

**Lecture 7, 8 and 9 : Thermodynamic process**

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7) Thermodynamic process, path and cycle :

Thermodynamic system undergoes changes due to the energy and mass interactions. Thermodynamic state of the system changes due to these interactions. The mode in which the change of state of a system takes place is termed as the process such as constant pressure process, constant volume process etc. Let us take gas contained in a cylinder and being heated up. The heating of gas in the cylinder shall result in change in state of gas as its pressure, temperature etc. shall increase. However, the mode in which this change of state in gas takes place during heating shall be constant volume mode and hence the process shall be called constant volume heating process. So, *any change that a system undergoes from one equilibrium state to another is called a process.*

The path refers to the series of state changes through which the system passes during a process. Thus, path refers to the loci of various intermediate states passed through by a system during a process.

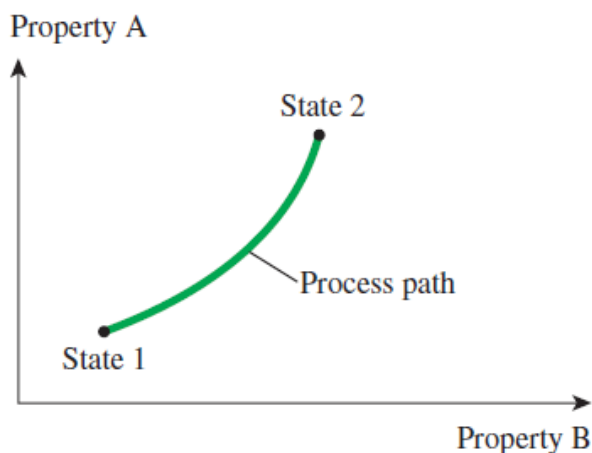


Figure (7-1) A process between states 1 and 2 and the process path.

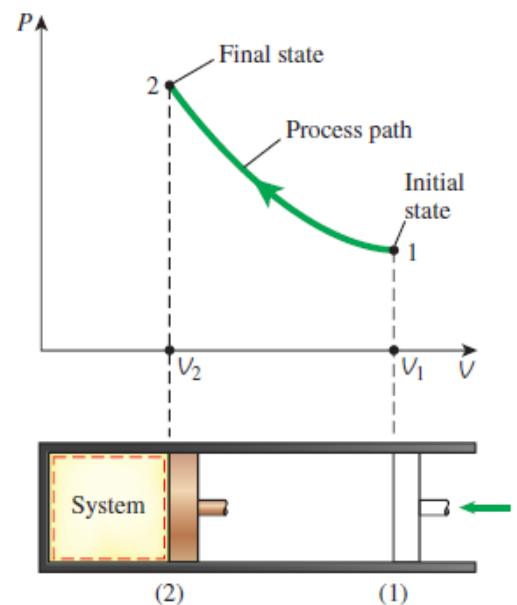


Figure (7-2) The P-V diagram of a compression process.



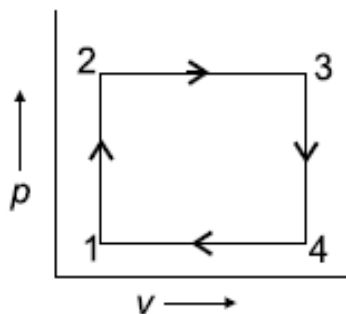
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Cycle refers to a typical sequence of processes in such a fashion that the initial and final states are identical. Thus, a cycle is the one in which the processes occur one after the other so as to finally bring the system at the same state. Thermodynamic path in a cycle is in closed loop form. After the occurrence of a cyclic process system shall show no sign of the processes having occurred.

Mathematically, it can be said that the cyclic integral of any property in a cycle is zero, i.e., $\oint dp = 0$, where p is any thermodynamic property.

Thermodynamic processes, path and cycle are shown on p-v diagram in Figure (7-3).



1-2-3-4-1 = Cycle
1-2, 2-3, 3-4 & 4-1 = Path
1-2 & 3-4 = Constant volume processes
2-3 & 4-1 = Constant pressure processes

Figure (7-3) Thermodynamic process, path and cycle.

**Lecture 7, 8 and 9 : Thermodynamic process***by: Asst. lect. Karrar Al-Mansoori***8) Reversibility and Irreversibility:**

Thermodynamic **processes** may have the change of state **occurring in two ways**. One is the change of state occurring so that if the system is to restore its original state, it can be had by reversing the factors responsible for occurrence of the process. Other change of state may occur such that the above restoration of original state is not possible.

*A **reversible process** (also sometimes known as quasi-static process) is defined as a process which can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states* (Figure 8–4). That is, both the system and the surroundings are returned to their initial states at the end of the reverse process. This is possible only if the net heat and net work exchange between the system and the surroundings is zero for the combined (original and reverse) process. Processes that are not reversible are called **irreversible processes**.

It should be pointed out that a system can be restored to its initial state following a process, regardless of whether the process is reversible or irreversible. But for reversible processes, this restoration is made without leaving any net change on the surroundings, whereas for irreversible processes, the surroundings usually do some work on the system and therefore does not return to their original state. Reversible processes actually do not occur in nature. They are merely idealizations of actual processes. Reversible processes can be approximated by actual devices, but they can never be achieved. **That is, all the processes occurring in nature are irreversible.** You may be wondering, **then, why we are bothering with such fictitious processes.** **There are two reasons.** **First, they are easy to analyze, since a system passes through a series of equilibrium states during a reversible process.** **Second, they serve as idealized models to which actual processes can be compared.**



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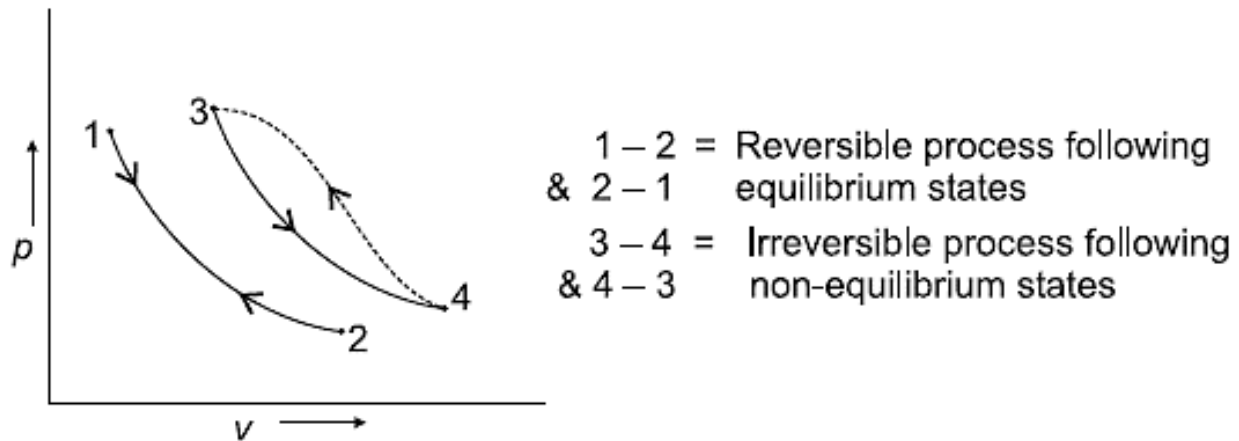


Figure (8-4) Reversible and Irreversible processes

9) Thermodynamic Processes and Calculation of Work:

Thermodynamic processes can be precisely categorized as cyclic process and non-cyclic process. **The cyclic process** is the one in which the initial and final states are identical i.e. system returns to its initial states after occurrence of process. **The non cyclic process** is the one in which the initial and final states are different i.e. the occurrence of process is accompanied by the state change.

Let us consider a system consisting of a tank filled with water and fitted with a stirrer at room temperature, Figure (9-5). Work can be transferred to the system by the stirrer and the temperature of water shall rise. When stirring stops, the system shall cool down till it reaches to the room temperature. Thus, the process is cyclic as the initial and final states are identical.



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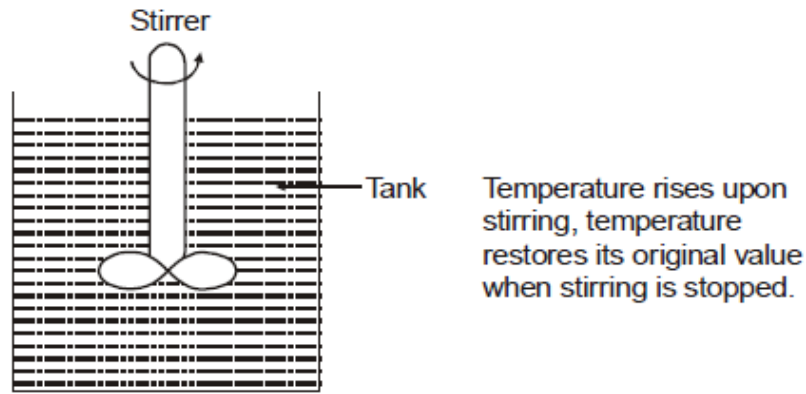


Figure (9-5) Cyclic process

Let us now take a cylinder having piston and gas filled inside. If the gas is made to expand due to heating, the piston shall undergo displacement and say the piston displacement is dx . If the force exerted by gas on face of piston is F and the cross section area of piston is A , then the displacement work done may be given by :

$$dW = F \cdot dx$$

For the gas pressure being p , the force may be given by $F = p \cdot A$. Substituting for F ,

$$dW = p \cdot A \cdot dx \quad \text{or,}$$

$dW = p \cdot dV$, where dV is the elemental change in volume or the volumetric displacement. If the total displacement of piston is given by L then the total work can be had by integrating the above dW with respect to x for displacement L , or with respect to volume for volume change.

$$W = \int p \cdot dV = \int p \cdot A \cdot dx$$

Now, what about the nature of process? Cyclic or non cyclic.

It is obvious that the initial and final states are not identical therefore, it is a non-cyclic process. Thus, the work W as defined above refers to thermodynamic work for a non-cyclic process. **Thermodynamic processes** can be further classified based on the thermodynamic constraints under which they occur. Different types of thermodynamic processes are as detailed below.



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9.1: Constant pressure process or isobaric process:

It refers to the thermodynamic process in which there is no change in pressure during the process. Such type of processes are also known as *isobaric processes*. To understand let us take a cylindrical vessel having gas in it. It has a piston above it. Piston is free to reciprocate in the cylinder. Under normal situation piston shall be subjected to atmospheric pressure. Now, let heat be added to cylinder from bottom of cylinder. Due to heat addition, presuming energy transfer taking place reversibly and system always remaining in equilibrium, the gas shall try to expand. Expansion of gas results in raising up of the piston and it attains a new state say 2. Process is shown on p-V diagram in Figure (9-6).

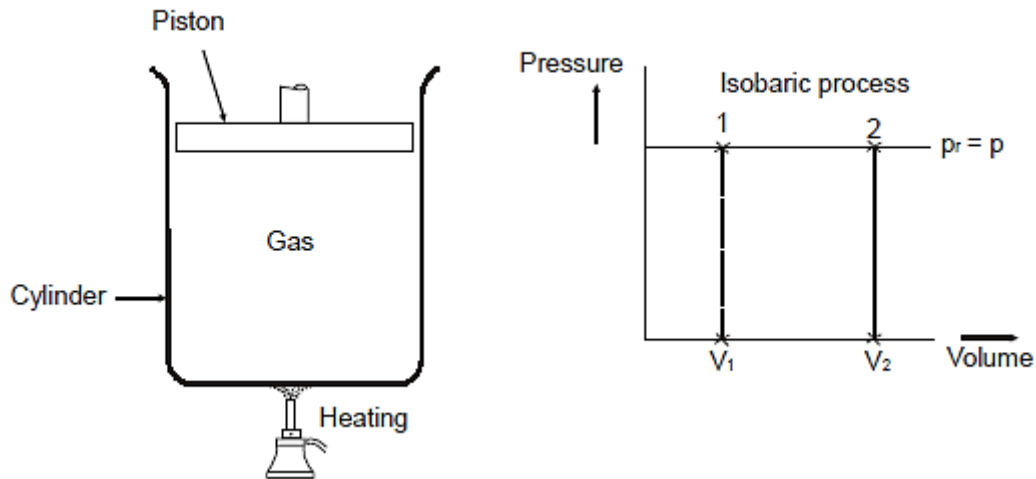


Figure (9-6) Isobaric process

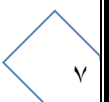
The work involved in the raising of piston shall be given by,

$$W_{1-2} = \int_1^2 \mathbf{P} \cdot d\mathbf{V} = \mathbf{P} \cdot (\mathbf{V}_2 - \mathbf{V}_1)$$

Mathematically from the first law of thermodynamics, it can be given that,

$$dQ = dU + dW$$

$$\int_1^2 dQ = \int_1^2 dU + \int_1^2 dW$$





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$$Q_{1-2} = m C_v (T_2 - T_1) + P (V_2 - V_1)$$

$$Q_{1-2} = m C_v (T_2 - T_1) + m R (T_2 - T_1)$$

Substituting for C_v , i.e : $C_v = \left(\frac{R}{\gamma - 1} \right)$

$$Q_{1-2} = m \left(\frac{R}{\gamma - 1} \right) (T_2 - T_1) + m R (T_2 - T_1)$$

$$= m R (T_2 - T_1) \left(\frac{1}{\gamma - 1} + 1 \right)$$

9.2: Constant volume process or isochoric process:

When a fluid undergoes a thermodynamic process in a fixed enclosed space such that the process occurs at constant volume, then the process is called constant volume process or isochoric process. Let us consider heating of a gas in fixed enclosure at constant volume. On p–V diagram this process is represented by a vertical line as shown in Figure (9-7) . Area under the process line is zero which indicates that there is rise in pressure but there is no work done as there is no change in volume.

Work involved shall be,

$$W_{1-2} = \int_1^2 P \cdot dV = P \cdot (V_2 - V_1) = 0$$

From first law of thermodynamics,

$$\int_1^2 dQ = \int_1^2 dU + \int_1^2 dW$$

$$Q_{1-2} = m C_v (T_2 - T_1) + 0$$

$$Q_{1-2} = U_2 - U_1 = m C_v (T_2 - T_1)$$

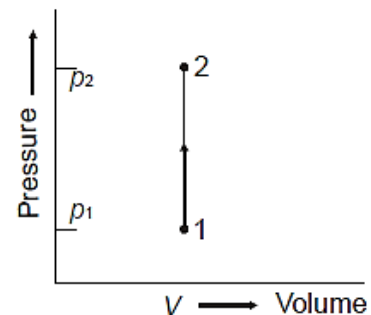
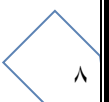


Figure (9-7) Isochoric process

Thus, it indicates that the effect of heat addition in constant volume process is to increase the temperature and consequently the internal energy of system.





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9.3: Constant temperature process or isothermal process:

Thermodynamic process in which the temperature remains constant is called constant temperature or isothermal process. In this case the gas or vapour may be heated at constant temperature and there shall be no change in internal energy. The work done will be equal to the amount of heat supplied, as shown ahead. For a perfect gas during isothermal process;

$$p_1 V_1 = p_2 V_2 = \text{Constant}, \quad \text{or}, \quad P = \frac{P_1 V_1}{V}$$

$$\text{so work involved, } W_{1-2} = \int_{V_1}^{V_2} P \cdot dV$$

$$W_{1-2} = \int_{V_1}^{V_2} \frac{P_1 V_1}{V} dV = p_1 V_1 \ln \frac{V_2}{V_1}$$

$$W_{1-2} = p_1 V_1 \ln r$$

where r = ratio of final and initial volumes.

By first law of thermodynamics :

$$\int_1^2 dQ = \int_1^2 dU + \int_1^2 dW$$

$$Q_{1-2} = W_{1-2} + (U_2 - U_1) = W_{1-2} + 0$$

$$U_2 - U_1 = m C_v (T_2 - T_1), \text{ and } T_1 = T_2$$

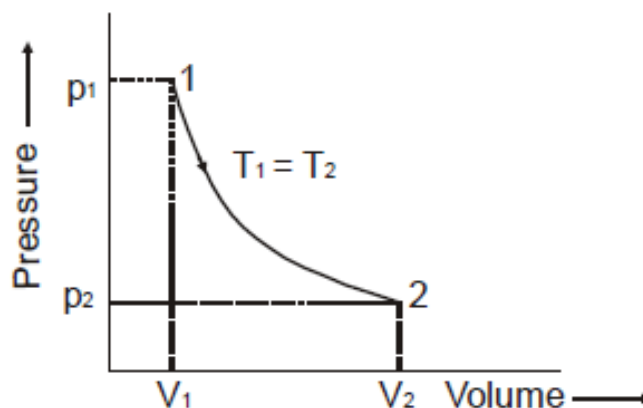


Figure (9-8) Isothermal process



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9.4: Adiabatic process:

An adiabatic process is the thermodynamic process in which there is no heat interaction during the process, i.e. during the process, $Q = 0$. In these processes the work interaction is there at the expense of internal energy. If we talk of adiabatic expansion then it shall mean that work is done at the cost of its own internal energy. The adiabatic process follows the law $PV^\gamma = \text{constant}$ where γ is called adiabatic index and is given by the ratio of two specific heats. Thus, it is obvious that adiabatic expansion shall be accompanied by the fall in temperature while temperature will rise during adiabatic compression. The adiabatic expansion process is shown on Figure (9-9) Work done during expansion shall be,

$W_{1-2} = \int_1^2 \mathbf{P} \cdot d\mathbf{V}$, where $PV^\gamma = \text{constant}$, therefore solving after substitution. Work shall be,

$$W_{1-2} = \frac{p_1 V_1 - p_2 V_2}{\gamma - 1}$$

From first law of thermodynamics :

$$\int_1^2 dQ = \int_1^2 dU + \int_1^2 dW$$

$$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

$$0 = (U_2 - U_1) + W_{1-2}$$

$$W_{1-2} = - (U_2 - U_1)$$

$$W_{1-2} = (U_1 - U_2)$$

$$W_{1-2} = m C_v (T_1 - T_2)$$

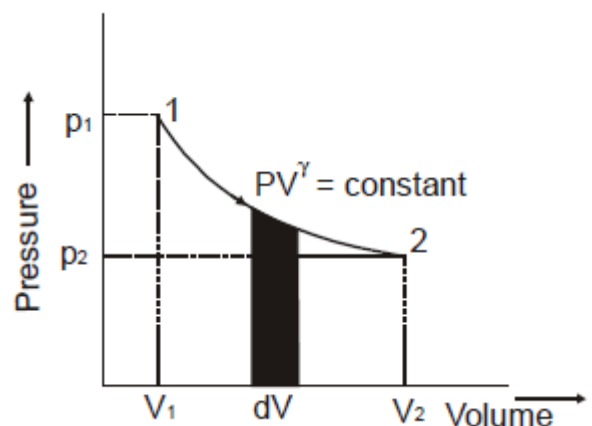


Figure (9-9) Adiabatic expansion



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9.5: Polytropic process:

Polytropic process is the most commonly used process in practice. In this, the thermodynamic process is said to be governed by the law $PV^n = \text{constant}$ where n is the index which can vary from $(-\infty \text{ to } +\infty)$. Figure (9-10) shows some typical cases in which the value of n is varied and the type of process indicated for different values of n . Thus the various thermodynamics processes discussed above are special cases of polytropic process. Work interaction in case of polytropic process can be given as,

$$W_{1-2} = \int_{V_1}^{V_2} P \cdot dV$$

Where $p_1 V_1^n = p_2 V_2^n = \text{constant}$

Solving the above, we get :

$$W_{1-2} = \frac{p_1 V_1 - p_2 V_2}{n - 1}$$

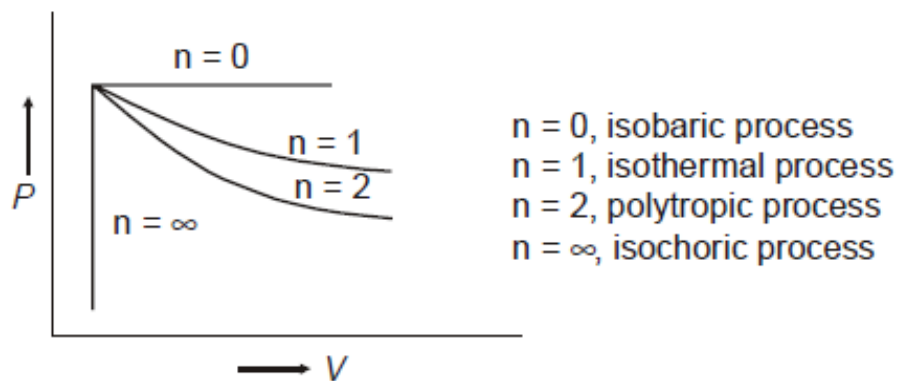


Figure (9-10) Polytropic process



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From first law of thermodynamics,

$$\int_1^2 dQ = \int_1^2 dU + \int_1^2 dW$$

$$Q_{1-2} = (U_2 - U_1) + \frac{p_1 V_1 - p_2 V_2}{n - 1}$$

$$Q_{1-2} = m C_v (T_2 - T_1) + \frac{m R (T_1 - T_2)}{n - 1}$$

$$\text{also, } C_v = \left(\frac{R}{\gamma - 1} \right) \quad \text{or, } R = C_v (\gamma - 1)$$

$$Q_{1-2} = m C_v \left\{ (T_2 - T_1) + \left(\frac{\gamma - 1}{n - 1} \right) * (T_1 - T_2) \right\}$$

$$Q_{1-2} = m C_v \left\{ (T_2 - T_1) + \left(\frac{\gamma - 1}{n - 1} \right) * - (T_2 - T_1) \right\}$$

$$Q_{1-2} = m C_v (T_2 - T_1) \left\{ 1 + \left(\frac{\gamma - 1}{1 - n} \right) \right\}$$

$$Q_{1-2} = m C_v (T_2 - T_1) \left\{ \frac{(1 - n) + (\gamma - 1)}{(1 - n)} \right\}$$

$$Q_{1-2} = m C_v (T_2 - T_1) \left\{ \frac{(1 - n) + (\gamma - 1)}{(1 - n)} \right\}$$

Thus heat transfer during a polytropic process for a perfect gas;

$$Q_{1-2} = m C_v (T_2 - T_1) * \left(\frac{\gamma - n}{1 - n} \right)$$

or also, substituting for C_v

$$Q_{1-2} = m \left(\frac{R}{\gamma - 1} \right) (T_2 - T_1) * \left(\frac{\gamma - n}{1 - n} \right)$$

$$Q_{1-2} = \left(\frac{m R (T_2 - T_1)}{1 - n} \right) * \left(\frac{\gamma - n}{\gamma - 1} \right)$$

$$Q_{1-2} = W * \left(\frac{\gamma - n}{\gamma - 1} \right)$$