First Law of Thermodynamics for a Closed System

THE FIRST LAW OF THERMODYNAMICS

- The conservation of energy principle
- Energy can be neither created nor destroyed during a process; it can only change forms

energy balance

The conservation of energy principle can be expressed as follows: *The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.*

$$\left(\begin{array}{c}\text{Total energy}\\\text{entering the system}\end{array}\right) - \left(\begin{array}{c}\text{Total energy}\\\text{leaving the system}\end{array}\right) = \left(\begin{array}{c}\text{Change in the total}\\\text{energy of the system}\end{array}\right)$$

or

$$E_{in} - E_{out} = \Delta E_{system}$$

Energy Change of a System, ΔEsystem

$$\text{Energy change} = \text{Energy at final state} - \text{Energy at initial state}$$

or

$$\Delta E_{\text{system}} = E_{\text{final}} - E_{\text{initial}} = E_2 - E_1$$

In the absence of electric, magnetic, and surface tension effects (i.e., for simple compressible systems), the change in the total energy of a system during a process is the sum of the changes in its internal, kinetic, and potential energies and can be expressed as

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

where,

$$\Delta U = m(u_2 - u_1)$$
$$\Delta KE = \tfrac{1}{2}m(V_2^2 - V_1^2)$$
$$\Delta PE = mg(z_2 - z_1)$$

Mechanisms of Energy Transfer, E_{in} and E_{out}

Energy can be transferred to or from a system in three forms:

1. Heat Transfer, Q
2. Work Transfer, W
3. Mass Flow, m

- Energy interactions are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process

- the energy balance can be written more explicitly as

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{system}$$

$$\Rightarrow \quad (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta U + \Delta KE + \Delta PE$$

Sign convention for Heat and Work

- Heat and work are *directional quantities,* and thus the complete description of a heat or work interaction requires the specification of both the *magnitude* and *direction.*

- The generally accepted **formal sign convention** for heat and work interactions is as follows:
  - *heat transfer to a system and work done by a system are positive;*
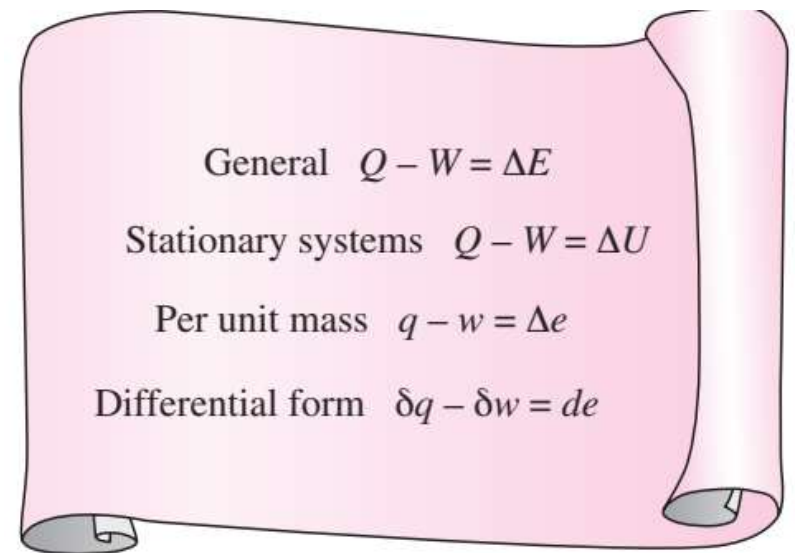 - *heat transfer from a system and work done on a system are negative*

it is common practice to use the classical thermodynamics sign convention and to assume heat to be transferred *into the system* (heat input) in the amount of Q and work to be done *by the system* (work output) in the amount of W, and then to solve the problem

$$Q_{net,in} - W_{net,out} = \Delta E_{system}$$

or $\quad Q - W = \Delta E$

where $Q = Q_{net,in} = Q_{in} - Q_{out}$ is the *net heat input*

$W = W_{net,out} = W_{out} - W_{in}$ is the *net work output*.

General $\quad Q - W = \Delta E$

Stationary systems $\quad Q - W = \Delta U$

Per unit mass $\quad q - w = \Delta e$

Differential form $\quad \delta q - \delta w = de$

FIGURE 4–12

Various forms of the first-law relation for closed systems.

$$Q - W = \Delta U + \Delta \text{KE} + \Delta \text{PE}$$

where

$$W = W_{\text{other}} + W_b$$

$$\Delta U = m(u_2 - u_1)$$

$$\Delta \text{KE} = \tfrac{1}{2}m(V_2^2 - V_1^2)$$

$$\Delta \text{PE} = mg(z_2 - z_1)$$

- For a closed system undergoing a **cycle**, the initial and final states are identical, and thus

$$\Delta E_{\text{system}} = E_2 - E_1 = 0$$

Then the energy balance for a cycle simplifies to

$$E_{\text{in}} - E_{\text{out}} = 0 \text{ or } E_{\text{in}} = E_{\text{out}}$$

Noting that a closed system does not involve any mass flow across its boundaries, the energy balance for a cycle can be expressed in terms of heat and work interactions as

$$W_{\text{net,out}} = Q_{\text{net,in}} \quad \text{or} \quad \dot{W}_{\text{net,out}} = \dot{Q}_{\text{net,in}}$$

the net work output during a cycle is equal to net heat input

$P \uparrow$

$Q_{\text{net,in}} = W_{\text{net,out}}$

V
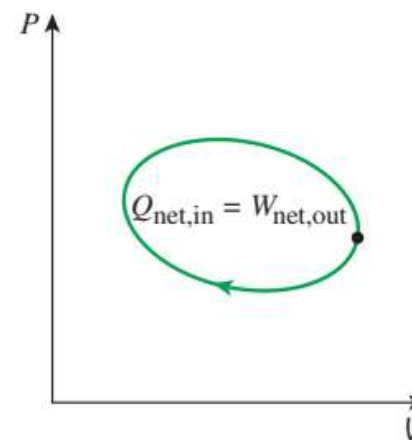
FIGURE 4–11

For a cycle $\Delta E = 0$, thus net heat input is equal to net work output.

Energy analysis of Closed Systems

- One form of mechanical work often encountered in practice is associated with the expansion or compression of a gas in a piston–cylinder device

- the expansion and compression work is often called **moving boundary work**, or simply **boundary work** also called as the *P dV* work.

- Moving boundary work is the primary form of work involved in *automobile engines.*

- During their expansion, the combustion gases force the piston to move, which in turn forces the crankshaft to rotate.
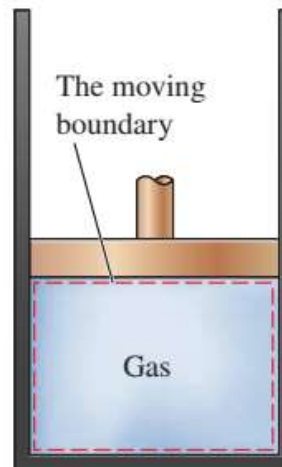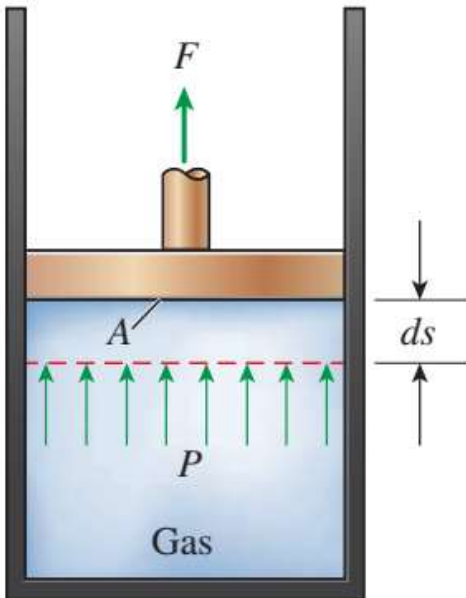
Consider the gas enclosed in the piston–cylinder device. The initial pressure of the gas is P, the total volume is V, and the cross-sectional area of the piston is A. If the piston is allowed to move a distance ds in a quasi-equilibrium manner, the differential work done during this process is

$$\delta W_b = F\,ds = PA\,ds = P\,dV$$

The total boundary work done during the entire process as the piston moves
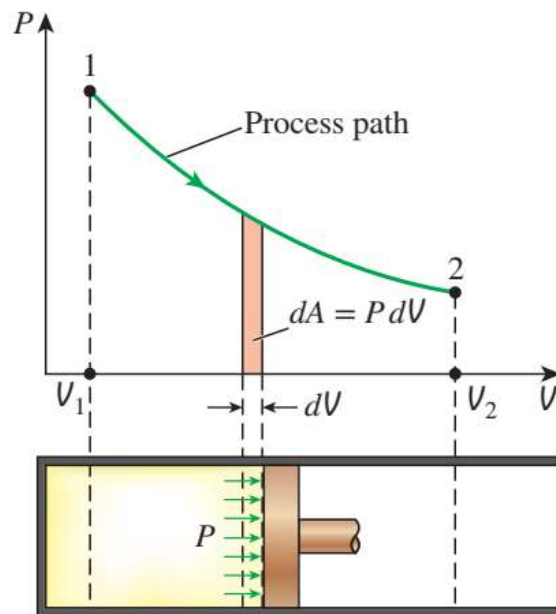
$$W_b = \int_1^2 P\,dV$$

FIGURE 4–3

The area under the process curve on a P-V diagram represents the boundary work.

The total boundary work done during the entire process as the piston moves

$$W_b = \int_1^2 P\,dV$$

This integral can be evaluated only if we know the functional relationship between P and V during the process. That is, $P = f(V)$ should be available. Note that $P = f(V)$ is simply the equation of the process path on a P-V diagram.

The quasi-equilibrium expansion process described is shown on a P-V diagram. The differential area dA is equal to $P\,dV$, which is the differential work. The total area A under the process curve 1–2 is obtained by adding these differential areas:

$$\text{Area} = A = \int_1^2 dA = \int_1^2 P\,dV$$

The area under the process curve on a P-V diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system
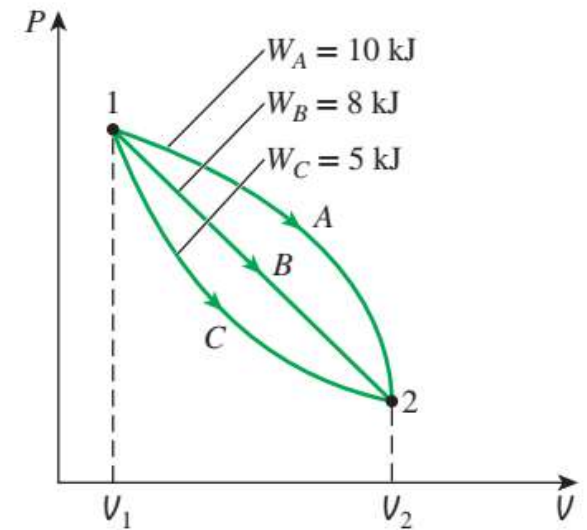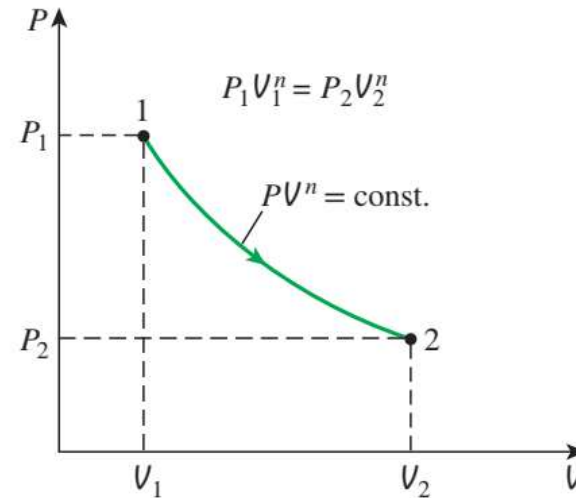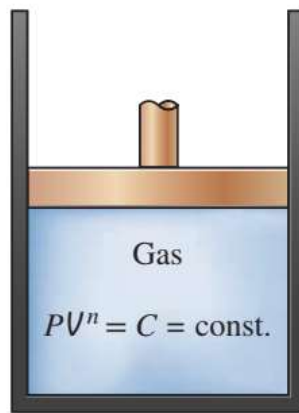

FIGURE 4–4

The boundary work done during a process depends on the path followed as well as the end states.

Polytropic Process

During actual expansion and compression processes of gases, pressure and volume are often related by $pV^n = C,$ where n and C are constants. A process of this kind is called a **polytropic process**
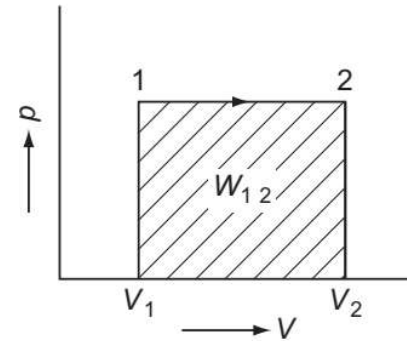

FIGURE 4–9

Schematic and P-V diagram for a polytropic process.

pdV-Work in Various Quasi-Static Processes

Constant pressure process
(isobaric or isopiestic process)

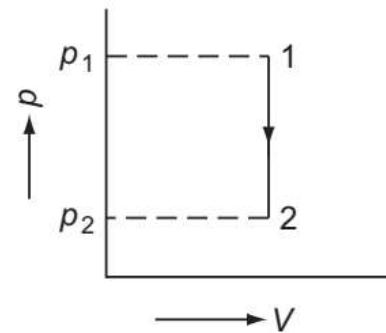$$W_{1-2} = \int_{V_1}^{V_2} p\,\mathrm{d}V = p(V_2 - V_1)$$

Fig. 3.7 *Constant pressure process*

Constant volume process
(isochoric process)

$$W_{1-2} = \int p\,\mathrm{d}V = 0$$

Fig. 3.8 *Constant volume process*

Process in which $pV = C$ (Fig. 3.9)

$$W_{1-2} = \int_{V_1}^{V_2} p\,dV, \quad pV = p_1 V_1 = C$$

$$p = \frac{(p_1 V_1)}{V}$$

$$W_{1-2} = p_1 V_1 \int_{V_1}^{V_2} \frac{dV}{V} = p_1 V_1 \ln \frac{V_2}{V_1}$$

$$= p_1 V_1 \ln \frac{p_1}{p_2}$$

Fig. 3.9 *Process in which $pV = constant$*

polytropic process

$$pV^n = C \qquad \rightarrow \qquad P = CV^{-n}$$

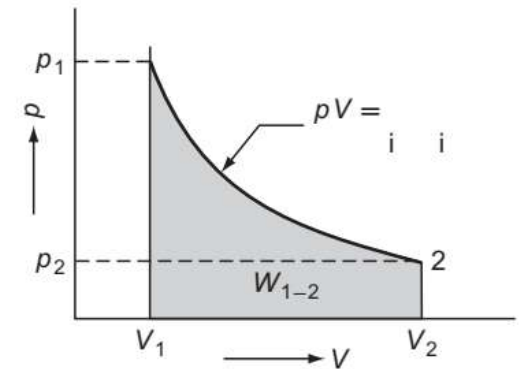$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\,\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2 V_2 - P_1 V_1}{1 - n}$$
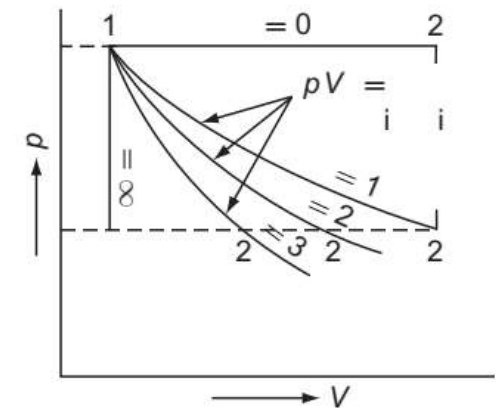

Fig. 3.10 *Process in which $pV^n = constant$*

Various forms of boundary work are expressed as follows:

(1) General
$$W_b = \int_1^2 P \, dV$$

(2) Isobaric process
$$W_b = P_0(V_2 - V_1) \quad (P_1 = P_2 = P_0 = \text{constant})$$

(3) Polytropic process
$$W_b = \frac{P_2 V_2 - P_1 V_1}{1 - n} \quad (n \neq 1) \quad (PV^n = \text{constant})$$

(4) Isothernal process of an ideal gas
$$W_b = P_1 V_1 \ln \frac{V_2}{V_1} = mRT_0 \ln \frac{V_2}{V_1} \quad (PV = mRT_0 = \text{constant})$$

A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.

A piston–cylinder device initially contains 0.4 m³ of air at 100 kPa and 80°C. The air is now compressed to 0.1 m³ in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.

Constant-Pressure Processes of Closed Systems

The energy balance for closed system is

$$Q - W = \Delta U + \Delta \text{KE} + \Delta \text{PE}$$

Separating the boundary work (W_b) from the other forms of work, the energy balance relation can be expressed as

$$Q - (W_b + W_{other}) = \Delta U + \Delta KE + \Delta PE$$

For a closed system undergoing constant pressure process, the boundary work is given by

$$W_b = W_{b,\text{out}} = P(V_2 - V_1) = P_2 V_2 - P_1 V_1$$

we get, after rearranging,

$$Q - W_{other} = (U_2 + P_2 V_2) - (U_1 + P_1 V_1) + \Delta KE + \Delta PE$$

But $H = U + PV$ is enthalpy by definition and thus $(U_2 + P_2V_2) - (U_1 + P_1V_1) = H_2 - H_1 = \Delta H$. Therefore,

$$Q - W_{other} = \Delta H + \Delta KE + \Delta PE$$

This equation is very convenient to use in the analysis of closed systems undergoing a ***constant-pressure quasi-equilibrium process*** since the boundary work is automatically taken care of by the enthalpy terms

PERPETUAL MOTION MACHINE OF THE FIRST KIND–PMM1

- A system which violates first law of thermodynamics is called PMM1
- There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of the first kind, or in brief, PMM1. A PMM1 is thus impossible.
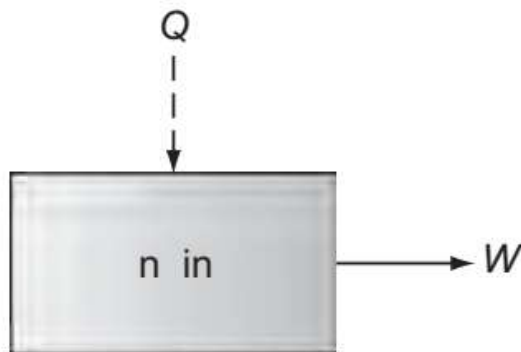
Fig. 4.8 *A PMMI*
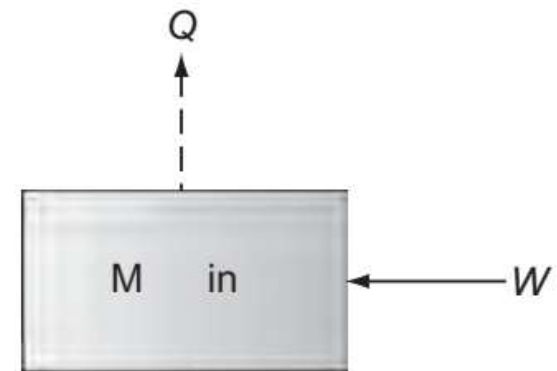


Fig. 4.9 *The converse of PMMI*

SPECIFIC HEAT

The *specific heat* of a substance is defined as the amount of heat required to raise a unit mass of the substance through a unit rise in temperature. The symbol c will be used for specific heat.

$$\therefore \qquad c = \frac{Q}{m \cdot \Delta t} \ \text{J/kg K}$$

where Q is the amount of heat transfer (J), m, the mass of the substance (kg), and Δt, the rise in temperature (K).

Energy depends on the type of the process. For gases, there are two kinds of specific heats: **specific heat at constant volume** c_v and **specific heat at constant pressure** c_p.
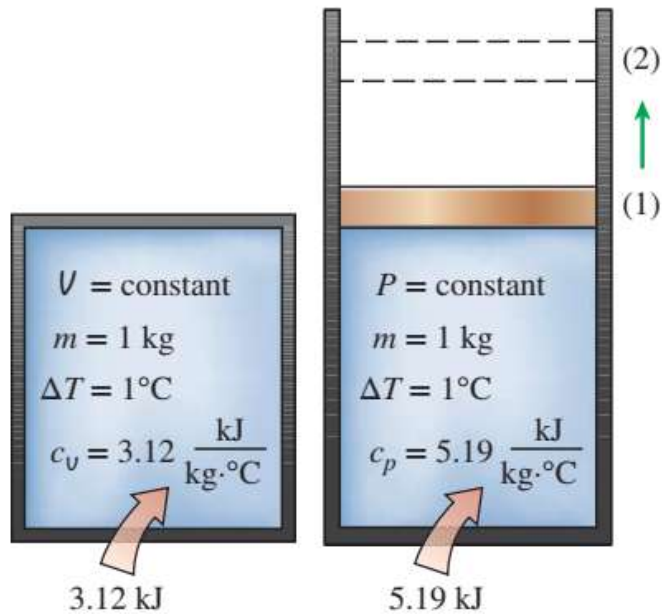
FIGURE 4–19
Constant-volume and constant-pressure specific heats c_v and c_p (values given are for helium gas).

The specific heat at constant volume c_v can be viewed as *the energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.*

The energy required to do the same as the pressure is maintained constant is the specific heat at constant pressure c_p.

$$c_v = \left(\frac{\partial u}{\partial T} \right)_v$$

$$c_p = \left(\frac{\partial h}{\partial T} \right)_p$$

Both c_p and c_v are point functions. They do not depend on the type of the process.

For ideal gases u, h, c_v, and c_p are functions of temperature alone. The Δu and Δh of ideal gases are expressed as

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T)\, dT \cong c_{v,\text{avg}}(T_2 - T_1)$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)\, dT \cong c_{p,\text{avg}}(T_2 - T_1)$$

For ideal gases, c_v and c_p are related by

$$c_p = c_v + R \qquad (\text{kJ/kg} \cdot \text{K})$$

where R is the gas constant. The *specific heat ratio k* is defined as

$$k = \frac{c_p}{c_v}$$

Internal Energy, Enthalpy for Ideal Gases

For ideal gases — Ideal gas law $\quad pV = mRT$

$$\text{(or)} \quad pv = RT$$

$$\text{(or)} \quad \boxed{p = \rho RT}$$

p	— pressure
V	— Volume
m	— mass
R	— Gas constant
T	— Temperature
v	— Specific Volume
ρ	— Density $\left(v = \frac{1}{\rho}\right)$

- Specific internal energy $\quad u = c_v T$
- Specific enthalpy $\quad h = c_p T$

- Internal energy $\quad U = mu = m c_v T$
- Enthalpy $\quad H = mh = m c_p T$

4–59 A student living in a 4-m × 6-m × 6-m dormitory room turns on her 150-W fan before she leaves the room on a summer day, hoping that the room will be cooler when she comes back in the evening. Assuming all the doors and windows are tightly closed and disregarding any heat transfer through the walls and the windows, determine the temperature in the room when she comes back 10 h later. Use specific heat values at room temperature, and assume the room to be at 100 kPa and 15°C in the morning when she leaves.