



(6) A molecule moves along a straight line between two successive collisions and the average distance travelled between two successive collisions is called the mean free path of the molecules.

(7) The collisions are almost instantaneous (i.e) the time of collision of two molecules is negligible as compared to the time interval between two successive collisions.

## Behavior of gases

It has been observed from experiments that for very low densities, the pressure, volume and temperature of gas are interrelated by some simple relations.

### Boyle's law

At constant temperature and low enough density, the pressure of a given quantity (mass) of gas is inversely proportional to its volume

Thus at constant mass and constant temperature

$$P \propto \frac{1}{V}$$

$$\text{Or } PV = \text{Constant}$$

### Charles's law

At constant pressure and low enough density, the volume of a given quantity (mass) of a gas is proportional to its absolute temperature

Thus at constant mass and constant pressure

$$V \propto T$$

$$\text{Or } \frac{V}{T} = \text{constant}$$

### Gay Lussac's law

For a given volume and low enough density the pressure of a given quantity of gas is proportional to its absolute temperature.

Thus at constant mass and constant volume

$$P \propto T$$

$$\text{Or } \frac{P}{T} = \text{constant}$$

### Avogadro's Number

"For given constant temperature and pressure, the number of molecules per unit volume is the same for all gases"

At standard temperature ( 273K) and pressure (1 atm), the mass of 22.4 litres of **any** gas is equal to its molecular mass ( in grams). This quantity of gas is called 1 mole.

The number of particles ( atoms or molecules) in one mole of substance (gas) is called Avogadro number, which has a magnitude  $N_A = 6.023 \times 10^{23} \text{ mol}^{-1}$

If N is the number of gas molecules in a container , then the number of mole of given gas is

$$\mu = \frac{N}{N_A}$$

If  $M$  is the total mass of gas in a container, and mass of one mole of gas called molar mass  $M_0$ , then the number of moles of gas is

$$\mu = \frac{M}{M_0}$$

Other important laws of an ideal gas

**Graham's law of diffusion** states that when two gases at the same pressure and temperature are allowed to diffuse into each other, the rate of diffusion of each gas is inversely proportional to the square root of the density of the gas

$$\text{rate of diffusion} \propto \sqrt{\frac{1}{\text{density of gas}}}$$

Dalton's law of partial pressure states that the pressure exerted by a mixture of several gases equals the sum of the pressure exerted by each gas occupying the same volume as that of the mixture

$P_1, P_2, \dots, P_n$  are the pressure exerted by individual gases of the mixture, then pressure of the mixture of the gas is

$$P = P_1 + P_2 + \dots + P_n$$

### Ideal gas-state equation and its different forms

If we combine Boyle's law and Charles's law we get

$$\frac{PV}{T} = \text{constant}$$

For a given quantity of gas, which shows that for constant temperature and pressure, if quantity or mass of gas varies, then volume of the gas is proportional to the quantity of gas.

Thus constant on the right hand side of the equation depends on the quantity of the gas. If quantity is represented in mole then

$$\frac{PV}{T} = \mu R$$

Equation is called an ideal gas-state equation

Here  $R$  is universal gas constant =  $8.314 \text{ J mole}^{-1} \text{ K}^{-1}$

If gas completely obeys equation

$$PV = \mu RT \quad \text{--- eq(1)}$$

at all values of pressure and temperature, then such a (imaginary) gas is called an ideal gas. By putting

$$\mu = \frac{N}{N_A}$$

In above equation we get

$$PV = \frac{N}{N_A} RT = N \frac{R}{N_A} T$$

Putting  $R/N_A = k_B$  ( Boltzmann's constant =  $1.38 \times 10^{-23} \text{ J K}^{-1}$  )

$$PV = Nk_B T$$

$$\therefore P = \frac{N}{V} k_B T$$

If  $n = N/V$  number of molecules per unit volume of gas

$$\therefore P = nk_B T \quad \text{--- eq(2)}$$

Putting

$$\mu = \frac{M}{M_0}$$

In equation (1)

$$PV = \frac{M}{M_0} RT$$

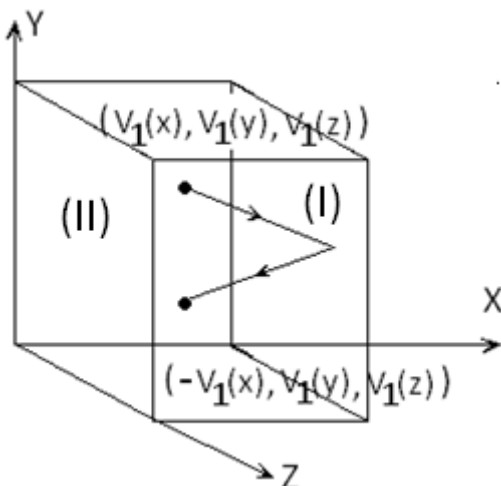
$$P = \frac{M}{V} \frac{RT}{M_0}$$

$$P = \frac{\rho RT}{M_0} \quad \text{--- eq(3)}$$

$\rho$  is the density of gas

### Pressure of an ideal gas and rms speed of gas molecules

The molecules of a gas are in a state of random motion. They continuously collide against the walls of the container. During each collision, momentum is transferred to the walls of the container.



The pressure exerted by the gas is due to the continuous collision of the molecules against the walls of the container. Due to this continuous collision, the walls experience a continuous force which is equal to the total momentum imparted to the walls per second. The force experienced per unit area of the walls of the container determines the pressure exerted by the gas.

Consider a cubic container of side  $L$  containing  $n$  molecules of perfect gas moving with velocities  $C_1, C_2, C_3 \dots C_n$

A molecule moving with a velocity  $v_1$ , will have

velocities  $C_1(x), C_1(y)$  and  $C_1(z)$  as components along the  $x, y$  and  $z$  axes respectively.

Similarly  $C_2(x), C_2(y)$  and  $C_2(z)$  are the velocity components of the second molecule and so on.

Let a molecule P shown in figure having velocity  $C_1$  collide against the wall marked I perpendicular to the x-axis. Only the x-component of the velocity of the molecule is relevant for the wall. Hence momentum of the molecule before collision is  $m C_1(x)$  where  $m$  is the mass of the molecule.

Since the collision is elastic, the molecule will rebound with the velocity  $C_1(x)$  in the opposite direction. Hence momentum of the molecule after collision is  $-mC_1(x)$

Change in the momentum of the molecule = Final momentum - Initial momentum

Change in the momentum of the molecule =  $-mC_1(x) - mC_1(x) = -2mC_1(x)$

During each successive collision on face I the molecule must travel a distance  $2L$  from face I to face II and back to face I.

Time taken between two successive collisions is  $= 2L / C_1(x)$

$$\therefore \text{Rate of change of momentum} = \frac{\text{change in momentum}}{\text{time taken}}$$

$$\text{Rate of change of momentum} = \frac{-2mC_1(x)}{\frac{2L}{C_1(x)}} = \frac{-mC_1^2(x)}{L}$$

$$\text{Force exerted on the molecule} = \frac{-mC_1^2(x)}{L}$$

According to Newton's third law of motion, the force exerted by the molecule =

$$= -\frac{-mC_1^2(x)}{L} = \frac{mC_1^2(x)}{L}$$

Force exerted by all the  $n$  molecules is

$$F_x = \frac{mC_1^2(x)}{L} + \frac{mC_2^2(x)}{L} + \frac{mC_3^2(x)}{L} + \dots + \frac{mC_n^2(x)}{L}$$

Pressure exerted by the molecules

$$P_x = \frac{F_x}{A}$$

$$P_x = \frac{1}{L^2} \left( \frac{mC_1^2(x)}{L} + \frac{mC_2^2(x)}{L} + \frac{mC_3^2(x)}{L} + \dots + \frac{mC_n^2(x)}{L} \right)$$

$$P_x = \frac{m}{L^3} (C_1^2(x) + C_2^2(x) + C_3^2(x) + \dots + C_n^2(x))$$

Similarly, pressure exerted by the molecules along Y and Z axes are

$$P_y = \frac{m}{L^3} (C_1^2(y) + C_2^2(y) + C_3^2(y) + \dots + C_n^2(y))$$

$$P_z = \frac{m}{L^3} (C_1^2(z) + C_2^2(z) + C_3^2(z) + \dots + C_n^2(z))$$

Since the gas exerts the same pressure on all the walls of the container

$$P_x = P_y = P_z$$

$$P = \frac{P_x + P_y + P_z}{3}$$

$$P = \frac{1}{3} \frac{m}{L^3} [(C_1^2(x) + C_2^2(x) + C_3^2(x) + \dots + C_n^2(x)) \\ + (C_1^2(y) + C_2^2(y) + C_3^2(y) + \dots + C_n^2(y)) \\ + (C_1^2(z) + C_2^2(z) + C_3^2(z) + \dots + C_n^2(z))]$$

$$P = \frac{1}{3} \frac{m}{L^3} [(C_1^2(x) + C_1^2(y) + C_1^2(z)) + (C_2^2(x) + C_2^2(y) + C_2^2(z)) + \dots \\ + (C_n^2(x) + C_n^2(y) + C_n^2(z))]$$

$$P = \frac{m}{3V} [C_1^2 + C_2^2 + \dots + C_n^2]$$

$$P = \frac{mn}{3V} \left[ \frac{C_1^2 + C_2^2 + \dots + C_n^2}{n} \right]$$

$$P = \frac{mn}{3V} \langle C^2 \rangle$$

Here V is volume of gas

Where  $\langle C^2 \rangle$  is called the root mean square (RMS) velocity, which is defined as the square root of the mean value of the squares of velocities of individual molecules.

Since  $mn$  = mass of gas and density  $\rho$  = mass/volume

$$P = \frac{\rho}{3} \langle C^2 \rangle$$

Relation between the pressure exerted by a gas and the mean kinetic energy of translation per unit volume of the gas

Mean kinetic energy of translation per unit volume of the gas

$$E = \frac{1}{2} \rho \langle C^2 \rangle$$

Thus

$$\frac{P}{E} = \frac{\frac{\rho}{3} \langle C^2 \rangle}{\frac{1}{2} \rho \langle C^2 \rangle} = \frac{2}{3}$$

$$\text{Or } P = (2/3)E$$

Average kinetic energy per molecule of the gas

Let us consider one mole of gas of mass M and volume V.

$$P = \frac{\rho}{3} \langle C^2 \rangle$$

$$P = \frac{M}{3V} \langle C^2 \rangle$$

$$PV = \frac{M}{3} \langle C^2 \rangle$$

From ideal gas equation for one mole of gas

$$PV = RT$$

$$\frac{M}{3} \langle C^2 \rangle = RT$$

$$M \langle C^2 \rangle = 3RT$$

$$\frac{1}{2} M \langle C^2 \rangle = \frac{3}{2} RT$$

Average kinetic energy of one mole of the gas is equal to = (3/2) RT

Since one mole of the gas contains  $N_A$  number of atoms where  $N_A$  is the Avogadro number we have  $M = N_A m$

$$\frac{1}{2} N_A m \langle C^2 \rangle = \frac{3}{2} RT$$

$$\frac{1}{2} m \langle C^2 \rangle = \frac{3R}{2N_A} T$$

$$\frac{1}{2} m \langle C^2 \rangle = \frac{3}{2} k_B T$$

$k_B$  is Boltzmann constant

Average kinetic energy per molecule of the gas is equal to (3/2)  $k_B T$

Hence, it is clear that the temperature of a gas is the measure of the mean translational kinetic energy per molecule of the gas

## Degrees of freedom

*The number of degrees of freedom of a dynamical system is defined as the total number of co-ordinates or independent variables required to describe the position and configuration of the system.*

- (i) A particle moving in a straight line along any one of the axes has one degree of freedom (e.g) Bob of an oscillating simple pendulum.
- (ii) A particle moving in a plane (X and Y axes) has two degrees of freedom. (eg) An ant that moves on a floor.
- (iii) A particle moving in space (X, Y and Z axes) has three degrees of freedom. (eg) a bird that flies.

A point mass cannot undergo rotation, but only translatory motion. Three degree of freedom

A rigid body with finite mass has both rotatory and translatory motion.

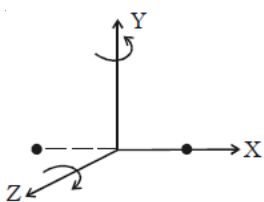
The rotatory motion also can have three co-ordinates in space, like translatory motion ; Therefore a rigid body will have six degrees of freedom ; three due to translatory motion and three due to rotator motion.

## Monoatomic molecule

Since a monoatomic molecule consists of only a single atom of point mass it has three degrees of freedom of translatory motion along the three co-ordinate axes

Examples : molecules of rare gases like helium, argon, etc.

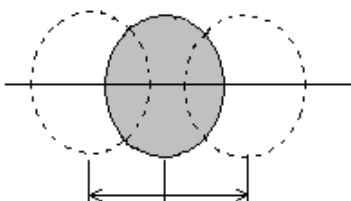
## Diatomic molecule rigid rotator



The diatomic molecule can rotate about any axis at right angles to its own axis. Hence it

has two degrees of freedom of rotational motion in addition to three degrees of freedom of translational motion along the three axes. So, a diatomic molecule has five degrees of freedom (Fig.). Examples : molecules of  $O_2$ ,  $N_2$ ,  $Cl_2$ , etc

**Diatomic molecule like CO** : Have five freedom as stated in rigid rotator apart from that they have two more freedoms due to vibration ( oscillation) about mean position



Plyatomic molecules posses rotational kinetic energy energy of vibration in addition to their translational energy.

Therefore when heat energy is given to such gases, it is utilized in increasing the translational kinetic energy, rotational kinetic energy and vibrational kinetic energy of the



gas molecules and hence more heat is required. This way polyatomic molecules possess more specific heat

## Law of equipartition of energy

*Law of equipartition of energy states that for a dynamical system in thermal equilibrium the total energy of the system is shared equally by all the degrees of freedom. The energy associated with each degree of freedom per molecule is  $(1/2)kT$*

where  $k$  is the Boltzmann's constant.

Let us consider one mole of a monoatomic gas in thermal equilibrium at temperature  $T$ .

Each molecule has 3 degrees of freedom due to translatory motion.

According to kinetic theory of gases, the mean kinetic energy of a molecule is  $(3/2)kT$

Let  $C_x$ ,  $C_y$  and  $C_z$  be the components of RMS velocity of a molecule along the three axes.

Then the average energy of a gas molecule is given by

$$\frac{1}{2}mC^2 = \frac{1}{2}mC_x^2 + \frac{1}{2}mC_y^2 + \frac{1}{2}mC_z^2$$

$$\frac{1}{2}mC_x^2 + \frac{1}{2}mC_y^2 + \frac{1}{2}mC_z^2 = \frac{3}{2}kT$$

Since molecules move at random, the average kinetic energy corresponding to each degree of freedom is the same.

$$\frac{1}{2}mC_x^2 = \frac{1}{2}mC_y^2 = \frac{1}{2}mC_z^2 = \frac{1}{2}kT$$

$\therefore$  Mean kinetic energy per molecule per degree of freedom is  $(1/2)kT$

## Mean free path

“The linear distance travelled by a molecule of gas with constant speed between two consecutive collisions (between molecules) is called free path. The average of such free paths travelled by a molecule is called mean free path”

Suppose molecules of gas are spheres of diameter  $d$ . If the centre between the two molecules is less or equal to  $d$  then they will collide when they come close.

Consider a molecule of diameter  $d$  moving with average speed  $v$ , and the other molecule is stationary. The molecule under consideration will sweep a cylinder of  $\pi d^2 vt$ . In time  $t$ .

If the number of molecules per unit volume is  $n$ , then the number of molecules in this cylinder is  $n\pi d^2 vt$ . Hence the molecule will undergo  $n\pi d^2 vt$  collisions in time  $t$

The mean free path  $l$  is the average distance between two successive collisions

$$\text{Mean free path} = \frac{\text{distance travelled in time } t}{\text{number of collisions in time } t}$$

$$l = \frac{vt}{2\pi d^2 vt}$$

$$l = \frac{1}{2\pi n d^2}$$

In this derivation other molecules are considered stationary. In actual practice all gas molecules are moving and their collision rate is determined by the average relative velocity  $\langle V \rangle$ . Hence mean free path formula is  $l = \frac{1}{\sqrt{2}n\pi d^2}$

### Solved Numerical

Q) Find the mean translational kinetic energy of a molecule of He at 27°C

Solution: Since He is mono atomic degree of freedom is 3

Kinetic energy  $= \frac{3}{2}k_B T$

Here  $k_B$  = Boltzmann's constant =  $1.38 \times 10^{-23} \text{ J K}^{-1}$  Temperature  $T = 27 + 273 = 300 \text{ K}$

$$K = \frac{3}{2} \times 1.38 \times 10^{-23} \times 300 = 6.21 \times 10^{-21} \text{ J}$$

Q) At what temperature rms velocity of  $\text{O}_2$  is equal to rms velocity of  $\text{H}_2$  at 27°C?

Solution

Kinetic energy

$$\frac{1}{2}m \langle C^2 \rangle = \frac{3}{2}k_B T$$

$$\langle C^2 \rangle = \frac{3k_B T}{m}$$

But rms velocity of  $\text{O}_2$  = rms velocity of He

$$\frac{3k_B T}{32} = \frac{3k_B \times 300}{4}$$

$$T = 2400 \text{ K}$$

Q) Find rms velocity of hydrogen at 0°C temperature and 1 atm pressure. Density of hydrogen gas is  $8.9 \times 10^{-2} \text{ kg m}^{-3}$

Solution:

From formula

$$P = \frac{\rho}{3} \langle C^2 \rangle$$

$$\langle C \rangle = \sqrt{\frac{3P}{\rho}}$$

$$\langle C \rangle = \sqrt{\frac{3 \times 1.01 \times 10^5}{8.9 \times 10^{-2}}} = 1845 \text{ m s}^{-1}$$

Q) If the molecular radius of hydrogen molecule is  $0.5 \text{ \AA}$ , find the mean free path of hydrogen molecule at 0°C temperature and 1 atm pressure

Solution

$$d = 2 \times r = 1 \text{ \AA}$$

From formula  $P = n k_B T$

$$n = \frac{P}{k_B T}$$

$$n = \frac{1.01 \times 10^5}{1.38 \times 10^{-23} \times 273} = 2.68 \times 10^{25}$$

$$\text{From formula for mean path } l = \frac{1}{\sqrt{2} \times 3.14 \times 2.68 \times 10^{25} \times (1 \times 10^{-10})^2} = 8.4 \times 10^{-7} \text{ m}$$

## SECTION II

### Thermodynamics

Some important terms

**Thermodynamic system** : It is a part of the universe under thermodynamic study. A system can be one, two or three dimensional. May consist of single or many objects or radiation

**Environment** : remaining part of universe around the thermodynamic system is Environment. Environment has direct impact on the behavior of the system

**Wall**: The boundary separating the system from the universe is wall

**Thermodynamic co-ordinates**: The macroscopic quantities having direct effect on the internal state of the system are called thermodynamic coordinates. For example take the simple example of a sample of gas with a fixed number of molecules. It need not be ideal. Its temperature,  $T$ , can be expressed as a function of just two variables, volume,  $V$ , and pressure,  $p$ . We can, it turns out, express all gas properties as functions of just two variables (such as  $p$  and  $V$  or  $p$  and  $T$ ). These properties include refractive index, viscosity, internal energy, entropy, enthalpy, the Helmholtz function, the Gibbs function. We call these properties 'functions of state'. The state is determined by the values of just two variables

**Thermodynamic system**: The system represented by the thermodynamic co-ordinate is called a thermodynamic system

**Thermodynamic process**: The interaction between a system and its environment is called a thermodynamic process

**Isolated system**: If a system does not interact with its surrounding then it is called an isolated system. Thermal and mechanical properties of such system is said to be in a definite thermodynamic equilibrium state

**Heat (Q) and Work(W)**: The amount of heat energy exchanged during the interaction of system with environment is called heat (Q) and the mechanical energy exchanged is called work (W).

**Thermodynamic variables:** Thermodynamic variables describe the momentary condition of a thermodynamic system. Regardless of the path by which a system goes from one state to another — i.e., the sequence of intermediate states — the total changes in any state variable will be the same. This means that the incremental changes in such variables are exact differentials. Examples of state variables include: Density ( $\rho$ ), Energy ( $E$ ), Gibbs free energy ( $G$ ), Enthalpy ( $H$ ), Internal energy ( $U$ ), Mass ( $m$ ), Pressure ( $p$ ), Entropy ( $S$ ) Temperature ( $T$ ), Volume ( $V$ )

**Extensive thermodynamic state variable:** The variables depending on the dimensions of the system are called extensive variables. For examples mass, volume, internal energy

**Intensive thermodynamic state variable:** The variables independent on the dimensions of the system are called intensive variables. For examples pressure, temperature, density

**Thermal equilibrium:** When two system having different temperatures are brought in thermal contact with each other, the heat flows from the system at higher temperature to that at lower temperature. When both the system attains equal temperatures, the net heat exchanged between them becomes zero. In this state they are said to be in thermal equilibrium state with each other.

**Zerth Law of thermodynamics:** "If the system A and B are in the thermal equilibrium with a third system C, then A and B are also in thermal equilibrium with each other"

**Temperature** may be defined as the particular property which determines whether a system is in thermal equilibrium or not with its neighbouring system when they are brought into contact

**adiabatic wall** – an insulating wall (can be movable) that does not allow flow of energy (heat) from one to another.

**diathermic wall** – a conducting wall that allows energy flow (heat) from one to another

### Specific heat capacity

Specific heat capacity of a substance is defined as the quantity of heat required to raise the temperature of 1 kg of the substance through 1K. Its unit is  $\text{J kg}^{-1}\text{K}^{-1}$ .

### Molar specific heat capacity of a gas

Molar specific heat capacity of a gas is defined as the quantity of heat required to raise the temperature of 1 mole of the gas through 1K. Its unit is  $\text{J mol}^{-1}\text{K}^{-1}$ .

Let  $m$  be the mass of a gas and  $C$  its specific heat capacity. Then  $\Delta Q = m \times C \times \Delta T$  where  $\Delta Q$  is the amount of heat absorbed and  $\Delta T$  is the corresponding rise in temperature.

### Case (i)

If the gas is insulated from its surroundings and is suddenly compressed, it will be heated up and there is rise in temperature, even though no heat is supplied from outside

(i.e)  $\Delta Q = 0 \therefore C = 0$

**Case (ii)**

If the gas is allowed to expand slowly, in order to keep the temperature constant, an amount of heat  $\Delta Q$  is supplied from outside, then

$$C = \frac{\Delta Q}{m\Delta T} = \frac{\Delta Q}{0} = +\infty$$

( $\because \Delta Q$  is +ve as heat is supplied from outside)

**Case (iii)**

If the gas is compressed gradually and the heat generated  $\Delta Q$  is conducted away so that temperature remains constant, then

$$C = \frac{-\Delta Q}{m\Delta T} = \frac{-\Delta Q}{0} = +\infty$$

( $\because \Delta Q$  is -ve as heat is supplied by the system)

Thus we find that if the external conditions are not controlled, the value of the specific heat capacity of a gas may vary from  $+\infty$  to  $-\infty$

Hence, *in order to find the value of specific heat capacity of a gas, either the pressure or the volume of the gas should be kept constant.* Consequently a gas has two specific heat capacities

- (i) Specific heat capacity at constant volume
- (ii) Specific heat capacity at constant pressure.

**Molar specific heat capacity of a gas at constant volume**

Molar specific heat capacity of a gas at constant volume  $C_v$  is defined as the quantity of heat required to raise the temperature of one mole of a gas through 1 K, keeping its volume constant

**Molar specific heat capacity of a gas at constant pressure**

Molar specific heat capacity of a gas at constant pressure  $C_p$  is defined as the quantity of heat to raise the temperature of one mole of a gas through 1 K keeping its pressure constant

**Specific heat of gas from the law of equipartition of energy**

The energy associated with each degree of freedom is  $(1/2)k_B T$ . It means that, if the degree of freedom of a gas molecule is  $f$  then the average heat energy of each molecule of gas is

$$E_{ave} = f \times \frac{1}{2} k_B T$$

If number of moles of an ideal gas is  $\mu$ , then the number of moles in the gas is  $\mu N_A$ .

Therefore the **internal energy** of  $\mu$  mole of ideal gas is

$$U = \mu N_A E_{average}$$

$$U = \mu N_A f \times \frac{1}{2} k_B T$$

$$U = \frac{f}{2} \mu RT \quad (\because R = N_A k_B)$$

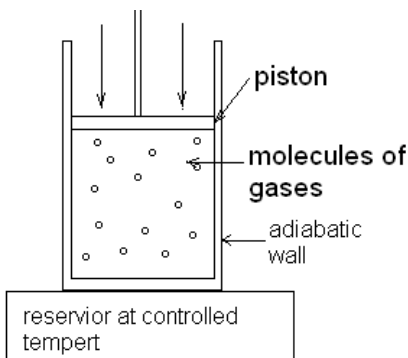
### Work in thermodynamics

The amount of mechanical energy exchanged between two bodies during mechanical interaction is called work. Thus work is a quantity related to mechanical interaction. A system can possess mechanical energy, but cannot possess work

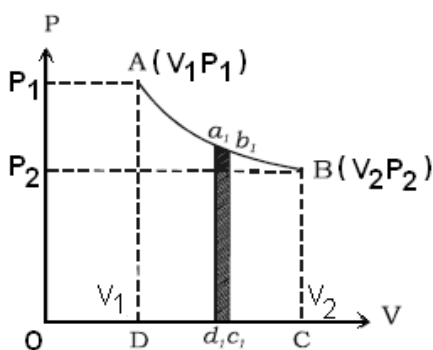
**In thermodynamics the work done by the system is considered positive and the work done on the system is considered negative.**

The reason behind such sign convention is due to the mode of working of heat engine in which the engine absorbs heat from the environment and converts it into work W means the energy of the system is reduced by W

### Formula for the work done during the compression of gas at constant temperature



As shown in figure  $\mu$  molecules of gas are enclosed in a cylindrical container at low pressure, and an air tight piston capable of moving without friction with area A is provided. The conducting bottom of the cylinder is placed on an arrangement whose temperature can be controlled.



At constant temperature, measuring the volume of the gas for different values of pressure, the graph of P-V can be plotted as shown in figure. These types of process are called isothermal process and the curve of P-V is called isotherm.

Suppose initial pressure and volume of the gas is represented by P<sub>1</sub> and V<sub>1</sub> respectively. Keeping the temperature T of the gas to be constant, volume of gas decreases slowly by pushing piston down. Let final pressure and volume of the gas be P<sub>2</sub> and V<sub>2</sub>

During the process, at one moment when pressure of the gas is P and volume V, at that time, let the piston move inward by  $\Delta x$ . Then the volume of the gas decreases by  $\Delta V$ . This displacement is so small that there is no apparent change in pressure.

Hence work done on the gas

$$\Delta W = F \Delta x$$

$$\Delta W = P A \Delta x$$

$$\Delta W = P \Delta V$$

If the volume of the gas is decreasing from  $V_1$  to  $V_2$  through such small changes, then the total work done on the gas

$$W = \sum_{V_1}^{V_2} P \Delta V$$

If this summation is taking the limit as  $\Delta V \rightarrow 0$  the summation results in integration

$$W = \int_{V_1}^{V_2} P dV$$

But the ideal gas equation for  $\mu$  moles of gas is  $PV = \mu RT$  thus

$$W = \int_{V_1}^{V_2} \frac{\mu RT}{V} dV$$

$$W = \mu RT \int_{V_1}^{V_2} \frac{dV}{V}$$

$$W = \mu RT [\ln V]_{V_1}^{V_2}$$

$$W = \mu RT [V_2 - V_1]$$

$$W = \mu RT \ln \left( \frac{V_2}{V_1} \right)$$

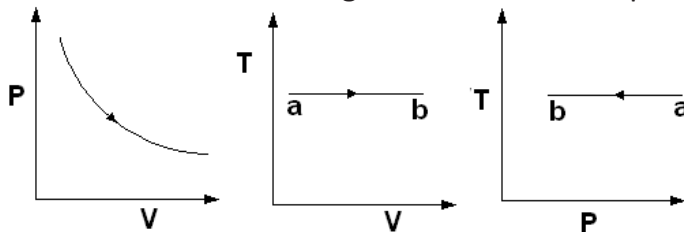
$$W = 2.303 \mu RT \log_{10} \left( \frac{V_2}{V_1} \right)$$

Equation does not give the work  $W$  by an ideal gas during every thermodynamic process, but it gives the work done only for a process in which the temperature is held constant.

Since  $V_2 < V_1$  hence  $\log(V_2/V_1)$  is negative. Thus we get negative value of work which represents that **during the compression of gas at constant temperature, the work is done on the gas**

If the gas is expanded then Since  $V_2 > V_1$  hence  $\log(V_2/V_1)$  is positive. Thus we get positive value of work which represents that **during the expansion of gas at constant temperature, the work is done by the gas**

The P-V, T-V and T-P diagram for isothermal process will be like the curves given below



ISOTHERMAL PROCESS

## Work done at constant volume and constant pressure

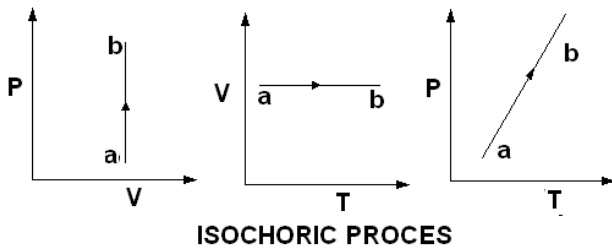
### Constant volume : Also called as isochoric process

If the volume is constant then  $dV = 0$  from equation

$$W = \int_{V_1}^{V_2} P dV$$

Work done is zero

The P-V, V-T and P-T diagrams for isochoric process will be like curves given below



### Constant pressure : Also called as isobaric process

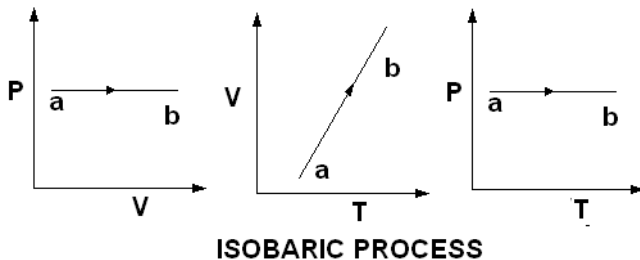
If the volume is changing while pressure is constant then from equation

$$W = \int_{V_1}^{V_2} P dV = P \int_{V_1}^{V_2} dV$$

$$W = P[V_2 - V_1]$$

$$W = P\Delta V \text{ ( for constant pressure )}$$

The P-V, V-T and P-T diagrams for isobaric process will be like curves given below



## Work done during adiabatic process

No exchange of heat takes place between system and its environment in this process. This is possible when (1) walls of a system are thermal insulators or (2) process is very rapid.

The relation between pressure and volume for ideal gas is

$$PV^\gamma = \text{constant}$$

$$\text{Where } \gamma = \frac{C_P}{C_V}$$

For an adiabatic process

$$W = \int_{V_1}^{V_2} P dV$$

Let



$$PV^\gamma = A$$

$$W = \int_{V_1}^{V_2} \frac{A}{V^\gamma} dV$$

$$W = A \int_{V_1}^{V_2} \frac{dV}{V^\gamma}$$

$$W = A \left[ \frac{V^{-\gamma+1}}{-\gamma+1} \right]_{V_1}^{V_2}$$

$$W = \frac{1}{1-\gamma} [AV_2^{-\gamma+1} - AV_1^{-\gamma+1}]$$

But  $A = P_2V_2^\gamma = P_1V_1^\gamma$

$$W = \frac{1}{1-\gamma} [P_2V_2^\gamma V_2^{-\gamma+1} - P_1V_1^\gamma V_1^{-\gamma+1}]$$

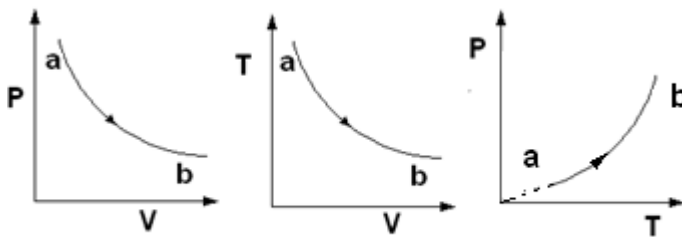
$$W = \frac{1}{1-\gamma} [P_2V_2 - P_1V_1]$$

$$W = \frac{1}{\gamma-1} [P_1V_1 - P_2V_2]$$

From ideal gas equation  $PV = \mu RT$

$$W = \frac{\mu R}{\gamma-1} [T_1 - T_2]$$

The P-V, T-V and P-T diagrams for adiabatic process will be lie the curves given below



**ADIABATIC PROCESS**

### Solved Numerical

Q) Calculate work done if one mole of ideal gas is compressed isothermally at a temperature  $27^\circ\text{C}$  from volume of 5 litres to 1 litre

Solution:

Formula for work done during iso-thermal process is

$$W = 2.303\mu RT \log_{10} \left( \frac{V_2}{V_1} \right)$$

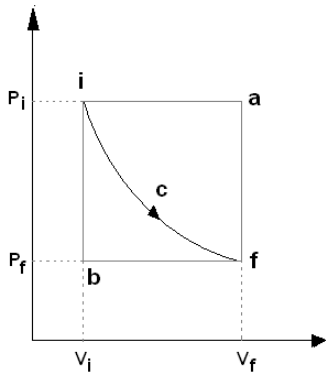
$$W = 2.303 \times 1 \times 8.31 \times 300 \times \log \left( \frac{1}{5} \right)$$

$$W = 2.303 \times 1 \times 8.31 \times 300 \times [\log 1 - \log 5]$$

$$W = 2.303 \times 1 \times 8.31 \times 300 \times [0 - 0.6990]$$

$$W = -4012.5\text{J}$$

### First law of thermodynamics



Suppose a system absorbs heat and as a result work is done by it (by the system). We can think of different paths (process) through which the system can be taken from initial state (i) to final state (f)

For the process iaf, ibf, icf. Suppose the heat absorbed by the system are  $Q_a, Q_b, Q_c$  respectively and the values of the work done are respectively  $W_a, W_b, W_c$ . Here

$Q_a \neq Q_b \neq Q_c$  and  $W_a \neq W_b \neq W_c$ , but difference of heat and work done turns out to be same

$$Q_a - W_a = Q_b - W_b = Q_c - W_c$$

Thus value of  $Q - W$  depends only on initial and final state of the system. A

thermodynamic state function can be defined such that the difference between any two states is equal to  $Q - W$ . Such a function is called internal energy  $U$  of system

The system gains energy  $Q$  in the form of heat energy and spends energy  $W$  to do work.

Hence the internal energy of the system changes by  $Q - W$ .

If the internal energies of system in initial state is  $U_i$  and final state is  $U_f$  then

$$U_i - U_f = \Delta U = Q - W \text{ Which is the first law of thermodynamics}$$

The first law is obeyed in all the changes occurring in nature

#### Isochoric process

Since in this process volume remains constant, the work done in this process is equal to zero. Applying first law of thermodynamics to this process, we get

$$\Delta Q = \Delta U + \Delta W$$

$$\Delta Q = \Delta U$$

So heat exchange in this process takes place at the expense of the internal energy of the system.

$$dQ = dU$$

$$\left(\frac{dQ}{dT}\right)_V = \left(\frac{dU}{dT}\right)_V$$

since  $U = \frac{f}{2}RT$

$$\left(\frac{dQ}{dT}\right)_V = \frac{f}{2}R$$

Thus above equation is for the energy required to increase temperature by one unit of one of ideal gas it is molar specific heat at constant volume  $C_V$

$$\left(\frac{dQ}{dT}\right)_V = \frac{f}{2}R = C_V$$

**Isobaric process**

Applying first law of thermodynamics to isobaric process we get

$$\Delta Q = \Delta U + P(V_2 - V_1)$$

$$\Delta Q = \Delta U + P\Delta V$$

But  $PV = RT$  for one mole of gas

$$\therefore P\Delta V = R\Delta T \text{ thus}$$

$$\therefore \Delta Q = \Delta U + R\Delta T$$

$$\text{since } U = \frac{f}{2}RT$$

$$\therefore \left(\frac{dQ}{dT}\right)_P = \frac{f}{2}R \frac{dT}{dT} + R \frac{dT}{dT}$$

$$\therefore \left(\frac{dQ}{dT}\right)_P = \frac{f}{2}R + R$$

Since  $dQ/dT$  is specific heat at constant pressure =  $C_p$

$$\therefore C_p = C_v + R$$

$$\text{OR } C_p - C_v = R$$

$$\gamma = \frac{C_p}{C_v} = \frac{\frac{f}{2}R + R}{\frac{f}{2}R}$$

$$\gamma = 1 + \frac{2}{f}$$

$f$  is degree of freedom

For monoatomic molecule  $f = 3$

$$C_v = \frac{3R}{2}, \quad C_p = \frac{5R}{2}, \quad \gamma = \frac{5}{3}$$

For the diatomic molecules ( rigid rotator)  $f = 5$

$$C_v = \frac{5R}{2}, \quad C_p = \frac{7R}{2}, \quad \gamma = \frac{7}{5}$$

For the diatomic molecules ( with vibration , molecule like CO)  $f = 7$

$$C_v = \frac{7R}{2}, \quad C_p = \frac{9R}{2}, \quad \gamma = \frac{9}{7}$$

According to the equipartion theorem the change in internal energy is related to the temperature of the system by

$$\Delta U = mC_v\Delta T$$

**Isothermal process**

For isothermal process  $\Delta U = 0$ .

Applying first law of thermodynamics we get

$$\Delta Q = W$$

$$\Delta Q = W = 2.303\mu RT \log_{10} \left( \frac{V_2}{V_1} \right)$$

### Adiabatic process

Applying first law of thermodynamics we get

$$\Delta Q = \Delta U + \Delta W$$

For adiabatic process  $\Delta Q = 0$

$$-\Delta U = \Delta W$$

The reduction in internal energy of the gas ( due to which temperature falls) is equal to the work done during an adiabatic expansion. Again during an adiabatic compression the work done on the gas causes its temperature rise. Adiabatic processes are generally very fast.

Example when we use air pump to fill air in bicycle tyre, pump get heated on pumping rapidly

### Solved Numerical

Q) At 27°C, two moles of an ideal monoatomic gas occupy a volume V. The gas expands adiabatically to a volume 2V. Calculate (a) final temperature of the gas (b) Change in its internal energy (c) Work done by the gas during the process

Take R = 8.31 J/mole/K

Solution:

For monoatomic gas  $\gamma = 5/3$ .

$$T = 27 + 273 = 300$$

(a) Gas expanded adiabatically

$$P_2 V_2^\gamma = P_1 V_1^\gamma$$

Since  $PV \propto T$

$P \propto T/V$

Thus

$$T_2 V_2^{\gamma-1} = T_1 V_1^{\gamma-1}$$

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

$$\therefore T_2 = 300 \left( \frac{1}{2} \right)^{5/3-1} = 189K$$

(b) For adiabatic process  $\Delta Q = 0$

$$-\Delta U = \Delta W$$

$$W = -\Delta U = \frac{\mu R}{\gamma - 1} [T_1 - T_2]$$

$$-\Delta U = \frac{2 \times 8.31}{\frac{5}{3} - 1} [300 - 189] = 2767.23 J$$

$$\Delta U = -2767.23 J$$

(c)  $\Delta W = -\Delta U$   
 $\Delta W = 2767.23 \text{ J}$

**Isothermal and adiabatic curves**

The relation between the pressure and volume of gas can be represented graphically. The curve for an isothermal process is called isothermal curve or an isotherm and there are different isotherms for different temperatures for a given gas. A similar curve for an adiabatic process is called an adiabatic curve or adiabatic

Since

$$\left(\frac{dP}{dV}\right)_{isothermal} = -\frac{P}{V}$$

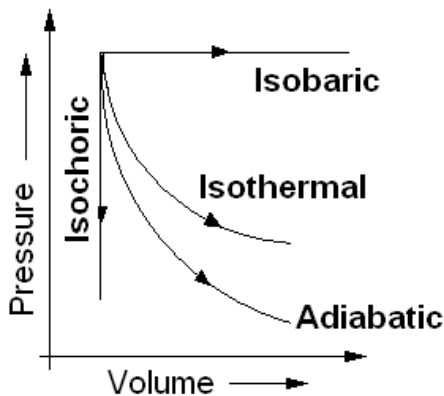
And

$$\left(\frac{dP}{dV}\right)_{adiabatic} = -\gamma \frac{P}{V}$$

So

$$\left(\frac{dP}{dV}\right)_{adiabatic} = \gamma \left(\frac{dP}{dV}\right)_{isothermal}$$

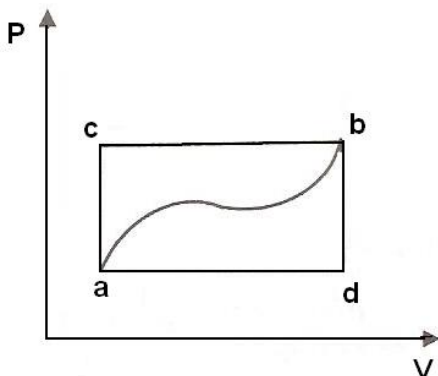
Since  $\gamma > 1$ , so adiabatic curve is steeper than the isothermal curve



To permit comparison between isothermal, adiabatic process, isochoric and isobaric process an isothermal curve, an adiabatic curve, isochoric and isobaric curves of gas are drawn on the same pressure-volume diagram starting from the same point.

**Solved Numerical**

Q) When a system is taken from state a to state b along the path acb it is found that a quantity of heat  $Q = 200\text{J}$  is absorbed by the system and a work  $W = 80\text{J}$  is done by it. Along the path adb,  $Q = 144\text{J}$



- (i) What is the work done along the path adb
- (ii) If the work done on the system along the curved path ba is 52J, does the system absorb or liberate heat and how much
- (iii) If  $U_a = 40\text{J}$ , what is  $U_b$

(iv) If  $U_d = 88\text{J}$ , what is  $Q$  for the path  $db$  and  $ad$ ?

Solution

From the first law of thermodynamics, we have

$$Q = \Delta U + \Delta W$$

$$Q = (U_b - U_a) + W$$

Where  $U_b$  is the internal energy in the state  $b$  and  $U_a$  is the internal energy in the state  $a$

For the path  $acb$ , it is given that

$$Q = 200\text{J (absorption) and}$$

$$Q = 80\text{J (work done by the system)}$$

$$\therefore U_b - U_a = Q - W = 200 - 80 = 120\text{J}$$

Which is the increase in the internal energy of the system for path  $acb$ . Whatever be the path between  $a$  and  $b$  the change in the internal energy will be  $120\text{J}$  only

(i) To determine the work done along the path  $adb$

$$\text{Given } Q = 144\text{J}$$

$$\Delta U = U_b - U_a = 120\text{J}$$

$$Q = (U_b - U_a) + W$$

$$144 = 120 + W$$

$$W = 24\text{J}$$

Since  $W$  is positive, work is done by the system

(ii) For the curved return path  $ba$ , it is given that

$$\text{Given } W = -52\text{J (work done on the system)}$$

$$\Delta U = -120\text{J (negative sign since } \Delta U = U_a - U_b)$$

$$Q = (U_a - U_b) + W$$

$$Q = (-120 - 52)\text{J} = -172\text{J}$$

Negative sign indicates heat is extracted out of the system

(iii) Since  $U_b - U_a = 120\text{J}$  and  $U_a = 40\text{J}$

$$U_b = U_a + 120 = 40 + 120 = 160\text{J}$$

(iv) For path  $db$ , the process is isochoric since it is at constant volume

Work done is zero

$$Q = \Delta U + W$$

$$Q = \Delta U$$

$$Q = U_b - U_d = 160 - 88 = 72\text{J}$$

For the path  $ad$ ,

$$Q = Q_{adb} - Q_{db} = 144\text{J} - 72\text{J} = 72\text{J}$$

Q) A mass of 8 g of oxygen at the pressure of one atmosphere and at temperature  $27^{\circ}\text{C}$  is enclosed in a cylinder fitted with a frictionless piston. The following operations are performed in the order given

- (a) The gas is heated at constant pressure to  $127^{\circ}\text{C}$
  - (b) then it is compressed isothermally to its initial volume and
  - (c) finally it is cooled to its initial temperature at constant volume
  - (i) What is the heat absorbed by the gas during process (A)?
  - (ii) How much work is done by the gas in process A
  - (iii) What is the work done on the gas in process B
  - (iv) How much heat is extracted from the gas in process (c)
- [Specific heat capacity of oxygen  $C_v = 670 \text{ J/KgK}$ ; ]

Solution:

Volume of gas at temperature  $27+273 = 300\text{K} = T_2$

Molecular weight of Oxygen = 32 thus 8g = 0.2 mole

At STP volume of 1 mole is 22.4 litre Thus volume of 0.25 mole is  $V_1 = 22.4/4$

Thus for formula volume at  $27^{\circ}\text{C}$  is

$$\frac{V_2}{T_2} = \frac{V_1}{T_1}$$

$$V_2 = \frac{T_2}{T_1} V_1$$

$$V_2 = \frac{300}{273} \times \frac{22.4}{4} = \frac{560}{91} \times 10^{-3} \text{ m}^3$$

Similarly

Volume at  $127^{\circ}\text{C}$  is

$$V_3 = V_2 \times \frac{400}{300} = \frac{4}{3} V_2$$

$$\frac{V_3}{V_2} = \frac{4}{3}$$

(i)

For Isothermal compression

$$dQ = dU + dW = mC_v \Delta T + P(V_3 - V_2)$$

$$dQ = \frac{8}{1000} \times 670 \times 100 + 1.013 \times 10^5 \times \left[ \frac{560 \times 10^{-3}}{3 \times 91} \right]$$

$$dQ = 536 + 207.8 = 743.8 \text{ J}$$

(ii)  $dW = P(V_3 - V_2) = 207.8 \text{ J}$

(iii) Work done in compressing the gas isothermally =

$$W = 2.303 \mu RT \log_{10} \left( \frac{V_3}{V_2} \right)$$

$$W = 2.303 \times \frac{m}{M} RT \log_{10} \left( \frac{V_3}{V_2} \right)$$

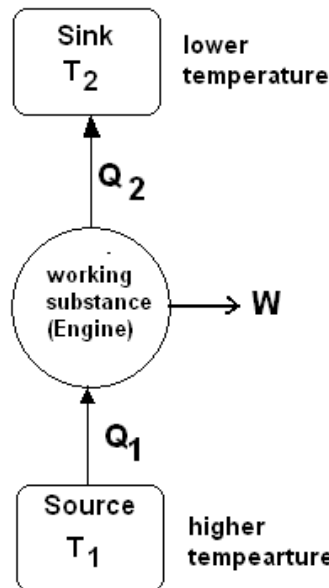
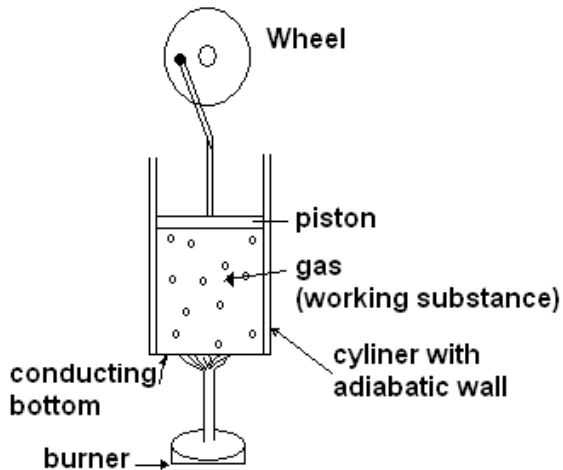
$$W = 2.303 \times \frac{8}{32} \times 8.31 \times 400 \times \log_{10} \left( \frac{4}{3} \right)$$

$$W = 831 \times 0.2877 = 239.1 J$$

(d) Heat given out by the gas in stage (C) =  $mC_v\Delta T$

$$\frac{8}{1000} \times 670 \times 100 = 536 J$$

### Heat Engine



A device converting heat energy into called heat engines.

A simple heat engine is shown in figure. The gas enclosed in a cylinder with a piston receives heat from the flame of a burner. On absorbing heat energy the gas expands and pushes the piston upwards. So the wheel starts rotating. To continue the rotations of the wheel an arrangement is done in the heat engine so that the piston can move up and down periodically. For this, when piston moves more in upward direction, then hot gas is released from the hole provided on upper side

Here gas is called working substance. The flame of the burner is called heat source and the arrangement in which gas is released is called heat sink.

Following figure shows working of the heat engines by line diagram

In the heat engine, the working substance undergoes a cyclic process. For this the working substance absorbs heat  $Q_1$ , from the heat source at higher temperature  $T_1$ , out of which a



part of energy is converted to mechanical energy (work  $W$ ) and remaining heat  $Q_2$  is released into the heat sink.

Hence, the net amount of heat absorbed by the working substance is

$$Q = Q_1 - Q_2$$

But for a cyclic process, the net heat absorbed by the system is equal to the net work done

$$\therefore Q = W$$

$$Q_1 - Q_2 = W$$

In the cyclic process, the ratio of the network ( $W$ ) obtained during one cycle is called the efficiency ( $\eta$ ) of the heat engine. That is

$$\eta = \frac{\text{Net work obtained per cycle}}{\text{Heat absorbed per cycle}}$$

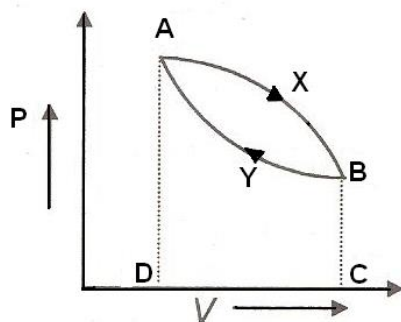
$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta = 1 - \frac{Q_2}{Q_1} \quad \text{--- eq(1)}$$

From equation(1) it can be said that if  $Q_2 = 0$ , then the efficiency of the heat engine is  $\eta = 1$ . This means that the efficiency of heat engine becomes 100% and total heat supplied to the working substance gets completely converted into work.

In practice, for any engine  $Q_2 \neq 0$  means that some heat  $Q_2$  is always wasted hence  $\eta < 1$

### Cyclic process and efficiency calculation



When a system after passing through various intermediate steps returns to its original state, then it is called a cyclic process.

Suppose a gas enclosed in cylinder is expanded from initial stage A to final stage B along path AXB as shown in figure. If  $W_1$  be the work done by the system during expansion, then

$$W_1 = + \text{Area AXBCDA}$$

Now let the gas be compressed from state B to state A along the path BYA, so as to return the system to the initial state. If  $W_2$  be the work done on the system during compression, then  $W_2 = -\text{Area BYADCB}$

According to sign convention, work done on the system during compression is negative and the net work done in the cyclic process AXBYA is

$$W = \text{Area AXBCDA} - \text{Area BRADCB} = \text{Area AXBYA}$$

Which is a positive quantity and hence net work will be done by the system

So the net amount of work done during a cyclic process is equal to the area enclosed by the cyclic path. It is evident from the figure that if the cyclic path is being traced in anticlockwise direction, the expansion curve will be below the compression curve and net

work done during the process will be negative. This implies that the net work will now be done on the system. Applying first law of thermodynamics to cyclic process, we get

$$\Delta Q = \Delta U + \Delta W$$

But  $\Delta U = 0$  for cyclic process

$$\text{So } \Delta Q = \Delta W$$

### Solved Numerical

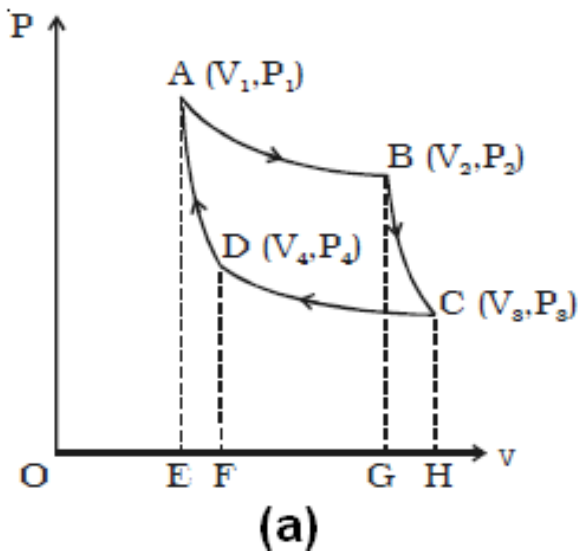
Q) An ideal monoatomic gas is taken round the cycle ABCD where co-ordinates of ABCD in P-V diagram are A(p, V), B(2p, V), C(2p, 2V) and D(p, 2V). Calculate work done during the cycle

Solution Area enclosed = pV

### Carnot Cycle and Carnot Engine

Carnot engine consists of a cylinder whose sides are perfect insulators of heat except the bottom and a piston sliding without friction. The working substance in the engine is  $\mu$  mole of a gas at low enough pressure (behaving as an ideal gas). During each cycle of the engine, the working substance absorbs energy as heat from a heat source at constant temperature  $T_1$  and releases energy as heat to a heat sink at a constant lower temperature  $T_2 < T_1$ .

The cyclic process, shown by P-V graph in figure a, is completed in four stages.



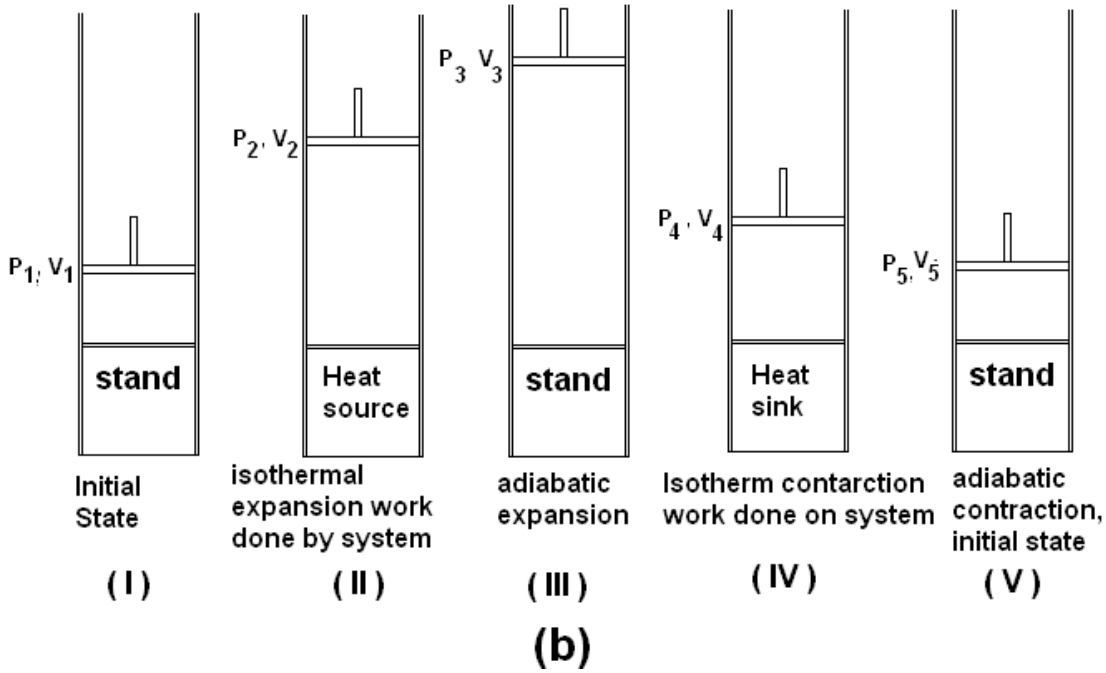
The Carnot engine and its different stages are shown in figure b

(I) First stage Isothermal expansion of gas from (a  $\rightarrow$  b)

Initial equilibrium state ( $P_1, V_1, T_1$ ) final equilibrium state ( $P_2, V_2, T_1$ ) Suppose gas absorbs heat  $Q_1$  during the process. Hence work done is

$$W_1 = Q_1 = \mu RT_1 \ln\left(\frac{V_2}{V_1}\right) \quad \text{--- eq(1)}$$

$$\text{Further } P_1V_1 = P_2V_2 \quad \text{---- eq(2)}$$



(II) Second stage Adiabatic expansion of gas ( b → c )

Now , the cylinder is placed on a thermally insulated stand and the gas is adiabatically expanded to attain the state c ( P<sub>3</sub>, V<sub>3</sub>, T<sub>2</sub>).

During this ( adiabatic process the gas does not absorb any heat but does work while expanding, so its temperature decreases. For this process

$$P_2 V_2^\gamma = P_3 V_3^\gamma \quad \text{--- eq(3)}$$

(III) Third Stage: Isothermal compression of gas ( c → d )

Now, the cylinder is brought in contact with heat sink at temperature T<sub>2</sub> and isothermally compressed slowly to attain an equilibrium state d ( P<sub>4</sub>, V<sub>4</sub>, T<sub>2</sub> ). Work done on the gas during this process of isothermal compression is negative as work is done on the gas from state c → d is

$$W_2 = Q_2 = -\mu RT_2 \ln \left( \frac{V_4}{V_3} \right)$$

$$W_2 = Q_2 = \mu RT_2 \ln \left( \frac{V_3}{V_4} \right) \quad \text{--- eq(4)}$$

Here Q<sub>2</sub> is released by the gas into heat sink

Further for isothermal process

$$P_3 V_3 = P_4 V_4 \quad \text{---- eq(5)}$$

(IV) Fourth Stage: Adiabatic compression of gas ( d → a )

Now, the cylinder is placed on a thermally insulated stand and compressed adiabatically to its original state a ( P<sub>1</sub> V<sub>1</sub> T<sub>1</sub> ). This process is adiabatic, therefore, there's no exchange of heat with surrounding, but the work is done on the gas and hence temperature increases from T<sub>2</sub> to T<sub>1</sub>

For this adiabatic process

$$P_4 V_4^\gamma = P_1 V_1^\gamma \quad \text{--- eq(6)}$$

Note that over the whole cycle, the heat absorbed by the gas is  $Q_1$  and the heat given out by the gas is  $Q_2$ . Hence the efficiency  $\eta$  of the Carnot engine is

$$\eta = 1 - \frac{Q_2}{Q_1}$$

From equation (1) and (4)

$$\eta = 1 - \frac{T_2 \ln\left(\frac{V_3}{V_4}\right)}{T_1 \ln\left(\frac{V_1}{V_2}\right)} \quad \text{--- eq(7)}$$

Multiplying equation (2), (3), (5) and 6 we get

$$P_1 V_1 P_2 V_2^\gamma P_3 V_3 P_4 V_4^\gamma = P_2 V_2 P_3 V_3^\gamma P_4 V_4 P_1 V_1^\gamma$$

$$\therefore (V_2 V_4)^{\gamma-1} = (V_3 V_1)^{\gamma-1}$$

$$\therefore V_2 V_4 = V_3 V_1$$

$$\frac{V_2}{V_1} = \frac{V_3}{V_4}$$

$$\therefore \ln\left(\frac{V_2}{V_1}\right) = \ln\left(\frac{V_3}{V_4}\right)$$

Using this result in equation (7) We get efficiency of Carnot engine as

$$\eta = 1 - \frac{T_2}{T_1} \quad \text{--- eq(8)}$$

Or

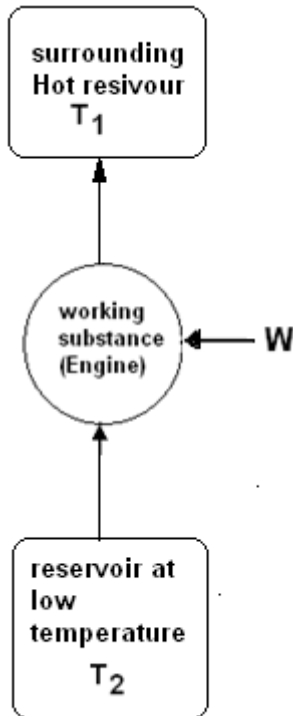
$$\eta = 1 - \frac{\text{low temp of sink}}{\text{high temperature of source}}$$

Equation (8) shows that the efficiency of the Carnot engine depends only on the temperature of the source and the sink. Its efficiency does not depend on the working substance (if it is ideal gas).

If the temperature of the source ( $T_1$ ) is infinite or the temperature of the sink ( $T_2$ ) is absolute zero (which is not possible) then only, the efficiency of Carnot engine will be 100%, which is impossible.

### Refrigerator / Heat pump and Coefficient of Performance

If the cyclic process performed on the working substance in heat engine is reversed, then the system works as a refrigerator or heat pump. Figure below shows the block diagram of refrigerator/ heat pump



In the refrigerator, the working substance absorbs heat  $Q_2$  from the cold reservoir at lower temperature  $T_2$ , external work  $W$ , is performed on the working substance and the working substance releases heat  $Q_1$  into the hot reservoir at higher temperature  $T_1$ . The ratio of the heat  $Q_1$  absorbed by the working substance to the work  $W$  performed on it, is called the coefficient of performance ( $\alpha$ ) of the refrigerator. That is

$$\alpha = \frac{Q_2}{W}$$

Here heat is released in surrounding

$$Q_1 = W + Q_2$$

$$Q_1 = W + Q_2$$

$$W = Q_1 - Q_2$$

$$\alpha = \frac{Q_2}{Q_1 - Q_2}$$

Here the value of  $\alpha$  can be more than 1 ( $\because Q_2 > Q_1 - Q_2$ ), but it can not be infinite