere at the surface is 15°C. Determine the maximum thermal efficiency for *any* power cycle operating between hot and cold reservoirs at these temperatures.

5.23 Power can be generated in principle by utilizing the naturally occurring decrease with depth of the temperature of ocean water. At one location the ocean surface temperature is 60°F, while at a depth of 1800 ft the temperature is 35°F. Determine the maximum thermal efficiency for *any* power cycle operating between hot and cold reservoirs at these temperatures.

5.24 During January, at a location in Alaska winds at −30°C can be observed, However, several meters below ground the temperature remains at 13°C. An inventor claims to have devised a power cycle working between these temperatures having a thermal efficiency of 5%. Investigate this claim.

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

5.26 As shown in Fig. P5.26, two reversible cycles arranged in series each produce the same net work, W_{cycle}. The first cycle receives energy Q_H by heat transfer from a hot reservoir at 1000°R and rejects energy Q by heat transfer to a reservoir at an intermediate temperature, T. The second cycle receives energy Q by heat transfer from the reservoir at temperature T and rejects energy Q_C by heat transfer to a reservoir at 400°R. All energy transfers are positive in the directions of the arrows. Determine

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

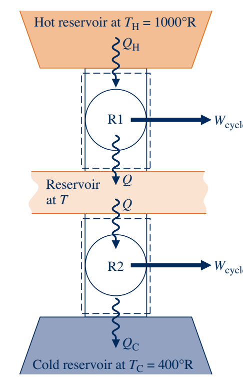


Fig.P5.26

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

(a) the intermediate temperature T, in °R, and the thermal efficiency for each of the two power cycles.
(b) the thermal efficiency of a *single* reversible power cycle operating between hot and cold reservoirs at 1000°R and 500°R, respectively.

5.28 The data listed below are claimed for power cycles operating between hot and cold reservoirs at 1000 K and 400 K, respectively. For each case determine whether such a cycle is in keeping with the first and second laws of thermodynamics.

(a) $Q_H = 300$ kJ, $W_{cycle} = 160$ kJ, $Q_C = 140$ kJ.
(b) $Q_H = 300$ kJ, $W_{cycle} = 180$ kJ, $Q_C = 120$ kJ.
(c) $Q_H = 300$ kJ, $W_{cycle} = 170$ kJ, $Q_C = 140$ kJ.
(d) $Q_H = 300$ kJ, $W_{cycle} = 200$ kJ, $Q_C = 100$ kJ.

5.29 A power cycle operates between a lake's surface water at a temperature of 300 K and water at a depth whose temperature is 285 K. At steady state the cycle develops a power output of 10 kW, while rejecting energy by heat transfer to the lower-temperature water at the rate 14,400 kJ/min. Determine (a) the thermal efficiency of the power cycle and (b) the maximum thermal efficiency for any such power cycle.

5.30 An inventor claims to have developed a power cycle having a thermal efficiency of 40%, while operating between hot and cold reservoirs at temperature T_H and $T_C = 300$ K, respectively, where T_H is (a) 900 K, (b) 500 K, (c) 375 K. Evaluate the claim for each case.

5.31 A power cycle receives 1000 Btu by heat transfer from a reservoir at 1000°F and discharges energy by heat transfer to a reservoir at 300°F. The thermal efficiency of the cycle is 75% of that for a reversible power cycle operating between the same reservoirs, (a) For the actual cycle, determine the thermal efficiency and the energy discharged to the cold reservoir, in Btu. (b) Repeat for the reversible power cycle.

5.32 Referring to the cycle of Fig. 5.13, if $p_1 = 2$ bar, $v_1 = 0.31$ m^3/kg, $T_H = 475$ K, $Q_H = 150$ kJ, and the gas is air obeying the ideal gas model, determine T_C, in K, the net work of the cycle, in kJ, and the thermal efficiency.

5.33 At steady state, a new power cycle is claimed by its inventor to develop net power at a rate of (a) 4 hp, (b) 5 hp for a heat addition rate of 300 Btu/min, while operating between hot and cold reservoirs at 1500°R and 500°R, respectively. Evaluate each claim.

5.34 A power cycle operates between hot and cold reservoirs at 500 K and 310 K, respectively. At steady state the cycle develops a power output of 0.1 MW. Determine the minimum theoretical rate at which energy is rejected by heat transfer to the cold reservoir, in MW.

5.35 At steady state, a new power cycle is claimed by its inventor to develop power at a rate of (a) 90 hp, (b) 100 hp, (c) 110 hp for a heat addition rate of 5.1×10^5 Btu/h, while operating between hot and cold reservoirs at 1000 and 500 K, respectively. Evaluate each claim.

5.36 An inventor claims to have developed a power cycle operating between hot and cold reservoirs at 1175 K and 295 K, respectively, that provides a steady-state power output of (a) 28 kW, (b) 31.2 kW, while receiving energy by heat transfer from the hot reservoir at the rate 150,000 kJ/h. Evaluate each claim.

5.37 At steady state, a power cycle develops a power output of 10 kW while receiving energy by heat transfer at the rate of 10 kJ *per cycle of operation* from a source at temperature T. The cycle rejects energy by heat transfer to cooling water at a lower temperature of 300 K. If there are 100 cycles per minute, what is the minimum theoretical value for T, in K?

5.38 A power cycle operates between hot and cold reservoirs at 600 K and 300 K, respectively. At steady state the cycle develops a power output of 0.45 MW while receiving energy by heat transfer from the hot reservoir at the rate of 1 MW.

(a) Determine the thermal efficiency and the rate at which energy is rejected by heat transfer to the cold reservoir, in MW.
(b) Compare the results of part (a) with those of a reversible power cycle operating between these reservoirs and receiving the same rate of heat transfer from the hot reservoir.

5.39 As shown in Fig. P5.39, a system undergoing a power cycle develops a net power output of 1 MW while receiving energy by heat transfer from steam condensing from saturated vapor to saturated liquid at a pressure of 100 kPa. Energy is discharged from the cycle by heat transfer to a nearby lake at 17°C. These are the only significant heat transfers. Kinetic and potential energy effects can be ignored. For operation at steady state, determine the minimum theoretical steam mass flow rate, in kg/s, required by any such cycle.

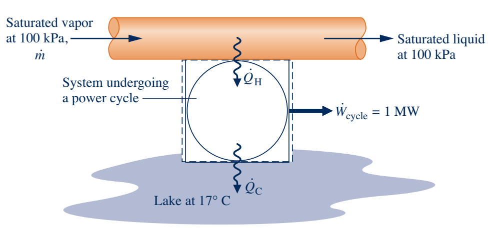


Fig.P5.39

5.40 A power cycle operating at steady state receives energy by heat transfer from the combustion of fuel at an average temperature of 1000 K. Owing to environmental considerations, the cycle discharges energy by heat transfer to the atmosphere at 300 K at a rate no greater than 60 MW. Based on the cost of fuel, the cost to supply the heat transfer is \$4.50 per GJ. The power developed by the cycle is valued at \$0.10 per kW · h. For 8000 hours of operation annually, determine for any such cycle, in \$ per year, (a) the maximum value of the power generated and (b) the corresponding fuel cost.

5.41 At steady state, a 750-MW power plant receives energy by heat transfer from the combustion of fuel at an average temperature of 317°C. As shown in Fig. P5.41, the plant discharges energy by heat transfer to a river whose mass flow rate is 1.65×10^5 kg/s. Upstream of the power plant the river is at 17°C. Plot the increase in the temperature of the river, ΔT, traceable to such heat transfer, in K, versus the thermal efficiency of the plant, ranging upward from 20%.

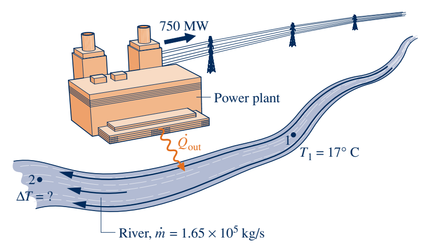


Fig.P5.41

5.42 Figure P5.42 shows a system for collecting solar energy and using it for generating electricity. The solar collector receives an average annual daily solar input of 4 kW-h per m^2 of collector area. The energy collected is transferred without loss to a storage unit whose temperature remains at 400 K. The power cycle receives energy by heat transfer from the storage unit and discharges energy by heat transfer to the surroundings at 285 K. The collector measures 15 m by 25 m. If the electricity generated can be sold for 8 cents per kW · h, plot the value of the electricity generated annually, in \$, versus the power cycle thermal efficiency. Comment.

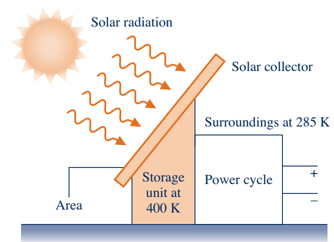


Fig.P5.42

Refrigeration and Heat Pump Cycle Applications

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

(a) $Q_C = 1000$ kJ, $W_{cycle} = 80$ kJ.
(b) $Q_C = 1200$ kJ, $Q_H = 2000$ kJ.
(c) $Q_H = 1575$ kJ, $W_{cycle} = 200$ kJ.
(d) $\beta = 6$.

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

(a) If the coefficient of performance is 3.5 and $T_C = -40$°F, determine T_H, in °F.
(b) If $T_C = -30$°C and $T_H = 30$°C, determine the coefficient of performance.
(c) If $Q_C = 500$ Btu, $Q_H = 800$ Btu, and $T_C = 20$°F, determine T_H, in °F.
(d) If $T_C = 30$°F and $T_H = 100$°F, determine the coefficient of performance.
(e) If the coefficient of performance is 8.9 and $T_C = -5$°C, find T_H, in °C.

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

(a) If $T_H = 13$°C and $T_C = 2$°C, determine the coefficient of performance.
(b) If $\dot{Q}_H = 10.5$ kW, $\dot{Q}_C = 8.75$ kW, and $T_C = 0$°C, determine T_H, in °C.
(c) If the coefficient of performance is 10 and $T_H = 27$°C, determine T_C, in °C.

5.46 A heating system must maintain the interior of a building at 20°C during a period when the outside air temperature is 5°C and the heat transfer from the building through its roof and walls is 3×10^6 kJ. For this duty heat pumps are under consideration that would operate between the dwelling and

(a) the ground at 15°C.
(b) a pond at 10°C.
(c) the outside air at 5°C.

For each case, evaluate the minimum theoretical net work input required by *any* such heat pump, in kJ.

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

5.48 The thermal efficiency of a reversible power cycle operating between hot and cold reservoirs is 20%. Evaluate the coefficient of performance of

(a) a reversible refrigeration cycle operating between the same two reservoirs.
(b) a reversible heat pump cycle operating between the same two reservoirs.

5.49 Shown in Fig. P5.49 is a system consisting of a power cycle and a heat pump cycle, each operating between hot and cold reservoirs whose temperature are 500 K and 300 K, respectively. All energy transfers are positive in the directions of the arrows. The accompanying table provides two sets of steady-state data, in kW. For each set of data, determine if the system is operating in accord with the first and second laws of thermodynamics.

	Power cycle			Heat pump cycle		
	$\dot{Q}_H$	$\dot{Q}_C$	$\dot{W}_{cycle}$	$\dot{Q}'_H$	$\dot{Q}'_C$	$\dot{W}'_{cycle}$
(a)	60	40	20	80	60	20
(b)	120	80	40	100	80	20

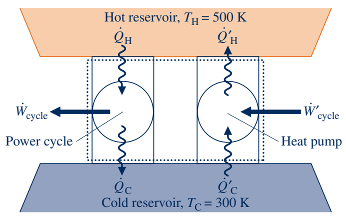


Fig.P5.49

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

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

5.52 An inventor claims to have developed a refrigerator that at steady state requires a net power input of 0.7 horsepower to remove 12,000 Btu/h of energy by heat transfer from the freezer compartment at 0°F and discharge energy by heat transfer to a kitchen at 70°F. Evaluate this claim.

5.53 An inventor claims to have devised a refrigeration cycle operating between hot and cold reservoirs at 300 K and 250 K, respectively, that removes an amount of energy Q_C by heat transfer from the cold reservoir that is a multiple of the net work input—that is, $Q_C = NW_{cycle}$, where all quantities are positive. Determine the maximum theoretical value of the number N for any such cycle.

5.54 Data are provided for two reversible refrigeration cycles. One cycle operates between hot and cold reservoirs at 27°C and −8°C, respectively. The other cycle operates between the same hot reservoir at 27°C and a cold reservoir at −28°C. If each refrigerator removes the same amount of energy by heat transfer from its cold reservoir, determine the ratio of the net work input values of the two cycles.

5.55 By removing energy by heat transfer from its freezer compartment at a rate of 1.25 kW, a refrigerator maintains the freezer at −26°C on a day when the temperature of the surroundings is 22°C. Determine the minimum theoretical power, in kW, required by the refrigerator at steady state.

5.56 At steady state, a refrigeration cycle maintains a *clean room* at 55°F by removing energy entering the room by heat transfer from adjacent spaces at the rate of 0.12 Btu/s. The cycle rejects energy by heat transfer to the outdoors where the temperature is 80°F.

(a) If the rate at which the cycle rejects energy by heat transfer to the outdoors is 0.16 Btu/s, determine the power required, in Btu/s.

(b) Determine the power required to maintain the clean room's temperature by a reversible refrigeration cycle operating between cold and hot reservoirs at 55°F and 80°F, respectively, and the corresponding rate at which energy is rejected by heat transfer to the outdoors, each in Btu/s.

5.57 For each kW of power input to an ice maker at steady state, determine the maximum rate that ice can be produced, in lb/h, from liquid water at 32°F. Assume that 144 Btu/lb of energy must be removed by heat transfer to freeze water at 32°F and that the surroundings are at 78°F.

5.58 At steady state, a refrigeration cycle operating between hot and cold reservoirs at 300 K and 275 K, respectively, removes energy by heat transfer from the cold reservoir at a rate of 600 kW.

(a) If the cycle's coefficient of performance is 4, determine the power input required, in kW.
(b) Determine the minimum theoretical power required, in kW, for *any* such cycle.

5.59 An air conditioner operating at steady state maintains a dwelling at 20°C on a day when the outside temperature is 35°C. Energy is removed by heat transfer from the dwelling at a rate of 2800 J/s while the air conditioner's power input is 0.8 kW. Determine (a) the coefficient of performance of the air conditioner and (b) the power input required by a reversible refrigeration cycle providing the same cooling effect while operating between hot and cold reservoirs at 35°C and 20°C, respectively.

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

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

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

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

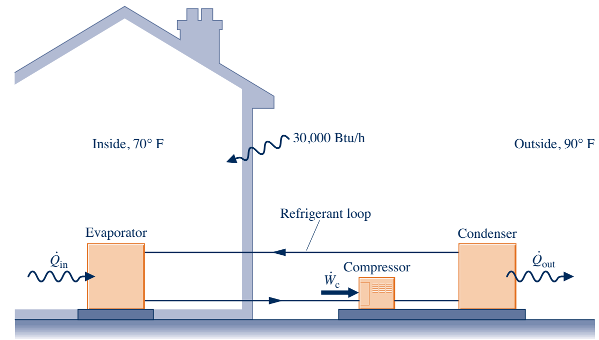


Fig.P5.64

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

5.63 A heat pump cycle is used to maintain the interior of a building at 21°C. At steady state, the heat pump receives energy by heat transfer from well water at 9°C and discharges energy by heat transfer to the building at a rate of 120,000 kJ/h. Over a period of 14 days, an electric meter records that 1490 kW · h of electricity is provided to the heat pump. Determine

(a) the amount of energy that the heat pump receives over the 14-day period from the well water by heat transfer, in kJ.
(b) the heat pump's coefficient of performance.
(c) the coefficient of performance of a reversible heat pump cycle operating between hot and cold reservoirs at 21°C and 9°C.

5.64 As shown in Fig P5.64, an air conditioner operating at steady state maintains a dwelling at 70°F on a day when the outside temperature is 90°F. If the rate of heat transfer into the dwelling through the walls and roof is 30,000 Btu/h, might a net power input to the air conditioner compressor of 3 hp be sufficient? If yes, determine the coefficient of performance. If no, determine the minimum theoretical power input, in hp.

5.65 At steady state, a refrigeration cycle driven by an electric motor maintains the interior of a building at $T_C = 20°C$ when the outside temperature is $T_H = 35°C$. The rate of heat transfer into the building through its walls and roof is given by $R(T_H - T_C)$, where R is a constant, in kW/K. The coefficient of performance of the cycle is 20% of a reversible refrigeration cycle operating between cold and hot reservoirs at T_C and T_H, respectively.

(a) If the power input to the motor is 3 kW, evaluate R.
(b) If R is reduced by 5%, determine the power input required, in kW, assuming all other data remain the same.

5.66 A refrigeration cycle driven by an electric motor must maintain a computer laboratory at 18°C when the outside temperature is 30°C The *thermal load* consists of heat transfers entering through the walls and roof of the laboratory at a rate of 75,000 kJ/h and from the computers, lighting, and occupants at a rate of 15,000 kJ/h.

(a) Determine the minimum theoretical power required by the electric motor, in kW, and the corresponding coefficient of performance.
(b) If the actual power required by the motor for this duty is 8.3 kW, determine the coefficient of performance.
(c) If the given temperature and thermal load data are observed for a total of 100 hours and electricity costs 13 cents per kW · h, determine the cost, in \$, over that period for each of cases (a) and (b).

5.67 At steady state, a heat pump driven by an electric motor maintains the interior of a building at $T_H = 293$ K. The rate of heat transfer, in kJ/h, from the building through its walls and roof is given by $8000(T_H - T_C)$, where T_C is the outdoor temperature. Plot the minimum theoretical electric power, in kW, required to drive the heat pump versus T_C ranging from 273 K to 293 K.

5.68 The refrigerator shown in Fig. P5.68 operates at steady state with a coefficient of performance of 5.0 within a kitchen at 23°C. The refrigerator rejects 4.8 kW by heat

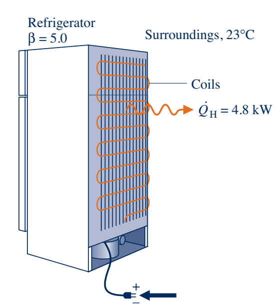


Fig.P5.68

transfer to its surroundings from metal coils located on its exterior. Determine

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

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

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

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

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

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

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

5.72 As shown in Fig. P5.72, a heat pump provides energy by heat transfer to water vaporizing from saturated liquid to saturated vapor at a pressure of 2 bar and a mass flow rate of 0.05 kg/s. The heat pump receives energy by heat transfer from a pond at 16°C. These are the only significant heat transfers. Kinetic and potential energy effects can be ignored. A faded, hard-to-read data sheet indicates the power required by the heat pump at steady state is 35 kW. Can this value be correct? Explain.

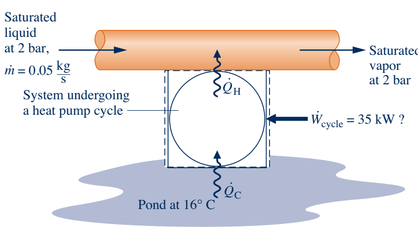


Fig.P5.72

5.73 As shown in Fig. P 5.73, a heat pump receives energy by heat transfer from below Earth's surface where the temperature is 50°F and delivers energy by heat transfer to ammonia vaporizing from saturated liquid to saturated vapor at 75°F. These are the only significant heat transfer. At steady state, the power input to the heat pump is 3 hp. Determine the maximum theoretical ammonia mass flow rate, in lb/min, for any such heat pump. For the ammonia ignore kinetic and potential energy effects.

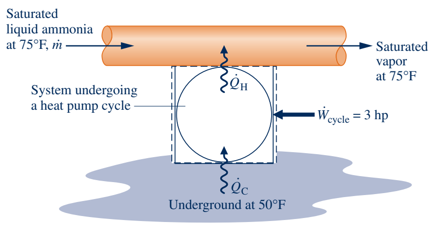


Fig.P5.73

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

5.75 A heating system must maintain the interior of a building at T_H = 20°C when the outside temperature is T_C = 2°C. If the rate of heat transfer from the building through its walls and roof is 16.4 kW, determine the electrical power required, in kW, to heat the building using (a) electrical-resistance heating, (b) a heat pump whose coefficient of performance is 3.0, (c) a reversible heat pump operating between hot and cold reservoirs at 20°C and 2°C, respectively.

Carnot Cycle Applications

5.76 A gas within a piston-cylinder assembly executes a Carnot power cycle during which the isothermal expansion occurs at T_H = 600 K and the isothermal compression occurs at T_C = 300 K. Determine

(a) the thermal efficiency.
(b) the percent change in thermal efficiency if T_H increases by 15% while T_C remains the same.
(c) the percent change in thermal efficiency if T_C decreases by 15% while T_H remains the same.
(d) the percent change in thermal efficiency if T_H increases by 15% and T_C decreases by 15%.

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

5.78 An ideal gas within a piston–cylinder assembly executes a Carnot power cycle. as shown in Fig. 5.13. The isothermal compression occurs at 300 K from 90 kPa to 120 kPa. If the thermal efficiency is 60%, determine (a) the temperature of the isothermal expansion, in K, and (b) the net work developed, in kJ per kmol of gas.

5.79 An ideal gas within a piston–cylinder assembly undergoes a Carnot refrigeration cycle, as shown in Fig. 5.16. The isothermal compression occurs at 325 K from 2 bar to 4 bar. The isothermal expansion occurs at 250 K. Determine (a) the coefficient of performance, (b) the heat transfer to the gas during the isothermal expansion, in kJ per kmol of gas, (c) the magnitude of the net work input, in kJ per kmol of gas.

5.80 Air within a piston-cylinder assembly executes a Carnot heat pump cycle, as shown in Fig 5.16. For the cycle, T_H = 600 K and T_C = 300 K. The energy rejected by heat transfer at 600 K has a magnitude of 250 kJ per kg of air. The pressure at the start of the isothermal expansion is 325 kPa. Assuming the ideal gas model for the air, determine (a) the magnitude of the net work input, in kJ per kg of air, and (b) the pressure at the end of the isothermal expansion, in kPa.

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

(a) Sketch the cycle on p–v coordinates.
(b) Evaluate the heat transfer per unit mass and work per unit mass for each process, in kJ/kg.
(c) Evaluate the thermal efficiency.

5.82 One and one-half pounds of water within a piston–cylinder assembly execute a Carnot power cycle. During isothermal expansion, the water is heated at 500°F from saturated liquid to saturated vapor. The vapor then expands adiabatically to a temperature of 100°F and a quality of 70.38%.

(a) Sketch the cycle on p–v coordinates.
(b) Evaluate the heat transfer and work for each process, in Btu.
(c) Evaluate the thermal efficiency.

5.83 Two kilograms of air within a piston–cylinder assembly execute a Carnot power cycle with maximum and minimum temperatures of 750 K and 300 K, respectively. The heat transfer to the air during the isothermal expansion is 60 kJ. At the end of the isothermal expansion the volume is 0.4 m^3. Assuming the ideal gas model for the air, determine

(a) the thermal efficiency.
(b) the pressure and volume at the beginning of the isothermal expansion, in kPa and m^3, respectively.
(c) the work and heat transfer for each of the four processes, in kJ.
(d) Sketch the cycle on p–V coordinates.

Clausius Inequality Applications

5.84 A system executes a power cycle while receiving 1000 kJ by heat transfer at a temperature of 500 K and discharging energy by heat transfer at a temperature of 300 K. There are no other heat transfers. Applying Eq. 5.13, determine σ_{cycle} if the thermal efficiency is (a) 100%, (b) 40%, (c) 25%. Identify cases (if any) that are internally reversible or impossible.

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

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

5.86 For the refrigerator of Example 5.2, apply Eq. 5.13 on a time-rate basis to determine whether the cycle operates reversibly, operates irreversibly, or is impossible. Repeat for the case where there is no power input.

5.87 For each data set of Prob. 5.49, apply Eq. 5.13 on a time-rate basis to determine whether the system operates reversibly, operates irreversibly, or is impossible.

5.88 The steady-state data listed below are claimed for a power cycle operating between hot and cold reservoirs at 1200 K and 400 K, respectively. For each case, evaluate the net power developed by the cycle, in kW, and the thermal efficiency. Also in each case apply Eq. 5.13 on a time-rate basis to determine whether the cycle operates reversibly, operates irreversibly, or is impossible.

(a) $\dot{Q}_H$ = 600 kW, $\dot{Q}_C$ = 400 kW
(b) $\dot{Q}_H$ = 600 kW, $\dot{Q}_C$ = 0 kW
(c) $\dot{Q}_H$ = 600 kW, $\dot{Q}_C$ = 200 kW

5.89 At steady state, a thermodynamic cycle operating between hot and cold reservoirs at 1000 K and 500 K, respectively, receives energy by heat transfer from the hot reservoir at a rate of 1500 kW, discharges energy by heat transfer to the cold reservoir, and develops power at a rate of (a) 1000 kW, (b) 750 kW, (c) 0 kW. For each case, apply Eq. 5.13 on a time-rate basis to determine whether the cycle operates reversibly, operates irreversibly, or is impossible.

5.90 Figure P5.90 gives the schematic of a vapor power plant in which water steadily circulates through the four components shown. The water flows through the boiler and condenser at constant pressure and through the turbine and pump adiabatically. Kinetic and potential energy effects can be ignored. Process data follow:

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

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

(a) Using Eq. 5.13 expressed on a time-rate basis, determine if the cycle is *internally reversible, irreversible,* or *impossible*.
(b) Determine the thermal efficiency using Eq. 5.4 expressed on a time-rate basis and steam table data.
(c) Compare the result of part (b) with the *Carnot efficiency* calculated using Eq. 5.9 with the boiler and condenser temperatures and comment.

5.91 Repeat Problem 5.90 for the following case:

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

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

5.92 Repeat Problem 5.90 for the following case:

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

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

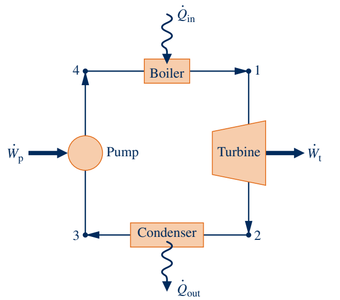


Fig.P5.90–92

5.93 As shown in Fig. P5.93, a system executes a power cycle while receiving 750 kJ by heat transfer at a temperature of 1500 K and discharging 100 kJ by heat transfer at a temperature of 500 K. Another heat transfer from the system occurs at a temperature of 1000 K. Using Eq. 5.13, plot the thermal efficiency of the cycle versus σ_{cycle}, in kJ/K.

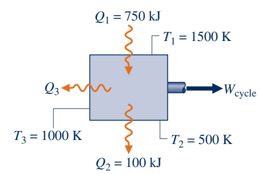


Fig.P5.93

5.94 Shown in Fig. P5.94 is a system that executes a power cycle while receiving 600 Btu by heat transfer at a temperature of 1000°R and discharging 400 Btu by heat transfer at a temperature of 800°R. A third heat transfer occurs at a temperature of 600°R. These are the only heat transfers experienced by the system.

(a) Applying an energy balance together with Eq. 5.13, determine the direction and allowed range of values, in Btu, for the heat transfer at 600°R.
(b) For the power cycle, evaluate the maximum theoretical thermal efficiency.

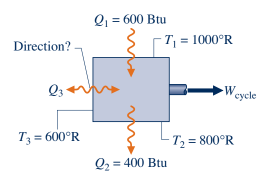


Fig.P5.94

▶ DESIGN & OPEN-ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE

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

5.2D Investigate adverse health conditions that might be exacerbated for persons living in urban *heat islands*. Write a report including at least three references.

5.3D For each of three comparably sized spaces in your locale, a preschool, an office suite with cubicles, and an assisted-living facility, investigate the suitability of a heat pump/air-conditioning system employing a *natural* refrigerant. Consider factors including, but not limited to, health and safety requirements, applicable codes, performance in meeting occupant comfort needs, annual electricity cost, and environmental impact, each in comparison to systems using conventional refrigerants for the same duty. Summarize your findings in a report, including at least three references.

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

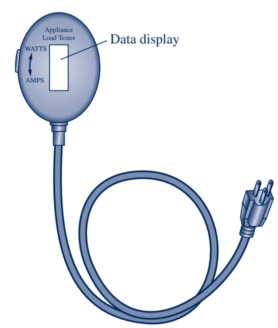


Fig. P5.4D

5.5D The objective of this project is to identify a commercially available heat pump system that will meet annual heating and cooling needs of an existing dwelling in a locale of your choice. Consider each of two types of heat pump: air source and ground source. Estimate installation costs, operating costs, and other pertinent costs for each type of heat pump. Assuming a 10-year life, specify the more economical heat pump system. What if electricity were to cost twice its current cost? Prepare a poster presentation of your findings.

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

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

5.8D Four hundred feet below a city in southern Illinois sits an abandoned lead mine filled with an estimated 70 billion gallons of water that remains at a constant temperature of about 58°F. The city engineer has proposed using the impounded water as a resource for heating and cooling the city's central administration building, a two-story, brick building constructed in 1975 having 8500 ft² of office space. You have been asked to develop a preliminary proposal, including a cost estimate. The proposal will specify commercially available systems that utilize the impounded water to meet heating and cooling needs. The cost estimate will include project development, hardware, and annual operating cost. Report your findings in the form of a PowerPoint presentation suitable for the city council.

5.9D Figure P5.9D shows one of those bobbing toy birds that seemingly takes an endless series of sips from a cup filled with water. Prepare a 30-min presentation suitable for a middle school science class explaining the operating principles of this device and whether or not its behavior is at odds with the second law.

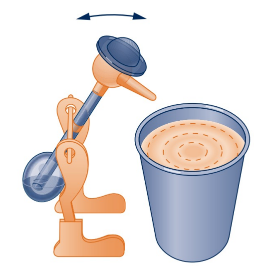


Fig. P5.9D

5.10D As shown in Fig. P5.10D, a pump delivers water to a 500-foot-long pipe at a pressure of 55 lbf/in.² and a temperature of 60°F. The pipe supplies water at a volumetric flow rate of 200 ft³/min to a storage tank whose pressure cannot be less than 20 lbf/in.². For an ANSI Schedule 40 steel pipe, determine the smallest *standard* pipe diameter, in inches, that meets these requirements. Assume steady state with negligible change in pipe elevation from inlet to exit, and the *Moody* friction factor diagram applies.

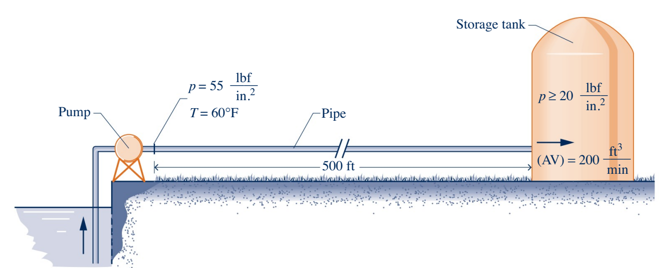


Fig. P5.10D