INTRODUCTION

THERMODYNAMIC SYSTEM AND ITS INTERACTIONS WITH THE SURROUNDINGS

Thermodynamics is a word derived from the Greek words *thermo* (meaning energy or temperature) and *dunamikos* (meaning movement). Its origin began as the study of converting *heat* to *work*, that is, energy into movement. Today, scientists use the principles of thermodynamics to study the physical and chemical properties of matter. Engineers, however, apply thermodynamic principles to understand how the state of a practical system responds to interactions—transfer of *mass*, *heat*, and *work*—between the system and its surroundings. This understanding allows for more efficient designs of thermal systems that include steam-power plants, gas turbines, rocket engines, internal combustion engines, refrigeration plants, and air-conditioning units.

This chapter lays down the foundation by introducing a system, its surroundings, and all possible interactions between them in the form of mass, heat, and work transfer. A thorough understanding of these interactions is necessary for any thermodynamic analysis, whose major goal is to predict how a system responds to such interactions or, conversely, to predict the interactions necessary to bring about certain changes in the system. Properties will be discussed in Chapter 1 to keep the focus on mass, heat, and work interactions.

Throughout this book, we will adhere to *Système International d’Unités* (SI units), in developing theories and understanding basic concepts, while using mixed units—a combination of SI and English system units—for problem solving.

The accompanying courseware, The Expert System for Thermodynamics (TEST), accessible from www.pearsonhighered.com/bhattacharjee, will be used throughout this book for several purposes. The online video tutorials are the best resource to get current information on frequently used modules: (i) animations that are used to supplement discussions throughout this textbook; (ii) web-based thermodynamic calculators called TESTcalc that are used as a numerical laboratory to develop a quantitative understanding of thermodynamic properties, step-by-step verification of manual solutions, and occasional “what-if” studies that provide deeper insights; (iii) Interactives that simulate thermodynamic systems, such as compressors, turbines, nozzles, internal combustion engines, etc., for exploring system behavior; and (iv) traditional and interactive tables and charts.

0.1 THERMODYNAMIC SYSTEMS

We are all familiar with the concept of a free-body diagram from our study of mechanics. To analyze the force balance on a body, or a portion of it, we isolate the region of interest with real or fictitious boundaries, call it a *free body*, and identify all relevant external forces that act on the surface and interior of the free body. For example, to determine the net reaction force, $R$, necessary to keep the book stationary (or moving without any acceleration) in Figure 0.1, we isolate the book and draw all the vertical forces acting on it. The ambient air applies uniform pressure all over the exposed surfaces. As a result there is no net contribution from the atmospheric pressure. Although pressure will be formally discussed in Sec. 1.5.5, it is sufficient for now to define *pressure* as the intensity of perpendicular compressive forces exerted by a fluid on a surface. In SI units, pressure is measured in kN/m² or kPa and in English units it is measured in lb/in² psi. To maintain mechanical equilibrium (no unbalanced force), the reaction force $R$ in Figure 0.1, therefore, must be equal to the book’s weight.

Applying the same process, we can obtain the pressure inside the piston-cylinder device of Figure 0.2 by drawing all the vertical forces acting on the piston after it has been

**FIGURE 0.1** Free-body diagram of a textbook (see Anim. 0.A.weight).
isolated in a free-body diagram. The steps involved in such an analysis are illustrated in Anim. 0.A.

In thermodynamics, a system is broadly defined as any entity of interest within a well-defined boundary. Just as a free-body diagram helps us analyze the force balance on a body, a thermodynamic system helps us analyze the interactions between a system and its surroundings.

Unlike a system in mechanics, a thermodynamic system does not need to have a fixed mass; it can be a practical device such as a pump or a turbine with all its possible interactions with its surroundings—whatever lies outside its boundary. Even a complete vacuum can constitute a valid (and interesting) system. A system’s boundary is carefully drawn with the objective of separating what is of interest from its surroundings. For example, if the hot coffee within the black boundary in Figure 0.3 constitutes the system, then everything else—the mug, the desk, and the rest of the world for that matter—make up the surroundings. Collectively, the system and its surroundings form the thermodynamic universe.

A boundary can be real or imaginary, rigid or non-rigid, stationary or mobile, and internal or external with respect to a wall. The physical wall of a system, such as a pump’s casing or the mug in Figure 0.3, is often considered a non-participant within the interactions between the system and its surroundings. As a result, the boundary can be placed internally or externally (outlined in black and red, respectively, in Fig. 0.3) without affecting the solution. The term internal system is sometimes used to identify the system bordered within the internal boundary. In this book, the external boundary passing through the ambient atmospheric air (as in Fig. 0.2) will be our default choice for a system boundary unless an analysis requires consideration of the internal system.

The material that constitutes or flows through a system is called the working substance. While the gasoline-air mixture in the cylinder of an automobile engine and steam flowing through a turbine are the working fluids of their respective systems, internal hardware such as the spark plug in the cylinder or blades inside the turbine can be considered non-participants and excluded from a thermodynamic analysis.

**EXAMPLE 0-1** Free-Body Diagram

In Figure 0.4, the area of the piston is 25 cm², the mass of the hanging weight is 10 kg, the atmospheric pressure is 100 kPa, and the acceleration due to gravity is 9.81 m/s². Determine (a) the pressure inside the cylinder in kN/m². What-if scenario: (b) What is the maximum possible mass that this configuration can support?

**SOLUTION**

Draw a free-body diagram of the piston and balance the horizontal forces.

**Assumptions**

Neglect friction, if any, between the piston and the cylinder.
Analysis

Figure 0.4 shows the free-body diagram of the piston and all the horizontal forces that act on it. Because the piston has no acceleration (it is in mechanical equilibrium), a horizontal force balance yields:

\[ p_i A_{\text{piston}} + \frac{mg}{(1000 \text{ N/kN})} = p_0 A_{\text{piston}}; \]
\[ \begin{align*}
\text{kN/m}^2 &= \text{kg m/s}^2 \text{N} = \text{kN}
\end{align*} \]

\[ \Rightarrow p_i = p_0 - \frac{mg}{(1000 \text{ N/kN})A_{\text{piston}}} = 100 - \frac{(10)(9.81)}{(1000 \text{ N/kN})(25 \times 10^{-4})} = 60.76 \text{ kN/m}^2 \]

What-if scenario

As \( m \) increases, the piston moves to the right and new equilibrium positions are established. With \( p_0 \) and \( A_{\text{piston}} \) remaining constant, \( p_i \) will decrease according to the horizontal force balance equation. The minimum value of \( p_i \) is zero (a negative absolute pressure is impossible since pressure is always compressive). Therefore, the maximum mass that can be supported by the atmospheric pressure is:

\[ m_{\text{max}} = \left( \frac{1000 \text{ N/kN}}{g} \right) \frac{p_0 A_{\text{piston}}}{p_i} \]

\[ \Rightarrow m_{\text{max}} = \left( \frac{1000 \text{ N/kN}}{9.81} \right) \frac{(100)(25 \times 10^{-4})}{(1000 \text{ N/kN})(25 \times 10^{-4})} = 25.48 \text{ kg} \]

Discussion

Notice the use of SI units in this problem. The unit of force used in thermodynamics is kN, as opposed to N in mechanics. The familiar expression for weight, \( mg \), therefore must be divided by a unit conversion factor of 1000 N/kN 1000 to express the force in kN. View Anim. 0.A. vacuumPressure and similar animations for further insight on the application of free-body diagrams.

0.2 TEST AND ANIMATIONS

As stated earlier, we will make frequent references to different modules of TEST. A task bar at the top of the home page provides access to all the modules.

The structure of this book closely follows the organization of animations in TEST. They are referenced by a standard format—a short title for the animation is preceded by the section number and chapter number. For example, Anim. 0.D. heatingValue can be accessed by launching TEST, and clicking the Animation tab, selecting Chapter 0, Section D, and heatingValue from the drop-down menu located in the control panel of the Animation tab. Many animations have radio-buttons with interactive features. In this animation, for example, you can toggle among heat release from cookies, wine, and gasoline by selecting the corresponding radio-buttons. The Interactives, which can be used for advanced analysis and thermal system design, have the same look and feel as the animations, but take the concept further when a complete thermal system, such as a gas turbine or a combustion chamber, is simulated.

0.3 EXAMPLES OF THERMODYNAMIC SYSTEMS

The definition of a thermodynamic system—any entity inside a well-defined boundary—can make the scope of thermodynamic analysis mind-boggling. Through suitable placement of a boundary, systems can be identified in applications ranging from power plants, internal combustion engines, rockets, and jet engines to household appliances, such as air conditioners, gas ranges, pressure cookers, refrigerators, water heaters, propane tanks, and even hair dryers.

An overview of the thermodynamic systems we are going to analyze across this textbook are presented in Sec. 0.B (System Tour) of the Animations module. As you browse through these systems, there seems to be little in common among this diverse range of devices. Yet, when

DID YOU KNOW?

- A 102-kg (225-lb) person weighs about 1 kN.
- In thermodynamic applications, N is too small for practical use. For instance, atmospheric pressure is around 100 kPa or 100,000 N/m². To avoid use of large numbers, kN and kPa are preferable SI units for force and pressure.
some of these systems are examined more closely through animations in Sec. 0.C (interactions) and in Figure 0.5, they reveal a remarkably similar pattern in how they interact with their surroundings. Let’s consider a few specific examples and explore these interactions throughout this chapter, qualitatively at first:

1. When we lift a car’s hood, most of us are amazed by the complexity of the modern automobile engine. However, if we familiarize ourselves with how an engine works, we can understand the simplified system diagram shown in Figure 0.5(a). While the transfer of mass (in the form of air, fuel, and exhaust gases) and work (through the crankshaft) are obvious, to detect the heat radiating from the hot engine we have to get close enough to feel the heat.

2. Two rigid tanks containing two different gases are connected by a valve in Figure 0.5(b). As the valve is opened, the two working fluids flow and diffuse into each other, eventually forming a uniform mixture. In analyzing this mixing process, we can avoid the complexity associated with the transfer of mass between the two tanks if we draw the boundary to encompass both tanks. Furthermore, if the system is insulated, there can be no mass, heat, or work transfer during the mixing process.

3. The piston-cylinder device of Figure 0.5(c) is the heart of all internal combustion engines and also is found in reciprocating pumps and compressors. If the working fluid trapped inside is chosen as the system, there is no mass transfer. Furthermore, if the compression takes place rapidly, there is little time for any significant transfer of heat. The transfer of work between the system and its surroundings requires analyzing the displacement of the piston (boundary) due to the internal and external forces present.

4. Now, consider the completely evacuated rigid tank of Figure 0.5(d). As the valve is opened, outside air rushes in to fill up the tank and equalize the inside and outside pressures. What is not trivial about this process is that the air that enters becomes hot—hotter than the boiling temperature of water at atmospheric pressure. Mass and work transfer occur as the outside atmosphere pushes air in, but heat transfer may be negligible if the tank is insulated or the process takes place rapidly.

5. Let’s now consider the household refrigerator shown in Figure 0.5(e). Energy is transferred into the system through the electric cord (to run the compressor), which constitutes work transfer in the form of electricity. Although a refrigerator is insulated, some amount of heat...
leaks in through the seals and walls into the cold space maintained by the refrigerator. To keep the refrigerator temperature from going up, heat must be “pumped” out of the system. If we locate the condenser, a coil of narrow-finned tube placed behind or under the refrigerator, we will find it to be warm. Heat, therefore, must be rejected into the cooler atmosphere, thereby removing energy from the refrigerator. For this system, heat and electrical work transfer are the only interactions.

6. Finally, the steam turbine of Figure 0.5(f) extracts part of the useful energy transported by the working fluid through the turbine and delivers it as external work to the shaft. Although the boundary of the extended system may enclose all the physical hardware—casing, blades, nozzles, shaft, etc.—the actual analysis only involves mass, heat, and work transfer across the boundary and the presence of the hardware can be ignored without any significant effect on the solution.

Here, our focus has been on the interactions between the system and the surroundings at the boundary. There is no need to complicate a system diagram with the complexities of non-participating hardware. The abstract or generic system shown in Figure 0.6 can represent each system discussed in this section adequately, as it incorporates all possible interactions between a system and its surroundings. The choice of an external (red) or internal (black) boundary cannot change the nature or the degree of these interactions.

0.4 INTERACTIONS BETWEEN THE SYSTEM AND ITS SURROUNDINGS

A careful examination of the interactions discussed previously reveals that the interactions between a system and its surroundings fall into one of the three fundamental categories: transfer of mass, heat, or work (Fig. 0.6). A quantitative understanding of heat and work as energy in transit is essential in developing further concepts in the chapters that follow.

The simplest type of interaction is no interaction. A system segregated from its surroundings is called an isolated system. An isolated system can be complex and worth studying. The isolated system shown in Figure 0.7 contains oxygen and hydrogen, separated by a membrane; this system can undergo many changes if the membrane ruptures, triggering for example an exothermic reaction. Despite the heat released during this oxidation reaction, leading to a sharp rise in temperature and pressure, the system remains isolated as long as there are no interactions between the system and its surroundings. As we will discuss later, sometimes interactions among different subsystems can be internalized by drawing a large boundary encompassing the subsystems so that the combined system is isolated (as in Fig. 0.5b). Carefully choosing a boundary can sometimes simplify complex analysis.

0.5 MASS INTERACTION

Mass interactions between a system and its surroundings are the easiest to recognize. Mass is the measure of amount of matter in a system. Mass cannot be created or destroyed, only transported. Mass interactions between a system and its surroundings are the easiest to recognize. Usually ducts, pipes, or tubes connected to a system transport mass across the system’s boundary. Depending on whether they carry mass in or out of the system, they are called either inlet or exit ports and are identified by the generic indices \( i \) and \( e \). (Note: the term outlet is avoided in favor of exit so that the symbol \( o \) can be reserved to indicate ambient properties.) The mass flow rate, defined as the amount of fluid that passes through a cross-section per-unit time and measured in \( \text{kg/s} \), is always represented by the symbol \( m \) (mdot in TEST). Thus, \( m_i \) and \( m_e \) symbolize the mass flow rates at the inlet \( i \) and exit \( e \) of the turbine in Figure 0.5(f). The dot on a thermodynamic symbol represents the rate of transport of a property as opposed to a time derivative in calculus. Thus, a system’s time rate of change of mass is represented by \( dm/dt \), not \( m \). The volume flow rate, the volume of fluid that passes through a cross-section, per-unit time measured in \( m^3/s \), can be regarded as the rate of transport of fluid volume and represented by the symbol \( V \) (Vdot in TEST).

To derive formulas for \( V \) and \( m \) at a given cross-section in a variable-area duct, consider Figure 0.8 in which the shaded differential element crosses the surface of interest (shown by the red line) in time \( \Delta t \). The volume and mass of
that element are given by $A \Delta x$ and $\rho A \Delta x$, respectively, where $A$ is the cross-sectional area and $\Delta x$ is the element’s length. The corresponding flow rates, therefore, are given by the following transport equations:

$$\dot{V} = \lim_{\Delta t \to 0} \frac{A \Delta x}{\Delta t} = A \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = AV; \quad \left[ \frac{m^3}{s} = \frac{m^2}{s} \right] \quad (0.1)$$

$$\dot{m} = \lim_{\Delta t \to 0} \frac{\rho(A \Delta x)}{\Delta t}; \quad \Rightarrow \dot{m} = \rho AV = \rho \dot{V}; \quad \left[ \frac{kg}{s} = \frac{kg m^3}{s} \right] \quad (0.2)$$

These equations express the instantaneous values of volume and mass flow rates, $\dot{V}$ and $\dot{m}$, at a given cross section in terms of flow properties $A$, $V$, and $\rho$. Implicit in this derivation is the assumption that $V$ and $\rho$ do not change across the flow area, and are allowed to vary only along the axial direction. This assumption is called the bulk flow or one-dimensional flow approximation, which restricts any change in flow properties only in the direction of the flow. In situations where the flow is not uniform, the average values (see Fig. 0.9) of $V$ and $\rho$ can be used in Eqs. (0.1) and (0.2) without much sacrifice in accuracy.

One way to remember these important formulas is to visualize a solid rod moving with a velocity $V$ past a reference mark as shown in Figure 0.10. Every second $AV$ m$^3$ of solid volume and $\rho AV$ kg of solid mass moves past that mark, which are the volume flow rate $\dot{V}$ and mass flow rate $\dot{m}$ of the solid flow respectively.

Mass transfer, or the lack of it, introduces the most basic classification of thermodynamic systems: those with no significant mass interactions are called closed systems and those with significant mass transfer with their surroundings are called open systems. Always assume a system is open unless established otherwise. The advantage to this assumption is that any equation derived for a general open system can be simplified for a closed system by setting terms involving mass transfer, called the transport terms, to zero.

A simple inspection of the system’s boundary can reveal if a system is open or closed. Open systems usually have inlet and/or exit ports carrying the mass in or out of the system. As a simple exercise, classify each system shown in Figure 0.5 as an open or closed system. Also, see animations in Sec. 0.C again, this time inspecting the system boundaries for any possible mass transfer. Select the Mass, Heat, or Work radio-button to identify the locations of a specific interaction. Sometimes the same physical system can be treated as an open or closed system depending on how its boundary is drawn. The system shown in Figure 0.11, in which air is charged into an empty cylinder, can be analyzed based on the open system, marked by the red boundary, or the closed system marked by the black boundary constructed around the fixed mass of air that passes through the valve into the cylinder.

**EXAMPLE 0-2** Mass Flow Rate

A pipe of diameter 10 cm carries water at a velocity of 5 m/s. Determine (a) the volume flow rate in m$^3$/min and (b) the mass flow rate in kg/min. Assume the density of water to be 997 kg/m$^3$.

**SOLUTION**

Apply the volume and mass transport equations: Eqs. (0.1) and (0.2).

**Assumptions**

Assume the flow to be uniform across the cross-sectional area of the pipe with a uniform velocity of 5 m/s (see Fig. 0.12).

**Analysis**

The volume flow rate is calculated using Eq. (0.1):

$$\dot{V} = AV = \frac{\pi (0.1)^2}{4} (5) = 0.0393 \, \frac{m^3}{s} = 2.356 \, \frac{m^3}{min}$$
The mass flow rate is calculated using Eq. (0.2):

\[ \dot{m} = \rho AV = \left(997\right) \frac{\pi(0.1^2)}{4} = 39.15 \text{ kg/s} = 2349 \text{ kg/min} \]

**TEST Analysis**

Although the manual solution is simple, a TEST analysis still can be useful in verifying results.

To calculate the flow rates:

1. Navigate to the TESTcalcs > States > Flow page;
2. Select the SL-Model (representing a pure solid or liquid working substance) to launch the SL flow-state TESTcalc;
3. Choose Water (L) from the working substance menu, enter the velocity (click the check box to activate input mode) and area (use the expression ‘=PI*0.1^2/4’ with the appropriate units), and press Enter. The mass flow rate (mdot1) and volume flow rate (Voldot1) are displayed along with other flow variables;
4. Now select a different working substance and click Calculate to observe how the flow rate adjusts according to the new material’s density.

**Discussion**

Densities of solids and liquids often are assumed constant in thermodynamic analysis and are listed in Tables A-1 and A-2. Density and many other properties of working substances are discussed in Chapter 1.

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**0.6 TEST AND THE TESTcalcs**

**TESTcalcs**, such as the one used in Example 0-2, are dedicated thermodynamic calculators that can help us verify a solution, visualize calculations in thermodynamic plots, and pursue “what-if” studies. Go through My First Solution in the Tutorial for a step-by-step introduction to a TESTcalc. Although there are a large number of TESTcalcs, they are organized in a tree-like structure (visit the TESTcalcs module) much like thermodynamic systems (e.g., open, closed, etc.). Each TESTcalc is labeled with its hierarchical location (see Fig. 0.13), which is a sequence of simplifying assumptions. For example, a page address \( x > y > z \) means that assumptions \( x, y, \) and \( z \) in sequence lead one into that particular branch of TESTcalcs to analyze the corresponding thermodynamic systems. To launch the SL flow-state TESTcalc click the Flow State node of the TESTcalcs, states, flow state branch to display all available models, and then the SL model icon.

Launch a few TESTcalcs and you will realize that they look strikingly similar, sometimes making it hard to distinguish one from another. Once you learn how to use one TESTcalc, you can use any other TESTcalc, without much of a learning curve. The I/O panel of each TESTcalc also doubles as a built-in calculator that recognizes property symbols. To evaluate any arithmetic expression, simply type it into the I/O panel beginning with an equal sign—use the syntax as in: \( \text{exp(-2)}*\sin(30) = \text{PI}*(15/100)^2/4 \), etc.—and press Enter to evaluate the expression. In the TEST solution of Example 0-2, you can use the expression ‘\( \rho_1\text{Vel1*A1} \)’ to calculate the mass flow rate at State-1 in the I/O panel.

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**0.7 ENERGY, WORK, AND HEAT**

Recall that there are only three types of possible interactions between a system and its surroundings: mass, heat, and work. In physics, heat and work are treated as different forms of energy, but in engineering thermodynamics, an important distinction is made between energy stored in a system and energy in transit. Heat and work are energies in transit—they lose their individual identity and become part of stored energy as soon as they enter or leave a system (see Fig. 0.14). Therefore, an understanding of energy is crucial.

Like mass, energy is difficult to define. In mechanics, energy is defined as the measure of a system’s capacity to do work, that is, how much work a system is capable of delivering. Then again, we need a definition for work, a precise definition
A typical house consumes about 40% of all the oil produced in the world.

About 500 billion dollars were spent on energy in the United States in year 2000.

A typical house consumes about 1 kW of electric power on average.

Passenger vehicles can deliver 20–200 kW of shaft power depending on the size of the engine.

In 2000, America produced more than 3.5 trillion kWh of electricity.

Table 0-1  Contribution from various sources to world energy consumption of 400 Quad (1 Quad = 1015 BTU or 1,055 x 1015 kJ) in year 2000 (see Anim. 0.D.energyStats).

<table>
<thead>
<tr>
<th>Source</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>40%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>23%</td>
</tr>
<tr>
<td>Coal</td>
<td>23%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>6.5%</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>7%</td>
</tr>
<tr>
<td>Others</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

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DID YOU KNOW?

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From our daily life experience, we know that gravitational potential energy (PE) can be easily converted to KE through a free fall of the system. Hence a system with higher PE must possess higher stored energy (see Anim. 0.D.pe). In fact, whenever a system is pushed or pulled by a force field (interconnected springs, electrical or magnetic fields, etc.), different modes of potential energy may arise. In this textbook, we will consider gravitational potential energy, represented by the symbol PE, as the only mode of potential energy (all other modes of PE are excluded in the kind of systems we generally study in engineering thermodynamics). The mechanical energy of a system is defined as the sum of its KE and PE (see Anim.0.D.mechanicalEnergy). Mechanical energy involves behavior (speed or position) of a system observable with naked eyes; KE and PE are, therefore, called macroscopic energy.

Besides mechanical energy, there are other modes of energy storage. After all, systems with little or no KE and PE can be used to lift a weight as shown in Anim. 0.D.aConstructive. Likewise, the battery of Figure 0.14, with no appreciable KE or PE, can be used to raise a weight. Similarly, fossil fuels with relatively little KE and PE possess enormous capacity for doing work or causing destruction (see Anim. 0.D.aDestructive). To appreciate how energy is stored in a system besides the familiar macroscopic modes (KE and PE), we must examine things at the microscopic level. Molecules or microscopic particles that comprise a system can also possess KE due to random or disorganized motion that is not captured in the macroscopic KE. For example, in a stationary solid crystal with zero macroscopic KE, a significant amount of energy can be stored in the vibrational KE of the molecules. Although molecular vibrations inside a solid cannot be seen with the naked eye, their effect can be directly felt as the solid’s temperature, which is proportional to the average microscopic KE of the molecules (see Anim. 0.D.uVibrationKE). For gases, molecular KE can have different modes such as translation, rotation, and vibration as illustrated in Anim. 0.D.uGasMoleculeKE. Temperature, for gases; however, is directly proportional to the average translational KE. Microscopic particles can also have PE, energy that can be easily converted to KE, which arises out of inter-particle forces. At the microscopic level, gravitational forces are very weak; but several much stronger forces such as molecular binding forces, Coulomb forces between electrons and their nuclei, nuclear binding forces among protons and neutrons, etc., contribute to various modes of microscopic PE. When there is a change of phase or a chemical composition, the molecular PE can change drastically even if molecular KE (reflected by temperature) remain unchanged.

The aggregate of the various modes of kinetic and potential energies of the microscopic particles is a significant repository of a system’s stored energy. For thermodynamic analysis, all are lumped into a single property called U, the internal energy of the system. Terms, such as microscopic energy, chemical energy, electrical energy, electronic energy, thermal energy, nuclear energy, used in other fields, are redundant in thermodynamics since U incorporates them all. Given the numerous types of energies that it encapsulates, U is difficult to measure in absolute terms. All we can claim is that it must be positive for all systems and zero for a perfect vacuum. Fortunately, it is not necessary to know the absolute internal energy of a system. In most analyses, it is the change in internal energy that matters.

While a change in mechanical energy of a system can be associated with changes in velocity and elevation, a change in
0.7 Energy, Work, and Heat

$U$ can be associated with a change in temperature, transformation of phase (as in boiling), or a change of composition through chemical reactions. However, for a large class of solids, liquids, and gases, a change in $U$ often can be related to a change in temperature only.

Having explored all its components, the total stored energy, $E$, of a system can be defined as the sum of the microscopic and macroscopic contributions: $E = U + KE + PE$ (Fig. 0.15). The term “stored” is used to emphasize the fact that $E$ resides within the system as opposed to heat and work, which are always in transit. Clearly, the concept of $E$ is much more general than mechanical energy. By definition, energy is stored not only in wind or water in a reservoir at high altitude, but also in stagnant air and water at sea level. Classical thermodynamics does not allow conversion of mass into energy. Hence the symbol for stored energy, $E$, should not be confused with Einstein’s $E = mc^2$ formula that relates energy release to mass annihilation.

Although the unit J (joule) is used in mechanics for KE and PE, in thermodynamics the standard SI unit for stored energy $E$ (and its components) is kJ. It is a good idea at this point to estimate the kinetic energy of some familiar objects as benchmarks and use the converter TESTcalc (located in basic tools branch) to relate some common units of energy, such as MJ, kWh, BTU, Therm, and Calorie, to kJ. We will discuss stored energy and all its components quantitatively in Sec. 1.5.7.

Now that we have defined stored energy, it is easier to define heat and work as two fundamental ways in which energy can penetrate the boundary of a system. When there is a temperature difference between two objects, nature finds a way to transfer energy from the hotter object to the cooler object through heat transfer. The amount of heat transfer depends on the temperature difference between a system and its surroundings, the duration, area of contact, and insulation. The best way to deduce if a particular energy interaction qualifies as heat transfer is to mentally eliminate the temperature difference between the system and its surroundings; the energy transfer will come to a halt if it is heat transfer. The $E$ of the fluid in Figure 0.16 can be raised, as evident from an increase in temperature, by bringing the system in contact with a hotter body, such as placing the system on top of a flame or under focused solar radiation. In each case, energy crosses the boundary of the system through heat transfer driven by the temperature difference between the system and its surroundings. We will discuss heat transfer further in Sec. 0.7.1.

When a net external horizontal force acts on a rigid system (Fig. 0.17), Newton’s second law of motion can explain the increase in velocity. However, in thermodynamic terms, we realize that the KE and, hence, the stored energy of the system has increased. In the absence of any heat transfer, there must be another fundamental way in which energy must have crossed the boundary of this closed system. Through application of Newton’s law, it will be shown in Sec. 1.5.7 that the increase in the system’s energy exactly equals the integral of force times distance, which is the operational definition of work in mechanics. Likewise, when a system is raised, the PE component of $E$ increases as work (force times distance) is transferred in lifting the system upward with a force equal to its weight. We will discuss in detail different modes of work transfer associated with various types of force displacing its point of application in Sec. 0.8. The shaft in Fig. 0.18, for example, turns a paddle wheel and raises the KE and $U$ of the system by transferring shaft work.

Once heat or work enters a system and becomes part of the system’s stored energy, there is no way of knowing how the energy was originally transferred into the system. Like mass, energy cannot be destroyed or created, but only transferred. Terms such as heat storage or work storage have no place in thermodynamics, and are replaced by a more appropriate term: energy storage.

In a closed system, heat and work are the only ways in which energy can be transferred across a boundary. In an open system energy can also be transported across the boundary by mass. For example, when a pipeline carries oil, cold milk is added to hot coffee, or superheated vapor enters a steam turbine (Fig. 0.19), energy is transported by mass regardless of how hot or cold the flow is. Precisely how much energy is transported by a flow, of course, depends on the condition (state) of the flow; however, the direction of the transport is always coincident with the flow direction. We will discuss energy transport by mass in Sec. 1.5.8. Commonly used phrases such as heat flow or heat coming out of an exhaust pipe should be avoided in favor of the more precise term energy transport when energy is carried by mass.

To summarize the discussion in this section, energy is stored in a system as mechanical (KE and PE) and internal energy ($U$). Energy can be transported by mass and transferred across
the boundary through heat and work. An analogy—we will call this the lake analogy illustrated in Figure 0.20—may be helpful to distinguish energy from heat and work. This figure shows a partially frozen lake that represents an open system; the total amount of water represents the stored energy. Just as stored energy consists of internal and mechanical energies, water in the lake consists of liquid water and ice. The water in the stream (analogous to transport of energy by mass), rain (analogous to heat), and evaporation (analogous to work) are all different ways of affecting the amount of stored water (stored energy) in the lake. Just as rain or vapor is different from water in the lake, heat and work are different from the stored energy of a system. The lake cannot hold rain or vapor just as a system cannot hold heat or work. Right after a rainfall, the rainwater loses its identity and becomes part of the stored water in the lake; heat or work added to a system, similarly, becomes indistinguishable from the stored energy of the system once they are assimilated.

Carrying this analogy further, it is difficult to determine the exact amount of stored water in the lake, and the same is true about the absolute value of stored energy in a system. However, it is much easier to determine the change in the stored water by monitoring the water level. The change in stored energy also can be determined by monitoring quantities such as velocity, elevation, temperature, and phase and chemical composition of the working substance in a system. We will call upon this analogy again in later sections.

The discussion above is meant to emphasize the careful use of the terms heat, work, and stored energy in thermodynamics. In our daily lives and in many industries, the term energy continues to be loosely used. Thus, energy production in Table 0-1 actually means heat or work delivered from various sources. Another misuse of the term energy will be discussed when a property called exergy is introduced in Chapter 1.

**0.7.1 Heat and Heating Rate (Q, \(\dot{Q}\))**

The symbol used for heat is \(Q\). In SI units, stored energy and all its components as well as heat and work have the unit of kJ. An estimate for a kJ is the amount of heat necessary to raise the temperature by 1°C of approximately 0.24 kg of water or 1 kg of air. In the English system, the unit of heat is a Btu, the amount of heat required to raise the temperature of 1 lbm of water by 1°F. The symbol used for the rate of heat transfer is \(\dot{Q}\) (Qdot in TEST), which has the unit of kJ/s or kW in SI and Btu/s in the English system. If \(\dot{Q}\) is known as a function of time, the total amount of heat transferred, \(Q\), in a process that begins at time \(t = t_b\) and finishes at time \(t = t_f\), can be obtained from:

\[
Q = \int_{t_b}^{t_f} \dot{Q} \, dt; \quad [\text{kJ} = \text{kW} \cdot \text{s}]
\]

For a constant value of \(\dot{Q}\) during the entire duration \(\Delta t = t_f - t_b\), Eq. (0.3) simplifies to:

\[
Q = \dot{Q} \Delta t; \quad [\text{kJ} = \text{kW} \cdot \text{s}]
\]

In this book, the phrase heat transfer means \(Q\) or \(\dot{Q}\), depending on its context. For example, the heat transfer, \(Q\), necessary to raise the temperature of 1 kg of water from 20°C (room temperature) to 100°C (boiling point) is about 335 kJ. Whereas the heat transfer, \(Q\), necessary to vaporize water at 100°C at a rate of 1 kg/s is about 2.260 kW or 2.26 MW under atmospheric
pressure. The second heat transfer refers to the rate of heat transfer, which is evident from its units. A perfectly insulated system for which $Q$ or $\dot{Q}$ are zero is called an adiabatic system. Classification of systems based on different kinds of interactions is illustrated in Anim. 0.C, systemTypes.

We are all familiar with the heat released from the combustion of fossil fuels or calories released from food during metabolism. A fuel’s heating value (which, illustrated in Anim. 0.D, heatingValue, will be more thoroughly discussed in Chapter 13), is the magnitude of the maximum amount of heat that can be extracted by burning a unit mass of fuel with air when the products leave at atmospheric temperature. The heating value of gasoline can be looked up from Table G-2 (Tables link in TEST) as 44 MJ/kg. This means that to supply heat at the rate of 44 MW, at least 1 kg of gasoline has to be burned every second. If the entire amount of heat released is used to vaporize liquid water at 100°C under atmospheric pressure, $\frac{44}{2.26} = 19.5$ kg of water vapor will be produced for every kilogram of gasoline burned. In our daily lives, we see calorific values printed on food products. For example, a can of soda can release a maximum of 140 calories (or whatever amount is printed on the nutrition information) or 586 kJ (1 calorie = 4.187 kJ) of heat when metabolized.

Heat transfer can add or remove energy from a system. Hence it is bi-directional from the point of view of a system. A non-standard set of phrases such as heat gain, heat addition, heating rate, heat loss, heat rejection, and cooling rate, and symbols with special suffixes such as $Q_{\text{in}}$, $Q_{\text{out}}$, and $Q_{\text{loss}}$, are used to represent heat transfer in specific systems. With the subscripts specifying the direction of the transfer, symbols such as $Q_{\text{in}}$, $Q_{\text{out}}$, $Q_{\text{loss}}$, etc., represent only the magnitude of heat transfer, which makes it difficult to formulate equations involving heat transfer. A more mathematical approach is to treat $Q$ and $\dot{Q}$ as algebraic quantities and use algebraic signs to indicate the direction of heat transfer (Anim. 0.D, WinHip). For this, we need a standard definition of positive heat transfer.

The sign convention that dates back to the days of early steam engines attributes heat added to a system with a positive sign.

To illustrate this sign convention, suppose two bodies A and B have two different temperatures, say $T_A = 200^\circ$C and $T_B = 300^\circ$C, and are placed in thermal contact as shown in Figure 0.21. Now suppose at a given instant the rate of heat transfer from B to A is 1 kW. In drawing the systems A and B separately, the heat transfer arrows are pointed in the positive directions irrespective of the actual directions of the transfers. This is a standard practice unless suffixes are used to indicate directions. Algebraically, we therefore express the heat transfers for the two systems as $\dot{Q}_A = 1$ kW and $\dot{Q}_B = -1$ kW. Similarly, if heat is lost from a system at a rate of 1 kW, it is expressed as either $\dot{Q}_{\text{loss}} = 1$ kW or $\dot{Q} = -1$ kW. If a system transfers heat with multiple external reservoirs, the net heat transfer can be calculated by summing the components, provided that each component has the correct sign.

The lake analogy (Sec. 0.7) in which we associated heat with rain also holds for the sign of heat transfer. A positive heat transfer adds energy to a system just as rainfall tends to increase the amount of water in the lake (Fig. 0.22).

The details of how heat is transferred can be found in any heat transfer textbook and only the overall mechanisms are illustrated in Anim. 0.D, heatTransfer. Regardless of the mechanism, the magnitude of heat transfer depends on the temperature difference, exposed surface area, thermal resistance (insulation), and exposure time. A system, therefore, tends to be adiabatic not
only when it is well insulated, but also when the duration of a thermodynamic event is small. Quick compression of a gas in a piston-cylinder device, thus, can be considered adiabatic even if the cylinder is water-cooled.

In open systems, the inlet and exit ports usually have relatively small cross-sectional areas compared with the rest of the system’s boundary area. Moreover, the flow of mass through the ports moderates the temperature gradient in the direction of the flow. Therefore, the rate of heat transfer \( Q \) through the ports of an open system can be neglected even as the flow transports significant amounts of energy. ‘Heat flows out of an exhaust pipe,’ thus, is an incorrect statement for several reasons: first, it is mass that flows out transporting energy and second, heat transfer across an opening is generally negligible.

Sometimes the rate of heat transfer is not uniform over the entire boundary of a system. For example, a system may be in thermal contact with multiple thermal reservoirs (Fig. 0.23). The boundary in such situations is divided into different segments and the net heat transfer is obtained by summing the contribution from each segment:

\[
Q = \sum Q_i; \quad [\text{kJ}]; \quad \dot{Q} = \sum \dot{Q}_i; \quad [\text{kW}]
\]  

(0.5)

Various suffixes such as \( \text{net}, \text{in}, \text{out} \), etc., often are used in conjunction with particular system configurations, as clarified in Example 0-3 and Anim. 0.C.WinHip, to indicate the direction of heat transfer.

### EXAMPLE 0-3 Heat Transfer Sign Convention

The net heat transfer rate between a system and its three surrounding reservoirs (Fig. 0.24) is \( \dot{Q} = -1 \text{ kW} \). Heat transfer rate from reservoir A to the system is 2 kW and \( \dot{Q}_{\text{out}} \) is 4 kW. (a) Determine the heat transfer (including its sign) between the system and reservoir C. (b) Assuming heat transfer to be the only interaction between the system and its surroundings, determine the rate of change of the stored energy of the system in kJ/min.

**SOLUTION**

Let \( \dot{Q}_A \), \( \dot{Q}_B \), and \( \dot{Q}_C \) represent the heat transfer between the system and the reservoirs. Using the sign convention, we can write \( \dot{Q}_A = 2 \text{ kW} \) and \( \dot{Q}_B = -\dot{Q}_{\text{out}} = -4 \text{ kW} \). Therefore,

\[
\dot{Q} = \dot{Q}_A + \dot{Q}_B + \dot{Q}_C; \quad [\text{kW}]
\]

\[
\Rightarrow \dot{Q}_C = \dot{Q} - \dot{Q}_A - \dot{Q}_B = (-1) - (2) - (-4) = 1 \text{ kW}
\]

The positive sign of \( \dot{Q}_C \) means heat must be added at a rate of 1 kW from reservoir C to the system.

With no other means of energy transfer, the net flow of heat into the system, \( \dot{Q} = -1 \text{ kW} \), must be the rate at which the stored energy \( E \) accumulates (or depletes in this case) in a system. Therefore,

\[
\frac{dE}{dt} = \dot{Q} = -1 \text{ kW} = -1 \frac{\text{kJ}}{s} = -60 \frac{\text{kJ}}{\text{min}}
\]

**Discussion**

In practical systems, in which the directions of heat transfer are known or fixed by convention, use of algebraic signs is avoided in favor of subscripts, such as \( \text{in}, \text{out} \), etc.

### 0.7.2 Work and Power (\( W, \dot{W} \))

The symbol used for work is \( W \), and like heat or stored energy, it has the unit of kJ. In English units, however, work is expressed in ft \( \cdot \) lbf while heat is expressed in Btu. The rate of work transfer \( W \) is called **power**. (Note the consistent use of a dot to indicate a time rate.) In SI units, \( W \) has the same unit as \( Q: \text{kJ/s} \) or kW, but in English units, it has the unit of ft \( \cdot \) lbf/s. If \( W \) is a function of time, the total amount of work \( W \) transferred in a process that begins at time \( t = t_i \) and finishes at time \( t = t_f \) can be obtained from:
0.8 Work Transfer Mechanisms

While overall heat transfer without the details of heat transfer calculations often is adequate for thermodynamic analysis, a thorough understanding of different modes of work transfer is necessary. Although displacement by a force is at the root of all work transfer (upon close examination, any form of work transfer can be traced to the fundamental definition of force times distance), it is advantageous to classify work based on specific types of work interactions. Various mechanisms of work transfer are illustrated in Anim. 0.D.workTransfer and discussed below.

0.8.1 Mechanical Work ($W_M$, $\dot{W}_M$)

Mechanical work is the work introduced in mechanics (see Anim. 0.D.mechanicalWork). If $F$ is the component of a force in the direction of displacement $x$ of the rigid body shown in Figure 0.26, then the energy transfer due to mechanical work is given as

$$W_M = -\int_{x_b}^{x_f} F dx; \quad [\text{kJ} = \text{kN} \cdot \text{m}]$$

(0.8)

where $x_b$ and $x_f$ mark the beginning and final positions of the point of application. For a constant $F$, the integral reduces to:

$$W_M = -F(x_f - x_b) = -F \Delta x; \quad [\text{kJ} = \text{kN} \cdot \text{m}]$$

(0.9)

The negative sign in this definition arises due to the WinHip sign convention (Sec. 0.7.2), indicating work is going into the system. A force, by itself, cannot transfer any energy into a system unless it succeeds in moving the point of application. When a force of 1 kN (approximately the weight of 50 textbooks) displaces a system (its point of application) by 1 m, then 1 kJ of mechanical work is done by the force. In thermodynamic terms, 1 kJ of work is transferred into the system or, in algebraic terms, $W = W_M = -1$ kJ. Suppose a body moves in the positive $x$ direction from $x_b$ to $x_f$, and is acted on by two constant opposing forces $F_1$ and $F_2$, as shown in Figure 0.27. If $F_1 > F_2$, the body accelerates in the $x$ direction, which results in an increase in its kinetic energy and, hence, stored energy. $F_1 > F_2$ also implies that the net work $W_N = -(F_1 - F_2)(x_f - x_b)$ is negative, that is, energy is transferred into the system, which is stored as kinetic energy. Now
suppose $F_1$ is only momentarily greater than $F_2$ so that the body starts moving in the direction of $F_1$. Thereafter, $F_1 = F_2$ will keep the body moving in the same direction at a constant velocity. In this case, there is no net work transfer as the work transferred into the system equals the work done by the system. As another benchmark for 1 kJ of work, consider the weightlifter in Figure 0.28 exerting an upward force of $0.981 \text{kN}$ to keep the 100-kg weight from falling ($g = 9.81 \text{m/s}^2$). Suppose the weightlifter succeeds in moving the weights up a distance of 1.02 m. In that case, the minimum work transferred to the weights is 1 kJ, that is, $W = W_M = -1 \text{kJ}$, which is stored as the weights’ (system’s) PE.

The time rate of work transfer, $W_M$, is called mechanical power and can be expressed in the instantaneous velocity of the system as follows (see Fig. 0.29):

$$W_M = -\lim_{\Delta t \to 0} \frac{F \Delta x}{\Delta t} = -FV; \quad \left[ \text{kN} \cdot \frac{\text{m}}{\text{s}} = \frac{\text{kJ}}{\text{s}} = \text{kW} \right]$$

(0.10)

The negative sign is necessary to comply with the WinHip sign convention. Using Eq. (0.10), it can be shown that a 100-kW engine can lift a 1000-kg weight vertically at a velocity of 36.7 km/h.

If the external force is in the opposite direction of the velocity, the rate of work transfer becomes positive, which is shown in Example 0-4.

**Example 0-4  Power in Mechanics**

The aerodynamic drag force in kN on an automobile (see Fig. 0.30) is given as

$$F_d = \frac{1}{2000} c_d A \rho V^2$$

where $c_d$ is the non-dimensional drag coefficient, $A$ is the frontal area in m$^2$, $\rho$ is the density of the surrounding air in kg/m$^3$, and $V$ is the velocity of air with respect to the automobile in m/s.

(a) Determine the power required to overcome the aerodynamic drag for a car with $c_d = 0.8$ and $A = 5 \text{m}^2$ traveling at a velocity of 100 km/h. Assume the density of air to be $\rho = 1.15 \text{kg/m}^3$. **What-if scenario:** (b) What would be the percent increase in power requirement if the car is traveling 20% faster?

**Solution**

The car must impart a force equal to $F_d$ on its surroundings in the opposite direction of the drag to overcome the drag force. The power required is the rate at which it has to do (transfer) work.

**Assumptions**

The drag force remains constant over time.
Analysis

Use the converter TESTcalc in TEST to verify that 100 km/h is 27.78 m/s. Using Eq. (0.10), the rate of mechanical work transfer can be calculated as

\[ \dot{W}_M = F_d V = \frac{1}{2000} c_d A \rho V^3 \left[ \frac{m}{s} = \frac{kN}{s} = kW \right] \]

\[ = \frac{(0.8)(5)(1.15)(27.78^3)}{2000} = 49.3 \text{kW} \]

What-if scenario

The power to overcome the drag is proportional to the cube of the automobile’s speed. A 20% increase in \( V \), therefore, will cause the power requirement for overcoming drag to go up by a factor of \( 1.23^3 = 1.728 \) or 72.8%.

Discussion

The sign of the work transfer is positive, meaning work is done by the system (the car engine). A gasoline (heating value: 44 MJ/kg) powered engine with an overall efficiency of 30% will require heat release at the rate of \( 49.31 \text{kJ/s} = 164.4 \text{kW} \) to supply 49.3 kW of shaft power. This translates to a consumption of 13.45 kg of fuel every hour, 7.43 km/kg, 5.57 km/L, or 13.1 mpg (assuming a gasoline density of 750 kg/m³) if the entire engine power is used to overcome drag only. Additional power is required for accelerating the car, raising it against a slope, and overcoming rolling resistance. At highway speed, the majority of the power, however, goes into overcoming aerodynamic drag.

0.8.2 Shaft Work \( (W_{sh}, \dot{W}_{sh}) \)

Torque acting through an angle (in radians) is the rotational counterpart of force acting through a distance. Work transfer through rotation of shafts is called shaft work and quite common in many practical systems such as automobile engines, turbines, compressors, and gearboxes.

The work done by a torque \( T \) in rotating a shaft through an angle \( \Delta \theta \) in radians is given by \( F \Delta s = Fr \Delta \theta = T \Delta \theta \) (see Fig. 0.31). The power transfer through a shaft, therefore, can be expressed as:

\[ W_{sh} = \lim_{\Delta t \rightarrow 0} \frac{T \Delta \theta}{\Delta t} = T \omega = \frac{2 \pi N}{60} \left[ \frac{kN \cdot m}{s} = kW \right] \]  

\[ (0.11) \]

where \( \omega \) is the rotational speed in \text{radians/s} and \( N \) is the rotational speed measured in \text{rpm} (revolutions per minute). At 3000 rpm, the torque in a shaft carrying 50 kW of power can be calculated from Eq. (0.11) as 0.159 kN·m. Work transfer over a certain period from \( t = t_b \) to \( t = t_f \) can be obtained by integrating \( W_{sh} \) over time. For a constant torque, \( W_{sh} \) is given as:

\[ W_{sh} = \int_{t_b}^{t_f} \dot{W}_{sh} dt = \frac{2 \pi N}{60} T \Delta t; \quad [\text{kW} \cdot \text{s} = \text{kJ}] \]  

\[ (0.12) \]

Appropriate signs must be given to these expressions based on the direction of work transfer. For a paddle-wheel stirring a liquid in a container (Anim. 2.E.paddleWheel), the sign of shaft work transfer must be negative.

0.8.3 Electrical Work \( (W_{el}, \dot{W}_{el}) \)

When electrons cross a boundary, mechanical work done by the electromotive force in pushing the charged particles is called electrical work. For a potential difference of \( V \) (in volts) driving a current \( I \) (in amps) across a resistance \( R \) (in ohms), the magnitude of the electrical work can be expressed as:

\[ \dot{W}_{el} = \frac{VI}{(1000 \ W/kW)} = \frac{V^2}{(1000 \ W/kW)R} = \frac{I^2R}{(1000 \ W/kW)}; \quad [\text{kW}] \]  

\[ (0.13) \]

\[ W_{el} = \int_{t_b}^{t_f} \dot{W}_{el} dt = \dot{W}_{el} \Delta t; \quad [\text{kJ}] \]  

\[ (0.14) \]
Like *shaft work*, *electrical* work is easy to identify and evaluate. Appropriate signs must be added to these expressions depending on the direction of the energy transfer in accordance with the WinHip convention. For example, suppose the electric heater in Figure 0.32 operates at 110 V and draws a current of 10 amps. For the heater as a system, the electrical work transfer rate can be evaluated as \( \dot{W}_e = -1.1 \text{ kW} \).

Sometimes an energy interaction can be worded in such a way that it is not immediately clear whether it is a heat or work interaction. For example, in an electrical water heater (Fig. 0.32), the water is said to be *heated* by electricity. To determine if this is a heat or work interaction, we must remember to examine the boundary rather than the system’s interior. Accordingly, it is \( \dot{W}_d = -1.1 \text{ kW} \) for the system within the red boundary and \( \dot{Q} = 1.1 \text{ kW} \) for the system defined by the black boundary. These algebraic values also can be expressed as magnitudes only if appropriate subscripts are used: \( \dot{W}_m = 1.1 \text{ kW} \) and \( \dot{Q}_m = 1.1 \text{ kW} \) in Figure 0.32. However, we will prefer the algebraic quantities which can be directly substituted into the balance equations to be developed in Chapter 2.

### 0.8.4 Boundary Work \( (\dot{W}_B, \dot{W}_B) \)

**Boundary work** is a general term that includes all types of work that involve displacement of any part of a system boundary. *Mechanical work*, work transfer during rigid-body motion, clearly qualifies as boundary work. However, boundary work is more general in that it can also account for distortion of the system. For example, work transferred while compressing or elongating a spring is a case in point. For a linear spring with a spring constant \( k \text{ (kN/m)} \), the boundary work transfer in pulling the spring from an initial position \( x = x_0 \) to a final position \( x = x_f \) (see Fig. 0.33) can be expressed as:

\[
\dot{W}_B = -\int_{x_0}^{x_f} Fdx = -\int_{x_0}^{x_f} kdx = -k \left[ \frac{x^2}{2} \right]_{x_0}^{x_f} = -\frac{k}{2} (x_f^2 - x_0^2); \quad [\text{kJ}] \tag{0.15}
\]

where \( x = 0 \) is the undisturbed position of the spring. The negative sign indicates that work has been transferred into the spring (the system). For a linear spring with a \( k \) of 200 kW/m, the work transferred to the spring by stretching it by 10 cm from its rest position is 1 kJ.

The most prevalent mode of boundary work in thermal systems, however, accompanies expansion or contraction of a fluid. Consider the trapped gas in the piston-cylinder device of Figure 0.34 as the system. Heated by an external source, the system (gas) expands and lifts the piston carrying a load. Positive boundary work is transferred during the process from the system (which is stored in the PE of the load). If the heating process is slow, the piston is assumed to be in quasi-equilibrium (quasi meaning almost) at all times, and a free-body diagram of the piston (revisit Anim. 0.A.pressure) can be used to establish that the internal pressure, \( p \), remains constant during the expansion process. Now suppose instead of heating the gas, the weight on top of the piston is increased incrementally as shown in Figure 0.35. As expected, the pressure inside will increase as weights are added. However, if the weights are differentially small, the piston can be assumed to be in quasi-equilibrium (equilibrium of the system is discussed in Sec. 1.2), allowing a free-body diagram of the piston to express \( p \) in the external forces on the piston.

---

**FIGURE 0.32** Electrical heating of water involves work or heat transfer depending on which boundary (the red or the black) defines the system (click \( \dot{W}_e \) in Anim. 0.D.workTransfer).

**FIGURE 0.33** To elongate a linear spring, the applied force has to be only differentially greater than \( kx \).

**FIGURE 0.34** The system expands due to heat transfer and raises the weights (click the heating option in Anim. 0.A.pressure).
Whether it is compression or expansion, as the piston moves from a beginning position \( x_b \) to a final position \( x_f \) (Fig. 0.36), the boundary work transfer is related to the pressure and volume of the system as follows:

\[
W_{pdV} = \int_b^f Fdx = \int_b^f pAdx = \int_b^f pdV; \quad \left[ kJ = \frac{kN}{m^2} \cdot m^3 \right]
\]  (0.16)

Although the force on the piston can vary, the piston’s internal pressure will adjust to a variable external force as long as the system can be assumed to be in quasi-equilibrium. Due to its frequent use, this type of boundary work is also called the \( pdV \) (pronounced p-d-V) work.

Equation (0.16) can be interpreted as the area under a \( p@V \) diagram as the system volume goes from an initial volume \( V_b \) to a final volume \( V_f \) (Fig. 0.36). Instead of evaluating the integral, it is easier to calculate the area under the \( p@V \) diagram and add the appropriate sign: positive for expansion and negative for compression. For a constant pressure or isobaric process, the boundary work equation simplifies to:

\[
W_{pdV} = p(V_f - V_b)
\]

Absolute pressure cannot be negative, so the boundary work must be positive when a system expands and negative when it is compressed.

The rate of \( pdV \) work transfer is deduced from Eq. (0.16) as follows:

\[
W_{pdV} = \frac{dW_{pdV}}{dt} = p\frac{dV}{dt}; \quad \left[ kW = \frac{kN \cdot m^3}{m^2 \cdot s} = \frac{kJ}{s} \right]
\]  (0.17)

In the absence of mechanical work, \( pdV \) work is the only type of boundary work that is present in stationary systems and it is common to use the symbols \( W_B \) or \( W_{pdV} \) interchangeably (see Anim. 0.D. externalWork). In the analysis of reciprocating devices, such as automobile engines and some pumps and compressors, the \( pdV \) work is the primary mode of work transfer. Despite the high-speed operation of these devices, the quasi-equilibrium assumption and the resulting \( pdV \) formula produce acceptable accuracy when evaluating boundary work transfer.

### Example 0-5 Boundary Work During Compression

A gas is compressed in a horizontal piston-cylinder device (see Fig. 0.37). At the start of compression, the pressure inside is 100 kPa and the volume is 0.1 m\(^3\). Assuming that the pressure is inversely proportional to the volume, determine the boundary work in kJ when the final volume is 0.02 m\(^3\).

**Solution**

Evaluate the \( pdV \) work using Eq. (0.16).

**Assumptions**

The gas is in quasi-equilibrium during the process.

**Analysis**

The pressure can be expressed as a function of volume and the conditions at the beginning of the process (\( p_b = 100 \) kPa, \( V_b = 0.1 \) m\(^3\)):

\[
pV = \text{constant} = p_bV_b = (100)(0.1) = 10; \quad \left[ \text{kPa} \cdot \text{m}^3 = \frac{\text{kN}}{m^2} \cdot \text{m}^3 = \text{kN} \cdot \text{m} = \text{kJ} \right]
\]

The boundary work, now, can be obtained by using Eq. (0.16):

\[
W_B = \int_b^f pdV = \int_b^f 10 \frac{dV}{0.02} = 10 \int_b^f 0.02 dV = 10 \ln \left( \frac{0.02}{0.1} \right) = -16.09 \text{ kJ}
\]

**Discussion**

The key to direct evaluation of the \( pdV \) work is to examine how the internal pressure \( p \) varies with respect to \( V \). To find a relationship between \( p \) and \( V \), a free-body diagram of the piston (see Anim. 0.A. pressure) is helpful. In this problem, we arrive at the answer without any
consideration of outside agents responsible for this work transfer. However, if we could calculate the exact amount of work done by the external link pushing the piston, it would be significantly less than 16.09 kJ. What other agent, do you think, is responsible for the difference? The outside atmosphere, of course.

### Example 0-6 Boundary Work During Expansion

A 9-mm pistol is test fired with sensors attached inside the barrel that measure the pressure of the explosive gases with respect to the projectile’s position. The sample data is as follows:

<table>
<thead>
<tr>
<th>Position of projectile, $x$, mm</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber pressure, $p$, MPa</td>
<td>250</td>
<td>220</td>
<td>200</td>
<td>180</td>
<td>150</td>
<td>120</td>
<td>100</td>
<td>80</td>
<td>40</td>
</tr>
</tbody>
</table>

Determine the boundary work transfer between (a) the gases and the projectile, and (b) the projectile and the outside air whose pressure is 101 kPa.

**SOLUTION**

**Assumptions**

Assume the measured pressure to be uniform. Represent the pressure at $x$ as the mean of the two nearest measured values.

**Analysis**

The area under the $p - x$ diagram can be divided into a number of adjacent rectangles (Figure 0.38) and approximated as follows:

$$W_B = \int_b^f p\,dx = A \int_b^f p\,dx = A \sum_{i=1}^{8} p_i \Delta x_i$$

$$= \frac{\pi (9 \times 10^{-3})^2}{4} (235 \times 0.01 + 210 \times 0.01 + \cdots + 60 \times 0.01) \left(\frac{10^5}{\text{MJ}}\right)$$

$$= 760 \text{ J}$$

If the projectile is treated as the system, the work transfer from the gases is $-760$ J. The work transfer from the projectile into the outside atmosphere is:

$$W_{atm} = p_{atm} \Delta V = (101) \frac{\pi (9 \times 10^{-3})^2}{4} (0.08) \left(\frac{10^5}{\text{kJ}}\right) = 0.514 \text{ J}$$

**Discussion**

The net boundary work transferred into the projectile goes KE and overcoming friction. If friction is neglected, the projectile’s velocity at the end of the barrel can be calculated by equating its kinetic energy to the net work transferred. In calculating the atmospheric work done by the outer surface of the projectile, it can be shown that the resultant force over the curved surface comes out as if the outer surface were flat.

### 0.8.5 Flow Work ($\dot{W}_F$)

If we examine the boundary of the system shown in Figure 0.39, it is easy to detect the electrical and shaft work transfer. The boundary work also becomes evident once we realize that the piston is moving, but what about the flow that is being pushed into the cylinder at the inlet port? Work must be done by the external push-force to introduce fluid into the cylinder against the resistance of the internal pressure. To obtain an expression for such work, let’s consider the force balance on a thin element of fluid at a particular port, say, the exit port $e$ of the open system shown in...
Figure 0.40. The element, which can be modeled as an imaginary piston, is subjected to the tremendous forces on its left and right sides. For the fluid in that element to be forced out of the system, the force exerted from the inside should be only differentially greater than the force from the outside (to overcome the small frictional force as the element rubs against the wall). By imagining the element to be sufficiently thin (wall friction becomes vanishingly small), the force on both faces of the element can be approximated as $p_e A_e$, where $p_e$ is the pressure at that port. The element being forced out with a velocity $V_e$, the rate at which work is done on the element can be obtained from Eq. (0.10) as:

$$W_{F,e} = F_e V_e = p_e A_e V_e; \quad \text{[kJ]} = \text{[kW]} \quad (0.18)$$

This is called the **flow work** or, more precisely, the rate of flow work transfer at the port. In Chapter 1 (Sec. 1.5.8), we will explore energy transfer by mass in full detail and realize that flow work is only part of the total energy transported by mass. Flow work always takes place in the direction of the flow and hence is bundled with all other modes of energy transferred by mass. To be consistent with the sign convention, flow work transfer at the exit port $e$ of a system, $p_e A_e V_e$, must be assigned a positive sign and the flow work transfer at the inlet $i$, $p_i A_i V_i$, a negative sign.

In Sec. 0.7.1, we discussed why heat transfer through the port openings can be neglected in open systems. Can we make the same assumption about the work transfer through the inlets and exits of an open system? The rate of the flow work, $W_F$, depends on the product of the pressure, velocity, and flow area. A small area, alone, cannot guarantee negligible flow work as the pressure can be quite high. If atmospheric air at 100 kPa enters a room through a 3 m × 1 m door at 3.33 m/s, the flow work transfer can be calculated as ~1 MW, a power that is equivalent to turning on 1000 1-kW heaters. When the air leaves the room through a window or another door (normally air breezes through a room only when there is a cross flow), an almost equivalent amount of work is transferred from the room to the outside surroundings; therefore, no net amount of energy is stored in the room. Conversely, when air enters an evacuated insulated tank (Fig. 0.5d), the flow work transferred by the incoming flow causes the stored energy to increase, which raises the air’s temperature inside the tank. Unlike shaft, electric, and boundary work, flow work is invisible (Fig. 0.40). We will exploit flow work’s invisibility in Chapter 1 by combining it with the stored energy transported by a flow and defining a new property called **flow energy**.

### 0.8.6 Net Work Transfer ($\dot{W}, W_{\text{ext}}$)

There are many other minor modes of work transfer, such as work transfer due to polarization or magnetism and work transfer in stretching a liquid film. Fortunately, an exhaustive knowledge of all these modes is not necessary for analyzing most thermodynamic systems.

Different modes of work transfer discussed so far can be algebraically added to produce an expression for the net work transfer, which can be split into various groups (see Fig. 0.41):

$$\dot{W} = \dot{W}_F + (\dot{W}_M + \dot{W}_{\text{pot}}) + (\dot{W}_{sh} + \dot{W}_{el} + \ldots) = \dot{W}_F + (\dot{W}_B + \dot{W}_O) = \dot{W}_{\text{ext}}; \quad \text{[kJ]} \quad (0.19)$$

where $\dot{W}_{\text{ext}} = \dot{W}_B + \dot{W}_{sh} + \dot{W}_{el}$ and $\dot{W}_F = \sum_{e} p_e A_e V_e - \sum_{i} p_i A_i V_i; \quad \text{[kJ]} \quad (0.20)$

In these equations, $\dot{W}_F$, the net flow work transferred out of a system, is expressed by summing the flow work expression given by Eq. (0.18) over all exit ports (positive work) and all inlet ports (negative work). Essentially, Eq. (0.19) divides total work transfer into two major components: Flow work, which takes place internally (and invisibly) within the working substance at the ports, and external work, which must cross the physical boundary of a system through a shaft, electrical cables, or movement of the boundary.

**External work**, a component of Eq. (0.19), consists of boundary work, which is the sum of mechanical and $pdV$ work, and all other work—the sum of the shaft, electrical, and any other type of work present. In most situations, however, external work is the sum of boundary, shaft, and electrical work as expressed by Eq. (0.20). In Chapters 1 and 2, flow work can be absorbed into other terms in the energy balance equation leaving external work as the only relevant work transfer in an energy analysis.
To identify a specific type of work transfer we must inspect the boundary and look for (a) displacement of any part of the boundary for boundary work, (b) electric cables for electrical work, (c) rotating shafts for shaft work, and (d) mass transfers for flow work. To determine the sign of work transfer, we must determine how the work transfer affects the stored energy of the system. In practical systems, only one or two of these modes may be present simultaneously. In closed systems the flow work, by definition, is absent so that \( W = W_{\text{ext}} \). In the system shown in Figure 0.42, the external work consists of electrical, shaft, and boundary work. In Figure 0.39, despite the presence of flow work, the constituents of the external work remain unchanged. In an energy analysis of open systems, flow work is absorbed in other terms (bundled with energy transport by mass) so that work transfer usually means external work transfer, even though \( W \neq W_{\text{ext}} \) according to Eq. (0.19).

**EXAMPLE 0-7 Different Types of Energy Interactions**

A gas trapped in a piston-cylinder device (Fig. 0.42) is subjected to the following energy interactions for 30 seconds: The electric resistance draws 0.1 amps from a 100-V source, the paddle wheel turns at 60 rpm with the shaft transmitting a torque of 5 N\( \cdot \)m, and 1 kJ of heat is transferred into the gas from the candle. The volume of the gas increases by 6 L during the process. If the atmospheric pressure is 100 kPa and the piston is weightless, (a) determine the net transfer of energy into the system. (b) Air is now injected into the cylinder using a needle. Calculate the flow work transfer as 10 L of air is injected into the cylinder at a constant pressure of 100 kPa.

**SOLUTION**

Evaluate the different types of energy transfers during the process and add them algebraically to find the net energy transfer.

**Assumptions**

The piston is at mechanical equilibrium (no force imbalance) at all times.

**Analysis**

Evaluate different modes of energy transfer by treating the gas as the system.

**Boundary Work:**

During the expansion of the gas, boundary work transferred is positive. To obtain a relationship between \( p_i \) and \( \mathcal{V}_b \), a vertical force balance on the piston (see the free-body in Fig. 0.42) yields the following:

\[
p_i A_{\text{piston}} = \frac{mg}{1000 \text{ N/kN}} + p_0 A_{\text{piston}}; \quad \Rightarrow \quad p_i = p_0
\]

From Eq. (0.16), \( W_B = \int_{b}^{f} p dV = p_0 (\mathcal{V}_f - \mathcal{V}_b) = p_0 (6 \times 10^{-3} \text{ m}^3) = 0.6 \text{ kJ} \)

**Shaft Work:** From Eq. (0.12):

\[
W_{\text{sh}} = -2\pi \frac{N}{60} \Delta t = -2\pi \frac{60}{60} \left( \frac{5}{1000} \right) 30 = -0.94 \text{ kJ}
\]

**Electrical Work:** From Eq. (0.14):

\[
W_{\text{el}} = - \frac{VI}{1000} \Delta t = \left( - \frac{100 \times 0.1}{1000} \right) \text{kW} (30 \text{ s}) = -0.3 \text{ kJ}
\]

**Heat Transfer:** \( Q = 1 \text{ kJ} \) (given)

The net work transfer is summed up as:

\[
W = W_{\text{ext}} = W_B + W_{\text{sh}} + W_{\text{el}} + Q = 0.6 - 0.94 - 0.3 = -0.64 \text{ kJ}
\]
Thus, 0.64 kJ of work and 1 kJ of heat are transferred into the system. Therefore, the net energy transfer into the system during the process is 1.64 kJ.

**Flow Work:**
Noting that there is a single inlet port, Eq. (0.20) can be simplified with the help of Eqs. (0.1) and (0.6) to produce:

$$ W_F = \sum_e p_e A_e V_e - \sum_i p_i A_i V_i = -p_i A_i V_i = -p_i V_i; \quad [\text{kW}] $$

$$ \Rightarrow W_F = \int_{t=b}^{t=t_f} W_{F_i} dt = -\int_{t=i}^{t_f} p_i \dot{V}_i dt = -p_i V_i; \quad [\text{kJ}] $$

$$ \Rightarrow W_F = -(100) \left[ \frac{10}{1000 \text{ L/m}^3} \right] = -1 \text{ kJ}; \quad [\text{kPa} \cdot \text{m}^3 = \text{kN} \cdot \text{m} = \text{kJ}] $$

The pressure at which the air is injected remains constant because the piston is free to move. This also simplifies the evaluation of the integral in the expression for $W_F$.

**Discussion**
When evaluating a particular mode of work or heat transfer, it is an acceptable practice to determine the magnitude before attaching an appropriate sign that specifies the energy transfer’s direction. The net energy transferred into the system must give rise to an increase in the stored energy. Kinetic and potential energies of the system remaining unchanged, the transferred energy must be stored in the internal energy of the system. The energy balance equation, to be developed in Chapter 2, will precisely relate the energy transfer through mass, heat, and work with the inventory of stored energy of a system.

### 0.8.7 Other Interactions
Are there other interactions between a system and its surroundings besides mass, heat, and work interactions? What about microwaves, radio waves, lasers, sound waves, nuclear radiation, or, for that matter, the scent of a perfume? Actually, none of these interactions is unique; each is a special case of heat or mass transfer. We can therefore conclude that mass, heat, and work interactions, summarized in Anim. 0.C.genericSystem, are sufficient to capture all thermodynamic activities between a system and its surroundings. The lack of mass transfer makes a system *closed*, the lack of heat transfer makes it *adiabatic*, and the lack of all interactions makes a system *isolated* (see Anim. 0.C.systemTypes). Classification of systems based on interactions will have an important role in later chapters.

### 0.9 CLOSURE
In this Introduction we have introduced the basic vocabulary of thermodynamics by defining a system, its surroundings, and their interactions. Aided by a series of animations, an overview of diverse thermodynamic systems was presented with particular attention to different types of interactions. Mass interaction is analyzed producing the mass flow rate formula. TESTcalc is introduced for calculating flow properties, including mass flow rate. Stored energy of a system was presented as a generalization of the familiar mechanical energy used in mechanics. Heat and work were introduced as energy in transit, as fundamental mechanisms of energy interactions. Different types of work transfer were analyzed, leading to a formula for the net work for its components: boundary work, shaft work, electrical work, and flow work. A lake analogy was formulated to explain the connection among heat, work, and stored energy and the sign convention for heat and work transfer.

**FIGURE 0.43** How do you classify this delightful interaction? Mass transfer, of course.
PROBLEMS

SECTION 0-1: FREE-BODY DIAGRAM

0-1-1 Two thermodynamics books, each with a mass of 1 kg, are stacked one on top of another. Neglecting the presence of atmosphere, draw the free-body diagram of the book at the bottom to determine the vertical force on its (a) top and (b) bottom faces in kN.

0-1-2 Determine (a) the pressure felt on your palm to hold a textbook of mass 1 kg in equilibrium. Assume the distribution of pressure over the palm to be uniform and the area of contact to be 25 cm². (b) What-if scenario: How would a change in atmospheric pressure affect your answer (0: No change; 1: increase; −1: decrease)?

0-1-3 The lift-off mass of a Space Shuttle is 2 million kg. If the lift-off thrust (the net force upward) is 10% greater than the minimum amount required for a lift off, determine the acceleration.

0-1-4 A body weighs 0.05 kN on Earth where \( g = 9.81 \text{ m/s}^2 \). Determine its weight on (a) the moon, and (b) on Mars with \( g = 1.67 \text{ m/s}^2 \) and \( g = 3.92 \text{ m/s}^2 \), respectively.

0-1-5 Calculate the weight of an object of mass 50 kg at the bottom and top of a mountain with (a) \( g = 9.8 \text{ m/s}^2 \) and (b) 9.78 m/s² respectively.

0-1-6 According to Newton’s law of gravity, the value of \( g \) at a given location is inversely proportional to the square of the distance of the location from the center of the Earth. Determine the weight of a textbook of mass 1 kg at (a) sea level and in (b) an airplane cruising at an altitude of 45,000 ft. Assume Earth to be a sphere of diameter 12,756 km.

0-1-7 The maximum possible frictional force on a block of mass \( m_A \) resting on a table (see accompanying figure) is given as \( F = \mu_s N \), where \( N \) is the normal reaction force from the table. Determine the maximum value for \( m_B \) that can be supported by friction. Assume the pulley to be frictionless.

0-1-8 If the block A in Problem 0-1-7 sits on a wedge with an angle \( \theta \) with the horizontal, how would the answer change?

0-1-9 A block with a mass of 10 kg is at rest on a plane inclined at 25° to the horizontal. If \( \mu_s = 0.6 \), determine the range of the horizontal push force \( F \) if the block is (a) about to slide down, and (b) about to slide up.

0-1-10 A vertical piston cylinder device contains a gas at an unknown pressure. If the outside pressure is 100 kPa, determine (a) the pressure of the gas if the piston has an area of 0.2 m² and a mass of 20 kg. Assume \( g = 9.81 \text{ m/s}^2 \). (b) What-if scenario: What would the pressure be if the orientation of the device were changed and it were now upside down?

0-1-11 Determine the mass of the weight necessary to increase the pressure of the liquid trapped inside a piston-cylinder device like the one in Figure 0.2 to 120 kPa. Assume the piston to be weightless with an area of 0.1 m², the outside pressure to be 100 kPa and \( g = 9.81 \text{ m/s}^2 \).
0-1-12 A mass of 100 kg is placed on the piston of a vertical piston-cylinder device containing nitrogen. The piston is weightless and has an area of 1 m². The outside pressure is 100 kPa. Determine (a) the pressure inside the cylinder. The mass placed on the piston is now doubled to 200 kg. Also, additional nitrogen is injected into the cylinder to double the mass of nitrogen. (b) Determine the pressure inside under these changed conditions. Assume temperature to remain unchanged at 300 K and R for nitrogen to be 0.296 kJ/kg·K.

0-1-13 A piston with a diameter of 50 cm and a thickness of 5 cm is made of a composite material with a density of 4000 kg/m³. (a) If the outside pressure is 101 kPa, determine the pressure inside the piston-cylinder assembly if the cylinder contains air. What-if scenario: (b) What would the inside pressure be if the piston diameter were 100 cm instead? (c) Would the answers change if the cylinder contained liquid water instead?

0-1-14 A piston-cylinder device contains 0.02 m³ of hydrogen at 300 K. It has a diameter of 10 cm. The piston (assumed weightless) is pulled by a connecting rod perpendicular to the piston surface. If the outside conditions are 100 kPa, 300 K, (a) determine the pull force necessary in kN to create a pressure of 50 kPa inside. (b) The piston is now released; as it oscillates back and forth and finally comes to equilibrium, the temperature inside is measured as 600 K (reasons unknown). What is the pressure of hydrogen at equilibrium? What-if scenario: (c) What would be the answer in part (a) if the gas were oxygen instead?

0-1-15 Air in the piston-cylinder device shown is in equilibrium at 200°C. If the mass of the hanging weight is 10 kg, atmospheric pressure is 100 kPa, and the piston diameter is 10 cm, (a) determine the pressure of air inside. Assume g = 9.81 m/s². (b) What-if scenario: What would the pressure be if the gas were hydrogen instead? The molar mass of air is 29 kg/kmol and that of hydrogen is 2 kg/kmol. Neglect piston mass and friction.

0-1-16 A vertical hydraulic cylinder has a piston with a diameter of 100 mm. If the ambient pressure is 100 kPa, determine the mass of the piston if the pressure inside is 1000 kPa.

0-1-17 Determine the pull force necessary on the rope to reduce the pressure of the liquid trapped inside the piston cylinder device to 80 kPa. Assume the piston to be weightless with a diameter of 0.1 m, the outside pressure to be 100 kPa, and g = 9.81 m/s².

0-1-18 A piston-cylinder device contains 0.17 m³ of hydrogen at 450°C. It has a diameter of 50 cm. The piston (assumed weightless) is pulled by a connecting rod perpendicular to the piston surface. If the outside conditions are 100 kPa, 25°C, (a) determine the pull force necessary in kN to create a pressure of 60 kPa inside. (b) The piston is now released. It oscillates back and forth and finally comes to equilibrium. Determine the pressure at that state.

0-1-19 A 5-cm diameter piston-cylinder device contains 0.04 kg of an ideal gas at equilibrium at 100 kPa, 300 K occupying a volume of 0.5 m³. Determine (a) the gas density. (b) A weight is now hung from the piston (see figure) so that the piston moves down to a new equilibrium position. Assuming the piston to be weightless, determine the mass of the hanging weight necessary to reduce the gas pressure to 50 kPa. (Data supplied: g = 9.81 m/s²; outside pressure: 100 kPa.)

0-1-20 In Problem 0-1-19, the gas is now cooled so that the piston moves upward toward the original position with the weight still hanging. Determine the pressure when the gas shrinks to its original volume of 0.5 m³.

SECTION 0-2: INTERACTIONS BETWEEN A SYSTEM AND ITS SURROUNDINGS

0-2-1 What do you call a system that has (a) no mass interaction, (b) no heat interaction, (c) no mass and energy interaction?
**Introduction • Thermodynamic System and Its Interactions with the Surroundings**

0-2-2 As shown in the figure below, electric current from the photo-voltaic (PV) cells runs an electric motor. The shaft of the motor turns the paddle wheel inside the water tank. Identify the interactions (mass, heat, work) for the following systems: (a) PV cells, (b) motor, (c) tank, and (d) the combined system that includes all these three subsystems.

0-2-3 On a hot day, a student turns on the fan and keeps the refrigerator door open in a closed kitchen room, thinking that it would cool down the hot kitchen. Treating the room as a closed insulated system, identify the possible energy interactions between the room and the surroundings. Also determine the sign of (a) $Q$ and (b) $W_{ext}$, if any.

0-2-4 An external force drags and accelerates a rigid body over a surface. Treating the body as a thermodynamic system, determine the sign of (a) $W_{ext}$ and (b) $Q$ across its boundary. Assume friction to be present.

0-2-5 During the free fall of a rigid body (system), identify the interactions between the system and its surroundings.

0-2-6 An electric adaptor for a notebook computer (converting 110 V to 19 V) operates 10°C warmer than the surrounding temperature. Determine the sign of (a) $W_{ext}$ and (b) $Q$ interactions.

0-2-7 A block of ice dropped into a tank of water as shown begins melting. Identify the interactions for the (a) ice as a system, (b) water in the tank as a system, and (c) water and ice together as a system.

0-2-8 A gas trapped in an insulated piston-cylinder assembly expands as it is heated by an electrical resistance heater placed inside the cylinder. Treating the gas and the heater as the system, identify the interactions with its surroundings and the sign of (a) $Q$ and (b) $W_{ext}$.

0-2-9 A piston-cylinder device contains superheated vapor at atmospheric pressure. The piston is pulled by an external force until the pressure inside drops by 50%. Determine the sign of $W_{ext}$, treating the vapor trapped inside the cylinder as the system. Where does the work done in pulling the piston go?

0-2-10 A warm cup of coffee gradually cools down to room temperature. Treating the coffee as the system, determine the sign of $Q$ during the cooling process.

0-2-11 A hot block of solid is dropped in an insulated tank of water at the temperature of the surroundings. Determine the sign of $Q$ treating (a) the block as the system, (b) the water as the system and (c) the entire tank (with the block and water).
0-2-12 An insulated tank containing high-pressure nitrogen is connected to another insulated tank containing oxygen at low pressure. Determine the possible interactions as the valve is opened and the two gases are allowed to form a mixture by treating (a) one of the tanks as a system and (b) two tanks together as a single system.

0-2-13 A fluid is accelerated by an insulated nozzle attached at the end of a pipe. Identify the interactions, treating the nozzle as an open system.

0-2-14 An insulated steam turbine produces $Q$ and $W_{sh}$ as steam flows through it, entering at a high pressure and a high temperature and leaving at a relatively low pressure. Identify the interactions between the turbine (as an open system) and its surroundings and determine the sign of (a) $Q$ and (b) $W_{ext}$.

0-2-15 Identify the possible interactions of a steam turbine with poor insulation with its surroundings and determine the sign of (a) $Q$ and (b) $W_{ext}$.

0-2-16 The pressure of a liquid flow is raised by a pump driven by an electrical motor. Identify the interactions treating (a) the pump as an open system and (b) the pump and the motor as a combined system.

0-2-17 An insulated compressor raises the pressure of a gas flow. The temperature of the gas also is increased as a result. Identify the possible interactions between the compressor and its surroundings and determine the sign of (a) $Q$ and (b) $W_{ext}$.

0-2-18 In a heat exchanger a flow of hot air is cooled by a flow of water. Identify the interactions treating (a) the entire heat exchanger as the system and (b) one of the streams as the system.

0-2-19 A pressure cooker containing water is heated on a stove. Determine the interactions and signs of (a) $Q$ and (b) $W_{ext}$, if any, as steam is released.

0-2-20 As you blow up a balloon, what are the interactions and the sign (positive: 1; negative: −1; none: 0) of (a) $Q$ and (b) $W_{ext}$, if any, between the balloon as a system and its surroundings?
Air rushes in to fill an evacuated insulated tank as the valve is opened. Determine the interactions and the sign of $Q$ and $W_{ext}$, if any, treating (a) the tank as the system and (b) the tank and the outside air that eventually enters as the system.

SECTION 0-3: MASS TRANSFER

0-3-1 Air with a density of 1 kg/m$^3$ flows through a pipe of diameter 20 cm at a velocity of 10 m/s. Determine (a) the volume flow rate ($\Phi$) in L/min and (b) mass flow rate ($\dot{m}$) in kg/min. Use the PG flow state TESTcalc to verify your answer.

0-3-2 Steam flows through a pipe of diameter 5 cm with a velocity of 50 m/s at 500 kPa. If the mass flow rate ($\dot{m}$) of steam is measured at 0.2 kg/s, determine (a) the specific volume ($v$) of steam in m$^3$/kg, and (b) the volume flow rate ($\Phi$) in m$^3$/s.

0-3-3 Water flows through a variable-area pipe with a mass flow rate ($\dot{m}$) of 10,000 kg/min. Determine the minimum diameter of the pipe if the flow velocity is not to exceed 5 m/s. Assume density ($\rho$) of water to be 1000 kg/m$^3$. Use the SL flow state TESTcalc to verify your answer.

0-3-4 A mixture of water ($\rho = 1000$ kg/m$^3$) and oil ($\rho = 800$ kg/m$^3$) is flowing through a tube of diameter 2 cm with a velocity of 4 m/s. The mass flow rate ($\dot{m}$) is measured to be 1.068 kg/s. Determine (a) the density ($\rho$) of the liquid mixture, (b) the percentage of oil in the mixture by mass. Assume liquids to be incompressible.

0-3-5 Air flows through a pipe of diameter 10 cm with an average velocity of 20 m/s. If the mass flow rate ($\dot{m}$) is measured to be 1 kg/s, (a) determine the density ($\rho$) of air in kg/m$^3$. (b) What-if scenario: What would be the answer if CO$_2$ were flowing instead (with all the readings unchanged)?

0-3-6 Air flows steadily through a constant-area duct. At the entrance the velocity is 5 m/s and temperature is 300 K. The duct is heated such that at the exit the temperature is 600 K. (a) If the specific volume ($v$) of air is proportional to the absolute temperature (in K) and the mass flow rate ($\dot{m}$) remains constant throughout the duct, determine the exit velocity. (b) How would heating affect the pressure?

0-3-7 Hydrogen flows through a nozzle exit of diameter 10 cm with an average velocity of 200 m/s. If the specific volume and the flow area at the inlet are measured as 0.1 m$^3$/kg and 0.01 m$^2$ respectively, determine (a) the volume flow rate ($\Phi$) in m$^3$/s, and (b) the mass flow rate ($\dot{m}$) in kg/s. Use the PC flow state TESTcalc to verify your answers.

SECTION 0-4: WORK TRANSFER

0-4-1 A bucket of concrete with a mass of 5000 kg is raised without any acceleration by a crane through a height of 20 m. (a) Determine the work transferred into the bucket. (b) Also determine the power delivered to the bucket if it is raised at a constant speed of 1 m/s. (c) What happens to the energy after it is transferred into the bucket?

0-4-2 The accompanying figure shows a body of mass 50 kg being lifted at a constant velocity of 1 m/s by the rope and pulley arrangement. Determine power delivered by the rope.
0-4-3 An elevator with a total mass of 1500 kg is pulled upward using a cable at a velocity of 5 m/s through a height of 300 m. (a) Determine the rate at which work is transferred into the elevator (magnitude only, no sign). (b) What is the sign of $W$? (c) The change in stored $E$ of the elevator assuming the KE and $U$ to remain unchanged.

0-4-4 In Problem 0-4-3, assume the energetic efficiency (work transfer to the elevator [desired] to the electrical work transfer [required] to the motor) of the system to be 80%. (a) determine the power consumption rate by the motor (magnitude only). (b) Assuming electricity costs 20 cents per kWh, determine the energy cost of operation in cents.

0-4-5 (a) Determine the constant force necessary to accelerate a car of mass 1000 kg from 0 to 100 km/h in 6 seconds. (b) Also calculate the work done by the force. (c) Verify that the work done by the force equals the change in KE of the car. Neglect friction. (d) What-if scenario: What would the work be if the acceleration were achieved in 5 seconds?

0-4-6 A driver locks the brake of a car traveling at 140 km/h. Without anti-lock brakes, the tires immediately start skidding. If the total mass of the car, including the driver, is 1200 kg, determine (a) the deceleration, (b) the stopping distance for the car and (c) the work transfer (include sign) treating the car as the system. Assume the friction coefficient between rubber and pavement to be 0.9. Neglect viscous drag.

0-4-7 A car delivers 200 hp to a winch used to raise a load of 1000 kg. Determine the maximum speed of lift.

0-4-8 A block of mass 100 kg is dragged on a horizontal surface with static and kinetic friction coefficients of 0.15 and 0.09 respectively. Determine (a) the pull force necessary to initiate motion (b) the work done by the pull force and (c) the work done against the frictional force as the block is dragged over a distance of 5 m. (d) What is the net work transfer between the block and its surroundings?

0-4-9 In the accompanying figure, determine (a) the work done by a force of 100 N acting at an angle 20° in moving the block of mass 10 kg by a distance of 3 m if the friction coefficient is 0.5. (b) What is the net work transfer if the block is treated as the system?

0-4-10 Twenty 50 kg suitcases are carried by a horizontal conveyor belt at a velocity of 0.5 m/s without any slippage. If $\mu_s = 0.9$, (a) determine the power required to drive the conveyor. Assume no friction loss on the pulleys. (b) What-if scenario: What would the power required be if the belt were inclined upward at an angle of 10°?

0-4-11 A person with a mass of 70 kg climbs the stairs of a 50 m tall building. (a) What is the minimum work transfer if you treat the person as a system? Assume standard gravity. (b) If the energetic efficiency (work output/heat released by food) of the body is 30%, how many calories are burned during this climbing process?

0-4-12 A person with a mass of 50 kg and an energetic efficiency of 35% decides to burn all the calories consumed from a can of soda (140 calories) by climbing stairs of a tall building. Determine the maximum height of the building necessary to ensure that all the calories from the soda can is expended in the work performed in climbing.

0-4-13 The aerodynamic drag force $F_d$ in kN on an automobile is given as $F_d = (1/2000) C_d A \rho V^2 [kN]$, where $C_d$ is the non-dimensional drag coefficient, $A$ is the frontal area in $m^2$, $\rho$ is the density of the surrounding air in $kg/m^3$, and $V$ is the velocity of air with respect to the automobile in m/s. Determine the power required to overcome the aerodynamic drag for a car with $C_d = 0.4$ and $A = 7 m^2$, traveling at a velocity of 100 km/h. Assume the density of air to be $\rho = 1.2 kg/m^3$.

0-4-14 The rolling resistance of the tires is the second major opposing force (next to aerodynamic drag) on a moving vehicle and is given by $F_r = fW [kN]$ where $f$ is the rolling resistance coefficient and $W$ is the weight of the vehicle in kN. Determine the power required to overcome the rolling resistance for a 2000 kg car traveling at a velocity of 100 km/h, if $f = 0.007$.

0-4-15 Determine the power required to overcome (a) the aerodynamic drag and (b) rolling resistance for a truck traveling at a velocity of 120 km/h, if $C_d = 0.8$, $A = 10 m^2$, $\rho = 1.2 kg/m^3$, $f = 0.01$, and $m = 20,000$ kg. Plot the power requirement—aerodynamic, rolling friction and total—against velocity within the range from 0 to 200 km/h.

0-4-16 Determine the power required to overcome (a) the aerodynamic drag and (b) rolling resistance for a bicyclist traveling at a velocity of 21 km/h, if $C_d = 0.8$, $A = 1.5 m^2$, $\rho = 1.2 kg/m^3$, $f = 0.01$ and $m = 100$ kg. Also determine (c) the metabolic energetic efficiency (work output/energy input) for the bicyclist if the rate at which calories are burned is measured at 650 calories/h.
0-4-17 Determine (a) the work transfer involved in compressing a spring with a spring constant of 150 kN/m from its rest position by 10 cm. (b) What is the work done in compressing the spring by an additional 10 cm?

0-4-18 An object with a mass of 200 kg is acted upon by two forces, 0.1 kN to the right and 0.101 kN to the left. Determine (a & b) the work done by the two faces and (c) the net work transfer as the system (the object) is moved a distance of 10 m.

0-4-19 A rigid chamber contains 100 kg of water at 500 kPa, 100°C. A paddle wheel stirs the water at 1000 rpm while an internal electrical resistance heater heats the water while consuming 10 amps of current at 110 Volts. At steady state, the chamber loses heat to the atmosphere at 27°C at a rate of 1.2 kW. Determine (a) $W_{sh}$ in kW, (b) the torque in the shaft in N-m.

0-4-20 A piston-cylinder device containing a fluid is fitted with a paddle-wheel stirring device operated by the fall of an external weight of mass 50 kg. As the mass drops by a height of 5 m, the paddle wheel makes 10,000 revolutions, transferring shaft work into the system. Meanwhile the free-moving piston (frictionless and weightless) of 0.5 m diameter moves out by a distance of 0.7 m. Find the $W_{net}$ for the system if the pressure outside is 101 kPa.

0-4-21 An insulated vertical piston-cylinder device contains steam at 300 kPa, 200°C, occupying a volume of 1 m$^3$, and having a specific volume of 0.716 m$^3$/kg. It is heated by an internal electrical heater until the volume of steam doubles due to an increase in temperature.
   (a) Determine the final specific volume of steam.
   (b) If the diameter of the piston is 20 cm and the outside pressure is 100 kPa, determine the mass of the weight placed on the piston to maintain a 300 kPa internal pressure.
   (c) Calculate the $W_p$ (magnitude only), which has been done by the steam in kJ.
   (d) Calculate the amount of $W_{gt}$ (magnitude only) transferred into the weight in kJ.
   (e) If you are asked to choose one of the three values—900 kJ, 300 kJ, 200 kJ—as the magnitude of $W_{el}$, which one will be your educated guess? Why?

0-4-22 A gas in a vertical piston-cylinder device has a volume of 0.5 m$^3$ and a temperature of 400 K. The piston has a mass of 50 kg and a cross-sectional area of 0.2 m$^2$. As the gas cools down to atmospheric temperature the volume decreases to 0.375 m$^3$. Neglect friction and assume atmospheric pressure to be 100 kPa. Determine (a) the work transfer during the process. (b) What-if scenario: What would the work transfer be if the piston weight were considered negligible?

0-4-23 A man weighing 100 kg is standing on the piston head of a vertical piston-cylinder device containing nitrogen. The gas now is heated by an electrical heater until the man slowly is lifted by a height of 1 m. The piston is weightless and has an area of 1 m$^2$. The outside pressure is 100 kPa. Determine (a) the initial pressure inside the cylinder, (b) the final pressure inside, (c) the boundary work (magnitude only) performed by the piston-cylinder device (nitrogen is the system) assuming an average pressure of 101 kPa inside the cylinder during the heating process, and (d) the work (magnitude only) transferred to the man (man as the system). Assume the acceleration due to gravity to be 9.81 m/s$^2$.

0-4-24 A 10 m$^3$ insulated rigid tank contains 20 kg of air at 25°C. An electrical heater within the tank is turned on, which consumes a current of 5 Amps for 30 min from a 110 V source. Determine the work transfer in kJ.

0-4-25 A paddle wheel stirs a water tank at 500 rpm. The torque transmitted by the shaft is 20 N-m. At the same time, an internal electric resistance heater draws 2 Amps of current from a 110 V source as it heats the water. Determine (a) $i$ in kW. (b) What is the total $W$ in 1 hour?

0-4-26 Determine the power conducted by the crankshaft of a car, which is transmitting a torque of 0.25 kN-m at 3000 rpm.

0-4-27 An electric motor draws a current of 16 amp at 110 V. The output shaft delivers a torque of 10 N-m at a speed of 1500 RPM. Determine (a) the electric power transferred, (b) shaft power, and (c) the rate of heat transfer if the motor operates at steady state.
0-4-28 Determine the boundary work transfer in blowing up a balloon to a volume of 0.01 m³. Assume that the pressure inside the balloon is equal to the surrounding atmospheric pressure, 100 kPa.

0-4-29 Air in a horizontal free-moving piston-cylinder assembly expands from an initial volume of 0.25 m³ to a final volume of 0.5 m³ as the gas is heated for 90 seconds by an electrical resistance heater consuming 1 kW of electric power. If the atmospheric pressure is 100 kPa, determine (a) \( W_g \) and (b) \( W_{net} \). (c) **What-if scenario:** How would the answers change if the cylinder contained pure oxygen instead?

0-4-30 A vertical piston-cylinder assembly (see figure) contains 10 L of air at 20°C. The cylinder has an internal diameter of 20 cm. The piston is 2 cm thick and is made of steel of density 7830 kg/m³. If the atmospheric pressure outside is 101 kPa, (a) determine the pressure of air inside the cylinder. The air is now heated until its volume doubles. (b) Determine the boundary work transfer during the process. **What-if scenario:** What would the (c) pressure and (d) work be if the piston weight were neglected?

0-4-31 Air in the accompanying piston-cylinder device is initially in equilibrium at 200°C. The mass of the hanging weight is 10 kg and the piston diameter is 10 cm. As air cools due to heat transfer to the surroundings, at 100 kPa the piston moves to the left, pulling the weight up. Determine (a) the boundary work and (b) the work done in raising the weight for a piston displacement of 37 cm. (c) Explain why the two are different.

0-4-32 A horizontal piston-cylinder device contains air at 90 kPa while the outside pressure is 100 kPa. This is made possible by pulling the piston with a hanging weight through a string-and-pulley arrangement (see accompanying figure). If the piston has a diameter of 20 cm:

(a) Determine the mass of the hanging weight in kg.
(b) The gas is now heated using an electrical heater and the piston moves out by a distance of 20 cm. Determine the boundary work (include sign) in kJ.
(c) What fraction of the boundary work performed by the gas goes into the hanging weight?
(d) How do you account for the loss of stored energy (in the form of PE) by the hanging weight?

0-4-33 An insulated, vertical piston-cylinder assembly (see figure) contains 50 L of steam at 105°C. The outside pressure is 101 kPa. The piston has a diameter of 20 cm and the combined mass of the piston and the load is 75 kg. The electrical heater and the paddle wheel are turned on and the piston rises slowly by 25 cm. Determine (a) the pressure of air inside the cylinder during the process (b) the boundary work performed by the gas and (c) the combined work transfer by the shaft and electricity if the net energy transfer into the cylinder is 3.109 kJ.

0-4-34 Steam is compressed from \( p_1 = 100 \text{ kPa}, V_1 = 1 \text{ m}^3 \) to \( p_2 = 200 \text{ kPa}, V_2 = 0.6 \text{ m}^3 \). The external force exerted on the piston is such that pressure increases linearly with a decrease in volume. Determine (a) the boundary work transfer and (b) show the work by shaded areas in a \( p-V \) diagram.

0-4-35 A gas in a piston-cylinder assembly is compressed (through a combination of external force on the piston and cooling) in such a manner that the pressure and volume are related by \( pV^n = \text{constant} \). Given an initial state of 100 kPa and 1 m³ and a final volume of 0.5 m³ evaluate the work transfer if (a) \( n = 0 \), (b) \( n = 1 \), (c) \( n = 1.4 \) and (d) plot a \( p-V \) diagram for each processes and show the work by shaded areas.
0-4-36 In the preceding problem the piston has a cross-sectional area of 0.05 m². If the atmospheric pressure is 100 kPa and the weight of the piston and friction are negligible, plot how the external force applied by the connecting rod on the piston varies with the gas volume for (a) \( n = 0 \), (b) \( n = 1 \) and (c) \( n = 1.4 \).

0-4-37 A piston-cylinder device contains 0.03 m³ of nitrogen at a pressure of 300 kPa. The atmospheric pressure is 100 kPa and the spring pressed against the piston has a spring constant of 256.7 kN/m. Heat now is transferred to the gas until the volume doubles. If the piston has a diameter of 0.5 m, determine (a) the final pressure of nitrogen, (b) the work transfer from nitrogen to the surroundings, and (c) the fraction of work that goes into the atmosphere.

0-4-38 A 100 kg block of solid is moved upward by an external force \( F \) as shown in the accompanying figure. After a displacement of 10 cm, the upper surface of the block reaches a linear spring at its rest position. The external force is adjusted so that the displacement continues for another 10 cm. If the spring constant is 100 kN/m and acceleration due to gravity is 9.81 m/s², determine (a) the work done by the external force. (b) What fraction of the energy transferred is stored in the spring?

0-4-39 Nitrogen in a horizontal piston-cylinder assembly expands from an initial volume of 0.1 m³ to a final volume of 0.5 m³ as the gas is heated for 5 minutes by an electrical resistance heater consuming 1 kW of electric power. If the pressure remains constant at 150 kPa and 70 kJ of heat is lost from the cylinder during the expansion process, determine (a) \( W_b \) (include sign), (b) \( W_{el} \) (include sign), and (c) \( W_{net} \) (absolute value) into the system through heat and work.

0-4-40 Water enters a horizontal system, operating at steady state, at 100 kPa, 25°C, 10 m/s at a mass flow rate of 200 kg/s. It leaves the system at 15 m/s, 1 MPa, 25°C. If the density of water is 1000 kg/m³, determine (a) the rate of flow work (\( W_{flow} \)) at the inlet (magnitude only), (b) the diameter of the pipe at the inlet.

0-4-41 The rate of energy transfer due to flow work (\( W_{flow} \)) at a particular cross-section is 20 kW. If the volume flow rate (\( \dot{V} \)) is 0.2 m³/min, determine the pressure at that location.

0-4-42 Water enters a pump at 100 kPa with a mass flow rate (\( \dot{m} \)) of 20 kg/s and exits at 500 kPa with the same mass flow rate. If the density of water is 1000 kg/m³, determine the net flow work transfer in kW.

0-4-43 Water (density 1000 kg/m³) flows steadily into a hydraulic turbine through an inlet with a mass flow rate (\( \dot{m} \)) of 500 kg/s. The conditions at the inlet are measured as 500 kPa, 25°C. (a) Determine the magnitude of the rate of flow work transfer in kW and (b) the sign of the work transfer treating the turbine as the system.

SECTION 0-5: HEAT TRANSFER

0-5-1 If a therm of heat costs $1.158 and a kW-h of electricity costs $0.106, then determine the prices of (a) heat and (b) electricity on the basis of GJ.

0-5-2 A power plant has an average load of 2000 MW (electrical). If the overall thermal efficiency is 38%, what is the annual cost of fuel for (a) natural gas ($1.26/Therm) and (b) No. 2 fuel oil ($9.40/MMBtu)?
0-5-3 A gas trapped inside a piston-cylinder device receives 20 kJ of heat as it expands, performing a boundary work (\( W_B \)) of 5 kJ. At the same time 10 kJ of electrical work (\( W_{el} \)) is transferred into the system. Evaluate (a) \( Q \) and (b) \( W \) with appropriate signs.

0-5-4 A gas station sells gasoline and diesel at $2.00/gallon and $1.75/gallon respectively. If the following data are known about the two fuels, compare the prices on the basis of MJ of energy: heating value: gasoline 47.3 MJ/kg, diesel 46.1 MJ/kg; density: gasoline 0.72 kg/L, diesel 0.78 kg/L.

0-5-5 A rigid cylindrical tank stores 100 kg of a substance at 500 kPa and 500 K while the outside temperature is 300 K. A paddle wheel stirs the system, transferring shaft work (\( W_{sh} \)) at a rate of 0.5 kW. At the same time an internal electrical resistance heater transfers electricity (\( W_{el} \)) at the rate of 1 kW. Determine \( Q \) necessary to ensure that no net energy enters or leaves the tank.

0-5-6 The nutrition label on a snack bar, which costs $1.00, reads—serving size 42 g; calories per serving 180. Determine (a) the heating value in MJ/kg, and (b) price in cents per MJ of heat release. (c) If gasoline with a heating value of 44 MJ/kg and a density of 750 kg/m\(^3\) costs $2.50 a gallon, what is the gasoline price in cents/MJ?

0-5-7 A popular soda can contains 0.355 kg of soda, which can be considered to be composed of 0.039 kg of sugar and the rest water. If the calorific value is written as 140 calorie (bio), (a) calculate the heating value (maximum heat that will be released by 1 kg of the food) of sugar in MJ/kg. (b) Compare the heating value of sugar with different fuels listed in Table G-2.

0-5-8 Consider three options for heating a house. Electric resistance heating with electricity priced at $0.10/kWh, gas heating with gas priced at $1.10/Therm and oil (density 0.8 kg/L, heating value 46.5 MJ/kg) heating with oil priced at $1.50/gal. Energetic efficiencies are 100% for the electrical heating system, 85% for the gas-heating system and 80% for the oil-heating system. Determine the cost of delivering 1 GJ of energy by each system.

0-5-9 To determine which is a cheaper fuel, a student collects the following data for gasoline and diesel respectively. Price per gallon: $2.90 vs. $3.10; heating value: 44 MJ/kg vs. 43.2 MJ/kg; density: 740 kg/m\(^3\) vs. 820 kg/m\(^3\); 1 Gallon = 3.785 L; 1 L = 10\(^{-3}\)m\(^3\). Determine (a) the price of gasoline in cents per MJ of heat release, (b) the price of diesel per MJ of heat release.

0-5-10 In 2003, the United States consumed (a) 20 MMbd (million barrels per day) of crude oil, (b) 21.9 tcf (trillion cubic feet) of natural gas, and (c) 1 billion tons (short) of coal. The Btu equivalents are as follows: 1 bbl crude oil: 5.8 million Btu; 1 Mcf gas: 1.03 million Btu; 1 ton coal: 21 million Btu. Compare the energy consumption in the consistent unit of Quad (1 Quad = 10\(^{15}\) Btu).

0-5-11 On Aug. 20, 2011, the prices for crude oil (heating value 43 MJ/kg) and natural gas were quoted as $82.26 USD/Bbl and 3.94 USD/MMBtu in the world market. Compare the prices on a comparable scale (USD/MJ). Use properties of heavy diesel to represent crude oil.

0-5-12 The United States consumed about 21 MMbd (million barrels per day) of crude oil (density 0.82 kg/L, heating value 47 MJ/kg), 67% of which is utilized in the transportation sector. Determine how many barrels of oil can be saved per year, if the fuel consumption in the transportation sector can be reduced by 20% through the use of hybrid technology.

SECTION 0-6: ENERGY CONVERSION

0-6-1 During charging, a battery pack loses heat at a rate of 0.2 kW. The electric current flowing into the battery from a 220 V source is measured as 10 amp. Determine (a) \( \dot{Q} \), (b) \( W_{el} \), and (c) \( W_{ext} \). Include sign.

0-6-2 A car delivers its power to a winch, which is used to raise a load of 1000 kg at a vertical speed of 2 m/s. Determine (a) the work delivered by the engine to the winch in kW, and (b) the rate (g/s) at which fuel is consumed by the engine. Assume the engine to be 35% efficient with the heating value of fuel to be 40 MJ/kg.

0-6-3 A car delivers 96.24 kW to a winch, which is used to raise a load of 1000 kg. (a) Determine the maximum velocity in m/s with which the load can be raised. (b) If the heating value of the fuel used is 45 MJ/kg and the engine has an overall efficiency of 35%, determine the rate of fuel consumption in kg/h.
A semi-truck of mass 25,000 lb (1 kg = 2.2 lb) enters a highway ramp at 10 mph (1 m/h = 0.447 m/s). It accelerates to 75 mph while merging with the highway at the end of the ramp at an elevation of 15 m. (a) Determine the change in mechanical energy of the truck. (b) If the heating value of diesel is 40 MJ/kg and the truck engine is 30% efficient (in converting heat to mechanical energy), determine the mass of diesel (in kg) burned on the ramp.

We are interested in the amount of gasoline consumed to accelerate a car of mass 5000 kg from 5 to 30 m/s (about 67 mph) on a freeway ramp. The ramp has a height of 15 m. Assuming the internal energy of the car to remain constant, (a) determine the change in stored energy \( E \) of the car. (b) If the heating value of gasoline is 44 MJ/kg and the engine has a thermal efficiency of 30%, determine the amount of gasoline (in kg) that will be consumed as the car moves through the ramp. Assume all the engine power goes into the kinetic and potential energies of the car.

A jumbo jet with a mass of 5 million kg requires a speed of 175 mph for takeoff. Assuming an overall efficiency of 20% (from heat release to kinetic energy of the aircraft), determine the amount of jet fuel (heating value: 44 MJ/kg) consumed during the takeoff.

A 0.1 kg projectile travelling with a velocity of 200 m/s (represented by State-1) hits a stationary block of solid (represented by State-2) of mass 1 kg and becomes embedded (combined system is represented by State-3). Assuming momentum is conserved (there are no external forces, including gravity, on any system), (a) determine the velocity of the combined system \( V_3 \) in m/s. (b) If the stored energies of the systems before and after the collision are same (that is, \( E_1 + E_2 = E_3 \)), determine the change in internal energy after the collision \( U_3 - U_1 - U_2 \) in kJ.

A semi-truck of mass 20,000 lb accelerates from 0 to 75 m/h (1 mi/h = 0.447 m/s) in 10 seconds. (a) What is the change in KE of the truck in 10 seconds? (b) If \( PE \) and \( U \) of the truck can be assumed constant, what is the average value of \( \frac{dE}{dt} \) of the truck during this period? (c) If 30% of the heat released from the combustion of diesel (heating value of diesel is 40 MJ/kg) is converted to KE, determine the average rate of fuel consumption in kg/s.

A gas trapped in a piston-cylinder device is subjected to the energy interactions shown in the accompanying figure for 30 seconds: the electric resistance draws 0.1 amp from a 100 V source, the paddle wheel turns at 60 rpm with the shaft transmitting a torque of 5 N-m and 1 kJ of heat is transferred into the gas from the candle. The volume of the gas increases by 6 L during the process. If the atmospheric pressure is 100 kPa and the piston can be considered weightless, determine (a) \( W_{B} \), (b) \( W_{sh} \), (c) \( W_{el} \), (d) \( W_{net} \).

A gas trapped inside a piston-cylinder device receives 20 kJ of heat while it expands, performing a boundary work of 5 kJ. At the same time 10 kJ of electrical work is transferred into the system. Evaluate (a) \( Q \) and (b) \( W \) with appropriate signs.

A gas at 300 kPa is trapped inside a piston-cylinder device. It receives 20 kJ of heat while it expands performing a boundary work of 5 kJ. At the same time 10 kJ of electrical work is transferred into the system. Evaluate (including sign) (a) \( Q \), (b) \( W_{el} \), (c) \( W_{p} \), (d) \( W_{net} \) with appropriate signs. (c) What is the net change in stored energy \( E \) of the system (magnitude only in kJ)? Neglect \( KE \) and \( PE \).

A person turns on a 100-W fan before he/she leaves the warm room at 100 kPa, 30°C, hoping that the room will be cooler when he/she comes back after 5 hours. Heat transfer from the room to the surroundings occurs at a rate of 0.2t (t in minutes) watts. Determine the net energy transfer into the room in 5 hours.

A fully charged battery supplies power to an electric car of mass 3000 kg. Determine the amount of energy depleted (in kJ) from the battery as the car accelerates from 0 to 140 km/h.

A photovoltaic array produces an average electric power output of 20 kW. The power is used to charge a storage battery. Heat transfer from the battery to the surroundings occurs at 1.5 kW. Determine the total amount of energy stored in the battery (in MJ) in 5 hours of operation.
0-6-16 The heating value (maximum heat released as a fuel is burned with atmospheric air) of diesel is 43 MJ/kg. Determine the minimum fuel consumption necessary to accelerate a 20-ton (short ton) truck from 0 to 70 mph speed. Assume that all the work done by the engine is used to raise the KE of the truck and the efficiency of the engine is 35%.

0-6-17 In 2002, the United States produced 3.88 trillion kWh of electricity. If coal (heating value 24.4 MJ/kg) accounted for 51% of the electricity production at an average thermal efficiency (electrical work output/heat input) of 40%, determine the total amount of coal (in short tons) consumed by the power plants in 2002.