Chapter 3

THE FIRST LAW APPLIED TO CLOSED SYSTEMS

One only ever understands what one tames. People no longer have the time to understand anything.

– Antoine De Saint-Exupéry (*The Little Prince*)

Chapter 1 stated that the first law of thermodynamics is simply the law of conservation of energy, and Chapter 2 introduced us to the thermodynamic meaning of terms such as system, property, and others. This chapter demonstrates how to apply the first law of thermodynamics to closed systems.

3.1 Energy Balance for a Closed System

The first law of thermodynamics states that energy is conserved, which means energy cannot be created or destroyed, but it may change its form. Applying the first law to a closed system involves accounting for energy, that is simply writing an energy balance over the closed system as follows:

change in total energy content of the system =
energy that entered the system
− energy that left the system.

Let us choose the closed system comprising a gas trapped within the piston-cylinder device shown in Figure 3.1. The dashed line of Figure 3.1 shows the cross-section of the boundary that separates the system from its surroundings, which includes the piston, the walls of the cylinder, and everything outside the piston and the cylinder. One may ignore the parts of the surroundings that have no influence on the system, or are not influenced by the system.

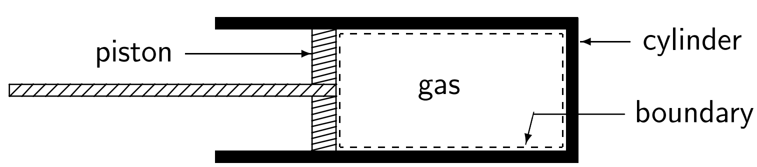


Figure 3.1 A closed system.

Initially, let us say that the closed system, that is the gas, contains an amount of energy E_o. The gas is compressed by pushing the piston, and W_{in} amount of energy is provided to the gas as work. The walls of the cylinder allow heat to pass through, and Q_{out} amount of energy is lost to the surroundings. Because of these work and heat energy interactions between the system and its surroundings, the energy content of the system changes to a new value, say E_f. Energy balance for the closed system then gives the following:

$$E_f - E_o = W_{in} - Q_{out}$$

Using $Q_{out} = -Q_{in}$, the energy balance could be rewritten as

$$E_f - E_o = W_{in} + Q_{in}$$

which could be rearranged to give

$$Q_{in} + W_{in} = \Delta E \tag{3.1}$$

where the notation ΔE is used to represent the change in the total energy content of the system $(E_f - E_o)$. Note that the value of ΔE depends on the initial and final states alone, and E, the energy content of the system, is a property of the system.

$$Q_{in} + W_{in} = \Delta E$$

`is the First Law of Thermodynamics`

`applicable to closed system.`

The total energy content of the system, denoted by E, is made up of internal energy, gravitational potential energy, kinetic energy, electrical energy, magnetic energy, surface energy, etc. Chapter 4 attempts to give an insight into the internal energy, denoted by U. For the time being, it is adequate to know that changes in the thermodynamic properties, such as temperature, pressure, and volume, are accounted for by the change in internal energy, denoted by ΔU. Changes in electrical, magnetic, and surface energy are not considered in this text since these changes are insignificant for most engineering systems.

Consequently, we write

$$\Delta E \;=\; \Delta U \;+\; \Delta(m\,g\,z) \;+\; \Delta\left(m\,\frac{c^2}{2}\right) \tag{3.2}$$

where the first term on the right hand side of (3.2) represents the change in internal energy U. The second term on the right hand side represents the change in gravitational potential energy, where m is the mass, g is the acceleration due to gravity, and z is the elevation of the system above a reference level. The last term of (3.2) represents the change in kinetic energy of the system owing to the motion of the system, where c is the speed at which the system is moving as a whole.

A closed system which does not experience any change in its gravitational potential energy or kinetic energy during a process is known as a **stationary system**. For a stationary system experiencing no change in electrical, magnetic or surface energy, (3.2) reduces to

$$\Delta E \;=\; \Delta U \tag{3.3}$$

which, in turn, transforms the first law of thermodynamics applied to a closed system, given by (3.1), to

$$Q_{in} + W_{in} = \Delta U \tag{3.4}$$

This is the first law of thermodynamics applied to **closed stationary systems** for which changes in electrical, magnetic and surface energy are insignificant. Such a system is known as the simple compressible system (see Section 2.7), and for which internal energy U is the sole representative of the total energy content of the system E.

The first law given by (3.4) can be presented in differential form as

$$dQ_{in} + dW_{in} = dU \tag{3.5}$$

Since the internal energy U is a property of state, integration of dU from an initial state (o) to a final state (f) gives

$$\int_{U_o}^{U_f} dU = U_f - U_o = \Delta U \tag{3.6}$$

which is the total change in the internal energy of the system.

Since Q_{in} and W_{in} are not properties of state, they depend on the **path** of the process. Therefore, integration of dQ_{in} and dW_{in} gives

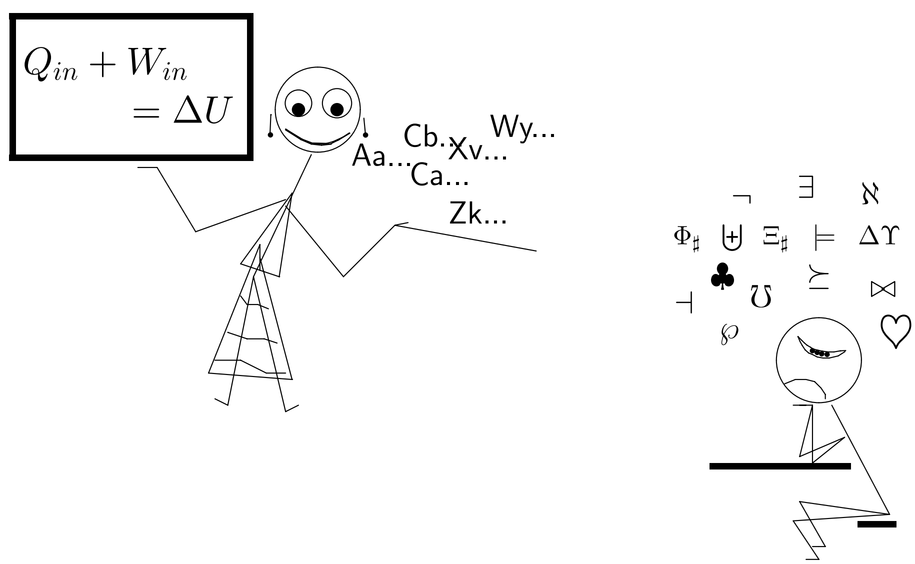
$$\int_o^f dQ_{in} = Q_{in} \qquad \text{(not } \Delta Q_{in}\text{)} \tag{3.7}$$

and

$$\int_o^f dW_{in} = W_{in} \qquad \text{(not } \Delta W_{in}\text{)} \tag{3.8}$$

where Q_{in} and W_{in} are the quantities of energy transfers between the system and the surroundings in the form of heat and work, respectively, when the system goes from state (o) to state (f) executing a process.

Thus, we see that integration of (3.5) yields (3.4).



3.2 A Word of Caution

In this textbook, we write the first law applied to closed simple compressible systems in the form given by (3.4). Since $W_{in} = -W_{out}$, (3.4) can also be written as

$$Q_{in} - W_{out} = \Delta U \tag{3.9}$$

If the subscripts in (3.9) are omitted, we get

$$Q - W = \Delta U \tag{3.10}$$

which is how some textbooks present the first law of thermodynamics applied to closed simple compressible systems. The apparent confusion in using different forms of the first law of thermodynamics applied to closed simple compressible systems vanishes if we learn to look at the equation concerned with proper subscripts, as shown in Figure 3.2.

$\boxed{Q + W = \Delta U}$ is the same as $\boxed{Q_{in} + W_{in} = \Delta U}$

$\boxed{Q - W = \Delta U}$ is the same as $\boxed{Q_{in} - W_{out} = \Delta U}$

Figure 3.2 Different forms of the first law applied to closed systems.

One can choose whichever the form that one prefers from Figure 3.2 to represent the first law of thermodynamics applied to closed simple compressible systems. There is absolutely no problem with it as far as one uses consistent set of signs for work and heat transfers in and out of the systems through the boundary.

It is important to keep in mind that for anyone of the four equations of Figure 3.2 to be valid, internal energy U alone must solely represent the total energy content E of the closed system considered. For such systems, changes in gravitational potential energy, kinetic energy, and electrical, magnetic and surface energy are all either completely absent or negligibly small.

3.3 Worked Example

Example 3.1

It is reported that a closed system undergoes a 3-step process in such a manner that the internal energy of the system at its initial state is identically the same as the internal energy at its final state. In the first step, the system absorbs 300 kJ of heat and performs 200 kJ of work on the surroundings. In the second step, the system loses 100 kJ of heat while it neither receives nor does any work. In the third step, there is 100 kJ of work done on the system and it looses 50 kJ of heat. Can you say whether this report is correct or not? Explain your answer.

Solution to Example 3.1

The system is said to undergo a 3-step process in such a manner that the internal energy of the system at its initial state is identically the same as the internal energy at the final state. Since internal energy is a property of a system, we have

$$\Delta U = U_{\text{at final state}} - U_{\text{at initial state}} = 0$$

The first law of thermodynamics applied to the closed system undergoing the given 3-step process therefore yields

$$Q_{in} + W_{in} = 0$$

Let us check this out by calculating $Q_{in} + W_{in}$ for the 3-step process from the data provided as follows:

$Q_{in} = 300 \text{ kJ} - 100 \text{ kJ} - 50 \text{ kJ} = 150 \text{ kJ}$

$W_{in} = -\ 200 \text{ kJ} + 0 + 100 \text{ kJ} = -\ 100 \text{ kJ}$

Therefore, $Q_{in} + W_{in} = 150 \text{ kJ} - 100 \text{ kJ} = 50 \text{ kJ} \neq 0$

There is something wrong here. One possibility is that there are errors in the experimental observations. The other possibility is, of course, that there may have been changes in some other modes of the energy of the system although the net change in the internal energy U of the system is zero.

Remember that the most general form of the first law of thermodynamics applied to a closed system is $Q_{in} + W_{in} = \Delta E$, where ΔE, the total energy change of the system, is given not only by ΔU but also by changes in the kinetic and potential energy, as given by (3.2). It is therefore possible that, even though there is no change in the internal energy of the system, the potential or the kinetic energy of the system as a whole could have undergone a change giving rise to $\Delta E = 50$ kJ, and thereby explaining why $Q_{in} + W_{in} = 50$ kJ for the given process even though $\Delta U = 0$.

That is, the given system may not be a stationary system.

3.4 Summary

First law applied to closed, simple compressible systems:

$$Q_{in} + W_{in} = \Delta U \qquad \textbf{(3.4)}$$

First law in differential form:

$$dQ_{in} + dW_{in} = dU \qquad \textbf{(3.5)}$$