3 USING ENERGY AND THE FIRST LAW OF THERMODYNAMICS

Introduction...

Energy is a fundamental concept of thermodlynamics 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. 5 the discussion is extended to control volumes.

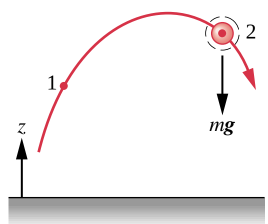
Energy is a familiar notion, and you already know a great deal about it. In the present chapter several important aspects of the energy concept are developed. Some of these we have encountered in Chap. 1. A basic idea is that energy can be *stored* within systems in various forms. Energy also can be *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 transformations and transfers.

chapter objective

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.

3.1 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. In the present section, we review mechanical concepts of energy.



3.1.1 Kinetic and Potential Energy

Consider a body of mass m that moves from a position where the magnitude of its velocity is V_1 and its elevation is z_1 to another where its velocity is V_2 and elevation is z_2, each relative to a specified coordinate frame such as the surface of the earth. The quantity $\frac{1}{2}mV^2$ is the ***kinetic energy,*** KE, of the body. The *change* in kinetic energy, ΔKE, of the body is

kinetic energy

$$\Delta KE = KE_2 - KE_1 = \frac{1}{2}m(V_2^2 - V_1^2) \tag{3.1}$$

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.

gravitational potential energy

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

$$\Delta \text{PE} = \text{PE}_2 - \text{PE}_1 = mg(z_2 - z_1) \tag{3.2}$$

Potential energy is associated with the force of gravity (Sec. 2.3) 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.

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.

Units. 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. Other commonly used units for 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

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

3.1.2 Work in Mechanics

In mechanics, when a body moving along a path is acted on by a resultant force that may vary in magnitude from position to position along the path, the work of the force is written as the scalar product (dot product) of the force vector **F** and the displacement vector of the body along the path $d\mathbf{s}$. That is

$$Work = \int_1^2 \mathbf{F} \cdot d\mathbf{s} \tag{3.3}$$

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.

3.1.3 Closure

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 above. 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 other 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.

conservation of energy

3.2 Broadening Our Understanding of Work

The work done by, or on, a system evaluated in terms of forces and displacements is given by Eq. 3.3. This relationship is important in thermodynamics, and is used later in the present section. It is also used in Sec. 3.3 to evaluate the work done in the compression or expansion of a gas (or liquid). 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.

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 an 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.

thermodynamic definition of work

For Example… consider Fig. 3.1 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 between the paddle wheel and the gas. Such an evaluation of work is consistent with Eq. 3.3, 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.

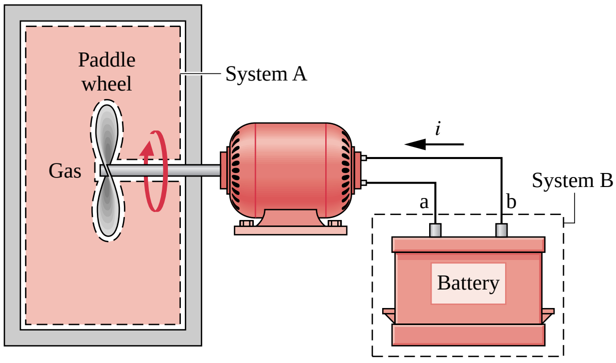


Figure 3.1 Two examples of work.

3.2.1 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, it is often convenient to consider such work as positive. That is,

$$W > 0\text{: work done } by \text{ the system}$$
$$W < 0\text{: work done } on \text{ the system}$$

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. 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.

METHODOLOGY UPDATE

Returning briefly to Eq. 3.3, to evaluate the integral 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. 3.3 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.

3.2.2 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 an 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

power

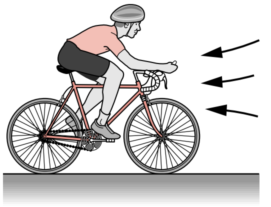
$$\dot{W} = \mathbf{F} \cdot \mathbf{V} \tag{3.4}$$

A dot appearing over a symbol, as in $\dot{W}$, is used to indicate a time rate. In principle, Eq. 3.4 can be integrated from time t_1 to time t_2 to get the total work done during the time interval

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

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. Other commonly used units for power are ft · lbf/s, Btu/h, and horsepower, hp.

For Example… to illustrate the use of Eq. 3.4, 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, discussed in Sec. 14.9, is given by



$$F_D = \tfrac{1}{2} C_D A \rho V^2$$

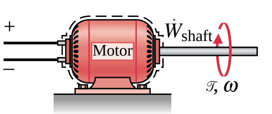
where C_D is a constant called the *drag coefficient,* A is the frontal area of the bicycle and rider, and ρ is the air density. By Eq. 3.4 the required power is $\mathbf{F}_D \cdot \mathbf{V}$ or

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

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

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

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 be expressed in terms of a tangential force F_t and radius R: $\mathcal{T} = F_t R$. 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. 3.4, we obtain an expression for the *power* transmitted from the shaft to the surroundings



$$\dot{W} = F_t V = (\mathcal{T}/R)(R\omega) = \mathcal{T}\omega \tag{3.5}$$

A related case involving a gas stirred by a paddle wheel is considered in the discussion of Fig. 3.1.

Electric Power. Shown in Fig. 3.1 is a system consisting of a battery 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. 3.1.

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

$$\dot{W} = -\mathscr{E}i \tag{3.6}$$

The minus sign is required to be in accord with our previously stated sign convention for power. 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.

3.3 Modeling Expansion or Compression Work

Let us evaluate the work done by the closed system shown in Fig. 3.2 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 pA, where A is the area of the piston face. The work done by the system as the piston is displaced a distance dx is

$$\delta W = p\mathrm{A}\, dx \tag{3.7}$$

The product A dx in Eq. 3.7 equals the change in volume of the system, dV. Thus, the work expression can be written as

$$\delta W = p\, dV \tag{3.8}$$

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. 3.8. 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. 3.8

$$W = \int_{V_1}^{V_2} p\, dV \tag{3.9}$$

Although Eq. 3.9 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.

Actual Expansion or Compression Processes

To perform the integral of Eq. 3.9 requires a relationship between the gas pressure *at the moving boundary* and the system volume, but this relationship may be difficult, or even impossible, to obtain for actual compressions and expansions. 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

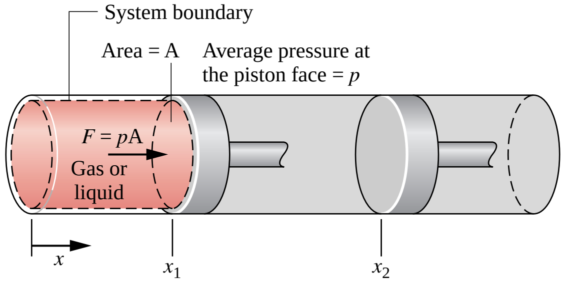


Figure 3.2 Expansion or compression of a gas or liquid.

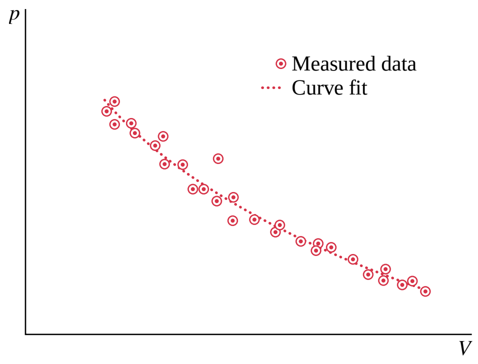


Figure 3.3 Pressure–volume data.

piston face required by Eq. 3.9. 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. 3.3. We will see later that in some cases where lack of the required pressure–volume relationship keeps us from evaluating the work from Eq. 3.9, the work can be determined alternatively from an *energy balance* (Sec. 3.6).

Quasiequilibrium Expansion or Compression Processes

An idealized type of process called a *quasiequilibrium* process is introduced in Sec. 2.2. A ***quasiequilibrium process*** is one in which all states through which the system passes may be considered equilibrium states. A particularly important aspect of the quasiequilibrium process concept is that the values of the intensive properties are uniform throughout the system, or every phase present in the system, at each state visited.

quasiequilibrium process

To consider how a gas (or liquid) might be expanded or compressed in a quasiequilibrium fashion, refer to Fig. 3.4, 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 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.

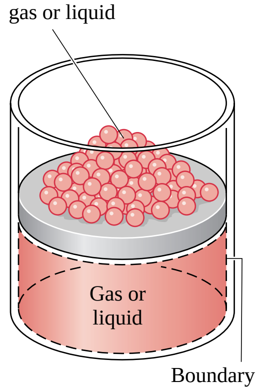


Figure 3.4 Illustration of a quasiequilibrium expansion or compression.

Equation 3.9 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. 3.5. 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. 3.5 is equal to the work for the process. Had the gas been *compressed* from 2 to 1 along the same path on

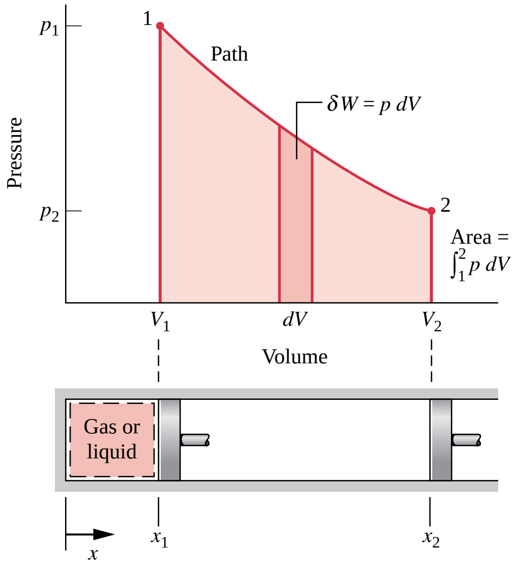


Figure 3.5 Work of a quasiequilibrium expansion or compression process.

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. 3.6. 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. 3.6. 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. Recalling the discussion of property given in Sec. 2.2, we can conclude that *work is not a property.* The value of work depends on the nature of the process between the end states.

The relationship between pressure and volume during an expansion or compression process also can be described analytically. An example is provided by the expression $pV^n = constant$, where the value of n is a constant for the particular process. A quasiequilibrium process described by such an expression is called a ***polytropic process.*** Additional analytical forms for the pressure–volume relationship also may be considered.

polytropic process

The example to follow illustrates the application of Eq. 3.9 when the relationship between pressure and volume during an expansion is described analytically as $pV^n = constant.$

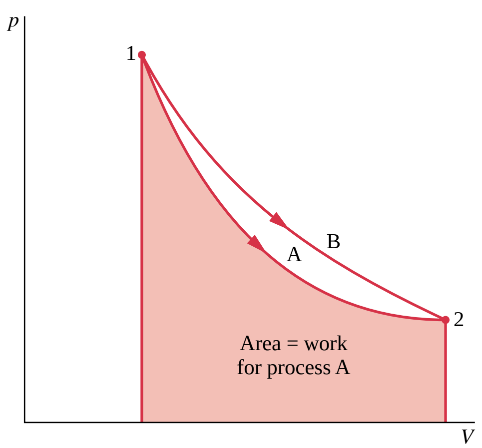


Figure 3.6 Illustration that work depends on the process.

Example 3.1 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.

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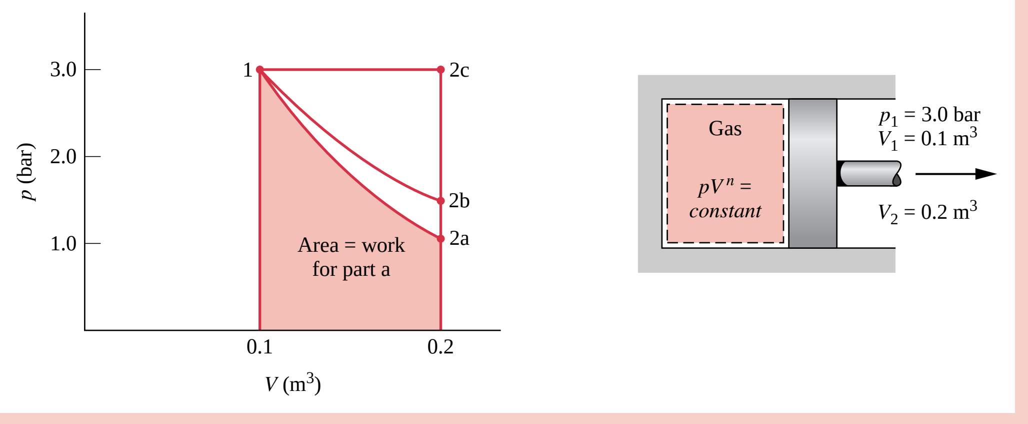


Figure E3.1

Assumptions:

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

Analysis: The required values for the work are obtained by integration of Eq. 3.9 using the given pressure–volume relation.

(a) Introducing the relationship $p = constant/V^n$ into Eq. 3.9 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
$$W = \left(\frac{(1.06\text{ bar})(0.2\text{ m}^3) - (3)(0.1)}{1 - 1.5}\right)\left|\frac{10^5\text{ N/m}^2}{1\text{ bar}}\right|\left|\frac{1\text{ kJ}}{10^3\text{ N}\cdot\text{m}}\right|$$
$$= +17.6\text{ kJ} \triangleleft$$

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

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

Substituting values

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

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.

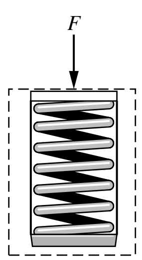
❷ The assumption of a polytropic process is significant. If the given pressure–volume relationship were obtained as a fit to experimental pressure–volume data, the value of $\int p\,dV$ would provide a plausible estimate of the work only when the measured pressure is essentially equal to that exerted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

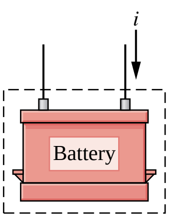
❸ Observe the use of unit conversion factors here and in part (b).

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 other properties 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.

3.4 Broadening Our Understanding of Energy

The objective in this section is to use our deeper understanding of work developed in Secs. 3.2 and 3.3 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.

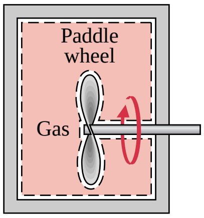




When work is done to compress a spring, energy is stored within the spring. When a battery is charged, the energy stored within it is increased. And when a gas (or liquid) initially at an equilibrium state in a closed, insulated vessel is stirred vigorously and allowed to come to a final equilibrium 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 kinetic or gravitational potential energy. 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

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

or (3.10)

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

All quantities in Eq. 3.10 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. 4 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 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.

microscopic interpretation of internal energy for a gas

3.5 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. An example is provided by a gas in a container undergoing a process while in contact with a flame at a temperature greater than that of the gas. This type of interaction is called an ***energy transfer by heat.***

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 thermal systems engineering, this section is devoted to a further consideration of energy transfer by heat.

3.5.1 Sign Convention and Notation

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.*

$Q > 0$: 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

sign convention for heat transfer

the system. Then the heat transfer is regarded as positive in the direction of the arrow. In an ***adiabatic process*** there is no energy transfer by heat.

adiabatic process

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

$$Q = \int_1^2 \delta Q$$

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 $Q_2 - Q_1$.

Methods based on experiment are available for evaluating energy transfer by heat. We refer to the different types of heat transfer processes as *modes.* There are three primary modes: conduction, convection, and radiation. *Conduction* refers to energy transfer by heat through a medium across which a temperature difference exists. *Convection* refers to energy transfer between a surface and a moving or still fluid having a different temperature. The third mode is termed thermal *radiation* and represents the net exchange of energy between surfaces at different temperatures by electromagnetic waves independent of any intervening medium. For these modes, the rate of energy transfer depends on the properties of the substances involved, geometrical parameters and temperatures. The physical origins and rate equations for these modes are introduced in Section 15.1.

Units. The units for Q and the heat transfer rate $\dot{Q}$ are the same as those introduced previously for W and $\dot{W}$, respectively.

3.5.2 Closure

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.

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 in Sec. 15.1. 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 in Sec. 15.1. When Q is the unknown, its value is usually found by using the *energy balance,* discussed next.

3.6 Energy Acounting: Energy Balance for Closed Systems

As our previous discussions indicate, the *only ways* the energy of a closed system can be changed is through transfer of energy by work or by heat. Further, a fundamental aspect of the energy concept is that energy is conserved. This is the ***first law of thermodynamics.*** These considerations are summarized in words as follows:

first law of thermodynamics

$$\left[\begin{array}{c}\textit{change}\text{ in the amount}\\ \text{of energy contained}\\ \text{within the system}\\ \text{during some time}\\ \text{interval}\end{array}\right] = \left[\begin{array}{c}\textit{net}\text{ amount of energy}\\ \text{transferred }\textit{in}\text{ across}\\ \text{the system boundary by}\\ \textit{heat}\text{ transfer during}\\ \text{the time interval}\end{array}\right] - \left[\begin{array}{c}\textit{net}\text{ amount of energy}\\ \text{transferred }\textit{out}\text{ across}\\ \text{the system boundary}\\ \text{by }\textit{work}\text{ during the}\\ \text{time interval}\end{array}\right]$$

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

$$E_2 - E_1 = Q - W \tag{3.11a}$$

Introducing Eq. 3.10 an alternative form is

energy balance

$$\Delta\text{KE} + \Delta\text{PE} + \Delta U = Q - W \tag{3.11b}$$

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. 3.11.

Note that the algebraic signs before the heat and work terms of Eqs. 3.11 are different. This follows from the sign conventions previously adopted. A minus sign 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.

Other Forms of the Energy Balance

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

$$dE = \delta Q - \delta W \tag{3.12}$$

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

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \tag{3.13}$$

time rate form of the energy balance

The rate form of the energy balance expressed in words is

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

Equations 3.11 through 3.13 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. 5 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. 3.7, in which three alternative systems are shown that include a quantity of a gas (or liquid) in a rigid, well-insulated container. In Fig. 3.7*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. 3.7*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. 3.7*c*, the boundary is located so that no energy is transferred across it by heat or work. ▲

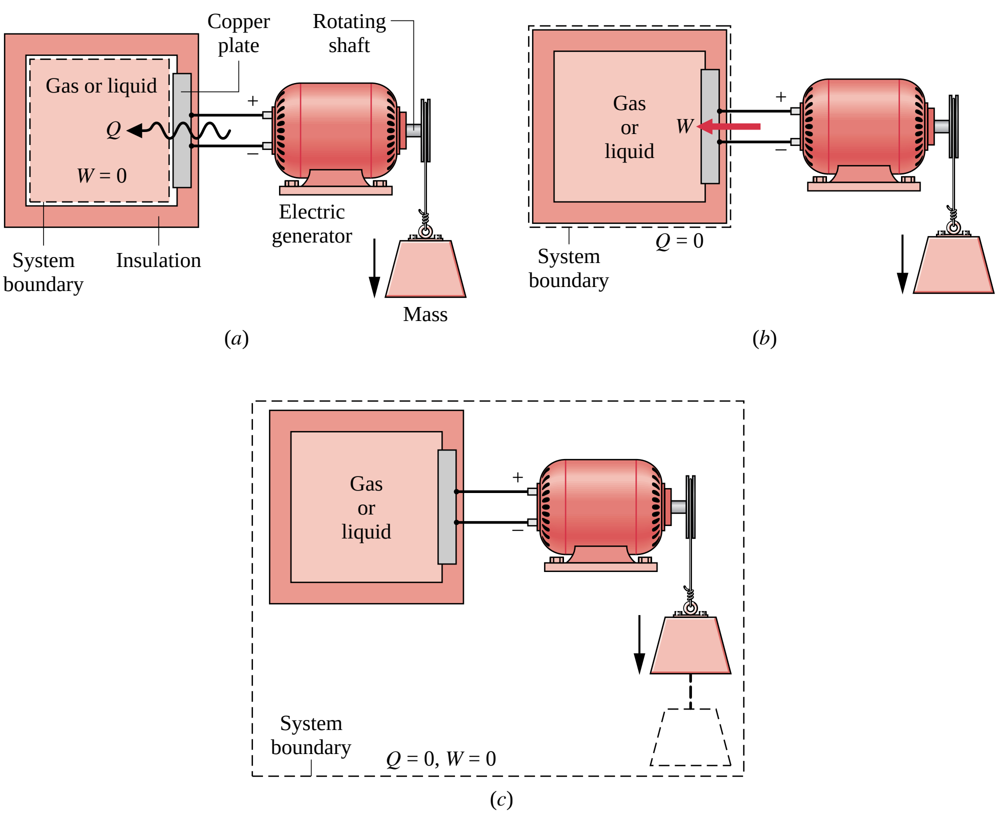


Figure 3.7 Alternative choices for system boundaries.

Closing Comment. 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.

Illustrations

The examples to follow bring out many 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.

METHODOLOGY UPDATE

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.

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. 4, we learn how to obtain thermodynamic property data using tables, graphs, equations, and computer software.

Example 3.2 Cooling a Gas in a Piston-Cylinder

Four kilograms 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 $u_2 - u_1 = -4.6$ 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

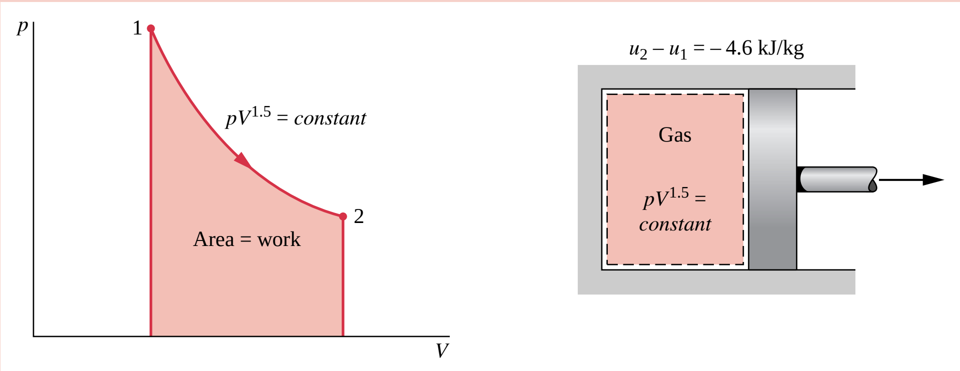


Figure E3.2

Assumptions:

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.

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

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

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 3.1: $W = +17.6$ kJ. The change in internal energy is obtained using given data as

$$m(u_2 - u_1) = 4\text{ kg}\left(-4.6\frac{\text{kJ}}{\text{kg}}\right) = -18.4\text{ kJ}$$

Substituting values

❷ $$Q = -18.4 + 17.6 = -0.8\text{ kJ} \triangleleft$$

---

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.

In the next example, we follow up the discussion of Fig. 3.7 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 3.3 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:

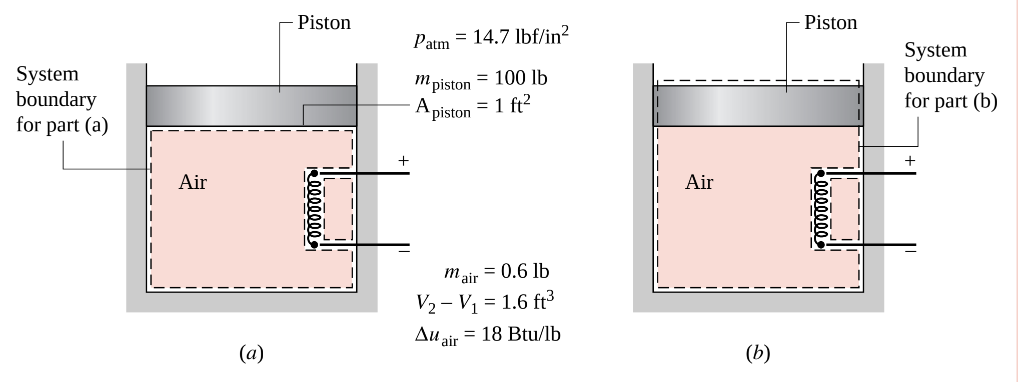


Figure E3.3

Assumptions:

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.

1 **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; $g = 32.0$ ft/s^2.

Analysis: **(a)** Taking the air as the system, the energy balance, Eq. 3.11b, reduces with assumption 3 to

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

Or, solving for Q

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

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. 3.9 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

$$pA_{piston} = m_{piston}\, g + p_{atm}A_{piston}$$

Solving for p and inserting values

$$p = \frac{m_{piston}\, g}{A_{piston}} + p_{atm}$$

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

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

$$Q = W + m_{air}(\Delta u_{air})$$
$$= 4.56 \text{ Btu} + (0.6 \text{ lb})\left(18 \frac{\text{Btu}}{\text{lb}}\right) = 15.4 \text{ Btu} \triangleleft$$

(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. 3.11*b*, reads

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

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

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

For this system, work is done at the *top* of the piston as it pushes aside the surrounding atmosphere. Applying Eq. 3.9

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

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

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

Thus, the potential energy change of the piston is

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

Finally

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

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

❶ Using the change in elevation Δz determined in the analysis, the change in potential energy of the air is about 10^{-3} Btu, which is negligible in the present case. The calculation is left as an exercise.

❷ 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.

Steady-State Operation. A system is at steady state if none of its properties change with time (Sec. 2.2). 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 3.4 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 heat is

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

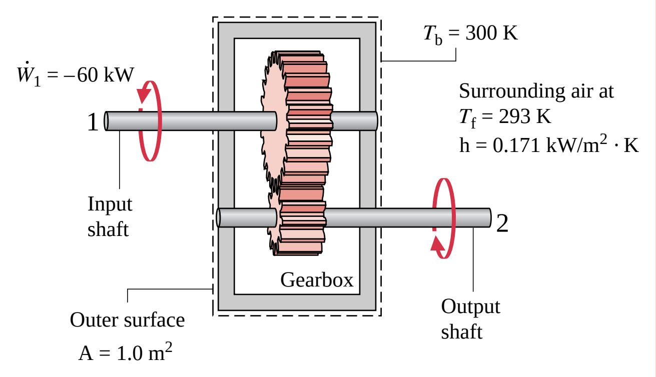
where h is a constant, h = 0.171 kW/m^2 · K, A = 1.0 m^2 is the outer surface area of the gearbox, T_b = 300 K (27°C) is the temperature at the outer surface, and T_f = 293 K (20°C) is the temperature of the surrounding air away from the immediate vicinity of the gearbox. For the gearbox, evaluate the 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:



Assumption: The gearbox is a closed system at steady state.

Figure E3.4

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

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

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

The energy rate balance, Eq. 3.13, 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
$$\begin{aligned}\dot{W}_2 &= \dot{Q} - \dot{W}_1\\ &= (-1.2\ \text{kW}) - (-60\ \text{kW})\\ &= +58.8\ \text{kW} \ \triangleleft\end{aligned}$$

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

---

❶ This expression accounts for heat transfer by convection (Sec. 15.1). It is written to be in accord with the sign convention for the heat transfer rate in the energy rate balance (Eq. 3.13): $\dot{Q}$ is negative when 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

Example 3.5 Silicon Chip at Steady State

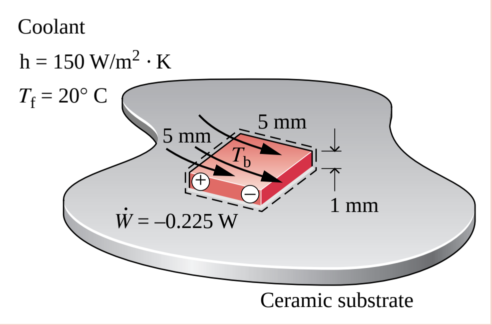
A silicon chip measuring 5 mm on a side and 1 mm in thickness is embedded in a ceramic substrate. At steady state, the chip has an electrical power input of 0.225 W. The top surface of the chip is exposed to a coolant whose temperature is 20°C. The rate of energy transfer by heat between the chip and the coolant is given by $\dot{Q} = -\text{hA}(T_b - T_f)$, where T_b and T_f are the surface and coolant temperatures, respectively, A is the surface area, and h = 150 W/m² · K. If heat transfer 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 other data are known.

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

Schematic and Given Data:



Assumptions:

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

Figure E3.5

Analysis: The surface temperature of the chip, T_b, can be determined using the energy rate balance, Eq. 3.13, which at steady state reduces as follows

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

With assumption 2, the only heat transfer is to the coolant, and is given by

❷ $$\dot{Q} = -\text{hA}(T_b - T_f)$$

Collecting results

$$0 = -\text{hA}(T_b - T_f) - \dot{W}$$

Solving for T_b

$$T_b = \frac{-\dot{W}}{\text{hA}} + T_f$$

In this expression, $\dot{W} = -0.225$ W, A = 25×10^{-6} m^2, h = 150 W/m$^2 \cdot$ K, and $T_f = 293$ K, giving

$$T_b = \frac{-(-0.225 \text{ W})}{(150 \text{ W/m}^2 \cdot \text{K})(25 \times 10^{-6} \text{ m}^2)} + 293 \text{ K}$$
$$= 353 \text{ K } (80°\text{C}) \triangleleft$$

❶ 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.

❷ This expression accounts for heat transfer by convection (Sec. 15.1). It is written to be in accord with the sign convention for heat transfer in the energy rate balance (Eq. 3.13): $\dot{Q}$ is negative when T_b is greater than T_f.

Transient Operation. Many devices undergo periods of transient operation where the state changes with time. This is observed during startup and shutdown periods. The next example illustrates the application of the energy rate balance to an electric motor during startup. The example also involves both electrical work and power transmitted by a shaft.

Example 3.6 Transient Operation of a Motor

The rate of heat transfer between a certain electric motor and its surroundings varies with time as

$$\dot{Q} = -0.2[1 - e^{(-0.05t)}]$$

where t is in seconds and $\dot{Q}$ is in kW. The shaft of the motor rotates at a constant speed of $\omega = 100$ rad/s (about 955 revolutions per minute, or RPM) and applies a constant torque of $\mathcal{T} = 18$ N $\cdot$ m to an external load. The motor draws a constant electric power input equal to 2.0 kW. For the motor, plot $\dot{Q}$ and $\dot{W}$, each in kW, and the change in energy ΔE, in kJ, as functions of time from $t = 0$ to $t = 120$ s. Discuss.

Solution (CD-ROM)

3.7 Energy Analysis of Cycles

In this section the energy concepts developed thus far are illustrated further by application to systems undergoing thermodynamic cycles. Recall from Sec. 2.2 that when a system at a given initial state goes through a sequence of processes and finally returns to that state, the system has executed a thermodynamic cycle. The study of systems undergoing cycles has played an important role in the development of the subject of engineering thermodynamics. Both the first and second laws of thermodynamics have roots in the study of cycles. In addition, there are many important practical applications involving power generation, vehicle propulsion, and refrigeration for which an understanding of thermodynamic cycles is necessary. In this section, cycles are considered from the perspective of the conservation of energy principle. Cycles are studied in greater detail in subsequent chapters, using both the conservation of energy principle and the second law of thermodynamics.

3.7.1 Cycle Energy Balance

The energy balance for any system undergoing a thermodynamic cycle takes the form

$$\Delta E_{\text{cycle}} = Q_{\text{cycle}} - W_{\text{cycle}} \quad (3.14)$$

where Q_{cycle} and W_{cycle} represent *net* amounts of energy transfer by heat and work, respectively, for the cycle. Since the system is returned to its initial state after the cycle, there is no *net* change

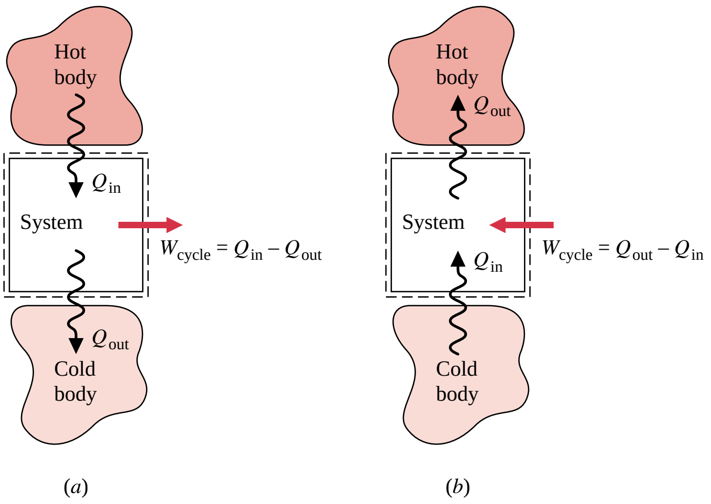


Figure 3.8 Schematic diagrams of two important classes of cycles. (*a*) Power cycles. (*b*) Refrigeration and heat pump cycles.

in its energy. Therefore, the left side of Eq. 3.14 equals zero, and the equation reduces to

$$W_{cycle} = Q_{cycle} \tag{3.15}$$

Equation 3.15 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 3.8 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. 3.8 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. 3.8*b* are opposite to those of Fig. 3.8*a*.

METHODOLOGY UPDATE

3.7.2 Power Cycles

power cycle

Systems undergoing cycles of the type shown in Fig. 3.8*a* deliver a net work transfer of energy to their surroundings during each cycle. Any such cycle is called a ***power cycle.*** From Eq. 3.15, the net work output equals the net heat transfer to the cycle, or

$$W_{cycle} = Q_{in} - Q_{out} \quad \text{(power cycle)} \tag{3.16}$$

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. 3.16 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:***

$$\eta = \frac{W_{cycle}}{Q_{in}} \qquad \text{(power cycle)} \tag{3.17a}$$

thermal efficiency

Introducing Eq. 3.16, an alternative form is obtained as

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \qquad \text{(power cycle)} \tag{3.17b}$$

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. 6 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: $\eta < 1$.

3.7.3 Refrigeration and Heat Pump Cycles

Next, consider the ***refrigeration and heat pump cycles*** shown in Fig. 3.8*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

refrigeration and heat pump cycles

$$W_{cycle} = Q_{out} - Q_{in} \qquad \text{(refrigeration and heat pump cycles)} \tag{3.18}$$

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

$$\beta = \frac{Q_{in}}{W_{cycle}} \qquad \text{(refrigeration cycle)} \tag{3.19a}$$

coefficient of performance

Introducing Eq. 3.18, an alternative expression for β is obtained as

$$\beta = \frac{Q_{in}}{Q_{out} - Q_{in}} \qquad \text{(refrigeration cycle)} \tag{3.19b}$$

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

coefficient of performance

$$\gamma = \frac{Q_{out}}{W_{cycle}} \qquad \text{(heat pump cycle)} \tag{3.20a}$$

Introducing Eq. 3.18, an alternative expression for this coefficient of performance is obtained as

$$\gamma = \frac{Q_{out}}{Q_{out} - Q_{in}} \qquad \text{(heat pump cycle)} \tag{3.20b}$$

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. 6, coefficients of performance must satisfy restrictions imposed by the second law of thermodynamics.

3.8 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 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 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. 3.11 and an accompanying time rate form is Eq. 3.13. Equation 3.15 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 terms listed here in the margin is particularly important in subsequent chapters.
- evaluate these energy quantities
  –kinetic and potential energy changes using Eqs. 3.1 and 3.2, respectively.
  –work and power using Eqs. 3.3 and 3.4, respectively.
  –expansion or compression work using Eq. 3.9
- 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 other units.
- conduct energy analyses for systems undergoing thermodynamic cycles using Eq. 3.15, and evaluating, as appropriate, the thermal efficiencies of power cycles and coefficients of performance of refrigeration and heat pump cycles.

internal energy
kinetic energy
potential energy
work
power
heat transfer
adiabatic process
energy balance
power cycle
refrigeration cycle
heat pump cycle

Problems

Energy Concepts from Mechanics

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

3.2 An object of weight 40 kN is located at an elevation of 30 m above the surface of the earth. For $g = 9.78$ m/s^2, determine the gravitational potential energy of the object, in kJ, relative to the surface of the earth.

3.3 (CD-ROM)

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

3.5 What is the change in potential energy, in ft · lbf, of an automobile weighing 2600 lbf at sea level when it travels from sea level to an elevation of 2000 ft? Assume the acceleration of gravity is constant.

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

3.7 (CD-ROM)

3.8 (CD-ROM)

Work and Power

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

$$F_D = C_D \mathrm{A} \tfrac{1}{2} \rho \mathrm{V}^2$$

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.

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

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

where f is a constant called the rolling resistance coefficient and $\mathscr{W}$ 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 $f = 0.0069$.

3.11 (CD-ROM)

3.12 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. 3.9 along with the result of part (a).

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

3.13 (CD-ROM)

3.14 One-half kg of a gas contained within a piston–cylinder assembly undergoes a constant-pressure process at 4 bar beginning at $v_1 = 0.72$ m^3/kg. For the gas as the system, the work is −84 kJ. Determine the final volume of the gas, in m^3.

3.15 (CD-ROM)

3.16 A gas is compressed from $V_1 = 0.09$ m^3, $p_1 = 1$ bar to $V_2 = 0.03$ m^3, $p_2 = 3$ bar. Pressure and volume are related linearly during the process. For the gas, find the work, in kJ.

3.17 Carbon dioxide gas in a piston–cylinder assembly expands from an initial state where $p_1 = 60$ lbf/in.^{2}, $V_1 = 1.78$ ft^3 to a final pressure of $p_2 = 20$ lbf/in.^{2} The relationship between pressure and volume during the process is $pV^{1.3} = constant$. For the gas, calculate the work done, in lb · lbf. Convert your answer to Btu.

3.18 A gas expands from an initial state where $p_1 = 500$ kPa and $V_1 = 0.1$ m^3 to a final state where $p_2 = 100$ kPa. The relationship between pressure and volume during the process is $pV = constant$. Sketch the process on a p–V diagram and determine the work, in kJ.

3.19 A closed system consisting of 0.5 lbmol of air undergoes a polytropic process from $p_1 = 20$ lbf/in.^{2}, $v_1 = 9.26$ ft^3/lb to a final state where $p_2 = 60$ lbf/in.^{2}, $v_2 = 3.98$ ft^3/lb. Determine the amount of energy transfer by work, in Btu, for the process.

3.20 Air undergoes two processes in series:

Process 1–2: polytropic compression, with $n = 1.3$, from $p_1 = 100$ kPa, $v_1 = 0.04$ m^3/kg to $v_2 = 0.02$ m^3/kg

Process 2–3: constant–pressure process to $v_3 = v_1$

Sketch the processes on a p–v diagram and determine the work per unit mass of air, in kJ/kg.

3.21 A gas undergoes three processes in series that complete a cycle:

Process 1–2: compression from $p_1 = 10$ lbf/in.^{2}, $V_1 = 4.0$ ft^3 to $p_2 = 50$ lbf/in.^{2} during which the pressure–volume relationship is $pv = constant$

Process 2–3: constant volume to $p_3 = p_1$

Process 3–1: constant pressure

Sketch the cycle on a p–V diagram and determine the *net* work for the cycle, in Btu.

3.22 (CD-ROM)

3.23 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 circumferentially 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.

3.24 Figure P 3.24 shows an object whose mass is 50 lb attached to a rope wound around a pulley. The radius of the pulley is 3 in. If the mass falls at a constant velocity of 3 ft/s, determine the power transmitted to the pulley, in horsepower, and the rotational speed of the pulley, in RPM. The acceleration of gravity is $g = 32.0$ ft/s^2.

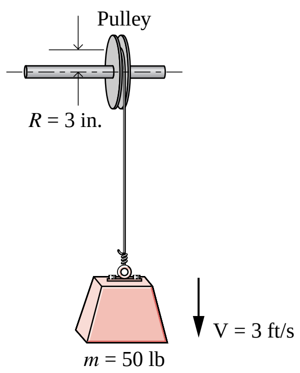


Figure P3.24

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

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

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

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

3.26 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.

3.27 (CD-ROM)

Energy Balance

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

Process	Q	W	E_1	E_2	ΔE
a	+50	−20		+50	
b	+50	+20	+20		
c	−40			+60	+20
d		−90		+50	0
e	+50		+20		−100

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

Process	Q	W	E_1	E_2	ΔE
a	+1000		+100	+800	
b		−500	+200	+300	
c	−200	+300		+1000	
d		−400	+400		+600
e	−400			+800	−400

3.30 A closed system of mass 2 kg undergoes a process in which there is heat transfer of magnitude 25 kJ from the system to the surroundings. The elevation of the system increases by 700 m during the process. The specific internal energy of the system *decreases* by 15 kJ/kg and there is no change in kinetic energy of the system. The acceleration of gravity is constant at $g = 9.6$ m/s^2. Determine the work, in kJ.

3.31 A closed system of mass 3 kg undergoes a process in which there is a heat transfer of 150 kJ from the system to the surroundings. The work done on the system is 75 kJ. If the initial specific internal energy of the system is 450 kJ/kg, what is the final specific internal energy, in kJ/kg? Neglect changes in kinetic and potential energy.

3.32 (CD-ROM)

3.33 A closed system of mass 2 lb undergoes two processes in series:

Process 1–2: $v_1 = v_2 = 4.434$ ft^3/lb, $p_1 = 100$ lbf/in.^{2}, $u_1 = 1105.8$ Btu/lb, $Q_{12} = -581.36$ Btu

Process 2–3: $p_2 = p_3 = 60$ lbf/in.^{2}, $v_3 = 7.82$ ft^3/lb, $u_3 = 1121.4$ Btu/lb

Kinetic and potential energy effects can be neglected. Determine the work and heat transfer for process 2–3, each in Btu.

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

(a) the total amount of energy stored in the battery, in kJ.

(b) the value of the stored energy, in \$, if electricity is valued at \$0.08 per kW · h.

3.35 (CD-ROM)

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

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

where t is time, in h, and $\dot{W}$ is in kW.

(a) What is the time rate of change of system energy at $t = 0.6$ h, in kW?

(b) Determine the change in system energy after 2 h, in kJ.

3.37 (CD-ROM)

3.38 A gas expands in a piston–cylinder assembly from $p_1 = 8.2$ bar, $V_1 = 0.0136$ m^3 to $p_2 = 3.4$ bar in a process during which the relation between pressure and volume is $pV^{1.2} =$ *constant*. The mass of the gas is 0.183 kg. If the specific internal energy of the gas *decreases* by 29.8 kJ/kg during the process, determine the heat transfer, in kJ. Kinetic and potential energy effects are negligible.

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

(a) the specific volume at the final state, in m^3/kg

(b) the energy transfer by work, in kJ.

(c) the change in specific internal energy of the air, in kJ/kg.

3.40 A gas is contained in a closed rigid tank. An electric resistor in the tank transfers energy *to* the gas at a constant rate of 1000 W. Heat transfer between the gas and the surroundings occurs at a rate of $\dot{Q} = -50t$, where $\dot{Q}$ is in watts, and t is time, in min.

(a) Plot the time rate of change of energy of the gas for $0 \leq t \leq 20$ min, in watts.

(b) Determine the net change in energy of the gas after 20 min, in kJ.

(c) If electricity is valued at \$0.08 per kW · h, what is the cost of the electrical input to the resistor for 20 min of operation?

3.41 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.

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

3.43 Air is contained in a vertical piston–cylinder assembly by a piston of mass 50 kg and having a face area of 0.01 m^2. The mass of the air is 4 g, and initially the air occupies a volume of 5 liters. The atmosphere exerts a pressure of 100 kPa on the top of the piston. Heat transfer of magnitude 1.41 kJ occurs slowly from the air to the surroundings, and the volume of the air decreases to 0.0025 m^3. Neglecting friction between the piston and the cylinder wall, determine the change in specific internal energy of the air, in kJ/kg.

3.44 (CD-ROM)

Thermodynamic Cycles

3.45 The following table gives data, in kJ, for a system undergoing a thermodynamic cycle consisting of four processes in series. For the cycle, kinetic and potential energy effects can be neglected. Determine

(a) the missing table entries, each in kJ.

(b) whether the cycle is a power cycle or a refrigeration cycle.

Process	ΔU	Q	W
1–2			−610
2–3	670		230
3–4		0	920
4–1	−360		0

3.46 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	950	50	0		1000	
2		0	50	−450		450
3	−650		0	−600		0
4	200	−100	−50		0	

3.47 A gas undergoes a thermodynamic cycle consisting of three processes:

Process 1–2: compression with $pV = constant$, from $p_1 = 1$ bar, $V_1 = 1.6$ m^3 to $V_2 = 0.2$ 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?

3.48 (CD-ROM)

3.49 A closed system undergoes a thermodynamic cycle consisting of the following processes:

Process 1–2: adiabatic compression with $pV^{1.4} = constant$ from $p_1 = 50$ lbf/in.^{2}, $V_1 = 3$ ft^3 to $V_2 = 1$ ft^3

Process 2–3: constant volume

Process 3–1: constant pressure, $U_1 - U_3 = 46.7$ Btu

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 Btu.

(c) Calculate the heat transfer for process 2–3, in Btu.

3.50 For a power cycle operating as in Fig. 3.8*a*, the heat transfers are $Q_{in} = 25{,}000$ kJ and $Q_{out} = 15{,}000$ kJ. Determine the net work, in kJ, and the thermal efficiency.

3.51 (CD-ROM)

3.52 The net work of a power cycle operating as in Fig. 3.8*a* is 8×10^6 Btu, and the heat transfer Q_{out} is 12×10^6 Btu. What is the thermal efficiency of the power cycle?

3.53 (CD-ROM)

3.54 A power cycle receives energy by heat transfer from the combustion of fuel at a rate of 300 MW. The thermal efficiency of the cycle is 33.3%.

(a) Determine the net rate power is developed, 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 the net work, in \$/year.

3.55 (CD-ROM)

3.56 For each of the following, what plays the roles of the hot body and the cold body of the appropriate Fig. 3.8 schematic?

(a) Window air conditioner

(b) Nuclear submarine power plant

(c) Ground-source heat pump

3.57 A refrigeration cycle operating as shown in Fig. 3.8*b* has heat transfer $Q_{out} = 3200$ Btu and net work of $W_{cycle} = 1200$ Btu. Determine the coefficient of performance for the cycle.

3.58 (CD-ROM)

3.59 A refrigeration cycle removes energy from the refrigerated space at a rate of 12,000 Btu/h. For a coefficient of performance of 2.6, determine the net power required, in Btu/h. Convert your answer to horsepower.

3.60 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.

3.61 (CD-ROM)

3.62 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.

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

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

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

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

3.8 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 $g = 32.0 \text{ ft/s}^2$.

3.11 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

$$F_r = f\mathscr{W}, \qquad F_D = C_D A \tfrac{1}{2}\rho V^2$$

where f and C_D are constants known as the rolling resistance coefficient and drag coefficient, respectively, $\mathscr{W}$ 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 $\mathscr{W} = 3550$ lbf, $A = 23.3 \text{ ft}^2$, and $C_D = 0.34$, and when $f = 0.02$ and $\rho = 0.08 \text{ lb/ft}^3$, determine the power required, in hp, to overcome rolling resistance and aerodynamic drag when V is 55 mi/h.

3.13 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. 3.9 along with the result of part (a).

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

3.15 Air is compressed in a piston–cylinder assembly from an initial state where $p_1 = 30 \text{ lbf/in.}^2$ and $V_1 = 25 \text{ ft}^3$. The relationship between pressure and volume during the process is $pV^{1.4} = constant$. For the air as the system, the work is −62 Btu. Determine the final volume, in ft^3, and the final pressure, in lbf/in^2.

3.22 For the cycle of Problem 2.26, determine the work for each process and the *net* work for the cycle, each in kJ.

3.27 For *your* lifestyle, estimate the monthly cost of operating the following household items: microwave oven, refrigerator, electric space heater, personal computer, hand-held hair drier, a 100-W light bulb. Assume the cost of electricity is \$0.08 per kW · h.

3.32 As shown in Fig. P3.32, 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.

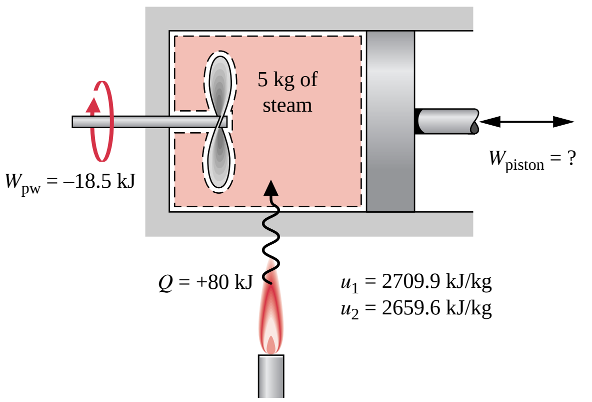


Figure P3.32

3.35 An electric motor operating at steady state requires an electric power input of 1 Btu/s. Heat transfer occurs from the motor to the surroundings at temperature T_o at a rate of $hA(T_b - T_o)$ where T_b is the average surface temperature of the motor, $hA = 10$ Btu/h · °R, and $T_o = 80$°F. The torque developed by the shaft of the motor is 14.4 ft · lbf at a rotational speed of 500 RPM. Determine T_b, in °F.

3.37 A storage battery develops a power output of

$$\dot{W} = 1.2 \exp(-t/60)$$

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

(a) plot the power output, in kW, and the change in energy of the battery, in kJ, each as a function of time.

(b) What are the limiting values for the power output and the change in energy of the battery as $t \rightarrow \infty$? Discuss.

3.44 A gas contained within a piston–cylinder assembly is shown in Fig. P3.44. Initially, the piston face is at $x = 0$ and the spring exerts no force on the piston. As a result of heat transfer, the gas expands, raising the piston until it hits the stops. At this point the piston face is located at $x = 0.06$ m, and the heat transfer ceases. The force exerted by the spring on the piston as the gas expands varies linearly with x according to

$$F_{\text{spring}} = kx$$

where $k = 9000$ N/m. Friction between the piston and the cylinder wall can be neglected. The acceleration of gravity is $g = 9.81$ m/s^2. Additional information is given on Fig. P3.44.

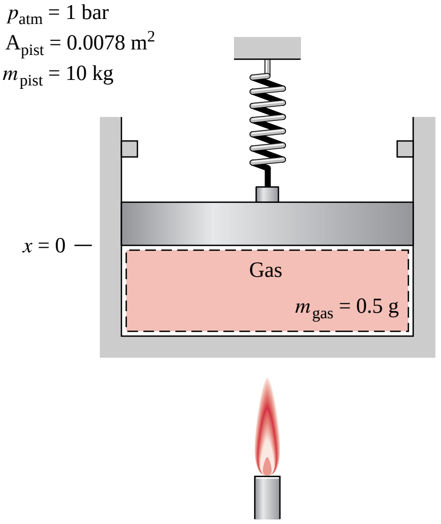


Figure P3.44

(a) What is the initial pressure of the gas, in kPa?
(b) Determine the work done by the gas on the piston, in J.
(c) If the specific internal energies of the gas at the initial and final states are 210 and 335 kJ/kg, respectively, calculate the heat transfer, in J.

3.48 A gas undergoes a thermodynamic cycle consisting of three processes:

Process 1–2: constant volume, $V = 0.028$ 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?

3.51 The thermal efficiency of a power cycle operating as shown in Fig. 3.8*a* is 30%, and $Q_{out} = 650$ MJ. Determine the net work developed and the heat transfer Q_{in}, each in MJ.

3.53 For a power cycle operating as in Fig. 3.8*a*, $W_{cycle} = 800$ Btu and $Q_{out} = 1800$ Btu. What is the thermal efficiency?

3.55 A power cycle has a thermal efficiency of 35% 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 the electricity generated per year.
(b) the annual fuel cost.

3.58 A refrigeration cycle operates as shown in Fig. 3.8*b* with a coefficient of performance $\beta = 2.5$. For the cycle, $Q_{out} = 2000$ kJ. Determine Q_{in} and W_{cycle}, each in kJ.

3.61 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.

Example 3.6 Transient Operation of a Motor

Solution

Known: A motor operates with constant electric power input, shaft speed, and applied torque. The time-varying rate of heat transfer between the motor and its surroundings is given.

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

Schematic and Given Data:

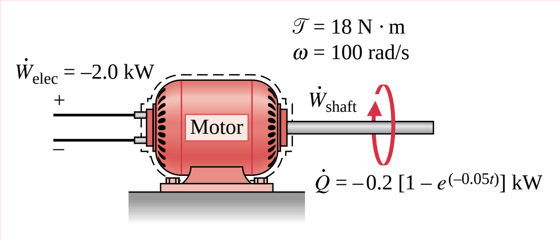


Figure E3.6

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

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. 3.5 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

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

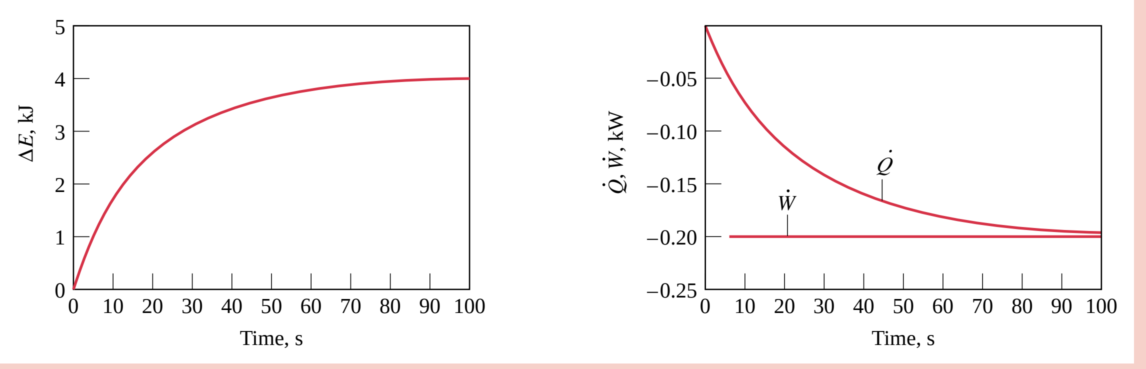
Integrating

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

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

❶ The accompanying plots 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 negative. In the first few seconds, the *net* rate that energy is carried in by work greatly exceeds the rate energy is carried out by heat transfer. Consequently, the energy stored in the motor increases rapidly as the motor "warms up." As time elapses, the value of $\dot{Q}$ approaches $\dot{W}$, and the rate of energy storage diminishes. After about 100 s, this *transient* operating mode is nearly over, and there is little further change in

❷ the amount of energy stored, or in any other property. We may say that the motor is then at steady state.



◁

❶ These plots can be developed using appropriate software or can be drawn by hand.

❷ At steady state, the value of $\dot{Q}$ is constant at -0.2 kW. This constant value for the heat transfer rate can be thought of as the portion of the electrical power input that is not obtained as a mechanical power output because of effects within the motor such as electrical resistance and friction.