3. Energy, Heat, and Work

In these Lecture Notes we examine the basis of thermodynamics – fundamental definitions and equations for energy, heat, and work.

3-1. Energy. Two of man's earliest observations was that: 1)useful work could be accomplished by exerting a force through a distance and that the product of force and distance was proportional to the expended effort, and 2)heat could be ‘felt’ in when close or in contact with a warm body. There were many explanations for this second observation including that of invisible particles traveling through space[1]. It was not until the early beginnings of modern science and molecular theory that scientists discovered a true physical understanding of ‘heat flow’. It was later that a few notable individuals, including James Prescott Joule, discovered through experiment that work and heat were the same phenomenon and that this phenomenon was energy:

Energy is the capacity, either latent or apparent, to exert a force through a distance.

The presence of energy is indicated by the macroscopic characteristics of the physical or chemical structure of matter such as its pressure, density, or temperature - properties of matter. The concept of hot versus cold arose in the distant past as a consequence of man's sense of touch or feel. Observations show that, when a hot and a cold substance are placed together, the hot substance gets colder as the cold substance gets hotter. The conclusion follows that energy is being transferred from the hot to the cold substance. Since the bodies are in intimate contact, the process is called conduction. Observations also show that the transfer of energy continues even though the bodies are not in contact and even when the space between the two bodies is evacuated. Descriptively, the transmission of energy through space is called radiation. But whenever energy flows from a hot to a cold body, changes occur in one or more properties of each body, such as the pressure, volume, electrical resistance, etc.

Thus, energy in various forms is considered to be a *companion* of mass, for example, energy of mass motion, called *kinetic energy;* energy of mass position, called *potential energy;* and energy of mass composition, called *internal energy.* Internal energy, like pressure, density, and temperature, is a property of matter:

[1] This was an initial error of our forefathers of the science of thermodynamics.

A fundamental axiom of modern thermodynamics is that internal energy is a property of matter.[2]

All the forms of energy accompanying mass are designated by the letter E (or e for energy per unit mass). The derived dimension for energy is [E] = [F][L].

There are several forms of energy. Classical thermodynamics lumps energy into distinct categories that relate to the thermodynamic system discussed earlier. Energy can be stored within the system in three ways:

1. Internal energy –energy contained within a body because of the motion of atoms and molecules.

2. Potential energy –energy existing because of attraction of one body to another caused by a gravitational or magnetic field.

3. Kinetic energy – energy existing because of the relative velocity difference between two bodies.

Energy can be transferred into or out of the system in two ways:

1. Heat – energy transfer resulting from a potential energy difference between system and surroundings.

2. Work – energy transfer resulting from a force exerted through a distance by the system to the surroundings.

Energy storage and energy transfer is limited to these and only these forms in classical thermodynamics. All energy categories noted above have the same dimensions, that of force X distance, or [E]=[F][L], and within a chosen dimensional system all categories have the same units.

This development is historically represented in USCS where heat has units of the British Thermal Unit, BTU, and work is represented as the foot-pound force. It wasn't until Joule's noted experiments that both were identified as the same phenomenon (energy) so a simple constant exists between the Btu and the foot-pound force:

$$1\ Btu = 778\ ft\ lb_f$$

Both are accepted units of energy in USCS. Later, due to James Prescott Joule, the SI system correctly noted that both heat and work are energy and both have a single unit in the SI system, the Joule or J.

3-2. Potential and. Kinetic Energy. The external forms of energy are named potential energy (PE), or energy of position, and kinetic energy (KE), or energy of motion.

[2] Although this axiom was not the first in the long history of thermodynamics, today it can serve as a logical starting point since it includes the pioneering work of Joule as well as the modern relativity laws of Einstein.

Potential energy is restricted here to gravitational energy, that is, energy arising from the elevation of a mass with respect to the earth. The gravitational attraction of the earth on the mass is the source of a force (weight) which is proportional to the mass.

This force can be exerted through a distance which is the elevation Z of the mass (since g is practically constant for small vertical displacements). Thus, energy of position equals

$$PE = mgz \qquad [F][L]$$

Whenever a mass undergoes a change in velocity, a force is exerted,

$$F = ma = m\frac{dV}{dt}$$

When the force is exerted over a distance L, the change in energy is

$$\Delta E = \int_{L_1}^{L_2} F dL = \int_{t_1}^{t_2} FV dt = m\int_{V_1}^{V_2} V dV$$

The kinetic energy associated with the velocity V and the mass m is found by integrating the above equation from a velocity V to zero,

$$KE = mV^2 \qquad [F][L]$$

Before potential energy can be calculated, an elevation with an assigned value of zero potential energy must be arbitrarily selected. From this elevation, the height of the mass is measured, and the potential energy relative to this datum is calculated. In measuring kinetic energy, a similar procedure is indicated, although, usually, the datum is automatically selected by measuring velocities relative to the earth. The same datum must be retained throughout a given problem for each form of energy.

3-3. Internal Energy. All matter has energy arising from the motions and from the configurations of its internal particles (rotation, vibration, translation of the atoms and molecules along with electron configuration). Such energy is called, quite descriptively, internal energy, and the amount of internal energy is reflected by properties such as pressure, temperature, and chemical composition The symbol to designate internal energy is U or, for unit mass, u.

Consider a mixture of air and gasoline vapor held under pressure and confined by a piston in a horizontal cylinder. Let the piston be connected by some means to an external load such that expansion of the mixture (but without ignition) will lift the load. Here internal energy of the mixture is transformed through the medium of pressure into potential energy of the load. The change in internal energy can be measured by the change in potential energy experienced by the external load. Examination of the mixture before and after the expansion would show no change in composition but a definite change in characteristics such as pressure (and temperature). Since chemical composition remained constant, the change in internal energy is sometimes called a change in sensible internal energy.

Let a small spark be used to ignite the gas-air mixture. Combustion will occur with the release of chemical internal energy far out of proportion to the energy of the electrical discharge, and a greater load than before can be lifted.

Suppose that the gas mixture is confined in the cylinder but with the piston locked in place. Suppose, too, that the temperature of the mixture is 500 C while the pressure is 800 kPa. If this combination is surrounded by a water bath at 20 C, it is soon apparent that the water is increasing in temperature while the temperature (and pressure) of the mixture is decreasing. Here internal energy of the mixture is decreased by transfer of energy through the walls of the cylinder to the water bath because of a temperature difference.

Consider, as the next example, the familiar lead storage battery. The current from the battery is called electrical energy to distinguish it from mechanical energy. But when the battery delivers energy, no matter the name, its "stored energy" - its internal energy - decreases. Chemical changes occur in the battery corresponding to this decrease in internal energy. Some evidence of the change is shown by a hydrometer whereby the specific gravity of the acid solution is evaluated.

Thus, whenever energy is withdrawn from a piston-cylinder combination, from a battery, or from any other object under scrutiny, corresponding increases in energy appear in the surroundings.

3-4. Units of Energy. One object of thermodynamics is to provide tools for evaluating energy of all kinds in terms of the more outward manifestations of energy, such as pressure and temperature (but coupled with knowledge of the chemical composition). A datum can be selected (say 100 kPa, 20 C) and the internal energy of a selected substance can be arbitrarily assigned a value of zero internal energy per pound mass. Then, by measurements of the energy that need be transferred to change the temperature and pressure to new values, relative values of internal energy (sensible) can be obtained. Similarly, the energy released or absorbed when a chemical reaction occurs can be measured, and the internal energy of the products relative to that of the mixture is obtained. Tables of data are thus compiled for the substances m common use, with, in general, pressure, temperature, and/or volume serving as parameters.

The values of internal energy, relative to the arbitrarily selected datum of zero internal energy, could be recorded in units of Newton-meters, but a larger measure is more convenient. The SI unit for energy is the Joule, designated J, where 1 J = 1 N x m, but since the J is a relatively small quantity the use of the kilojoule, or kJ, is used throughout.

There are many other forms of energy units. For instance, the kWhr associated with the delivery of electrical energy to residential and commercial customers is equal to

$$1\ kWhr \times \frac{kJ}{kW \cdot s} \times 3600\frac{s}{hr} = 3600\ kJ$$

3-5. Relativity Effects. With the development of the theory of relativity, it became evident that mass and energy were different forms of the same fundamental phenomenon. The inquisitive student sometimes asks 'What about Einstein's relationship equating mass and energy?" Thus, the mass of a body is a measure of its energy content, and changes in mass accompany changes in energy from any cause whatsoever. The so-called absolute energy of mass is given by the Einstein mass-energy equation,

$$E = mc^2$$

where m is the mass and c is the velocity of light. Thus, theoretically, a means is available for calculating the energy of a substance on an absolute, rather than on a relative, basis. Noted however is the fact that the conversion of mass to energy and vice versa is insignificant when one considers that the velocities encountered in engineering applications are dwarfed by the speed of light. In classical thermodynamics relativistic variations of mass are ignored, since minute changes are beyond the precision of engineering measurements. The classical assumption that mass and energy are always conserved will be retained, although on a relativity basis, kinetic, potential, and internal energies should philosophically be considered companions of mass.

3-6. Heat. Consider a system which contains, within itself, hot and cooler regions. Here energy, because of the temperature difference, will transfer from the hot to the cold region by conduction, radiation, and/or convection. Heat is assigned only to energy transfer, but not mass transfer, passing to or from the surface of the system. Heat into or out of the system occurs when the system undergoes a change of state. Heat is not a property, hence not single valued. The amount of heat transferred is a function of the process (how the system moves from state 1 to state 2).

Heat is energy transferred through the surface of the system by the mechanisms of conduction and radiation.

Note that the process of convection is not included since convection involves a mass flow and the energy accompanying mass will be evaluated separately. Thus, quite arbitrarily, heat is defined as a surface effect:

Heat is energy transferred, without transfer of mass, across the boundary of a system because of a temperature difference between system and surroundings.

Observe that the process of conduction (but not radiation) dictates a temperature gradient at the boundary of the system.

With this definition, it is wrong to speak of heat contained in a system— the correct phrase is internal energy. Nor can heat be carried by a mass flow since heat is a concept divorced from mass.

Processes or systems that do not involve heat are called adiabatic.

3.7. Work. Work, like heat, is transitional in nature and cannot be stored in mass or in a system. Work exists or occurs only during a transfer of energy into or out of a system and, like heat, is a surface concept. After the work is done, no work is present, only the result of the work: energy. Like heat, work into or out of the system occurs when the system undergoes a change of state. Work is not a property, hence not single valued. The amount of work transferred is a function of the process (how the system moves from state 1 to state 2).

A general definition for all forms of work can be made by paraphrasing the definition for heat:

Work is energy transferred, without transfer of mass, across the boundary of a system because of an intensive property difference other than temperature that exists between system and surroundings.

The usual intensive property encountered in engineering problems is stress (including pressure). The stress on the surface of the system gives rise to a force, and the action of the force through a distance is the concept called mechanical work:

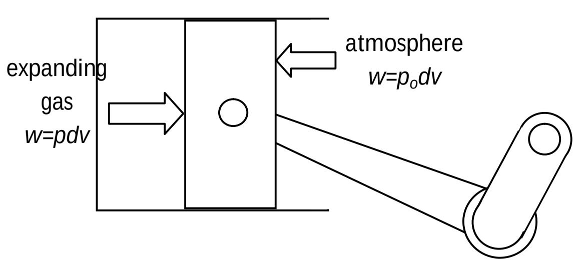
Mechanical work is energy alone crossing the boundary of a system in the form of force acting through a distance of boundary displacement.

Since electrical energy can be completely converted into mechanical work by a perfect motor, electrical work is simply electrical energy crossing the boundary of the system.

In classical thermodynamics work can cross the system boundary in two modes: shaft work and boundary work.

The first mode is shaft work – that of a mechanical device penetrating the system boundary and either rotating or translating with a corresponding force (again, force through a distance). Shaft work is a relatively easy concept to visualize. An example of shaft work could be a pump lifting water up an elevation or a steam turbine driving an electrical generator.

The second mode is that of system boundary work – that of a piston expanding in a cylinder or an expanding (or collapsing) membrane like that of a balloon exerting a force through a distance without movement of the system itself (which would be identified as kinetic energy). Examples are shown below:



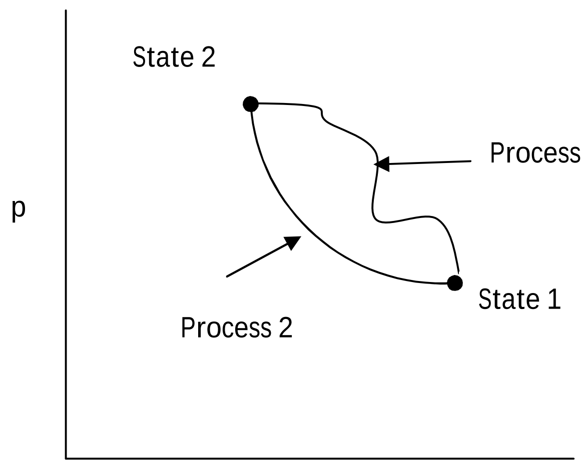
Boundary work, like shaft work, is a force through a distance. It can be conveniently represented by properties within the system – that of pressure and volume. The product of the dimensions of pressure and volume results in a force through a distance.

$W = pressure\frac{[F]}{[L]^2} \times volume[L]^3 = [F][L]$

Thus, if p is the pressure acting on surface A through a distance s then an increment in work is equal to

$W = \int \delta W = \int_{S_1}^{S_2} pAds = \int_{V_1}^{V_2} pdV$

There are no limits on the integral of work because work is not a property (Article 3-8 below) hence there is no W_1 nor W_2. The property p cannot be taken outside of the integral of volume because pressure is a function of volume (except in the special case where the process occurs at constant pressure which is discussed later.) Work can be conveniently illustrated on a plot of pressure vs. volume, a pv diagram as shown below.

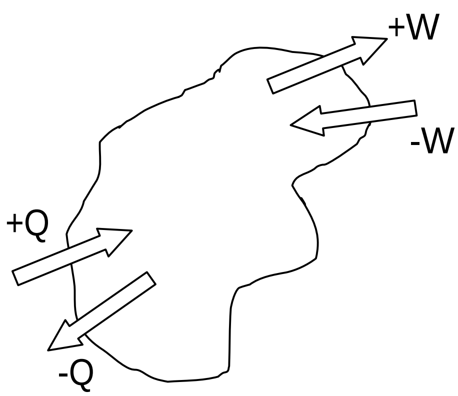


Work is the area underneath the pV diagram. It is dependent upon the path, hence not a property. The work in process 1 is different from the work in process 2.

3-8. Notation and Sign Convention. The symbols for heat and work will be Q and W and the dimension that of energy. Although heat, work, and energy have the same dimension, only energy is a property of a system. Heat and work are not properties because they appear only when a process occurs and disappear when the process is completed.

Internal energy is represented by the notation *U*. An infinitesimal change in internal energy is thus *dU* (or better ∂U since *U* is a function of more than one variable). Internal energy is a thermostatic property, hence it is single valued and the increment from state 1 to state 2, $\Delta U = U_2 - U_1$, is constant no matter what the process. Work and heat on the other hand are not properties and are not single valued. The amount of heat and work transferred during a process are dependent upon the process (or upon the path followed). Infinitesimal work and heat are thus represented by the notation δW and δQ.

Algebraic signs that imply direction to energy in transition in the form of heat and work are completely arbitrary providing consistency is followed throughout the analysis. In general however, a sign convention is followed so that engineers can communicate with one another. In these lecture notes the algebraic signs for heat and work are as follows:



Heat into the system is positive
Heat out of the system is negative
Work into the system is negative
Work out of the system is positive

This sign convention has some historical foundation in that early pioneers working with steam engines added fuel to the boiler; hence heat into the system was considered positive. The steam engines produced work; hence work out of the system was positive and any work into the system was thus negative.