Not part of this reading.

- A cycle is a sequence of processes that begins and ends at the same state. At the conclusion of a cycle, all properties have the same values they had at the beginning of the cycle. Thus, there is no change in the system's state at the end of a cycle.
- An equation of state is a relationship between properties of a particular substance or class of substances. Equations of state cannot be obtained from thermodynamics but are obtained either from experimental measurements or from some molecular model. Note that there can be various types of equations of state, e.g., two equations of state for an ideal gas include a thermal equation of state, which is the ideal gas law, $p = \rho RT$, and a caloric equation of state, which describes the relationship between the internal energy and temperature, $du = c_v dT$.

3.2. Energy, Work, and Heat

Now let's move our discussion to the three basic thermodynamic concepts of energy, work, and heat.

3.2.1. Energy

The energy associated with some phenomenon is not a physical quantity but is, in fact, just a number resulting from a formula containing physically measurable quantities related to that phenomenon. For example, the energy associated with the macroscopic motion of a system of mass, m, moving with a speed, V, is equal to $\frac{1}{2}mV^2$. By itself, the energy associated with a phenomenon is not a very useful quantity. However, experiments examining the total energy of a system, i.e., the sum of all the various energies, have resulted in a very remarkable observation. When the system does not interact with its surroundings, the total energy of the system remains constant. The energy associated with a particular phenomenon may change; however, it can only change at the expense of the energy associated with some other phenomenon. We'll examine this observation in greater detail a little later, but for now we will define the various types of energy that are most commonly encountered in engineering thermodynamics.

3.2.1.1. Kinetic Energy, KE

The energy associated with the macroscopic motion of a system relative to a coordinate system xyz is known as the kinetic energy, KE,

$$KE = \frac{1}{2}mV^2, \tag{3.1}$$

where m is the mass of the system and V_{xyz} is the speed of the system in the coordinate system xyz.

3.2.1.2. Potential Energy, PE

The energy associated with a system's ability to do work in an external force field, such as a gravity field, is known as the potential energy, PE. For example, the gravitational potential energy for a mass, m, located in a gravitational field with gravitational acceleration, g, pointing in the $-z$ direction is,

$$PE = mgz, \tag{3.2}$$

where z is the height of the mass above some reference plane.

3.2.1.3. Internal Energy, U

The internal energy of a system is comprised of a number of sub-classes of energy which include:

(1) sensible energy. This is the energy associated with the internal molecular translational, rotational, and vibrational motion. Temperature is a measure of this type of internal energy. The larger the temperature of a system, the greater its sensible energy.
(2) latent energy. This is the energy associated with the attraction between molecules. We concern ourselves with latent energy most often when examining processes that involve a change of phase, such as going from a solid to a liquid or from a liquid to a gas (or vice versa).
(3) chemical energy. This is the energy associated with the attraction between atoms.

(4) nuclear energy. This is the energy associated with the attraction between particles within an atom, such as the attraction between protons and neutrons. There are other forms of internal energy (e.g., the energy associated with electric and magnetic dipole moments) but we rarely encounter these in typical engineering applications. In these notes we'll only concern ourselves with sensible energy.

The total energy of a system, E, is the sum of these various types of energy,

$$E = U + KE + PE. \tag{3.3}$$

Note that the total, internal, kinetic, and potential energies are extensive properties, i.e., the magnitude of these energies depends on the system mass. In terms of specific quantities (extensive properties per unit mass) we have,

$$e = u + \frac{1}{2}V^2 + G, \tag{3.4}$$

where e is the specific total energy, u is the specific internal energy, V is the velocity magnitude (i.e., speed), and G is a (conservative) potential energy function. Note that the force per unit mass resulting from a conservative potential energy function is found by taking the negative of its gradient, i.e., if $G = gz$ where g is the gravitational acceleration and z is the height of the system above some reference plane, then $\mathbf{f}_{\text{gravity}} = -\boldsymbol{\nabla} G = -g\hat{\mathbf{k}}$.

The values of the specific internal energy, u, at different states for various substances are tabulated in thermodynamic property tables. Most introductory thermodynamics books have such tables for steam, refrigerants, and a variety of gases.

3.2.2. Work, W

Work is an energy interaction (a way to transfer energy) occurring at the boundary between a system and its surroundings. Thus, work is not a property of a system but rather is associated with a process that the system is undergoing. The work done on the system by its surroundings depends on the path of the process. A quantity that is also commonly encountered when discussing work is the power, $\dot{W}$, defined as the work done per unit time,

$$\dot{W} = \frac{\delta W}{dt}. \tag{3.5}$$

The small amount of work done on a system, $\delta W_{\text{on sys}}$, is equal to the dot product of the force acting on the system, $\mathbf{F}_{\text{on sys}}$, and the distance over which the force acts, $d\mathbf{s}$,

$$\underbrace{\delta W_{\text{on sys}}}_{\substack{\text{small amount of work}\\ \text{on the system}}} = \underbrace{\mathbf{F}_{\text{on sys}}}_{\substack{\text{force acting}\\ \text{on the system}}} \cdot \underbrace{d\mathbf{s}}_{\substack{\text{small distance over}\\ \text{which the force acts}}}. \tag{3.6}$$

The corresponding <u>power</u> is,

$$\dot{W} = \frac{\delta W}{dt} = \mathbf{F} \cdot \frac{d\mathbf{s}}{dt} = \mathbf{F} \cdot \mathbf{V}, \tag{3.7}$$

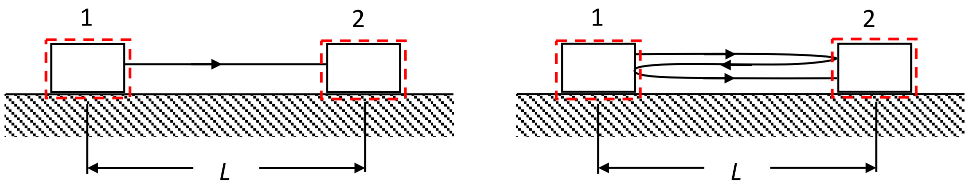
where $\mathbf{V}$ is the velocity.

The total work required in going from state 1 (indicated by s_1) to state 2 (s_2), W_{12}, may be found by integrating Eq. (3.6) between the two states,

$$W_{12} = \int_{s_1}^{s_2} \delta W = \int_{s_1}^{s_2} \mathbf{F} \cdot d\mathbf{s}. \tag{3.8}$$

Note that the <u>work depends on the path</u> taken from s_1 to s_2, so in addition to the integral, the path in going from s_1 to s_2 must be known.

A block with weight, *w*, is pushed on a frictional surface. The friction coefficient between the block and the surface is μ. Determine the amount of work done by the friction force on the block when moving the block from state 1 to state 2 using the paths shown.



(a) (b)

SOLUTION:
The magnitude of the friction force acting on the block is $F = \mu w$, which acts over the small horizontal displacement dx. Since the friction force always acts in the direction opposite to the displacment,

$$\delta W_{\text{on block}} = \mathbf{F} \cdot d\mathbf{s} = -\mu w dx \ . \tag{1}$$

For case (a) the total displacement is just *L*. Hence, the total work done on the block is,

$$W_{\text{on block},12} = \int_1^2 \delta W = -\mu w L \ . \tag{2}$$

The total displacement for case (b) is 3*L*. Hence, the total work for this case is,

$$W_{\text{on block},12} = \int_1^2 \delta W = -3\mu w L \ . \tag{3}$$

Thus, even though the block starts and ends at the same location, the work done on the block by the friction during the process is different since the paths are different.

Now let's consider a few different types of work that can be done by or on a system. The types of work we'll present here include work due to gravity, acceleration, pressure, electricity, springs, and rotating shafts. In the following drawings, the system is enclosed by a dashed line.

3.2.2.1. Gravitational Work (aka Potential Energy)

Consider the minimum amount of work required to move an object with mass, m, to a higher elevation in a gravity field, assuming a quasi-static process so that accelerations can be neglected (Figure 3.2),

$$W_{\text{on sys},12} = \int_0^{\Delta h} \mathbf{F}_{\text{on sys}} \cdot d\mathbf{s}, \tag{3.9}$$

$$= \int_0^{\Delta h} (mg\hat{\mathbf{e}}_z) \cdot (dz\hat{\mathbf{e}}_z), \tag{3.10}$$

$$\boxed{W_{\text{on sys},12} = mg\Delta h}. \tag{3.11}$$

The work is equal to the change in the potential energy of the system! Note that the work on the surroundings

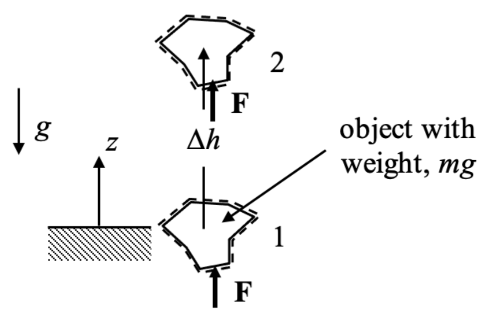


Figure 3.2. Illustration of the work due to a change in elevation.

is equal to, but has the opposite sign, of the work done on the system.

3.2.2.2. Acceleration Work (aka Kinetic Energy)

Consider the minimum work required to accelerate an object with mass, m, from speed, V_1, to speed, V_2 (Figure 3.3),

$$W_{\text{on sys},12} = \int_1^2 \mathbf{F}_{\text{on sys}} \cdot d\mathbf{s}, \tag{3.12}$$

$$= \int_{V_1}^{V_2} \Bigg(\underbrace{m\frac{dV}{dt}}_{\text{Newton's 2nd Law}} \hat{\mathbf{e}}_x \Bigg) \cdot \Big(\underbrace{V\,dt}_{=dx} \hat{\mathbf{e}}_x \Big), \tag{3.13}$$

$$= m \int_{V_1}^{V_2} V\,dV, \tag{3.14}$$

$$\boxed{W_{\text{on sys},12} = \frac{1}{2} m \left(V_2^2 - V_1^2\right)}. \tag{3.15}$$

The work is equal to the change in the kinetic energy of the system!

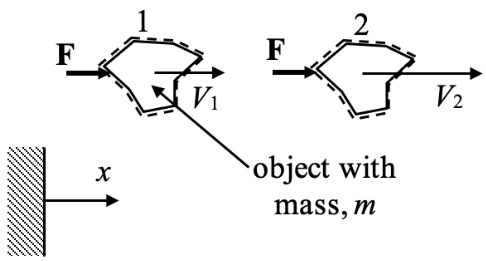


FIGURE 3.3. Illustration of the work due to acceleration.

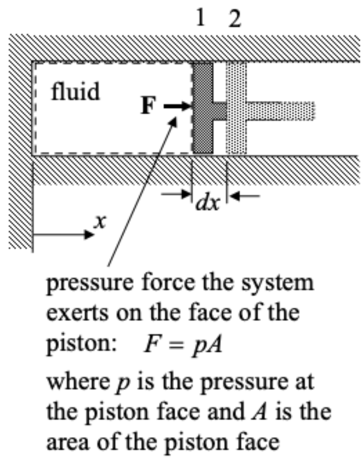


FIGURE 3.4. Illustration of the work due to a pressure force.

Not part of this reading.

3.2.2.3. Pressure Work

Consider the work done by the expansion of a fluid (a gas or liquid) in a piston (Figure 3.4),

$$W_{\text{on surr},12} = \int_1^2 \mathbf{F}_{\text{on surr}} \cdot d\mathbf{s}, \tag{3.16}$$

$$= \int_{x_1}^{x_2} (pA\hat{\mathbf{e}}_x) \cdot (dx\hat{\mathbf{e}}_x), \tag{3.17}$$

$$= \int_{x_1}^{x_2} pAdx, \tag{3.18}$$

$$\boxed{W_{\text{on surr},12} = \int_{V_1}^{V_2} pdV}. \tag{3.19}$$

Note that $dV = Adx$. Note also that in this example, the work on the surroundings has been calculated instead of the work acting on the system. To get the work done on the system, we simply have, $W_{\text{on sys}} = -W_{\text{on surr}}$.

If we plot how the pressure changes with volume, we get a p-V diagram, as shown in Figure 3.5. Note that different paths from state 1 to state 2 will give different work values, as shown in Figure 3.6. One example of a particular pressure-volume relationship is known as a polytropic process in which the pressure and volume are related by,

$$pV^n = c, \tag{3.20}$$

where n and c are constants.