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 understand 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. 164
mass flow rates, p. 164
mass rate balance, p. 164
one-dimensional flow, p. 166
volumetric flow rate, p. 167
steady state, p. 167
flow work, p. 173
energy rate balance, p. 174
nozzle, p. 177
diffuser, p. 177
turbine, p. 180
compressor, p. 184
pump, p. 184
heat exchanger, p. 189
throttling process, p. 195
system integration, p. 196
transient analysis, p. 199

KEY EQUATIONS

$\dot{m} = \dfrac{AV}{v}$	(4.4b) p. 166	Mass flow rate, one-dimensional flow (See Fig. 4.3.)
$\dfrac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$	(4.2) p. 164	Mass rate balance.
$\sum_i \dot{m}_i = \sum_e \dot{m}_e$ (mass rate in) (mass rate out)	(4.6) p. 167	Mass rate balance at steady state.
$\dfrac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i\left(h_i + \dfrac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(h_e + \dfrac{V_e^2}{2} + gz_e\right)$	(4.15) p. 174	Energy rate balance.
$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i\left(h_i + \dfrac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(h_e + \dfrac{V_e^2}{2} + gz_e\right)$	(4.18) p. 175	Energy rate balance at steady state.
$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left[(h_1 - h_2) + \dfrac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)\right]$	(4.20a) p. 175	Energy rate balance for one-inlet, one-exit control volumes at steady state.
$0 = \dfrac{\dot{Q}_{cv}}{\dot{m}} - \dfrac{\dot{W}_{cv}}{\dot{m}} + (h_1 - h_2) + \dfrac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)$	(4.20b) p. 175	
$h_2 = h_1 \qquad (p_2 < p_1)$	(4.22) p. 195	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. Why does the relative velocity *normal* to the flow boundary, V_n, appear in Eqs. 4.3 and 4.8?

3. When a slice of bread is placed in a toaster and the toaster is activated, is the toaster in steady-state operation, transient operation, 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. How is the work done by the heart measured?

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. Why is it that when air at 1 atm is *throttled* to a pressure of 0.5 atm, its temperature at the valve exit is closely the same as at the valve inlet, yet when air at 1 atm *leaks* into an insulated, rigid, initially-evacuated tank until the tank pressure is 0.5 atm, the temperature of the air in the tank is greater than the air temperature outside the tank?

13. If the expansion valve of a refrigerator becomes ice encased, does the *throttling process* model still apply? Explain.

14. Why does *evapotranspiration* in a tree require so much energy?

15. What are intra-articular pain pumps?

▶ PROBLEMS: DEVELOPING ENGINEERING SKILLS

Applying Conservation of Mass

4.1 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.

4.2 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.

4.3 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.

4.4 Data are provided for the crude oil storage tank shown in Fig. P4.4. 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.

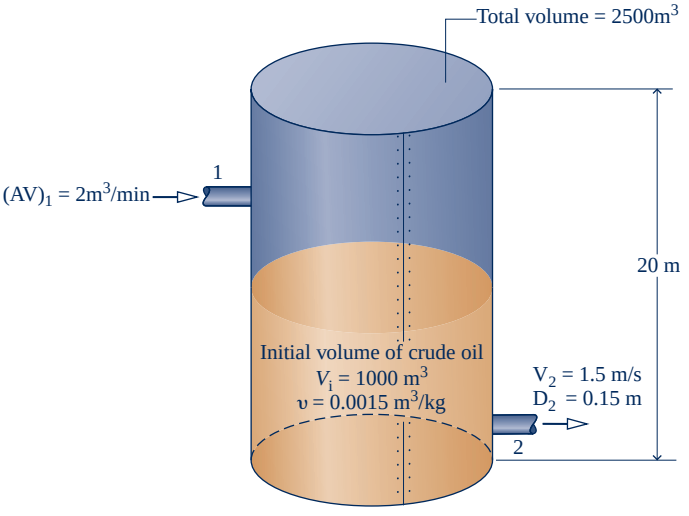


Fig. P4.4

4.5 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.

4.6 Figure P4.6 shows a mixing tank initially containing 3000 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 1.3 lb/s. Water exits through a single exit pipe at a mass flow rate of 2.6 lb/s. Determine the amount of water, in lb, in the tank after one hour.

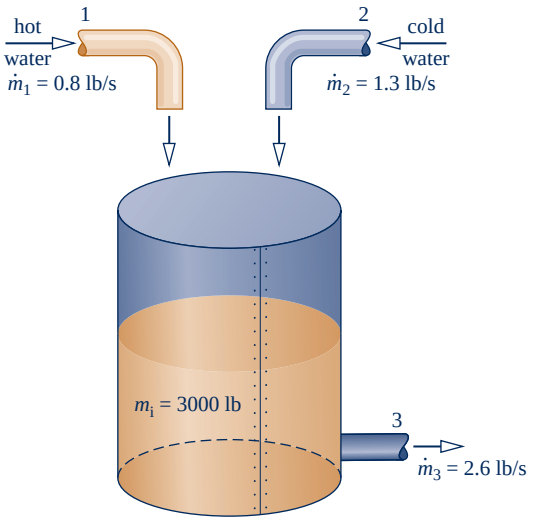


Fig. P4.6

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.

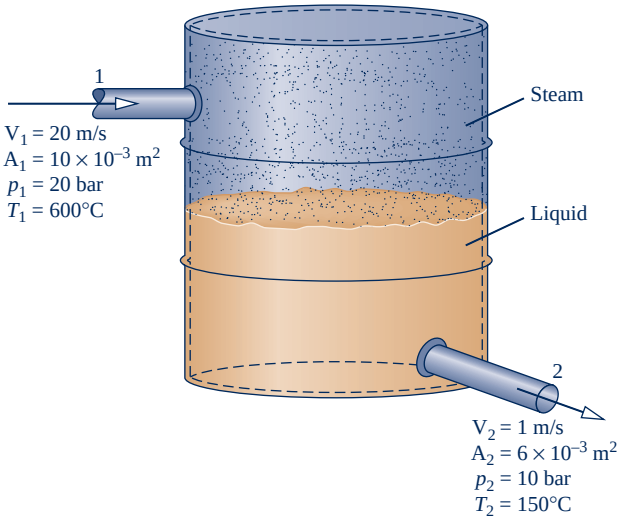


Fig. P4.7

4.8 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.

4.9 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.

4.10 The small two-story office building shown in Fig. P4.10 has 36,000 ft^3 of occupied space. Due to cracks around windows and outside doors, air leaks in on the windward side of the building and leaks out on the leeward side of the building. Outside air also enters the building when outer doors are opened. On a particular day, tests were conducted. The outdoor temperature was measured to be 15°F. The inside temperature was controlled at 70°F. Keeping the doors closed, the infiltration rate through the cracks was determined to be 75 ft^3/min. The infiltration rate associated with door openings, averaged over the work day, was 50 ft^3/min. The pressure difference was negligible between the inside and outside of the building. (a) Assuming ideal gas behavior, determine at steady state the volumetric flow rate of air exiting the building, in ft^3/min. (b) When expressed in terms of the volume of the occupied space, determine the number of building air changes per hour.

4.11 As shown in Fig. P4.11, 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.

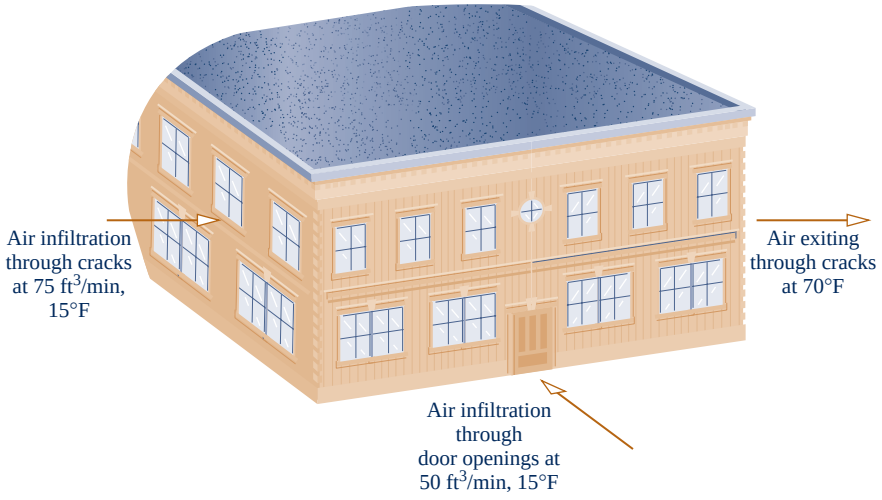


Fig. P4.10

(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.

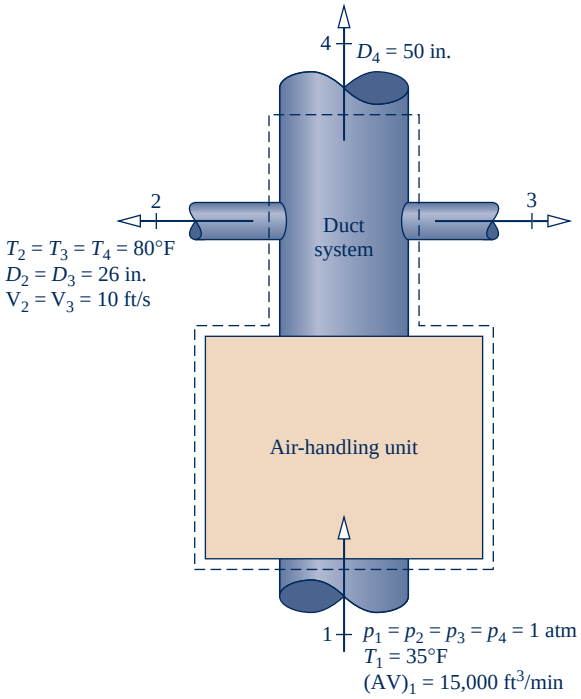


Fig. P4.11

4.12 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.

4.13 As shown in Fig. P4.13, 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.

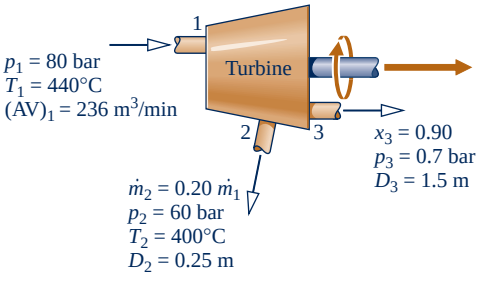


Fig. P4.13

4.14 Figure P4.14 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.

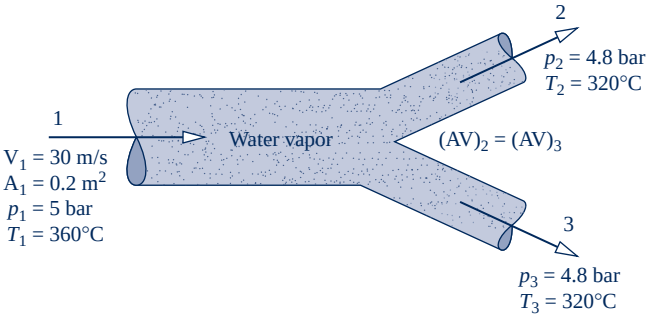


Fig. P4.14

4.15 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.

4.16 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.

4.17 Liquid water at 70°F enters a pump though an inlet pipe having a diameter of 6 in. The pump operates at steady state and supplies water to two exit pipes having diameters of 3 in. and 4 in., respectively. The velocity of the water exiting the 3-in. pipe is 1.31 ft/s. At the exit of the 4-in. pipe the velocity is 0.74 ft/s. The temperature of the water in each exit pipe is 72°F. Determine (a) the mass flow rate, in lb/s, in the inlet pipe and each of the exit pipes, and (b) the volumetric flow rate at the inlet, in ft^3/min.

4.18 Figure P4.18 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

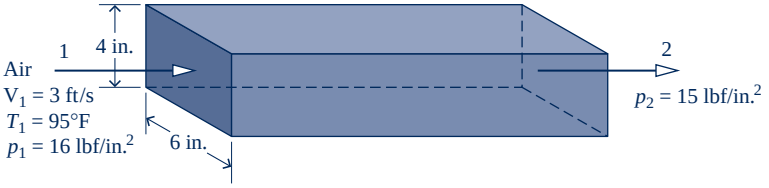


Fig. P4.18

volumetric flow rate and mass flow rate at the exit, evaluate them. If not, explain.

4.19 A water storage tank initially contains 100,000 gal of water. The average daily usage is 10,000 gal. If water is added to the tank at an average rate of 5000[exp(−t/20)] gallons per day, where t is time in days, for how many days will the tank contain water?

4.20 A pipe carrying an incompressible liquid contains an expansion chamber as illustrated in Fig. P4.20.

(a) Develop an expression for the time rate of change of liquid level in the chamber, dL/dt, in terms of the diameters D_1, D_2, and D, and the velocities V_1 and V_2.
(b) Compare the relative magnitudes of the mass flow rates $\dot{m}_1$ and $\dot{m}_2$ when $dL/dt > 0$, $dL/dt = 0$, and $dL/dt < 0$, respectively.

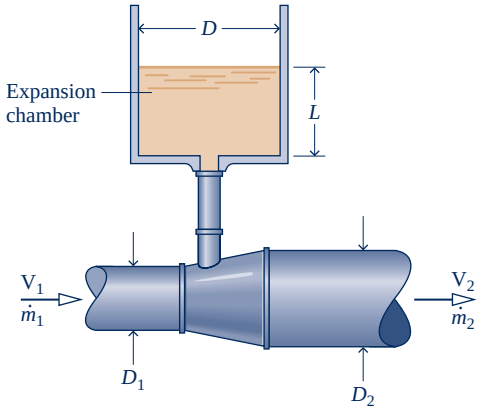


Fig. P4.20

4.21 Velocity distributions for *laminar* and *turbulent* flow in a circular pipe of radius R carrying an incompressible liquid of density ρ are given, respectively, by

$$V/V_0 = [1 - (r/R)^2]$$
$$V/V_0 = [1 - (r/R)]^{1/7}$$

where r is the radial distance from the pipe centerline and V_0 is the centerline velocity. For each velocity distribution

(a) plot V/V_0 versus r/R.
(b) derive expressions for the mass flow rate and the average velocity of the flow, V_{ave}, in terms of V_0, R, and ρ, as required.
(c) derive an expression for the *specific* kinetic energy carried through an area normal to the flow. What is the percent error if the specific kinetic energy is evaluated in terms of the average velocity as $(V_{ave})^2/2$?

Which velocity distribution adheres most closely to the idealizations of one-dimensional flow? Discuss.

4.22 Figure P4.22 shows a cylindrical tank being drained through a duct whose cross-sectional area is 3×10^{-4} m^2. The velocity of the water at the exit varies according to $(2gz)^{1/2}$, where z is the water level, in m, and g is the acceleration of gravity, 9.81 m/s^2. The tank initially contains 2500 kg of liquid water. Taking the density of the water as 10^3 kg/m^3, determine the time, in minutes, when the tank contains 900 kg of water.

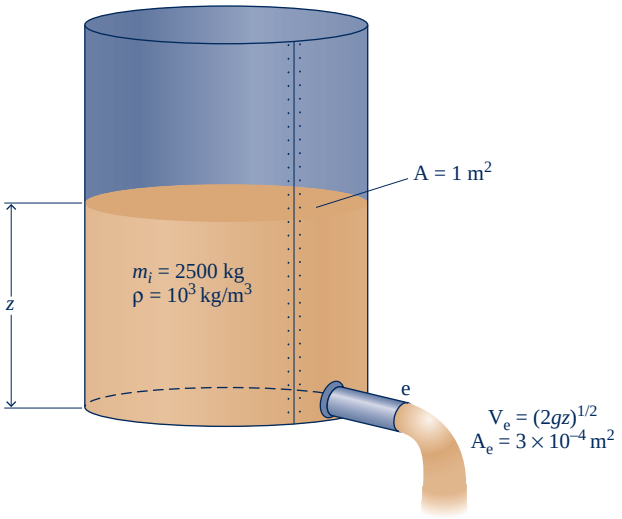


Fig. P4.22

Energy Analysis of Control Volumes at Steady State

4.23 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, determine the rate of heat transfer between the pipe and its surroundings, in kW.

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.

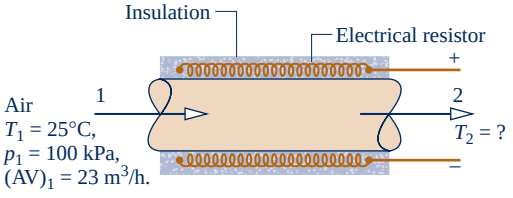


Fig. P4.25

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

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

4.29 Refrigerant 134a flows at steady state through a horizontal pipe having an inside diameter of 4 cm, entering as saturated vapor at −8°C with a mass flow rate of 17 kg/min. Refrigerant vapor exits at a pressure of 2 bar. If the heat transfer rate to the refrigerant is 3.4 kW, determine the exit temperature, in °C, and the velocities at the inlet and exit, each in m/s.

4.30 Water vapor enters an insulated nozzle operating at steady state at 500°C, 40 bar, with a velocity of 100 m/s, and exits at 300°C, 10 bar. The velocity at the exit, in m/s, is approximately

(a) 104, (c) 888,
(b) 636, (d) 894.

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 5 lb/s enters a horizontal nozzle operating at steady state at 800°R, 50 lbf/in.^{2} and a velocity of 10 ft/s. At the exit, the temperature is 570°R and the velocity is 1510 ft/s. Using the ideal gas model for air, determine (a) the area at the inlet, in ft^2, and (b) the heat transfer between the nozzle and its surroundings, in Btu per lb of air flowing.

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 Methane (CH_4) gas enters a horizontal, well-insulated nozzle operating at steady state at 80°C and a velocity of 10 m/s. Assuming ideal gas behavior for the methane, plot the temperature of the gas exiting the nozzle, in °C, versus the exit velocity ranging from 500 to 600 m/s.

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.

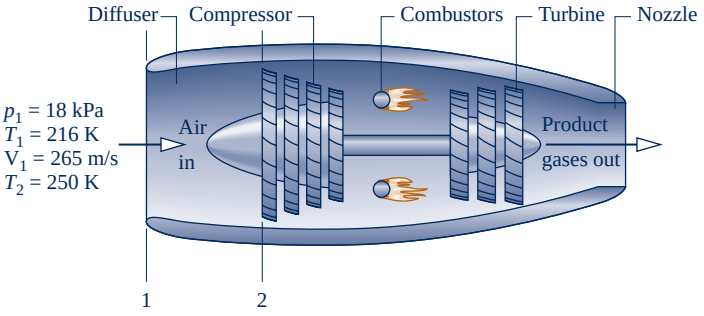


Fig. P4.37

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 nozzle, determine the exit temperature, in °R, the exit pressure, in lbf/in.^{2}, and the mass flow rate, in lb/s.

4.41 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.

4.42 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.

4.43 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

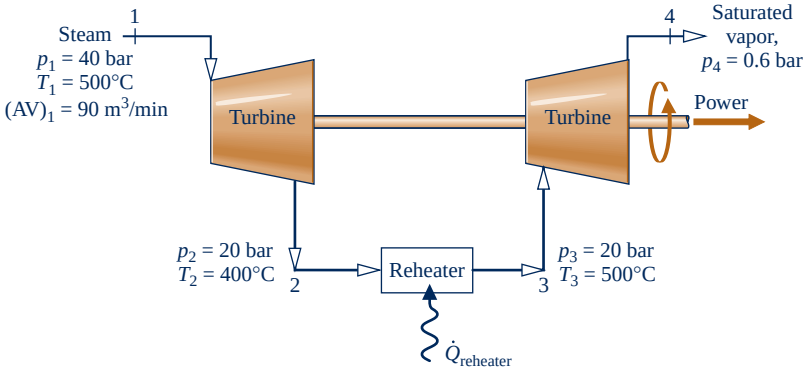


Fig. P4.50

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.

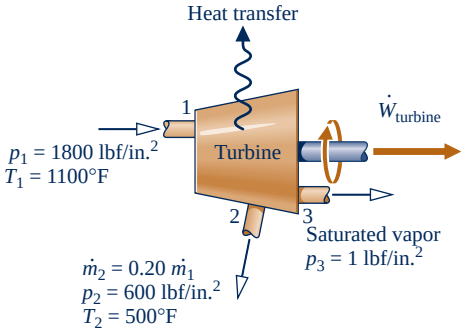


Fig. P4.51

4.52 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. If the compressor power input is 77 kW, determine the rate of heat transfer between the compressor and its surroundings, in kW. Neglect kinetic and potential energy effects and assume the ideal gas model.

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 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 power 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 is compressed at steady state from 1 bar, 300 K, to 6 bar with a mass flow rate of 4 kg/s. Each unit of mass passing from inlet to exit undergoes a process described by $pv^{1.27}$ = *constant*. Heat transfer occurs at a rate of 46.95 kJ per kg of air flowing to cooling water circulating in a water jacket enclosing the compressor. If kinetic and potential energy changes of the air from inlet to exit are negligible, determine the compressor power, in kW.

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 occurs at a rate of 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.

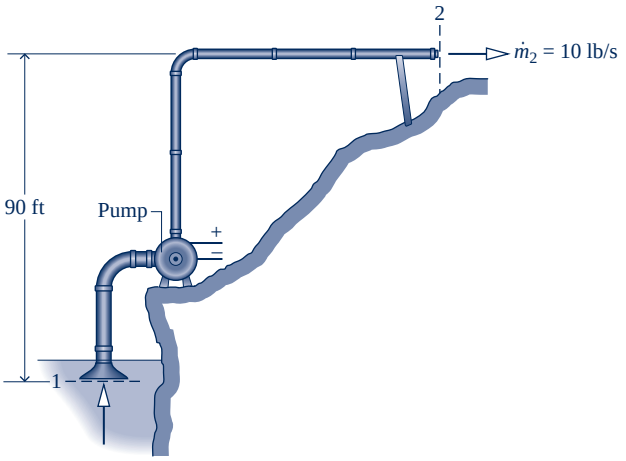


Fig. P4.65

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 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.

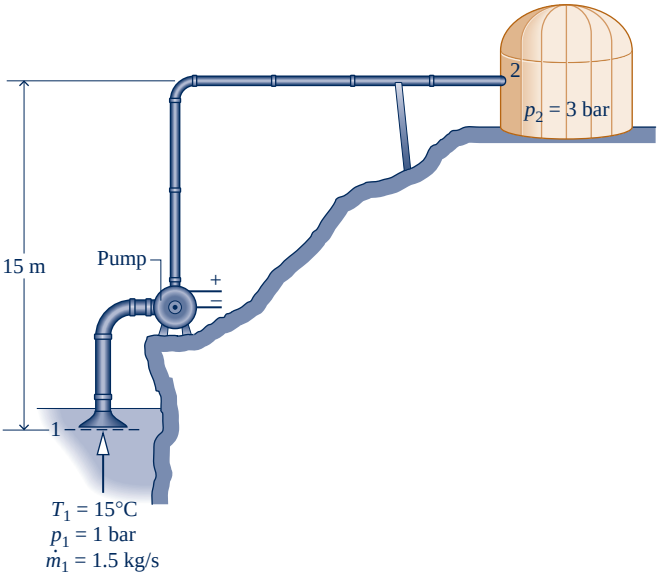


Fig. P4.66

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 cents per liter, and comment.

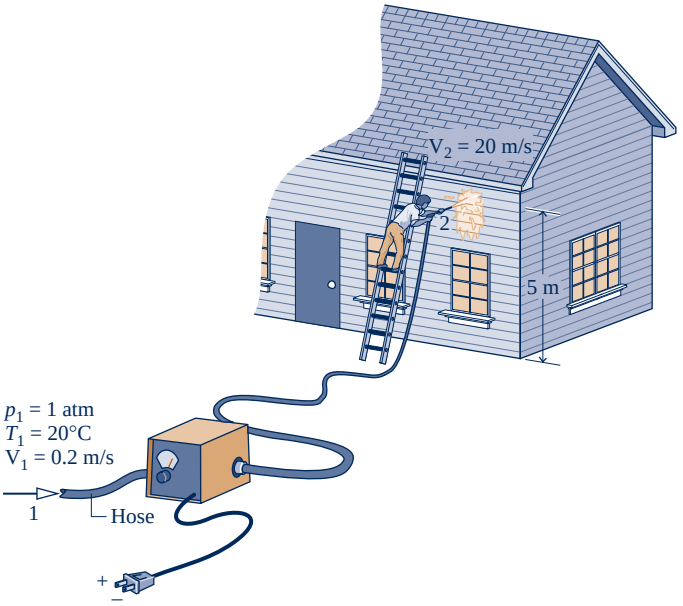


Fig. P4.68

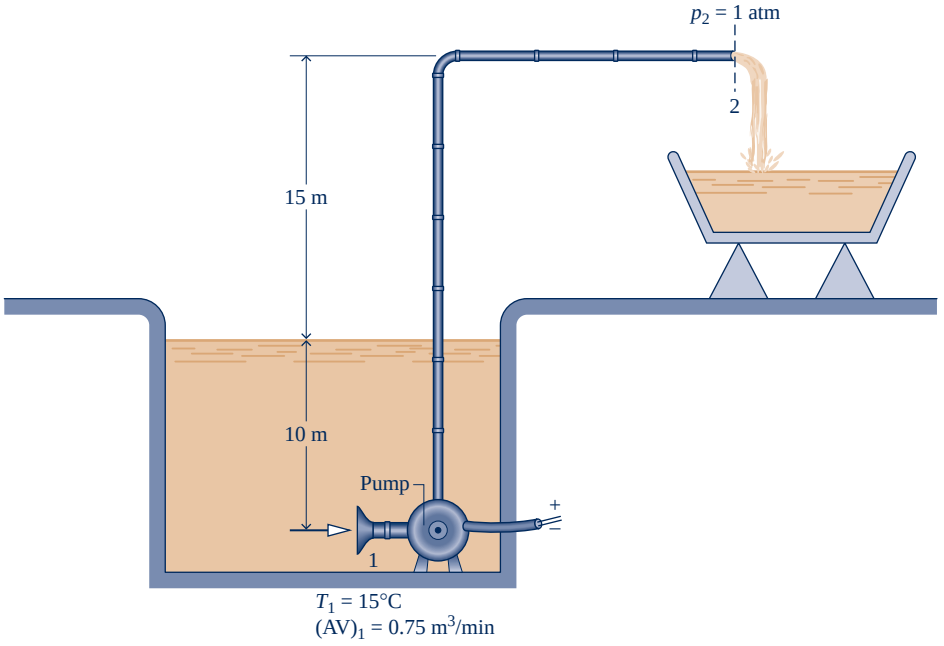


Fig. P4.67

4.69 An oil pump operating at steady state delivers oil at a rate of 12 lb/s through a 1-in.-diameter pipe. The oil, which can be modeled as incompressible, has a density of 100 lb/ft^3 and experiences a pressure rise from inlet to exit of 40 lbf/in.^{2} There is no significant elevation difference between inlet and exit, and the inlet kinetic energy is negligible. Heat transfer between the pump and its surroundings is negligible, and there is no significant change in temperature as the oil passes through the pump. If pumps are available in 1/4-horsepower increments, determine the horsepower rating of the pump needed for this application.

4.70 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.

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

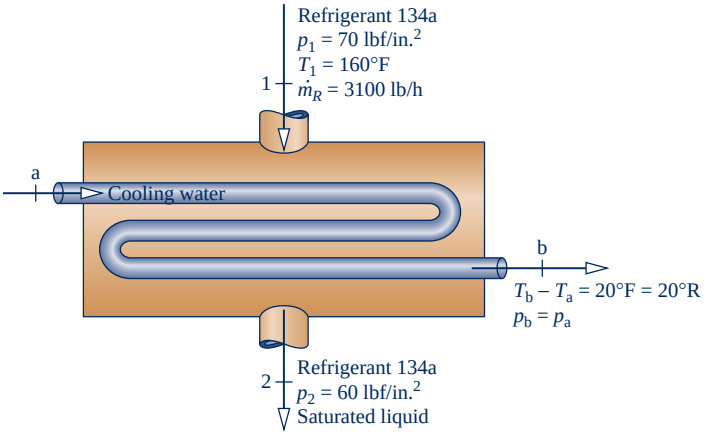


Fig. P4.73

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.

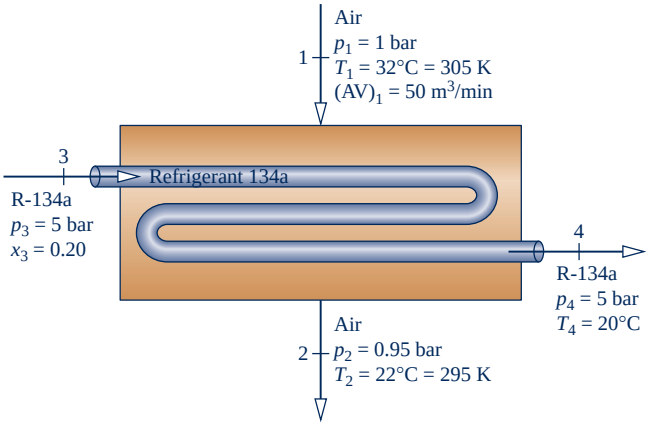


Fig. P4.75

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

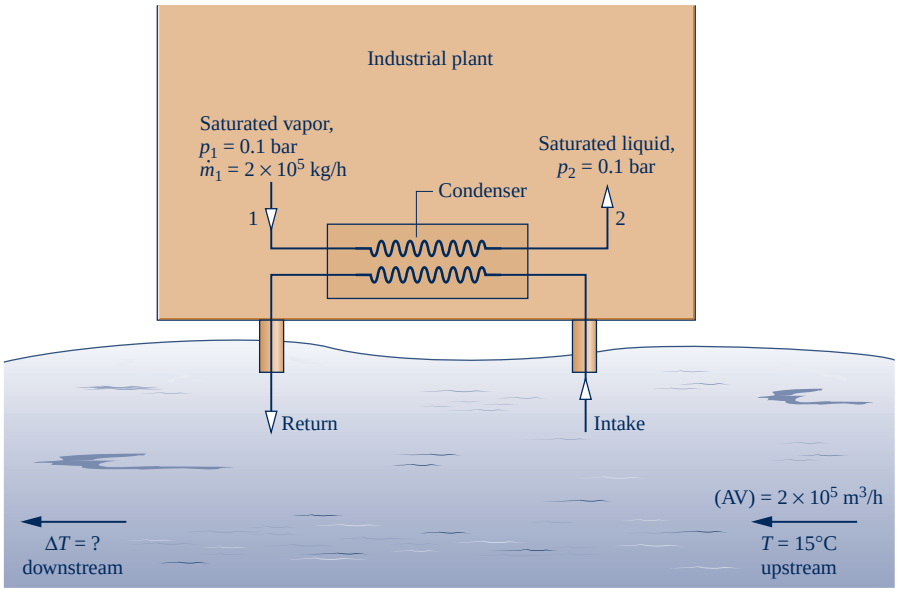
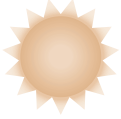


Fig. P4.78

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.

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.



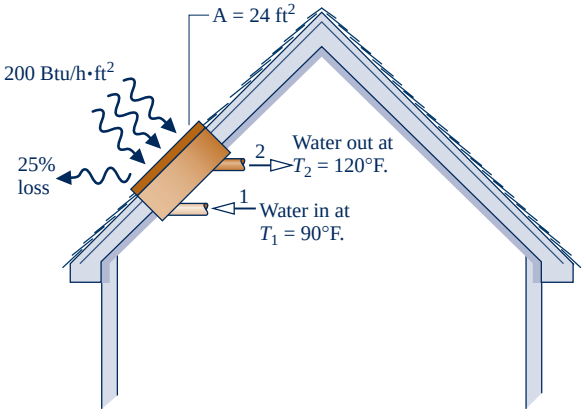


Fig. P4.79

4.80 A feedwater heater in a vapor power plant operates at steady state with liquid entering at inlet 1 with $T_1 = 45$°C and $p_1 = 3.0$ bar. Water vapor at $T_2 = 320$°C and $p_2 = 3.0$ bar enters at inlet 2. Saturated liquid water exits with a pressure of $p_3 = 3.0$ bar. Ignore heat transfer with the surroundings and all kinetic and potential energy effects. If the mass flow rate of the liquid entering at inlet 1 is $\dot{m}_1 = 3.2 \times 10^5$ kg/h, determine the mass flow rate at inlet 2, $\dot{m}_2$, in kg/h.

4.81 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.

4.82 For the *desuperheater* shown in Fig. P4.82, 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,

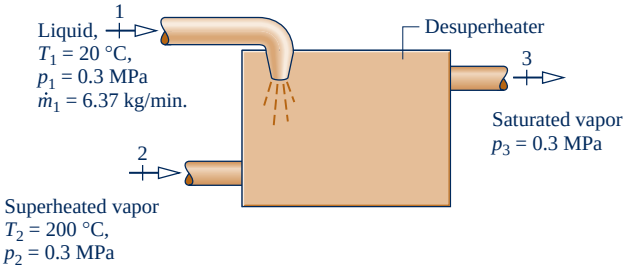


Fig. P4.82

determine the mass flow rate of the incoming superheated vapor, in kg/min.

4.83 As shown in Fig. P4.83, 15 kg/s of steam enters a *desuperheater* operating at steady state at 30 bar, 320°C, where it is mixed with liquid water at 25 bar and temperature T_2 to produce saturated vapor at 20 bar. Heat transfer between the device and its surroundings and kinetic and potential energy effects can be neglected.

(a) If $T_2 = 200$°C, determine the mass flow rate of liquid, $\dot{m}_2$, in kg/s.
(b) Plot $\dot{m}_2$, in kg/s, versus T_2 ranging from 20 to 220°C.

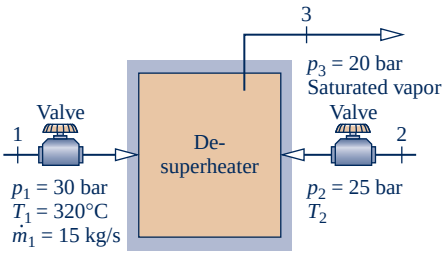


Fig. P4.83

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.

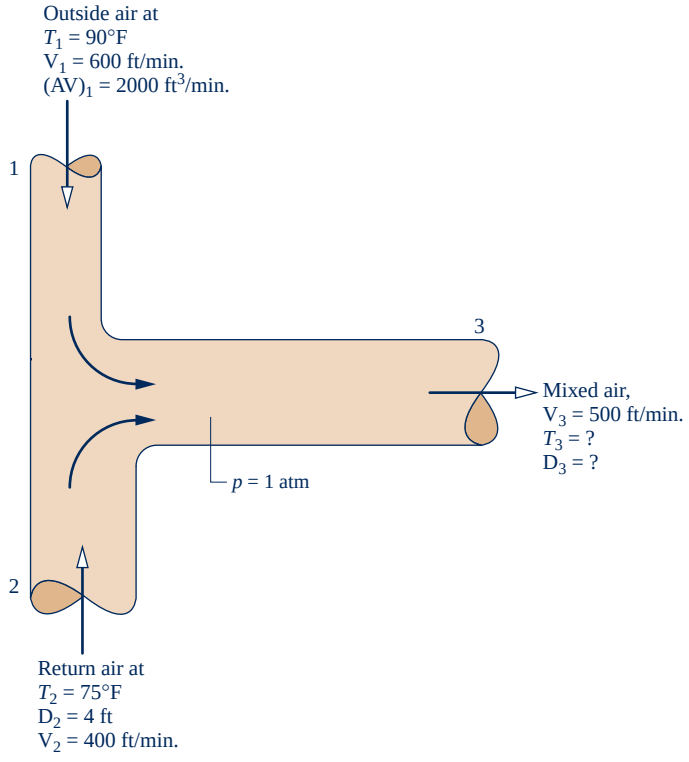


Fig. P4.84

4.85 Figure P4.85 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.

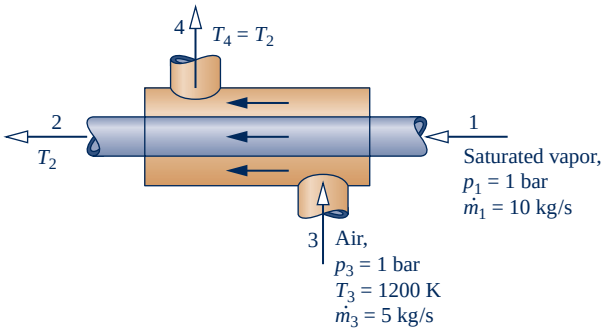


Fig. P4.85

4.86 Figure P4.86 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.

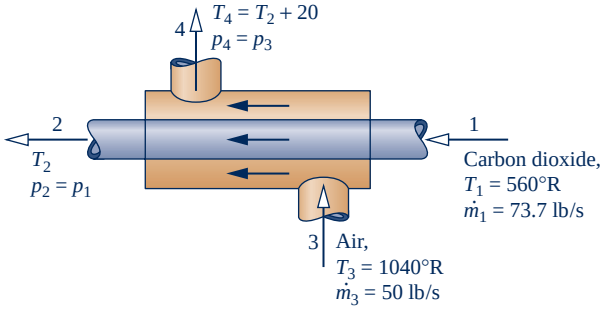


Fig. P4.86

4.87 Ten kg/min of cooling water circulates through a water jacket enclosing a housing filled with electronic components. At steady state, water enters the water jacket at 22°C and exits with a negligible change in pressure at a temperature that cannot exceed 26°C. There is no significant energy transfer by heat from the outer surface of the water jacket to the surroundings, and kinetic and potential energy effects can be ignored. Determine the maximum electric power the electronic components can receive, in kW, for which the limit on the temperature of the exiting water is met.

4.88 As shown in Fig. P4.88, 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.

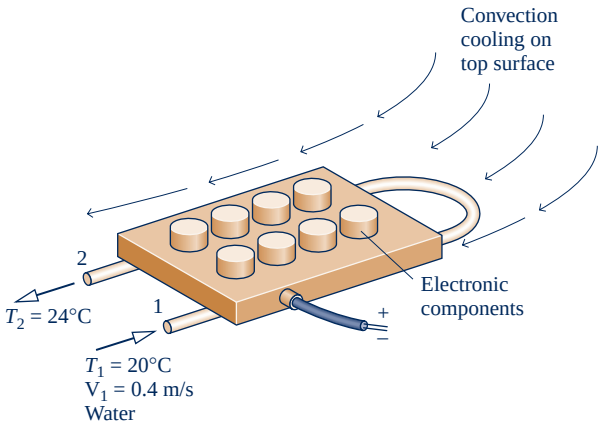


Fig. P4.88

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 A large pipe carries steam as a two-phase liquid–vapor mixture at 1.0 MPa. A small quantity is withdrawn through a throttling calorimeter, where it undergoes a throttling process to an exit pressure of 0.1 MPa. For what range of exit temperatures, in °C, can the calorimeter be used to determine the quality of the steam in the pipe? What is the corresponding range of steam quality values?

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 power 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 Steam at 500 lbf/in.^{2}, 500°F enters a well-insulated valve operating at steady state with a mass flow rate of 0.11 lb/s through a 1-in.-diameter pipe. The steam expands to 200 lbf/in.^{2} with no significant change in elevation. The expansion is not necessarily a throttling process.

(a) Determine the exit velocity, in ft/s, and the exit temperature, in °F, if the ratio of inlet to exit pipe diameters, d_1/d_2, is 0.64.
(b) To explore the effects of area change as the steam expands, plot the exit velocity, in ft/s, the exit temperature, in °F, and the exit specific enthalpy, in Btu/lb, for d_1/d_2 ranging from 0.25 to 4.

Reviewing Concepts

4.94 For review, complete the following:

(a) Answer the following true or false. Explain.
(i) 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.
(ii) *Flow work* is the work done on a flowing stream by a paddlewheel or piston.
(iii) *Transient* operation denotes a change in state with time.
(iv) In this book the flow at control volume inlets and exits is normally taken as *one-dimensional*.
(v) Where mass crosses the boundary of a control volume, the accompanying energy transfer is accounted for by the internal energy of the mass only.

(b) Answer the following true or false. Explain.
(i) 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.
(ii) The human body is an example of an *integrated* system.
(iii) 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.
(iv) The hot and cold streams of *cross-flow* heat exchangers flow in the same direction.
(v) The thermodynamic performance of a device such as a turbine through which mass flows is best analyzed by studying the flowing mass alone.

(c) Answer the following true or false. Explain.
(i) 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.
(ii) An *open feedwater* heater is a special type of a counterflow heat exchanger.
(iii) A key step in thermodynamic analysis is the careful listing of modeling assumptions.
(iv) An automobile's radiator is an example of a cross-flow heat exchanger.
(v) 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.

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

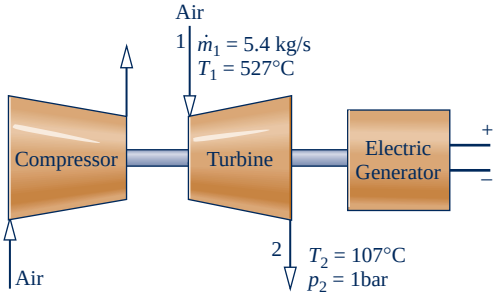


Fig. P4.95

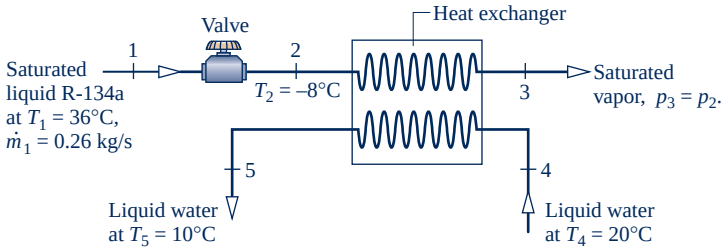


Fig. P4.96

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.

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 $T_1 = 36°C$ with a mass flow rate of 0.26 kg/s and is throttled to $T_2 = -8°C$. The refrigerant then enters the heat exchanger, exiting as saturated vapor with no significant decrease in pressure. In a separate stream, liquid water enters the heat exchanger at $T_4 = 20°C$ and exits as a liquid at $T_5 = 10°C$. Stray heat transfer and kinetic and potential energy effects can be ignored. Determine (a) the pressure at state 2, in kPa, and (b) the mass flow rate of the liquid water stream, in kg/s.

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.

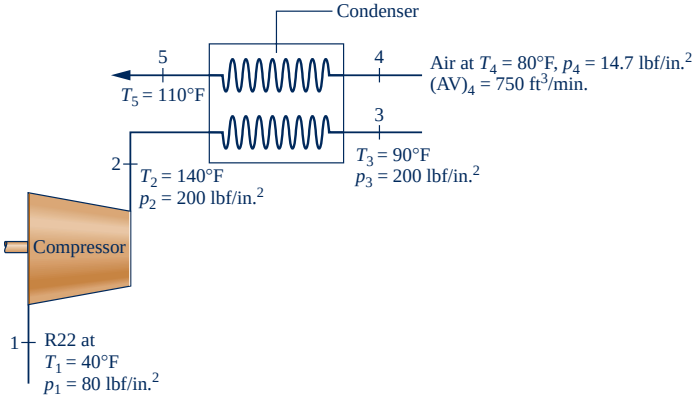


Fig. P4.97

4.98 Fig. P4.98 shows part of a refrigeration system consisting of a heat exchanger, an evaporator, a throttling valve, and associated piping. Data for steady-state operation with Refrigerant 134a are given in the figure. There is no significant heat transfer to or from the heat exchanger, valve, and piping. Kinetic and potential energy effects are negligible. Determine the rate of heat transfer between the evaporator and its surroundings, in Btu/h.

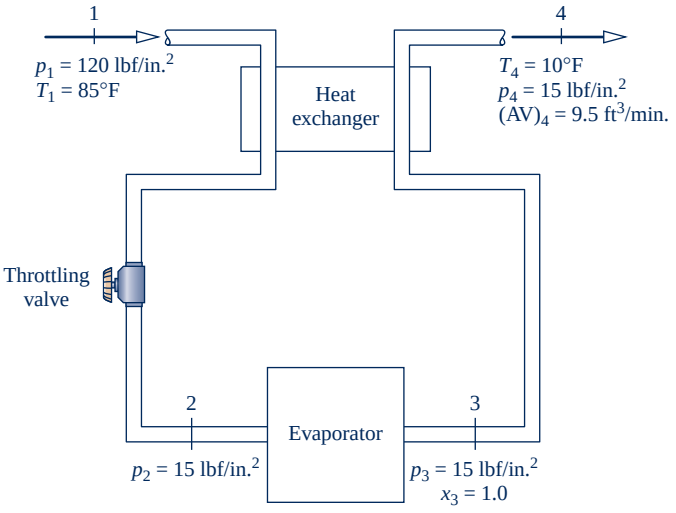


Fig. P4.98

4.99 Refrigerant 134a enters the flash chamber operating at steady state shown in Fig. P4.99 at 10 bar, 36°C, with a mass flow rate of 482 kg/h. Saturated liquid and saturated vapor exit as separate streams, each at pressure p. Heat transfer to

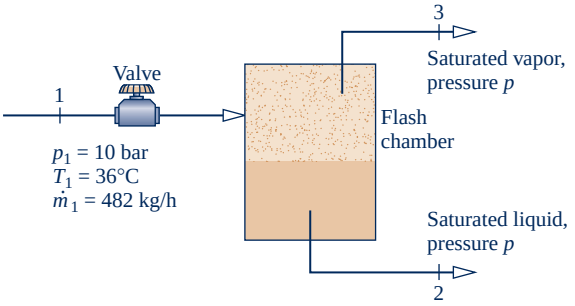


Fig. P4.99

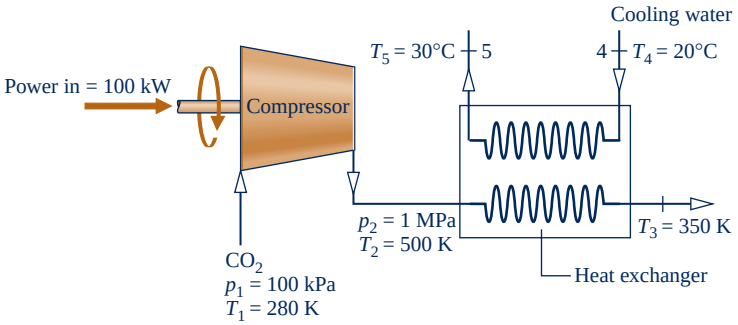


Fig. P4.100

the surroundings and kinetic and potential energy effects can be ignored.

(a) Determine the mass flow rates of the exiting streams, each in kg/h, if $p = 4$ bar.

(b) Plot the mass flow rates of the exiting streams, each in kg/h, versus p ranging from 1 to 9 bar.

4.100 Carbon dioxide (CO_2) modeled as an ideal gas flows through the compressor and heat exchanger shown in Fig. P4.100. The power input to the compressor is 100 kW. A separate liquid cooling water stream flows through the heat exchanger. All data are for operation at steady state. Stray heat transfer with the surroundings can be neglected, as can all kinetic and potential energy changes. Determine (a) the mass flow rate of the CO_2, in kg/s, and (b) the mass flow rate of the cooling water, in kg/s.

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.

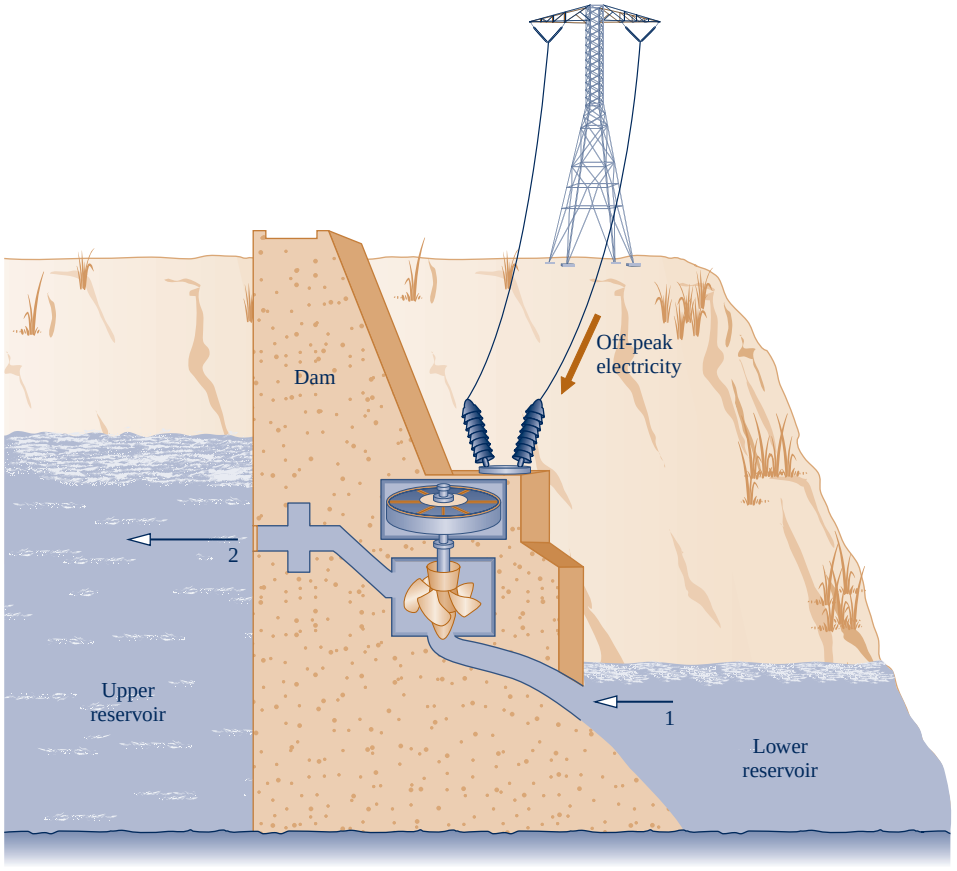


Fig. P4.101

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.

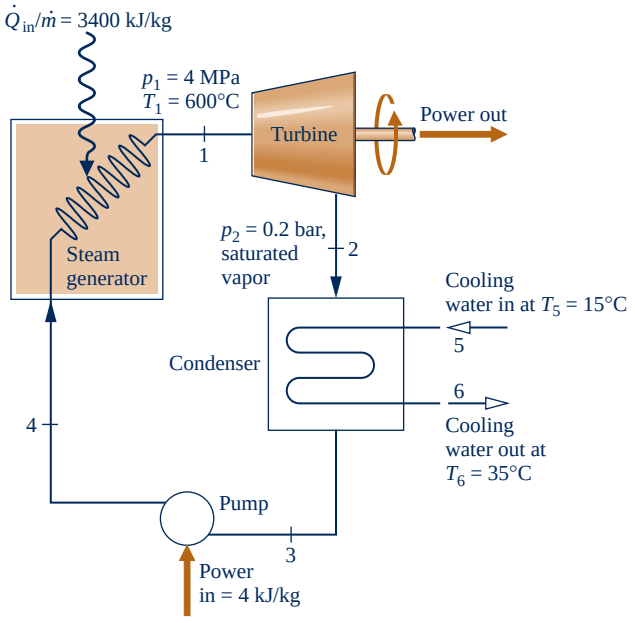


Fig. P4.102

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.

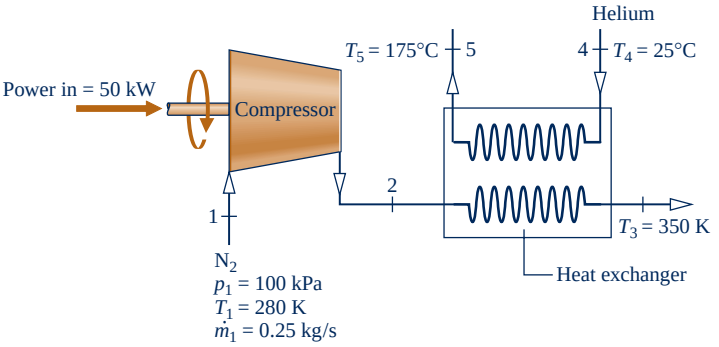


Fig. P4.103

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.

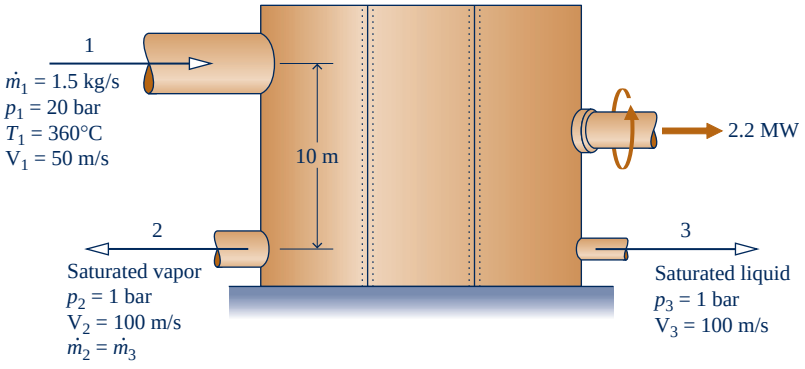


Fig. P4.104

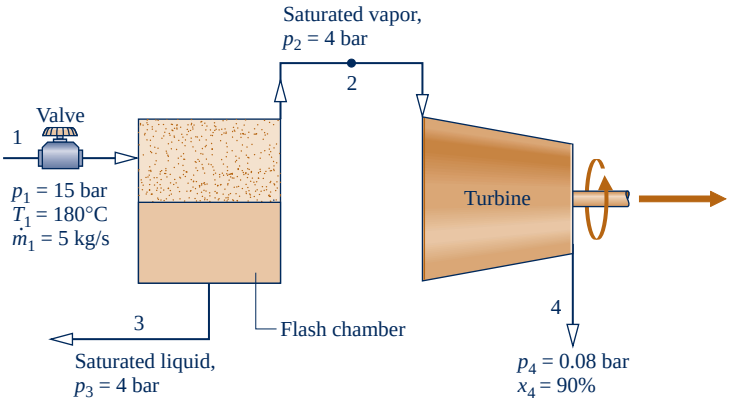


Fig. P4.105

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.

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.

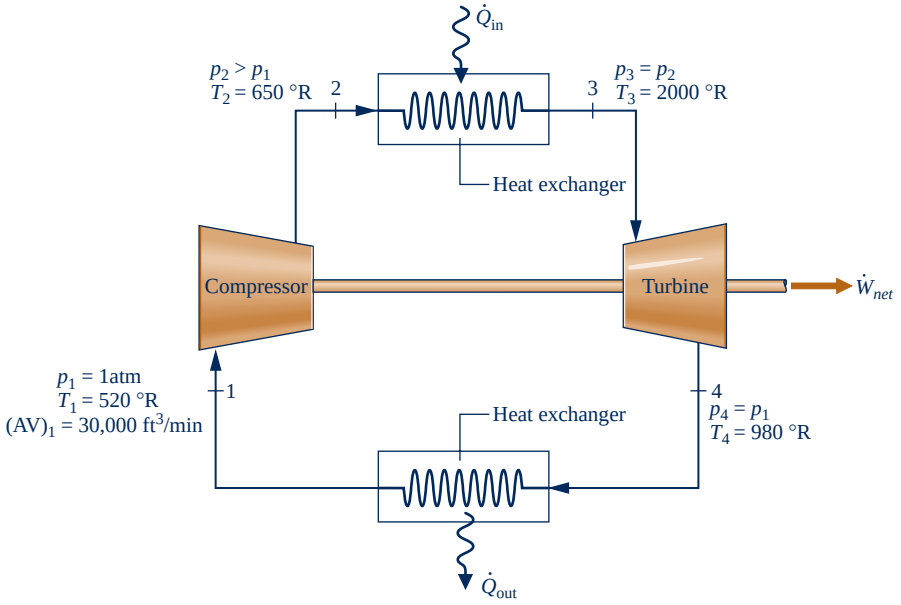


Fig. P4.106

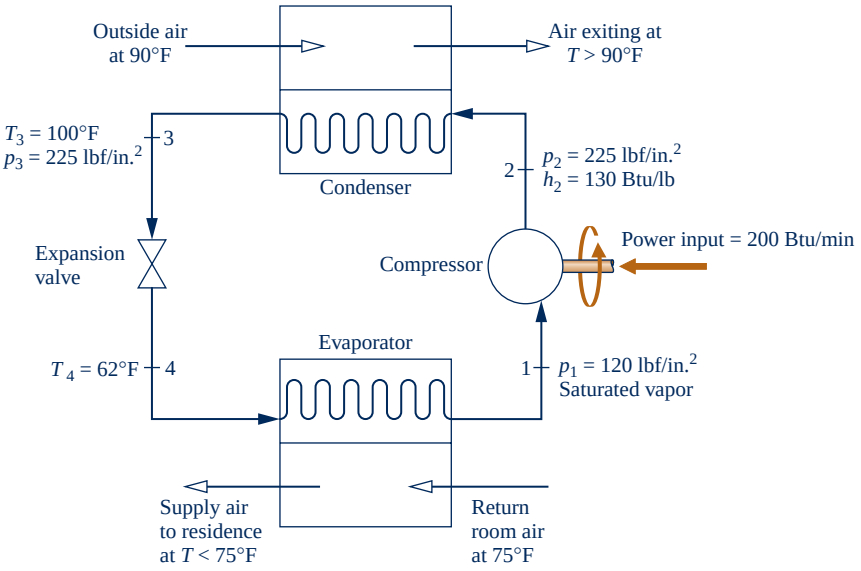


Fig. P4.107

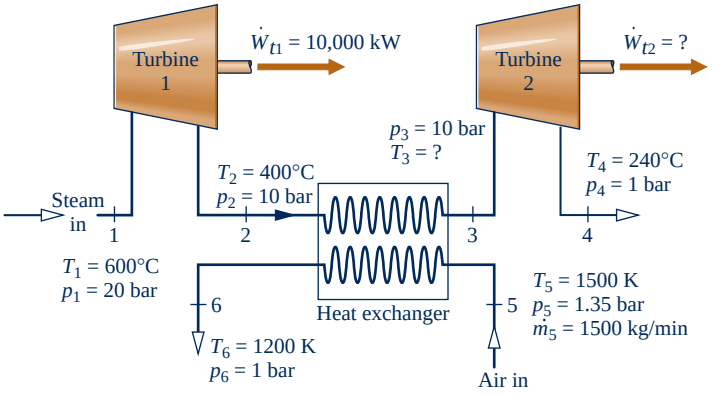


Fig. P4.108

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.

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.

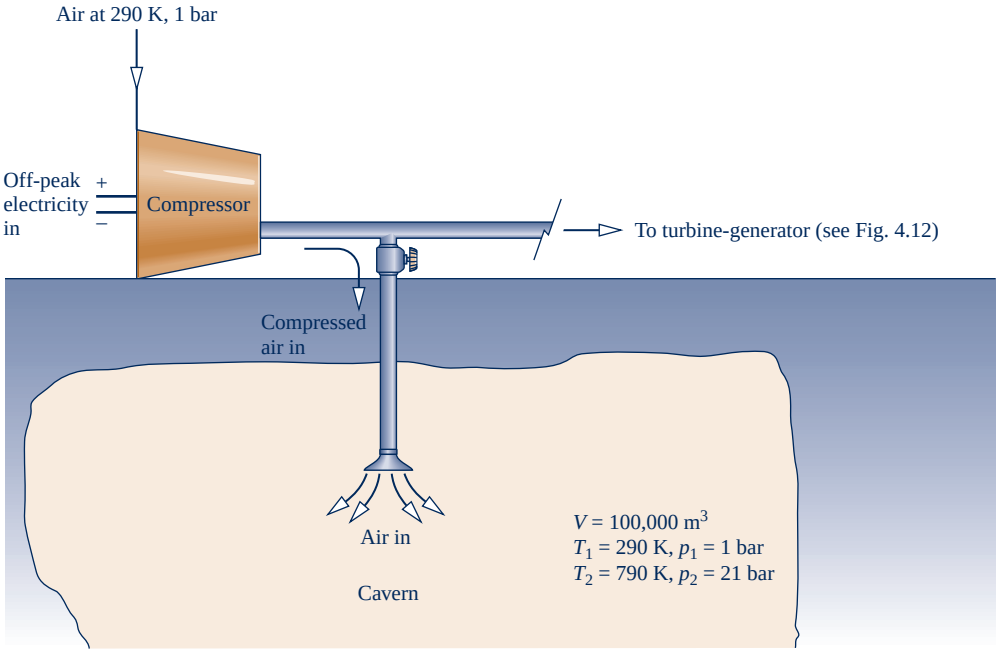


Fig. P4.114

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.

4.116 As shown in Fig. P4.116, a 300-ft^3 tank contains H_2O initially at 30 $lbf/in.^2$ and a quality of 80%. The tank is connected to a large steam line carrying steam at 200 $lbf/in.^2$, 450°F. Steam flows into the tank through a valve until the tank pressure reaches 100 $lbf/in.^2$ and the temperature is 400°F, at which time the valve is closed. Determine the amount of mass, in lb, that enters the tank and the heat transfer between the tank and its surroundings, in Btu.

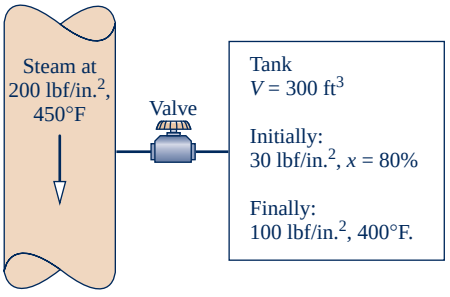


Fig. P4.116

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 0.5 m^3 is initially evacuated. At time $t = 0$, air from the surroundings at 1 bar, 21°C begins to flow into the tank. An electric resistor transfers energy to the air in the tank at a constant rate of 100 W for 500 s, after which time the pressure in the tank is 1 bar. What is the temperature of the air in the tank, in °C, at the final time?

4.120 A well-insulated rigid tank of volume 10 m^3 is connected to a large steam line through which steam flows at 15 bar and 280°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 $p = 15$ bar.
(b) Plot the quantities of part (a) versus p ranging from 0.1 to 15 bar.

4.121 A well-insulated piston–cylinder assembly is connected by a valve to an air supply at 100 $lbf/in.^2$, 80°F, as shown in Fig. P4.121. The air inside the cylinder is initially at 14.7 $lbf/in.^2$, 80°F, and occupies a volume of 0.1 ft^3. Initially, the piston

face is located at $x = 0$ and the spring exerts no force on the piston. The atmospheric pressure is 14.7 lbf/in.^{2}, and the area of the piston face is 0.22 ft^2. The valve is opened, and air is admitted slowly until the volume of the air inside the cylinder is 0.4 ft^3. During the process, the spring exerts a force on the piston that varies according to $F = kx$. The ideal gas model applies for the air, and there is no friction between the piston and the cylinder wall. For the air within the cylinder, plot the final pressure, in lbf/in.^{2}, and the final temperature, in °F, versus k ranging from 650 to 750 lbf/ft.

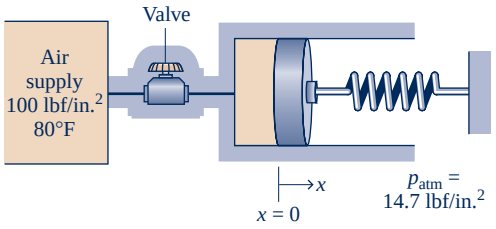


Fig. P4.121

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 The rigid tank illustrated in Fig. P4.124 has a volume of 0.06 m^3 and initially contains a two-phase liquid–vapor mixture of H_2O at a pressure of 15 bar and a quality of 20%. As the tank contents are heated, a pressure-regulating valve keeps the pressure constant in the tank by allowing saturated vapor to escape. Neglecting kinetic and potential energy effects

(a) determine the total mass in the tank, in kg, and the amount of heat transfer, in kJ, if heating continues until the final quality is $x = 0.5$.

(b) plot the total mass in the tank, in kg, and the amount of heat transfer, in kJ, versus the final quality x ranging from 0.2 to 1.0.

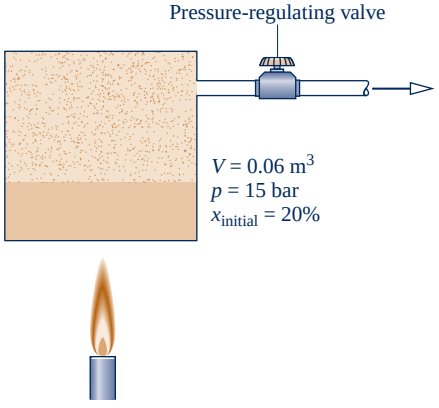


Fig. P4.124

4.125 A well-insulated rigid tank of volume 7 ft^3 initially contains helium at 160°F and 30 lbf/in.^{2} A valve connected to the tank is opened, and helium is withdrawn slowly until the pressure within the tank drops to p. An electrical resistor inside the tank maintains the temperature at 160°F.

(a) Determine the mass of helium withdrawn, in lb, and the energy input to the resistor, in Btu, when $p = 18$ lbf/in.^{2}

(b) Plot the quantities of part (a) versus p ranging from 15 to 30 lbf/in.^{2}

4.126 A tank of volume 1 m^3 initially contains steam at 6 MPa and 320°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 320°C. Neglecting all kinetic and potential energy effects,

(a) determine the heat transfer, in kJ, if $p = 1.5$ MPa.

(b) plot the heat transfer, in kJ, versus p ranging from 0.5 to 6 MPa.

4.127 A 1 m^3 tank initially contains air at 300 kPa, 300 K. Air slowly escapes from the tank until the pressure drops to 100 kPa. The air that remains in the tank undergoes a process described by $pv^{1.2} = constant$. For a control volume enclosing the tank, determine the heat transfer, in kJ. Assume ideal gas behavior with constant specific heats.

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 A well-insulated chamber of volume 1 ft^3 is shown in Fig. P4.130. Initially, the chamber contains air at 14.7 lbf/in.^{2} and 100°F. Connected to the chamber are supply and discharge pipes equipped with valves that control the flow rates into and out of the chamber. The supply air is at 30 lbf/in.^{2}, 200°F. Both valves are opened simultaneously,

allowing air to flow with a mass flow rate $\dot{m}$ through each valve. The air within the chamber is well mixed, so the temperature and pressure at any time can be taken as uniform throughout. Neglecting kinetic and potential energy effects, and using the ideal gas model with constant specific heats for the air, plot the temperature, in °F, and the pressure, in lbf/in.^{2}, of the air in the chamber versus time for $\dot{m}$ = 1, 2, and 5 lb/min.

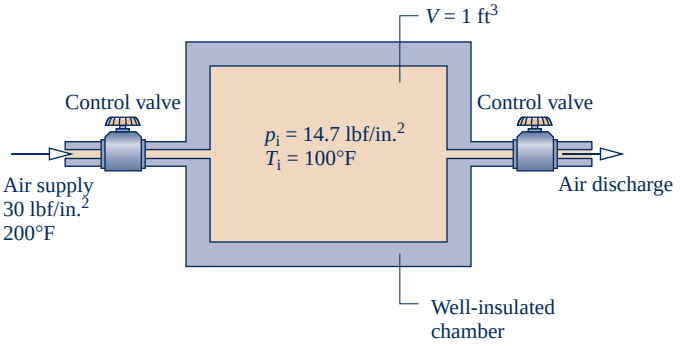


Fig. P4.130

▶ 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, 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

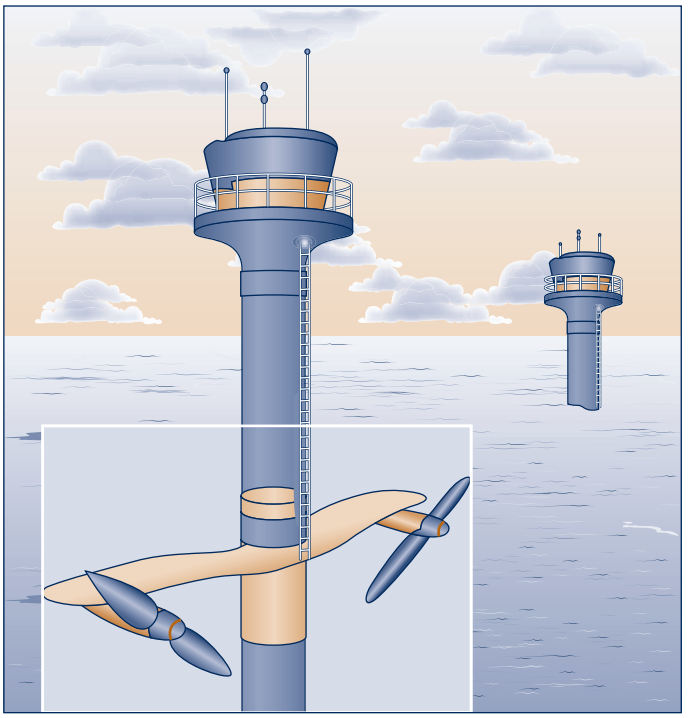


Fig. P4.4D

development, including identifying key technical challenges and prospects for overcoming them. Summarize your findings in a report, including at least three references.

4.6D Identify sites in your state where wind turbines for utility-scale electrical generation are feasible but do not yet exist. Prepare a memorandum to an appropriate governing or corporate entity with your recommendations as to whether wind-turbine electrical generation should be developed at the most promising sites. Consider engineering, economic, and societal aspects.

4.7D Recent disasters, including major oil spills, floods, hurricanes, and tsunamis have revealed the vulnerability of municipal water distribution systems to water-borne contamination. For the water distribution system of a municipality selected by, or assigned to, your project group, study the existing procedure for restoring the system to safe use after contamination. If no suitable decontamination procedure exists, make recommendations. Suggest easy-to-implement, cost-effective, environmentally-responsible measures. Document your findings in a memorandum.

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 Forced-air warming systems involving inflatable thermal blankets commonly are used to prevent subnormal body temperature (hypothermia) during and following surgery. A heater and blower provide a stream of warmed air to the blanket. While the air temperature leaving the heater/blower is monitored by a temperature sensor, the temperature of the air providing warming to patients can vary widely, causing in some instances overheating and localized burning of patients. The object of this project is to develop cost-effective modifications of existing thermal blankets that would control the air temperature and eliminate injurious "hot spots." The modifications must conform to standards governing the safety of systems involving heating in medical applications. Summarize your conclusions in a report, including sample calculations and at least three references.

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.

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.

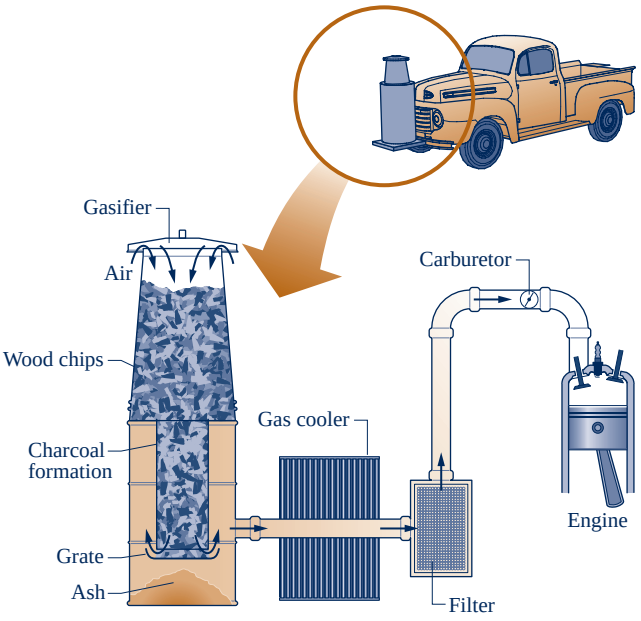


Fig. P4.11D