4 Thermodynamics

4.1 Introduction

Note :

1. **Thermodynamics:**
    Thermodynamics is the branch of science that deals with the concepts of heat and temperature and the inter-conversion of heat and other forms of energy.

2. **Thermodynamic System:**
    An assembly of a very large number of particles having a certain value of pressure, volume and temperature is called its thermodynamic system.

3. **Surroundings:**
    Everything outside the system which can have a direct effect on the system is called as surroundings.

4. **Thermodynamic variables:**
    The quantities like pressure (P), volume (V), and temperature (T)   which help us to study the behaviour of a thermodynamic system are called thermodynamic variables.

5. **Equation of state:**
    The mathematical relation between the pressure, volume and temperature of a thermodynamic system is called its equation of state. For example, the equation of state for n moles of an ideal gas can be written as $PV = nRT$.

4.2 Thermal Equilibrium

Q.1   When do two systems are said to be in thermal equilibrium?

Ans:

i.   Two systems in thermal contact with each other are said to be in thermal equilibrium if they do not trnsfer heat between each other.

ii. When two objects are at the same temperatre, they are in thermal equilibrium.

4.3 Zeroth law of thermodynamics

Q.2   State and explain zeroth law of thermodynamics. Give its physical significance.

Ans: Statement : *If two systems are each in thermal equilibrium with a third system, they are also in thermal equilibrium with each other.*
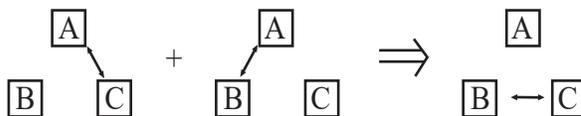
i.   In figure the double arrow represents thermal equilibrium between systems.

ii. If system A and C are in thermal equilibrium, and systems A and B in thermal equilibrium, then systems B and C must be in thermal equilibrium.

iv. Then it can be concluded that system A, B and C are at the same temperature.

Physical Significance:

i. The zeroth law enables us to use a thermometer to compare the temperatures of different objects.

ii. When we use a thermometer, the thermometer and the object are in thermal equilibrium and the thermometer indicates the temperature of the object.

iii. Temperature is defined on the basis of zeroth law of thermodynamics.

4.4 Heat, Internal energy and work

Q.3 **Define thermodynamic system. Give classification of thermodynamic system.**

Ans:

i. *A thermodynamic system is a collection or a group of objects that can form a unit which may have ability to exchange energy with its surroundings.*

ii. Thermodynamic systems can be classified on the basis of the possible transfer of heat and matter to environment. Based on this, they are classified as :
1. Open System
2. Closed System
3. Isolated System

1. Open system:
   a. An open system is a system that freely allows exchange of energy and matter with its environment.
   b. For example : water boiling in a kettle is an open system. Heat escapes into the air. This is the exchange of energy with the surroundings. At the same timesteam also escapes into the air. This is exchanges of matter with the surroundings.
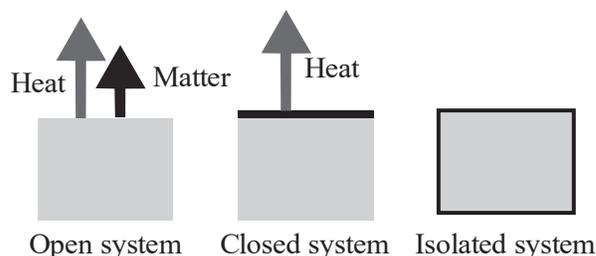
2. Closed system:
   a. A closed system, on the other hand, does not allow the exchange of matter but allows energy to be transferred.
   b. For example : water boiling in a boiler is a closed system. It

allows heat (energy) to be transfered from the source of heat (a burner) to the water (system) inside.

Similarly, heat is also transferred to the surroundings.Steam (matter) is not allowed to escape as long as the valve is kept closed.

3. Isolated system :
   a. An isolated system is completely sealed (isolated from its environment). Matter as well as heat cannot be exchanged with its environment.
   b. A thermos flask is a very familiar example of an isolated system.

Thermodynamic system; open system, closed system, and isolated system.

Q.4 **Explain thermodynamics process with example.**

Ans:

i. *A thermodynamic process is a process in which the thermodynamic state of a system is changed.*

ii. **For example :** Water contained in a vessel with a lid on it is a closed system. When the pot is heated externally, water starts boiling after sometime and steam is produced which exerts pressure on the walls of the vessel. In this case, the state of the water in the container is changed. This is because, the temperature(T), the volume (V), and the pressure (P) of the water inside the vessel change when it starts boiling.

iii. Thus, we can describe the state of a sytem by using temprature, pressure and volume as its variables.

Q.5 **(A) Explain the concept of heat**

Ans:

i.   **Heat:** Heat is a form of energy which produces in us the sensation of hotness or coldness.

ii.   For example, if we touch a piece of ice, heat flows from our body towards ice and we feel cold. Similarly, when we stand near a fire, heat from the fire flows towards our body and we feel hot.

Q.5   (B) Define heat ?

Ans :

i.   Heat is the form of energy that is transfered between the system and its enviroment due to temperature difference that exists between the two

ii.   symbol : Q

iii.   SI unit : Joule (J)
       c us unit : erg.

Note :

Whenever a given amount of work (W) is converted into into heat, always the same amount of heat (Q) is produced, thus.

$W \propto Q$ or $W = JQ$

or $J = \dfrac{W}{Q}$

If $Q = 1$, than $J = W$

The proportionality constant J is called Joule's mechanical equivalent of heat. If may be defined as the amount of work that must be done to produce a unit quantity of heat.
$J = 4.186 \, J \, cal^{-1} = 4.186 \times 10^7 \, erg \, cal^{-1}$

Q.6   Define Internal energy

Ans: Internal energy of a system is defined as the sum of the kinetic energies of the atoms and molecules belonging to the system, and the potential energies associated with the interactions between these constituents (atoms and molecules).
Symbol : U

Note :

i.   The internal energy of a system is the sum of molecular kinetic and potential energies in the frame of refrence relative to which the centre of mass of the system is at rest.

ii.   The molecules of a real gas exert mutual force of attraction on one another. Hence they possess inter molecular potential energy. If the volume of the gas increases, work is done by the gas against intermolecular attraction and so its potential energy increases. Thus intermolecular potential energy of a real gas is a function of its volume.

iii.   The molecules of a gas are always in a state of random motion. The motion may be translational, rotational and vibrational. Hence the molecules posses kinetic energy. As the temperature increases, the average kinetic energy of the gas molecules also increases. Thus the internal kinetic energy of a gas is a function of its temperature.

iv.   The internal energy does not include the over-all kinetic energy of the system as a whole. It includes only the (disordered) energy associated with the random motion of the molecules of the system. We donate it by u.

v.   Internal energy of a system is a thermodynamic state variable. That is its value depends only on the state of existence of the system and not on the path along which that state has been brought about. Thus the internal energy of a given mass of a gas depends only on its state described by the specific values of pressure, volume and temperature.

vi.   Internal energy of an ideal gas is purely kinetic in nature. In an ideal gas, there are no molecular forces of attraction. So the gas does not possess intermolecular potential energy. Its internal energy is just the sum of kinetic energies associated with various random (translation, rotational and vibration) motions of its molecules. Thus the internal energy of an ideal gas is wholly kinetic in nature and depends only on its temperature.

**Q.7   Explain the relation between heat and internal energy.**

Ans:

i.   Consider a glass filled with water on a table, The glass, along with the water in it forms a system.

ii. Let the temperature of this system be T_S. The table on which the glass is kept and the other relevant parts of the room will then be its surrounding or the environment.

iii. Let the temperature of the environment be T_E.

iv. We notice that if T_S and T_E are not the same, the T_S will change until both the temperatures are equal and a thermal equilibrium will be reached between the 'system' and the 'environment' reach thermal equilibrium.

v. If the environment is very large, the change in T_E may not be measurable, but certainly not zero.

vi. Such a change in temprature is caused by the transfer of internal energy between the system and its environment. In this case, the transfer of energy is between the glass of water and its surrounding.

Let T_S and T_E be the temperatures of the system and its environment respectively.

Let Q be the energy transferred between the system and its environment.

Case I: If $T_S < T_E$, the system gains energy, and Q is positive.

Environment (T_E)

System(T_S)   Q > 0
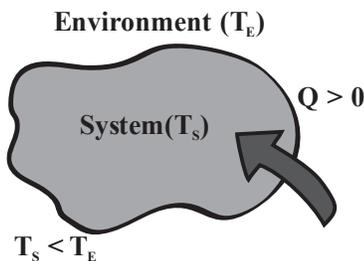
$T_S < T_E$

Case II: If $T_S > T_E$ the system loses energy, and Q is negative.

Environment (T_E)

System(T_S)   Q > 0
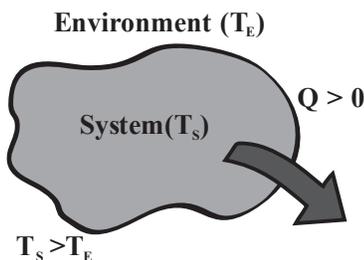
$T_S > T_E$

Case III: If $T_S = T_E$, the system and the environment are in thermal equilibrium and there is no transfer of energy (Q=0).

**Environment (T_E)**

Q = 0

System(T_S)

$T_S = T_E$
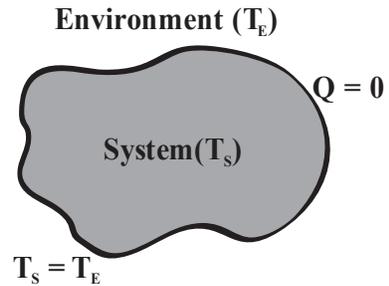
Q.8 **Explain the process to change the internal energy of the system.**

Ans:

i. Consider the experiment of a cylinder filled with some gas in it. This cylinder is provided with a movable, massles, and frictionless piston at one end.

ii. The gas inside the cylinder is our system and the rest is its environment. Let the temperature of the gas be T_S and that of the environment be T_E.

iii. Internal energy of the system (the gas) can be changed in two different ways or by both.

Case I : By Heating

a. The cylinder can be brought in contact with a source of heat such as a burner

b. The temperature difference between the source of heat (environment) and the system will cause a flow of energy (heat) towards the gas in the cylinder. This is because $T_E > T_S$.

c. Thus, there will be an increase in the internal energy of the gas.

d. If the surrounding is at temperature lower than the gas, $T_S > T_E$, the gas will lose energy to its environment and cool down.

T = 200C

Heat supplied to gas (Q)

T = 100C

Initial state

Burner
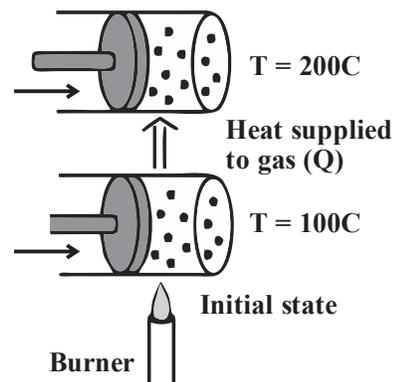
Case II : By doing work

a. The other way to increase the internal energy of the gas is to quickly push the piston inside the cylinder, so that the gas is compressed.

b. In this case, we know that the piston does some work on the gas in moving it through some distance.

c. The gas gains energy and itstemperature is increased.

d. On the other hand, if the gas pushes the piston out, so that the gas is expanded, some work is done by the gas.

e. It loses some of its energy and the gas cools down.

Initial state
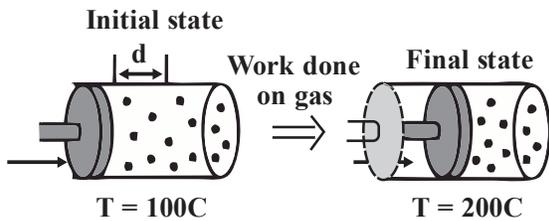
Thus, we see that the internal energy of a system can be changed in two different ways 1) by heating it or 2) by doing work on it.

INTEXT QUESTION

Calculate the internal energy of argon and oxygen.

Solution:

i. **Internal energy of Argon :**
Internal energy of a gas depends only on its temperature.
Argon is a monatomic gas.
Its internal energy is purely translational.

Thus, it is given by $\frac{3}{2} k_B T$.

ii. **Internal energy of oxygen :**
Oxygen is a diatomic gas hence its internal energy consits of translational as well as rotational kinetic energies. Thus, each mode

contributes energy equal to $\frac{1}{2} k_B T$.

The internal energy for oxygen molecule

$= 3 \times \frac{1}{2} k_B T + 2 \times \frac{1}{2} k_B T = \frac{5}{2} k_B T.$

Q.9 **Explain the concept of positive and negative work done**

Ans:

i. Consider an ideal gas enclosed in a cylinder with a movable, massless, and frictionless piston.

ii. In this case, the gas inside the cylinder is considered as the system and the cylinder along with the piston is cosidered to be the environment.

Case I : Positive work done

Assume that, the gas is expanding. During expansion, the gas molecules which strike the piston transfer their momentum to it and exert pressure on it. As a result, the piston moves through a finite distance.
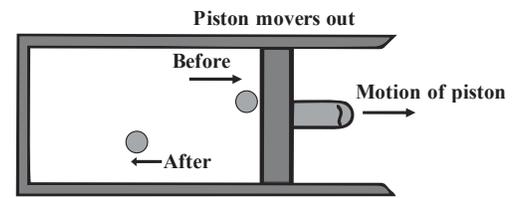
Case II: Negative work done

When the piston is pushed in so that the volume of the gas decreases, the gas molecules striking the piston gain momentum from the piston. As a result , a negative work is done by the gas on the piston during compression.

Note :

Sign conventions used :

i. *Heat absorbed by a system is positive. Heat given out by a system is negative.*

ii. *Work done by system is positive. Work done on a system is negative.*

iii. *The increase in internal energy of a system is positive. The decrease in internal energy of a system is negative.*

Q.10 **Obtain an expression for work done by gas.**

Ans:

i. Consider a system enclosed in a cylinder with a movable, massless, and frictionless piston

so that its volume can change.

ii. Let the cross sectional area of the cylinder (and the piston) be A, and the constant pressure exerted by the system on the piston be p.

System

dx

A

F = pA
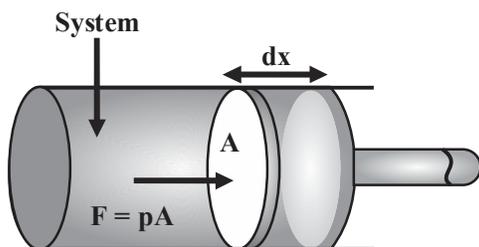
Force that system exerts on piston

iii. The total force exerted by the system on the piston will be F = pA.

iv. If the piston moves through an infinitesimal (very small) distance dx, the work done by this force is,

dw = Fdx

dw = p (A dx)

v. But the infinitesimal change in the volume of the cylinder is dV = Adx. Hence, the work done by the system in bringing out this infinitesimal change in the volume can be written as,

dw = pdV ....(1)

vi. If the initial volume of the cylinder is V_i and its volume after some finite change V_f, then the total work done in changing the volume of the cylinder is,

$$W = \int_{V_i}^{V_f} pdV = p(V_f - V_i)$$ ....(2)

vii. As, the internal energy of a system can be changed by doing some work on it (or extracting work from it), equation (2) gives the amount of work done in changing the volume of a system.

Q.11 **State the first law of thermodynamics.**

Ans: **First law of thermodynamics:** The change in the internal energy of a system (ΔU) is the difference between the heat supplied to the system (Q) and the work done by the system on its surroundings (W).

Mathematically, $\Delta U = Q - W$

which is the same as $Q = \Delta U + W$.

★**Q.12** **A resistor held in running water carries electric current. Treat the resistor as the system.**

i. **Does heat flow into the resistor?**

ii. **Is there a flow of heat into the water?**

iii. **Is any work done?**

iv. **Assuming the state of resistance to remain unchanged, apply the first law of thermodynamics to this process.**

Ans: Assuming water to be at lower temperature than that of resistor:

i. No heat flows into the resistor.

ii. According to Joule's law heating effect of resistor causes heat to flow from resistor to water.

iii. As volume of water is constant, no work is done.

iv. According to first law of thermodynamics, as no work is done

∴ Q is – ve and W = 0

$\Delta U = Q - W$

∴ $\Delta U = - Q$

Type - I
Numerical based on work done and first law of Thermodynamics

Formula used:

1. $W = P \Delta V$

$W = P(V_f - V_i)$

2. $Q = \Delta U + W$

★**1)** **A gas enclosed in a cylinder is expanded to double its initial volume ($V_i = 0.5$ units) at a constant pressure of one atmosphere. How much work is done in this process? Is this work done on the gas or by the gas? How do you know this?**

Data: $p = 1$ atm $= 1.01 \times 10^5$

$\Delta V = (V_f - V_i) = (2V_i - V_i) = 0.5$ units

To find: W

Formula: $W = P\Delta V = P(V_f - V_i)$

Solution:

$W = P\Delta V = P(V_f - V_i)$

$W = 1.01 \times 10^5 \times 0.5 = 0.505 \times 10^5$

$= 5.05 \times 10^4 J$

Positive sign of the work done implies

that the work is done by the gas.

Ans : Work done in the process is 5.05×10^4 J. The positive work done implies that the work is done by the gas.

★ **2)** **104 kJ of work is done on certain volume of a gas. If the gas releases 125 kJ of heat, calculate the change in internal energy (in kJ) of the gas.**

Data: W = – 104 kJ, Q = – 125 kJ

To find: ΔU

Formula: $\Delta U = |Q| - |W|$

Solution:

$$\Delta U = |Q| - |W|$$

$\therefore$ $\Delta U = (125 - 104) = 21$ kJ

Ans : Change in internal energy 21 kJ.

★ **3)** **A gas contained in a cylinder fitted with a frictionless piston expands agianst a constant external pressure of 1 atm from a volume of 5 litres to a volume of 10 litres. In doing so it absorbs 400 J of thermal energy from its surroundings. Determine the change in internal energy of system.**

Data: p = 1atm = 1.013×10^5 pa, Q = 400 J,
V$_i$ = 5 L = 5×10^{-3} m^3,
V$_f$ = 10 L = 10×10^{-3} m^3

To find: ΔU

Formulae: i. $W = p\Delta V = p(V_f - V_i)$

ii. $\Delta U = |Q| - |W|$

Solution:

i. $W = p\Delta V = p(V_f - V_i)$
$W = 1.013 \times 10^5 (10 \times 10^{-3} - 5 \times 10^{-3})$
$= 1.013 \times 10^5 \times 5 \times 10^{-3}$
$= 5.065 \times 10^2 = 506.5$ J

ii. $\Delta U = |Q| - |W|$

$\Delta U = |400| - |506.5| = -106.5$ J

Ans : The change in the internal energy of the system is -106.5 J.

★ **4)** **1.0 kg of liquid water is boiled at 100°C and all of it is converted to steam. If the change of state takes place at the atmospheric pressure (1.01×10^5Pa), calculate**

i. **the energy transferred to the system,**
ii. **the work done by the system during this change, and**
iii. **the change in the internal energy of the system. Given, the volume of water changes from 1.0×10^{-3} m^3 in liquid form to 1.671 m^3 when in the form of steam. Can you explain how the work done by the sytem is utilized?**

Data: m = 1.0 kg,
p = 1.01×105 Pa, T = 100°C = 373 K,
V$_{steam}$ = 1.671 m^3, V$_{liq}$ = 1.0×10^{-3} m^3
$\therefore$ L$_{vap}$ = 2256 kJ/kg

To find: i. Q   ii. W   iii. ΔU

Formulae: i. Q = mL   ii. W = pΔV
iii. $\Delta U = Q - W$

Solution:

i. $dV = (V_{steam} - V_{liq}) = (1.671 - 0.001)$
$= 1.670$ m^3

ii. Q = mL = $1.0 \times 2256 = 2256$ kJ

iii. W = pΔV
W = $(1.01 \times 10^5) \times 1.670$
$= 1.687 \times 10^5$ J = 168.7 kJ
$\Delta U = |Q| - |W|$
$\Delta U = 2256 - 168.7 = 2087.3$ kJ
The work done by the water is utilised in increasing the volume occupied by steam as well as in increasing the temperature of the surrounding.

★

Problem for Practice

1. A gas is compressed by an external pressure of 5 atm. The work done in the process is 1034 J. How much volume of the gas is reduced?

Ans: 2.04 lit

2. A system releases 100 KJ of heat while 80KJ of work is done on the system. Calculate the change in internal energy?

Ans: –20KJ

3. A gas contained in a cylinder fitted with a frictionless piston expands aginst a constant pressure of 1 atm from a volume of 2 lit to a volume of 6 lit. In doing so it absorbs 800 J thermal energy from surrounding. Determine the increase in internal energy of the process.

Ans: +394.8J

4.6 Thermodynamics State Variables

Q.13 **What is property of a system or state variable of a system. Also give macroscopic variable of system.**

Ans:

i.   The property of a system or a system variable is any measurable or observable characteristic or property of the system when the system remains in equilibrium.

ii. Pressure, volume, temperature, density, mass, specific volume, amount of substance (expressed in mole) are macroscopic variables of a system.

Q.14 **Explain the terms intensive and extensive variables.**

Ans:

i.   Intensive variables do not depend on the size of the system.

ii. Extensive variables depend on the size of the system.

iii. Consider a system in equilibrium. Let this system be divided into two equal compartments, each with half the original volume.

iv. The pressure p, temperature T, and density ρ are the same as initial in both compartments. These are intensive variables.

v.   The total mass M, and internal energy U of the system however get equally divided in the two compartments. Thus, each compartment now has mass M/2 and internal energy U/2. Hence, these are extensive variables of the system.

Q.15 **What are the conditions for system to be in:**
   i.   Mechanical equilibrium
   ii. Chemical equilibrium
   iii. Thermal equilibrium

Ans:

i.   **Mechanical equilibrium:**
   a.   For a system to be in mechanical equilibrium, there should not be any unbalanced forces acting within the system and between the system and its surrounding.
   b.   Also, The pressure in the system should be same throughout the system and should not change with time.

ii. **Chemical equilibrium:**
   a.   For a system to be in chemical equilibrium there should be no chemical reactions going on within the system.
   b.   There is no transfer of matter from one part of the system to the other due to diffusion.
   c.   A system to be in chemical equilibrium its chemical composition has to be same throughout and should not change with time.

iii. **Thermal equilibrium:**
   a.   For a system to be in thermal equilibrium, the temperature of the system should be uniform throughout and it should not change with time.
   b.   A system when in thermal equilibrium is described in terms of state variables.

Note:

Indicator Diagram

i.   *The state of a thermodynamic system can be completely described if only two thermodynamical variables are known because the third variable gets automatically fixed by the equaion of the state of the system.*

ii. *A graphical representation of the state of system with the help of two thermodynamical variables is called an indicator diagram.*

iii. *A graph drawn between the pressure and volume of a gas under thermodynamic operation is called p-V diagram.*

iv. *Such diagrams are drawn witht the help of a device called indicator which records the changes in volume and pressure accompanying the movement of the piston in*

the cylinder.

A(V₁,p₁) p₁, Expansion, p, p₂, B(V₂,p₂), V₁, V, V₂

A(V₁,p₁) p₁, Compression, p, p₂, B(V₂,p₂), V₁, V, V₂
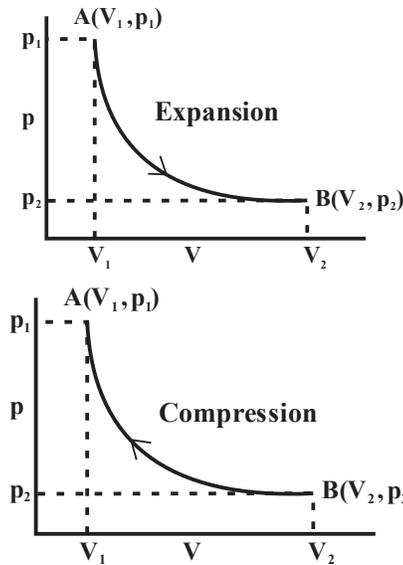
v. **Importance of p-V diagram.**

The area under the p-V diagram is numerically equal to the work done by a system or on the system.

Q.16 What is a p-V diagram?

Ans : The graphical representation of equation of state of a system (of a gas) is called the p-V diagram, or the p – V curve (the pressure – volume curve), or the indicator diagram of the system.

★ **Q.17 Draw a p-V diagram and explain the concept of positive and negative work. Give one example each.**

Ans:

i. A gas confined to a cylinder with a movable, frictionless, and massles piston can be expanded with varying pressure or it can be compressed with varying pressure. It can also expand at constant pressure.

ii. let us consider expansion of the gas at constant temperature. Its volume increases due to outward displacement of the piston and the pressure of the gas decreases. The work done by the gas in this case is given by,
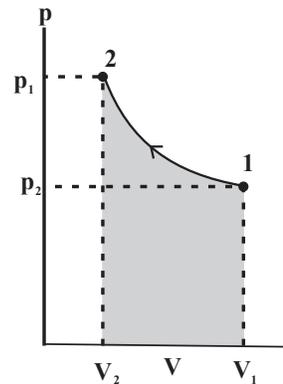
$$W = \int_{V_i}^{V_f} dW = \int_{V_i}^{V_f} pdV$$

As dV > 0, the work done is positive.

Work = Area under curve (shaded)

$$= \int_{V_i}^{V_f} pdV > 0$$

p, p₁, 1, p₂, 2, V₁, V, V₂
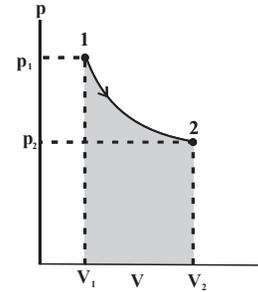
iii. Let us consider compression due to inward displacement of the piston. The pressure of the gas is increased and the work done by the gas is now negative as volume is decreased.


p, p₁, 2, p₂, 1, V₂, V, V₁

iv. For example:

a. When water is boiled and does work on the surrounding is the example of positive work done.

b. When spring is compressed work is done on spring is the example of negative work done.

Q.18 Verify that the area under the p-V curve has dimensions of work.

Ans:

i. Consider graphical representation of work done by a gas in expanding at constant pressure.

P, A, B, P, D, C, 0, V₁, V₂, V
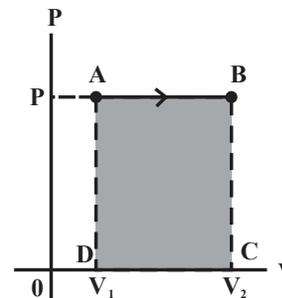
ii.   Area under the p-V curve is,

Area of □ ABCD = $(V_2 - V_1) \times (p_1 - 0)$

∴   [Area] = [Volume] × [Pressure]

$$= [\text{Volume}] \times \frac{[\text{force}]}{[\text{Area}]}$$

$$= [L^3] \times \frac{[M^1L^1T^{-2}]}{[M^0L^2T^0]}$$

$$= [M^1L^2T^{-2}]$$

iii.   Now, dimensions of work done are,

[Work] = [Force] × [displacement]

$$= [M^1L^2T^{-2}] \times [L^1]$$

$$= [M^1L^2T^{-2}]$$

iv.   Thus, it can be concluded that, the area under the p-V curve has the dimensions of work.

Type - II
Problem based on Indicator diagram

Formula used

1.   Work done during the expansion or compression of a gas is equal to the area enclosed between the p-V curve and the volume axis.

2.   Work done per cycle = Area of the loop representing the cycle.

3.   If the loop is traced clockwise, the work done is positive and work is done by the system.

4.   If the loop is traced anticlockwise, the work done is negative and work is done on the system.

★ 1)   **The system is taken to its final state from initial state in hypothetical paths as shown in figure calculate the work done in each case.**

P(10⁵Pa) diagram
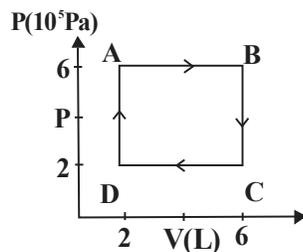
Solution:

i.   **Work done along path AB**

$|W_{AB}|$ = Area under curve AB

$$= (6 - 0) \times 10^5 \times (6 - 2) \times 10^{-3}$$

....(As $1L = 10^{-3}$ m³)

$$= 6 \times 10^5 \times (4 \times 10^{-3})$$

$$= 24 \times 10^3 \text{ J}$$

ii.   **Work done along path BC and DA**

The volume remains constant during the paths BC and DA.

∴ $W_{BC} = W_{DA} = 0$

iii. **Work done along path CD**

$|W_{CD}|$ = Area under curve CD

$$= (2 - 0) \times 10^5 \times (2 \times 10^{-3} - 6 \times 10^{-3})$$

$$= 2 \times 10^5 \times (-4 \times 10^{-3}) = -8 \times 10^2 \text{ J}$$

Ans : i.   Work done along path AB is 2.4×10^3 J

ii. Work done along path BC and DA is zero.

iii. Work done along path CD is -8×10^2 J.

★ 2)   **A hypothetical thermodynamic cycle is shown in the figure. Calculate the work done in 25 cycles.**
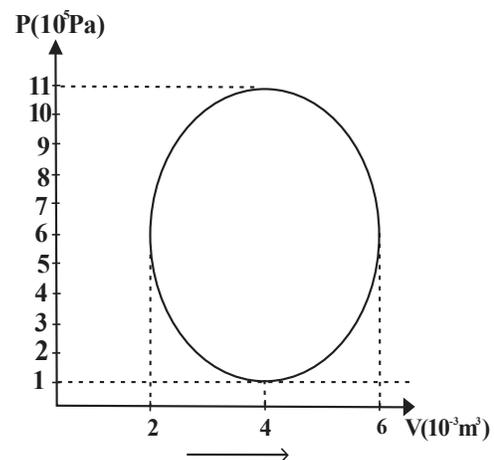
Solution:

i.   Work done by a gas in one cycle is given by the area under the p-V curve.
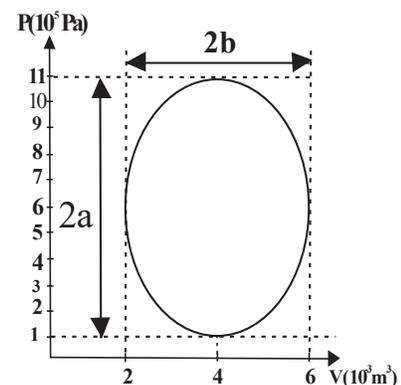
ii.   As figure represents an ellipse,

a = Length of semi major axis

$$\therefore \quad a = \frac{(11-1)\times 10^5}{2} = 5\times 10^5 \, \text{Pa}$$

b = length of semi minor axis

$$= \frac{(6-2)\times 10^{-3}}{2} = 2\times 10^{-3}\, \text{m}^3$$

iii. Area enclosed by curve = Area of ellipse

= π ab

$= 3.14 \times 5 \times 10^5 \times 2 \times 10^{-3} = 3.14 \times 10^3$

iv. Work done in 25 cycles

W = 25 × Area enclosed by ellipse

= 25 × 3.14 × 10³

= 78.5 × 10³ J = 7.85 × 10⁴ J

Ans : Work done in 25 cycles is 7.85×10^4 J.

Problem for practice

1. One mole of an ideal gas undergoes a cyclic change ABCD. From the given diagram. Calculate the net work done in the process.
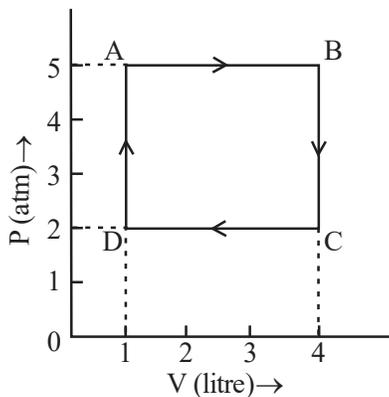
Ans: 9 × 10⁹ erg.

2. One mole of an ideal gas undergoes a cyclic change ABCD where the (P, V) co-ordinates are A(5, 1), B(5, 3), C(2, 3) and D(2, 1). P is in atmosphere and V is in litre. Calculate work done along AB, BC, CD and DA and also net work done in the process. Given 1 atmosphere = 1.01×10^5 Nm⁻².

Ans: 1010 J, –404J, 0, 606J

4.7 Thermodynamic process

Q.19 What is a thermodynamic process? Mention its different types.

Ans: Thermodynamic process:

A thermodynamic process is said to occur if the thermodynamic variables of a system undergo a change with time.

Different types of thermodynamic processes are as follows:

i. **Isothermal process:**
It is a thermodynamic process which occurs at a constant temperature.

ii. **Isobaric process:**
It is a thermodynamic process which occurs at a constant pressure

iii. **Isochoric process:**
It is a thermodynamic process in which occurs at a constant volume.

iv. **Adiabatic process:**
It is a thermodynamic process in which there is no exchange of heat energy between system and surroundings.

Q.20 What are quasi static processes?

Ans:

i. Processes in which changes in the state variables of a system occur infinitesimally slowly are called quasi static processes.

ii. During quasistatic process, the system is always in thermodynamic equilibrium.

Note :

The state of a system can be changed from initial to final in different ways.

i. P-V diagram for work done when system undergoes 1st change involume at constant pressure and the change in pressure at constant volume.

a. *Consider the system changes its state from A to B at constant pressure.*
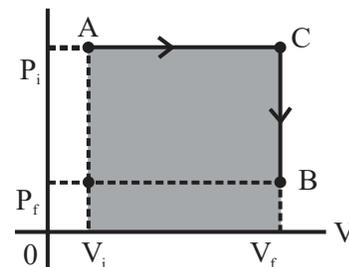
Figure (a)

b. *In this case, the volume increases to V_i from the point A up to the point C at the constant pressure P_i.*

c. After point C, the pressure of the system decreases to P_f at constant volume

d. The system thus, reaches its final state B with co-ordinates (V_f, P_f) Work done in this process is represented by the shaded area under the curve

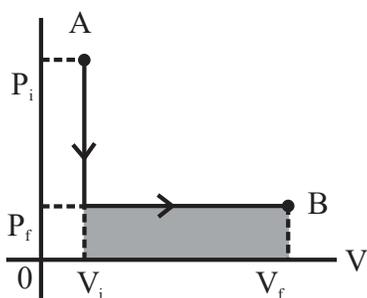ii. **P-V diagram of work done when system undergoes 1st change in pressure at constant volume and then change in volume at constant pressure.**

a. Consider the system changes its state from A to B as shown in figure (b).

Figure (b)

b. In this case, the pressure decreases from P_i to P_f at constant volume V_i long the path AD.

c. After point D, the volume of the system increases to V_f at constant pressure P_f as shown in.

d. Work done in this process is represented by the shaded area under the curve.

iii. From we can conclude that the work done is more when the system follows path ACB than the work done by the system along the path ADB.

Q.21 **What do you understand by reversible and irreversible processes? Give examples. What are the necessary conditions fot a process to be reversible?**

Ans:

A. **Reversible process :**

1. Any process which can be made to proceed in the reverse direction by variation in its conditions such that any change occuring in any part of the direct process is exactly reversed in the corresponding part of reverse process is called a reversed in the in the corresponding part of reverse process is called a reversible process.

2. Thus if some work is done by the system in the direct process, an equal amount of work must be done on the system in the reverse process.

3. If some heat is absorbded by the system in the direct process, it must release an equal amount of heat to the surrounding in the reverse process.

4. At the end of the reversible process, both the system and surrounding must return to their initial states.

Necessaary conditions for a reversible process :

a. The process must be quasi-static. For this, the process must be carried out infinitesimally slowly so that the system remains in thermal an mechanical equilibrium with the surroundings throughout.

b. The dissipative forces such as viscosity, friction inelasticity etc. should be absent.

Example :

a. The process of gradual compression and extension of an elastic sping is approximately reversible.

b. A working substance taken along the complete carnot's cycle.

c. A working substance taken along the complete carnot's cycle.

d. The process of electrolysis is reversible if the resistance offered by the electrolyte is negligibly small.

B. **Irreversible process :** Any process which cannot be retraced in the reverse direction exactly is called an irreversible process. Most of the processes occurring in the nature are irreversible processes

Example :
i.   Diffusion of gases.
ii.   Dissolution of salt in water
iii. Rusting of iron.
iv.   Sudden expansion of contraction of gas.

Q.23   Distinguish between reversible and irreversible processes.

Ans:

No.	Reversible process	Irreversible process
a.	A reversible process is a change that can be retraced in reverse (opposite) direction.	An irreversible process is a change that cannot be retraced in reverse (opposite) direction.
b.	The path of a reversible process is the same in the forward and the reverse direction.	The path of an irreversible process is not the same in the forward and the reverse direction.
c.	Reversible changes are very slow and there is no loss of any energy in the process.	There is a permanent loss of energy from the system due to friction or other dissipative forces in an irreversible process.
d.	Reversible processes are ideal processes.	Irreversible processes are real processes.

Q.23   State the two reasons of irreversibility of thermodynamic process.

Ans: There are two main reasons of the irreversibility of a thermodynamic process.

i.   Many processes such as a free expansion or an explosive chemical reaction take the system to non-equilibrium states.

ii.   Most processes involve friction, viscosity or some other dissipative forces.

Q.24   What are the assumptions made for studying various thermodynamic processes?

**Ans: Assumptions to study various thermodynamic processes:**

i.   Majority of the thermodynamic processes are reversible. That is, they are quasi-static in nature. They are extremely slow and the system undergoes infinitesimal change at every stage except the adiabatic processes. The system is therefore, in thermodynamic equilibrium during all the change.

ii.   The system involved in all the processes is an ideal gas enclosed in a cylinder having a movable, frictionless, and massless piston.

iii. The ideal gas equation is applicable to the system.

A. Isothermal Process

Q.25   What is an isothermal process? Give an example. What are the essential conditions for an isothermal process to take place? Write the equation for an isothermal process.

Ans:

i.   **Isothermal process:** An isothermal process is one in which the pressure and volume of the system change but temperature remains constant.
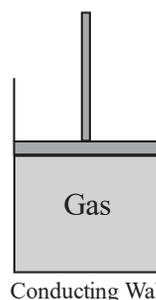
Conducting Wall

ii.   Consider an ideal gas enclosed in cylinder provided with a piston and having conducting walls. If the gas is slowly compressed, the heat produced due to the work done on the gas is transferred to the surroundings so that temperature of the gas remains constant.

iii. Similarly, when the gas is allowed to expand slowly, its temperature tends to fall but some heat from the surroundings is conducted to the gas, keeping the temperature constant.

iv.   **Essential conditions for an isothermal process to take place:**

a.   The walls of the container must be perfectly conducting to allow free exchange of heat between the system

and the surroundings.

b. The process of compression or expanssion should be very slow, so as to provide sufficient time for the exchange of heat.

v. Equation of isothermal process:

The ideal gas equation for n moles of a gas is

PV = nRT

For a fixed mass (n is constant) of gas undergoing an isothermal process (Tis constant), the above equation gives

$$\boxed{PV = constant}$$

This equation is the equation of state of an is othermal process.

It is a nothing but Boyle's law according to which the pressure of a given mass of a gas varies inversely as its volume.

Q.27 Determine the expression for the work done and heat transferred for an isothermal process.

Ans:

i. Consider the isothermal expansion of an ideal gas. Let its initial volume V_i and the final volume be V_f.

ii. The work done in an indinitesimally small isothermal expansion is given by,

dW = pdV

iii. The total work done in bringing out the expansion from the initial volume V_i to the final volume V_f is given by,

$$W = \int_{V_i}^{V_f} pdV \qquad ....(1)$$

iv. But, for an ideal gas, pV = nRT.

$$\therefore \quad p = \frac{nRT}{V}$$

Substituting in Equation (1) we get,

$$W = nRT \int_{V_i}^{V_f} \frac{dV}{V}$$

$$\therefore \quad W = nRT \left[l_n V \right]_{V_i}^{V_f}$$

$$W = nRT \left[l_n V_f - l_n V_i \right]$$

$$\therefore \quad W = nRT ln \frac{V_f}{V_i} \qquad ....(2)$$

vi. For an ideal gas, its internal energy depends on its temperature. Therefore, during an isothermal process, The internal energy of an ideal gas remains cosntant ($\Delta U = 0$) because its temperature is constant ($\Delta T = 0$).

vii. Therefore, according to the first law of thermodynamics, for an isothermal process.

Q = W

$$\therefore \quad \boxed{Q = W = nRT ln \frac{V_f}{V_i}}$$

viii. Thus, the heat transferred to the gas is completely converted into the work done, i.e., for expansion of the gas.

Note:

i. *consider an isothermal process where pressure changes from P_i to P_f.*

ii. *For isothermal process, as temperature is constant, PV = constant.*

$$\therefore \quad p_i V_i = p_f V_f$$

$$\therefore \quad \frac{V_f}{V_i} = \frac{p_i}{p_f}$$

iii. *Thus, work done in isothermal process is,*

$$\boxed{W = nRTln \left(\frac{V_f}{V_i} \right) = nRTln \left(\frac{p_i}{p_f} \right)}$$

Type - III
Numerical based on isothermal process

Formula used

1. Equation for isothermal process.
PV = constant
$P_1 V_1 = P_2 V_2$

2. Work done under isothermal condition

$$W = 2.303 \times nRT \ log \frac{V_2}{V_1}$$

$$w = 2.303 \ nRT \ log \frac{p_1}{p_2}$$

★ 1) An ideal gas is taken through an isothermal process. If it does 2000 J of work on its environment, how much heat is added to it?

Data: $|W| = 2000$ J

To find: Q

Formula: $\Delta U = |Q| - |W|$

Solution:

i. For isothermal process

$\Delta U = 0$

ii. Form 1 st law of thermodynamics

$\Delta U = |Q| - |W|$

$0 = |Q| - 2000$

$|Q| = 2000$ J

Ans : Heat added to the gas system in this process is 2000J

★ 2) 0.5 mole of gas at temperature 300 K expands isothermally from an initial volume of 2.0 L to final volume of 6.0 L.
   i. What is the work done by the gas? (R = 8.31 J mol K),
   ii. How much heat is supplied to the gas?
   iii. Can you explain the significance of positive sign of the work done and the heat?

Data: n = 0.5 mol, T = 300K, V_i = 2.0 L, V_f = 6.0L, R = 8.31 J mol^{-1}K^{-1}

To find: i. W   ii. Q

Formulae: i. $W = 2.303\, nRT \log \dfrac{V_f}{V_i}$

ii. $\Delta U = |Q| - |W|$

Solurtion:

i. $W = 2.303\, nRT \log \left(\dfrac{V_f}{V_i}\right)$

$= 2.303 \times 0.5 \times 8.31 \times 300 \log \left(\dfrac{\cancel{6}^3}{\cancel{2}_1}\right)$

$= 2.87 \times 10^3 \log 3$

$= 2.87 \times 10^3 \times 0.4771$

$W = 1.369 \times 10^3$ J

$W = 1.369$ KJ

ii. For isothermal process

$\Delta U = 0$

$\therefore \quad \Delta U = |Q| - |W|$

$O = |Q| - |W|$

$\therefore \quad |Q| = |W|$

$Q = 1.369$ kJ.

The positive sign of the heat indicates that heat is absorbed by the gas. Also, positive sign of work indicates the work is done by the gas and the gas expands.

Ans : i. Work done by gas is 1.369 kJ.
ii. Heat supplied to gas is 1.369 kJ.

3) Three moles of an ideal gas kept at a constant temprature of 300 K are compressed from a volume of 4 litre to 1 litre. Calculate the work done in the process. Given R = 8.31 J mol^{-1} K^{-1}.

Data: n = 3, T = 300 K, V_1 = 4 litre, V_2 = 1 litre.

To find: W

Formula: $W = 2.303 \times nRT \log \dfrac{V_2}{V_1}$

Solution:

$W = 2.303 \times nRT \log \dfrac{V_2}{V_1}$

$= 2.303 \times 3 \times 8.31 \times 300 \log_{10} \dfrac{1}{4}$

$= 2.303 \times 3 \times 8.31 \times 300 \times 2 \times 0.3010$

$= -1.037 \times 10^4$ J.

Ans : Work done in isothermal process is -1.037×10^4 J.

Problem for Practice

1. One mole of an ideal gas expands at a constant temprature of 300 K from its initial volume of 10 litres to a final volume of 20 litres. find the work done in expanding gas.

Ans: 1728 J

2. 3 mole of a gas at temperature of 400 K expands isothermally from initial volume of 4 litre to the final volume of 8 litre. Find work done by the gas.

Ans: 6.912 KJ

B. Isobaric process

Q.27 **What is isobaric process? Also State what is isobar.**

Ans:

i. *A thermodynamic process which is carried out at constant pressure is called isobaric process.*

ii. Boiling of water at normal atmospheric pressure is an example of isobaric process.

iii. For an isobaric process, none of the quantities ΔU, Q and W is zero.

iv. Temperature of system changes, i.e., $\Delta T \neq 0$.

v. Energy exchanged is used to do work as well as to change internal energy causing increase in temperature. Thus, $Q = \Delta U + W$.

vi. As work is done volume changes during the process.

vii. The p-V diagram for an isobaric process is called isobar. It is shown in figure.
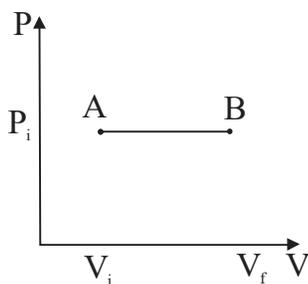
viii. The different curves shown on the maps provided by the meterology department are isobars. They indicate the locations having same pressure region.

Q.28 **Derive the expression for heat exchanged in case of an isobaric process.**

Ans:

i. In isobaric process, pressure of the system remains constant i.e., $\Delta p = 0$.

ii. Consider an ideal gas undergoing volume expansion at constant pressure.

iii. If V_i and T_i are its volume and temperature in the initial state of a system and V_f and T_f are its final volume and temperature respectively, the work done in the expansion is given by,
$$W = pdV = p(V_f - V_i) = nRT(T_f - T_i) \quad ....(1)$$

iv. Also, the change in the internal energy of a system is given by,

$$\Delta U = nC_V \Delta T = nC_V(T_f - T_i) \quad ....(2)$$

Where, C_V is the specific heat at constant volume and $\Delta T = (T_f - T_i)$ is the change in its temperature during the isobaric process.

v. According to the first law of thermodynamics, the heat exchanged is given by, $Q = \Delta U + W$ Substituing w and ΔU Equation (1) and (2) we get

$$Q = nC_V(T_f - T_i) + nR(T_f - T_i)$$

$\therefore$ $\quad Q = (nC_V + nR)(T_f - T_i)$

$\therefore$ $\quad Q = nC_P(T_f - T_i) \quad ....(\because CP = C_V + R)$

Where, C_P is the specific heat at constant pressure.

C. Isochoric Process

Q.29 **Write a short note on isochoric process.**

Ans:

i. *A thermodynamic process in which volume of the system is kept constant is called isochoric process.*

ii. A system does no work on its environment during an isochoric process.
As $\Delta U = 0$

$\therefore$ $\quad \Delta W = 0$

iii. p-V diagram of isochoric process is as shown below:
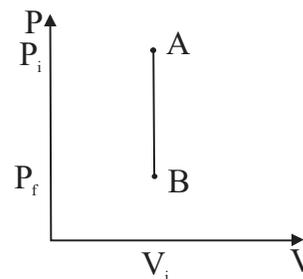
iv. From the first law of thermodynamics,
$$\Delta U = Q - W$$
$\therefore$ $\quad \Delta U = Q$

v. This means that for an isochoric change, all the energy added in the form of heat remains in the system itself and causes an increase in its internal energy. Also, as volume is unchanged, no work is done.

vi. Temperature of the system changes,
i.e., $\Delta T \neq 0$.

vii. Heating a gas in a constant volume container

or diffusion of a gas in a closed chamber are some examples of isochoric process.

Q.30 **Derive an expression for heat exchanged in an isochoric process.**

Ans:

i. For an isochoric process, $\Delta V = 0$.
Therefor $W = 0$

ii. The system does not do any work and all the energy supplied to the system is converted into its internal energy.

iii. The first law of thermodynamics for isochoric process is,
$Q = \Delta U + W = \Delta U$ ....(1)

iv. The change in internal energy is given by,
$\Delta U = nC_V \Delta T$ ....(2)

v. The heat exchanged is given by,
$Q = \Delta U = nC_V \Delta T$

Q.31 **A mixture of fuel and oxygen is burned in a constant-volume chamber surrounded by a water bath. It was noticed that the temperature of water is increased during the process. Treating the mixture of fuel and oxygen as the system,**
  i.   Has heat been transferred?
 **ii. Has work been done?**
  iii. What is the sign of ΔU ?

Ans: The given process is carried out at constant volume. Thus, the process is isochoric.

i. Yes, heat has been transferred.

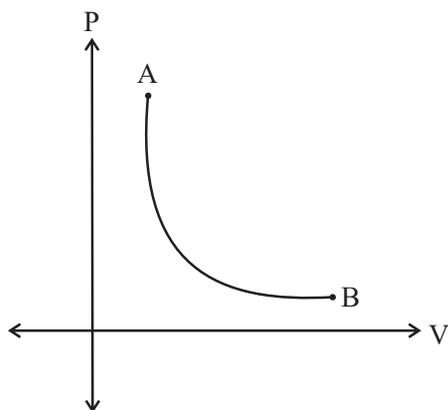ii. No, no work has been done.

iii. The sign of ΔU is negative.

Q.32 **What is an adiabatic process? Give an example. What are the essential conditions for an adiabatic process to occure?**

Ans:

i. **Adiabatic process:** An adiabataic process is one in which the pressure, volume and temperature of the system change but there is no exchange of heat between the system and surroundings
a = not, dia = through, bates = heat, so the Greak word adiabatic means heat not passing through).

Gas
Non - Conducting Wall
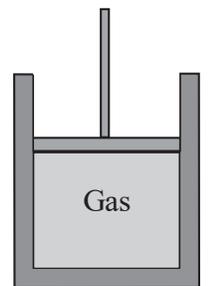
ii. Consider a gas enclosed in a cylinder having perfectly insulated walls. Suppose the gas is allowed to expand very quickly. Work is done by the gas during its expansion, so its internal energy deceases. As the heat cannot enter the system from the surroundings, so the temperature of the gas falls.

iii. Similarly, when the gas is suddenly compressed, work is done on the gas. This increases the internal energy of the gas. As heat cannot escape to the surroundings, the temperature of the gas increases.

iv. **Essential conditions for an adiabatic process to take place:**
  a. The walls of the container must be perfectly insulated so that there cannot be any exchange of heat between the gas and the surroundings.
  b. The process of compression or expansion shold be sudden, so that heat does not get time to get exchanged with the surroundings.

v. Equation of adiacatic process
PV = constant
Where is adiabatic constant
Which is $\dfrac{C_P}{C_V}$

vi. For adiabatic Process
$Q = 0$
According to 1st law of thermodynamics
$\Delta U = Q - w$
$\therefore$ $\Delta U = -w$

vii. P-v diagram of adiabatic process

This is the adiabatic relation between volume V and temperature T of an ideal gas.

Note:-

The ratio of the specific heat at constant pressure to the specific heat at constant volume is called the adiabatic ratio, i,.e.,

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

For moderate temperature changes, the values of γ are :

Monotomic gas : $\gamma_{mono} = \dfrac{5}{3}$

Diatomic gas: $\gamma_{di} = \dfrac{7}{5}$ and

Polyatomic gas: $\gamma_{poly} = \dfrac{8}{6} = \dfrac{4}{3}$

Q.34 Obtain relation between P and T and also between V and T in adiabatic process.

Ans:

i. **Adiabatic relation between P and T**. For one mole of a gas PV = RT,

$\therefore \quad V = \dfrac{RT}{P}$ ......(1)

Equation of adiabatic process is
$PV^\gamma = $ constant

$P\left(\dfrac{RT}{P}\right)^\gamma = K$ ......(From 1)

$\therefore \quad P \times \dfrac{R^\gamma\, T^\gamma}{P^{\gamma-1}}$

$\therefore \quad P^{1-\gamma}T^\gamma = \dfrac{K}{R^\gamma} = $ another constant

i.e., $\boxed{P^{1-\gamma}T^\gamma = \text{constant}}$

This is the adiabatic relation between pressure P and temperature T of an ideal gas.

ii. **Adiabatic relation between V and T.** Again for one mole of a gas PV = RT, therefore

$P = \dfrac{RT}{V}$ ......(2)

Putting in $PV^\gamma = K$, we get

$\dfrac{RT}{V}.V^\gamma = K$ or

$TV^{\gamma-1} = \dfrac{K}{R} = $ another number

$\boxed{TV^{\gamma-1} = \text{constant}}$

Q.34 Derive an expression for work done in an adiabatic process.

Ans:

i. An adiabatic system is thermally isolated from its environment; therefore, it cannot exchange heat with it. Therefore, when a system undergoes an adiabatic change, its temperature and internal energy both change.
The change in internal energy is,

$\Delta U = nC_V(\Delta T)$

ii. The work done is,

$W = \displaystyle\int_{V_i}^{V_f} pdV$ ....(1)

iii. For an adiabatic change,
$PV^\gamma = $ constant $= K$

iv. Using equation (2) in equation (1), we have

$W = K\displaystyle\int_{V_i}^{V_f} \dfrac{dV}{V^\gamma}$

$W = K\displaystyle\int_{V_i}^{V_f} V^{-\gamma}\, dV$

$W = K \times \left[\dfrac{V^{-\gamma+1}}{1-\gamma}\right]_{V_i}^{V_f}$

PHYSICS

where V changes from V_i to V_f

$$\therefore \quad W = \frac{K}{(1-\gamma)} \times \left[\frac{1}{V_f^{(\gamma-1)}} - \frac{1}{V_i^{(\gamma-1)}} \right]$$

$$W = \frac{1}{1-\gamma} \left[\frac{1}{V_f^{\gamma-1}} - \frac{1}{V_i^{\gamma-1}} \right] \quad ...(3)$$

v. Also, from equation (2),

$$P_i V_i^\gamma = P_f V_f^\gamma = K \quad ...(4)$$

vi. Substituting (4) in Eq (3) we get

$$W = \frac{1}{1-\gamma} \left[\frac{p_f V_f^\gamma}{V_f^{\gamma-1}} - \frac{p_i V_f^\gamma}{V_i^{\gamma-1}} \right]$$

$$W = \frac{1}{1-\gamma} \left[p_f V_f^{\gamma-\gamma+1} - p_i V_i^{\gamma-\gamma+1} \right]$$

$$\boxed{W = \frac{1}{1-\gamma} \left[p_f V_f - p_i V_i \right]} \quad ....(5)$$

$\therefore \quad PV = nRT$

We can write equation (5) as

$$W = \frac{1}{1-\gamma} \left[nRT_f - nRT_i \right]$$

$$\boxed{W = \frac{nR(T_f - T)_i}{1-\gamma}} \quad ....(6)$$

★ **Q.35** **A mixture of hydrogen and oxygen is enclosed in a rigid insulating cylinder. It is ignited by a spark. The temperature and the pressure both increase considerably. Assume that the energy supplied by the spark is negligible, what conclusions may be drawn by application of the first law of thermodynamics?**

Ans:

i. Consider the mixture of hydrogen and oxygen to be a system.

ii. As the system is insulated from surroundings, the process is adiabatic.

iii. For adiabatic change, Q = 0.
From first law of thermodynamics,
$\Delta U = - W$

iv. From concluded that as temperature is increased, then ΔU is positive. This implies, work done is negative.

v. Negative work done corresponds to compression of the gas. Hence, the system undergoes adiabatic compression.

Q.36 **What is a cyclic process? Explain with a diagram.**

Ans:

i. A thermodynamic process in which the system returns to its initial state is called a cyclic process. Path 1 shows how the state of the system (ideal gas) is changed from (P_i, V_i) [point A] to (P_f, V_f) [point B]. Path 2 shows the return of the system from point B to point A. As the system returns to its initial state, the total change in its internal energy is zero.

ii. Hence, according to the first law of thermodynamics, heat supplied is given by.
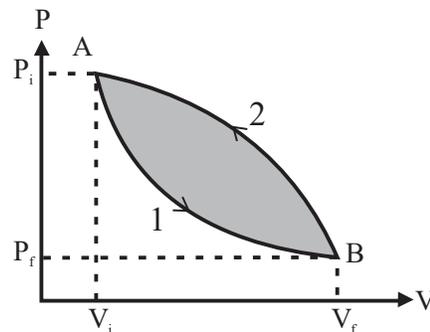
p-V diagram of a cyclic process
$Q = \Delta U + W = 0 + W = W.$

iii. The area enclosed by the cycle in p-V plane gives the work done (W) by the system.

Intext question

The total work done in the cyclic process shown in the figure is −1000 J.
i. **What does the negative sign mean?**
ii. **What is the change in internal energy and the heat transferred during this procss?**
iii. **What will happen when the direction of he cycle is changed?**

PHYSICS

Ans:

i. The negative sign of work done means that the work is done on the system by its surroundings.

ii. As the process is cyclic, intial and final state of the system is same. Therefore, the change in internal energy of the system is zero. Also, from first law of thermodynamics,
$Q = \Delta U + W = 0 + W = -1000$ J.

iii. If the direction of the cycle is changed, the net work done will be positive. i.e., the work will be done by the system.

Q.37 **Distinguish between following thermodynamic processes.**
i. **Isothermal process and Adiabatic process**
ii. **isobaric process and Isochoric proces.**
Ans:
i.

Sr. No.	Isothermal process	Adiabatic process
a.	It is process in which change, in pressure and volume takes place at a constant temperature.	It is a process during which there is no transfer of heat from or to the system.
b.	$\Delta T = 0$ and the system is in perfect thermal equilibrium with the surroundings	$\Delta T \neq 0$. Temperature of the system changes.
c.	No change in internal energy of the system takes place ($\Delta U = 0$)	All the work is utilised to change the internal energy of the system ($\Delta U = -W$).
d.	Energy is exchanged with the environment and utilised to do work. ($Q = W$). Thus, total amount of heat of system does not remain constatn.	The system is perfectly insulated from the environment i.e., no heat is exchanged with the environment ($Q = 0$)
e.	It is a very slow change.	Most of the times, it is a sudden and very rapid change.

ii.

Sr. No.	Isothermal process	Adiabatic process
a.	It is a constant pressure process (i.e., $\Delta p = 0$)	It is a constant volume process (i.e., $\Delta V = 0$)
b.	Work done in the isobaric process changes volume of the system. ($W = p\Delta V$)	No work is done in an isochoric process as volume remains constant. ($W = 0$)
c.	Energy exchanged is used to do work and also to change internal energy.	Energy exchanged is used to change internal energy($Q = \Delta U$)
d.	**p-V diagram:**	**p-V diagram:**

INTEXT QUESTION

Distinguish between following thermodynamic processes.
i. **Isothermal proc**
(a) **Give an example of some familiar process in which no heat is added to or removed form a system, but the temperature of the system changes.**
Ans : Bursting of inflated ballon is a sudden process which does not allow transfer of heat to or from the system but the air coming out from the ballon can be felt to be cooled.

(b) **A gas contained in a cylinder surrounded by a thick layer of insulating material is quickly compresses.**
i. **Has there been a transfer of heat?**
ii.Has work been done?
Ans : As the cylinder is surrounding by a layer of insulating material and the process of compression is performed quickly the process is an adiabatic compression

i. No, there has not been any transfer of heat

ii. Yes work has been dojne on the gas to compress it.

PHYSICS

**A cyclic process ABCD is shown in V-T diagram. It is performed with a constant mass of ideal gas. How will this transform to a p-V diagram?**

Ans:
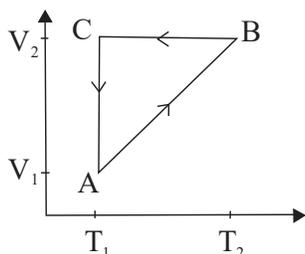
i. $\dfrac{\text{for path } A \to B}{V \alpha T}$

$\therefore$ Pressure is Constant.
So path AB is P-V diagram will be a straight line parallel to V-axis.

ii.   For path $B \to C$ volume is constant and temperature is decreasing which means it is isochoric process so path BC in P-V diagram is a straight line parallel to P-axis.

iii.   For path CA along path CA, volume is decreasing at constant temperature. Thus, it is an isothermal process. For isothermal process,
pV = constant.
The path CA on p-V diagram will be an isotherm.
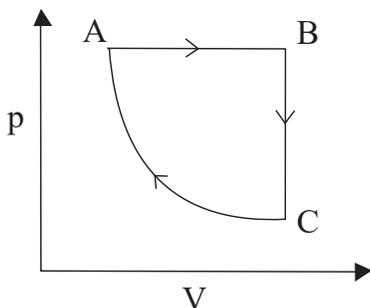
Type - IV
Numerical based on adiabatic process

Formula used

i.   Equations for adiabatic processes,

a. $P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$

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

c. $\dfrac{P_1^{\gamma-1}}{T_1^{\gamma}} = \dfrac{P_2^{\gamma-1}}{T_2^{\gamma}}$ where $\gamma = C_P / C_V$

ii.   Work done when 1 mole of a gas expands adiabatically and its temperature falls from T_1 to T_2.

a. $W_{iso} = \dfrac{R}{\gamma-1}\left[T_1 - T_2\right]$

b. $W_{adi} = \dfrac{1}{\gamma-1}\left[P_1 V_1 - P_2 V_2\right]$

1)   **One mole of an ideal gas is initially kept in a cylinder with a movabel, frictionless and massless piston at pressure of 1.0 MPa, and temprature 27°C. It is then expanded till its volume is doubled. How much work is done if the expansion is isobaric?**

Data: p = 1.0×10⁶ Pa,
T = 27°C = 24 + 273 = 300K,
n = 1 mol
$V_f = 2V_i$

To find: Work done by gas (W)

Formulae: i.   pV = nRT   ii.   W = pΔV

Solution:

pV = nRT

$V_i = \dfrac{RT_i}{p} = \dfrac{8.31 \times 300}{1 \times 10^6} = 24.9 \times 10^{-4}\, m^3$

W = pΔV
W = p(2V_i - V_i) = pV_i
= 1×10⁶×24.9×10⁻⁴
= 2.49 × 10³J
= 2.5× 10³J = 2.5 kJ

Ans :   Work done by gas is 2.5kJ

2)   **An ideal monatomic gas is adiabatically compressed so that its final temperature is twice its initial temperature. What is the ratio of the final pressure to its initial pressure?**

Data: As the gas is monatomic, $\gamma = \dfrac{5}{3}$

$T_2 = 2T_1 \Rightarrow \dfrac{T_2}{T_1} = 2$

To find: Ratio of final pressure to its initial

pressure $\left(\dfrac{P_2}{P_1}\right)$

4.   THERMODYNAMICS

PHYSICS

Formula: $P_1^{\gamma-1}T_1^{\gamma} = P_2^{\gamma-1}T_2^{\gamma}$

Solution:

$$P_1^{\gamma-1}T_1^{\gamma} = P_2^{\gamma-1}T_2^{\gamma}$$

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

$$\left(\frac{P_1}{P_2}\right)^{\frac{-2}{3}} = \left(\frac{T_2}{T_1}\right)^{\frac{5}{3}}$$

$$\left(\frac{P_2}{P_1}\right)^{\frac{2}{3}} = \left(\frac{T_2}{T_1}\right)^{\frac{5}{3}}$$

On taking cube of both sides, we get

$$\frac{P_2}{P_1} = \sqrt{32} = 4\sqrt{2} = 4\times1.41 = 5.6$$

Ans: The ratio of final pressure to its initial pressure is 5.6.

3) **An ideal gas of volume 1.0 L is adiabatically compressed to (1/15)th of its initial volume. Its initial pressure and temperature is 1.01 × 10⁵ Pa and 27°C respectively. Given C$_v$ for ideal gas = 20.8J/mol K and γ = 1.4, calculate**
   i. **Final pressure,**
   ii. **work done, and**
   iii. **final temperature.**
   iv. **How would your answer change, if the process were isothermal?**
   v. **The work done during adiabatic compression is more than the work done during isothermal compression. Can you explain this? What happens to this work which is apperently 'lost'?**

Data: $V_i = 1.0$ L, $V_f = \dfrac{V_i}{15} \Rightarrow \dfrac{V_i}{V_f} = 15$,

$P_i = 1.01 \times 10^5$ Pa
$T_i = 27°C = 27+273 = 300$K
$C_v = 20.8$ J/mol K, $\gamma = 1.4$

To find: i. Final pressure (pr)
ii. Work done (W)

iii. Final temperature (Tf)
iv. Final pressure, work done and final temperature if system is isothermal.

Formulae:

For adiabatic process:

a. $T_f V_f^{\gamma} = T_i V_i^{\gamma}$

b. $W = \dfrac{p_f V_f - p_i V_i}{1-\gamma}$

c. $T_f V_f^{\gamma-1} = T_i V_i^{\gamma-1}$

For isothermal process:

d. $p_f V_f - p_i V_i$

e. $W = nRT \ln\left(\dfrac{V_f}{V_i}\right)$

Solution:

i. $T_f V_f^{\gamma} = T_i V_i^{\gamma}$

$$p_f = p_i \times \left(\frac{V_i}{V_f}\right)^{\gamma}$$

$$= 1.01\times10^5\times(15)^{1.4}$$
$$= 4.475\times10^6$$
$$= 44.75 \times 10^5 \text{ Pa} \approx 45\text{atm}$$

ii. $W = \dfrac{p_f V_f - p_i V_i}{1-\gamma}$

$$= \frac{\left(1.01\times10^5\right)\times\left(1\times10^{-3}\right) - \left(44.75\times10^5\right)\times\left(\dfrac{1}{15}\times10^{-3}\right)}{1.4-1}$$

$$= \frac{\left[1.01 - \left(\dfrac{44.75}{15}\right)\right]\times10^2}{0.4}$$

$$= \frac{1.01 - 2.983}{0.4}\times10^2$$

$$= \frac{-1.973}{0.4}\times10^2$$

$$= -4.933\times10^2$$

$$= -493.3\text{J}$$

iii. $T_f V_f^{\gamma-1} = T_i V_i^{\gamma-1}$

$$T_f = T_i \left(\frac{V_i}{V_f}\right)^{\gamma-1}$$

$= 300 \times (15)^{(1.4-1)} = 300 \times (15)^{0.4}$

$= 8.861 \times 10^2$

$= 886.1 \text{ K} \approx 613°C$

iv. If process were isothermal,

a. $p_f V_f - p_i V_i$

$$p_f = \frac{p_i V_i}{V_f}$$

$= (1.01 \times 10^5)(15) = 15 \text{atm}$

b. 1 mol of ideal gas has volume of 22.4 L. The number of moles in 1 L of gas would be

$$n = \frac{1}{22.4} = 0.045$$

$$W = nRT \ln\left(\frac{V_f}{V_i}\right)$$

$$= 0.045 \times 8.31 \times 300 \times \ln\left(\frac{1}{15}\right)$$

$= -3.039 \times 10^2 = -303.9 \text{ J}$

c. As the process is isothermal, temperature doesn't change.

v. a. During adiabatic compression, as no energy is exchanged between system and the surrounding, the increase in temperature as well as pressure in temperature as well as pressure on the system is very large.

b. Whereas, in isothermal comression the system can exchange energy with the sur roundings and thus, pressure gets adjusted accordingly. Thus, the work done on the gas is less in isothermal compression.

c. Also, for same change in volume, the isothermal and adiabatic curves can be drawn on the p-V diagram as shown in figure.
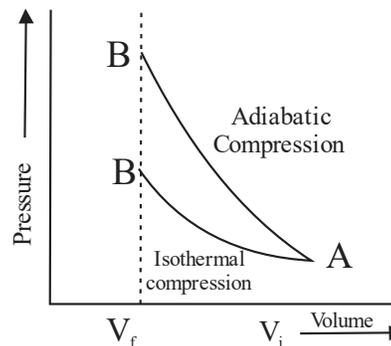
d. According to the figure, the area under the adiabatic curve is more than that under isothermal curve. Thus, work done is adiabatic compression is more than that in isothermal compression.

Problem for practice

1. The compression ratio of a certain diesel engine is 15. This means that air in the cylinder is compressed to 1/15 of its initial volume. If the initial pressure is 1.0×10^5 Pa and the initial temperature is 300 K, find the final pressure and temperature after compression. Air is mostly a mixture of oxygen and nitrogen and $\gamma = 1.4$.

Ans: 44.3×10^5 Pa, 886 K

2. Calculate the fall in temperature of helium initially at 15°C, when it is suddenly expanded to 8 times its volume. Given $\gamma = \frac{5}{3}$.

Ans: 216 K or 216°C.

3. A tyre pumped to a pressure of 3.375 atmosphere and at 27°C suddenly bursts. Calculate the temperature of escaping air. Given $\gamma = 1.5$.

Ans: –73°C

4. A cylinder containing one gram molecule of the gas was compressed adiabatically until its temprature rose from 27° C to 97°C. Calculate the work done in the process. Given R = 8.31 J mol^{-1} K^{-1}.

Ans: 276.67 cal

5. A sample of gas ($\gamma = 1.5$) is compressed

PHYSICS

adiabatically from a volume of 1600 cm³ to 400 cm³. If the initial pressure is 150 kPa, what is the final pressure and how much work is done on the gas in the process?

Ans: 1200 kPa, –480J

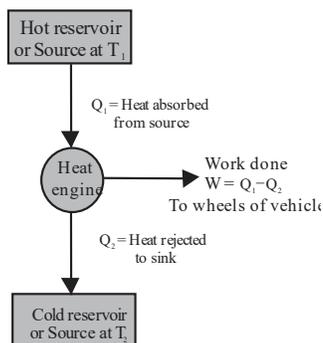### 4.8 Heat Engines

Q.39 **What is a heat engine? Explain its working principle. Define its efficiency.**

Ans: **Heat engine:** It is a device which converts continuously heat energy into mechanical energy in a cylic process.

As shown in figure a heat engine has the following essential parts:

i. **Source:** It is a heat reservoir at higher temperature T_1. It is supposed to have infinite thermal capacity so that any amount of heat can be drawn from it without changing its temprature.

Hot reservoir or Source at T_1

Q_1 = Heat absorbed from source

Heat engine

Work done $W = Q_1 - Q_2$ To wheels of vehicle

Q_2 = Heat rejected to sink

Cold reservoir or Source at T_2

ii. **Sink:** It is a heat reservoir at a lower temperature T_2. It has also infinite thermal capacity so that any amount of heat can be added to it without changing its temperature.

iii. **Working substance:** Working subsrtance is any material (solid, liquid or gas) which performs mechanical work when heat is supplied to it.

For example, a mixture of fuel vapour and air is used in gasoline or diesel engine or steam in a steam engine.

Working: In every cycle of operation, the working substance absorbs a definite amount of heat Q_1 from the source at higher temperature T_1, converts a part of this heat energy into mechanical work W and rejects the remaining heat Q_2 to the sink at lower temperature T_2. The work done W in a cycle is transferred to the environment by some arrangement e.g., the working substance may be in a cylinder with a moving piston that transfers mechanical energy to the wheels of a vehicle via a shaft.

Efficiency of a heat engine: The efficiencey of a heat engine is defined as the ratio of the net work done by the engine is defined as the ratio of the net work done by the engine in one cycle to the amount of heat absorbed by the working substance from the source.

As the working substance returns to its initial state after completing one cycle, there is no change in its internal energy. Hence by first law of thermodynamics,

Net heat absorbed in a cycle = Work done

$$Q_1 - Q_2 = W$$

The efficiency of heat engine is given by

$$\eta = \frac{\text{Work done by engine (output)}}{\text{Heat absorbed form source (input)}}$$

$$\frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} \quad \text{or}$$

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

Efficiency of a heat engine is always less than unity: Clearly, when $Q_2 = 0$, $\eta = 1$ or 100%. But any working substance working in a cycle cannot convert all the heat extracted form the source into work. It has to reject some amount of heat to the sink. That is why the efficiency of a heat engine is always less than unity. The efficiency of a steam engine varies from 12 to 16% the maximum efficiency of a petrol engine is 26% and that of a diesel engine is 40%

Q.40 **What are the two basic types of heat engine? Give examples.**

Ans: **Types of heat engines:**

i. External combustion engine: In such a heat engine, the heat needed for the working substance is produced by burning the fuel outside the cylinder and piston arrangement of the engine. A steam engine is an external combustion engine.

ii.Internal combustion engine: In such a heat engine, the heat needed for the engine is produced by burning the fuel inside the main cylinder. The petrol

and diesel engines are internal combustion engines.

Q.41 **Explain the p-V diagram of a general heat engine. Give its importance.**

Ans:

i. The operation of a heat engine is a cyclic process. Therefore, its p-V diagram is a closed loop. The area of the loop represents the work done during one complete cycle.

ii. A heat engine uses energy absorbed in the form of heat to do work and then rejects the heat which cannot be used to do work. Heat is absorbed in one part of the cycle, work is done in another part, and the unused heat is rejected in yet other part of the cycle.

iii. The p-V diagram of a typical heat engine is shown in figure:
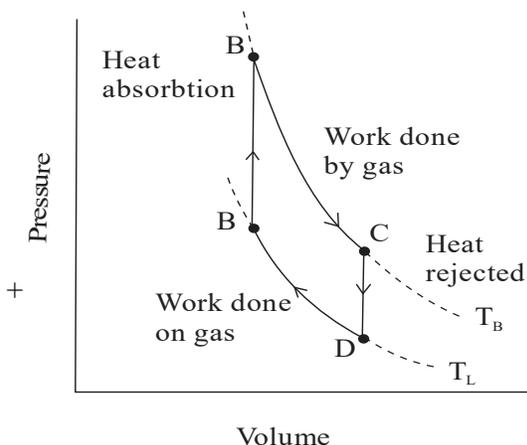
iv. The operating cycle begins at the point A in the cycle. The working substance absorbs heat at constant volume and no work is done by the gas or on the gas. The pressure is increased till the point B is reached. The temperature of the gas also increases and its internal energy increases.

v. The gas starts expanding by pushing the piston away and its volume changes from the point B to the point C. Because the gas expands, its pressure is reduced. The gas does work in this part of the cycle.

vi. When the point C is reached, the heat that is not utilized in doing work by the gas, is rejected. The gas cools down and its internal energy decreases. This process is again at constant volume. The pressure of the gas is reduced and point D on the p-V diagram is reached.

vii. The gas is now compressed. Its volume decreases and its pressure increases. The change continues till the point A is reached. The cycle is complete and the system is ready for the next cycle.

viii. The p-V diagram is a visual tool for the study of heat engines.

ix. Study of the p-V diagram helps us understand the behaviour of the three state variables of a gas throughout the operational cycle.

x. The operation of a heat engine is a cyclic process. Therefore, its p-V diagram is a closed loop. The area of the loop represents the work done during one complete cycle.

xi. Since work is done by the gas , or on the gas, only when its volume changes, the p-V diagram provides a visual interpretation of the work done during one complete cycle.

xii. Similarly, the internal energy of the gas depends upon its temperature. Hence, the p-V diagam along with the temperatures calculated from the ideal gas law determines the changes in the internal energy of the gas. Thus, a p-V diagram helps us analyze the performance of any heat engine which uses a gas as its working substance.

Q.42 **What sets the limits on efficiency of a heat engine?**

Ans: Second law of thermodynamics sets limits on the efficiency of a heat engine.

**Q.43** **What are refrigerators. Explain mechanism of refrigerator with schematic diagram.**

Ans:

i. Refrigeration ia a process of cooling a space or substance of a system and / or to maintain its temperature below its ambient temperature.

ii. In simple words, refrigeration is artificial cooling.
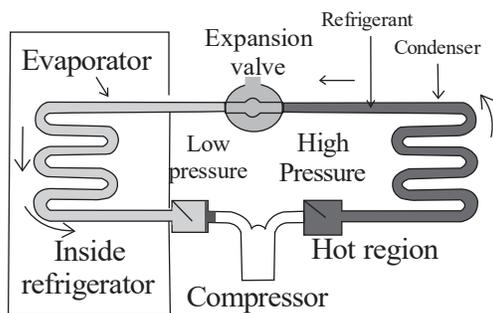
Schematics of a refrigerator

iii. A refrigerator extracts heat from a cold region (inside the chamber, or the compartments) and delivers it to the surrounding (the atmospher) thus, further cooling the cold region.

iv. **Mechanism of Refrigerator:**
   a. It consists of a compressor, an expansion valve, and a closed tube which carries the refrigerant.
   b. Part of the tube, called the cooling coil, is in the region which is to be cooled at l ower temperature and lower pressure.
   c. The other part which is exposed to the surrounding (generally, the atmosphere) is at a higher temperature and higher pressure.
   d. A fluid such as (fluorinated hydrocarbons) is used as refrigerant. Normally, the cold and the hot part of the coil contain the refrigerant as a mixture of liquid and vapour phase in equilibrium.
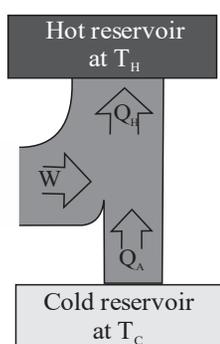
The refrigerant goes through the following steps in one complete cycle of refrigeration.

Q.44 **Explain step involved in one cycle of refrigeration.**

Ans: **Step 1:** The fluid passes through a nozzle and expands into a low-pressure area. Similar to the way carbon dioxide comes out of a fire extinguisher and cools down, the fluid turns into a gas and cools down. This is essentially an adiabatic expansion.

Step 2: The cool gas is in thermal contact with the inner compartment of the fridge. If heats up as heat is transferred to it from the contents of the fridge. This takes place at constant presure, so it's an isobaric expansion.

Step 3: The gas is transferred to a compressor, which does most of the work in this process. The gas is compressed adiabatically, heating it and turning it back to a liquid.

Step 4: The hot liquid passes through coils on the outside of the fridge, and heat is transferred to the atmosphere. This is an isobaric compression process.

The compressor is driven by an external energy source and it does the work |W| on the working substance during each cycle.

Q.45 **Write a note on coefficient of performance.**

Ans:

i. It is defined as amount of heat removed (Q_C) per cycle to the mechanical work (W) required to be done on it.

ii. Symbol is K or β

iii. Formula

$$K = \frac{Q_C}{W}$$

iv. According to 1st law of thermodynamics.

$$W = \left|Q_H\right| - \left|Q_C\right|$$

$$\therefore \quad K = \frac{\left|Q_C\right|}{\left|W\right|} = \frac{\left|Q_C\right|}{\left|Q_H\right| - \left|Q_C\right|}$$

v. K is ratio of same quantities i.e. energy. therefore it is diamensionless quantity.

Q.46 **Write a short note on air conditioner.**

Ans:

i. Working of an air conditioner and a refrigerator is exactly similar. It differs from a refrigerator only in the volume of the chamber/room it cools down.

ii. For an air conditioner, the evaporator coils are inside the room that is to be cooled and the condenser is outside the room.

iii. The air cooled by the evaporator coils inside the room is circulated by a fan placed inside the air conditioning unit.

iv.   The performance of an air conditioner is defined by $K = \dfrac{|Q_C|}{|W|}$.

v.   In case of air conditione, the rate of heat removed by working substance or the heat current is given as, $H = \dfrac{|Q_C|}{t}$. Also, the power P required to remove this heat Q_C is given as, $P = \dfrac{W}{t}$

vi.   Therefore, coefficient to performance is

$$K = \dfrac{|Q_C|}{|W|} = \dfrac{Ht}{Pt} = \dfrac{H}{P}$$

Q.47   Write a short note on heat pumps.
Ans:
i.   Heat pump is a device which works similar to a refrigerator. They are heat engines that work in backward direction converting mechanical work into heat.
ii.   A heat pump works like a refrigerator operating inside out. It is used to heat a building or a similar larger structure by cooling the air outside it.
iii.   In this case, the evaporator coils are outside and absorb heat from the cold air from outside.
iv.   The condenser coil are inside the building. They release the absorbed heat to the air inside it warming the building.

4.10 Second law of Thermodynamics

Q.48   State and explain second law of thermodynamics. What is its significance?
Ans: Second law thermodynamics: There are many processes in which energy is conserved and yet they are never observed. The principle which disallows such phenomena (as discussed in limitations of first law of thermodynamics) consistent with the first law of thermodynamics is called second law of thermodynamics. it can be stated in a number of ways as follows:
i.   **Kelvin-Planck staement:** It is impossible to construct an engine, which will produce no effect other than extrating heat from a reservoir and performing and equivalent amount of work.

This is applicable to a heat engine. It indicates that a working substance, operating in a cycle, cannot convert all the heat extracted from the source into mechanical work. It must reject some heat to the sink at a lower temperature.
ii.   **Clausius statement:** It is impossible for a selfacting machine, unaided by any external agency, to transfer heat from a body to another at higher temperature.

This is applicable to a refrigerator. The working substance can absorb heat from a cold body only if work is done on it. The work is done, by an electric compressor. If no external work is done, the refrigerator will not work.

Significance of Second law:
The second law of thermodynamics puts a fundamental limit to the efficiency of a heat engine and the coefficient of performance of a refrigerator.
a. According to second law, the efficiency of a heat engine can never be unity. This in turn, implies that the heat released to the cold resrvior can never be made zero.
b. According to second law, the coefficient of performance of a refrigerator can never be infinite. This implies that the external work (W) can never be zero.

4.11 Cornot Cycle or Carnot Engine

Note:- *Carnot engine:*
It is an ideal reversible heat engine that operates between two temperatures T_1 (Source) and T_2 (Sink). It was first conseived by a French engineer, Sadi Carnot in 1824. It operates through a series of two isothermal and two adiabatic processes called Carnot cycle. It is a theoratical heat engine with which the efficiency of practical engines is compared.
Construction: As shown in figure a Carnot engine has the following main parts:
i. Cylinder: This main part of the engine has conducting base and insulating walls. It is fitted with an insulating and frictionless piston.
ii.Source: It is a heat reservoir at a higher temperature T_1 from which the engine draws heat. It is supposed that the source has an infinite thermal capacity and so any amount of heat can be drawn from it

without changing its temperature.

iii. **Sink:** *It is heat reservoir at a lower temperature T2 to which any amount of heat can be rejected by the engine. It has also infinite thermal capacity and so any amount of heat can be added to it without changing its temperature.*

iv. **Working substance:** *The working substance is an ideal gas contained in the cylinder.*

v. **Insulating stand:** *When the base of the cylinder is attached to the insulating stand, the working substance gets isolated from the surroundings.*

Q.49 **Why should a Carnot cycle have two isothermal two adiabatic processes?**

Ans: In a Carnot engine, there are basically two processes:

i. **Exchange of heat:**
   a. For an ideal condition, the processof exchange of heat to be reversible, it should be carried out isothermally. i.e., the temperature of the working substance must be TH while absorbing heat form hot reservoir and it should be TC while rejecting heat to a cold reservoir.
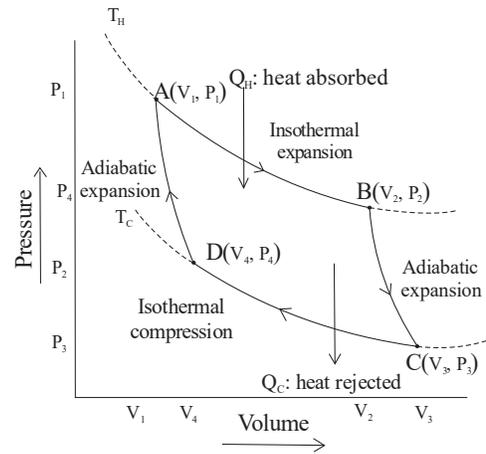   b. The curves AB and CD represent the isothermal changes in the given p-V diagram.

ii. **Work done:**
   a. The work done to be reversible, the processes must be adiabatic.
   b. The curves BC and DA represent the adiabatic changes in the given p-V diagram.

iii. Thus, the cycle includes two isothermal and two adiabatic processes for maximum efficiency.

Q.50 **Give the expression for the efficiency of Carnot engine.**

Ans: Efficiency of a Carnot engine is given as,

$$\eta = \frac{W}{Q_H} = 1 - \frac{|Q_C|}{|Q_H|} = 1 - \frac{T_C}{T_H}$$

Q.51 **Derive the expression for coefficient of performance of Carnot refrigerator using $K = K = \dfrac{|Q_C|}{W}$.**

Ans:

Coefficient of performance for a regular refrigerator,

$$K = \frac{|Q_C|}{W}$$

$\therefore$
$$K = \frac{|Q_C|}{|Q_H| - |Q_C|} = \frac{\dfrac{|Q_C|}{|Q_H|}}{1 - \dfrac{|Q_C|}{Q_H}}$$

But, $\dfrac{|Q_C|}{|Q_H|} = \dfrac{T_C}{T_H}$

$\therefore$
$$K = \frac{T_C}{T_H - T_C}$$

Q.52 **What does expression for coefficient of performance of performance of a Carnot refrigerator signify?**

Ans:

i. Coefficient of performance of a Carnot refrigerator is given as,

$$K = \frac{T_C}{T_H - T_C}$$

ii. This indicates that the coefficient of performance of a Carnot refrigerator depends on only the temperature difference of the hot and the cold reservoir.

iii. When the temperature difference is very small, the coefficient is very large. In this case, a large quantity of heat can be removed from the lower temperature to higher temperature by doing very small amount of work.

iv. The coefficient of performance is very small when the temperature difference is large. In this case, a small quantity of heat will be removed even when a large amount of work is done.

**Q.53 Write a short note on Sterling cycle.**

Ans:

i. Sterling cycle is a closed thermodynamic cycle.

ii. All the processes in the Sterling cycle are reversible processes.

iii. The working substance used in a Sterling engine is air, helium, hydrogen, nitrogen etc.

iv. Whem the gas is heated, the Sterling engine produces useful work. When work is done on the gas, it works as a refrigerator. This is reverse working of a Sterling cycle.

v. The reversed Sterling cycle is extensively used in the field of cryogenics to produces extremely low temperatures or to liquify air or gases used as working substance.

Q.54 Describe processes in a Sterling cycle in brief using p-V diagram.

Ans: The ideal Sterling cycle has two isothermal processes and two isobaric processes. Heat is absorbed at constant temperature T_H and rejected at constant temperature T_C. The four processesin a Sterling cycle are described briefly as:

i. **Isothermal expansion (AB):**
The gas is heated by supplying heat Q_H at constant temperature T_H. Useful work is done by the gas in this part of the cycle.

ii. **Isochoric process (BC):**

Part of the heat absorbed (Q_H) by the gas in the part AB of the cycle is released by the gas to the refrigerator. This heat (Q) is used in the next part of the cycle. The gas cools down to temperature T_C.
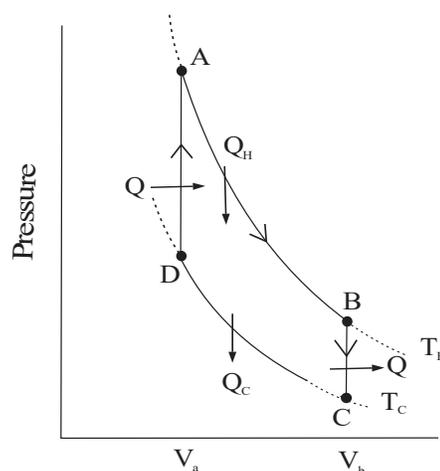
Sterling Cycle

iii. **Isothermal compression (CD):**
The heat generates in this part of cycles (Q_C) is rejected to the coolant (sink). The temperature of the gas is maintained at T_C during this process.

iv. **Isobaric heat absorption (DA):**
The compressed gas absorbs heat (Q) during this process. Its temperature is increased to T_H. The cycle repeats when the process reaches the point A.

Type 5

1. **A Carnot refrigerator operates between 250 K and 300 K. Calculate its coefficient of performance.**

Data: $T_C = 250$ K, $T_H = 300$K

To find: Coefficient of performance of refrigerator (K)

Formula: $K = \dfrac{T_C}{T_H - T_C}$

Solution:

$$K = \frac{T_C}{T_H - T_C}$$

$$K = \frac{250}{300 - 250} = 5$$

Ans : The coefficent of performance of refrigerator is 5.

2. **Efficiency of a Carnot cycle is 75%. If temperature of the hot reservoir is 727°C, calculate the temperature of the cold reservoir.**

Data: $\eta = 75\% = 0.75$, $T_H = 721°C = 1000K$

To find: Temperature of cold reservoir (T_C)

Formula:

$$\eta = \frac{T_H - T_C}{T_H}$$

Solution:

$$\eta = \frac{T_H - T_C}{T_H}$$

$$T_C = (1 - H)T_H$$
$$= (1 - 0.75)(1000)$$
$$= 250 \text{ K}$$
$$= (250 - 273)°C$$
$$= -23°C$$

Ans : The temperature of the cold reservoir is -23°C.

3. **A Carnot engine receives 2.0 kJ of heat from a reservoir at 500 K, does some work, and rejects some heat to a reservoir at 350 K.**

i. **How much work does it do?**
ii. **How much heat is rejected?**
iii. **What is its efficiency?**
iv. **Is there any simple way to calculate efficiency?**

Data: $Q_H = 2 \text{ kJ} = 2000 \text{ J}$, $T_H = 500 \text{ K}$, $T_C = 350 \text{ K}$

To find:
i. Heat rejected by heat engine (Q_C)
ii. Work done by engine (W)
iii. Efficiency of engine (η)

Formulae:

i. $\dfrac{|Q_C|}{|Q_H|} = \dfrac{T_C}{T_H}$

ii. $W = |Q_H| - |Q_C|$

iii. $\eta = 1 - \dfrac{T_C}{T_H}$

iv. $\eta = \dfrac{W}{Q_H}$

Solution:

$$\frac{|Q_C|}{|Q_H|} = \frac{T_C}{T_H}$$

$$Q_C = -Q_H \frac{T_C}{T_H}$$

The negative sign indicates that heat is rejected by the working substance.

$$\therefore \quad Q_C = -(2000)\left(\frac{350}{500}\right) = -1400J$$

$$W = |Q_H| - |Q_C|$$
$$W = |2000| - |1400| = 600J$$

$$\eta = 1 - \frac{T_C}{T_H}$$

$$\eta = 1 - \frac{350}{500} = \frac{500 - 350}{500} = \frac{150}{500} = 0.30$$
$$= 30\%$$

$$\eta = \frac{W}{Q_H}$$

$$= \frac{600}{2000} = 0.30 = 30\%$$

Ans : i. The heat rejected by the engine is -1400J.
ii. Work done by engine is 600 J.
iii. The efficieny of Carnot engine is 30%.

❑ ❑ ❑

PHYSICS