Meandering Road from Dynamics to Thermodynamics and Vice Versa: What Is Work?

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Abstract

The science of mechanics may trace back to Aristotle (384-322 B.C.) and Archimedes (c. 287-212 B.C.), while thermal science may trace back to the steam engines by Savery in 1697 and Newcomen in 1712 or to the works of Rankine, Clausius, and Lord Kelvin in the 1850s. Both are old sciences where, from time to time, definitions formulated for terms to serve the purpose of previous existing physical understanding are later found inadequate, incorrect, or inconvenient for the description of more complete modern knowledge. Some definitions and conventions in dynamics and thermodynamics are given differently and can be confusing to unsuspecting undergraduate students who are taking them in their curricula. To a certain extent, this is the case with the terms *heat*, *work*, *potential energy*, and *conservation of energy*. This paper is aimed at pointing out the curvy and bumpy stretches on the road from dynamics to thermodynamics, and vice versa. It is hoped that better inter-disciplinary understanding will enhance effective communication for instructors and better learning for engineering students.

I. Concepts of Process, Path, and Heat

A **process** is any change (or transformation) that a system undergoes from one state to another. The series of states through which a system passes during a process is called the **path** of the process. To describe a process completely in thermodynamics, one needs to specify the initial and final states of the process, the path it follows, and the interactions with the surroundings. A *quasi-static*, or *quasi-equilibrium*, *process* is one which proceeds in such a way that the system remains infinitely close to an equilibrium state all the time.

The *old* caloric theory asserts that *heat* is a fluid-like substance called *caloric*, which is a massless, colorless, and tasteless substance that can be transferred from one body into another body to increase the temperature of the latter. This theory came under attack soon after its introduction by the French chemist Antonie Lavoisier (1743-1794). In 1798, Count Rumford (1753-1814) showed in his paper that heat can be "generated" continuously through friction. It was only after the careful experiments of James P. Joule (1818-1889), published in 1843, that the true physical nature of *heat* was understood through the *kinetic theory*. This theory treats molecules as tiny balls that are in motion and thus possess kinetic energy. Joule convinced the skeptics that heat was not a substance after all. Heat was then defined as the energy associated with the kinetic energy of the random motion of atoms and molecules. Although the caloric theory was totally abandoned in the middle of the nineteenth century, it contributed greatly to the development of thermal science.

A precise definition for energy is difficult to find. However, **energy** may be viewed as something that has the ability to cause changes. Energy is a property possessed by a system, but heat is *not* a property possessed by any system. In daily life, "heat" and "thermal energy" are often synonymously used. In thermodynamics, "heat transfer" and "energy transfer by heat" are interchangeably used.

Today, some instructors and authors[1,2] describe *heat* as the "*energy* being transferred" from the hot side to the cold side of a system boundary; but other instructors and authors[3,4] describe *heat* as the "*transfer* of energy" from the hot side to the cold side of a system boundary. Clearly, the gist in the description given by the former is different from that given by the latter. Since *energy* ≠ *transfer*, readers can find that basic descriptions for *heat* may be given differently in different thermodynamics textbooks! This is a beginning *curve* on the road in thermodynamics.

For this paper, we adopt the definition that **heat** is the energy in transition, during a *process*, between two systems (or a system and its surroundings) by virtue of a temperature difference. Heat is recognized only as it crosses the boundary of a system. There are three mechanisms by which heat is transferred: *conduction*, *convection*, and *radiation*.

II. Concepts of Work in Dynamics and Thermodynamics

A force or a moment does work on a body or a system, and a body or a system receives work done by a force or a moment that acts on it if it undergoes a corresponding displacement in the direction of the force or moment during the action. It is the force or the moment, rather than the body or the system, which does work. This is what students would learn in **dynamics**, which is a physical science that describes and predicts the conditions of bodies under the action of unbalanced force systems.

In dynamics,[5,6,7,8] the **work** done by a force **F** on a body moving from position A_1 along a path C to position A_2 is usually denoted by $U_{1\to 2}$ and is defined by a line integral

$$U_{1\to 2} = \int_{A_1}^{A_2} \mathbf{F} \cdot d\mathbf{r} \tag{1}$$

where $\cdot$ denotes a dot product, and $d\mathbf{r}$ is the differential displacement of the body moving along the path C during the action of **F** on the body.

The **work** $U_{1\to 2}$ done by a moment **M** (or a couple of moment **M**) on a body during its finite rotation, parallel to **M**, from angular position θ_1 to angular position θ_2 is given by

$$U_{1\to 2} = \int_{\theta_1}^{\theta_2} M \, d\theta \tag{2}$$

In thermodynamics, some instructors and authors[1,2] describe *work* as the "*energy* being transferred," during a process, by virtue of a force acting through a displacement on the system; but other instructors and authors[3,4] describe *work* as the "*transfer* of energy," during a process, by virtue of a force acting through a displacement on the system. Again, the gist in the description given by the former is different from that given by the latter. Since *energy* ≠ *transfer*, readers can find that basic descriptions for *work* may be given differently in different thermodynamics textbooks! This is another beginning *curve* on the road in thermodynamics.

For this paper, we adopt the definition that **work** is also energy in transition, during a *process*, to a system as a result of a force (or generalized force) acting through a displacement (or generalized displacement) on the system. Work, like heat, is a function of the path of a process and is an inexact differential. Systems never possess heat or work, but either or both cross the system boundary when a system undergoes a process. Both *heat* and *work* are **transient phenomena** as well as **boundary phenomena**.

The forms of work in thermodynamics may include mechanical work (such as those done by forces and moments) and nonmechanical work. Examples of nonmechanical work include

- **Electric work**, where the generalized force is the *voltage* (the electric potential) and the generalized displacement is the *electrical charge*;
- **Magnetic work**, where the generalized force is the *magnetic field strength* and the generalized displacement is the total *magnetic dipole moment*;
- **Electric polarization work**, where the generalized force is *electric field strength* and the generalized displacement is the *polarization of the medium* (the sum of the electric dipole rotation moments of the molecules).

In thermodynamics, it is said that work can be done by a system (i.e., a body) on its surroundings, and work can also be done by the surroundings on the system. This phraseology in thermodynamics differs from that in dynamics, where it is held that "a force or a moment (*not* a body) does work and a body receives work." Perhaps, those in thermal science were influenced by their major interests in the work output from a thermal system and the conversion of *heat* into *work* by heat engines (e.g., car engines and power plants). Naturally, this is a slight *bump* on the road from dynamics to thermodynamics, and vice versa.

It is helpful to bear in mind that thermodynamics is a physical science of *energy*. Thermodynamics has a great deal to do with the transfer, storage, and conversion of energy in quasi-equilibrium processes, but it has little to do with dynamics of particles and rigid bodies from the mechanics point of view.

III. Conservative and Nonconservative Forces

In mechanics,[5,6,7,8] forces may be classified as *conservative forces* or *nonconservative forces*. A force **F** is a **conservative force** if it is derivable from a potential function ϕ of space variables such that $\mathbf{F} = \nabla\phi$; otherwise, it is a **nonconservative force.** For example, the weight force $\mathbf{W}$ of a body, at a height y above a reference datum, is a force of gravity expressible as

$$\mathbf{W} = -W\mathbf{j} = \nabla\phi \tag{3}$$

where

$$\phi = -Wy \tag{4}$$

Thus, a **weight force** is derivable from a potential function and is a *conservative force*.

When a linear spring of modulus k is stretched by an amount x to the right, the elastic restoring force $\mathbf{F}_e$, pointing to the left, can be written as

$$\mathbf{F}_e = -kx\mathbf{i} = \nabla\phi \tag{5}$$

where

$$\phi = -\frac{1}{2}kx^2 \tag{6}$$

Since $\mathbf{F}_e$ is derivable from a potential function ϕ, the **elastic restoring force** is another kind of *conservative force*. It can be shown that any **constant force** is a *conservative force*. A conservative force is said to possess a *potential*.

The magnitudes and directions of friction forces at a given position are not analytic functions of space variables; they depend on the properties of the media, normal forces, and relative velocities. **Friction forces** are not derivable from potential functions and *are nonconservative forces*. The work done on a body by a conservative force is dependent only on the initial and final positions of the body. The distinction between "conservative forces" and "nonconservative forces," or "conservative systems" and "nonconservative systems" is usually not emphasized or pointed out in beginning thermodynamics. One should watch out for such a *curve* in communication when traveling on the road from dynamics to thermodynamics, and vice versa.

IV. Forms of Energy and Total Energy

An effective study of thermodynamics requires a good understanding of the various forms of energy that comprise the *total energy* of a system, as well as an ability to recognize the forms of energy transfer during a process. The various forms of energy that make up the total energy of a system may be divided into two groups: *macroscopic* and *microscopic*. The **macroscopic** forms of energy are those a system possesses as a whole with respect to an outside reference frame (an inertial reference frame). The **kinetic energy** (KE) and **potential energy** (PE) of a system are macroscopic forms of energy of the system.

- For a particle of mass m moving with a speed v, its *kinetic energy* is

$$\mathrm{KE} = \frac{1}{2}mv^2 \tag{7}$$

  The kinetic energy given in Eq. (7) is equivalent to the net amount of work to be done on the particle of mass m if the particle is to be brought from a state of rest to a state with a speed v.

- In plane motion, the *kinetic energy* of a rigid body with an angular speed w and a mass moment of inertia I_C about its instantaneous center of zero velocity (i.e., the velocity center) C is

$$\mathrm{KE} = \frac{1}{2} I_C \omega^2 \tag{8}$$

- In three-dimensional motion, the *kinetic energy* of a rigid body with a total mass m, angular velocity vector $\boldsymbol{\omega}$, and angular momentum vector $\mathbf{H}_G$ about its mass center G, which is moving with a speed $\bar{v}$, is

$$\mathrm{KE} = \frac{1}{2} m \bar{v}^2 + \frac{1}{2} \boldsymbol{\omega} \cdot \mathbf{H}_G \tag{9}$$

A body is said to possess a *potential energy* in its current position if it is under the influence of a conservative force field. The **potential energy** of a body in its current position with respect to a reference datum in a conservative force field is defined as the amount of work done by the conservative force on the body if the body travels from its current position to the reference datum.[6]

- For a body of weight W at a height y above a reference datum in the vicinity of the surface of the earth, its *gravitational potential energy* is

$$\mathrm{PE} = Wy \tag{10}$$

- For a spacecraft coasting around the earth or an orbiting earth satellite at a radial distance r from the center of the earth, its *gravitational potential energy* is

$$\mathrm{PE} = -\frac{GMm}{r} \tag{11}$$

where G is the constant of gravitation, M is the mass of the earth, m is the mass of the spacecraft or the satellite, and the reference datum is at $r = \infty$.

- For a body connected to a linear spring of modulus k that is stretched or compressed by an amount x with the unstretched position of the spring as the reference datum, its *elastic potential energy* is

$$\mathrm{PE} = \frac{1}{2} k x^2 \tag{12}$$

- A constant force has a constant magnitude and a constant direction. An applied constant force acting on a body is a force suddenly (*not* gradually) applied to the body. For a body subjected to an applied constant force $\mathbf{P}$, its *applied potential energy*[6] is

$$\mathrm{PE} = \mathbf{P} \cdot \mathbf{q} \tag{13}$$

  where $\mathbf{q}$ is the displacement vector from the current position of the force $\mathbf{P}$ to the reference datum, which is the original equilibrium position of the particle on which $\mathbf{P}$ acts.

The **microscopic** forms of energy are those related to the molecular structure and the degree of molecular activity in a system; they may be viewed as the sum of the kinetic and potential energies of the molecules and are independent of the outside reference frame. The **internal energy**, usually denoted by U in thermodynamics, is defined as the *sum of all the microscopic forms of* *energy* in the system. Examples of *internal energy* include sensible energy, latent energy, chemical energy, nuclear energy, energy present in a charged capacitor, etc. Students starting to take a course in thermodynamics after having taken a course in dynamics will most likely note that the term *internal energy* is new to them. This is a learning *curve* from dynamics to thermodynamics. Nevertheless, *internal energy* is an important form of energy in the study of thermodynamics.

The **total energy** of a system, usually denoted by E in thermodynamics, is the sum of *internal energy* (U), *kinetic energy* (KE), *potential energy* (PE), *electric energy*, and *magnetic energy*. In the absence of electric, magnetic, and surface tension effects, we write

$$E = U + \mathrm{KE} + \mathrm{PE} \tag{14}$$

The **change in total energy** of a system during a process is taken as the sum of the *changes* in internal, kinetic, and potential energies; i.e.,

$$\Delta E = \Delta U + \Delta \mathrm{KE} + \Delta \mathrm{PE} \tag{15}$$

V. Heat versus Internal Energy

The relationship between *heat* and *internal energy* may be illustrated by the phenomenon exhibited by the dish of casserole, hot from the oven, sitting on a table in a closed and insulated room. There are two systems whose boundaries are represented by a dotted small rectangle and a large rectangular frame of the room as shown in Fig. 1. The first system is the dish of casserole enclosed by the dotted rectangle, and the second system includes the air and everything except the dish of casserole in the room. A temperature difference exists between the two systems because the temperature of the casserole is initially much higher than the room temperature.

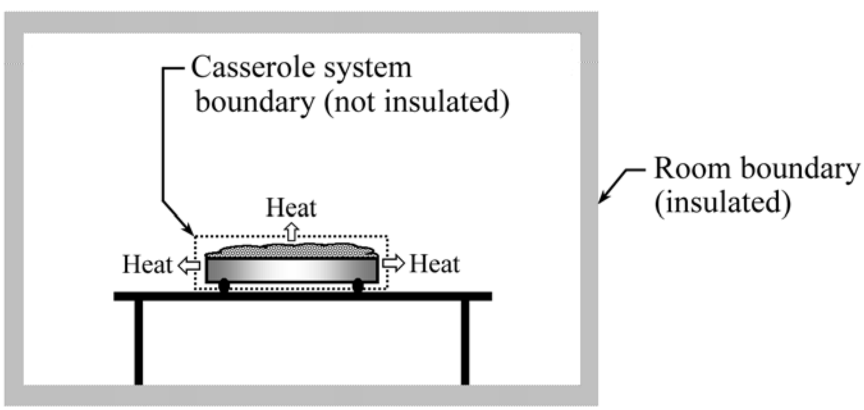

Fig. 1 A hot dish of casserole on a table in a closed and insulated room

Recall that *heat is energy in transition* from the hot side to the cold side. Heat is recognized only as it crosses the boundary of a system into its surroundings. The hot dish of casserole in the first system contains **internal energy**. This *internal energy* is **heat** only as it crosses the boundary into the second system with temperature difference as the driving force. Once crossing into the second system, the transferred heat becomes the additional amount of the **internal energy** of the second system. Consequently, the air and the table in the second system may get warmer because the internal energy in the second system is increased. The transfer of internal energy from the casserole to the room will continue until equilibrium of temperature is established. Thenceforth, energy transfer by heat no longer exists between the two systems.

Internal energy is a property possessed by a system, but heat is not. Heat is usually a transient phenomenon, but internal energy is not. Clearly, heat is identified at the boundary of the system, for heat is the energy being transferred across the system boundary.

VI. Dependence of Work and Heat on Paths

The amount of energy transferred by **work** or **heat** is dependent on the **path** of the process, not just on the states of the system in the initial and final positions of the path. For illustration, let us consider the system in Fig. 2, where an ideal gas[1] is compressed by a force **F** that pushes the piston from position *A* to position *C*. In this process, the gas is finally compressed to a *preset pressure* in the cylinder, but *different paths* (e.g., insulation and removal of insulation) are arranged to make the initial and final *gas temperatures* the *same* as the ambient *room temperature*.

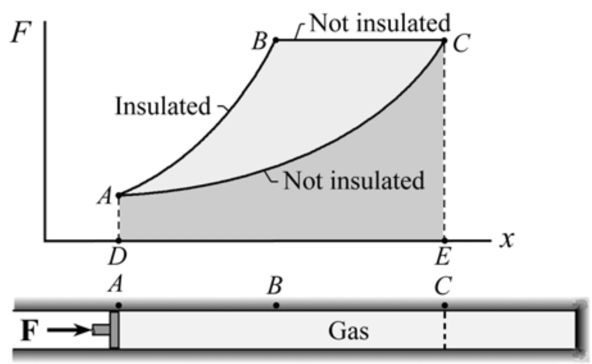

Fig. 2 Work and heat transfer in and out of the gas in a cylinder: dependence on paths

- **Work done W_{AC} and heat transferred Q_{AC} during the process along the path *AC*.**

  First, suppose that the cylinder is **not insulated** and the magnitude F of the force **F** is *slowly* increased in pushing the piston from position A all the way to position C to reach the *preset pressure*. The work done on the gas by **F** is, of course, expected to cause its internal energy, hence the temperature, to increase. Since the cylinder is not insulated, heat output from the gas, hence decrease of its internal energy, can take place. Thus, the temperature of the gas hovers at the room temperature during the process. We find that the relation between F and the displacement x of the piston is given by the curve AC in the graph in Fig. 2. The **work done** W_{AC} by **F** on the gas and **heat transferred** Q_{AC} *to* the gas during the process are equal in magnitude and are, therefore, both given by the shaded area *DACED*. We have

$$W_{AC} = (\text{Area})_{DACED} \tag{16}$$

$$Q_{AC} = -(\text{Area})_{DACED} \tag{17}$$

■ **Work done W_{ABC} and heat transferred Q_{ABC} during the process along the path *ABC*.**

Next, suppose that the cylinder is **initially insulated** while the piston is pushed by **F** to compress the gas from position *A* to position *B*, at which the *preset pressure* for the gas is reached. **Then the insulation is removed** to allow the gas to cool down to room temperature. During the cooling process, the volume of the gas decreases and the piston travels from position *B* to position *C* under the same magnitude of **F** at position *B*. This time, the relation between *F* and *x* is given by the curve *AB* and the horizontal straight line *BC* in the graph in Fig. 2. The **work done** W_{ABC} by **F** on the gas and **heat transferred** Q_{ABC} *to* the gas are equal in magnitude and can be computed from the sum of the shaded areas *DACED* and *ABCA*. We have

$$W_{ABC} = (\text{Area})_{DACED} + (\text{Area})_{ABCA} \tag{18}$$

$$Q_{ABC} = -[(\text{Area})_{DACED} + (\text{Area})_{ABCA}] \tag{19}$$

We observe that

$$W_{AC} \neq W_{ABC} \qquad\qquad Q_{AC} \neq Q_{ABC}$$

Clearly, when the *paths* (e.g., *AC* and *ABC* for the system in Fig. 2) connecting the same sets of initial and final states of a system are *different* during a process, the *energy transferred* by work or heat will be *different*. The energy transferred by work or heat is highly dependent on the *path* of the process undergone by the system. *Work* and *heat* are said to be **path functions**.

VII. First Law of Thermodynamics: Energy Balance

The various forms of energy such as heat *Q*, work *W*, and total energy *E* of a system have been discussed individually in preceding sections of this paper. The *first law of thermodynamics* provides a sound basis for studying the relationships among the various forms of energy and energy interactions. The **first law of thermodynamics** states that *the net energy transfer to a system from its surroundings is equal to the net increase in the total energy of the system.* This law is really a law of **energy balance**, as often referred to in *continuum mechanics*.

In dynamics, the sum of the *kinetic energy* and the *potential energy* of a body is referred to as the **mechanical energy**, or simply as **energy**, of the body. This *energy* is **conserved** when the body is subjected to only *conservative* forces. In dynamics, **conservation of energy** means "conservation of mechanical energy." If a *nonconservative* force (e.g., friction force) acts on a body, the *energy* of the body is **not conserved**. Therefore, "mechanical energy" is not always conserved! It is held in thermodynamics that energy can be neither created nor destroyed; it can only change forms. The **first law of thermodynamics** asserts that *total energy* is a thermodynamic property. This law is regarded as the **conservation of energy principle** in thermodynamics. The term "conservation of energy" used in dynamics and thermodynamics really has different intended situations and different meanings in these two subjects of study. It may appear confusing to unsuspecting students. Naturally, one may regard the concept of *conservation of energy* as a *curve* on the road from dynamics to thermodynamics, and vice versa.

There are two distinct systems: a *closed system* where its mass does not cross the system boundary, and an *open system* where mass can cross the system boundary. Most systems considered in undergraduate dynamics are closed systems. Equations for the first law of thermodynamics, or *energy balance*, may be written for these two distinct systems as follow:

- Closed System

For a closed system, energy transfer can take place only by *heat* and *work*. Thus, the **energy balance** can be written as

$$Q_{\text{net}} + W_{\text{net}} = \Delta E \tag{20}$$

Substituting Eq. (15) into Eq. (20), we may alternatively write the **energy balance** as

$$Q_{\text{net}} + W_{\text{net}} = \Delta U + \Delta \text{KE} + \Delta \text{PE} \tag{21}$$

The symbols in Eqs. (20) and (21) are defined as follows:

Q_{net} = net amount of *heat* transferred from the surroundings *to the system*

W_{net} = net amount of *work* done *on the system* by nonconservative or generalized forces which do not contribute to the change of the potential energy of the system

ΔE = *change* in total energy of the system

ΔU = *change* in internal energy of the system

ΔKE = *change* in kinetic energy of the system

ΔPE = *change* in potential energy of the system

- Open System

Recall that mass can flow into and out of an open system. Thus, energy transfer, in the case of an open system, can take place by *heat*, *work*, and *mass* (or flow of mass). First, the **mass balance** (conservation of mass) for a system undergoing any process can be expressed as

$$m_{\text{i}} - m_{\text{e}} = \Delta m_{\text{system}} \tag{22}$$

where

m_{i} = net amount of *mass* that moves *into* the system

m_{e} = net amount of *mass* that *exits* the system

Δm_{system} = *change* in mass of the system

Next, the **energy balance** for the open system can be expressed as

$$Q_{\text{net}} + W_{\text{net}} + m_{\text{i}}e_{\text{i}} - m_{\text{e}}e_{\text{e}} = \Delta E_{\text{system}} \tag{23}$$

where Q_{net} and W_{net} have the same meaning as defined earlier, and

e_i = energy per unit mass (e.g., J/kg) of the *incoming* mass m_i

e_e = energy per unit mass (e.g., J/kg) of the *exiting* masses m_e

ΔE_{system} = *change* in total energy of the system

VIII. Degeneration of First Law of Thermodynamics into Principles in Dynamics

Since systems considered in undergraduate dynamics are closed systems, we first refer to the **first law of thermodynamics** as represented by Eq. (21):

$$Q_{net} + W_{net} = \Delta U + \Delta \mathrm{KE} + \Delta \mathrm{PE} \tag{21}$$

(Repeated)

For a rigid body moving from position 1 to position 2 in dynamics, we neglect net amount of *heat* transferred from the surroundings to the body and we assume that the change in internal energy of the rigid body is negligible; thus, we have

$$Q_{net} = 0 \tag{24}$$

$$\Delta U = 0 \tag{25}$$

Neglecting the generalized forces, we find that W_{net} is the net amount of *work* done *on* the body by the *nonconservative forces*, if any. We write

$$W_{net} = U^{N}_{1\to 2} \tag{26}$$

where $U^{N}_{1\to 2}$ represents the work done by the nonconservative forces on the body as it moves from position 1 to position 2. Letting the kinetic energies of the body in positions 1 and 2 be represented by T_1 and T_2, respectively, we can write the *change in kinetic energy* as

$$\Delta \mathrm{KE} = T_2 - T_1 \tag{27}$$

Denoting the potential energies of the body in positions 1 and 2 by V_1 and V_2, respectively, we can write the *change in potential energy* as

$$\Delta \mathrm{PE} = V_2 - V_1$$

Recall that the **potential energy** of a body in its current position with respect to a reference datum in a conservative force field is defined as the amount of work done by the conservative force on the body if the body travels from its current position to the reference datum. Moreover, recall that the work done by any conservative force is independent of path. Using the superscript ^{C} to denote conservative forces and the subscripts $_1$, $_2$, and $_{RD}$ to denote the positions of 1, 2, and the reference datum, which are on the paths traversed, we write

$$\Delta \mathrm{PE} = V_2 - V_1 = U^{C}_{2\to RD} - \left(U^{C}_{1\to 2} + U^{C}_{2\to RD}\right) = -U^{C}_{1\to 2} \tag{28}$$

Substituting Eqs. (24) through (28) into Eq. (21), we write

$$0 + U_{1\to 2}^{N} = 0 + (T_2 - T_1) - U_{1\to 2}^{C}$$

$$T_1 + \left(U_{1\to 2}^{N} + U_{1\to 2}^{C}\right) = T_2 \tag{29}$$

Since the sum of the works done by the nonconservative and conservative forces is equal to the total work done by the entire force system on the body, we have

$$U_{1\to 2} = U_{1\to 2}^{N} + U_{1\to 2}^{C}$$

$$\boxed{T_1 + U_{1\to 2} = T_2} \tag{30}$$

Equation (30) is the well-known **principle of work and kinetic energy** in dynamics. If the force system consists of conservative forces only, then

$$U_{1\to 2} = U_{1\to 2}^{C} = U_{1\to RD}^{C} + U_{RD\to 2}^{C} = U_{1\to RD}^{C} - U_{2\to RD}^{C} = V_1 - V_2 \tag{31}$$

Substituting Eq. (31) into Eq. (30) and rearranging the terms in the equation, we get

$$\boxed{T_1 + V_1 = T_2 + V_2} \tag{32}$$

Equation (32) is the well-know **principle of conservation of mechanical energy** in dynamics. We clearly see that the *first law of thermodynamics*, the *principle of work and kinetic energy*, and the *principle of conservation of mechanical energy* in dynamics are the *general case*, the *special case*, and *another special case* of the **energy balance**, respectively.

IX. Illustrative Examples: Work, Heat, and Energy Interactions

This section of the paper is devoted to illustrate the concepts of *work*, *heat*, and *energy interactions* with examples, and to alert the travelers to the curvy and bumpy parts on the road from dynamics to thermodynamics, and vice versa.

▪ What is the work done on the system in Fig. 3?

The drawing of a *free-body diagram* (showing the force system) is greatly emphasized in mechanics, while the drawing of a *system diagram* (showing the system boundary and energy interactions between the system and the surroundings, instead of the force system) is similarly emphasized in thermodynamics. However, the concept of *work* is a *bump* on the road from dynamics to thermodynamics, and vice versa. To illustrate the point, let us first consider a system that is composed of a roomful of fixed empty space and a block of weight **W** as shown in Fig. 3.

If the block in Fig. 3 is suddenly released to fall under gravity through a height *h* toward the bottom of the fixed empty space, what is the work done on the system? A student having taken and understood a course in dynamics, but not thermodynamics, says, “The work done on the system is equal to *Wh*.” This student’s friend having taken and understood a course in thermodynamics, but not dynamics, shakes his head and proclaims, “The work done on the system is zero!” Why do they give different answers?

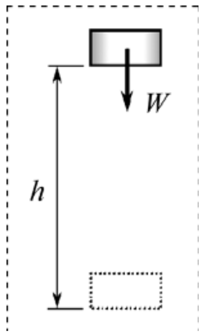

Fig. 3 System consisting of a fixed space and a falling block under gravity

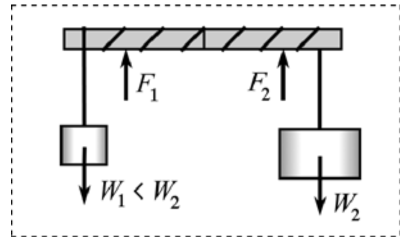

Fig. 5 System consisting of a fixed space and a supported rotating shaft that winds and unwinds blocks under gravity

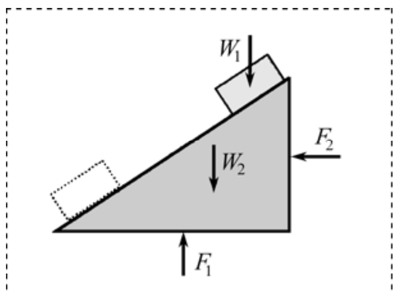

Fig. 4 System consisting of a fixed space and a block sliding with friction by gravity on a supported wedge

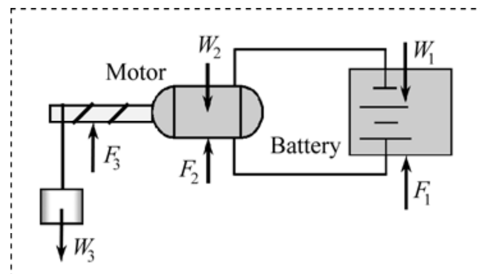

Fig. 6 System consisting of a fixed space, a supported motor with battery, and a weight being raised against gravity

In thermodynamics, the key word is *energy*. It is important to remember that the *total energy* of a system is composed of its *internal energy*, *kinetic energy*, and *potential energy*. Furthermore, whenever a thermal system is subjected to a conservative force field, the potential energy associated with the conservative force, rather than the conservative force itself, is *preferentially* used in the formulation and study. To *many* instructors and in *many* thermodynamics textbooks, **conservative forces in thermodynamics are disfranchised to do work** because their effects are accounted for in the change of potential energy of the system! This disfranchisement is not a recognized convention in dynamics, where a *conservative force* as well as a *nonconservative force* can do work if the body, on which it acts, has a displacement component in the direction of action of the force. An unsuspecting student, who is taking a thermodynamics course soon after having taken and understood a dynamics course will find that the said disfranchisement is a big *bump* on the road from dynamics to thermodynamics.

Having learned the above “disfranchisement” in thermodynamics, we may return to the question posed for the system in Fig. 3. The student, who has taken and understood a course in dynamics, but not thermodynamics, obviously employs the *principle of work and kinetic energy* as given in Eq. (30), which is applicable to conservative as well as nonconservative systems, to compute the work $U_{1\to 2}$ done on the block by the weight force **W**. Naturally, he asserts, “The work done on the system is equal to *Wh*.”

On the other hand, the energy mentality in the student who has taken and understood a course in thermodynamics, but not dynamics, will, of course, prompt him to disfranchise the weight force **W** (a conservative force) to do work. Naturally, he proclaims, "The work done on the system is zero!" As a matter of fact, this latter student will say that no work is done in all of the systems shown in Figs. 4 through 6, as described by the captions of the figures, because *the weight force is disfranchised to do work* and he sees no work crossing the system boundary defined by each of the dashed rectangles.

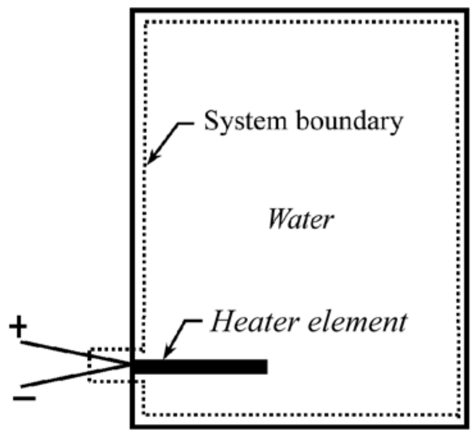

Fig. 7 System consisting of *water* and *heater element* in a tank

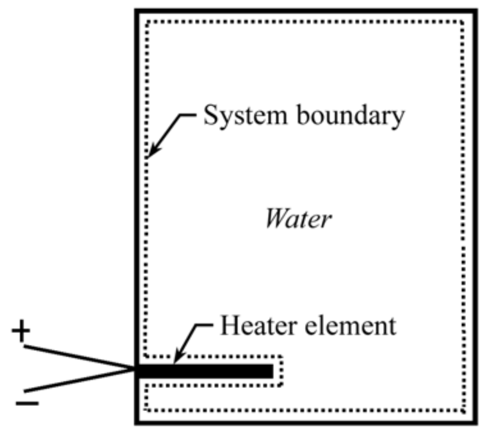

Fig. 8 System consisting of just *water* in a tank

■ The water is getting hotter. Is the energy transfer by "work" or "heat" to the system in Fig. 7?

The system shown in Fig.7 consists of *water* and the *heater element* in a tank, where an electric power source is connected to the heater element. The energy transfer across the dotted system boundary in Fig. 7 is in the form of (electric) **work**, where the generalized force is the voltage (the electric potential) and the generalized displacement is the electrical charge. Since the heater element is included in the system under consideration, the energy transfer is **not heat** even though the water is getting hotter.

■ The water is getting hotter. Is the energy transfer by "work" or "heat" to the system in Fig. 8?

The system shown in Fig.8 consists of just *water* in a tank, where the heater element is excluded from the system under consideration. The electric power source connected to the heater element causes the heater element to get very hot; thus, a temperature difference is created. The energy transfer from the heater element across the dotted system boundary to the water is driven by a temperature difference. Therefore, by definition, the energy transfer to the system in Fig. 8 is in the form of **heat**.

■ A 60-kg insulated sack of sand in Fig. 9 is dropped from rest from a loading dock to fall through a height of 1.5 m onto a concrete pavement. Take the system to be the sand and its sack and assume that the perfectly plastic impact is completed in 0.5 s. Neglecting air resistance, determine the work done on the system, the energy interaction, and the average force of impact.

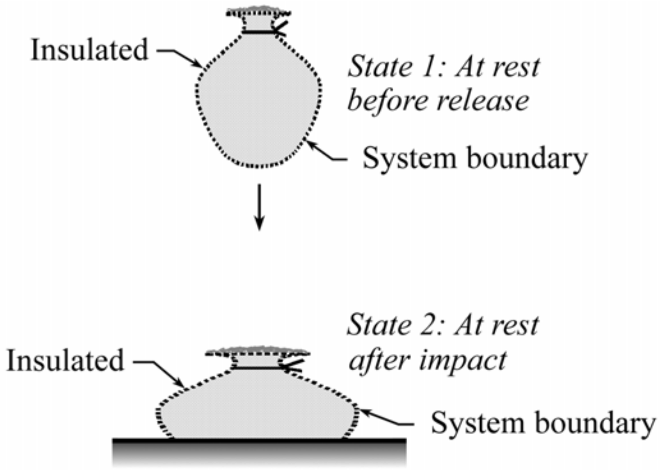

Fig. 9 A sack of sand released from rest to fall and impact on a concrete pavement

Since air resistance is negligible, the weight force (a conservative force) is disfranchised to do work, and the force exerted by the pavement on the sack does not act through a displacement, we conclude that **no work** is *done on the system*.

We note that the system is at rest in both states 1 and 2. In the *energy balance*,

$$Q_{\text{net}} + W_{\text{net}} = \Delta U + \Delta \text{KE} + \Delta \text{PE}$$

we see that the process is adiabatic and

$$Q_{\text{net}} = 0 \qquad W_{\text{net}} = 0 \qquad \Delta\text{KE} = 0$$

$$\Delta\text{PE} = -\,mgh = -\,60 \text{ kg } (9.81 \text{ m/s}^2)\,(1.5 \text{ m}) = -\,882.9 \text{ J} \approx -\;883 \text{ J}$$

Thus, by energy balance, there is an *increase* in **internal energy** given by

$$\Delta U = 883 \text{ J}$$

This increase in internal energy may result in more energetic vibrations of the particles, or an increase in temperature, of the system. This aspect of the system behavior is usually not investigated in dynamics.

The impulse of the sack of sand just before impact is equal to its mass times its velocity; i.e.,

$$\text{Imp}_{1\to 2} = m\sqrt{2gh} = 60 \text{ kg } \sqrt{2(9.81 \text{ m/s}^2)(1.5 \text{ m})} = 325.5 \text{ kg}\cdot\text{m/s}$$

The average force of impact is determined from the *principle of impulse and momentum* as follows:

$$\text{Imp}_{1\to 2} = F(\Delta t): \qquad 325.5 \text{ kg}\cdot\text{m/s} = F(0.5 \text{ s}) \qquad F = 651 \text{ N}$$

Here, we obtain that the **average force of impact** is 651 N. Similarly, this aspect of the system behavior is usually not investigated in thermodynamics. Clearly, by combining the tools in dynamics and thermodynamics, an engineer can know more about what may happen to the system.

X. Concluding Remarks

Dynamics and thermodynamics have similar sounding names but considerably different subject contents. Systems studied in thermodynamics undergo quasi-equilibrium processes. From the mechanics point of view, there is little dynamics in thermodynamics. The frames of mind required to effectively learn dynamics and thermodynamics are different, and the emphases and conventions in these two subjects are also different for good reasons. The main interest in thermodynamics is the study of energy: its storage, transfer, and conversion in engineering systems. Naturally, the energy mentality in many instructors and textbook authors of thermodynamics is robust and compelling. This is why many thermodynamics students are taught that *conservative forces are disfranchised to do work*. **Work** and **heat** serve as the means by which energy is transferred to or from closed systems. For open systems, **mass** (or flow of mass) is an additional means by which energy is transferred.

Written by instructors teaching dynamics and thermodynamics, this paper reviews important basic concepts and alerts "travelers" to several curvy and bumpy parts on the road from dynamics to thermodynamics, and vice versa. These parts include the following:

- The basic descriptions for **heat** and **work** may be given differently by different *instructors* and in different thermodynamics *textbooks*.
- In dynamics, it is the force or moment (*not* the body) that **does work** on a body, and a body **receives work** from a force or moment. In thermodynamics, a body or a system (i.e., *not* a force or moment) is said to do work on, or receive work from, another body or system.
- The distinction between **conservative forces** and **nonconservative forces** is emphasized and utilized in dynamics, but not in thermodynamics.
- The concept of **internal energy** of a system is emphasized and utilized in thermodynamics, but not in dynamics.
- In dynamics, the sum of the *kinetic energy* and the *potential energy* of a body is referred to as the **mechanical energy** of the body. It asserts that the *mechanical energy* is **not conserved** if nonconservative forces act on the body during its motion. The *first law of thermodynamics* is regarded as the **conservation of energy principle** in thermodynamics, where it asserts that energy can be neither created nor destroyed; energy can only change forms.
- To *many* instructors and in *many* thermodynamics textbooks, **conservative forces in thermodynamics are disfranchised to do work** because their effects are accounted for in the change of potential energy of the system. This disfranchisement is not a recognized convention in dynamics.

It is hoped that by watching out for, and paying special attention to, the curvy and bumpy parts on the meandering road from dynamics to thermodynamics, and vice versa, better interdisciplinary understanding can be gained. Being aware of the differences in terminology and phraseology in different subjects, instructors can enhance their effectiveness in communicating with students, and students will learn these subjects more effectively.

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