Chapter

3 THERMODYNAMIC PROCESSES

3.1 THERMODYNAMIC PROCESS

The continuous series of states followed by the working medium as it liberates, transfers, transforms or receives energy is known as thermodynamic process. Fig. 3.1 shows a process.

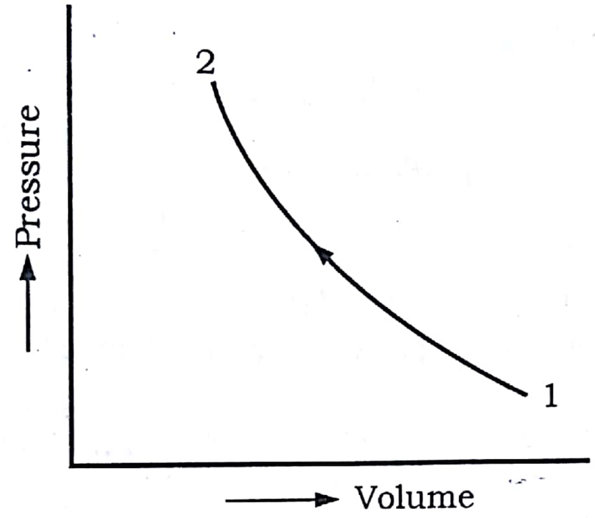


Fig. 3.1: Thermodynamics Process

3.2 TYPES OF THERMODYNAMIC PROCESSES

The important thermodynamic processes are:

A. **Reversible Non-flow processes :**

1. Constant volume process (Isochoric process),
2. Constant pressure process (Isobaric process),
3. Constant temperature process (Isothermal process),
4. Adiabatic process,
5. Polytropic process.

1. **Constant Volume Process:** The main characteristic of this process is that *the displacement work is eliminated.* The boundary of the system is rigid, but paddle way may be there. The process is shown in fig. 3.2

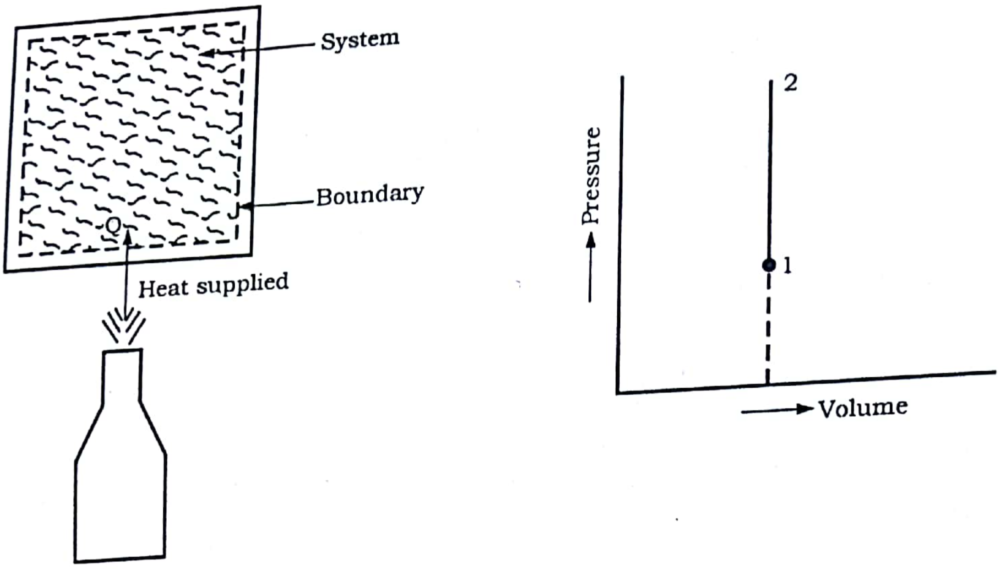


Fig. 3.2: Constant Volume Process

From first law of thermodynamics,

$$Q_{1-2} - W_{1-2} = U_2 - U_1$$

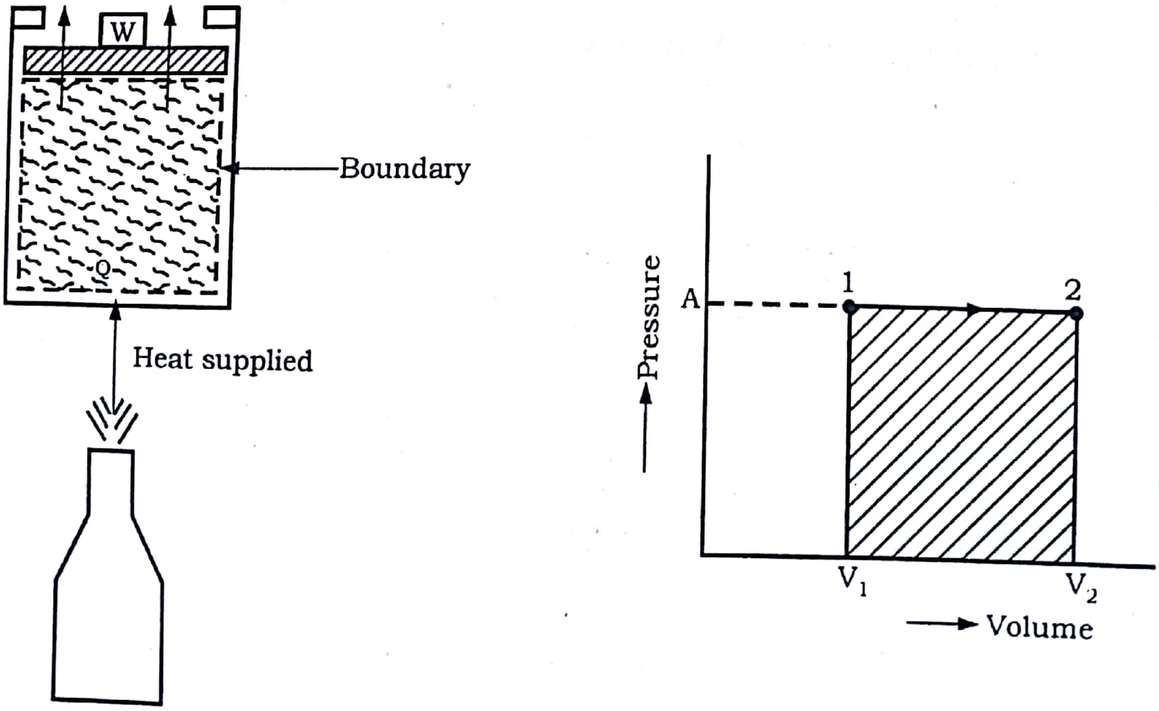
But, $$W_{1-2} = \int_1^2 PdV = U_2 - U_1 \qquad (\because \; dV = 0)$$

$$Q_{1-2} = U_2 - U_1$$

or $$Q_{1-2} = mC_V(T_2 - T_1) \qquad \ldots(3.1)$$

Thus, during a constant volume process, the heat transfer equals the change in internal energy of the system.

2. Constant Pressure Process: In constant pressure process, *the system is subjected to constant hydrostatic pressure at its boundaries*. The fluid is free to expand and the change in system boundary causes displacement work against the constant pressure due to weight W. The process is shown in fig. 3.3.



If the work is carried out quasi-statically,

$$\int_1^2 \delta W = \int_1^2 P dV$$

Then, from first law of thermodynamics,

$$\int_1^2 \delta Q - \int_1^2 \delta W = \int_1^2 dU$$

or
$$\int_1^2 \delta Q = \int_1^2 \delta W + \int_1^2 dU$$

$$= \int_1^2 P dV + \int_1^2 dU$$

$$= \int_1^2 d(U + PV)$$

or
$$\int_1^2 \delta Q = \int_1^2 dH \qquad (\therefore H = U + PV)$$

Also
$$\int_1^2 \delta Q = \int_1^2 m C_P dT$$

or
$$Q_{1-2} = mC_P (T_2 - T_1)$$

Thus, the heat supplied at constant pressure is equal to change in enthalpy of the system.

3. **Hyperbolic Process:** *The process in which gas is heated or expanded in such a way that the product of its pressure and volume remains constant, is known as hyperbolic process.* A hyperbolic process is shown in figure 3.4.

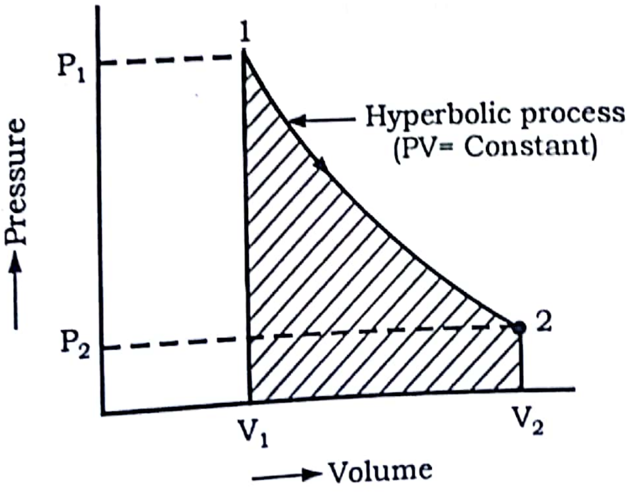


Fig. 3.4 : Hyperbolic Process

This process is governed by Boyle's law and its practical application is isothermal process.

4. **Isothermal Process:** *In this, the system has movable boundary. Therefore, displacement work is present, but the system temperature is maintained constant by contact of the system with a constant temperature reservoir.* During the expansion the volume will increase to maintain the temperature constant. The process is shown in fig. **3.5.**

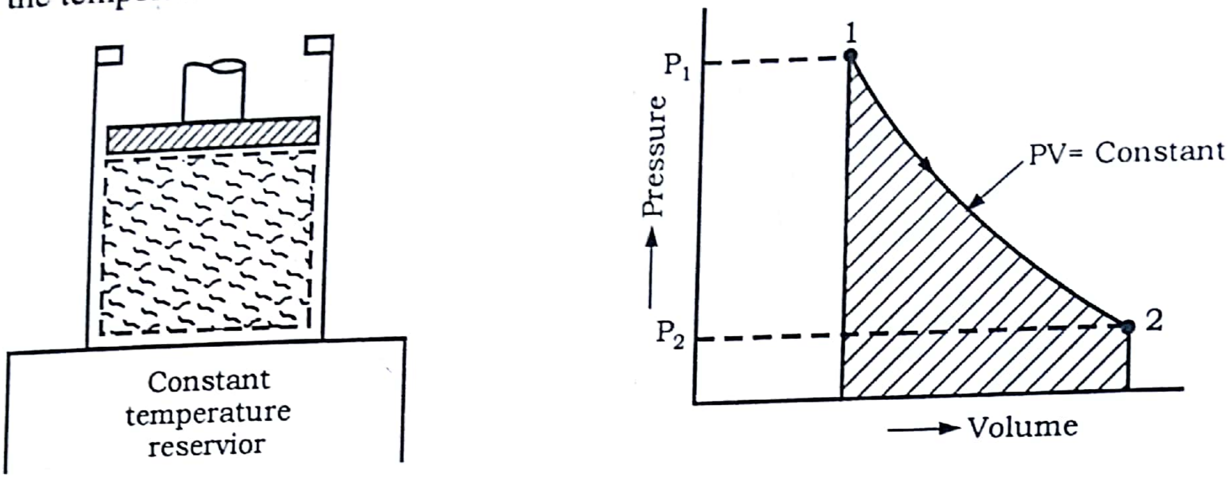


Fig. 3.5 : Constant Temperature (Isothermal) Process

From first law of thermodynamics,

$$\delta Q - \delta W = dU$$

But $$dU = mC_V dT$$

Now, as $$dT = 0$$

$\therefore$ $$dU = 0$$

$\therefore$ $$\delta Q - \delta W = 0$$

or $$\delta Q = \delta W$$

For quasi-static process, $$\int_1^2 \delta W = \int_1^2 P dV$$

or $$W_{1-2} = \int_1^2 P dV = \int_1^2 \frac{PV dV}{V}$$

or $$Q_{1-2} = PV \log_e \left(\frac{V_2}{V_1}\right) \qquad (\because W_{1-2} = Q_{1-2})$$

or $$Q_{1-2} = P_1 V_1 \log_e \left(\frac{V_2}{V_1}\right) \qquad (\because PV = P_1 V_1 = P_2 V_2)$$

or $$Q_{1-2} = mRT_1 \log_e \left(\frac{V_2}{V_1}\right)$$

Hence, the heat supplied during isothermal process is equivalent to non-flow work during the process.

5. **Adiabatic Process:** *The process during which work is done and no heat is transferred across the system boundary is known as adiabatic process.*

Heat transferred, $Q_{1-2} = 0$

From first law of thermodynamics,

$$Q_{1-2} - W_{1-2} = U_2 - U_1$$

or $$O - W_{1-2} = \Delta U \qquad (\because Q_{1-2} = 0)$$

or $$-W_{1-2} = \Delta U \qquad \ldots(i)$$

i.e. Work done = Change in internal energy.

For perfect gases, we know that

$$\Delta U = m \times C_V \times (T_2 - T_1) \qquad \ldots(ii)$$

Also $$W_{1-2} = \int_1^2 PdV \qquad \ldots(iii)$$

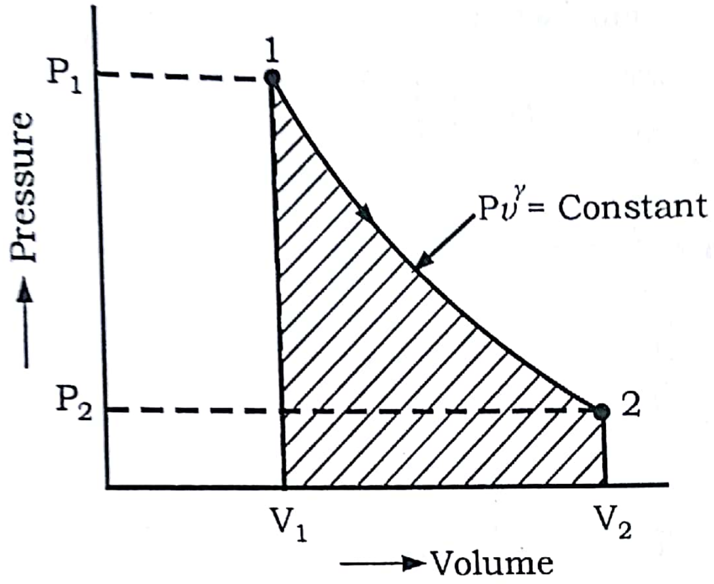


Fig. 3.6 : Adiabatic Process

Putting the values of ΔU and W_{1-2} from equations (*ii*) and (*iii*) in equation (*i*), we get

$$\therefore \quad -\int_1^2 PdV = m.C_V (T_2 - T_1)$$

or $$PdV = -m.\, C_V\, dT \qquad \ldots(iv)$$

But $$PV = mRT$$

or $$P = \frac{mRT}{V} \qquad \ldots(v)$$

Putting the value of P from equation (*v*) in equation (*iv*), we get

$$\therefore \quad \frac{mRT}{V}.dV = -m.C_V.dT$$

or $$\frac{dT}{T} = \frac{-R}{C_V} \times \frac{dV}{V} \qquad \ldots(vi)$$

Now $$R = C_P - C_V$$

$$\therefore \quad \frac{R}{C_V} = \frac{C_P - C_V}{C_V}$$ (Dividing both sides by C_v)

$$= \frac{C_P}{C_V} - 1$$

$$= \gamma - 1$$ ...(*vii*)

Putting the value of $\frac{R}{C_V}$ from equation (*vii*) in equation (*vi*), we get

$$\frac{dT}{T} = -(\gamma - 1).\frac{dV}{V}$$

Integrating between the limits, we get

$$\int_1^2 \frac{dT}{T} = -(\gamma - 1)\int_1^2 \frac{dV}{V}$$

or $$\log e\frac{T_2}{T_1} = -(\gamma - 1)\log e\frac{V_2}{V_1}$$

or $$\frac{T_2}{T_1} = \left(\frac{V_2}{V_1}\right)^{-(\gamma-1)}$$

or $$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{(\gamma-1)}$$ ...(3

or $$TV^{\gamma-1} = \text{Constant}$$

But $$\frac{V_1}{V_2} = \frac{P_2T_1}{P_1T_2}$$ (From gas equati

$$\therefore \quad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \times \frac{T_1}{T_2}\right)^{(\gamma-1)}$$

or $$\frac{T_2}{T_1} \times \left(\frac{T_2}{T_1}\right)^{\gamma-1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1}$$

or $$\left(\frac{T_2}{T_1}\right)^{\gamma} = \left(\frac{P_2}{P_1}\right)^{\gamma-1}$$

or $$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$ ...(

From equations 3.2 and 3.3, we get

$$\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

or $$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$

or $$PV^{\gamma} = \text{Constant} \qquad \ldots(3.4)$$

Work done, $$W_{1-2} = \int_1^2 P\,dV$$

But $$PV^{\gamma} = P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

or $$P = \frac{P_1V_1^{\gamma}}{V^{\gamma}}$$

$\therefore$ $$W_{1-2} = \int_1^2 \frac{P_1V_1^{\gamma}}{V^{\gamma}}\,dV$$

$$= P_1V_1^{\gamma}\int_1^2 V^{-\gamma}.dV = P_1V_1^{\gamma}\left[\frac{V^{-\gamma+1}}{-\gamma+1}\right]_1^2$$

$$= \frac{P_1V_1^{\gamma}}{1-\gamma}\left[V_2^{1-\gamma} - V_1^{1-\gamma}\right]$$

$$= \frac{P_1V_1^{\gamma}.V_2^{1-\gamma} - P_1V_1^{\gamma}.V_1^{1-\gamma}}{1-\gamma}$$

$$= \frac{P_2V_2 - P_1V_1}{1-\gamma} \qquad \left(\because\ P_1V_1^{\gamma} = P_2V_2^{\gamma}\right)$$

$$= \frac{P_1V_1 - P_2V_2}{\gamma-1}$$

$\therefore$ $$W_{1-2} = \frac{mR(T_1 - T_2)}{\gamma-1}$$

It should be noted that during reversible adiabatic process, entropy remains constant, so the process is also known as isentropic process.

In order to make the adiabatic process reversible (*i.e.* isentropic), the following conditions must be fulfilled:

(*i*) The process should be frictionless.

(*ii*) No heat should be transferred.

(*iii*) Work should be done by the gas or on the gas.

In real practice, isentropic process is not possible.

6. Polytropic Process: It is found that in actual practice many processes approximate to reversible process of the form PV^n = Constant, where n is called polytropic index. Both vapour and perfect gases follow this type of process closely. Work done during the process from state to state 2 by system,

$$\int_1^2 \delta W = \int_1^2 PdV = \int_1^2 \frac{P_1V_1^n}{V^n}\,dV$$

or
$$W_{1-2} = P_1V_1^n\left[\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1}\right]$$

or
$$W_{1-2} = \frac{P_1V_1^nV_2^{-n+1} - P_1V_1^n\,V_1^{-n+1}}{-n+1}$$

or
$$W_{1-2} = \frac{P_2V_2^nV_2^{-n+1} - P_1V_1^n.\,V_1^{-n+1}}{-n+1} \qquad (\because P_1V_1^n = P_2V_2^n)$$

or
$$W_{1-2} = \frac{P_2V_2 - P_1V_1}{-n+1}$$

or
$$W_{1-2} = \frac{P_1V_1 - P_2V_2}{n-1}$$

Note: In a polytropic process, the index n depends upon the heat and work quantities during the process. The various processes discussed above are special cases of polytropic process for a perfect gas.

If $n = 0$ $\Rightarrow PV^\circ = \text{Constant} \Rightarrow P = \text{Constant}$ (Isobaric process)

If $n = \infty$ $\Rightarrow PV^\infty = \text{Constant} \Rightarrow P^{1/\infty}.V = \text{Constant} \Rightarrow V = \text{Constant}$ (Isochoric process)

If $n = 1$ $\Rightarrow PV = \text{Constant} \Rightarrow T = \text{Constant} \left(\because T = \frac{PV}{R}\right)$ (Isothermal process)

If $n = \gamma$ $\Rightarrow PV^\gamma = \text{Constant}$ *i.e.* Reversible adiabatic process.

B. Irreversible Non-Flow Processes: In thermodynamics, most of the processes are irreversible due to friction. The important non-flow irreversible process is free expansion.

Free Expansion: *The expansion of gas in perfect vacuum is called free expansion.* Let a system A contains a gas at some pressure P, while the other system B having common boundary with system A is perfectly evacuated *i.e.* no gas is present there. (Refer fig. 3.7). When common boundary gets punctured, the gas expands in B to acquire the volume without any restriction, so it is also called unrestricted flow.