THERMODYNAMICS

Thermodynamics : It is a branch of physics in which we shall study the process where work is converted into heat and vice versa.

Thermodynamic variables : In thermodynamics the state of a gas is specified by macroscopic variables such as pressure, temperature, volume, mass and composition that are felt by our sense perceptions and are measurable.

Thermal equilibrium : In general at thermal equilibrium the temperatures of the two bodies or systems are equal.

In thermally isolated system it is said to be in thermal equilibrium if the thermodynamic variables such as pressure, volume, temperature, mass and composition do not change with time and they have fixed values.

Zeroth law of thermodynamics : It states that if two systems say A & B are in thermal equilibrium with a third system 'C' separately then the two systems A and B are also in thermal equilibrium with each other.

Note : The thermodynamic variable which has the same value when two systems are in thermal equilibrium is temperature 'T' only.

Internal energy : It includes only the energy associated with random motion of molecules of the system i.e. internal energy is simply the sum of kinetic and potential energies of these molecules. Internal energy is denoted by 'U'.

First law of thermodynamics : The heat energy (dQ) supplied to a system is partly used to increase its internal energy (dU) and the rest is used to do work (dW)

i.e. $dQ = dU + dW$. (OR)

Heat energy supplied to a system (dQ) always equals to the sum of change in internal energy (dU) and workdone (dW).

This law is a consequence of law of conservation of energy.

Isothermal expansion : If a system is taken through a thermodynamic process in which $\Delta U = 0$ then it is called isothermal process.

In isothermal process change in internal energy $\Delta U = 0$ i.e. temperature of the system is constant. Isothermal process obeys gas equation $PV = RT$.

Adiabatic process : In an adiabatic process system is insulated from the surroundings. So energy absorbed or released is zero ($\Delta Q = 0$). In adiabatic process temperature of the system may change. It follows the equation PV^{γ} = constant. Where $\gamma = \frac{C_P}{C_V}$ ratio of specific heats of a gas.

Isobaric process : In isobaric process pressure 'P' is kept constant, volume and temperature changes are permitted. Work done in isobaric process $W = P(V_2 - V_1) = \mu R(T_2 - T_1)$.

Isochoric process : In isochoric process volume (V) of the system is kept constant. Work done by isochoric process is zero. In this process heat energy absorbed is totally used to increase the internal energy of the system.

Cyclic process : In a cyclic process the system returns to initial state (P, V and T). Change in internal energy $\Delta U = 0$. Heat absorbed during cyclic process is equal to work done.

Reversible process : A thermodynamic process is said to be reversible if the process can be turned back such that both the system and surroundings return to their original state, with no other change any where else in universe.

Irreversible process : If a thermodynamic process cannot be reversed exactly in opposite direction of direct process then it is called irreversible process.

All spontaneous process of nature are irreversible.

Quasi static process : In a quasi static process at every stage the difference on pressure and temperature of systems and surroundings is infinitesimally small. i.e. $P + \Delta V \simeq P$ and $T + \Delta T \simeq T$.

In this process the thermodynamic variables (P,V,T) will change very slowly so that it remains in thermal and mechanical equilibrium with surroundings throughout that process.

Note : Quasi static process is an imaginary concept only.

Heat engines : A heat engine is a device by which a system is made to undergo a cyclic process. As a result heat is converted into work.

Work done by heat engine $W = Q_1 - Q_2$; efficiency $\eta = 1 - \frac{Q_2}{Q_1}$.

Important parts of heat engine : every heat engine mainly consists of 1) hot source, 2) working substance, 3) cold reservoir.

Refrigerators or heat pumps : A Refrigerator is a heat pump which is a reverse of heat engine. Here working substance extracts heat Q_2 from cold body at temperature T_2 and delivers it to hot reservoir at temperature T_1. Coefficient of performance of refrigerator $\alpha = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}$.

Second law of thermodynamics :

a) **Kelvin - Planck statement :** No process is possible whose sole resultant is the absorption of heat from a reservoir and the complete conversion of heat into work.

b) **Clausius statement :** No process is possible whose sole resultant is the transfer of heat from a colder object to a hotter object.

Second law of thermodynamics gives a fundamental limitation to the efficiency of heat engine i.e. heat released to a colder body will never become zero. So 100% efficiency of heat engine cannot be achieved.

Carnot engine : Carnot engine operates between a hot reservoir of temperature T_1 and a cold reservoir of temperature T_2 through a cyclic process.

This cyclic process consists of 1) Isothermal expansion, 2) Adiabatic expansion, 3) Isothermal compression and 4) Adiabatic compression.

In this cyclic process it absorbs heat energy Q_1 from source and releases heat energy Q_2 to cold reservoir efficiency of Carnot engine $\eta = 1 - \frac{T_2}{T_1}$.

Carnot theorem : (a) Any heat engine working between two given temperatures T_1 and T_2 cannot have efficiency more than that of carnot engine. (b) The efficiency of a carnot engine is independent of nature of working substance.

Isotherm : The pressure (p) and volume (v) curve for a given temperature is called isotherm.

adiabatic wall : An insulating wall that does not allow heat energy to flow from one side to another side is called adiabatic wall.

diathermic wall : It is a conducting wall which transfers heat energy from one side to another side.

Heat mechanical equivalent (J) : In M.K.S system heat and work are measured with same unit 'joule'. But in C.G.S system heat is measured in calorie and work in erg (1 joule = 10^7 erg).

So in C.G.S system a conversion factor heat mechanical equivalent (J) is used to convert work into heat or vice versa.

1 Calorie = 4.2 Joules $\Rightarrow$ J = 4.2 Joule/cal. or J = 4200 joule/kilocal.

Calorie : The amount of heat energy required to rise the temperature of 1 gram of water through 1°C or 1 K is defined as calorie.

Note : Magnitude of calorie slightly changes with the initial temperature of water.

Mean 15 °C calorie : The amount of heat energy required to rise the temperature of 1 gram of water from 14.5 °C to 15.5 °C is called mean 15 °C calorie.

★ From 1st Law of thermodynamics, $dQ = dU + dW$

★ Heat capacity of a body = $\frac{\Delta Q}{\Delta t}$ = mc (i.e., mass × specific heat)

★ Specific heat S or C = $\frac{\Delta Q}{m\,\Delta t} = \frac{\text{Heat energy supplied}}{\text{mass} \times \text{temperature difference}}$

★ From method of mixtures, Heat lost by hot body = Heat gained by cold body

★ When two spheres of radii $r_1 : r_2$ and ratio of specific heats $S_1 : S_2$ and densities $\rho_1 : \rho_2$ then their

thermal capacities ratio = $\frac{m_1 S_1}{m_2 S_2} = \left(\frac{r_1}{r_2}\right)^3 \left(\frac{\rho_1}{\rho_2}\right)\left(\frac{S_1}{S_2}\right)$

★ a) Specific heat of a gas, $C_p = \Delta Q / m\Delta T$

b) Molar specific heat, $C_p = \frac{\Delta Q}{n\Delta t}$ (n = Number of moles)

c) Ratio of specific heats, $\gamma = C_P / C_V$; $C_V = \frac{R}{\gamma - 1}$, $C_P = \frac{\gamma R}{\gamma - 1}$

$$C_V = \frac{C_V}{M} = \frac{1}{M}\frac{R}{(\gamma-1)} = \frac{PV}{M(\gamma-1)T}\,\frac{P}{\rho T(\gamma-1)}\ \text{J/kg–K or } C_V = \frac{P}{J\rho T(\gamma-1)}\ \text{k.cal/kg.K}$$

- Work done in expanding a gas against constant pressure (P) is $W = P\,dV$.
- Work done during ideal expansion

  a) $W = P(V_2 - V_1)$ or $W = nR(T_2 - T_1)$

  n = number of moles of gas; R = universal gas constant.
- Relation between C_P and C_V is $C_P - C_V = R$.
- Isothermal relation between P, V & T is $PV = RT$ or $PV = nRT$.
- Adiabatic relation between P, V & T are

  1) PV^{γ} = constant 2) $TV^{\gamma-1}$ = constant 3) $PV^{1-\gamma}T^{\gamma}$ = constant.
- Work done in Isothermal process

  a) $W = RT \log_e \frac{V_2}{V_1}$ b) $W = 2.303\,RT \log_{10} \frac{V_2}{V_1}$

VERY SHORT ANSWER QUESTIONS (2 Marks)

1. **Define Thermal equilibrium. How does it lead to Zeroth Law of Thermodynamics ?**

A. **Thermal Equilibrium :** A thermodynamical system is said to be in thermodynamical equilibrium when macroscopic variables (like pressure, volume, temperature, mass, composition etc.) that characterise the system do not change with time.

Generally at thermal equilibrium the temperature of two systems is same. This concept leads to Zeroth law of thermodynamics.

Zeroth law of thermodynamics : It states that if two systems say A & B are in thermal equilibrium with a third system 'C' separately then the two systems A and B are also in thermal equilibrium with each other.

2. **Define Calorie. What is the relation between calorie and mechanical equivalent of heat ?**

A. **Calorie :** The amount of heat required to rise the temperature of 1g of water by 1°C is called calorie.

Relation between calorie and mechanical equivalent of heat is, 1 calorie = 4.2 J.

3. **What thermodynamic variables can be defined by a) Zeroth Law b) First Law ?**

A. Zeroth law defines temperature and first law defines internal energy.

4. **Define specific heat capacity of the substance. On what factors does it depend ?**

A. **Specific heat capacity :** The quantity of heat required to rise the temperature of unit mass of the substance through 1°C or 1K is called the specific heat capacity of the substance.

$$S = \frac{dQ}{m.dT}$$

The specific heat capacity depends upon the factors like temperature and nature of the substance.

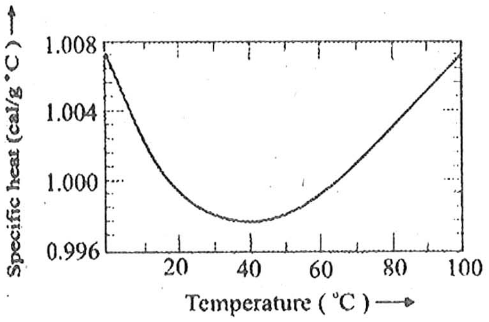
5. **Define molar specific heat capacity.**

A. **Molar specific heat capacity :** It is defined as the amount of heat required to rise the temperature of one mole of a gas through 1°C or 1K.

6. For a solid, what is the total energy of an oscillator ?

A. For a solid, the total energy of an oscillator can be expressed as the sum of its potential and kinetic energies.

7. Indicate the graph showing the variation of specific heat of water with temperature. What does it signify ?



Variation of specific heat capacity of water with temperature

A. The variation of specific heat of water with the temperature is as shown in the graph.

From the graph, we find that at $T = 15°C$, specific heat of water, $S = 1$ calg^{-1} °C^{-1}

At $T = 0°C$, $S = 1.008$ Calg^{-1} °C^{-1}, the highest and at $T = 30°C$, $s = 0.9976$ Calg^{-1} °C^{-1}, the lowest and beyond 30°C, specific heat of water increases slightly with rise in temperature.

At $T = 100°C$, specific heat of water is 1.0057 cal g^{-1} °C^{-1}.

It signifies that the specific heat of water decreases with increase in temperature from 0° to 30°C and increases from 30° – 100°C.

8. Define state variables and equation of state.

A. **State variables :** The variables which determine the thermodynamic behaviour of a system are called state variables.

If the system is a gas, then P, V and T (for a given mass) are called state variables.

Equation of state : The general relationship between pressure, volume and temperature for a given mass of the system (eg., gas) is called equation of the state.

For n moles of an ideal gas, the equation of state is, $PV = nRT$.

9. Why a heat engine with 100% efficiency can never be realised in practise ?

A. The efficiency of heat engine, $\eta = 1 - \frac{T_2}{T_1}$

The efficiency will be 100%, or 1, if $T_2 = 0K$ or $T_1 = \infty$.

Since, both these conditions cannot be attained practically, a heat engine cannot have 100% efficiency.

10. In summer, when the valve of a bicycle tube is opened, the escaping air appears cold. Why ?

A. This happens due to adiabatic expansion of the air in the tube of the bicycle. Hence the air cools.

11. Why does the brake drum of an automobile get heated up while moving down at constant speed ?

A. When an automobile moving down with constant speed its potential energy decreases. This decrease in potential energy is converted in the form of heat energy. As a result the break drum of an automobile get heated.

12. Can a room be cooled by leaving the door of an electric refrigerator open ?

A. No. When a refrigerator is working in a closed room with its door closed, it is rejecting heat from inside to the air in the room. So, temperature of room increases gradually.

When the door of refrigerator is kept open, heat rejected by the refrigerator to the room will be more than the heat taken by the refrigerator from the room. Therefore, temperature of room will increase at a slower rate compared to the first case.

Hence, a room cannot be cooled by leaving the door of an electric refrigerator open.

13. Which of the two will increase the pressure more, an adiabatic or an isothermal process, in reducing the volume to 50% ?

A. In an adiabatic process, no exchange of heat is allowed between the system and surroundings. Hence, the work done during reducing the volume to 50% results in the increase in the temperature of the system thereby further increase in the pressure ($\because PV = RT$). In case of isothermal compression, the excess heat is exchanged with the surroundings, maintaining constant temperature. Hence the increase in pressure is only due to decrease in volume obeying Boyle's law.

Hence adiabatic compression increases the pressure more than isothermal compression.

14. A thermos flask containing a liquid is shaken vigorously. What happens to its temperature ?

A. Temperature of the liquid increases, because work is done in shaking the liquid. $W \propto Q$.

15. A sound wave is sent into a gas pipe. Does its internal energy change ?

A. Yes, the internal energy changes when a sound wave is sent into a gas pipe. Because, the sum of all the energies contained in the system in equilibrium is called its internal energy.

16. How much will be the internal energy change in

i) isothermal process ii) adiabatic process

A. i) In an isothermal process, T = constant i.e., $dT = 0$ $\therefore dU = 0$

So, in a isothermal process, the internal energy does not change.

ii) In an adiabatic process, Q = constant i.e., $dQ = 0$ $\therefore dU = -dW \neq 0$

So, in an adiabatic process, the change in internal energy is equal to the amount of work done.

17. The coolant in a chemical or a nuclear plant should have high specific heat. Why ?

A. Specific heat of a substance is the amount of heat required to raise the temperature of unit mass of the substance through 1°C or 1K. The coolant in a chemical or nuclear plant should be able to absorb more amount of heat released from the plant. Hence, the coolant should have high specific heat.

18. Explain the following processes i) Isochoric process ii) Isobaric process

A. **i) Isochoric process :** The process that occurs at constant volume is called Isochoric process or Isovolumic process. $\therefore dV = 0$.

ii) Isobaric process : The process that occurs at constant pressure is called Isobaric process.

$\therefore dP = 0$

SHORT ANSWER QUESTIONS (4 Marks)

1. State and explain first law of thermodynamics.

A. First law of thermodynamics :

The heat energy (dQ) supplied to a system is equal to the sum of the increase in the internal energy (dU) of the system and external work done (dW) by it

i.e. $dQ = dU + dW$ ....(1)

If dV is the increase in the volume under constant pressure (P) then $dW = PdV$.

$\therefore\ dQ = dU + PdV$ ....(2)

The importance of this law is that it defines, the thermodynamic quantity, internal energy which has a fixed value in a state.

Increase in internal energy $dU = nC_vdT$

Where n is the number of moles of the gas. This equation helps to calculate change of internal energy of the system when the temperature change by ΔT.

Limitations of 1st law of thermodynamics : 1st law of thermodynamics has two limitations.

1) It does not tell about the direction of heat flow. That is it does not specify the conditions under which a body can use the heat energy to produce the work.
2) It does not give any information about the efficiency with which heat can be converted into work.

2. Define two principal specific heats of a gas. Which is greater and why ?

A. The two principal specific heats of a gas are

i) Specific heat of a gas at constant volume (C_v)

ii) Specific heat of a gas at constant pressure (C_p)

i) Specific heat of a gas at constant volume (C_v) : It is defined as the amount of heat energy required to raise the temperature of one gram of gas through 1°C or 1K, when volume of the gas is kept constant.

It is measured in $cal.g^{-1}.K^{-1}$ or $J.g^{-1}.K^{-1}$.

ii) Specific heat of a gas at constant pressure (C_p) : It is defined as the amount of heat energy required to raise the temperature of one gram of gas through 1°C or 1K, when pressure of the gas is kept constant.

It is also measured in $cal.\ g^{-1}.K^{-1}$ or $J.g^{-1}.K^{-1}$.

Out of the two principal specific heats of a gas, $C_p > C_v$. This can be justified as follows :

a) When heat is given to a gas at constant volume, it is only used in increasing the internal energy of the gas, i.e., in raising the temperature of the gas and no heat is spent in the expansion of the gas.

b) When heat is given to a gas at constant pressure, it is spent in two ways :

   i) Part of the heat is increasing the internal energy of the gas and hence the temperature of the gas.

   ii) Remaining amount of heat is used in doing work i.e., in the expansion of the gas against the external pressure.

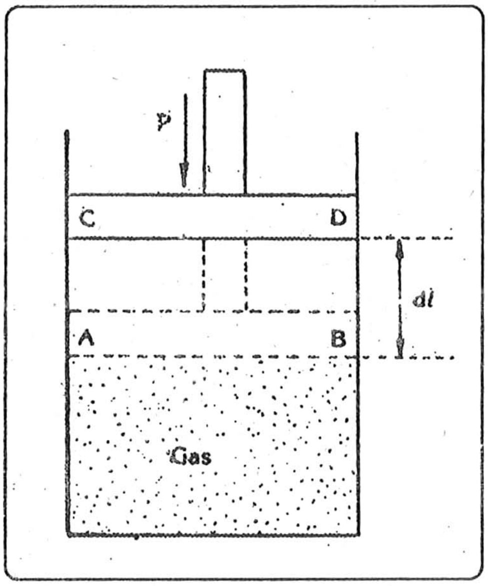
   Therefore to raise the temperature of 1 mole of a gas through 1°C or 1K, more heat is required at constant pressure (C_p) than at constant volume (C_p). Hence, $C_p > C_v$.

3. Derive a relation between the two specific heat capacities of gas on the basis of first law of thermodynamics.

A. *Relationship between the two specific heat capacities of gas :*

To derive $C_P - C_V = R$:

Let one gram mole of given mass of gas is enclosed within a cylinder with a frictionless air tight-piston. Let P, V be the pressure and volume of the gas at a temperature T.



i) In specific heat at constant volume, the volume of the given mass of gas must remain constant. Hence, the piston is fixed in position AB.

Let C_V be the amount of heat energy supplied. It is utilised only to raise the temperature of the gas by 1°C.

$\therefore dU = C_V dT$

ii) In specific heat at constant pressure, the pressure must remain constant. Hence the piston is allowed to move freely. The amount of heat energy supplied is used not only to do external work but also to increase the temperature of the gas by 1°C.

In this case the piston moves forward and work is done against external pressure. Suppose by the time the piston moves from AB to CD, the temperature increases by 1°C.

Let the work done in moving the piston through a distance 'dl' be dW.

The energy supplied has to increase the internal energy and to do external work.

$\therefore C_P dT = dQ = dU + dW$

From first law of thermodynamics $dQ = dU + dW$

$\therefore C_P dT = C_V dT + dW$

$(C_P - C_V)\, dT = dW = PdV$

But work done, $dW = F \times S$

$= P \times A \times dl$ (where A is area of cross section of the piston) $= PdV$

But $PV = RT$ (for one mole of gas).

$\therefore dW = PdV = RdT$ OR $(C_P - C_V)\, dT = RdT$

But change of temperature $= dT = 1°C$ (from definition of specific heat)

$\therefore C_P - C_V = R$

So difference of molar specific heats of the gas is equals to universal gas constant R.

4. Obtain an expression for the work done by an ideal gas during isothermal change.

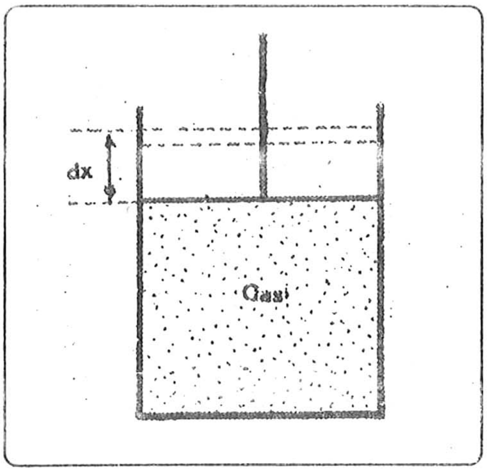
A. *Work done during isothermal process :*

Consider n mole of a perfect gas contained in a cylinder. When the piston moves through a small distance dx, then small work dW will be done by it

$\therefore dW = P\, a\, dx = P\, dV,$

where a is the area of cross-section of the piston.

Therefore, when the system goes from initial state A (P_1, V_1) to the final state B (P_2, V_2), the amount of work done,



$$W = \int_{V_1}^{V_2} PdV \quad \text{.....................} \quad (1)$$

But $PV = nRT$ (or)

$$P = \frac{nRT}{V}$$

Substituting for P in equation (1), we have

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

During an isothermal process, temperature remains constant.

$$\therefore \; W_{iso} = nRT \int_{V_1}^{V_2} \frac{1}{V} dV = nRT \left[\log_e V\right]_{V_1}^{V_2}$$

$$= nRT \left[\log_e V_2 - \log_e V_1 \right]$$

$$\text{or} \quad W = nRT \log_e \frac{V_2}{V_1} = 2.303 \, nRT \log_{10} \frac{V_2}{V_1}$$

$\therefore$ Work done in an isothermal process $= 2.303 \, nRT \log_{10} \left(\frac{V_2}{V_1} \right)$

All the heat supplied to the gas is used only to do work since temperature remains constant, internal energy does not change.

$\therefore \; dQ = PdV$

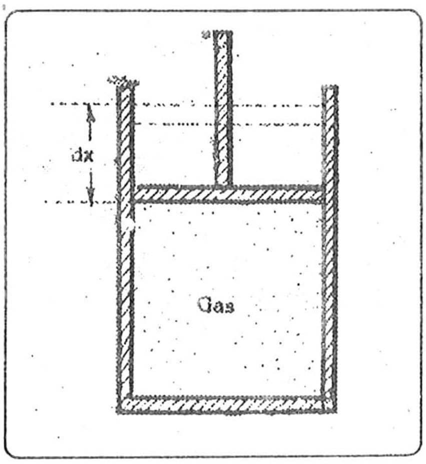
5. Obtain an expression for the work done by an ideal gas during adiabatic change and explain.

A. *Work done during Adiabatic process :*

Consider n mole of perfect gas contained in a cylinder having insulating walls. When piston moves through a small distance dx, then small work (dW) will be done.

$\therefore \quad dW = (Pa)\, dx = PdV,$

where a is area of cross-section of the piston. Therefore, when the system goes from initial state A (P_1, V_1) to the final state B (P_2, V_2) the amount of work done,



$$W = \int_{V_1}^{V_2} PdV \quad \text{.....................} \quad (1)$$

For an adiabatic change,

$PV^{\gamma} = K$ (a constant)

or $P = KV$

Substituting for P in equation (1), the work done in an adiabatic process

$$W_{adi} = \int_{V_1}^{V_2} KV^{-\gamma}dV = K\int_{V_1}^{V_2} V^{-\gamma}dV$$

$$= K\left[\frac{V^{1-\gamma}}{1-\gamma}\right]_{V_1}^{V_2} = \frac{K}{1-\gamma}\left[V_2^{1-\gamma} - V_1^{1-\gamma}\right] = \frac{1}{\gamma-1}\left[KV_1^{1-\gamma} - KV_2^{1-\gamma}\right]$$

Since, $K = P_1V_1^{\gamma} = P_2V_2^{\gamma}$

$$W_{adi} = \frac{1}{\gamma-1}\left[P_1V_1^{\gamma}V_1^{1-\gamma} - P_2V_2^{\gamma}V_2^{1-\gamma}\right] = \frac{1}{\gamma-1}\ [\ P_1V_1 - P_2V_2\ ]$$

$\therefore$ Work done in adiabatic process, $W = \dfrac{1}{\gamma-1}\ [\ nRT_1 - nRT_2\ ]$

Since $P_1V_1 = nRT_1$ and $P_2V_2 = nRT_2$

$$= \frac{nR}{\gamma-1}\ (T_1 - T_2)$$

$\therefore$ Work done in adiabatic change $W = \dfrac{nR}{(\gamma-1)}\ (T_1 - T_2)$

Since heat is not supplied to the gas, it can do work only by expanding its internal energy. $dQ = 0 = dU + PdV$ or $PdV = -dU$. So the gas cools in adiabatic expansion.

6. **Compare isothermal and an adiabatic process.**

A.

Isothermal changes	**Adiabatic changes**
1. Temperature (T) remains constant, i.e., $\Delta T = 0$	1. Heat content (Q) remains constant, i.e., $\Delta Q = 0$.
2. System is thermally conducting to the surroundings.	2. System is thermally insulated from the surroundings.
3. The changes occur slowly.	3. The changes occur suddenly.
4. Internal energy (U) remains constant, i.e., $\Delta U = 0$.	4. Internal energy changes, i.e., $U \neq$ constant $\therefore \Delta U \neq 0$.
5. Specific heat becomes infinite.	5. Specific heat becomes zero.
6. Equation of isothermal changes is PV = constant.	6. Equation of adiabatic changes is PV^{γ} = constant
7. Slope of isothermal curve, $\frac{dP}{dV} = -(P/V)$	7. Slope of adiabatic curve, $\frac{dP}{dV} = -\gamma(P/V)$
8. Coefficient of Isothermal elasticity; $E_i = P$	8. Coefficient of adiabatic elasticity ; $E_a = \gamma P$

7. Explain the following processes

i) Cyclic process with example

ii) Non cyclic process with example

A. i) Cyclic process : A process in which the system after passing through various stages such as change in pressure, volume and temperature etc. returns to its initial state is defined as cyclic process.

For a thermodynamic system the internal energy of the system depends on thermodynamic variables such as pressure, volume, temperature etc. In cyclic process the system finally returns to the initial state and it is in thermal equilibrium with surroundings. So change in internal energy of the system $dU = 0$.

Hence, in a cyclic process work done is equal to energy absorbed in the cyclic process.

So for cyclic process $dU = 0$ and $dQ = dW$.

Example : Generally all heat engines (or) refrigerators are operated in cyclic process.

ii) Non-cyclic process : A non-cyclic process consists of a series of changes involved do not return the system back to its initial state.

Example : Suppose a gas with variables P_1, V_1, T_1 is taken through a series of different states subjecting to a number of changes including isothermal expansions and compressions. In the final state, if the system does not come back to $P_1V_1T_1$, then the gas is said to be undergo a non-cyclic process.

Work done in a non cyclic process depends upon the path chosen or the series of changes involved.

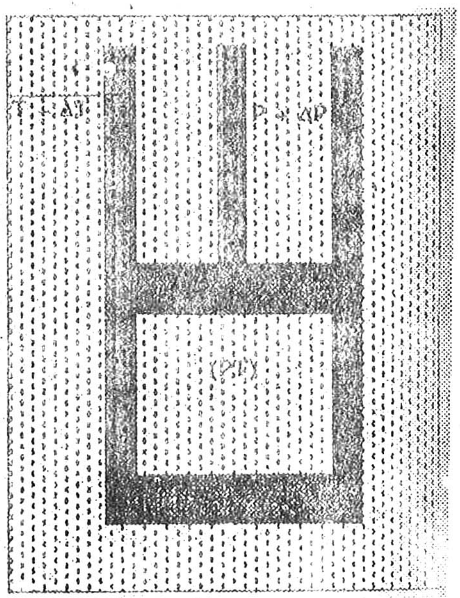
8. Write a short note on Quasi-static process.

A. Quasi-static process : A Quasi-static process can be defined as an infinitesimally show process in which at each and every intermediate stage the system remains in thermal and mechanical (thermodynamic) equilibrium with the surroundings through out the entire process.

Explanation : A non-equilibrium thermodynamic system can be treated as an idealized process in which at every stage the system is in equilibrium state.

In a thermodynamic system let the piston moves in a frictionless manner. Instead of sudden compression of piston imagine the piston moves very very slowly i.e., it appears almost static. Then the pressure inside the cylinder $P + \Delta P$ and temperature $T + \Delta T$ are almost equal to external pressure P and temperature T.

Since for extremely slow process the values of ΔP and ΔT are so small that we can treat $P + \Delta P = P$ and $T + \Delta T = T$. Such type of process is called Quasi static process.



A Quasi-static process

For Example, to take a gas from the state (P, T) to another state ($P^{|}$, $T^{|}$), via a quasi – static process, we change the external pressure / temperature by a very small amount and allow the system to equalise its pressure / temperature with the surroundings. Continue the process infinitely slowly till the final state ($P^{|}$, $T^{|}$) is attained.

A quasi – static process is a hypothetical construct. The process must be infinitely slow, should not involve large temperature differences or accelerated motion of the piston of the container.

9. **Explain qualitatively the working of a heat engine.**

A. **Heat engine :** A heat engine is a device used to convert heat energy into mechanical work.

Generally heat engines will work in a cyclic process. Heat engine consists of three important units.

1) **Source :** Which is an object or system at high temperature. A heat engine will absorb heat energy Q_1 from source.
2) **Working substance :** Every heat engine requires a working substance to do work. Generally the working substance is like steam or fuel vapour and air mixture etc. A part of heat energy of working substance is converted into mechanical work.
3) **Sink :** In every heat engine heat energy content of working substance is not converted into work totally. So some energy (Q_2) is wasted or rejected by the engine. This rejected energy (Q_2) is delivered to some other body or system at low temperature. This body with low temperature is called sink.

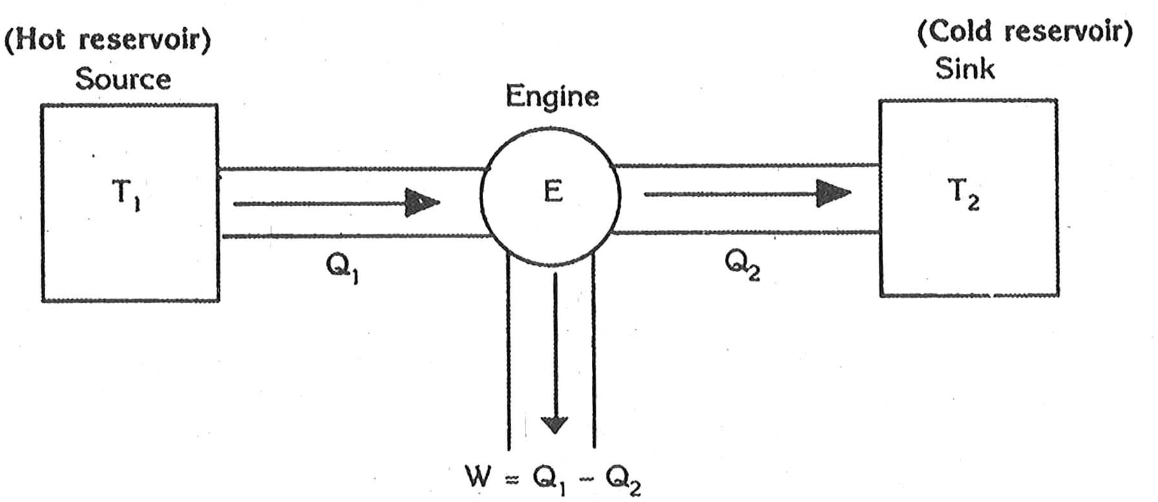
Efficiency of heat engine, $\eta = \frac{\text{Work done}}{\text{Heat energy supplied}} = \frac{W}{Q_1}$ (But $W = Q_1 - Q_2$)

(or) $\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} \Rightarrow \eta = 1 - \frac{Q_2}{Q_1}$ where

Q_1 = heat energy supplied by source

Q_2 = heat energy delivered to sink

Block diagram of heat engine is as shown.



Block diagram of Heat Engine

LONG ANSWER QUESTIONS (8 Marks)

1. **Explain reversible and irreversible processes. Describe the working of Carnot engine. Obtain an expression for the effieciency.** **(March 2014)**

A. **Reversible process :** In reversible process a thermodynamic system can be retraced back in opposite direction to the changes that take place in the direct process or in forward process. Finally the system must be in thermal equilibrium with surroundings even other returning to original state with no other change any where else in the universe.

A reversible process is only an ideal concept.

Conditions for reversible process : A reversible process must obey the following conditions.

1) Changes must take place at an infinitesimally slow rate.

2) The system must always be in thermal and mechanical equilibrium with surroundings.

3) There should be no loss of energy in any form.

4) No amount of heat is to be converted into electric or magnetic forms.

Examples for reversible process :

1) Peltier effect and Seebeck effect.

2) Fusion of ice and vapourisation of water.

Irreversible process : A thermodynamic process that cannot be taken back in opposite direction is called an irreversible process.

Examples :

1) Work done against friction.

2) Magnetization of materials.

In an irreversible process the thermodynamic system cannot be operated in reverse direction without loss of energy or system cannot be taken to original state without loss of energy.

3) All spontaneous natural processes are irreversible.

4) Diffusion of gases.

5) Joule heating in a conductor by passing current through it.

Carnot's Engine : Carnot's engine works on the principle of reversible process within the temperatures T_1 and T_2.

It consists of four continuous processes. The total process is known as Carnot Cycle.

Step 1 : In Carnot cycle the 1st step consists of isothermal expansion of gases. So temperature T is constant, P, V changes are shown as $P_1V_1T_1 \xrightarrow{to} P_2V_2T_1$

Work done in isothermal process

$$W_{1\to 2} = Q_1 = \mu RT_1 \log_e\left(\frac{V_2}{V_1}\right) \qquad \text{.............} (1)$$

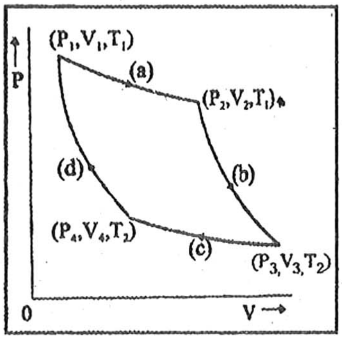
Step 2 : In this stage gases will expand adiabatically. So energy to the system Q is constant.

So P, V relation is

$P_2V_2T_1 \xrightarrow{\text{to}} P_3V_3T_2$

Work done in adiabatic process

$$W_{2\to3} = \frac{\mu R(T_1 - T_2)}{\gamma - 1} \qquad \text{.............. (2)}$$



Step 3 : In this stage gases will be compressed isothermally. So P_1V changes are

$P_3V_3T_2 \xrightarrow{\text{to}} P_4V_4T_2$

Work done in isothermal compression

$$W_{3\to4} = Q_2 = \mu RT \log_e\left(\frac{V_3}{V_4}\right) \qquad \text{.............. (3)}$$

Step 4 : In the fourth stage the gas suffers adiabatic compression and returns to original stage.

So P, V changes are $P_4V_4T_2 \xrightarrow{\text{to}} P_1V_1T_1$

$$\text{Work done } W_{4\to1} = \mu R\frac{(T_2 - T_1)}{\gamma - 1} \qquad \text{.............. (4)}$$

Total work done in Carnot Cycle $W = W_{1,2} + W_{2,3} + W_{3,4} + W_{4,1}$

$$\text{Total work done } W = \mu RT_1 \log\left(\frac{V_2}{V_1}\right) + \frac{\mu R}{\gamma - 1}(T_1 - T_2) - \mu RT_2 \log\left(\frac{V_3}{V_4}\right) - \frac{\mu R}{\gamma - 1}(T_1 - T_2)$$

$$\therefore W = \mu RT_1 \log\left(\frac{V_2}{V_1}\right) - \mu RT_2 \log\left(\frac{V_3}{V_4}\right)$$

The total work done $W = Q_1 - Q_2$ i.e., the difference to heat energy absorbed from source and heat energy given to sink

$$\text{Efficiency of Carnot engine } \eta = \frac{\text{work done by Carnot engine}}{\text{heat energy supplied}}$$

$$\therefore \eta = \frac{Q_1 - Q_2}{Q_1} \text{ or } \eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

2. **State second law of thermodynamics. How is heat engine different from a refrigerator ? (May 2014)**

A. ***Second Law of Thermodynamics :*** First law of thermodynamics is based on Law of conservation of energy, while second law of thermodynamics gives information about the transformation of heat energy. There are two conventional statements of second law depending on common experience.

   1) Kelvin-Plank statement : It is impossible for an engine working in a cyclic process to extract heat from a hot body and to convert it completely into work. In other words 100% conversion of heat into work is impossible.

2) ***Clausius Statement :*** It is impossible for a self acting machine, unaided by any external agency to transfer heat from a cold body to a hot reservoir. In other words heat cannot by itself flow from a colder body to a hotter body.

Both statements are identical : Suppose a heat engine absorbs heat from a hot body, converts a part of it into work and rejects the rest of heat to a body at lower temperature. When temperatures of both become equal, flow of heat stops and the engine stops working.

Heat engine : A heat engine is a device used to convert heat energy into mechanical work. Generally heat engines will work in a cyclic process. Heat engine consists of three important units.

1) **Source :** Which is an object or system at high temperature. A heat engine will absorb heat energy Q_1 from source.
2) **Working substance :** Every heat engine requires a working substance to do work. Generally the working substance is like steam or fuel vapour and air mixture etc. A part of heat energy of working substance is converted into mechanical work.
3) **Sink :** In every heat engine heat energy content of working substance is not converted into work totally. So some energy (Q_2) is wasted or rejected by the engine. This rejected energy (Q_2) is delivered to some other body or system at low temperature. This body with low temperature is called sink.

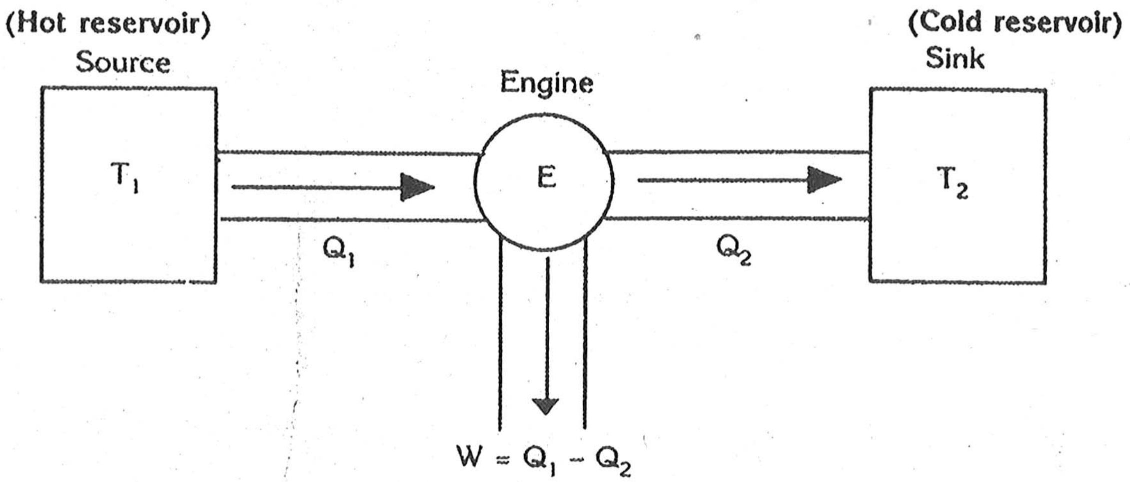
Efficiency of heat engine, $\eta = \dfrac{\text{Work done}}{\text{Heat energy supplied}} = \dfrac{W}{Q_1}$ (But $W = Q_1 - Q_2$)

(or) $\eta = \dfrac{W}{Q_1} = \dfrac{Q_1 - Q_2}{Q_1} \Rightarrow \eta = 1 - \dfrac{Q_2}{Q_1}$ where

Q_1 = heat energy supplied by source

Q_2 = heat energy delivered to sink

Block diagram of heat engine is as shown.



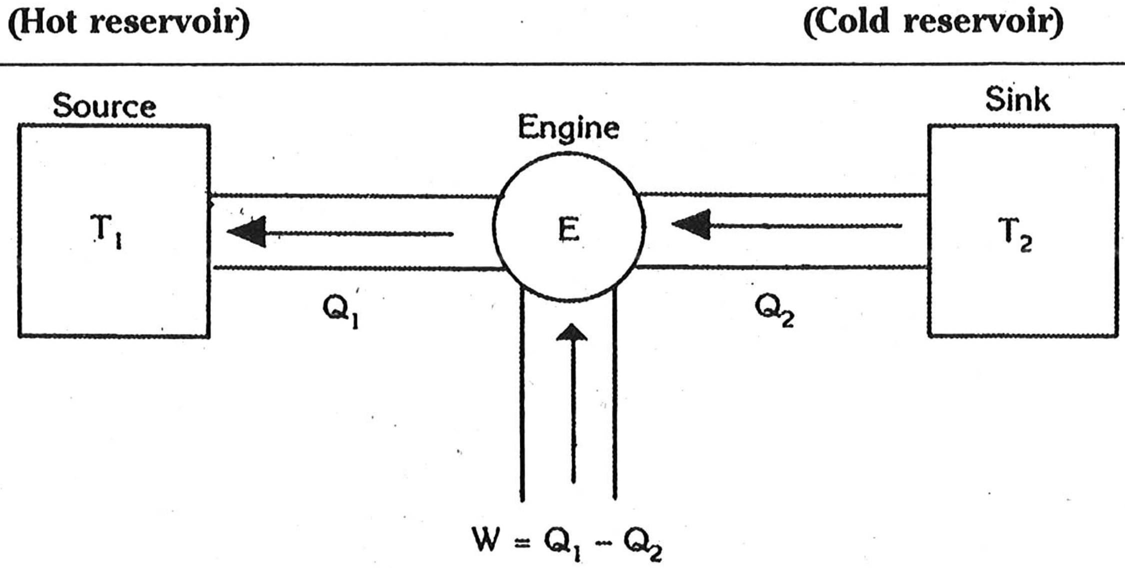
Block diagram of Heat Engine

Refrigerator : A refrigerator works in the reverse process of heat engine. It extracts heat energy Q_2 from sink i.e., from low temperature body with the help of external work and delivers heat energy Q_1 to high temperature body called source.

Work done $W = Q_1 - Q_2$.

In refrigerators external work is done on working substance.

A block diagram of refrigerator is as shown.



Block diagram of Refrigerator

Refrigerator extracts heat energy from sink i.e., from low temperature body with the help of external work and delivers heat energy to high temperature body called source. A heat engine will absorb heat energy from source and reject heat energy to the sink. Heat engine will work in a reversible process but the refrigerator works in the reverse process of heat engine.