3.11 Determine the volume, in m³, of 1.5 kg of ammonia at 2 bar, 20°C.

3.12 A two-phase liquid–vapor mixture of H₂O at 200 lb/in² has a specific volume of 1.5 ft³/lb. Determine the quality of a two-phase liquid–vapor mixture at 100 lb/in² with the same specific volume.

3.13 A closed vessel with a volume of 0.018 m³ contains 1.2 kg of Refrigerant 22 at 10 bar. Determine the temperature, in °C.

3.14 Determine the volume, in ft³, occupied by 2 lb of H₂O at a pressure of 1000 lb/in² and
(a) a temperature of 600°F,
(b) a quality of 80%,
(c) a temperature of 200°F.

3.15 Calculate the volume, in m³, occupied by 2 kg of a two-phase liquid–vapor mixture of Refrigerant 134a at −10°C with a quality of 80%.

3.16 A closed vessel with a volume of 2 ft³ contains 5 lb of Refrigerant 134a. A pressure sensor in the tank wall reads 71.39 lb/in² (gage). If the atmospheric pressure is 14.4 lb/in², what is the temperature of the refrigerant, in °F?

3.17 A two-phase liquid–vapor mixture of H₂O has a temperature of 300°C and occupies a volume of 0.05 m³. The masses of saturated liquid and vapor present are 0.75 kg and 2.26 kg, respectively. Determine the specific volume of the mixture, in m³/kg.

3.18 Ammonia is stored in a tank with a volume of 0.21 m³. Determine the mass, in kg, assuming saturated liquid at 20°C. What is the pressure, in kPa?

3.19 A storage tank in a refrigeration system has a volume of 0.006 m³ and contains a two-phase liquid–vapor mixture of Refrigerant 134a at 180 kPa. Plot the total mass of refrigerant, in kg, contained in the tank and the corresponding fractions of the total volume occupied by saturated liquid and saturated vapor, respectively, as functions of quality.

3.20 A closed system consists of a two-phase liquid–vapor mixture of H₂O in equilibrium at 400°F. The quality of the mixture is 0.2 (20%) and the mass of liquid water present is 0.1 lb. Determine the mass of vapor present, in lb, and the total volume of the system, in ft³.

3.21 Five kilograms of H₂O are contained in a closed rigid tank at an initial pressure of 20 bar and a quality of 50%. Heat transfer occurs until the tank contains only saturated vapor. Determine the volume of the tank, in m³, and the final pressure, in bar.

3.22 A rigid tank contains 5 lb of a two-phase, liquid–vapor mixture of H₂O, initially at 260°F with a quality of 0.6. Heat transfer to the contents of the tank occurs until the temperature is 320°F. Show the process on a p–v diagram. Determine the mass of vapor, in lb, initially present in the tank and the final pressure, in lb/in².

3.23 Two thousand kg of water, initially a saturated liquid at 150°C, is heated in a closed, rigid tank to a final state where the pressure is 2.5 MPa. Determine the final temperature, in °C, the volume of the tank, in m³, and sketch the process on T–s and p–v diagrams.

3.24 Steam is contained in a closed rigid container. Initially, the pressure and temperature of the steam are 15 bar and 240°C, respectively. The temperature drops as a result of heat transfer to the surroundings. Determine the pressure at which condensation first occurs, in bar, and the fraction of the total mass that has condensed when the temperature reaches 100°C. What percentage of the volume is occupied by saturated liquid at the final state?

3.25 Water vapor is heated in a closed, rigid tank from saturated vapor at 160°C to a final temperature of 400°C. Determine the initial and final pressures, in bar, and sketch the process on T–v and p–v diagrams.

3.26 Ammonia undergoes an isothermal process from an initial state at T₁ = 80°F and p₁ = 10 ft/lb to saturated vapor. Determine the initial and final pressures, in lb/in², and sketch the process on T–v and p–v diagrams.

3.27 A two-phase liquid–vapor mixture of H₂O is initially at a pressure of 30 bar. If on heating at fixed volume, the critical point is attained, determine the quality at the initial state.

3.28 A two-phase liquid–vapor mixture of H₂O is initially at a pressure of 450 lb/in². If on heating at fixed volume, the critical point is attained, determine the quality at the initial state.

3.29 Three lb of saturated water vapor, contained in a closed rigid tank whose volume is 13.3 ft³, is heated to a final temperature of 400°F. Sketch the process on a T–v diagram. Determine the pressures at the initial and final states, each in lb/in².

3.30 Refrigerant 134a undergoes a constant-pressure process at 1.4 bar from T₁ = 20°C to saturated vapor. Determine the work for the process, in kJ per kg of refrigerant.

3.31 Three lb of water vapor is compressed at a constant pressure of 100 lb/in² from a volume of 14.9 ft³ to a volume of 13.3 ft³. Determine the temperatures at the initial and final states, each in °F, and the work for the process, in Btu.

3.32 Water vapor in a piston–cylinder assembly is heated at a constant temperature of 400°F from saturated vapor to a pressure of 100 lb/in². Determine the work, in Btu per lb of water vapor, by integration of Eq. 2.17
(a) numerically with steam table data.
(b) using IT.

3.33 Two pounds mass of Refrigerant 134a, initially at p₁ = 180 lb/in² and T₁ = 120°F, undergo a constant-pressure process to a final state where the quality is 76.5%. Determine the work for the process, in Btu.
Kinetic and potential energy effects are negligible. Determine the heat transfer, in Btu, for each process.

3.63 Two kilograms of Refrigerant 22, initially at 6 bar and occupying a volume of 0.06 m$^3$, undergoes a process at constant pressure until the volume has increased by 50%. Kinetic and potential energy effects are negligible. Determine the work and heat transfer for the process, each in kJ.

3.64 Ammonia in a piston–cylinder assembly undergoes two processes in series. At the initial state, $p_1 = 120$ lbf/in$^2$ and the quality is 100%. Process 1–2 occurs at constant volume until the temperature is 100°F. The second process, from state 2 to state 3, occurs at constant temperature, with $Q_2 = -98.9$ Btu, until the quality is again 100%. Kinetic and potential energy effects are negligible. For 2.2 lb of ammonia, determine (a) the heat transfer for Process 1–2 and (b) the work for Process 2–3, each in Btu.

3.65 Ammonia vapor is compressed in a piston–cylinder assembly from saturated vapor at $-20°C$ to a final state where $p_2 = 9$ bar and $T_2 = 88°C$. During the process, the pressure and specific volume are related by $p v^n = constant$. Neglecting kinetic and potential energy effects, determine the work and heat transfer per unit mass of ammonia, each in kJ/kg.

3.66 A system consisting of 2 kg of ammonia undergoes a cycle composed of the following processes:

Process 1–2: constant volume from $p_1 = 10$ bar, $x_1 = 0.6$ to saturated vapor

Process 2–3: constant temperature to $p_3 = p_1$, $Q_3 = +228$ kJ

Process 3–1: constant pressure

Sketch the cycle on $p-v$ and $T-v$ diagrams. Neglecting kinetic and potential energy effects, determine the net work for the cycle and the heat transfer for each process, all in kJ.

3.67 A system consisting of 1 kg of H$_2$O undergoes a power cycle composed of the following processes:

Process 1–2: Constant-pressure heating at 10 bar from saturated vapor.

Process 2–3: Constant-volume cooling to $p_3 = 5$ bar, $T_3 = 160°C$.

Process 3–4: Isothermal compression with $Q_3 = -815.8$ kJ.

Process 4–1: Constant-volume heating.

Sketch the cycle on $T-v$ and $p-v$ diagrams. Neglecting kinetic and potential energy effects, determine the thermal efficiency.

3.68 A system consisting of 1 lb of Refrigerant 22 undergoes a cycle composed of the following processes:

Process 1–2: constant pressure from $p_1 = 30$ lbf/in$^2$, $x_1 = 0.95$ to $T_2 = 40°F$.

Process 2–3: constant temperature to saturated vapor with $W_2 = -11.82$ Btu

Process 3–1: adiabatic expansion

Sketch the cycle on $p-v$ and $T-v$ diagrams. Neglecting kinetic and potential energy effects, determine the net work for the cycle and the heat transfer for each process, all in Btu.

3.69 A well-insulated copper tank of mass 13 kg contains 4 kg of liquid water. Initially, the temperature of the copper is 27°C and the temperature of the water is 50°C. An electrical resistor of negligible mass transfers 100 kJ of energy to the contents of the tank. The tank and its contents come to equilibrium. What is the final temperature, in °C?

3.70 A steel bar of mass 50 lb, initially at 20°F, is placed in an open tank together with 5 ft$^3$ of liquid water, initially at 70°F. For the water and the bar as the system, determine the final equilibrium temperature, in °F, ignoring heat transfer between the tank and its surroundings.

3.71 An isolated system consists of a 10-kg copper slab, initially at 30°C, and 0.2 kg of saturated water vapor, initially at 130°C. Assuming no volume change, determine the final equilibrium temperature of the isolated system, in °C.

3.72 A system consists of a liquid, considered incompressible with constant specific heat $c$, filling a rigid tank whose surface area is $A$. Energy transfer by work from a paddle wheel to the liquid occurs at a constant rate. Energy transfer by heat occurs at a rate given by $Q = -h A (T - T_0)$, where $T$ is the instantaneous temperature of the liquid, $T_0$ is the temperature of the surroundings, and $h$ is an overall heat transfer coefficient. At the initial time, $t = 0$, the tank and its contents are at the temperature of the surroundings. Obtain a differential equation for temperature $T$ in terms of time $t$ and relevant parameters. Solve the differential equation to obtain $T(t)$.

3.73 A large steel plate of thickness 4 cm and initially at 400°C is quenched in an oil bath at 30°C. Applying an energy rate balance to an element of differential thickness within the plate and introducing Fourier's laws, derive a partial differential equation for the variation of temperature within the plate as a function of time and position. Use data from Table A-19 to evaluate the physical parameters appearing in the differential equation. List all assumptions.

Using Generalized Compressibility Data

3.74 Determine the compressibility factor for water vapor at 100 bar and 400°C, using

(a) data from the compressibility chart.

(b) data from the steam tables.

3.75 Determine the volume, in m$^3$, occupied by 40 kg of nitrogen (N$_2$) at 17 MPa, 180 K.

3.76 Nitrogen (N$_2$) occupies a volume of 6 ft$^3$ at 360°F, 3000 lbf/in$^2$. Determine the mass of nitrogen, in lb.
3.98 Consider a gas mixture whose apparent molecular weight is 33, initially at 3 bar and 300 K, and occupying a volume of 0.1 m³. The gas undergoes an expansion during which the pressure-volume relation is $pV^n = constant$. Neglecting kinetic and potential energy effects, determine:

(a) the final temperature, in K.
(b) the final pressure, in bar.
(c) the final volume, in m³.
(d) the work, in kJ.

3.99 Argon (Ar) gas initially at 1 bar, 100 K undergoes a polytropic process, with $n = k$, to a final pressure of 15.59 bar. Determine the work and heat transfer for the process, each in kJ per kg of argon. Assume ideal gas behavior.

3.100 Two uninsulated, rigid tanks contain air. Initially, tank A holds 1 lb of air at 1440°F, and tank B has 2 lb of air at 900°F. The initial pressure in each tank is 50 lb/in². A valve in the line connecting the two tanks is opened and the contents are allowed to mix. Eventually, the contents of the tanks come to equilibrium at the temperature of the surroundings, 58°F. Assuming the ideal gas model, determine the amount of energy transfer by heat, in Btu, and the final pressure, in lb/in².

3.101 Two kilograms of a gas with molecular weight 28 are contained in a closed, rigid tank fitted with an electric resistor. The resistor draws a constant current of 10 amp at a voltage of 12 V for 10 min. Measurements indicate that when equilibrium is reached, the temperature of the gas has increased by 40.3°C. Heat transfer to the surroundings is estimated to occur at a constant rate of 20 W. Assuming ideal gas behavior, determine an average value of the specific heat, $c_p$, in J/kg·K, of the gas in this temperature interval based on the measured data.

3.102 Carbon dioxide (CO₂) gas, initially at $T_i = 530^\circ$R, $p_i = 15$ lb/in², and $V_i = 1$ ft³, is compressed in a piston-cylinder assembly. During the process, the pressure and specific volume are related by $pV^{1.3} = constant$. The amount of energy transferred to the gas by work is 45 Btu per lb of CO₂. Assuming ideal gas behavior, determine the final temperature, in °R, and the heat transfer, in Btu per lb of gas.

3.103 A gas is confined to one side of a rigid, insulated container divided by a partition. The other side is initially evacuated. The following data are known for the initial state of the gas: $p_i = 3$ bar, $T_i = 300$ K, and $V_i = 0.025$ m³. When the partition is removed, the gas expands to fill the entire container and achieves a final equilibrium pressure of 1.5 bar. Assuming ideal gas behavior, determine the final volume, in m³.

3.104 A rigid tank initially contains 3 kg of air at 500 kPa, 290 K. The tank is connected by a valve to a piston-cylinder assembly oriented vertically and containing 0.05 m³ of air initially at 200 kPa, 290 K. Although the valve is closed, a slow leak allows air to flow into the cylinder until the tank pressure falls to 200 kPa. The weight of the piston and the pressure of the atmosphere maintain a constant pressure of 200 kPa in the cylinder; and owing to heat transfer, the temperature stays constant at 290 K. For the air, determine the total amount of energy transfer by work and by heat, each in kJ. Assume ideal gas behavior.

3.105 A piston–cylinder assembly contains 1 kg of nitrogen gas (N₂). The gas expands from an initial state where $T_i = 700$ K and $p_i = 5$ bar to a final state where $p_f = 2$ bar. During the process the pressure and specific volume are related by $pV^{1.3} = constant$. Assuming ideal gas behavior and neglecting kinetic and potential energy effects, determine the heat transfer during the process, in kJ, using:

(a) a constant specific heat evaluated at 300 K.
(b) a constant specific heat evaluated at 600 K.
(c) data from Table A-23.

3.106 Air is compressed adiabatically from $p_i = 1$ bar, $T_i = 300$ K to $p_f = 15$ bar, $v_f = 0.1227$ m³/kg. The air is then cooled at constant volume to $T_f = 300$ K. Assuming ideal gas behavior, and ignoring kinetic and potential energy effects, calculate the work for the first process and the heat transfer for the second process, each in kJ per kg of air. Solve the problem each of two ways:

(a) using data from Table A-22.
(b) using a constant specific heat evaluated at 300 K.

3.107 A system consists of 2 kg of carbon dioxide gas initially at state 1, where $p_1 = 1$ bar, $T_1 = 300$ K. The system undergoes a power cycle consisting of the following processes:

- **Process 1–2**: constant volume to $p_2$, $p_2 > p_1$.
- **Process 2–3**: expansion with $pV^{1.3} = constant$.
- **Process 3–1**: constant-pressure compression.

Assuming the ideal gas model and neglecting kinetic and potential energy effects:

(a) sketch the cycle on a $p$–$V$ diagram.
(b) plot the thermal efficiency versus $p/p_1$, ranging from 1.05 to 4.

3.108 One lb of air undergoes a power cycle consisting of the following processes:

- **Process 1–2**: constant volume from $p_1 = 20$ lb/in², $T_1 = 500^\circ$R to $T_2 = 820^\circ$R.
- **Process 2–3**: adiabatic expansion to $v_3 = 1.4v_2$.
- **Process 3–1**: constant-pressure compression.

Sketch the cycle on a $p$–$V$ diagram. Assuming ideal gas behavior, determine:

(a) the pressure at state 2, in lb/in².
(b) the temperature at state 3, in °R.
(c) the thermal efficiency of the cycle.
9. Why are the symbols $\Delta U$, $\Delta KE$, and $\Delta PE$ used to denote the energy change during a process, but the work and heat transfer for the process represented, respectively, simply as $W$ and $Q$?

10. If the change in energy of a closed system is known for a process between two end states, can you determine if the energy change was due to work, to heat transfer, or to some combination of work and heat transfer?

11. Referring to Fig. 2.8, can you tell which process, A or B, has the greater heat transfer?

12. What form does the energy balance take for an isolated system? Interpret the expression you obtain.

13. How would you define an appropriate efficiency for the gearbox of Example 2.4?

14. Two power cycles each receive the same energy input $Q_{in}$ and discharge energy $Q_{out}$ to the same lake. If the cycles have different thermal efficiencies, which discharges the greater amount $Q_{out}$? Does this have any implications for the environment?

### Problems

#### Energy Concepts from Mechanics

2.1 An automobile has a mass of 1200 kg. What is its kinetic energy, in kJ, relative to the road when traveling at a velocity of 50 km/h? If the vehicle accelerates to 100 km/h, what is the change in kinetic energy, in kJ?

2.2 An object of weight 40 kN is located at an elevation of 30 m above the surface of the earth. For $g = 9.76 \text{ m/s}^2$, determine the gravitational potential energy of the object, in kJ, relative to the surface of the earth.

2.3 Because of the action of a resultant force, an object whose mass is 100 lb undergoes a decrease in kinetic energy of 1000 ft-lbf and an increase in potential energy. If the initial velocity of the object is 50 ft/s, determine the final velocity, in ft/s.

2.4 A body whose volume is 1.5 ft$^3$ and whose density is 3 lb/ft$^3$ experiences a decrease in gravitational potential energy of 500 ft-lbf. For $g = 31.0 \text{ ft/s}^2$, determine the change in elevation, in ft.

2.5 What is the change in potential energy, in ft-lbf, of an automobile weighing 2000 lb at sea level when it travels from sea level to an elevation of 2000 ft? Assume the acceleration of gravity is constant.

2.6 An object of mass 10 kg, initially having a velocity of 500 m/s, decelerates to a final velocity of 100 m/s. What is the change in kinetic energy of the object, in J?

2.7 An airplane whose mass is 5000 kg is flying with a velocity of 150 m/s at an altitude of 10,000 m, both measured relative to the surface of the earth. The acceleration of gravity can be taken as constant at $g = 9.78 \text{ m/s}^2$.

(a) Calculate the kinetic and potential energies of the airplane, both in J.

(b) If the kinetic energy increased by 10,000 J with no change in elevation, what would be the final velocity, in m/s?

2.8 An object whose mass is 1 lb has a velocity of 100 ft/s. Determine

(a) the final velocity, in ft/s, if the kinetic energy of the object decreases by 100 ft-lbf.

(b) the change in elevation, in ft, associated with a 100 ft-lbf change in potential energy. Let $g = 32.0 \text{ ft/s}^2$.

2.9 An object whose mass is 50 kg is accelerated from a velocity of 20 m/s to a final velocity of 50 m/s by the action of a resultant force. Determine the work done by the resultant force, in J, if there are no other interactions between the object and its surroundings.

2.10 An object whose mass is 300 lb undergoes a change in kinetic energy owing to the action of a resultant force. The work done by the resultant force is 100 Btu. There are no other interactions between the object and its surroundings, and there is no change in the object's elevation. If the final velocity of the object is 200 ft/s, what is its initial velocity, in ft/s?

2.11 A disk-shaped flywheel, of uniform density $\rho$, outer radius $R$, and thickness $w$, rotates with an angular velocity $\omega$, in rad/s.

(a) Show that the moment of inertia, $I = \int r^2 \, dm$, can be expressed as $I = \pi \rho w R^2 / 2$ and the kinetic energy can be expressed as $KE = \frac{1}{2} I \omega^2$.

(b) For a steel flywheel rotating at 3000 RPM, determine the kinetic energy, in N·m, and the mass, in kg, if $R = 0.38 \text{ m}$ and $w = 0.025 \text{ m}$. 
2.33 A gas undergoes three processes in series that complete a cycle:

**Process 1→2**: compression from $p_1 = 10$ bbl/in.\(^2\); $V_1 = 4.0$ ft\(^3\) to $p_2 = 50$ bbl/in.\(^2\); during which the pressure volume relationship is $pv = \text{constant}$

**Process 2→3**: constant volume to $p_3 = p_1$

**Process 3→1**: constant pressure

Sketch the processes on a $p$–$v$ diagram and determine the net work for the cycle, in Btu.

2.34 For the cycle of Problem 1.35, determine the work for each process and the net work for the cycle, each in kJ.

2.35 Figure P2.35 shows an object whose mass is 50 lb attached to a rope wound around a pulley. The radius of the pulley is 3 in. If the mass falls at a constant velocity of 3 ft/s, determine the power transmitted to the pulley, in horsepower, and the rotational speed of the pulley, in RPM. The acceleration of gravity is $g = 32.0$ ft/s\(^2\).

![Figure P2.35](image)

2.36 The driveshaft of a building’s air-handling fan is turned at 300 RPM by a belt running on a 0.3-m-diameter pulley. The net force applied by the belt on the pulley is 2000 N. Determine the torque applied by the belt on the pulley, in N-m, and the power transmitted, in kW.

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

(a) the electric power required by the motor and the power developed by the output shaft, each in kW,

(b) the net power input to the motor, in kW,

(c) the amount of energy transferred to the motor by electrical work and the amount of energy transferred out of the motor by the shaft, in kW·h during 2 h of operation.

2.38 A 12-V automotive storage battery is charged with a constant current of 2 amp for 24 h. If electricity costs $0.08 per kWh, determine the cost of recharging the battery.

2.39 For your lifestyle, estimate the monthly cost of operating the following household items: microwave oven, refrigerator, electric space heater, personal computer, hand-held hair dryer, a 100-W light bulb. Assume the cost of electricity is $0.08 per kWh.

2.40 A solid cylindrical bar (see Fig. 2.9) of diameter 5 mm is slowly stretched from an initial length of 10 cm to a final length of 10.1 cm. The normal stress in the bar varies according to $\sigma = C(x - x_0)/x$, where $x$ is the length of the bar, $x_0$ is the initial length, and $C$ is a material constant (Young’s modulus). For $C = 2 \times 10^5$ kPa, determine the work done on the bar, in J, assuming the diameter remains constant.

2.41 A steel wire suspended vertically has a cross-sectional area of 0.1 in.\(^2\). A downward force applied to the end of the wire causes the wire to stretch. The length of the wire varies linearly with the applied force from an initial length of $x_0 = 10$ ft when no force is applied to $x = 10.01$ ft when the force is 2500 lb. Assuming the area remains constant, determine

(a) the work done, in ft·lb,

(b) the Young’s modulus (see Prob. 2.40), in lb/in.\(^2\).

2.42 A wire of cross-sectional area $A$ and initial length $x_0$ is stretched. The normal stress $\sigma$ acting in the wire varies linearly with strain, $e$, where

$$ e = (x - x_0)/x_0 $$

and $x$ is the length of the wire. Assuming the cross-sectional area remains constant, derive an expression for the work done on the wire as a function of strain.

2.43 A soap film is suspended on a 5 cm x 5 cm wire frame, as shown in Fig. 2.10. The movable wire is displaced 1 cm by an applied force, while the surface tension of the soap film remains constant at $25 \times 10^{-3}$ N/cm. Determine the work done in stretching the film, in J.

2.44 A liquid film is suspended on a rectangular wire frame, as shown in Fig. 2.10. The length of the movable wire is 2 in., and the other dimension initially is 6 in. The movable wire is displaced 1 in. by an applied force, while the surface tension of the liquid film remains constant at $2.5 \times 10^{-4}$ lb/in. Determine the work done in stretching the film, in ft-lbf.

2.45 Derive an expression to estimate the work required to inflate a common balloon. List all simplifying assumptions.

**Heat Transfer**

2.46 A 0.08-m-thick plane wall is constructed of common brick. At steady state, the energy transfer rate by conduction through a 1-m\(^2\) area of the wall is 0.2 kW. If the temperature distribution is linear through the wall, what is the temperature difference across the wall, in K?
Kinetic and potential energy effects can be neglected. Determine the work and heat transfer for process 2-3, each in Btu.

### 2.69
An electric generator coupled to a windmill produces an average electric power output of 15 kW. The power is used to charge a storage battery. Heat transfer from the battery to the surroundings occurs at a constant rate of 1.8 kW. Determine, for 8 h of operation

(a) the total amount of energy stored in the battery, in kJ.
(b) the value of the stored energy, in $s$, if electricity is valued at $0.08$ per kWh.

### 2.60
An electric motor operating at steady state requires an electric power input of 1.86 kW. Heat transfer occurs from the motor to the surroundings at temperature $T_s$ at a rate of $hA(T_m - T_s)$, where $T_m$ is the average surface temperature of the motor, $h = 10$ Btu/h · ft$^{-2}$ · R, and $T_s = 80$ °F. The torque developed by the shaft of the motor is 14.4 ft · lb at a rotational speed of 500 RPM. Determine $T_m$, in °F.

### 2.61
A closed system undergoes a process during which there is energy transfer from the system by heat at a constant rate of 10 kW, and the power varies with time according to

$$ W = \begin{cases} \frac{-8t}{t} & 0 < t \leq 1 \text{ h} \\ \frac{-8}{t} & t > 1 \text{ h} \end{cases} $$

where $t$ is time, in h, and $W$ is in kW.

(a) What is the time of change of system energy at $t = 0.6$ h, in kW?
(b) What are the limiting values for the power output and the change in energy of the battery as $t \to \infty$? Discuss.

### 2.62
A storage battery develops a power output of

$$ W = 2.1 \exp(-t/0.9) $$

where $W$ is power, in kW, and $t$ is time, in s. Ignoring heat transfer

(a) plot the power output, in kW, and the change in energy of the battery, in kJ, each as a function of time.
(b) What are the limiting values for the power output and the change in energy of the battery as $t \to \infty$? Discuss.

### 2.63
A gas expands in a piston-cylinder assembly from $p_1 = 8.2$ bar, $V_1 = 0.0136$ m$^3$ to $p_2 = 3.4$ bar in a process during which the relation between pressure and volume is $pV^{1/2} = constant$. The mass of the gas is 0.183 kg. If the specific internal energy of the gas decreases by 29.8 kJ/kg during the process, determine the heat transfer, in kJ. Kinetic and potential energy effects are negligible.

### 2.64
Air is contained in a rigid well-insulated tank with a volume of 0.6 m$^3$. The tank is fitted with a paddle wheel that transfers energy to the air at a constant rate of 4 W for 1 h. The initial density of the air is 1.2 kg/m$^3$. If no changes in kinetic or potential energy occur, determine

(a) the specific volume at the final state, in m$^3$/kg,
(b) the energy transfer by work, in kJ.

### 2.65
A gas is combined in a closed rigid tank. An electric resistor in the tank transfers energy to the gas at a constant rate of 1000 W. Heat transfer between the gas and the surroundings occurs at a rate of $Q = -50t$, where $Q$ is in watts, and $t$ is time, in min.

(a) Plot the time rate of change of energy of the gas for $0 \leq t \leq 20$ min, in watts.
(b) Determine the net change in energy of the gas after 20 min, in kJ.
(c) If electricity is valued at $0.08$ per kWh, what is the cost of the electrical input to the resistor for 20 min of operation?

### 2.66
Steam in a piston-cylinder assembly undergoes a polytropic process, with $n = 1.2$, from an initial state where $p_1 = 500$ lbf/in$^2$, $v_1 = 1.701$ ft$^3$/lbf, $u_1 = 1363.3$ Btu/lbf to a final state where $u_2 = 990.58$ Btu/lbf. During the process, there is a heat transfer from the steam of magnitude 342.9 Btu. The mass of steam is 1.2 lb. Neglecting changes in kinetic and potential energy, determine the work, in Btu, and the final specific volume, in ft$^3$/lbf.

### 2.67
A gas undergoes a process from state 1, where $p_1 = 60$ lbf/in$^2$, $v_1 = 6.6$ ft$^3$/lbf, to state 2 where $p_2 = 20$ lbf/in$^2$, according to $p^{n-1} = constant$. The relationship between pressure, specific volume, and internal energy is

$$ u = (0.2651)p - 95.436 $$

where $p$ is in lbf/in$^2$, $v$ is in ft$^3$/lbf, and $u$ is in Btu/lbf. The mass of gas is 10 lb. Neglecting kinetic and potential energy effects, determine the heat transfer, in Btu.

### 2.68
A gas is contained in a vertical piston-cylinder assembly by a piston weighing 675 lb and having a face area of 8 in$^2$. The atmosphere exerts a pressure of 14.7 lbf/in$^2$ on the top of the piston. An electrical resistor transfers energy to the gas in the amount of 3 Btu. The internal energy of the gas increases by 1 Btu, which is the only significant internal energy change of any component present. The piston and cylinder are poor thermal conductors and friction can be neglected. Determine the change in elevation of the piston, in ft.

### 2.69
Air is contained in a vertical piston-cylinder assembly by a piston of mass 50 kg and having a face area of 0.01 m$^2$. The mass of the air is 4 g, and initially the air occupies a volume of 5 L. The atmosphere exerts a pressure of 100 kPa on the top of the piston. Heat transfer of magnitude 1.41 kJ occurs slowly from the air to the surroundings, and the volume of the air decreases to 0.025 m$^3$. Neglecting friction between the piston and the cylinder wall, determine the change in specific internal energy of the air, in kJ/kg.

### 2.70
A gas contained within a piston-cylinder assembly is shown in Fig. P2.70. Initially, the piston face is at $x = 0$,
5.54 A heat pump provides 30,000 Btu/h to maintain a
dwelling at 68°F on a day when the outside temperature
is 55°F. The power input to the heat pump is 5 hp. If
electricity costs 8 cents per kW·h, compare the actual
operating cost with the minimum theoretical operating
cost for each day of operation.

5.55 By supplying energy to a dwelling at a rate of 8 kW,
a heat pump maintains the temperature of the dwelling
at 21°C when the outside air is at 0°C. If electricity costs
8 cents per kW·h, determine the minimum theoretical
operating cost for each day of operation.

5.56 At steady state, a refrigeration cycle maintains a food
freezer at 0°F by removing energy by heat transfer from
the inside at a rate of 2000 Btu/h. The cycle discharges
energy by heat transfer to the surroundings at 72°F. If
electricity costs 8 cents per kW·h, determine the minimum
theoretical operating cost for each day of operation.

5.57 By supplying energy at an average rate of 21,100
kW/h, a heat pump maintains the temperature of a dwelling
at 22°C. If electricity costs 8 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 −5°C.
(b) well water at 8°C.

5.58 A heat pump with a coefficient of performance of
3.8 provides energy at an average rate of 75,000 kJ/h to
maintain a building at 21°C on a day when the outside
temperature is 0°C. If electricity costs 8 cents per kW·h
(a) Determine the actual operating cost and the minimum
theoretical operating cost, each in São Day.
(b) Compare the results of part (a) with the cost of electrical
resistance heating.

5.59 A heat pump maintains a dwelling at temperature
T when the outside temperature averages 5°C. The heat
transfer rate through the walls and roof is 2000 kJ/h per
degree of temperature difference between the inside and
outside. If electricity costs 8 cents per kW·h
(a) determine the minimum theoretical operating cost for
each day of operation when T = 20°C.
(b) plot the minimum theoretical operating cost for each
day of operation as a function of T ranging from 18
to 23°C.

5.60 A heat pump maintains a dwelling at temperature T
when the outside temperature is 20°F. The heat transfer
rate through the walls and roof is 1500 Btu/h per degree
temperature difference between the inside and outside.
(a) If electricity costs 8 cents per kW·h, plot the minimum
theoretical operating cost for each day of operation
for T ranging from 68 to 72°F.
(b) If T = 70°F, plot the minimum theoretical operating
cost for each day of operation for a cost of electricity
ranging from 4 to 15 cents per kW·h.

Carnot Cycle

5.61 One-half kilogram of water executes a Carnot power
cycle. During the isothermal expansion, the water is heated
until it is a saturated vapor from an initial state where the
pressure is 15 bar and the quality is 25%. The vapor then
expands adiabatically to a pressure of 1 bar while doing
403.8 kJ/kg of work.
(a) Sketch the cycle on p–v coordinates.
(b) Evaluate the heat and work for each process, in kJ.
(c) Evaluate the thermal efficiency.

5.62 One-tenth pound of water executes a Carnot power
cycle. During the isothermal expansion, the water is heated
at 1500 lbf/in ² from a saturated liquid to a saturated vapor.
The vapor then expands adiabatically to a temperature of
60°F and a quality of 62.8%.
(a) Sketch the cycle on p–v coordinates.
(b) Evaluate the heat and work for each process, in Btu.
(c) Evaluate the thermal efficiency.

5.63 One kilogram of air as an ideal gas executes a Carnot
power cycle having a thermal efficiency of 40%. The heat
transfer to the air during the isothermal expansion is 40 kJ.
At the end of the isothermal expansion, the pressure is
5.6 bar and the volume is 0.3 m³. Determine
(a) the maximum and minimum temperatures for the cycle,
in K.
(b) the pressure and volume at the beginning of the iso-
thermal expansion in bar and m³, respectively.
(c) the work and heat transfer for each of the four pro-
cesses, in kJ.
(d) Sketch the cycle on p–v coordinates.

5.64 The pressure–volume diagram of a Carnot power cy-
cle executed by an ideal gas with constant specific heat
ratio γ is shown in Fig. P5.64. Demonstrate that
(a) \( V_1/V_2 = V_2/V_1 \).
(b) \( T_1/T_2 = (p_2/p_1)^{\gamma - 1} \).
(c) \( T_2/T_3 = (V_3/V_2)^{\gamma - 1} \).

\[ \text{Figure P5.64} \]
6.75 An insulated vessel is divided into two equal-sized compartments connected by a valve. Initially, one compartment contains steam at 50 ft²/in² and 700°F, and the other is evacuated. The valve is opened and the steam is allowed to fill the entire volume. Determine
(a) the final temperature, in °F.
(b) the amount of entropy produced, in Btu/lb °R.

6.76 Two insulated tanks are connected by a valve. One tank initially contains 70 kg of air at 80°C, 1 bar, and the other contains 10 kg of air at 50°C, 2 bar. The valve is opened and the two quantities of air are allowed to mix until equilibrium is attained. Employing the ideal gas model with $c_v = 0.72$ ft²-lb/s-lb °R, determine
(a) the final temperature, in °C.
(b) the final pressure, in atm.
(c) the amount of entropy produced, in kJ/K.

6.77 An insulated cylinder is initially divided into two halves by a frictionless, thermally conducting piston. On one side of the piston is 5 ft³ of a gas at 500°F and 2 atm. On the other side is 5 ft³ of the same gas at 500°F and 1 atm. The piston is released and equilibrium is attained, with the piston experiencing no change of state. Employing the ideal gas model for the gas, determine
(a) the final temperature, in °R.
(b) the final pressure, in atm.
(c) the amount of entropy produced, in Btu/°R.

6.78 An insulated, rigid tank is divided into two compartments by a frictionless, thermally conducting piston. One compartment initially contains 1 m³ of saturated water vapor at 4 MPa and the other compartment contains 1 m³ of water vapor at 20 MPa, 80°C. The piston is released and equilibrium is attained, with the piston experiencing no change of state. For the water as the system, determine
(a) the final pressure, in MPa.
(b) the final temperature, in °C.
(c) the amount of entropy produced, in kJ/K.

6.79 A system consisting of air initially at 300 K and 1 bar experiences the two different types of interactions described below. In each case, the system is brought from the initial state to a state where the temperature is 500 K, while volume remains constant.
(a) The temperature rise is brought about adiabatically by stirring the air with a paddle wheel. Determine the amount of entropy produced, in kJ/kg °K.
(b) The temperature rise is brought about by heat transfer from a reservoir at temperature $T$. The temperature at the system boundary where heat transfer occurs is also $T$. Plot the amount of entropy produced, in kJ/kg °K, versus $T$ for $T \geq 500$ K. Compare the result of (a) and discuss.

6.80 A cylindrical copper rod of base area $A$ and length $L$ is insulated on its lateral surface. One end of the rod is in contact with a wall at temperature $T_w$. The other end is in contact with a wall at a lower temperature $T_c$. At steady state, the rate at which energy is conducted into the rod from the hot wall is
\[ Q_0 = \frac{\kappa A (T_w - T_c)}{L} \]
where $\kappa$ is the thermal conductivity of the copper rod.
(a) For the rod as the system, obtain an expression for the rate of entropy production in terms of $A$, $L$, $T_w$, $T_c$, and $\kappa$.
(b) If $T_w = 327°C$, $T_c = 77°C$, $\kappa = 0.4$ kJ/m °K, $A = 0.1$ m², plot the heat transfer rate $Q_0$, in kW, and the rate of entropy production, in kW/K, each versus $L$ ranging from 0.01 to 1.0 m. Discuss.

6.81 A system undergoes a thermodynamic cycle while receiving energy by heat transfer from a tank of liquid water initially at 200°F and rejecting energy by heat transfer at 60°F to the surroundings. If the final water temperature is 60°F, determine the minimum theoretical volume of water in the tank, in gal, for the cycle to produce net work equal to $1.5 \times 10^6$ Btu.

6.82 The temperature of an incompressible substance of mass $m$ and specific heat $c$ is reduced from $T_i$ to $T$ (< $T_i$) by a refrigeration cycle. The cycle receives energy by heat transfer at $T$ from the substance and discharges energy by heat transfer at $T$, to the surroundings. There are no other heat transfers. Plot $(W/mcT_i)$ versus $T$ for $T_i$ ranging from 0.8 to 1.0, where $W/mcT_i$ is the minimum theoretical work input required by the cycle.

6.83 The temperature of a 12-oz (0.354-L) can of soft drink is reduced from 20 to 5°C by a refrigeration cycle. The cycle receives energy by heat transfer to $T$ from the substance and discharges energy by heat transfer at $T$ to the surroundings. There are no other heat transfers. Determine the minimum theoretical work input required by the cycle. Figure 6.84, in kJ, assuming the soft drink is an incompressible liquid with the properties of liquid water. Ignore the aluminum can.

6.84 As shown in Fig. 6.84, a turbine is located between two tanks. Initially, the smaller tank contains steam at 3.0 MPa, 200°C and the larger tank is evacuated. Steam is allowed to flow from the smaller tank, through the turbine, and into the larger tank until equilibrium is attained. The heat transfer with the surroundings is negligible. Determine
The air enters the duct at 15°C, 1 atm and exits at 25°C with a negligible change in pressure. Kinetic and potential energy changes can be ignored.

(a) For the resistor as the system, determine the rate of entropy production, in kW/K.

(b) For a control volume enclosing the air in the duct and the resistor, determine the volumetric flow rate of the air entering the duct, in m³/s, and rate of entropy production, in kW/K.

Why do the entropy production values of (a) and (b) differ?

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

6.106 For the computer of Problem 4.70, determine the rate of entropy production, in kW/K, ignoring the change in pressure between the inlet and exit.

6.107 For the water-jacketed electronics housing of Problem 4.71, determine the rate of entropy production, in kW/K, when water exits at 24°C.

6.108 For the electronics-laden cylinder of Problem 4.73, determine the rate of entropy production, in W/K, when air exits at 40°C with a negligible change in pressure. Assume convective cooling occurs on the outer surface of the cylinder in accord with hA = 3.4 W/K, where h is the heat transfer coefficient and A is the surface area. The temperature of the surroundings away from the vicinity of the cylinder is 25°C.

6.109 Steam at 1000 lb/in², 1100°F enters an insulated turbine operating at steady state with a mass flow rate of 50,000 lbm/h. At steady state, 20% of the total flow is extracted at 300 lb/in², 800°F and diverted for use in another process. The remainder of the total flow continues to expand through the turbine, exiting at 1 lb/in² and quality x. Changes in kinetic and potential energy can be ignored.

(a) For x = 99%, determine the power developed, in Btu/h, and the rate of entropy production, in Btu/h·°R.

(b) Plot the quantities of part (a), each versus x ranging from 90 to 100%.

6.110 Steam at 550 lb/in², 700°F enters an insulated turbine operating at steady state with a mass flow rate of 1 lbm/s. A two-phase liquid-vapor mixture exits the turbine with quality x. Plot the power developed, in Btu/s, and the rate of entropy production, in Btu/R·s, each versus x.

6.111 Steam enters a horizontal 6-in.-diameter pipe as a saturated vapor at 20 lb/in² with a velocity of 30 ft/s and exits at 14.7 lb/in² with a quality of 95%. Heat transfer from the pipe to the surroundings at 80°F takes place at an average outer surface temperature of 220°F. For operation at steady state, determine

(a) the velocity at the exit, in ft/s.

(b) the rate of heat transfer from the pipe, in Btu/h.

(c) the rate of entropy production, in Btu/s·R, for a control volume comprising only the pipe and its contents.

(d) the rate of entropy production, in Btu/s·°R, for an enlarged control volume that includes the pipe and enough of its immediate surroundings so that heat transfer from the control volume occurs at 80°F. Why do the answers of parts (c) and (d) differ?

6.112 Steam enters a turbine operating at steady state at a pressure of 3 MPa, a temperature of 400°C, and a velocity of 160 m/s. Saturated vapor exits at 100°C, with a velocity of 100 m/s. Heat transfer from the turbine to its surroundings takes place at the rate of 30 kW per kg of steam at a location where the average surface temperature is 350 K.

(a) For a control volume including only the turbine and its contents, determine the work developed, in kJ/kg, and the rate at which entropy is produced, in kJ/kg, each per kg of steam flowing.

(b) The steam turbine of part (a) is located in a factory where the ambient temperature is 27°C. Determine the rate of entropy production, in kJ/kg, each per kg of steam flowing, for an enlarged control volume that includes the turbine and enough of its immediate surroundings so that heat transfer takes place from the control volume at the ambient temperature.

Explain why the entropy production value of part (b) differs from that calculated in part (a).

6.113 Air enters a turbine operating at steady state with a pressure of 75 lb/in², a temperature of 800°F, and a velocity of 400 ft/s. At the turbine exit, the conditions are 15 lb/in², 600°F, and 100 ft/s. Heat transfer from the turbine to its surroundings takes place at a location where the average surface temperature is 620°F. The rate of heat transfer is 10 Btu per lb of air passing through the turbine.

(a) For a control volume including only the turbine and its contents, determine the work developed, in Btu, and the rate at which entropy is produced, in Btu/R, per lb of air flowing.

(b) For a control volume including the turbine and a portion of its immediate surroundings so that the heat transfer occurs at the ambient temperature, 40°F, determine the rate of entropy production in Btu/R per lb of air passing through the turbine.
6.114 Oxygen (O_2) enters a nozzle operating at steady state at 3.8 MPa, 387°C, and 10 m/s. At the nozzle exit, the conditions are 150 kPa, 37°C, and 700 m/s, respectively.

(a) For a control volume enclosing the nozzle only, determine the heat transfer, in kW, and the change in specific entropy, in kJ/kg, each per kg of oxygen flowing through the nozzle. What additional information would be required to evaluate the rate of entropy production?

(b) Evaluate the rate of entropy production, in kW/K, per kg of oxygen flowing, for an enlarged control volume enclosing the nozzle and a portion of its immediate surroundings so that the heat transfer occurs at the ambient temperature, 20°C.

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

(a) For a control volume enclosing the compressor only, determine the heat transfer rate, in kW, and the change in specific entropy from inlet to exit, in kJ/kg. What additional information would be required to evaluate the rate of entropy production?

(b) Calculate the rate of entropy production, in kW/K, for an enlarged control volume enclosing the compressor and a portion of its immediate surroundings so that heat transfer occurs at the ambient temperature, 22°C.

6.116 Air is compressed in an axial-flow compressor operating at steady state from 27°C, 1 bar to a pressure of 2.1 bar. The work input required is 94.6 kJ per kg of air flowing through the compressor. Heat transfer from the compressor occurs at the rate of 14 kJ per kg at a location on the compressor’s surface where the temperature is 40°C. Kinetic and potential energy changes can be ignored. Determine

(a) the temperature of the air at the exit, in °C,
(b) the rate at which entropy is produced within the compressor, in kJ/K per kg of air flowing.

6.117 Determine the rate of entropy production, in Btu/ min °R, for the duct system of Problem 4.68.

6.118 Air enters a compressor operating at steady state at 1 bar, 20°C with a volumetric flow rate of 9 m³/min and exits at 5 bar, 160°C. Cooling water is circulated through a water jacket enclosing the compressor at a rate of 8.6 kg/min, entering at 17°C, and exiting at 25°C with a negligible change in pressure. There is no significant heat transfer from the outer surface of the water jacket, and all kinetic and potential effects are negligible. For the water-jacketed compressor as the control volume, determine the power required, in kW, and the rate of entropy production, in kW/K.

6.119 Ammonia enters a counterflow heat exchanger at −20°C, with a quality of 15%, and leaves as saturated vapor at −20°C. Air at 300 K, 1 atm enters the heat exchanger in a separate stream with a flow rate of 4 kg/s and exits at 285 K, 0.98 atm. The heat exchanger is at steady state, and there is no appreciable heat transfer from its outer surface. Neglecting kinetic and potential energy effects, determine the mass flow rate of the ammonia, in kg/s, and the rate of entropy production within the heat exchanger, in kW/K.

6.120 A counterflow heat exchanger operates at steady state with negligible kinetic and potential energy effects. In one stream, liquid water enters at 17°C and exits at 25°C with a negligible change in pressure. In the other stream, Refrigerant 134a enters at 14 bar, 80°C with a mass flow rate of 3 kg/min and exits as saturated liquid at 52°C. Heat transfer from the outer surface of the heat exchanger can be ignored. Determine

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

6.121 Steam at 0.7 MPa, 350°C enters an open feedwater heater operating at steady state. A separate stream of liquid water enters at 0.7 MPa, 35°C. A single mixed stream exits as saturated liquid at pressure p. Heat transfer with the surroundings and kinetic and potential energy effects can be ignored.

(a) If p = 0.7 MPa, determine the ratio of the mass flow rates of the incoming streams and the rate at which entropy is produced within the feedwater heater, in kW/K per kg of liquid exiting.

(b) Plot the quantities of part (a), each versus pressure p ranging from 0.6 to 0.7 MPa.

6.122 At steady state, steam with a mass flow rate of 10 lb/s enters a turbine at 800°F and 600 lb/ft² and expands to 60 lb/ft². The power developed by the turbine is 2852 horsepower. The steam then passes through a counterflow heat exchanger with a negligible change in pressure, exiting at 800°F. Air enters the heat exchanger in a separate stream at 1 atm, 102°F and exits at 1 atm, 62°F. Kinetic and potential energy changes can be ignored and there is no significant heat transfer between either component and its surroundings. Determine

(a) the mass flow rate of air, in lb/s,
(b) the rate of entropy production in the turbine, in Btu/°R.
(c) the rate of entropy production in the heat exchanger, in Btu/°R.

6.123 Determine the rates of entropy production, in Btu/ min °R, for the steam generator and turbine of (a) Example 4.10, (b) Problem 4.83. In each case, identify the component that contributes most to inefficient operation of the overall system.