Energy and the First Law of Thermodynamics

Engineering Context

Energy is a fundamental concept of thermodynamics and one of the most significant aspects of engineering analysis. In this chapter we discuss energy and develop equations for applying the principle of conservation of energy. The current presentation is limited to closed systems. In Chap. 4 the discussion is extended to control volumes.

Energy is a familiar notion, and you already know a great deal about it. In the present chapter several important aspects of the energy concept are developed. Some of these you have encountered before. A basic idea is that energy can be *stored* within systems in various forms. Energy also can be *converted* from one form to another and *transferred* between systems. For closed systems, energy can be transferred by *work* and *heat transfer*. The total amount of energy is *conserved* in all conversions and transfers.

The objective of this chapter is to organize these ideas about energy into forms suitable for engineering analysis. The presentation begins with a review of energy concepts from mechanics. The thermodynamic concept of energy is then introduced as an extension of the concept of energy in mechanics.

Learning Objectives

When you complete your study of this chapter you will be able to...

- ✓ demonstrate understanding of key concepts related to energy and the first law of thermodynamics . . . including internal, kinetic, and potential energy, work and power, heat transfer and heat transfer modes, heat transfer rate, power cycle, refrigeration cycle, and heat pump cycle.
- ✓ apply closed system energy balances, appropriately modeling the case at hand, and correctly observing sign conventions for work and heat transfer.
- ✓ conduct energy analyses of systems undergoing thermodynamic cycles, evaluating as appropriate thermal efficiencies of power cycles and coefficients of performance of refrigeration and heat pump cycles.

2.1 Reviewing Mechanical Concepts of Energy

Building on the contributions of Galileo and others, Newton formulated a general description of the motions of objects under the influence of applied forces. Newton's laws of motion, which provide the basis for classical mechanics, led to the concepts of *work, kinetic energy,* and *potential energy,* and these led eventually to a broadened concept of energy. The present discussion begins with an application of Newton's second law of motion.

2.1.1 Work and Kinetic Energy

The curved line in Fig. 2.1 represents the path of a body of mass m (a closed system) moving relative to the x–y coordinate frame shown. The velocity of the center of mass of the body is denoted by **V**.[1] The body is acted on by a resultant force **F**, which may vary in magnitude from location to location along the path. The resultant force is resolved into a component $\mathbf{F}_s$ along the path and a component $\mathbf{F}_n$ normal to the path. The effect of the component $\mathbf{F}_s$ is to change the magnitude of the velocity, whereas the effect of the component $\mathbf{F}_n$ is to change the direction of the velocity. As shown in Fig. 2.1, s is the instantaneous position of the body measured along the path from some fixed point denoted by 0. Since the magnitude of **F** can vary from location to location along the path, the magnitudes of $\mathbf{F}_s$ and $\mathbf{F}_n$ are, in general, functions of s.

Let us consider the body as it moves from $s = s_1$, where the magnitude of its velocity is V_1, to $s = s_2$, where its velocity is V_2. Assume for the present discussion that the only interaction between the body and its surroundings involves the force **F**. By Newton's second law of motion, the magnitude of the component $\mathbf{F}_s$ is related to the change in the magnitude of **V** by

$$F_s = m\frac{dV}{dt} \tag{2.1}$$

Using the chain rule, this can be written as

$$F_s = m\frac{dV}{ds}\frac{ds}{dt} = mV\frac{dV}{ds} \tag{2.2}$$

where $V = ds/dt$. Rearranging Eq. 2.2 and integrating from s_1 to s_2 gives

$$\int_{V_1}^{V_2} mV\,dV = \int_{s_1}^{s_2} F_s\,ds \tag{2.3}$$

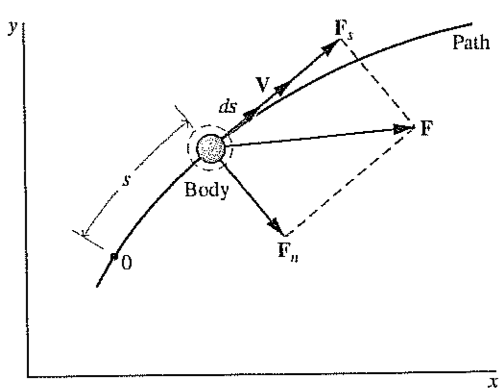


Fig. 2.1 Forces acting on a moving system.

[1]Boldface symbols denote vectors. Vector magnitudes are shown in lightface type.

The integral on the left of Eq. 2.3 is evaluated as follows

$$\int_{V_1}^{V_2} mV\, dV = \frac{1}{2}mV^2\Big]_{V_1}^{V_2} = \frac{1}{2}m(V_2^2 - V_1^2) \tag{2.4}$$

The quantity $\frac{1}{2}mV^2$ is the ***kinetic energy,*** KE, of the body. Kinetic energy is a scalar quantity. The *change* in kinetic energy, ΔKE, of the body is[2]

kinetic energy

$$\Delta KE = KE_2 - KE_1 = \frac{1}{2}m(V_2^2 - V_1^2) \tag{2.5}$$

The integral on the right of Eq. 2.3 is the *work* of the force F_s as the body moves from s_1 to s_2 along the path. Work is also a scalar quantity.

With Eq. 2.4, Eq. 2.3 becomes

$$\frac{1}{2}m(V_2^2 - V_1^2) = \int_{s_1}^{s_2} \mathbf{F} \cdot d\mathbf{s} \tag{2.6}$$

where the expression for work has been written in terms of the scalar product (dot product) of the force vector **F** and the displacement vector *d***s**. Equation 2.6 states that the work of the resultant force on the body equals the change in its kinetic energy. When the body is accelerated by the resultant force, the work done on the body can be considered a *transfer* of energy *to* the body, where it is *stored* as kinetic energy.

Kinetic energy can be assigned a value knowing only the mass of the body and the magnitude of its instantaneous velocity relative to a specified coordinate frame, without regard for how this velocity was attained. Hence, *kinetic energy is a property* of the body. Since kinetic energy is associated with the body as a whole, it is an *extensive* property.

Energy & Environment

Did you ever wonder what happens to the kinetic energy when you step on the brakes of your moving car? Automotive engineers have, and the result is the *hybrid electric* vehicle combining an electric motor with a small conventional engine.

When a hybrid is braked, some of its kinetic energy is harvested and stored in batteries. The electric motor calls on the stored energy to help the car start up again. A specially designed transmission provides the proper split between the engine and the electric motor to minimize fuel use. Because stored energy assists the engine, these cars get better fuel economy than comparably sized conventional vehicles. Tomorrow's hybrids may get even better fuel economy if plans develop for a *plug-in* version whereby the storage batteries are charged from an electrical outlet when the vehicle is idle, thereby allowing drivers of plug-in hybrids to get most of the energy they need for transportation from the electricity grid—not by way of the gas pump.

Better fuel economy not only stretches increasingly scarce and costly oil supplies but also reduces the release of CO_2 into the atmosphere, which has been linked to *global warming.* Each gallon of gasoline burned by a vehicle produces about 9 kg (20 lb) of CO_2. Annually, a conventional vehicle produces several tons of CO_2. Fuel-thrifty hybrids produce much less.

2.1.2 Potential Energy

Equation 2.6 is a principal result of the previous section. Derived from Newton's second law, the equation gives a relationship between two *defined* concepts: kinetic energy and work. In this section it is used as a point of departure to extend the concept of

[2]The symbol Δ always means "final value minus initial value."

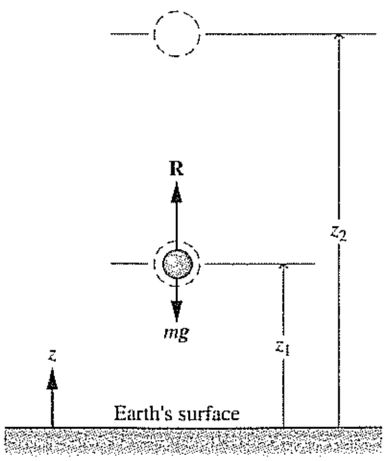


Fig. 2.2 Illustration used to introduce the potential energy concept.

energy. To begin, refer to Fig. 2.2, which shows a body of mass m that moves vertically from an elevation z_1 to an elevation z_2 relative to the surface of the earth. Two forces are shown acting on the system: a downward force due to gravity with magnitude mg and a vertical force with magnitude R representing the resultant of all *other* forces acting on the system.

The work of each force acting on the body shown in Fig. 2.2 can be determined by using the definition previously given. The total work is the algebraic sum of these individual values. In accordance with Eq. 2.6, the total work equals the change in kinetic energy. That is

$$\frac{1}{2}m(V_2^2 - V_1^2) = \int_{z_1}^{z_2} R\,dz - \int_{z_1}^{z_2} mg\,dz \tag{2.7}$$

A minus sign is introduced before the second term on the right because the gravitational force is directed downward and z is taken as positive upward.

The first integral on the right of Eq. 2.7 represents the work done by the force **R** on the body as it moves vertically from z_1 to z_2. The second integral can be evaluated as follows:

$$\int_{z_1}^{z_2} mg\,dz = mg(z_2 - z_1) \tag{2.8}$$

where the acceleration of gravity has been assumed to be constant with elevation. By incorporating Eq. 2.8 into Eq. 2.7 and rearranging

$$\frac{1}{2}m(V_2^2 - V_1^2) + mg(z_2 - z_1) = \int_{z_1}^{z_2} R\,dz \tag{2.9}$$

gravitational potential energy

The quantity mgz is the ***gravitational potential energy,*** PE. The *change* in gravitational potential energy, ΔPE, is

$$\Delta PE = PE_2 - PE_1 = mg(z_2 - z_1) \tag{2.10}$$

Potential energy is associated with the force of gravity and is therefore an attribute of a system consisting of the body and the earth together. However, evaluating the force of gravity as mg enables the gravitational potential energy to be determined for a specified value of g knowing only the mass of the body and its elevation. With this view, potential energy is regarded as an *extensive property* of the body. Throughout this book it is assumed that elevation differences are small enough that the gravitational force can be considered constant. The concept of gravitational potential energy can be formulated to account for the variation of the gravitational force with elevation, however.

To assign a value to the kinetic energy or the potential energy of a system, it is necessary to assume a datum and specify a value for the quantity at the datum. Values of kinetic and potential energy are then determined relative to this arbitrary choice of datum and reference value. However, since only *changes* in kinetic and potential energy between two states are required, these arbitrary reference specifications cancel.

2.1.3 Units for Energy

Work has units of force times distance. The units of kinetic energy and potential energy are the same as for work. In SI, the energy unit is the newton-meter, N · m, called the joule, J. In this book it is convenient to use the kilojoule, kJ. Commonly used English units for work, kinetic energy, and potential energy are the foot-pound force, ft · lbf, and the British thermal unit, Btu.

When a system undergoes a process where there are changes in kinetic and potential energy, special care is required to obtain a consistent set of units.

FOR EXAMPLE... to illustrate the proper use of units in the calculation of such terms, consider a system having a mass of 1 kg whose velocity increases from 15 m/s to 30 m/s while its elevation decreases by 10 m at a location where $g = 9.7$ m/s^2. Then

$$\begin{aligned}\Delta \text{KE} &= \frac{1}{2}m(\text{V}_2^2 - \text{V}_1^2) \\ &= \frac{1}{2}(1\text{ kg})\left[\left(30\frac{\text{m}}{\text{s}}\right)^2 - \left(15\frac{\text{m}}{\text{s}}\right)^2\right]\left|\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right|\left|\frac{1\text{ kJ}}{10^3\text{ N}\cdot\text{m}}\right| \\ &= 0.34\text{ kJ} \\ \Delta \text{PE} &= mg(z_2 - z_1) \\ &= (1\text{ kg})\left(9.7\frac{\text{m}}{\text{s}^2}\right)(-10\text{ m})\left|\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right|\left|\frac{1\text{ kJ}}{10^3\text{ N}\cdot\text{m}}\right| \\ &= -0.10\text{ kJ}\end{aligned}$$

For a system having a mass of 1 lb whose velocity increases from 50 ft/s to 100 ft/s while its elevation decreases by 40 ft at a location where $g = 32.0$ ft/s^2, we have

$$\begin{aligned}\Delta \text{KE} &= \frac{1}{2}(1\text{ lb})\left[\left(100\frac{\text{ft}}{\text{s}}\right)^2 - \left(50\frac{\text{ft}}{\text{s}}\right)^2\right]\left|\frac{1\text{ lbf}}{32.2\text{ lb}\cdot\text{ft/s}^2}\right|\left|\frac{1\text{ Btu}}{778\text{ ft}\cdot\text{lbf}}\right| \\ &= 0.15\text{ Btu} \\ \Delta \text{PE} &= (1\text{ lb})\left(32.0\frac{\text{ft}}{\text{s}^2}\right)(-40\text{ ft})\left|\frac{1\text{ lbf}}{32.2\text{ lb}\cdot\text{ft/s}^2}\right|\left|\frac{1\text{ Btu}}{778\text{ ft}\cdot\text{lbf}}\right| \\ &= -0.05\text{ Btu}\end{aligned}$$

2.1.4 Conservation of Energy in Mechanics

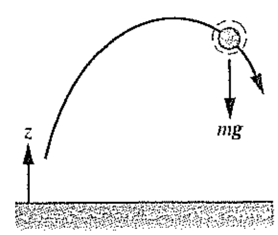
Equation 2.9 states that the total work of all forces acting on the body from the surroundings, with the exception of the gravitational force, equals the sum of the changes in the kinetic and potential energies of the body. When the resultant force causes the elevation to be increased, the body to be accelerated, or both, the work done by the force can be considered a *transfer* of energy *to* the body, where it is stored as gravitational potential energy and/or kinetic energy. The notion that *energy is conserved* underlies this interpretation.

The interpretation of Eq. 2.9 as an expression of the conservation of energy principle can be reinforced by considering the special case of a body on which the only force acting is that due to gravity, for then the right side of the equation vanishes and the equation reduces to

$$\frac{1}{2}m(\text{V}_2^2 - \text{V}_1^2) + mg(z_2 - z_1) = 0$$

or

$$\frac{1}{2}m\text{V}_2^2 + mgz_2 = \frac{1}{2}m\text{V}_1^2 + mgz_1 \tag{2.11}$$



Under these conditions, the *sum* of the kinetic and gravitational potential energies *remains constant.* Equation 2.11 also illustrates that energy can be *converted* from one form to another: For an object falling under the influence of gravity *only,* the potential energy would decrease as the kinetic energy increases by an equal amount.

2.1.5 Closing Comment

The presentation thus far has centered on systems for which applied forces affect only their overall velocity and position. However, systems of engineering interest normally interact with their surroundings in more complicated ways, with changes in other properties as well. To analyze such systems, the concepts of kinetic and potential energy alone do not suffice, nor does the rudimentary conservation of energy principle introduced in this section. In thermodynamics the concept of energy is broadened to account for other observed changes, and the principle of *conservation of energy* is extended to include a wide variety of ways in which systems interact with their surroundings. The basis for such generalizations is experimental evidence. These extensions of the concept of energy are developed in the remainder of the chapter, beginning in the next section with a fuller discussion of work.

2.2 Broadening Our Understanding of Work

The work W done by, or on, a system evaluated in terms of macroscopically observable forces and displacements is

$$W = \int_{s_1}^{s_2} \mathbf{F} \cdot ds \tag{2.12}$$

This relationship is important in thermodynamics, and is used later in the present section to evaluate the work done in the compression or expansion of gas (or liquid), the extension of a solid bar, and the stretching of a liquid film. However, thermodynamics also deals with phenomena not included within the scope of mechanics, so it is necessary to adopt a broader interpretation of work, as follows.

thermodynamic definition of work

A particular interaction is categorized as a work interaction if it satisfies the following criterion, which can be considered the ***thermodynamic definition of work:*** *Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight.* Notice that the raising of a weight is, in effect, a force acting through a distance, so the concept of work in thermodynamics is a natural extension of the concept of work in mechanics. However, the test of whether a work interaction has taken place is not that the elevation of a weight has actually taken place, or that a force has actually acted through a distance, but that the sole effect *could have been* an increase in the elevation of a weight.

➡ **FOR EXAMPLE...** consider Fig. 2.3 showing two systems labeled A and B. In system A, a gas is stirred by a paddle wheel: the paddle wheel does work on the gas. In principle, the work could be evaluated in terms of the forces and motions at the boundary

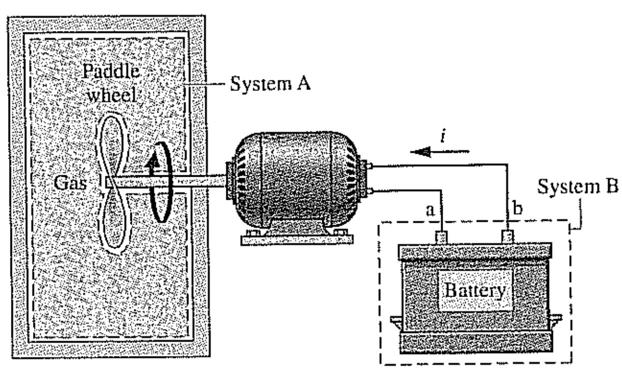


Fig. 2.3 Two examples of work.

Horizons

Nanoscale Machines on the Move

Engineers working in the field of nanotechnology, the engineering of molecular-sized devices, look forward to the time when practical nanoscale machines can be fabricated that are capable of movement, sensing and responding to stimuli such as light and sound, delivering medication within the body, performing computations, and numerous other functions that promote human well being. For inspiration, engineers study biological nanoscale *machines* in living things that perform functions such as creating and repairing cells, circulating oxygen, and digesting food. These studies have yielded positive results. Molecules mimicking the function of mechanical devices have been fabricated, including gears, rotors, ratchets, brakes, switches, and abacus-like structures. A particular success is the development of molecular motors that convert light to rotary or linear motion. Although devices produced thus far are rudimentary, they do demonstrate the feasibility of constructing nanomachines, researchers say.

between the paddle wheel and the gas. Such an evaluation of work is consistent with Eq. 2.12, where work is the product of force and displacement. By contrast, consider system B, which includes only the battery. At the boundary of system B, forces and motions are not evident. Rather, there is an electric current i driven by an electrical potential difference existing across the terminals a and b. That this type of interaction at the boundary can be classified as work follows from the thermodynamic definition of work given previously: We can imagine the current is supplied to a *hypothetical* electric motor that lifts a weight in the surroundings.

Work is a means for transferring energy. Accordingly, the term work does not refer to what is being transferred between systems or to what is stored within systems. Energy is transferred and stored when work is done.

2.2.1 Sign Convention and Notation

Engineering thermodynamics is frequently concerned with devices such as internal combustion engines and turbines whose purpose is to do work. Hence, in contrast to the approach generally taken in mechanics, it is often convenient to consider such work as positive. That is,

$W > 0$: work done *by* the system

$W < 0$: work done *on* the system

sign convention for work

This ***sign convention*** is used throughout the book. In certain instances, however, it is convenient to regard the work done *on* the system to be positive, as has been done in the discussion of Sec. 2.1. To reduce the possibility of misunderstanding in any such case, the direction of energy transfer is shown by an arrow on a sketch of the system, and work is regarded as positive in the direction of the arrow.

To evaluate the integral in Eq. 2.12, it is necessary to know how the force varies with the displacement. This brings out an important idea about work: The value of W depends on the details of the interactions taking place between the system and surroundings during a process and not just the initial and final states of the system. It follows that ***work is not a property*** of the system or the surroundings. In addition, the limits on the integral of Eq. 2.12 mean "from state 1 to state 2" and cannot be interpreted as the *values* of work at these states. The notion of work at a state *has no meaning*, so the value of this integral should never be indicated as $W_2 - W_1$.

work is not a property

The differential of work, δW, is said to be *inexact* because, in general, the following integral cannot be evaluated without specifying the details of the process

$$\int_1^2 \delta W = W$$

On the other hand, the differential of a property is said to be *exact* because the change in a property between two particular states depends in no way on the details of the process linking the two states. For example, the change in volume between two states can be determined by integrating the differential dV, without regard for the details of the process, as follows

$$\int_{V_1}^{V_2} dV = V_2 - V_1$$

where V_1 is the volume *at* state 1 and V_2 is the volume *at* state 2. The differential of every property is exact. Exact differentials are written, as above, using the symbol d. To stress the difference between exact and inexact differentials, the differential of work is written as δW. The symbol δ is also used to identify other inexact differentials encountered later.

2.2.2 Power

power

Many thermodynamic analyses are concerned with the time rate at which energy transfer occurs. The rate of energy transfer by work is called ***power*** and is denoted by $\dot{W}$. When a work interaction involves a macroscopically observable force, the rate of energy transfer by work is equal to the product of the force and the velocity at the point of application of the force

$$\dot{W} = \mathbf{F} \cdot \mathbf{V} \tag{2.13}$$

A dot appearing over a symbol, as in $\dot{W}$, is used throughout this book to indicate a time rate. In principle, Eq. 2.13 can be integrated from time t_1 to time t_2 to get the total work done during the time interval

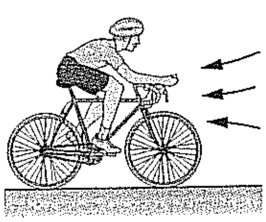
$$W = \int_{t_1}^{t_2} \dot{W}\, dt = \int_{t_1}^{t_2} \mathbf{F} \cdot \mathbf{V}\, dt \tag{2.14}$$

units for power

The same sign convention applies for $\dot{W}$ as for W. Since power is a time rate of doing work, it can be expressed in terms of any units for energy and time. In SI, the ***unit for power*** is J/s, called the watt. In this book the kilowatt, kW, is generally used. Commonly used English units for power are ft · lbf/s, Btu/h, and horsepower, hp.

FOR EXAMPLE... to illustrate the use of Eq. 2.13, let us evaluate the power required for a bicyclist traveling at 20 miles per hour to overcome the drag force imposed by the surrounding air. This *aerodynamic drag* force is given by

$$F_d = \tfrac{1}{2} C_d A \rho V^2$$



where C_d is a constant called the *drag coefficient*, A is the frontal area of the bicycle and rider, and ρ is the air density. By Eq. 2.13 the required power is $\mathbf{F}_d \cdot \mathbf{V}$ or

$$\begin{aligned} \dot{W} &= (\tfrac{1}{2} C_d A \rho V^2) V \\ &= \tfrac{1}{2} C_d A \rho V^3 \end{aligned}$$

Using typical values: $C_d = 0.88$, $A = 3.9\ \text{ft}^2$, and $\rho = 0.075\ \text{lb/ft}^3$, together with $V = 20\ \text{mi/h} = 29.33\ \text{ft/s}$, and also converting units to horsepower, the power required is

$$\begin{aligned} \dot{W} &= \frac{1}{2}(0.88)(3.9\ \text{ft}^2)\left(0.075\frac{\text{lb}}{\text{ft}^3}\right)\left(29.33\frac{\text{ft}}{\text{s}}\right)^3 \left|\frac{1\ \text{lbf}}{32.2\ \text{lb} \cdot \text{ft/s}^2}\right| \left|\frac{1\ \text{hp}}{550\ \text{ft} \cdot \text{lbf/s}}\right| \\ &= 0.183\ \text{hp} \end{aligned}$$

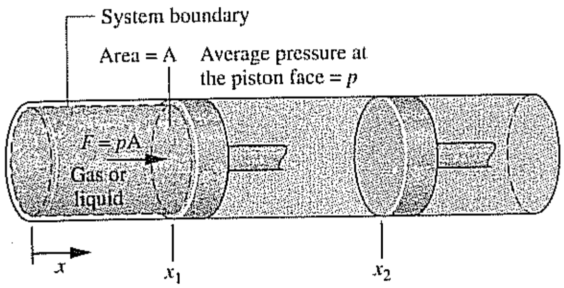


Fig. 2.4 Expansion or compression of a gas or liquid.

2.2.3 Modeling Expansion or Compression Work

There are many ways in which work can be done by or on a system. The remainder of this section is devoted to considering several examples, beginning with the important case of the work done when the volume of a quantity of a gas (or liquid) changes by expansion or compression.

Let us evaluate the work done by the closed system shown in Fig. 2.4 consisting of a gas (or liquid) contained in a piston–cylinder assembly as the gas expands. During the process the gas pressure exerts a normal force on the piston. Let p denote the pressure acting at the interface between the gas and the piston. The force exerted by the gas on the piston is simply the product $p\mathrm{A}$, where A is the area of the piston face. The work done by the system as the piston is displaced a distance dx is

$$\delta W = p\mathrm{A}\, dx \tag{2.15}$$

The product A dx in Eq. 2.15 equals the change in volume of the system, dV. Thus, the work expression can be written as

$$\delta W = p\, dV \tag{2.16}$$

Since dV is positive when volume increases, the work at the moving boundary is positive when the gas expands. For a compression, dV is negative, and so is work found from Eq. 2.16. These signs are in agreement with the previously stated sign convention for work.

For a change in volume from V_1 to V_2, the work is obtained by integrating Eq. 2.16

$$W = \int_{V_1}^{V_2} p\, dV \tag{2.17}$$

Although Eq. 2.17 is derived for the case of a gas (or liquid) in a piston–cylinder assembly, it is applicable to systems of *any* shape provided the pressure is uniform with position over the moving boundary.

2.2.4 Expansion or Compression Work in Actual Processes

There is no requirement that a system undergoing a process be in equilibrium *during* the process. Some or all of the intervening states may be nonequilibrium states. For many such processes we are limited to knowing the state before the process occurs and the state after the process is completed. Typically, at a nonequilibrium state intensive properties vary with position at a given time. Also, at a specified position intensive properties may vary with time, sometimes chaotically. In certain cases, spatial and temporal variations in properties such as temperature, pressure, and velocity can be measured, or obtained by solving appropriate governing equations, which are generally differential equations.

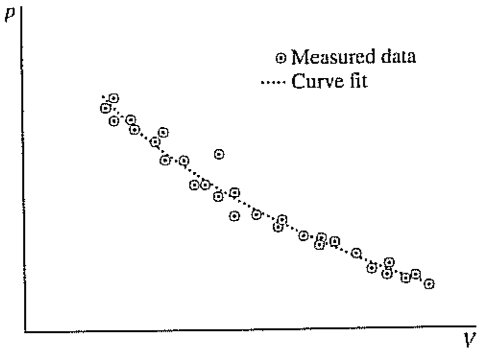


Fig. 2.5 Pressure–volume data.

To perform the integral of Eq. 2.17 requires a relationship between the gas pressure *at the moving boundary* and the system volume. However, due to nonequilibrium effects during an *actual* expansion or compression process, this relationship may be difficult, or even impossible, to obtain. In the cylinder of an automobile engine, for example, combustion and other nonequilibrium effects give rise to nonuniformities throughout the cylinder. Accordingly, if a pressure transducer were mounted on the cylinder head, the recorded output might provide only an approximation for the pressure at the piston face required by Eq. 2.17. Moreover, even when the measured pressure is essentially equal to that at the piston face, scatter might exist in the pressure–volume data, as illustrated in Fig. 2.5. Still, performing the integral of Eq. 2.17 based on a curve fitted to the data could give a *plausible estimate* of the work.

We will see later that in some cases where lack of the required pressure–volume relationship keeps us from evaluating the work from Eq. 2.17, the work can be determined alternatively from an *energy balance* (Sec. 2.5).

2.2.5 Expansion or Compression Work in Quasiequilibrium Processes

quasiequilibrium process

Processes are sometime modeled as an idealized type of process called a ***quasiequilibrium (or quasistatic) process.*** A quasiequilibrium process is one in which the departure from thermodynamic equilibrium is at most infinitesimal. All states through which the system passes in a quasiequilibrium process may be considered equilibrium states. Because nonequilibrium effects are inevitably present during actual processes, systems of engineering interest can at best approach, but never realize, a quasiequilibrium process. Still the quasiequilibrium process plays a role in our study of engineering thermodynamics. For details, see the box.

To consider how a gas (or liquid) might be expanded or compressed in a quasiequilibrium fashion, refer to Fig. 2.6, which shows a system consisting of a gas initially at an equilibrium state. As shown in the figure, the gas pressure is maintained uniform throughout by a number of small masses resting on the freely moving piston. Imagine that one of the masses is removed, allowing the piston to move upward as the gas expands slightly. During such an expansion the state of the gas would depart only slightly from equilibrium. The system would eventually come to a new equilibrium state, where the pressure and all other intensive properties would again be uniform in value. Moreover, were the mass replaced, the gas would be restored to its initial state, while again the departure from equilibrium would be slight. If several

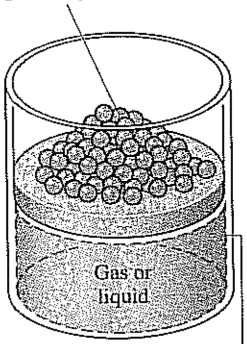


Fig. 2.6 Illustration of a quasiequilibrium expansion or compression.

Using the Quasiequilibrium Process Concept

Our interest in the quasiequilibrium process concept stems mainly from two considerations:

- Simple thermodynamic models giving at least *qualitative* information about the behavior of actual systems of interest often can be developed using the quasiequilibrium process concept. This is akin to the use of idealizations such as the point mass or the frictionless pulley in mechanics for the purpose of simplifying an analysis.
- The quasiequilibrium process concept is instrumental in deducing relationships that exist among the properties of systems at equilibrium (Chaps. 3, 6, and 11).

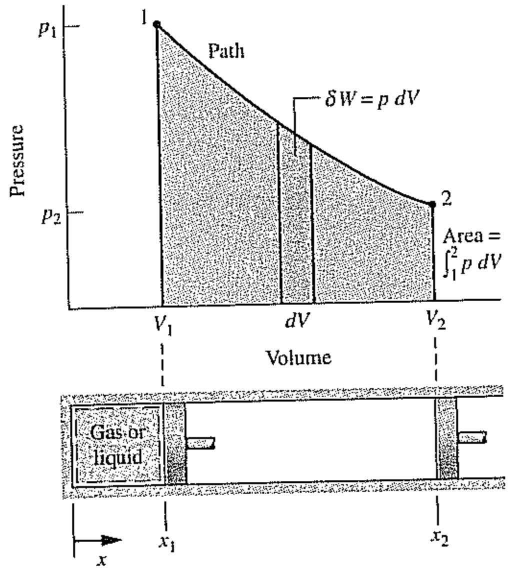


Fig. 2.7 Work of a quasiequilibrium expansion or compression process.

of the masses were removed one after another, the gas would pass through a sequence of equilibrium states without ever being far from equilibrium. In the limit as the increments of mass are made vanishingly small, the gas would undergo a quasiequilibrium expansion process. A quasiequilibrium compression can be visualized with similar considerations.

Equation 2.17 can be applied to evaluate the work in quasiequilibrium expansion or compression processes. For such idealized processes the pressure p in the equation is the pressure of the entire quantity of gas (or liquid) undergoing the process, and not just the pressure at the moving boundary. The relationship between the pressure and volume may be graphical or analytical. Let us first consider a graphical relationship.

A graphical relationship is shown in the pressure–volume diagram (p–V diagram) of Fig. 2.7. Initially, the piston face is at position x_1, and the gas pressure is p_1; at the conclusion of a quasiequilibrium expansion process the piston face is at position x_2, and the pressure is reduced to p_2. At *each* intervening piston position, the uniform pressure throughout the gas is shown as a point on the diagram. The curve, or *path*, connecting states 1 and 2 on the diagram represents the equilibrium states through which the system has passed during the process. The work done by the gas on the piston during the expansion is given by $\int p\,dV$, which can be interpreted as the area under the curve of pressure versus volume. Thus, the shaded area on Fig. 2.7 is equal to the work for the process. Had the gas been *compressed* from 2 to 1 along the same path on the p–V diagram, the *magnitude* of the work would be the same, but the sign would be negative, indicating that for the compression the energy transfer was from the piston to the gas.

The area interpretation of work in a quasiequilibrium expansion or compression process allows a simple demonstration of the idea that work depends on the process. This can be brought out by referring to Fig. 2.8. Suppose the gas in a piston–cylinder assembly goes from an initial equilibrium state 1 to a final equilibrium state 2 along two different paths, labeled A and B on Fig. 2.8. Since the area beneath each path represents the work for that process, the work depends on the details of the process as defined by the particular curve and not just on the end states. Using the test for a property given in Sec. 1.3, we can conclude again (Sec. 2.2.1) that *work is not a property*. The value of work depends on the nature of the process between the end states.

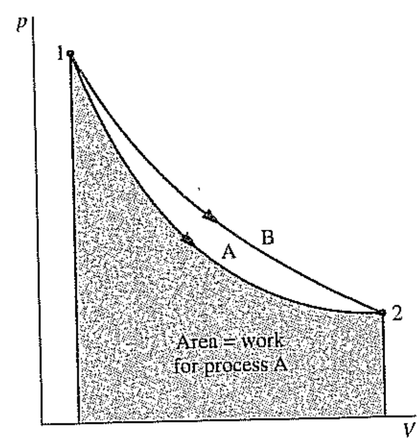


Fig. 2.8 Illustration that work depends on the process.

polytropic process

The relation between pressure and volume, or pressure and specific volume, also can be described analytically. A quasiequilibrium process described by $pV^n = constant$, or $pv^n = constant$, where n is a constant, is called a ***polytropic process.*** Additional analytical forms for the pressure–volume relationship also may be considered.

The example to follow illustrates the application of Eq. 2.17 when the relationship between pressure and volume during an expansion is described analytically as $pV^n = constant$.

Example 2.1 EVALUATING EXPANSION WORK

A gas in a piston–cylinder assembly undergoes an expansion process for which the relationship between pressure and volume is given by

$$pV^n = constant$$

The initial pressure is 3 bar, the initial volume is 0.1 m^3, and the final volume is 0.2 m^3. Determine the work for the process, in kJ, if (a) $n = 1.5$, (b) $n = 1.0$, and (c) $n = 0$.

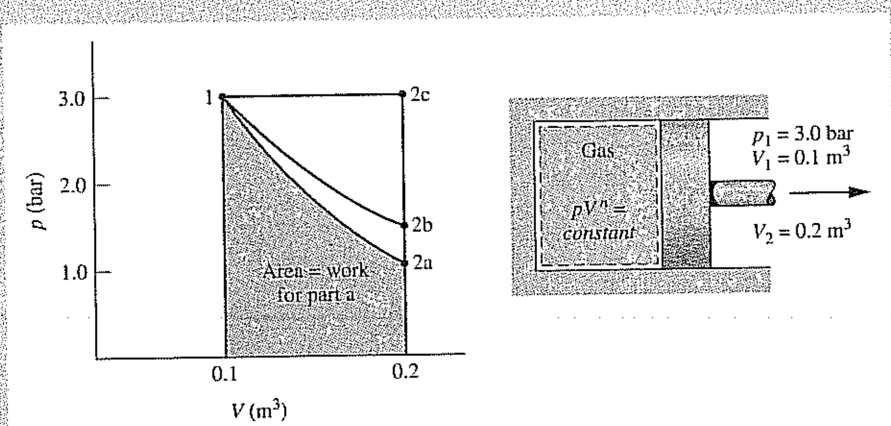
Solution

Known: A gas in a piston–cylinder assembly undergoes an expansion for which $pV^n = constant$.

Find: Evaluate the work if (a) $n = 1.5$, (b) $n = 1.0$, (c) $n = 0$.

Schematic and Given Data: The given p–V relationship and the given data for pressure and volume can be used to construct the accompanying pressure–volume diagram of the process.

❶



Engineering Model:

1. The gas is a closed system.
2. The moving boundary is the only work mode.
3. The expansion is a polytropic process. ❷

Fig. E2.1

Analysis: The required values for the work are obtained by integration of Eq. 2.17 using the given pressure–volume relation.

(a) Introducing the relationship $p = constant/V^n$ into Eq. 2.17 and performing the integration

$$W = \int_{V_1}^{V_2} p\,dV = \int_{V_1}^{V_2} \frac{constant}{V^n}\,dV$$

$$= \frac{(constant)\,V_2^{1-n} - (constant)\,V_1^{1-n}}{1-n}$$

The constant in this expression can be evaluated at either end state: $constant = p_1V_1^n = p_2V_2^n$. The work expression then becomes

$$W = \frac{(p_2V_2^n)V_2^{1-n} - (p_1V_1^n)\,V_1^{1-n}}{1-n} = \frac{p_2V_2 - p_1V_1}{1-n} \qquad (1)$$

This expression is valid for all values of n except $n = 1.0$. The case $n = 1.0$ is taken up in part (b).

To evaluate W, the pressure at state 2 is required. This can be found by using $p_1V_1^n = p_2V_2^n$, which on rearrangement yields

$$p_2 = p_1\left(\frac{V_1}{V_2}\right)^n = (3\text{ bar})\left(\frac{0.1}{0.2}\right)^{1.5} = 1.06\text{ bar}$$

Accordingly,

❸
$$W = \left(\frac{(1.06\text{ bar})(0.2\text{ m}^3) - (3)(0.1)}{1 - 1.5}\right)\left|\frac{10^5\text{ N/m}^2}{1\text{ bar}}\right|\left|\frac{1\text{ kJ}}{10^3\text{ N}\cdot\text{m}}\right|$$
$$= +17.6\text{ kJ}$$

(b) For $n = 1.0$, the pressure–volume relationship is $pV = constant$ or $p = constant/V$. The work is

$$W = constant\int_{V_1}^{V_2}\frac{dV}{V} = (constant)\ln\frac{V_2}{V_1} = (p_1V_1)\ln\frac{V_2}{V_1} \tag{2}$$

Substituting values

$$W = (3\text{ bar})(0.1\text{ m}^3)\left|\frac{10^5\text{ N/m}^2}{1\text{ bar}}\right|\left|\frac{1\text{ kJ}}{10^3\text{ N}\cdot\text{m}}\right|\ln\left(\frac{0.2}{0.1}\right) = +20.79\text{ kJ}$$

❹ **(c)** For $n = 0$, the pressure–volume relation reduces to $p = constant$, and the integral becomes $W = p(V_2 - V_1)$, which is a special case of the expression found in part (a). Substituting values and converting units as above, $W = +30$ kJ.

---

❶ In each case, the work for the process can be interpreted as the area under the curve representing the process on the accompanying p–V diagram. Note that the relative areas are in agreement with the numerical results.

❷ The assumption of a polytropic process is significant. If the given pressure–volume relationship were obtained as a fit to experimental pressure–volume data, the value of $\int p\,dV$ would provide a plausible estimate of the work only when the measured pressure is essentially equal to that exerted at the piston face.

❸ Observe the use of unit conversion factors here and in part (b).

❹ It is not necessary to identify the gas (or liquid) contained within the piston–cylinder assembly. The calculated values for W are determined by the process path and the end states. However, if it is desired to evaluate a property such as temperature, both the nature and amount of the substance must be provided because appropriate relations among the properties of the particular substance would then be required.

Skills Developed — Ability to…
- ✓ apply the problem-solving methodology.
- ✓ define a closed system and identify interactions on its boundary.
- ✓ evaluate work using Eq. 2.17.
- ✓ apply the pressure–volume relation: $pV^n = constant$.

Quick Quiz

Evaluate the work, in kJ, for a two-step process consisting of an expansion with $n = 1.0$ from $p_1 = 3$ bar, $V_1 = 0.1$ m³ to $V = 0.15$ m³, followed by an expansion with $n = 0$ from $V = 0.15$ m³ to $V_2 = 0.2$ m³.

Ans. 22.16 kJ.

2.2.6 Further Examples of Work

To broaden our understanding of the work concept, we now briefly consider several other examples of work.

Extension of a Solid Bar

Consider a system consisting of a solid bar under tension, as shown in Fig. 2.9. The bar is fixed at $x = 0$, and a force F is applied at the other end. Let the force be represented as $F = \sigma \text{A}$, where A is the cross-sectional area of the bar and σ the *normal stress acting at the end* of the bar. The work done as the end of the bar moves a distance dx is given by $\delta W = -\sigma \text{A}\, dx$. The minus sign is required because work is done *on* the bar when dx is positive. The work for a change in length from x_1 to x_2 is found by integration

$$W = -\int_{x_1}^{x_2} \sigma \text{A}\, dx \tag{2.18}$$

Equation 2.18 for a solid is the counterpart of Eq. 2.17 for a gas undergoing an expansion or compression.

Stretching of a Liquid Film

Figure 2.10 shows a system consisting of a liquid film suspended on a wire frame. The two surfaces of the film support the thin liquid layer inside by the effect of *surface tension*, owing to microscopic forces between molecules near the liquid–air interfaces. These forces give rise to a macroscopically measurable force perpendicular to any line in the surface. The force per unit length across such a line is the surface tension. Denoting the surface tension *acting at the movable wire* by τ, the force F indicated on the figure can be expressed as $F = 2l\tau$, where the factor 2 is introduced because two film surfaces act at the wire. If the movable wire is displaced by dx, the work is given by $\delta W = -2l\tau\, dx$. The minus sign is required because work is done *on* the system when dx is positive. Corresponding to a displacement dx is a change in the total area of the surfaces in contact with the wire of $dA = 2l\, dx$, so the expression for work can be written alternatively as $\delta W = -\tau\, d\text{A}$. The work for an increase in surface area from A_1 to A_2 is found by integrating this expression

$$W = -\int_{\text{A}_1}^{\text{A}_2} \tau\, d\text{A} \tag{2.19}$$

Power Transmitted by a Shaft

A rotating shaft is a commonly encountered machine element. Consider a shaft rotating with angular velocity ω and exerting a torque $\mathcal{T}$ on its surroundings. Let the torque

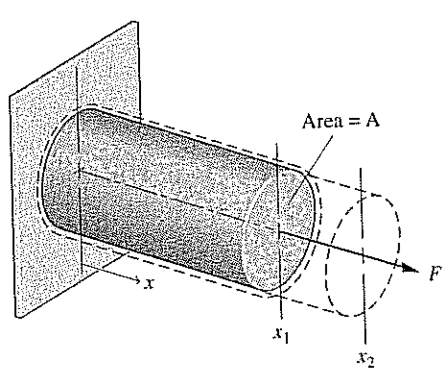


Fig. 2.9 Elongation of a solid bar.

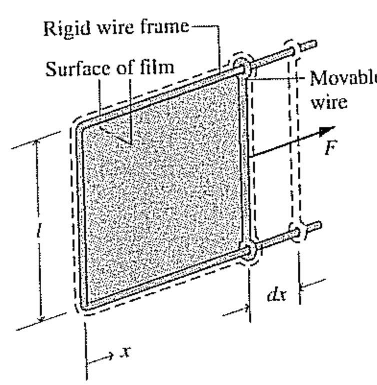
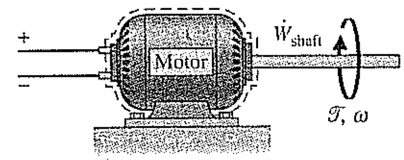


Fig. 2.10 Stretching of a liquid film.



be expressed in terms of a tangential force F_t and radius R: $\mathcal{T} = F_tR$. The velocity at the point of application of the force is $V = R\omega$, where ω is in radians per unit time. Using these relations with Eq. 2.13, we obtain an expression for the *power* transmitted from the shaft to the surroundings

$$\dot{W} = F_t V = (\mathcal{T}/R)(R\omega) = \mathcal{T}\omega \tag{2.20}$$

A related case involving a gas stirred by a paddle wheel is considered in the discussion of Fig. 2.3.

Electric Power

Shown in Fig. 2.11 is a system consisting of an electrolytic cell. The cell is connected to an external circuit through which an electric current, i, is flowing. The current is driven by the electrical potential difference $\mathscr{E}$ existing across the terminals labeled a and b. That this type of interaction can be classed as work is considered in the discussion of Fig. 2.3.

The rate of energy transfer by work, or the power, is

$$\dot{W} = -\mathscr{E}i \tag{2.21}$$

Since the current i equals dZ/dt, the work can be expressed in differential form as

$$\delta W = -\mathscr{E}\, dZ \tag{2.22}$$

where dZ is the amount of electrical charge that flows into the system. The minus signs are required to be in accord with our previously stated sign convention for work. When the power is evaluated in terms of the watt, and the unit of current is the ampere (an SI base unit), the unit of electric potential is the volt, defined as 1 watt per ampere.

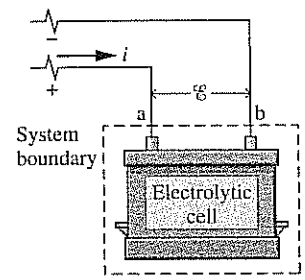


Fig. 2.11 Electrolytic cell used to discuss electric power.

Work Due to Polarization or Magnetization

Let us next refer briefly to the types of work that can be done on systems residing in electric or magnetic fields, known as the work of polarization and magnetization, respectively. From the microscopic viewpoint, electrical dipoles within dielectrics resist turning, so work is done when they are aligned by an electric field. Similarly, magnetic dipoles resist turning, so work is done on certain other materials when their magnetization is changed. Polarization and magnetization give rise to *macroscopically* detectable changes in the total dipole moment as the particles making up the material are given new alignments. In these cases the work is associated with forces imposed on the overall system by fields in the surroundings. Forces acting on the material in the system interior are called *body forces*. For such forces the appropriate displacement in evaluating work is the displacement of the matter on which the body force acts.

2.2.7 Further Examples of Work in Quasiequilibrium Processes

Systems other than a gas or liquid in a piston–cylinder assembly also can be envisioned as undergoing processes in a quasiequilibrium fashion. To apply the quasiequilibrium process concept in any such case, it is necessary to conceive of an *ideal situation* in which the external forces acting on the system can be varied so slightly that the resulting imbalance is infinitesimal. As a consequence, the system undergoes a process without ever departing significantly from thermodynamic equilibrium.

The extension of a solid bar and the stretching of a liquid surface can readily be envisioned to occur in a quasiequilibrium manner by direct analogy to the piston–cylinder case. For the bar in Fig. 2.9 the external force can be applied in such a way that it differs only slightly from the opposing force within. The normal stress is then essentially uniform throughout and can be determined as a function of the instantaneous length: $\sigma = \sigma(x)$. Similarly, for the liquid film shown in Fig. 2.10 the external force can be applied to the movable wire in such a way that the force differs only slightly from the opposing force within the film. During such a process, the surface tension is essentially uniform throughout the film and is functionally related to the instantaneous area: $\tau = \tau(\mathrm{A})$. In each of these cases, once the required functional relationship is known, the work can be evaluated using Eq. 2.18 or 2.19, respectively, in terms of properties of the system as a whole as it passes through equilibrium states.

Other systems also can be imagined as undergoing quasiequilibrium processes. For example, it is possible to envision an electrolytic cell being charged or discharged in a quasiequilibrium manner by adjusting the potential difference across the terminals to be slightly greater, or slightly less, than an ideal potential called the cell *electromotive force* (emf). The energy transfer by work for passage of a differential quantity of charge *to* the cell, dZ, is given by the relation

$$\delta W = -\mathscr{E}\, dZ \tag{2.23}$$

In this equation $\mathscr{E}$ denotes the cell emf, an intensive property of the cell, and not just the potential difference across the terminals as in Eq. 2.22.

Consider next a dielectric material residing in a *uniform electric field*. The energy transferred by work from the field when the polarization is increased slightly is

$$\delta W = -\mathbf{E} \cdot d(V\mathbf{P}) \tag{2.24}$$

where the vector $\mathbf{E}$ is the electric field strength within the system, the vector $\mathbf{P}$ is the electric dipole moment per unit volume, and V is the volume of the system. A similar equation for energy transfer by work from a *uniform magnetic field* when the magnetization is increased slightly is

$$\delta W = -\mu_0 \mathbf{H} \cdot d(V\mathbf{M}) \tag{2.25}$$

where the vector $\mathbf{H}$ is the magnetic field strength within the system, the vector $\mathbf{M}$ is the magnetic dipole moment per unit volume, and μ_0 is a constant, the permeability of free space. The minus signs appearing in the last three equations are in accord with our previously stated sign convention for work: W takes on a negative value when the energy transfer is *into* the system.

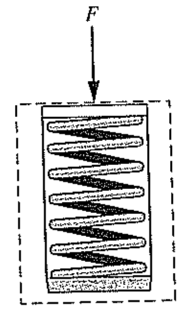
2.2.8 Generalized Forces and Displacements

The similarity between the expressions for work in the quasiequilibrium processes considered thus far should be noted. In each case, the work expression is written in the form of an intensive property and the differential of an extensive property. This is brought out by the following expression, which allows for one or more of these work modes to be involved in a process

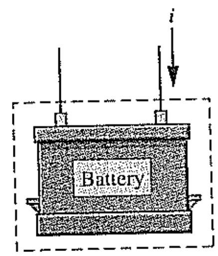
$$\delta W = p\, dV - \sigma d(\mathrm{A}x) - \tau\, d\mathrm{A} - \mathscr{E}\, dZ - \mathbf{E} \cdot d(V\mathbf{P}) - \mu_0 \mathbf{H} \cdot d(V\mathbf{M}) + \cdots \tag{2.26}$$

where the last three dots represent other products of an intensive property and the differential of a related extensive property that account for work. Because of the notion of work being a product of force and displacement, the intensive property in these relations is sometimes referred to as a "generalized" force and the extensive property as a "generalized" displacement, even though the quantities making up the work expressions may not bring to mind actual forces and displacements.

Owing to the underlying quasiequilibrium restriction, Eq. 2.26 does not represent every type of work of practical interest. An example is provided by a paddle wheel that stirs a gas or liquid taken as the system. Whenever any shearing action takes place, the system necessarily passes through nonequilibrium states. To appreciate more fully the implications of the quasiequilibrium process concept requires consideration of the second law of thermodynamics, so this concept is discussed again in Chap. 5 after the second law has been introduced.

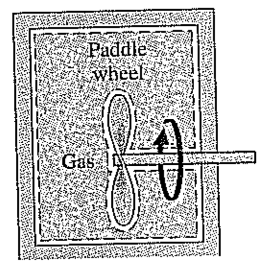


2.3 Broadening Our Understanding of Energy



The objective in this section is to use our deeper understanding of work developed in Sec. 2.2 to broaden our understanding of the energy of a system. In particular, we consider the *total* energy of a system, which includes kinetic energy, gravitational potential energy, and other forms of energy. The examples to follow illustrate some of these forms of energy. Many other examples could be provided that enlarge on the same idea.

When work is done to compress a spring, energy is stored within the spring. When a battery is charged, the energy stored within it is increased. And when a gas (or liquid) initially at an equilibrium state in a closed, insulated vessel is stirred vigorously and allowed to come to a final equilibrium state, the energy of the gas is increased in the process. In each of these examples the change in system energy cannot be attributed to changes in the system's *overall* kinetic or gravitational potential energy as given by Eqs. 2.5 and 2.10, respectively. The change in energy can be accounted for in terms of *internal energy,* as considered next.



In engineering thermodynamics the change in the total energy of a system is considered to be made up of three *macroscopic* contributions. One is the change in kinetic energy, associated with the motion of the system *as a whole* relative to an external coordinate frame. Another is the change in gravitational potential energy, associated with the position of the system *as a whole* in the earth's gravitational field. All other energy changes are lumped together in the ***internal energy*** of the system. Like kinetic energy and gravitational potential energy, *internal energy is an extensive property* of the system, as is the total energy.

internal energy

Internal energy is represented by the symbol U, and the change in internal energy in a process is $U_2 - U_1$. The specific internal energy is symbolized by u or $\bar{u}$, respectively, depending on whether it is expressed on a unit mass or per mole basis.

The change in the total energy of a system is

$$E_2 - E_1 = (U_2 - U_1) + (\mathrm{KE}_2 - \mathrm{KE}_1) + (\mathrm{PE}_2 - \mathrm{PE}_1) \tag{2.27}$$

or

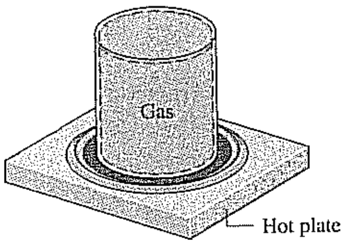
$$\Delta E = \Delta U + \Delta \mathrm{KE} + \Delta \mathrm{PE}$$

All quantities in Eq. 2.27 are expressed in terms of the energy units previously introduced.

The identification of internal energy as a macroscopic form of energy is a significant step in the present development, for it sets the concept of energy in thermodynamics apart from that of mechanics. In Chap. 3 we will learn how to evaluate changes in internal energy for practically important cases involving gases, liquids, and solids by using empirical data.

To further our understanding of internal energy, consider a system we will often encounter in subsequent sections of the book, a system consisting of a gas contained *microscopic interpretation of internal energy for a gas*

in a tank. Let us develop a ***microscopic interpretation of internal energy*** by thinking of the energy attributed to the motions and configurations of the individual molecules, atoms, and subatomic particles making up the matter in the system. Gas molecules move about, encountering other molecules or the walls of the container. Part of the internal energy of the gas is the *translational* kinetic energy of the molecules. Other contributions to the internal energy include the kinetic energy due to *rotation* of the molecules relative to their centers of mass and the kinetic energy associated with *vibrational* motions within the molecules. In addition, energy is stored in the chemical bonds between the atoms that make up the molecules. Energy storage on the atomic level includes energy associated with electron orbital states, nuclear spin, and binding forces in the nucleus. In dense gases, liquids, and solids, intermolecular forces play an important role in affecting the internal energy.



2.4 Energy Transfer by Heat

energy transfer by heat

Thus far, we have considered quantitatively only those interactions between a system and its surroundings that can be classed as work. However, closed systems also can interact with their surroundings in a way that cannot be categorized as work. **FOR EXAMPLE...** when a gas in a rigid container interacts with a hot plate, the energy of the gas is increased even though no work is done. This type of interaction is called an ***energy transfer by heat.***

On the basis of experiment, beginning with the work of Joule in the early part of the nineteenth century, we know that energy transfers by heat are induced only as a result of a temperature difference between the system and its surroundings and occur only in the direction of decreasing temperature. Because the underlying concept is so important in thermodynamics, this section is devoted to a further consideration of energy transfer by heat.

2.4.1 Sign Convention, Notation, and Heat Transfer Rate

The symbol Q denotes an amount of energy transferred across the boundary of a system in a heat interaction with the system's surroundings. Heat transfer *into* a system is taken to be *positive,* and heat transfer *from* a system is taken as *negative.*

sign convention for heat transfer

$Q > 0$: heat transfer *to* the system

$Q < 0$: heat transfer *from* the system

This ***sign convention*** is used throughout the book. However, as was indicated for work, it is sometimes convenient to show the direction of energy transfer by an arrow on a sketch of the system. Then the heat transfer is regarded as positive in the direction of the arrow.

The sign convention for heat transfer is just the *reverse* of the one adopted for work, where a positive value for W signifies an energy transfer *from* the system to the surroundings. These signs for heat and work are a legacy from engineers and scientists who were concerned mainly with steam engines and other devices that develop a work output from an energy input by heat transfer. For such applications, it was convenient to regard both the work developed and the energy input by heat transfer as positive quantities.

heat is not a property

The value of a heat transfer depends on the details of a process and not just the end states. Thus, like work, ***heat is not a property,*** and its differential is written as δQ. The amount of energy transfer by heat for a process is given by the integral

$$Q = \int_1^2 \delta Q \tag{2.28}$$

where the limits mean "from state 1 to state 2" and do not refer to the values of heat at those states. As for work, the notion of "heat" at a state has no meaning, and the integral should *never* be evaluated as $Q_2 - Q_1$.

rate of heat transfer

The net ***rate of heat transfer*** is denoted by $\dot{Q}$. In principle, the amount of energy transfer by heat during a period of time can be found by integrating from time t_1 to time t_2

$$Q = \int_{t_1}^{t_2} \dot{Q}\, dt \tag{2.29}$$

To perform the integration, it is necessary to know how the rate of heat transfer varies with time.

In some cases it is convenient to use the *heat flux*, $\dot{q}$, which is the heat transfer rate per unit of system surface area. The net rate of heat transfer, $\dot{Q}$, is related to the heat flux $\dot{q}$ by the integral

$$\dot{Q} = \int_{A} \dot{q}\, dA \tag{2.30}$$

where A represents the area on the boundary of the system where heat transfer occurs.

The units for heat transfer Q and heat transfer rate $\dot{Q}$ are the same as those introduced previously for W and $\dot{W}$, respectively. The units for the heat flux are those of the heat transfer rate per unit area: kW/m^2 or Btu/h · ft^2.

adiabatic

The word ***adiabatic*** means *without heat transfer*. Thus, if a system undergoes a process involving no heat transfer with its surroundings, that process is called an *adiabatic process*.

Bio... connections

Medical researchers have found that by gradually increasing the temperature of cancerous tissue to 41–45°C the effectiveness of chemotherapy and radiation therapy is enhanced for some patients. Different approaches can be used, including raising the temperature of the entire body with heating devices and, more selectively, by beaming microwaves or ultrasound onto the tumor or affected organ. Speculation about why a temperature increase may be beneficial varies. Some say it helps chemotherapy penetrate certain tumors more readily by dilating blood vessels. Others think it helps radiation therapy by increasing the amount of oxygen in tumor cells, making them more receptive to radiation. Researchers report that further study is needed before the efficacy of this approach is established and the mechanisms whereby it achieves positive results are known.

2.4.2 Heat Transfer Modes

Methods based on experiment are available for evaluating energy transfer by heat. These methods recognize two basic transfer mechanisms: *conduction* and *thermal radiation*. In addition, empirical relationships are available for evaluating energy transfer involving a *combined* mode called *convection*. A brief description of each of these is given next. A detailed consideration is left to a course in engineering heat transfer, where these topics are studied in depth.

Conduction

Energy transfer by *conduction* can take place in solids, liquids, and gases. Conduction can be thought of as the transfer of energy from the more energetic particles of a substance to adjacent particles that are less energetic due to interactions between particles. The time rate of energy transfer by conduction is quantified macroscopically by *Fourier's law*. As an elementary application, consider Fig. 2.12 showing a

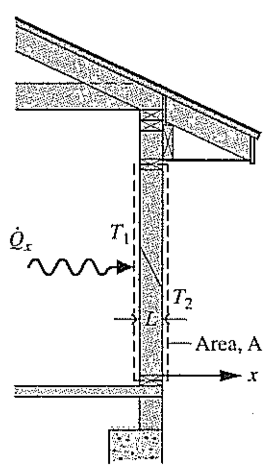


Fig. 2.12 Illustration of Fourier's conduction law.

plane wall of thickness L at steady state, where the temperature $T(x)$ varies linearly with position x. By ***Fourier's law***, the rate of heat transfer across any plane normal to the x direction, $\dot{Q}_x$, is proportional to the wall area, A, and the temperature gradient in the x direction, dT/dx

Fourier's law

$$\dot{Q}_x = -\kappa A \frac{dT}{dx} \tag{2.31}$$

where the proportionality constant κ is a property called the *thermal conductivity*. The minus sign is a consequence of energy transfer in the direction of *decreasing* temperature. **FOR EXAMPLE...** in the case of Fig. 2.12 the temperature varies linearly; thus, the temperature gradient is

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L} (< 0)$$

and the rate of heat transfer in the x direction is then

$$\dot{Q}_x = -\kappa A\left[\frac{T_2 - T_1}{L}\right]$$

Values of thermal conductivity are given in Table A-19 for common materials. Substances with large values of thermal conductivity such as copper are good conductors, and those with small conductivities (cork and polystyrene foam) are good insulators.

Radiation

Thermal radiation is emitted by matter as a result of changes in the electronic configurations of the atoms or molecules within it. The energy is transported by electromagnetic waves (or photons). Unlike conduction, thermal radiation requires no intervening medium to propagate and can even take place in a vacuum. Solid surfaces, gases, and liquids all emit, absorb, and transmit thermal radiation to varying degrees. The rate at which energy is emitted, $\dot{Q}_e$, *from* a surface of area A is quantified macroscopically by a modified form of the ***Stefan–Boltzmann law***

Stefan–Boltzmann law

$$\dot{Q}_e = \varepsilon \sigma A T_b^4 \tag{2.32}$$

which shows that thermal radiation is associated with the fourth power of the absolute temperature of the surface, T_b. The emissivity, ε, is a property of the surface that indicates how effectively the surface radiates ($0 \leq \varepsilon \leq 1.0$), and σ is the Stefan–Boltzmann constant:

$$\sigma = 5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4 = 0.1714 \times 10^{-8}\ \text{Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{R}^4$$

In general, the *net* rate of energy transfer by thermal radiation between two surfaces involves relationships among the properties of the surfaces, their orientations with respect to each other, the extent to which the intervening medium scatters, emits, and absorbs thermal radiation, and other factors. A special case that occurs frequently is radiation exchange between a surface at temperature T_b and a much larger surrounding surface at T_s, as shown in Fig. 2.13. The *net* rate of radiant exchange between the smaller surface, whose area is A and emissivity is ε, and the larger surroundings is

$$\dot{Q}_e = \varepsilon \sigma A[T_b^4 - T_s^4] \tag{2.33}$$

Convection

Energy transfer between a solid surface at a temperature T_b and an adjacent gas or liquid at another temperature T_f plays a prominent role in the performance of

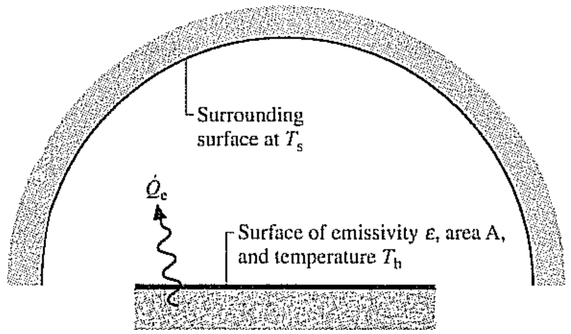


Fig. 2.13 Net radiation exchange.

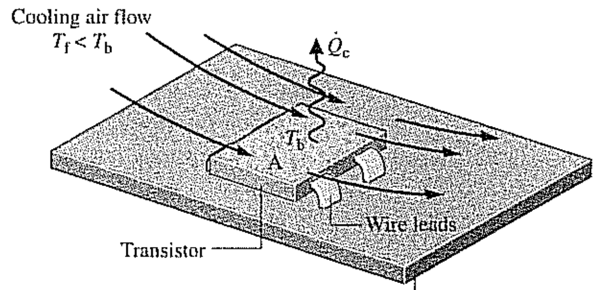


Fig. 2.14 Illustration of Newton's law of cooling.

many devices of practical interest. This is commonly referred to as *convection*. As an illustration, consider Fig. 2.14, where $T_b > T_f$. In this case, energy is transferred *in the direction indicated by the arrow* due to the *combined* effects of conduction within the air and the bulk motion of the air. The rate of energy transfer *from* the surface *to* the air can be quantified by the following *empirical* expression:

$$\dot{Q}_c = hA(T_b - T_f) \tag{2.34}$$

known as ***Newton's law of cooling.*** In Eq. 2.34, A is the surface area and the proportionality factor h is called the *heat transfer coefficient.* In subsequent applications of Eq. 2.34, a minus sign may be introduced on the right side to conform to the sign convention for heat transfer introduced in Sec. 2.4.1.

Newton's law of cooling

The heat transfer coefficient is *not* a thermodynamic property. It is an empirical parameter that incorporates into the heat transfer relationship the nature of the flow pattern near the surface, the fluid properties, and the geometry. When fans or pumps cause the fluid to move, the value of the heat transfer coefficient is generally greater than when relatively slow buoyancy-induced motions occur. These two general categories are called *forced* and *free* (or natural) convection, respectively. Table 2.1 provides typical values of the convection heat transfer coefficient for forced and free convection.

2.4.3 Closing Comments

The first step in a thermodynamic analysis is to define the system. It is only after the system boundary has been specified that possible heat interactions with the surroundings are considered, for these are *always* evaluated at the system boundary. In ordinary conversation, the term *heat* is often used when the word *energy* would be more correct thermodynamically. For example, one might hear, "Please close the door or 'heat' will be lost." In *thermodynamics,* heat refers only to a particular means whereby energy is transferred. It does not refer to what is being transferred between systems or to what is stored within systems. Energy is transferred and stored, not heat.

Table 2.1

Typical Values of the Convection Heat Transfer Coefficient

Applications	h (W/m^2 · K)	h (Btu/h · ft^2 · °R)
Free convection		
Gases	2–25	0.35–4.4
Liquids	50–1000	8.8–180
Forced convection		
Gases	25–250	4.4–44
Liquids	50–20,000	8.8–3500

Sometimes the heat transfer of energy to, or from, a system can be neglected. This might occur for several reasons related to the mechanisms for heat transfer discussed above. One might be that the materials surrounding the system are good insulators, or heat transfer might not be significant because there is a small temperature difference between the system and its surroundings. A third reason is that there might not be enough surface area to allow significant heat transfer to occur. When heat transfer is neglected, it is because one or more of these considerations apply.

In the discussions to follow, the value of Q is provided or it is an unknown in the analysis. When Q is provided, it can be assumed that the value has been determined by the methods introduced above. When Q is the unknown, its value is usually found by using the *energy balance,* discussed next.

2.5 Energy Accounting: Energy Balance for Closed Systems

As our previous discussions indicate, the *only ways* the energy of a closed system can be changed are through transfer of energy by work or by heat. Further, based on the experiments of Joule and others, a fundamental aspect of the energy concept is that *energy is conserved;* we call this the ***first law of thermodynamics.*** For further discussion of the first law, see the box.

first law of thermodynamics

These considerations are summarized in words as follows:

[*change* in the amount of energy contained within a system during some time interval] = [*net* amount of energy transferred *in* across the system boundary by *heat* transfer during the time interval] − [*net* amount of energy transferred *out* across the system boundary by *work* during the time interval]

This word statement is just an accounting balance for energy, an energy balance. It requires that in any process of a closed system the energy of the system increases or decreases by an amount equal to the net amount of energy transferred across its boundary.

The phrase *net amount* used in the word statement of the energy balance must be carefully interpreted, for there may be heat or work transfers of energy at many different places on the boundary of a system. At some locations the energy transfers may be into the system, whereas at others they are out of the system. The two terms on the right side account for the *net* results of all the energy transfers by heat and work, respectively, taking place during the time interval under consideration.

The ***energy balance*** can be expressed in symbols as

$$E_2 - E_1 = Q - W \tag{2.35a}$$

energy balance

Introducing Eq. 2.27 an alternative form is

$$\Delta \text{KE} + \Delta \text{PE} + \Delta U = Q - W \tag{2.35b}$$

which shows that an energy transfer across the system boundary results in a change in one or more of the macroscopic energy forms: kinetic energy, gravitational potential energy, and internal energy. All previous references to energy as a conserved quantity are included as special cases of Eqs. 2.35.

Note that the algebraic signs before the heat and work terms of Eqs. 2.35 are different. This follows from the sign conventions previously adopted. A minus sign

Joule's Experiments and the First Law

In classic experiments conducted in the early part of the nineteenth century, Joule studied processes by which a closed system can be taken from one equilibrium state to another. In particular, he considered processes that involve work interactions but no thermal interactions between the system and its surroundings. Any such process is an *adiabatic process,* in keeping with the discussion of Sec. 2.4.1.

Based on his experiments Joule deduced that the value of the net work is the same for *all* adiabatic processes between two equilibrium states. In other words, the value of the net work done by or on a closed system undergoing an adiabatic process between two given states *depends solely on the end states* and not on the details of the adiabatic process.

If the net work is the same for all adiabatic processes of a closed system between a given pair of end states, it follows from the definition of property (Sec. 1.3) that the net work for such a process is the change in some property of the system. This property is called *energy.*

Following Joule's reasoning, the *change in energy* between the two states is *defined* by

$$E_2 - E_1 = -W_{ad} \tag{a}$$

where the symbol E denotes the energy of a system and W_{ad} represents the net work for *any* adiabatic process between the two states. The minus sign before the work term is in accord with the previously stated sign convention for work. Finally, note that since any arbitrary value E_1 can be assigned to the energy of a system at a given state 1, no particular significance can be attached to the value of the energy at state 1 or at *any* other state. Only *changes* in the energy of a system have significance.

The foregoing discussion is based on experimental evidence beginning with the experiments of Joule. Because of inevitable experimental uncertainties, it is not possible to prove by measurements that the net work is *exactly* the same for *all* adiabatic processes between the same end states. However, the preponderance of experimental findings supports this conclusion, so it is adopted as a fundamental principle that the work actually is the same. This principle is an alternative formulation of the *first law,* and has been used by subsequent scientists and engineers as a springboard for developing the *conservation of energy* concept and the *energy balance* as we know them today.

appears before W because energy transfer by work *from* the system *to* the surroundings is taken to be positive. A plus sign appears before Q because it is regarded to be positive when the heat transfer of energy is *into* the system *from* the surroundings.

2.5.1 Important Aspects of the Energy Balance

Various special forms of the energy balance can be written. For example, the energy balance in differential form is

$$dE = \delta Q - \delta W \tag{2.36}$$

where dE is the differential of energy, a property. Since Q and W are not properties, their differentials are written as δQ and δW, respectively.

The instantaneous ***time rate form of the energy balance*** is

time rate form of the energy balance

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \tag{2.37}$$

The rate form of the energy balance expressed in words is

$$\begin{bmatrix}\text{time } \textit{rate of change} \\ \text{of the energy} \\ \text{contained within} \\ \text{the system } \textit{at} \\ \textit{time t}\end{bmatrix} = \begin{bmatrix}\text{net } \textit{rate} \text{ at which} \\ \text{energy is being} \\ \text{transferred in} \\ \text{by heat transfer} \\ \textit{at time t}\end{bmatrix} - \begin{bmatrix}\text{net } \textit{rate} \text{ at which} \\ \text{energy is being} \\ \text{transferred out} \\ \text{by work } \textit{at} \\ \textit{time t}\end{bmatrix}$$

Since the time rate of change of energy is given by

$$\frac{dE}{dt} = \frac{d\text{KE}}{dt} + \frac{d\text{PE}}{dt} + \frac{dU}{dt}$$

Equation 2.37 can be expressed alternatively as

$$\frac{d\text{KE}}{dt} + \frac{d\text{PE}}{dt} + \frac{dU}{dt} = \dot{Q} - \dot{W} \tag{2.38}$$

Equations 2.35 through 2.38 provide alternative forms of the energy balance that may be convenient starting points when applying the principle of conservation of energy to closed systems. In Chap. 4 the conservation of energy principle is expressed in forms suitable for the analysis of control volumes. When applying the energy balance in *any* of its forms, it is important to be careful about signs and units and to distinguish carefully between rates and amounts. In addition, it is important to recognize that the location of the system boundary can be relevant in determining whether a particular energy transfer is regarded as heat or work.

FOR EXAMPLE... consider Fig. 2.15, in which three alternative systems are shown that include a quantity of a gas (or liquid) in a rigid, well-insulated container. In Fig. 2.15*a*, the gas itself is the system. As current flows through the copper plate, there is an energy transfer from the copper plate to the gas. Since this energy transfer occurs as a result of the temperature difference between the plate and the gas, it is classified as a heat transfer. Next, refer to Fig. 2.15*b*, where the boundary is drawn to include the copper plate. It follows from the thermodynamic definition of work that the energy transfer that occurs as current crosses the boundary of this system must be regarded as work. Finally, in Fig. 2.15*c*, the boundary is located so that no energy is transferred across it by heat or work.

Thus far, we have been careful to emphasize that the quantities symbolized by W and Q in the foregoing equations account for transfers of *energy* and not transfers of work and heat, respectively. The terms work and heat denote different *means* whereby energy is transferred and not *what* is transferred. However, to achieve economy of expression in subsequent discussions, W and Q are often referred to simply as work and heat transfer, respectively. This less formal manner of speaking is commonly used in engineering practice.

The examples provided in Secs. 2.5.2.–2.5.4 bring out important ideas about energy and the energy balance. They should be studied carefully, and similar approaches should be used when solving the end-of-chapter problems. In this text, most applications of the energy balance will not involve significant kinetic or potential energy changes. Thus, to expedite the solutions of many subsequent examples and end-of-chapter problems, we indicate in the problem statement that such changes can be neglected. If this is not made explicit in a problem statement, you should decide on the basis of the problem at hand how best to handle the kinetic and potential energy terms of the energy balance.

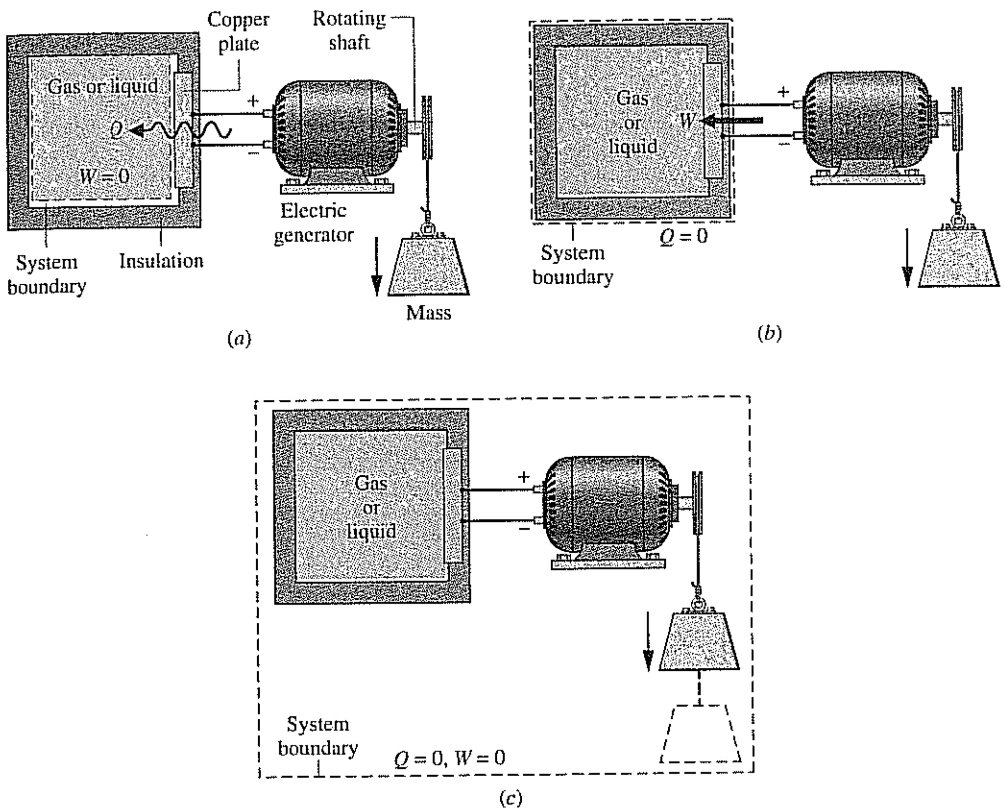


Fig. 2.15 Alternative choices for system boundaries.

Bio... connections

The energy required by animals to sustain life is derived from oxidation of ingested food. We often speak of food being *burned* in the body. This is an appropriate expression because experiments show that when food is burned with oxygen in a chamber, approximately the same energy is released as when the food is oxidized in the body. Such a chamber is the well-insulated, constant-volume *calorimeter* shown in Fig. 2.16.

A carefully weighed food sample is placed in the chamber of the calorimeter together with oxygen (O_2). The entire chamber is submerged in the calorimeter's water bath. The chamber contents are then electrically ignited, fully oxidizing the food sample. The energy released during the

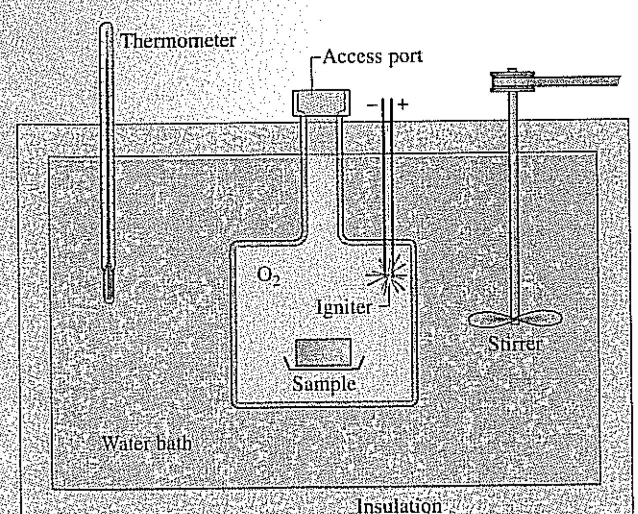


Fig. 2.16 Constant-volume calorimeter.

reaction within the chamber results in an increase in calorimeter temperature. Using the measured temperature rise, the energy released can be calculated from an energy balance for the calorimeter as the system. This is reported as the calorie value of the food sample, usually in terms of kilocalorie (kcal), which is the "Calorie" seen on food labels.

2.5.2 Using the Energy Balance: Processes of Closed Systems

The next two examples illustrate the use of the energy balance for processes of closed systems. In these examples, internal energy data are provided. In Chap. 3, we learn how to obtain internal energy and other thermodynamic property data using tables, graphs, equations, and computer software.

Example 2.2 COOLING A GAS IN A PISTON–CYLINDER

Four-tenths kilogram of a certain gas is contained within a piston–cylinder assembly. The gas undergoes a process for which the pressure–volume relationship is

$$pV^{1.5} = constant$$

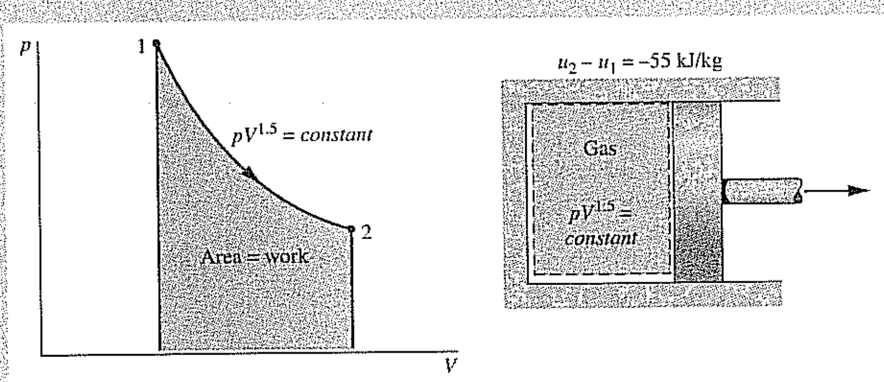
The initial pressure is 3 bar, the initial volume is 0.1 m^3, and the final volume is 0.2 m^3. The change in specific internal energy of the gas in the process is $u_2 - u_1 = -55$ kJ/kg. There are no significant changes in kinetic or potential energy. Determine the net heat transfer for the process, in kJ.

Solution

Known: A gas within a piston–cylinder assembly undergoes an expansion process for which the pressure–volume relation and the change in specific internal energy are specified.

Find: Determine the net heat transfer for the process.

Schematic and Given Data:

1 

Engineering Model:

1. The gas is a closed system.
2. The process is described by $pV^{1.5} = constant$.
3. There is no change in the kinetic or potential energy of the system.

Fig. E2.2

Analysis: An energy balance for the closed system takes the form

$$\cancel{\Delta KE}^{0} + \cancel{\Delta PE}^{0} + \Delta U = Q - W$$

where the kinetic and potential energy terms drop out by assumption 3. Then, writing ΔU in terms of specific internal energies, the energy balance becomes

$$m(u_2 - u_1) = Q - W$$

where m is the system mass. Solving for Q

$$Q = m(u_2 - u_1) + W$$

The value of the work for this process is determined in the solution to part (a) of Example 2.1: $W = +17.6$ kJ. The change in internal energy is obtained using given data as

$$m(u_2 - u_1) = 0.4 \text{ kg}\left(-55\frac{\text{kJ}}{\text{kg}}\right) = -22 \text{ kJ}$$

Substituting values

❷ $$Q = -22 + 17.6 = -4.4 \text{ kJ}$$

❶ The given relationship between pressure and volume allows the process to be represented by the path shown on the accompanying diagram. The area under the curve represents the work. Since they are not properties, the values of the work and heat transfer depend on the details of the process and cannot be determined from the end states only.

❷ The minus sign for the value of Q means that a net amount of energy has been transferred from the system to its surroundings by heat transfer.

Skills Developed — Ability to:
✓ define a closed system and identify interactions on its boundary.
✓ apply the closed system energy balance.

Quick Quiz

If the gas undergoes a process for which $pV = constant$ and $\Delta u = 0$, determine the heat transfer, in kJ, keeping the initial pressure and given volumes fixed.

Ans. 20.79 kJ.

In the next example, we follow up the discussion of Fig. 2.15 by considering two alternative systems. This example highlights the need to account correctly for the heat and work interactions occurring on the boundary as well as the energy change.

Example 2.3 CONSIDERING ALTERNATIVE SYSTEMS

Air is contained in a vertical piston–cylinder assembly fitted with an electrical resistor. The atmosphere exerts a pressure of 14.7 lbf/in.^{2} on the top of the piston, which has a mass of 100 lb and a face area of 1 ft^2. Electric current passes through the resistor, and the volume of the air slowly increases by 1.6 ft^3 while its pressure remains constant. The mass of the air is 0.6 lb, and its specific internal energy increases by 18 Btu/lb. The air and piston are at rest initially and finally. The piston–cylinder material is a ceramic composite and thus a good insulator. Friction between the piston and cylinder wall can be ignored, and the local acceleration of gravity is $g = 32.0$ ft/s^2. Determine the heat transfer from the resistor to the air, in Btu, for a system consisting of **(a)** the air alone, **(b)** the air and the piston.

Solution

Known: Data are provided for air contained in a vertical piston–cylinder fitted with an electrical resistor.

Find: Considering each of two alternative systems, determine the heat transfer from the resistor to the air.

Schematic and Given Data:

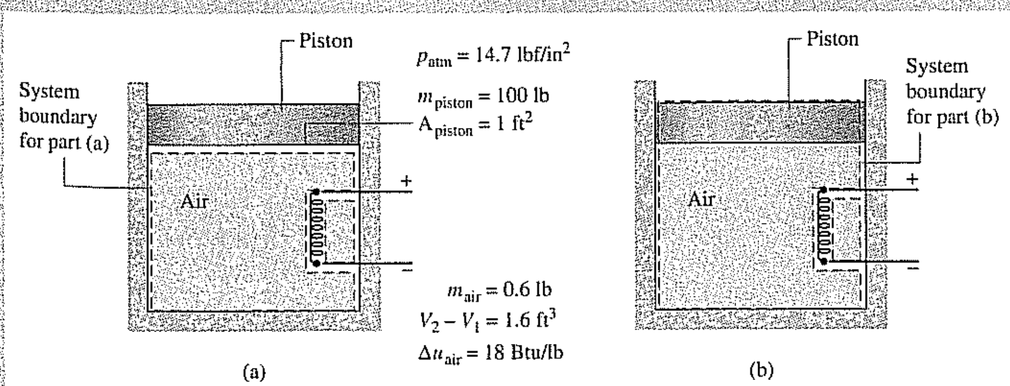


Fig. E2.3

Engineering Model:

1. Two closed systems are under consideration, as shown in the schematic.
2. The only significant heat transfer is from the resistor to the air, during which the air expands slowly and its pressure remains constant.
3. There is no net change in kinetic energy; the change in potential energy of the air is negligible; and since the piston material is a good insulator, the internal energy of the piston is not affected by the heat transfer.
4. Friction between the piston and cylinder wall is negligible.
5. The acceleration of gravity is constant; $g = 32.0\ \text{ft/s}^2$.

Analysis: **(a)** Taking the air as the system, the energy balance, Eq. 2.35, reduces with assumption 3 to

$$(\cancel{\Delta \text{KE}}^0 + \cancel{\Delta \text{PE}}^0 + \Delta U)_{\text{air}} = Q - W$$

Or, solving for Q

$$Q = W + \Delta U_{\text{air}}$$

For this system, work is done by the force of the pressure p acting on the *bottom* of the piston as the air expands. With Eq. 2.17 and the assumption of constant pressure

$$W = \int_{V_1}^{V_2} p\, dV = p(V_2 - V_1)$$

To determine the pressure p, we use a force balance on the slowly moving, frictionless piston. The upward force exerted by the air on the *bottom* of the piston equals the weight of the piston plus the downward force of the atmosphere acting on the *top* of the piston. In symbols

$$p\,\text{A}_{\text{piston}} = m_{\text{piston}}\, g + p_{\text{atm}}\text{A}_{\text{piston}}$$

Solving for p and inserting values

$$p = \frac{m_{\text{piston}}\, g}{\text{A}_{\text{piston}}} + p_{\text{atm}}$$

$$= \frac{(100\ \text{lb})(32.0\ \text{ft/s}^2)}{1\ \text{ft}^2}\left|\frac{1\ \text{lbf}}{32.2\ \text{lb}\cdot\text{ft/s}^2}\right|\left|\frac{1\ \text{ft}^2}{144\ \text{in.}^2}\right| + 14.7\frac{\text{lbf}}{\text{in.}^2} = 15.4\frac{\text{lbf}}{\text{in.}^2}$$

Thus, the work is

$$W = p(V_2 - V_1)$$

$$= \left(15.4\frac{\text{lbf}}{\text{in.}^2}\right)(1.6\ \text{ft}^3)\left|\frac{144\ \text{in.}^2}{1\ \text{ft}^2}\right|\left|\frac{1\ \text{Btu}}{778\ \text{ft}\cdot\text{lbf}}\right| = 4.56\ \text{Btu}$$

With $\Delta U_{\text{air}} = m_{\text{air}}(\Delta u_{\text{air}})$, the heat transfer is

$$Q = W + m_{\text{air}}(\Delta u_{\text{air}})$$

$$= 4.56\ \text{Btu} + (0.6\ \text{lb})\left(18\frac{\text{Btu}}{\text{lb}}\right) = 15.4\ \text{Btu}$$

(b) Consider next a system consisting of the air and the piston. The energy change of the overall system is the sum of the energy changes of the air and the piston. Thus, the energy balance, Eq. 2.35, reads

$$(\cancel{\Delta \text{KE}}^0 + \cancel{\Delta \text{PE}}^0 + \Delta U)_{\text{air}} + (\cancel{\Delta \text{KE}}^0 + \Delta \text{PE} + \cancel{\Delta U}^0)_{\text{piston}} = Q - W$$

where the indicated terms drop out by assumption 3. Solving for Q

$$Q = W + (\Delta \text{PE})_{\text{piston}} + (\Delta U)_{\text{air}}$$

For this system, work is done at the *top* of the piston as it pushes aside the surrounding atmosphere. Applying Eq. 2.17

$$W = \int_{V_1}^{V_2} p\, dV = p_{\text{atm}}(V_2 - V_1)$$
$$= \left(14.7 \frac{\text{lbf}}{\text{in.}^2}\right)(1.6\ \text{ft}^3)\left|\frac{144\ \text{in.}^2}{1\ \text{ft}^2}\right|\left|\frac{1\ \text{Btu}}{778\ \text{ft} \cdot \text{lbf}}\right| = 4.35\ \text{Btu}$$

The elevation change, Δz, required to evaluate the potential energy change of the piston can be found from the volume change of the air and the area of the piston face as

$$\Delta z = \frac{V_2 - V_1}{A_{\text{piston}}} = \frac{1.6\ \text{ft}^3}{1\ \text{ft}^2} = 1.6\ \text{ft}$$

Thus, the potential energy change of the piston is

$$(\Delta \text{PE})_{\text{piston}} = m_{\text{piston}} g \Delta z$$
$$= (100\ \text{lb})\left(32.0 \frac{\text{ft}}{\text{s}^2}\right)(1.6\ \text{ft})\left|\frac{1\ \text{lbf}}{32.2\ \text{lb} \cdot \text{ft/s}^2}\right|\left|\frac{1\ \text{Btu}}{778\ \text{ft} \cdot \text{lbf}}\right| = 0.2\ \text{Btu}$$

Finally,

$$Q = W + (\Delta \text{PE})_{\text{piston}} + m_{\text{air}} \Delta u_{\text{air}}$$
$$= 4.35\ \text{Btu} + 0.2\ \text{Btu} + (0.6\ \text{lb})\left(18 \frac{\text{Btu}}{\text{lb}}\right) = 15.4\ \text{Btu}$$

❶ which agrees with the result of part (a).

❶ Although the value of Q is the same for each system, observe that the values for W differ. Also, observe that the energy changes differ, depending on whether the air alone or the air and the piston is the system.

Skills Developed Ability to...
- ✓ define alternative closed systems and identify interactions on their boundaries.
- ✓ evaluate work using Eq. 2.17.
- ✓ apply the closed-system energy balance.

Quick Quiz

What is the change in potential energy of the air, in Btu?
Ans. $\approx 10^{-3}$ Btu.

2.5.3 Using the Energy Rate Balance: Steady-State Operation

A system is at steady state if none of its properties change with time (Sec. 1.3). Many devices operate at steady state or nearly at steady state, meaning that property variations with time are small enough to ignore. The two examples to follow illustrate the application of the energy rate equation to closed systems at steady state.

Example 2.4 GEARBOX AT STEADY STATE

During steady-state operation, a gearbox receives 60 kW through the input shaft and delivers power through the output shaft. For the gearbox as the system, the rate of energy transfer by convection is

$$\dot{Q} = -\text{h}A(T_b - T_f)$$

where $\text{h} = 0.171\ \text{kW/m}^2 \cdot \text{K}$ is the heat transfer coefficient, $A = 1.0\ \text{m}^2$ is the outer surface area of the gearbox, $T_b = 300\ \text{K}$ (27°C) is the temperature at the outer surface, and $T_f = 293\ \text{K}$ (20°C) is the temperature of the surrounding air away from the immediate vicinity of the gearbox. For the gearbox, evaluate the heat transfer rate and the power delivered through the output shaft, each in kW.

Solution

Known: A gearbox operates at steady state with a known power input. An expression for the heat transfer rate from the outer surface is also known.

Find: Determine the heat transfer rate and the power delivered through the output shaft, each in kW.

Schematic and Given Data:

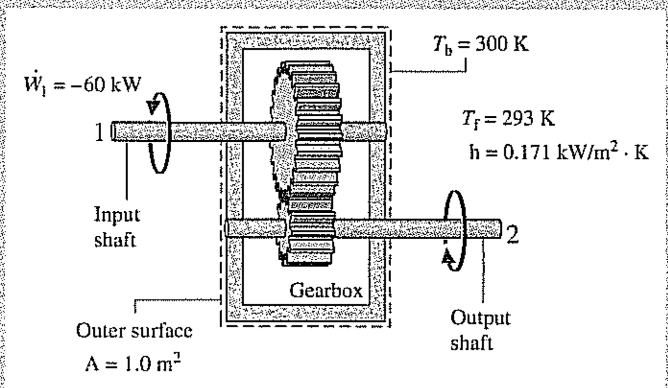


Fig. E2.4

Engineering Model:

1. The gearbox is a closed system at steady state.
2. For the gearbox, convection is the dominant heat transfer mode.

Analysis: Using the given expression for $\dot{Q}$ together with known data, the rate of energy transfer by heat is

❶
$$\begin{aligned}\dot{Q} &= -\mathrm{h}A(T_b - T_f) \\ &= -\left(0.171\frac{\mathrm{kW}}{\mathrm{m}^2 \cdot \mathrm{K}}\right)(1.0\ \mathrm{m}^2)(300 - 293)\ \mathrm{K} \\ &= -1.2\ \mathrm{kW}\end{aligned}$$

The minus sign for $\dot{Q}$ signals that energy is carried *out* of the gearbox by heat transfer.

The energy rate balance, Eq. 2.37, reduces at steady state to

❷
$$\cancelto{0}{\frac{dE}{dt}} = \dot{Q} - \dot{W} \quad \text{or} \quad \dot{W} = \dot{Q}$$

The symbol $\dot{W}$ represents the *net* power from the system. The net power is the sum of $\dot{W}_1$ and the output power $\dot{W}_2$

$$\dot{W} = \dot{W}_1 + \dot{W}_2$$

With this expression for $\dot{W}$, the energy rate balance becomes

$$\dot{W}_1 + \dot{W}_2 = \dot{Q}$$

Solving for $\dot{W}_2$, inserting $\dot{Q} = -1.2$ kW, and $\dot{W}_1 = -60$ kW, where the minus sign is required because the input shaft brings energy *into* the system, we have

❸
$$\begin{aligned}\dot{W}_2 &= \dot{Q} - \dot{W}_1 \\ &= (-1.2\ \mathrm{kW}) - (-60\ \mathrm{kW}) \\ &= +58.8\ \mathrm{kW}\end{aligned}$$

❹ The positive sign for $\dot{W}_2$ indicates that energy is transferred from the system through the output shaft, as expected.

---

❶ In accord with the sign convention for the heat transfer rate in the energy rate balance (Eq. 2.37), Eq. 2.34 is written with a minus sign: $\dot{Q}$ is negative since T_b is greater than T_f.

❷ Properties of a system at steady state do not change with time. Energy E is a property, but heat transfer and work are not properties.

❸ For this system, energy transfer by work occurs at two different locations, and the signs associated with their values differ.

❹ At steady state, the rate of heat transfer from the gear box accounts for the difference between the input and output power. This can be summarized by the following energy rate "balance sheet" in terms of *magnitudes:*

	Input	Output
	60 kW (input shaft)	58.8 kW (output shaft)
		1.2 kW (heat transfer)
Total:	60 kW	60 kW

Skills Developed: Ability to...
- ✓ define a closed system and identify interactions on its boundary.
- ✓ evaluate the rate of energy transfer by convection.
- ✓ apply the energy rate balance for steady-state operation.
- ✓ develop an energy rate balance sheet.

Quick Quiz

For an emissivity of 0.8 and taking $T_s = T_f$, use Eq. 2.33 to determine the net rate at which energy is radiated from the outer surface of the gearbox, in kW.

Ans. 0.03 kW.

Example 2.5 SILICON CHIP AT STEADY STATE

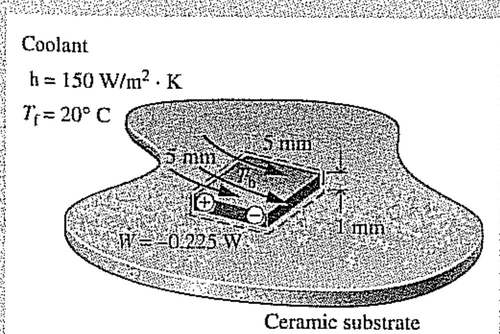
A silicon chip measuring 5 mm on a side and 1 mm in thickness is embedded in a ceramic substrate. At steady state, the chip has an electrical power input of 0.225 W. The top surface of the chip is exposed to a coolant whose temperature is 20°C. The heat transfer coefficient for convection between the chip and the coolant is 150 W/m² · K. If heat transfer by conduction between the chip and the substrate is negligible, determine the surface temperature of the chip, in °C.

Solution

Known: A silicon chip of known dimensions is exposed on its top surface to a coolant. The electrical power input and convective heat transfer coefficient are known.

Find: Determine the surface temperature of the chip at steady state.

Schematic and Given Data:



Engineering Model:

1. The chip is a closed system at steady state.
2. There is no heat transfer between the chip and the substrate.

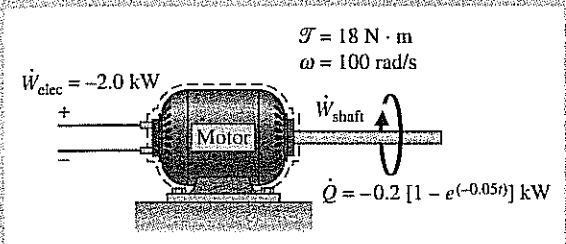
Fig. E2.5

Analysis: The surface temperature of the chip, T_b, can be determined using the energy rate balance, Eq. 2.37, which at steady state reduces as follows

❶
$$\frac{dE}{dt}^{0} = \dot{Q} - \dot{W}$$

Find: Plot $\dot{Q}$, $\dot{W}$, and ΔE versus time. Discuss.

Schematic and Given Data:



Engineering Model: The system shown in the accompanying sketch is a closed system.

Fig. E2.6a

Analysis: The time rate of change of system energy is

$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

$\dot{W}$ represents the *net* power *from* the system: the sum of the power associated with the rotating shaft, $\dot{W}_{shaft}$, and the power associated with the electricity flow, $\dot{W}_{elec}$

$$\dot{W} = \dot{W}_{shaft} + \dot{W}_{elec}$$

The rate $\dot{W}_{elec}$ is known from the problem statement: $\dot{W}_{elec} = -2.0$ kW, where the negative sign is required because energy is carried into the system by electrical work. The term $\dot{W}_{shaft}$ can be evaluated with Eq. 2.20 as

$$\dot{W}_{shaft} = \mathcal{T}\omega = (18\text{ N}\cdot\text{m})(100\text{ rad/s}) = 1800\text{ W} = +1.8\text{ kW}$$

Because energy exits the system along the rotating shaft, this energy transfer rate is positive.

In summary,

$$\dot{W} = \dot{W}_{elec} + \dot{W}_{shaft} = (-2.0\text{ kW}) + (+1.8\text{ kW}) = -0.2\text{ kW}$$

where the minus sign means that the electrical power input is greater than the power transferred out along the shaft.

With the foregoing result for $\dot{W}$ and the given expression for $\dot{Q}$, the energy rate balance becomes

$$\frac{dE}{dt} = -0.2[1 - e^{(-0.05t)}] - (-0.2) = 0.2e^{(-0.05t)}$$

Integrating

$$\Delta E = \int_0^t 0.2e^{(-0.05t)}\,dt$$

$$= \frac{0.2}{(-0.05)}e^{(-0.05t)}\bigg]_0^t = 4[1 - e^{(-0.05t)}]$$

❶ The accompanying plots, Figs. E2.6*b, c*, are developed using the given expression for $\dot{Q}$ and the expressions for $\dot{W}$ and ΔE obtained in the analysis. Because of our sign conventions for heat and work, the values of $\dot{Q}$ and $\dot{W}$ are

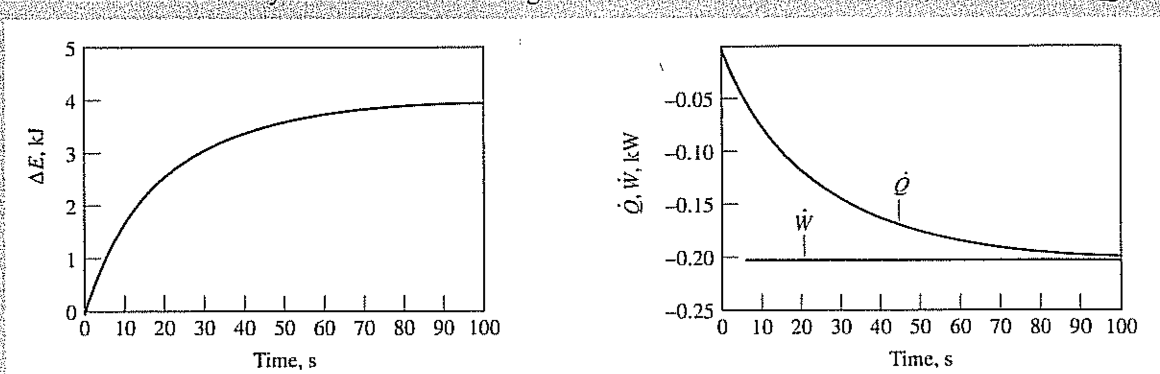


Fig. E2.6b, c

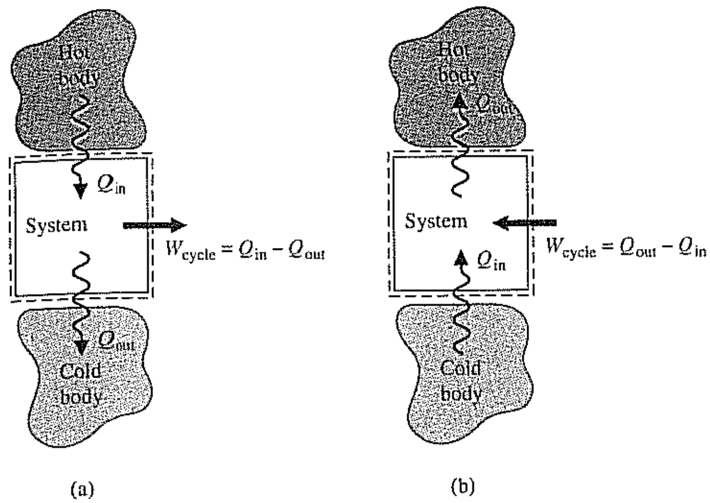


Fig. 2.17 Schematic diagrams of two important classes of cycles. (*a*) Power cycles. (*b*) Refrigeration and heat pump cycles.

Equation 2.40 is an expression of the conservation of energy principle that must be satisfied by *every* thermodynamic cycle, regardless of the sequence of processes followed by the system undergoing the cycle or the nature of the substances making up the system.

Figure 2.17 provides simplified schematics of two general classes of cycles considered in this book: power cycles and refrigeration and heat pump cycles. In each case pictured, a system undergoes a cycle while communicating thermally with two bodies, one hot and the other cold. These bodies are systems located in the surroundings of the system undergoing the cycle. During each cycle there is also a net amount of energy exchanged with the surroundings by work. Carefully observe that in using the symbols Q_{in} and Q_{out} on Fig. 2.17 we have departed from the previously stated sign convention for heat transfer. In this section it is advantageous to regard Q_{in} and Q_{out} as transfers of energy in the *directions indicated by the arrows.* The direction of the net work of the cycle, W_{cycle}, is *also indicated by an arrow.* Finally, note that the directions of the energy transfers shown in Fig. 2.17*b* are opposite to those of Fig. 2.17*a*.

Take Note...

When analyzing cycles, we normally take energy transfers as positive in the directions of arrows on a sketch of the system and write the energy balance accordingly.

2.6.2 Power Cycles

Systems undergoing cycles of the type shown in Fig. 2.17*a* deliver a net work transfer of energy to their surroundings during each cycle. Any such cycle is called a ***power cycle.*** From Eq. 2.40, the net work output equals the net heat transfer to the cycle, or

power cycle

$$W_{cycle} = Q_{in} - Q_{out} \qquad \text{(power cycle)} \qquad (2.41)$$

where Q_{in} represents the heat transfer of energy *into* the system from the hot body, and Q_{out} represents heat transfer *out* of the system to the cold body. From Eq. 2.41 it is clear that Q_{in} must be greater than Q_{out} for a *power* cycle. The energy supplied by heat transfer to a system undergoing a power cycle is normally derived from the combustion of fuel or a moderated nuclear reaction; it can also be obtained from solar radiation. The energy Q_{out} is generally discharged to the surrounding atmosphere or a nearby body of water.

The performance of a system undergoing a *power cycle* can be described in terms of the extent to which the energy added by heat, Q_{in}, is *converted* to a net work output, W_{cycle}. The extent of the energy conversion from heat to work is expressed by the following ratio, commonly called the ***thermal efficiency***

thermal efficiency

$$\eta = \frac{W_{cycle}}{Q_{in}} \quad \text{(power cycle)} \tag{2.42}$$

Introducing Eq. 2.41, an alternative form is obtained as

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \quad \text{(power cycle)} \tag{2.43}$$

Since energy is conserved, it follows that the thermal efficiency can never be greater than unity (100%). However, experience with *actual* power cycles shows that the value of thermal efficiency is invariably *less* than unity. That is, not all the energy added to the system by heat transfer is converted to work; a portion is discharged to the cold body by heat transfer. Using the second law of thermodynamics, we will show in Chap. 5 that the conversion from heat to work cannot be fully accomplished by any power cycle. The thermal efficiency of *every* power cycle must be less than unity: $\eta < 1$.

Energy & Environment

Today fossil-fueled power plants can have thermal efficiencies of 40%, or more. This means that up to 60% of the energy added by heat transfer during the power plant cycle is discharged from the plant other than by work, principally by heat transfer. One way power plant cooling is achieved is to use water drawn from a nearby river or lake. The water is eventually returned to the river or lake but at a higher temperature, which is a practice having several possible environmental consequences.

The return of large quantities of warm water to a river or lake can affect its ability to hold dissolved gases, including the oxygen required for aquatic life. If the return water temperature is greater than about 35°C (95°F), the dissolved oxygen may be too low to support some species of fish. If the return water temperature is too great, some species also can be stressed. As rivers and lakes become warmer, non-native species that thrive in the warmth can take over. Warmer water also fosters bacterial populations and algae growth.

Regulatory agencies have acted to limit warm water discharges from power plants, which has made cooling towers (Sec. 12.9) adjacent to power plants a common sight.

2.6.3 Refrigeration and Heat Pump Cycles

refrigeration and heat pump cycles

Next, consider the ***refrigeration and heat pump cycles*** shown in Fig. 2.17*b*. For cycles of this type, Q_{in} is the energy transferred by heat *into* the system undergoing the cycle *from* the cold body, and Q_{out} is the energy discharged by heat transfer *from* the system *to* the hot body. To accomplish these energy transfers requires a net work *input*, W_{cycle}. The quantities Q_{in}, Q_{out}, and W_{cycle} are related by the energy balance, which for refrigeration and heat pump cycles takes the form

$$W_{cycle} = Q_{out} - Q_{in} \quad \text{(refrigeration and heat pump cycles)} \tag{2.44}$$

Since W_{cycle} is positive in this equation, it follows that Q_{out} is greater than Q_{in}.

Although we have treated them as the same to this point, refrigeration and heat pump cycles actually have different objectives. The objective of a refrigeration cycle is to cool a refrigerated space or to maintain the temperature within a dwelling or other building *below* that of the surroundings. The objective of a heat pump is to maintain the temperature within a dwelling or other building *above* that of the surroundings or to provide heating for certain industrial processes that occur at elevated temperatures.

Since refrigeration and heat pump cycles have different objectives, their performance parameters, called *coefficients of performance,* are defined differently. These coefficients of performance are considered next.

Refrigeration Cycles

The performance of *refrigeration cycles* can be described as the ratio of the amount of energy received by the system undergoing the cycle from the cold body, Q_{in}, to the net work into the system to accomplish this effect, W_{cycle}. Thus, the ***coefficient of performance,*** β, is

$$\beta = \frac{Q_{in}}{W_{cycle}} \quad \text{(refrigeration cycle)} \tag{2.45}$$

coefficient of performance: refrigeration

Introducing Eq. 2.44, an alternative expression for β is obtained as

$$\beta = \frac{Q_{in}}{Q_{out} - Q_{in}} \quad \text{(refrigeration cycle)} \tag{2.46}$$

For a household refrigerator, Q_{out} is discharged to the space in which the refrigerator is located. W_{cycle} is usually provided in the form of electricity to run the motor that drives the refrigerator.

FOR EXAMPLE... in a refrigerator the inside compartment acts as the cold body and the ambient air surrounding the refrigerator is the hot body. Energy Q_{in} passes to the circulating refrigerant *from* the food and other contents of the inside compartment. For this heat transfer to occur, the refrigerant temperature is necessarily below that of the refrigerator contents. Energy Q_{out} passes *from* the refrigerant *to* the surrounding air. For this heat transfer to occur, the temperature of the circulating refrigerant must necessarily be above that of the surrounding air. To achieve these effects, a work *input* is required. For a refrigerator, W_{cycle} is provided in the form of electricity.

Heat Pump Cycles

The performance of *heat pumps* can be described as the ratio of the amount of energy discharged from the system undergoing the cycle to the hot body, Q_{out}, to the net work into the system to accomplish this effect, W_{cycle}. Thus, the ***coefficient of performance,*** γ, is

$$\gamma = \frac{Q_{out}}{W_{cycle}} \quad \text{(heat pump cycle)} \tag{2.47}$$

coefficient of performance: heat pump

Introducing Eq. 2.44, an alternative expression for this coefficient of performance is obtained as

$$\gamma = \frac{Q_{out}}{Q_{out} - Q_{in}} \quad \text{(heat pump cycle)} \tag{2.48}$$

From this equation it can be seen that the value of γ is never less than unity. For residential heat pumps, the energy quantity Q_{in} is normally drawn from the surrounding atmosphere, the ground, or a nearby body of water. W_{cycle} is usually provided by electricity.

The coefficients of performance β and γ are defined as ratios of the desired heat transfer effect to the cost in terms of work to accomplish that effect. Based on the definitions, it is desirable thermodynamically that these coefficients have values that are as large as possible. However, as discussed in Chap. 5, coefficients of performance must satisfy restrictions imposed by the second law of thermodynamics.

✓ Chapter Summary and Study Guide

In this chapter, we have considered the concept of energy from an engineering perspective and have introduced energy balances for applying the conservation of energy principle to closed systems. A basic idea is that energy can be stored within systems in three macroscopic forms: internal energy, kinetic energy, and gravitational potential energy. Energy also can be transferred to and from systems.

Energy can be transferred to and from closed systems by two means only: work and heat transfer. Work and heat transfer are identified at the system boundary and are not properties. In mechanics, work is energy transfer associated with macroscopic forces and displacements at the system boundary. The thermodynamic definition of work introduced in this chapter extends the notion of work from mechanics to include other types of work. Energy transfer by heat to or from a system is due to a temperature difference between the system and its surroundings, and occurs in the direction of decreasing temperature. Heat transfer modes include conduction, radiation, and convection. These sign conventions are used for work and heat transfer:

✓ $W, \dot{W} \begin{cases} > 0\text{: work done by the system} \\ < 0\text{: work done on the system} \end{cases}$

✓ $Q, \dot{Q} \begin{cases} > 0\text{: heat transfer to the system} \\ < 0\text{: heat transfer from the system} \end{cases}$

Energy is an extensive property of a system. Only changes in the energy of a system have significance. Energy changes are accounted for by the energy balance. The energy balance for a process of a closed system is Eq. 2.35 and an accompanying time rate form is Eq. 2.37. Equation 2.40 is a special form of the energy balance for a system undergoing a thermodynamic cycle.

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.
- ✓ evaluate these energy quantities
  - –kinetic and potential energy changes using Eqs. 2.5 and 2.10, respectively.
  - –work and power using Eqs. 2.12 and 2.13, respectively.
  - –expansion or compression work using Eq. 2.17
- ✓ apply closed system energy balances in each of several alternative forms, appropriately modeling the case at hand, correctly observing sign conventions for work and heat transfer, and carefully applying SI and English units.
- ✓ conduct energy analyses for systems undergoing thermodynamic cycles using Eq. 2.40, and evaluating, as appropriate, the thermal efficiencies of power cycles and coefficients of performance of refrigeration and heat pump cycles.

Key Engineering Concepts

kinetic energy p. 33
potential energy p. 34
work p. 36
power p. 38
internal energy p. 47
heat transfer p. 48
first law of thermodynamics p. 52
energy balance p. 52
thermodynamic cycle p. 64
power cycle p. 65
refrigeration cycle p. 66
heat pump cycle p. 66

Key Equations

$\Delta E = \Delta U + \Delta \text{KE} + \Delta \text{PE}$	(2.27)	Change in total energy of a system.
$\Delta \text{KE} = \text{KE}_2 - \text{KE}_1 = \frac{1}{2}m(\text{V}_2^2 - \text{V}_1^2)$	(2.5)	Change in kinetic energy of a mass m.
$\Delta \text{PE} = \text{PE}_2 - \text{PE}_1 = mg(z_2 - z_1)$	(2.10)	Change in gravitational potential energy of a mass m at constant g.

$E_2 - E_1 = Q - W$	(2.35a)	Energy balance for closed systems.
$\frac{dE}{dt} = \dot{Q} - \dot{W}$	(2.37)	Energy rate balance for closed systems.
$W = \int_{s_1}^{s_2} \mathbf{F} \cdot d\mathbf{s}$	(2.12)	Work due to action of a force **F**.
$\dot{W} = \mathbf{F} \cdot \mathbf{V}$	(2.13)	Power due to action of a force **F**.
$W = \int_{V_1}^{V_2} p\, dV$	(2.17)	Expansion or compression work related to fluid pressure. See Fig. 2.4.
	Thermodynamic Cycles	
$W_{cycle} = Q_{in} - Q_{out}$	(2.41)	Energy balance for a *power cycle.* As in Fig. 2.17a, all quantities are regarded as positive.
$\eta = \frac{W_{cycle}}{Q_{in}}$	(2.42)	Thermal efficiency of a power cycle.
$W_{cycle} = Q_{out} - Q_{in}$	(2.44)	Energy balance for a *refrigeration* or *heat pump cycle.* As in Fig. 2.17b, all quantities are regarded as positive.
$\beta = \frac{Q_{in}}{W_{cycle}}$	(2.45)	Coefficient of performance of a refrigeration cycle.
$\gamma = \frac{Q_{out}}{W_{cycle}}$	(2.47)	Coefficient of performance of a heat pump cycle.

Exercises: things engineers think about

1. What forces act on the bicycle and rider considered in Sec. 2.2.2? Sketch a free-body diagram.

2. Why is it incorrect to say that a system *contains* heat?

3. What examples of heat transfer by conduction, radiation, and convection do you encounter when using a charcoal grill?

4. When a meteor impacts the earth and comes to rest, what happens to its kinetic and potential energies?

5. After running 5 miles on a treadmill at her campus rec center, Ashley observes that the treadmill belt is warm to the touch. Why is the belt warm?

6. When cooking ingredients are mixed in a blender, what happens to the energy transferred to the ingredients? Is the energy transfer by work, by heat transfer, or by work and heat transfer?

7. When microwaves are beamed onto a tumor during cancer therapy to increase the tumor's temperature, this interaction is considered work and not heat transfer. Why?

8. Experimental molecular motors are reported to exhibit movement upon the absorption of light, thereby achieving a conversion of electromagnetic radiation into motion. Should the incident light be considered work or heat transfer?

9. Why are the symbols ΔU, ΔKE, and ΔPE used to denote the energy change during a process, but the work and heat transfer for the process are 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, which process, A or B, has the greater heat transfer?

12. What form does the energy balance take for an *isolated* system?

13. How would you define an *efficiency* for the motor of Example 2.6?

14. How many tons of CO_2 are produced annually by a conventional automobile?

Problems: developing engineering skills

Exploring Energy Concepts

2.1 A baseball has a mass of 0.3 lb. What is the kinetic energy relative to home plate of a 94 mile per hour fastball, in Btu?

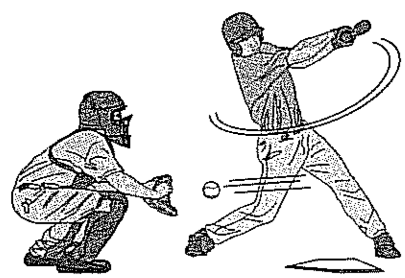


Fig. P2.1

2.2 An object whose mass is 400 kg is located at an elevation of 25 m above the surface of the earth. For $g = 9.78\ \text{m/s}^2$, determine the gravitational potential energy of the object, in kJ, relative to the surface of the earth.

2.3 An object whose weight is 100 lbf experiences a decrease in kinetic energy of 500 ft · lbf and an increase in potential energy of 1500 ft · lbf. The initial velocity and elevation of the object, each relative to the surface of the earth, are 40 ft/s and 30 ft, respectively. If $g = 32.2\ \text{ft/s}^2$, determine

(a) the final velocity, in ft/s
(b) the final elevation, in ft

2.4 A 2.5 × 3.5 × 6 in. brick whose density is 120 lb/ft^3 slips off the top of a building under construction and falls 69 ft. For $g = 32.0\ \text{ft/s}^2$, determine the change in gravitational potential energy of the brick, in ft · lbf.

2.5 What is the overall change in potential energy, in ft · lbf and Btu, of an automobile weighing 2500 lbf in a drive from San Diego, CA to Santa Fe, NM? Take g constant.

2.6 An object of mass 1000 kg, initially having a velocity of 100 m/s, decelerates to a final velocity of 20 m/s. What is the change in kinetic energy of the object, in kJ?

2.7 A 30-seat turboprop airliner whose mass is 14,000 kg takes off from an airport and eventually achieves its cruising speed of 620 km/h at an altitude of 10,000 m. For $g = 9.78\ \text{m/s}^2$, determine the change in kinetic energy and the change in gravitational potential energy of the airliner, each in kJ.

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 2 kg is accelerated from a velocity of 200 m/s to a final velocity of 500 m/s by the action of a resultant force **F**. Determine the work done by the resultant force, in kJ, if there are no other interactions between the object and its surroundings.

2.10 An object whose mass is 300 lb experiences changes in its kinetic and potential energies owing to the action of a resultant force **R**. The work done on the object by the resultant force is 140 Btu. There are no other interactions between the object and its surroundings. If the object's elevation increases by 100 ft and its final velocity is 200 ft/s, what is its initial velocity, in ft/s? Let $g = 32.2\ \text{ft/s}^2$.

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

(a) Show that the moment of inertia, $I = \int_{vol} \rho r^2\, dV$, can be expressed as $I = \pi \rho w R^4/2$ and the kinetic energy can be expressed as $\text{KE} = I\omega^2/2$.
(b) For a steel flywheel rotating at 3000 RPM, determine the kinetic energy, in N · m, and the mass, in kg, if $R = 0.38$ m and $w = 0.025$ m.
(c) Determine the radius, in m, and the mass, in kg, of an aluminum flywheel having the same width, angular velocity, and kinetic energy as in part (b).

2.12 Using $\text{KE} = I\omega^2/2$ from Problem 2.11a, how fast would a flywheel whose moment of inertia is 200 lb · ft^2 have to spin, in RPM, to store an amount of kinetic energy equivalent to the potential energy of a 100 lb mass raised to an elevation of 30 ft above the surface of the earth? Let $g = 32.2\ \text{ft/s}^2$.

2.13 Two objects having different masses fall freely under the influence of gravity from rest and the same initial elevation. Ignoring the effect of air resistance, show that the magnitudes of the velocities of the objects are equal at the moment just before they strike the earth.

2.14 An object whose mass is 50 lb is projected upward from the surface of the earth with an initial velocity of 200 ft/s. The only force acting on the object is the force of gravity. Plot the velocity of the object versus elevation. Determine the elevation of the object, in ft, when its velocity reaches zero. The acceleration of gravity is $g = 31.5\ \text{ft/s}^2$.

2.15 A block of mass 10 kg moves along a surface inclined 30° relative to the horizontal. The center of gravity of the block is elevated by 3.0 m and the kinetic energy of the block *decreases* by 50 J. The block is acted upon by a constant force **R** parallel to the incline and by the force of gravity. Assume frictionless surfaces and let $g = 9.81\ \text{m/s}^2$. Determine the magnitude and direction of the constant force **R**, in N.

2.16 Beginning from rest, an object of mass 200 kg slides down a 10-m-long ramp. The ramp is inclined at an angle of 40° from the horizontal. If air resistance and friction between the object and the ramp are negligible, determine the velocity of the object, in m/s, at the bottom of the ramp. Let $g = 9.81\ \text{m/s}^2$.

2.17 Jack, who weighs 150 lbf, runs 5 miles in 43 minutes on a treadmill set at a one-degree incline. The treadmill display shows he has *burned* 620 kcal. For Jack to break even caloriewise, how much vanilla ice cream, in cups, may he have after his workout?

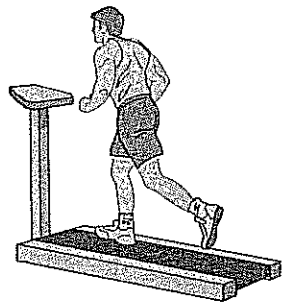


Fig. P2.17

Evaluating Work

2.18 A system with a mass of 5 kg, initially moving horizontally with a velocity of 40 m/s, experiences a constant horizontal *deceleration* of 2 m/s^2 due to the action of a resultant force. As a result, the system comes to rest. Determine the length of time, in s, the force is applied and the amount of energy transfer by work, in kJ.

2.19 An object of mass 80 lb, initially at rest, experiences a constant horizontal acceleration of 12 ft/s^2 due to the action of a resultant force applied for 6.5 s. Determine the work of the resultant force, in ft · lbf, and in Btu.

2.20 The drag force, F_d, imposed by the surrounding air on a vehicle moving with velocity V is given by

$$F_d = C_d A \tfrac{1}{2} \rho V^2$$

where C_d is a constant called the drag coefficient, A is the projected frontal area of the vehicle, and ρ is the air density. Determine the power, in kW, required to overcome aerodynamic drag for a truck moving at 110 km/h, if $C_d = 0.65$, A = 10 m^2, and ρ = 1.1 kg/m^3.

2.21 A major force opposing the motion of a vehicle is the rolling resistance of the tires, F_r, given by

$$F_r = f \mathcal{W}$$

where f is a constant called the rolling resistance coefficient and $\mathcal{W}$ is the vehicle weight. Determine the power, in kW, required to overcome rolling resistance for a truck weighing 322.5 kN that is moving at 110 km/h. Let f = 0.0069.

2.22 The two major forces opposing the motion of a vehicle moving on a level road are the rolling resistance of the tires, F_r, and the aerodynamic drag force of the air flowing around the vehicle, F_d, given respectively by

$$F_r = f \mathcal{W}, \qquad F_d = C_d A \tfrac{1}{2} \rho V^2$$

where f and C_d are constants known as the rolling resistance coefficient and drag coefficient, respectively, $\mathcal{W}$ and A are the vehicle weight and projected frontal area, respectively, V is the vehicle velocity, and ρ is the air density. For a passenger car with $\mathcal{W}$ = 3550 lbf, A = 23.3 ft^2, and C_d = 0.34, and when f = 0.02 and ρ = 0.08 lb/ft^3

(a) determine the power required, in hp, to overcome rolling resistance and aerodynamic drag when V is 55 mi/h.
(b) plot versus vehicle velocity ranging from 0 to 75 mi/h (i) the power to overcome rolling resistance, (ii) the power to overcome aerodynamic drag, and (iii) the total power, all in hp.

What implication for vehicle fuel economy can be deduced from the results of part (b)?

2.23 Measured data for pressure versus volume during the compression of a refrigerant within the cylinder of a refrigeration compressor are given in the table below. Using data from the table, complete the following:

(a) Determine a value of n such that the data are fit by an equation of the form pV^n = *constant*.
(b) Evaluate analytically the work done on the refrigerant, in Btu, using Eq. 2.17 along with the result of part (a).
(c) Using graphical or numerical integration of the data, evaluate the work done on the refrigerant, in Btu.
(d) Compare the different methods for estimating the work used in parts (b) and (c). Why are they estimates?

Data Point	p (lbf/in.^{2})	V (in.^{3})
1	112	13.0
2	131	11.0
3	157	9.0
4	197	7.0
5	270	5.0
6	424	3.0

2.24 Measured data for pressure versus volume during the expansion of gases within the cylinder of an internal combustion engine are given in the table below. Using data from the table, complete the following:

(a) Determine a value of n such that the data are fit by an equation of the form, pV^n = *constant*.
(b) Evaluate analytically the work done by the gases, in kJ, using Eq. 2.17 along with the result of part (a).
(c) Using graphical or numerical integration of the data, evaluate the work done by the gases, in kJ.
(d) Compare the different methods for estimating the work used in parts (b) and (c). Why are they estimates?

Data Point	p (bar)	V (cm^3)
1	15	300
2	12	361
3	9	459
4	6	644
5	4	903
6	2	1608

2.25 One-fourth kg of a gas contained within a piston–cylinder assembly undergoes a constant-pressure process at 5 bar beginning at v_1 = 0.20 m^3/kg. For the gas as the system, the work is −15 kJ. Determine the final volume of the gas, in m^3.

2.26 Carbon dioxide (CO_2) gas within a piston–cylinder assembly undergoes an expansion from a state where p_1 = 20 lbf/in.^{2}, V_1 = 0.5 ft^3 to a state where p_2 = 5 lbf/in.^{2}, V_2 = 2.5 ft^3. The relationship between pressure and volume during the process is $p = A + BV$, where A and B are constants. (a) For the CO_2, evaluate the work, in ft · lbf and Btu. (b) Evaluate A, in lbf/in.^{2}, and B, in (lbf/in.^{2})/ft^3.

2.27 A gas is compressed from $V_1 = 0.3\ \text{m}^3, p_1 = 1$ bar to $V_2 = 0.1\ \text{m}^3, p_2 = 3$ bar. Pressure and volume are related linearly during the process. For the gas, find the work, in kJ.

2.28 Nitrogen (N_2) gas within a piston–cylinder assembly undergoes a compression from $p_1 = 0.2$ MPa, $V_1 = 2.75\ \text{m}^3$ to a state where $p_2 = 2$ MPa. The relationship between pressure and volume during the process is $pV^{1.35} = constant$. For the N_2, determine (a) the volume at state 2, in m^3, and (b) the work, in kJ.

2.29 Oxygen (O_2) gas within a piston–cylinder assembly undergoes an expansion from a volume $V_1 = 0.01\ \text{m}^3$ to a volume $V_2 = 0.03\ \text{m}^3$. The relationship between pressure and volume during the process is $p = AV^{-1} + B$, where $A = 0.06\ \text{bar} \cdot \text{m}^3$ and $B = 3.0$ bar. For the O_2, determine (a) the initial and final pressures, each in bar, and (b) the work, in kJ.

2.30 A closed system consisting of 0.2 lbmol of air undergoes a polytropic process from $p_1 = 20\ \text{lbf/in.}^2$, $v_1 = 11.50\ \text{ft}^3/\text{lb}$ to a final state where $p_2 = 80\ \text{lbf/in.}^2$, $v_2 = 3.98\ \text{ft}^3/\text{lb}$. Determine the amount of energy transfer by work, in Btu, for the process.

2.31 Warm air is contained in a piston–cylinder assembly oriented horizontally as shown in Fig. P2.31. The air cools slowly from an initial volume of $0.003\ \text{m}^3$ to a final volume of $0.002\ \text{m}^3$. During the process, the spring exerts a force that varies linearly from an initial value of 900 N to a final value of zero. The atmospheric pressure is 100 kPa, and the area of the piston face is $0.018\ \text{m}^2$. Friction between the piston and the cylinder wall can be neglected. For the air, determine the initial and final pressures, in kPa, and the work, in kJ.

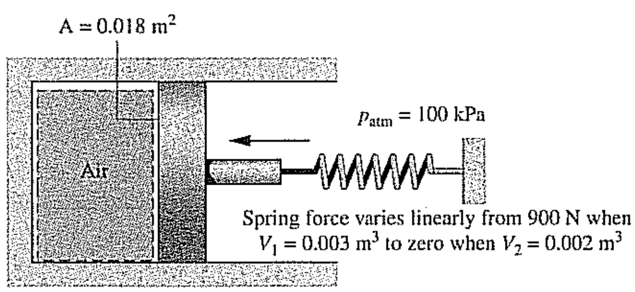


Fig. P2.31

2.32 Air contained within a piston–cylinder assembly is slowly heated. As shown in Fig. P2.32, during this process the pressure first varies linearly with volume and then remains constant. Determine the total work, in kJ.

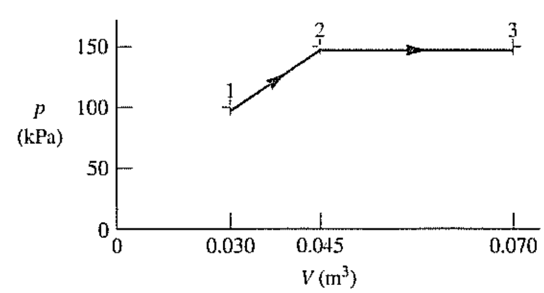


Fig. P2.32

2.33 Carbon monoxide gas (CO) contained within a piston–cylinder assembly undergoes three processes in series:

Process 1–2: Expansion from $p_1 = 5$ bar, $V_1 = 0.2\ \text{m}^3$ to $V_2 = 1\ \text{m}^3$, during which the pressure-volume relationship is $pV = constant$.

Process 2–3: Constant-volume heating from state 2 to state 3, where $p_3 = 5$ bar.

Process 3–1: Constant-pressure compression to the initial state.

Sketch the processes in series on p-V coordinates and evaluate the work for each process, in kJ.

2.34 Air contained within a piston–cylinder assembly undergoes three processes in series:

Process 1–2: Compression at constant pressure from $p_1 = 10\ \text{lbf/in}^2$, $V_1 = 4\ \text{ft}^3$ to state 2.

Process 2–3: Constant-volume heating to state 3, where $p_3 = 50\ \text{lbf/in}^2$.

Process 3–1: Expansion to the initial state, during which the pressure-volume relationship is $pV = constant$.

Sketch the processes in series on p-V coordinates. Evaluate (a) the volume at state 2, in ft^3, and (b) the work for each process, in Btu.

2.35 The belt sander shown in Fig. P2.35 has a belt speed of 1500 ft/min. The coefficient of friction between the sander and a plywood surface being finished is 0.2. If the downward (normal) force on the sander is 15 lbf, determine (a) the power transmitted by the belt, in Btu/s and hp, and (b) the work done in one minute of sanding, in Btu.

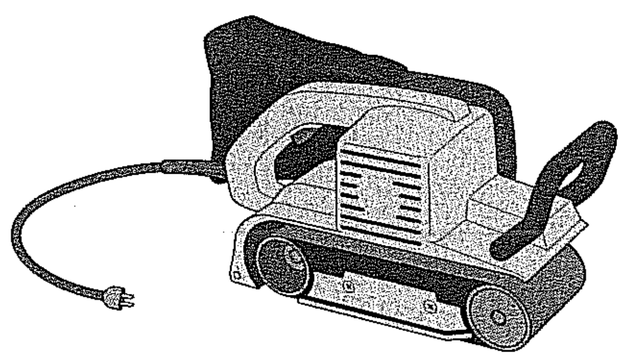


Fig. P2.35

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 A 10-V battery supplies a constant current of 0.5 amp to a resistance for 30 min. (a) Determine the resistance, in ohms. (b) For the battery, determine the amount of energy transfer by work, in kJ.

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 kW · h, determine the cost of recharging the battery.

2.39 As shown in Fig. P2.39, a steel wire suspended vertically having a cross-section area A and an initial length x_0 is stretched by a downward force F applied to the end of the wire. The normal stress in the wire varies linearly according to $\sigma = C\varepsilon$, where ε is the *strain*, given by $\varepsilon = (x - x_0)/x_0$, and x is the stretched length of the wire. C is a material constant (Young's modulus). Assuming the cross-sectional area remains constant

(a) obtain an expression for the work done on the wire.
(b) evaluate the work done on the wire, in ft · lbf, and the magnitude of the downward force, in lbf, if $x_0 = 10$ ft, $x = 10.01$ ft, $A = 0.1$ in², and $C = 2.5 \times 10^7$ lbf/in².

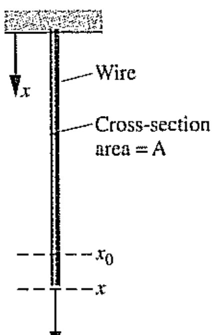


Fig. P2.39

2.40 A soap film is suspended on a wire frame, as shown in Fig. 2.10. The movable wire is displaced by an applied force F. If the surface tension remains constant

(a) obtain an expression for the work done in stretching the film in terms of the surface tension τ, length ℓ, and displacement Δx.
(b) evaluate the work done, in J, if $\ell = 5$ cm, $\Delta x = 0.5$ cm, and $\tau = 25 \times 10^{-5}$ N/cm.

2.41 As shown in Fig. P2.41, a spring having an initial unstretched length of ℓ_0 is stretched by a force F applied at its end. The stretched length is ℓ. By *Hooke's law*, the force is linearly related to the spring extension by $F = k(\ell - \ell_0)$, where k is the *stiffness*. If stiffness is constant

(a) obtain an expression for the work done in changing the spring's length from ℓ_1 to ℓ_2.
(b) evaluate the work done, in J, if $\ell_0 = 3$ cm, $\ell_1 = 6$ cm, $\ell_2 = 10$ cm, and the stiffness is $k = 10^4$ N/m.

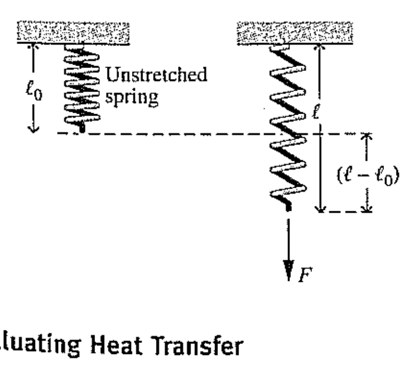


Fig. P2.41

Evaluating Heat Transfer

2.42 A flat surface having an area of 2 m² and a temperature of 350 K is cooled convectively by a gas at 300 K. Using data from Table 2.1, determine the largest and smallest heat transfer rates, in kW, that might be encountered for (a) free convection, (b) forced convection.

2.43 A 0.2-m-thick plane wall is constructed of concrete. At steady state, the energy transfer rate by conduction through a 1-m² area of the wall is 0.15 kW. If the temperature distribution is linear through the wall, what is the temperature difference across the wall, in K?

2.44 As shown in Fig. P2.44, the 6-in.-thick exterior wall of a building has an average thermal conductivity of 0.32 Btu/h · ft · °R. At steady state, the temperature of the wall decreases linearly from $T_1 = 70$°F on the inner surface to T_2 on the outer surface. The outside ambient air temperature is $T_0 = 25$°F and the convective heat transfer coefficient is 5.1 Btu/h · ft² · °R. Determine (a) the temperature T_2, in °F, and (b) the rate of heat transfer through the wall, in Btu/h per ft² of surface area.

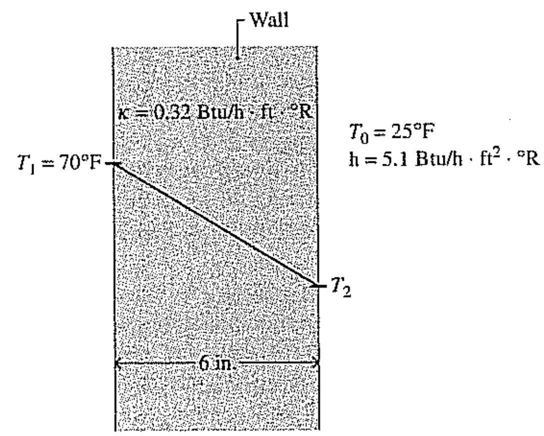


Fig. P2.44

2.45 As shown in Fig. P2.45, an oven wall consists of a 0.25-in.-thick layer of steel ($\kappa_s = 8.7$ Btu/h · ft · °R) and a layer of brick ($\kappa_b = 0.42$ Btu/h · ft · °R). At steady state, a temperature decrease of 1.2°F occurs over the steel layer. The inner temperature of the steel layer is 540°F. If the temperature of the outer surface of the brick must be no greater than 105°F, determine the minimum thickness of brick, in in., that ensures this limit is met.

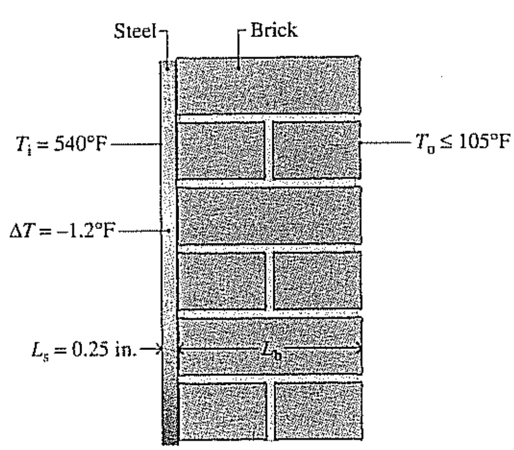


Fig. P2.45

2.46 A composite plane wall consists of a 9-in.-thick layer of brick ($\kappa_b = 1.4$ Btu/h · ft · °R) and a 4-in.-thick layer of insulation (κ_i = 0.05 Btu/h · ft · °R). The outer surface temperatures of the brick and insulation are 1260°R and 560°R, respectively, and there is perfect contact at the interface between the two layers. Determine at steady state the instantaneous rate of heat transfer, in Btu/h per ft^2 of surface area, and the temperature, in °R, at the interface between the brick and the insulation.

2.47 A composite plane wall consists of a 75-mm-thick layer of insulation (κ_i = 0.05 W/m · K) and a 25-mm-thick layer of siding (κ = 0.10 W/m · K). The inner temperature of the insulation is 20°C. The outer temperature of the siding is −13°C. Determine at steady state (a) the temperature at the interface of the two layers, in °C, and (b) the rate of heat transfer through the wall, in W per m^2 of surface area.

2.48 An insulated frame wall of a house has an average thermal conductivity of 0.04 Btu/h · ft · °R. The thickness of the wall is 6 in. The inside air temperature is 70°F, and the heat transfer coefficient for convection between the inside air and the wall is 2 Btu/h · ft · °R. On the outside, the ambient air temperature is 32°F and the heat transfer coefficient for convection between the wall and the outside air is 5 Btu/h · ft · °R. Determine at steady state the rate of heat transfer through the wall, in Btu/h per ft^2 of surface area.

2.49 Figure P2.49 shows a flat surface at temperature T_s covered with a layer of insulation whose thermal conductivity is κ. The top surface of the insulation is at temperature T_i and is exposed to air at temperature $T_0(<T_s)$. The heat transfer coefficient for convection is h. Radiation can be ignored.

(a) Show that at steady state the temperature T_i is given by

$$T_i = \frac{BT_0 + T_s}{B + 1}$$

where B = hL/κ.

(b) For fixed T_s and T_0, sketch the variation of T_i versus B. Discuss.

(c) For T_s = 300°C and T_0 = 30°C, determine the minimum value of B such that T_i is no greater than 60°C. If h = 4 W/m^2 · K and L = 0.06 m, what restriction does this limit on B place on the allowed values for thermal conductivity? Repeat for h = 20 W/m^2 · K.

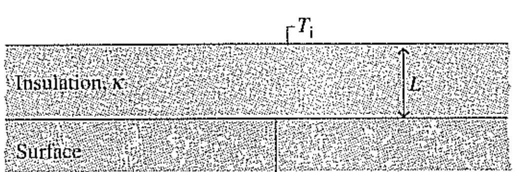


Fig. P2.49

2.50 At steady state, a spherical interplanetary electronics-laden probe having a diameter of 0.5 m transfers energy by radiation from its outer surface at a rate of 150 W. If the probe does not receive radiation from the sun or deep space, what is the surface temperature, in K?

2.51 A body whose surface area is 0.5 m^2, emissivity is 0.8, and temperature is 150°C is placed in a large, evacuated chamber whose walls are at 25°C. What is the rate at which radiation is *emitted* by the surface, in W? What is the *net* rate at which radiation is *exchanged* between the surface and the chamber walls, in W?

2.52 The outer surface of the grill hood shown in Fig. P2.52 is at 47°C and the emissivity is 0.93. The heat transfer coefficient for convection between the hood and the surroundings at 27°C is 10 W/m^2 · K. Determine the net rate of heat transfer between the grill hood and the surroundings by convection and radiation, in kW per m^2 of surface area.

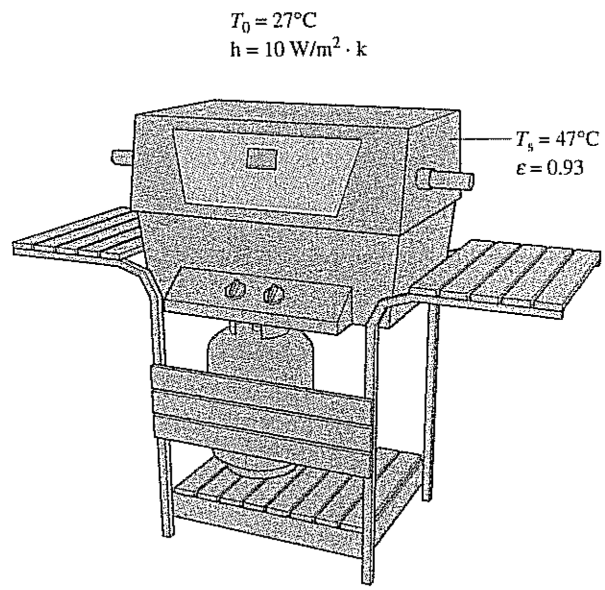


Fig. P2.52

Using the Energy Balance

2.53 Each line in the following table gives information about a process of a closed system. Each entry has the same energy units. Fill in the blank spaces in the table.

Process	Q	W	E_1	E_2	ΔE
a		−20		+50	+70
b	+50		+20	+50	
c		−60		+60	+20
d		−90		+50	0
e	+50	+150	+20		

2.54 A vertical cylindrical mass of 10 lb undergoes a process during which the velocity decreases from 100 ft/s to 50 ft/s, while the elevation remains unchanged. The initial specific internal energy of the mass is 0.5 Btu/lb and the final specific internal energy is 0.8 Btu/lb. During the process, the mass receives 2 Btu of energy by heat transfer through its bottom surface and loses 1 Btu of energy by heat transfer through its top surface. The lateral surface experiences no heat transfer. For this process, evaluate (a) the change in kinetic energy of the mass in Btu, and (b) the work in Btu.

2.55 A mass of 10 kg undergoes a process during which there is heat transfer from the mass at a rate of 5 kJ per kg, an elevation decrease of 50 m, and an increase in velocity from 15 m/s to 30 m/s. The specific internal energy decreases by 5 kJ/kg and the acceleration of gravity is constant at 9.7 m/s^2. Determine the work for the process, in kJ.

2.56 As shown in Fig. P2.56, 5 kg of steam contained within a piston–cylinder assembly undergoes an expansion from state 1, where the specific internal energy is u_1 = 2709.9 kJ/kg, to state 2, where u_2 = 2659.6 kJ/kg. During the process, there is heat transfer *to* the steam with a magnitude of 80 kJ. Also, a paddle wheel transfers energy *to* the steam by work in the amount of 18.5 kJ. There is no significant change in the kinetic or potential energy of the steam. Determine the energy transfer by work from the steam to the piston during the process, in kJ.

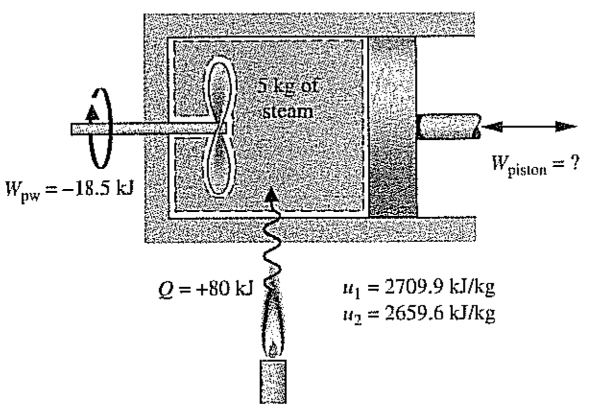


Fig. P2.56

2.57 A gas contained within a piston–cylinder assembly undergoes two processes, A and B, between the *same end states,* 1 and 2, where p_1 = 10 bar, V_1 = 0.1 m^3, U_1 = 400 kJ and p_2 = 1 bar, V_2 = 1.0 m^3, U_2 = 200 kJ:

Process A: Process from 1 to 2 during which the pressure-volume relation is pV = *constant*

Process B: Constant-volume process from state 1 to a pressure of 2 bar, followed by a linear pressure-volume process to state 2.

Kinetic and potential energy effects can be ignored. For each of the processes A and B, (a) sketch the process on p-V coordinates, (b) evaluate the work, in kJ, and (c) evaluate the heat transfer, in kJ.

2.58 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. For 8 h of operation, determine the total amount of energy stored in the battery, in kJ.

2.59 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 for the motor, each in kW

(a) the electric power required.
(b) the power developed by the output shaft.
(c) the rate of heat transfer.

2.60 As shown in Fig. P2.60, the outer surface of a transistor is cooled convectively by a fan-induced flow of air at a temperature of 25°C and a pressure of 1 atm. The transistor's outer surface area is 5 × 10^{-4} m^2. At steady state, the electrical power to the transistor is 3 W. Negligible heat transfer occurs through the base of the transistor. The convective heat transfer coefficient is 100 W/m^2 · K. Determine (a) the rate of heat transfer between the transistor and the air, in W, and (b) the temperature at the transistor's outer surface, in °C.

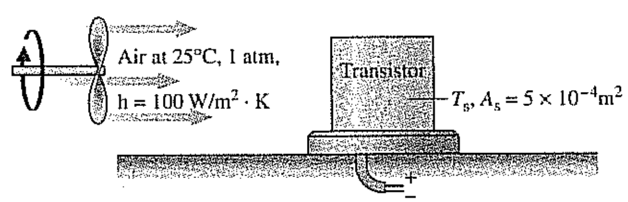


Fig. P2.60

2.61 One kg of Refrigerant 22, initially at p_1 = 0.9 MPa, u_1 = 232.92 kJ/kg, is contained within a rigid closed tank. The tank is fitted with a paddle wheel that transfers energy *to* the refrigerant at a constant rate of 0.1 kW. Heat transfer *from* the refrigerant *to* its surroundings occurs at a rate Kt, in kW, where K is a constant, in kW per minute, and t is time, in minutes. After 20 minutes of stirring, the refrigerant is at p_2 = 1.2 MPa, u_2 = 276.67 kJ/kg. No overall changes in kinetic or potential energy occur. (a) For the refrigerant, determine the work and heat transfer, each in kJ. (b) Determine value of the constant K appearing in the given heat transfer relation, in kW/min.

2.62 An electric generator supplies electricity to a storage battery at a rate of 15 kW for a period of 12 hours. During this 12-h period there also is heat transfer from the battery to the surroundings at a rate of 1.5 kW. Then, during the next 12-hour period the battery discharges electricity to an external load at a rate of 5 kW while heat transfer from the battery to the surroundings occurs at a rate of 0.5 kW.

(a) For the first 12-h period, determine, in kW, the time rate of change of energy stored within the battery.
(b) For the second 12-h period, determine, in kW, the time rate of change of energy stored in the battery.
(c) For the *full* 24-h period, determine, in kJ, the *overall* change in energy stored in the battery.

2.63 A gas expands in a piston–cylinder assembly from p_1 = 8 bar, V_1 = 0.02 m^3 to p_2 = 2 bar in a process during which the relation between pressure and volume is $pV^{1.2}$ = *constant*. The mass of the gas is 0.25 kg. If the specific internal energy of the gas *decreases* by 55 kJ/kg during the process, determine the heat transfer, in kJ. Kinetic and potential energy effects are negligible.

2.64 Two kilograms of 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 10 W for 1 h. 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.
(c) the change in specific internal energy of the air, in kJ/kg.

2.65 Helium gas is contained in a closed rigid tank. An electric resistor in the tank transfers energy *to* the gas at a constant rate of 1 kW. Heat transfer *from* the gas to its surroundings occurs at a rate of $5t$ watts, where t is time, in minutes. Plot the change in energy of the helium, in kJ, for $t \geq 0$ and comment.

2.66 Steam in a piston–cylinder assembly undergoes a polytropic process, with $n = 2$, from an initial state where $p_1 = 500\ lbf/in.^2$, $v_1 = 1.701\ ft^3/lb$, $u_1 = 1363.3$ Btu/lb to a final state where $u_2 = 990.58$ Btu/lb. 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/lb.

2.67 A gas undergoes a process from state 1, where $p_1 = 60\ lbf/in.^2$, $v_1 = 6.0\ ft^3/lb$, to state 2 where $p_2 = 20\ lbf/in.^2$, according to $pv^{1.3} = constant$. The relationship between pressure, specific volume, and internal energy is

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

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

2.68 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 5 g, and initially the air occupies a volume of 5 liters. The atmosphere exerts a pressure of 100 kPa on the top of the piston. The volume of the air slowly decreases to 0.002 m^3 as the specific internal energy of the air decreases by 260 kJ/kg. Neglecting friction between the piston and the cylinder wall, determine the heat transfer to the air, in kJ.

2.69 Gaseous CO_2 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 CO_2 is 4 g. The CO_2 initially occupies a volume of 0.005 m^3 and has a specific internal energy of 657 kJ/kg. The atmosphere exerts a pressure of 100 kPa on the top of the piston. Heat transfer in the amount of 1.95 kJ occurs slowly from the CO_2 to the surroundings, and the volume of the CO_2 decreases to 0.0025 m^3. Friction between the piston and the cylinder wall can be neglected. The local acceleration of gravity is 9.81 m/s^2. For the CO_2, determine (a) the pressure, in kPa, and (b) the final specific internal energy, in kJ/kg.

2.70 A gas is contained in a vertical piston–cylinder assembly by a piston weighing 1000 lbf and having a face area of 12 $in.^2$ 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 5 Btu as the elevation of the piston increases by 2 ft. The piston and cyclinder are poor thermal conductors and friction can be neglected. Determine the change in internal energy of the gas, in Btu, assuming it is the only significant internal energy change of any component present.

Analyzing Thermodynamic Cycles

2.71 The following table gives data, in Btu, for a system undergoing a thermodynamic cycle consisting of four processes in series. Determine

(a) the missing table entries, each in Btu.
(b) whether the cycle is a power cycle or a refrigeration cycle.

Process	ΔU	ΔKE	ΔPE	ΔE	Q	W
1–2	72	−5	−6		0	
2–3	64	0			90	
3–4	−97		0			92
4–1		0	3			0

2.72 The following table gives data, in Btu, for a system undergoing a power cycle consisting of four processes in series. Determine (a) the missing table entries, each in Btu, and (b) the thermal efficiency.

Process	ΔU	ΔKE	ΔPE	ΔE	Q	W
1–2	950	50	0		1000	
2–3		0	50	−450		450
3–4	−650		0	−600		0
4–1	200	−100	−50		0	

2.73 Figure P2.73 shows a power cycle executed by a gas in a piston-cylinder assembly. For process 1-2, $U_2 - U_1 = 15$ kJ. For process 3-1, $Q_{31} = 10$ kJ. There are no changes in kinetic or potential energy. Determine (a) the work for each process, in kJ, (b) the heat transfer for processes 1-2 and 2-3, each in kJ, and (c) the thermal efficiency.

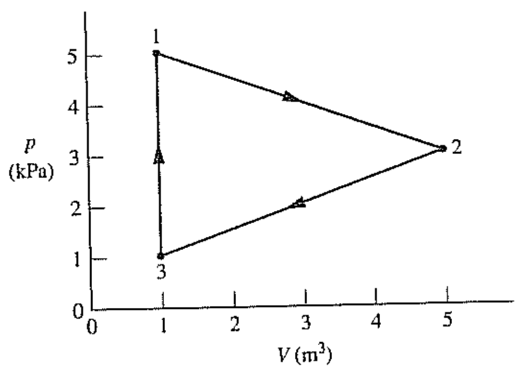


Fig. P2.73

2.74 A gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes in series, beginning at state 1 where $p_1 = 1$ bar, $V_1 = 1.5\ m^3$, as follows:

Process 1–2: Compression with $pV = constant$, $W_{12} = -104$ kJ, $U_1 = 512$ kJ, $U_2 = 690$ kJ.

Process 2–3: $W_{23} = 0$, $Q_{23} = -150$ kJ.

Process 3–1: $W_{31} = +50$ kJ.

There are no changes in kinetic or potential energy. (a) Determine Q_{12}, Q_{31}, and U_3, each in kJ. (b) Can this cycle be a power cycle? Explain.

2.75 A gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes:

Process 1–2: Compression with $pV = constant$, from $p_1 = 1$ bar, $V_1 = 1.6\ \text{m}^3$ to $V_2 = 0.2\ \text{m}^3$, $U_2 - U_1 = 0$.

Process 2–3: Constant pressure to $V_3 = V_1$.

Process 3–1: Constant volume, $U_1 - U_3 = -3549$ kJ.

There are no significant changes in kinetic or potential energy. Determine the heat transfer and work for Process 2–3, in kJ. Is this a power cycle or a refrigeration cycle?

2.76 A gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes:

Process 1–2: Constant volume, $V = 0.028\ \text{m}^3$, $U_2 - U_1 = 26.4$ kJ.

Process 2–3: Expansion with $pV = constant$, $U_3 = U_2$.

Process 3–1: Constant pressure, $p = 1.4$ bar, $W_{31} = -10.5$ kJ.

There are no significant changes in kinetic or potential energy.

(a) Sketch the cycle on a p–V diagram.
(b) Calculate the net work for the cycle, in kJ.
(c) Calculate the heat transfer for process 2–3, in kJ.
(d) Calculate the heat transfer for process 3–1, in kJ.

Is this a power cycle or a refrigeration cycle?

2.77 As shown in Fig. P2.77, a gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes in series:

Process 1–2: Compression with $U_2 = U_1$.

Process 2–3: Constant-volume cooling to $p_3 = 140$ kPa, $V_3 = 0.028\ \text{m}^3$.

Process 3–1: Constant-pressure expansion with $W_{31} = 10.5$ kJ.

For the cycle, $W_{cycle} = -8.3$ kJ. There are no changes in kinetic or potential energy. Determine (a) the volume at state 1, in m³, (b) the work and heat transfer for process 1-2, each in kJ. (c) Can this be a power cycle? A refrigeration cycle? Explain.

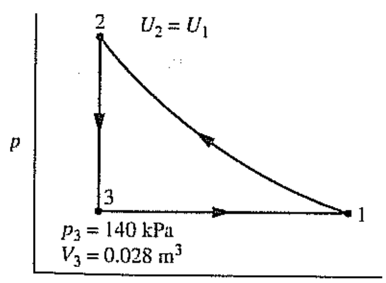


Fig. P2.77

2.78 For a power cycle operating as in Fig. 2.17*a*, the heat transfers are $Q_{in} = 50$ kJ and $Q_{out} = 35$ kJ. Determine the net work, in kJ, and the thermal efficiency.

2.79 The thermal efficiency of a power cycle operating as shown in Fig. 2.17*a* is 35%, and $Q_{out} = 40$ MJ. Determine the net work developed and the heat transfer Q_{in}, each in MJ.

2.80 For a power cycle operating as in Fig. 2.17a, $Q_{in} = 2600$ Btu and $Q_{out} = 1800$ Btu. What is the net work developed, in Btu, and the thermal efficiency?

2.81 For a power cycle operating as in Fig. 2.17*a*, $W_{cycle} = 800$ Btu and $Q_{out} = 1800$ Btu. What is the thermal efficiency?

2.82 A power cycle receives energy by heat transfer from the combustion of fuel and develops power at a net rate of 150 MW. The thermal efficiency of the cycle is 40%.

(a) Determine the net rate at which the cycle receives energy by heat transfer, in MW.
(b) For 8000 hours of operation annually, determine the net work output, in kW · h per year.
(c) Evaluating the net work output at \$0.08 per kW · h, determine the value of net work, in \$ per year.

2.83 A power cycle has a thermal efficiency of 40% and generates electricity at a rate of 100 MW. The electricity is valued at \$0.08 per kW · h. Based on the cost of fuel, the cost to supply $\dot{Q}_{in}$ is \$4.50 per GJ. For 8000 hours of operation annually, determine, in \$,

(a) the value of electricity generated per year.
(b) the annual fuel cost.
(c) Does the difference between the results of parts (a) and (b) represent *profit*? Discuss.

2.84 Shown in Fig. P2.84 is a *cogeneration* power plant operating in a thermodynamic cycle at steady state. The plant provides electricity to a community at a rate of 80 MW. The energy discharged from the power plant by heat transfer is denoted on the figure by $\dot{Q}_{out}$. Of this, 70 MW is provided to the community for water heating and the remainder is discarded to the environment without use. The electricity is valued at \$0.08 per kW · h. If the cycle thermal efficiency is 40%, determine the (a) rate energy is added by heat transfer, $\dot{Q}_{in}$, in MW, (b) rate energy is discarded to the environment, in MW, and (c) value of the electricity generated, in \$ per year.

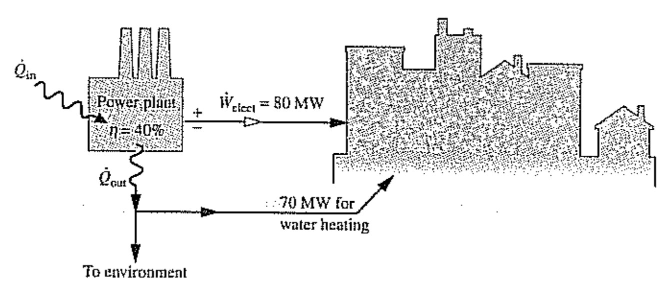


Fig. P2.84

2.85 For each of the following, what plays the roles of the hot body and the cold body of the appropriate Fig. 2.17 schematic?

(a) Window air conditioner
(b) Nuclear submarine power plant
(c) Ground-source heat pump

2.86 In what ways do automobile engines operate analogously to the power cycle shown in Fig. 2.17*a*? How are they different? Discuss.

2.87 A refrigeration cycle operating as shown in Fig. 2.17*b* has heat transfer $Q_{out} = 2400$ Btu and net work of $W_{cycle} = 800$ Btu. Determine the coefficient of performance for the cycle.

2.88 A refrigeration cycle operates as shown in Fig. 2.17*b* with a coefficient of performance $\beta = 1.5$. For the cycle, $Q_{out} = 500$ kJ. Determine Q_{in} and W_{cycle}, each in kJ.

2.89 A household refrigerator operating steadily and with a coefficient of performance of 2.4 removes energy from a refrigerated space at a rate of 600 Btu/h. Evaluating electricity at \$0.08 per kW · h, determine the cost of electricity in a month when the refrigerator operates for 360 hours.

2.90 A heat pump cycle operating at steady state receives energy by heat transfer from well water at 10°C and discharges energy by heat transfer to a building at the rate of 1.2×10^5 kJ/h. Over a period of 14 days, an electric meter records that 1490 kW · h of electricity is provided to the heat pump. These are the only energy transfers involved. Determine (a) the amount of energy that the heat pump receives over the 14-day period from the well water by heat transfer, in kJ, and (b) the heat pump's coefficient of performance.

2.91 A heat pump cycle whose coefficient of performance is 2.5 delivers energy by heat transfer to a dwelling at a rate of 20 kW.

(a) Determine the net power required to operate the heat pump, in kW.

(b) Evaluating electricity at \$0.08 per kW · h, determine the cost of electricity in a month when the heat pump operates for 200 hours.

2.92 A heat pump cycle delivers energy by heat transfer to a dwelling at a rate of 60,000 Btu/h. The power input to the cycle is 7.8 hp.

(a) Determine the coefficient of performance of the cycle.

(b) Evaluating electricity at \$0.08 per kW · h, determine the cost of electricity in a month when the heat pump operates for 200 hours.

2.93 A household refrigerator with a coefficient of performance of 2.4 removes energy from the refrigerated space at a rate of 600 Btu/h. Evaluating electricity at \$0.08 per kW · h, determine the cost of electricity in a month when the refrigerator operates for 360 hours.

Design & open ended problems: exploring engineering practice

2.1D Critically evaluate and compare the various hybrid electric automobiles on the market today. In a memorandum, summarize your findings and conclusions.

2.2D Design a go-anywhere, use-anywhere wind screen for outdoor recreational and casual-living activities, including sunbathing, reading, cooking, and picnicking. The wind screen must be lightweight, portable, easy to deploy, and low cost. A key constraint is that the wind screen can be set up anywhere, including hard surfaces such as parking lots for tailgating, wood decks, brick and concrete patios, and at the beach. A cost analysis should accompany the design.

2.3D In living things, energy is stored in the molecule *adenosine triphosphate,* called ATP for short. ATP is said to *act like a battery,* storing energy when it is not needed and instantly releasing energy when it is required. Investigate how energy is stored and the role of ATP in biological processes. Write a report including at least three references.

2.4D For a 2-week period, keep a diary of your calorie intake for food and drink and the calories *burned* due to your full range of activities over the period, each in kcal. Interpret your results using concepts introduced in this chapter. In a memorandum, summarize results and interpretations.

2.5D Develop a list of the most common home-heating options in your locale. For a 2500-ft^2 dwelling, what is the annual fuel cost or electricity cost of each option? Also, what is the installed cost of each option? For a 15-year life, which option is the most economical?

2.6D Homeowners concerned about interruption of electrical power from their local utility because of weather-related and utility system outages can acquire a standby generator that produces electricity using the home's existing natural gas or liquid propane (LP) fuel source. For a single-family dwelling of your choice, identify a standby generator that would provide electricity during an outage to a set of essential devices and appliances you specify. Summarize your findings in a memorandum including installed-cost and operating-cost data.

2.7D An advertisement describes a portable heater claimed to cut home heating bills by up to 50%. The heater is said to be able to heat large rooms in minutes without having a high outer-surface temperature, reducing humidity and oxygen levels, or producing carbon monoxide. A typical deployment is shown in Fig. P2.7D. The heater is an enclosure containing electrically-powered quartz infrared lamps that shine on copper tubes. Air drawn into the enclosure by a fan flows over the tubes and then is directed back into the living space. Heaters requiring 500 watts of power cost about \$400 while the 1000-W model costs about \$500. Critically evaluate the technical and economic merit of such heaters. Write a report including at least three references.

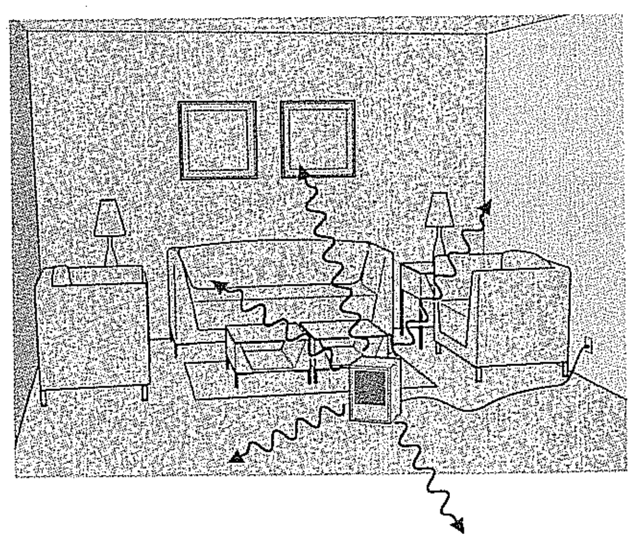


Fig. P2.7D

2.8D Fossil-fuel power plants produce most of the electricity generated annually in the United States. The cost of electricity is determined by several factors, including the power plant thermal efficiency, the unit cost of the fuel, in $ per kW · h, and the plant capital cost, in $ per kW of power generated. Prepare a memorandum comparing typical ranges of these three factors for coal-fired steam power plants and natural gas-fired gas turbine power plants. Which type of plant is most prevalent in the United States?

2.9D According to the New York City Transit Authority, the operation of subways raise tunnel and station temperatures as much as 14–20°F above ambient temperature. Principal contributors to the temperature rise include train motor operation, lighting, and energy from the passengers themselves. Passenger discomfort can increase significantly in hot-weather periods if air conditioning is not provided. Still, because on-board air-conditioning units discharge energy by heat transfer to their surroundings, such units contribute to the overall tunnel and station energy management problem. Investigate the application to subways of *alternative* cooling strategies that provide substantial cooling with a minimal power requirement, including but not limited to thermal storage and nighttime ventilation. Write a report with at least three references.

2.10D An inventor proposes *borrowing* water from municipal water mains and storing it *temporarily* in a tank on the premises of a dwelling equipped with a heat pump. As shown in Fig. P2.10D, the stored water serves as the cold body for the heat pump and the dwelling itself serves as the hot body. Since the energy of the stored water decreases as energy is removed from it by the heat pump, water is drawn from the mains periodically to restore the energy level and an equal amount of lower-energy water is returned to the mains. As the invention requires no *net* water from the mains, the inventor maintains that nothing should be paid for water usage. The inventor also maintains that this approach not only gives a coefficient of performance superior to those of *air-source* heat pumps but also avoids the installation costs associated with *ground-source* heat pumps. In all, significant cost savings result, the inventor says. Critically evaluate the inventor's claims. Write a report including at least three references.

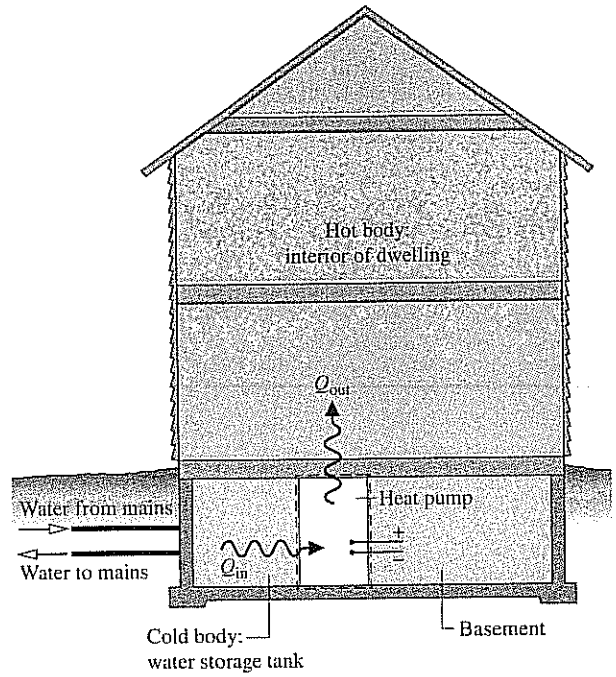


Fig. P2.10D