# 11 Thermodynamics


*Cooling machines, such as refrigerators and air conditioners, actually use heat, simply reversing the usual process by which particles are heated. The refrigerator pulls heat from its inner compartment and transfers it to the outside region. This is why the back of a refrigerator is warm. You will study such a phenomenon of thermodynamics in this chapter.*

## Topic Notes

- *Temperature and the First Law of Thermodynamics*
- *Second Law of Thermodynamics and Carnot Engine*

# TEMPERATURE AND THE FIRST LAW OF THERMODYNAMICS 1

## TOPIC 1

## SYSTEM OF THERMODYNAMICS

### Thermal equilibrium

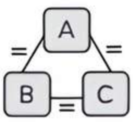
Thermal equilibrium is a situation in which two objects would not exchange energy by heat or electromagnetic radiation if they were placed in thermal contact. Heat is the transfer of energy from one object to another object as a result of a difference in temperature between them. It is the investigation of the interactions between heat and other forms of energy.

#### System of Thermodynamics

A large collection of matter molecules (solid, liquid or gas) that are as arranged so that they have specific pressure values. A thermodynamic system is made up of volume and temperature. The pressure, volume, temperature, internal energy and other factors that influence the state or condition of a system are referred to as thermodynamic state variables. We deal with thermodynamic systems in thermodynamics as a whole and investigate the interaction of heat and energy during the transition from one thermodynamic state to another.

### Zeroth law of thermodynamics

If objects A and B are separately in thermal equilibrium with a third object C (say thermometer), then objects A and B are in thermal equilibrium with each other. Zeroth law of thermodynamics introduces the concept of temperature. Two objects (or systems) are said to be in thermal equilibrium if their temperature are the same.




In measuring the temperature of a body, it is important that the thermometer should be in thermal equilibrium with the body whose temperature is to be measured.

**Example 1.1: When frozen at 0°C and at normal atmospheric pressure, the volume of 1g of water increases from 1 cm³ to 1.091 cm³. What will happen to its internal energy? Normal atmospheric pressure is 1.013 × 10⁵ N/m² and ice's latent heat of fusion is 80 cal/g. [NCERT]**

**Ans.** Heat released by water on freezing,

$$Q = -mL$$
$$= -1 \times 80 = -80 \text{ cal}$$
$$= -336 \text{ J}$$

During freezing water expands against the atmospheric pressure.

Hence, work done in the process

$$W = P\Delta V$$
$$= (1.013 \times 10^5) \times (1.091 - 1) \times 10^{-6}$$
$$= 0.092 \text{ J}$$

By the first law of thermodynamics

$$Q = \Delta U + W$$

or
$$-336 = \Delta U + 0.092$$
$$\Delta U = -336.092 \text{ J}$$

**Example 1.2: At atmospheric pressure and 100°C temperature, 1.0 $m^3$ of water is converted into 1671 $m^3$ of steam. Water has a latent heat of vaporisation of 2.3 × $10^6$ J/kg. How much internal energy will be gained if 2.0 kg of water is converted into steam at atmospheric pressure and 100°C temperature? Water density is 1.0 × $10^3$ kg/$m^3$, and atmospheric pressure is 1.01 × $10^5$ N/$m^2$. [NCERT]**

**Ans.** Heat given to water to change into steam,

$$Q = ML$$
$$= 2.0 \times 2.3 \times 10^6$$
$$= 4.6 \times 10^6 \text{ J}$$

Volume of water

$$V = \frac{\text{Mass}}{\text{Density}}$$
$$= \frac{2.0}{10^3} = 2.0 \times 10^{-3} \text{ m}^3$$

Volume of steam formed will be,

$$= 2.0 \times 10^{-3} \times 1671$$
$$= 3342 \times 10^{-3} \text{ m}^3$$

The change in volume in the process,

$$\Delta V = V$$
$$= (3342 \times 10^{-3}) - (2.0 \times 10^{-3})$$
$$= 3340 \times 10^{-3} \text{ m}^3$$

The work done against the atmospheric pressure;

$$W = P\Delta V$$
$$= (1.01 \times 10^5) \times (3340 \times 10^{-3})$$
$$= 0.337 \times 10^6 \text{ J}$$

By the first law of thermodynamics,

$$Q = \Delta U + W$$
$$\Delta U = Q - W$$
$$= 4.6 \times 10^6 - 0.337 \times 10^6$$
$$= 4.263 \times 10^6 \text{ J}$$

Here, the positive value of ΔU indicates that internal energy in the process increases.

# TOPIC 2

## HEAT, WORK AND INTERNAL ENERGY

Internal Energy is the energy that any system possesses as a result of its molecular K.E. and molecular P.E. Here, K.E. and P.E. are in relation to the centre of mass frame. This internal energy is entirely dependent on the state and thus a state variable. The only source of internal energy for a real gas is its molecular unit.

Equation of Internal Energy is,

$$\frac{nfRT}{3} \text{ for ideal gases.}$$

Where,

$n$ = number of moles

$f$ = Degree of freedom

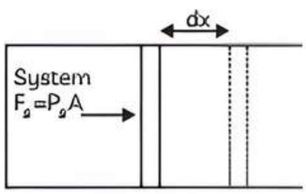
R = Universal Gas Constant

T = Temperature (in Kelvin)

Internal energy can be changed by either supplying heat energy or performing work.

Heat energy is the energy that is transferred to or from a system due to temperature differences via conduction, convection or radiation.

The energy that is transferred from one system to another by force moving its point of application in its direction is called work.




Work done by the system

$$W = \int F dx$$

$$W = \int P_g A dx$$

$$W = \int P_g dv$$

Where $P_g$ is the pressure of the system on the piston. This work done by the system is positive if the system expands and it is negative if the system contracts.

(1) Work and heat are path functions whereas, the internal energy is a state function.

(2) Heat and work are two different terms though they might look the same.

**Example 1.3: A geyser heats water flowing at the rate of 3.0 liter/min from 27°C to 77°C. If the geyser operates on a gas burner, what is the rate of consumption of the fuel, if its heat of combustion is 4.0 × $10^4$ J/g? [NCERT]**

**Ans.** Given,

Volume of water heated = 3 liter/min.

Mass of water heated,

$$m = 3000 \text{ g/min}$$

Rise in temperature,

$$\Delta T = 77 - 27 = 50°C,$$

Specific heat of water,

$$c = 4.2 \text{ Jg}^{-1}{}^\circ\text{C}^{-1}$$

Amount of heat used,

$$\Delta Q = mc\Delta T$$

$$= 3000 \times 4.2 \times 50$$

$$= 63 \times 10^4 \text{ J/min}$$

Heat of combustion

$$= 4 \times 10^4 \text{ J/g}$$

Rate of combustion of fuel

$$= \frac{63 \times 10^4}{4 \times 10^4}$$

$$= 15.75 \text{ g/m}$$

**Example 1.4: What amount of heat must be supplied to 2.0 × $10^{-2}$ kg of nitrogen at room temperature to raise its temperature by 45°C at constant pressure? (Given molecular mass of $N_2$ = 28, R = 8.3 J $mol^{-1}$ $K^{-1}$). [NCERT]**

**Ans.** Given,

$$m = \text{Mass of gas}$$

$$= 2 \times 10^{-2} \text{ kg}$$

$$= 20 \text{ g}$$

Rise in temperature

$$\Delta T = 45°C$$

Molecular mass,

$$M = 28$$

Heat required,

$$\Delta Q = nC_P\Delta T$$

$$= \left(\frac{m}{M}\right) C_P \Delta T$$

$$= \left(\frac{20}{28}\right)\left(\frac{7}{2}R\right)(45)$$

$$\Delta Q = \frac{20}{28}\left(\frac{7}{2} \times 8.3\right)45$$

$$= 933.4 \text{ J}$$

# TOPIC 3

# FIRST LAW OF THERMODYNAMICS

(1) This law is applicable to every process in nature.

(2) The first law of thermodynamics introduces the concept of internal energy.

(3) The first law of thermodynamics is based on the law of conservation of energy.

(4) $\delta Q$, $\delta U$ and $\delta W$ must be expressed in the same units (either in units of work or in units of heat).

(5) This law is applicable to all three phases of matter. *i.e.*, solid, liquids and gas.

(6) $\delta U$ is a characteristic of the state of a system, it may be any type of internal energy-translational kinetic energy, vibrational, rotational kinetic energy, binding energy etc.

## Applications of First Law of Thermodynamics

### Melting process

When a substance melts, the change in volume ($dV$) is very small and can be neglected. The temperature of a substance remains unchanged during the melting process.

Let us consider the melting of a mass $m$ of the solid. Let L be the latent heat of fusion *i.e.*, the required L to change a unit mass of a solid to a liquid phase at a constant temperature.

Heat absorbed during the melting process,

$$Q = mL$$

By the first law of thermodynamics,

$$Q = \Delta U + W$$

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

where U is volume change during phase change.

### Boiling process

When a liquid is heated, it changes into vapour at a constant temperature (called boiling point) and pressure when water is heated at normal atmospheric pressure, it boils at 100°C. The temperature remains unchanged during the boiling process. Let us consider the vaporisation of liquid of mass $m$. Let $V_l$ and $V_v$ be the volume of the liquid and vapours respectively.

The work done in expanding at constant temperature and pressure P,

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

$$= P(V_v - V_l)$$

Let the latent heat of vaporisation = L

∴ Heat absorbed during the boiling process,

$$\delta Q = mL$$

Let $U_l$ and $U_v$ be the internal energies of the liquid and vapours respectively then

$$\Delta U = U_v - U_l$$

According to the first law of thermodynamics,

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

$$\therefore \quad mL = (U_v - U_l) + P(V_v - V_l)$$

**Example 1.5: An electric heater supplies heat to a system at a rate of 100W. If the system performs work at a rate of 75 joules per second. At what rate the internal energy increase? [NCERT]**

**Ans.** Given,

$$\Delta Q = 100 \text{ W} = 100 \text{ J/s}$$

Useful work done,

$$\Delta W = 75 \text{ Js}^{-1}$$

Now,

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

$$= 100 - 75 = 25 \text{ J/s.}$$

**Example 1.6: Case Based:**

*Consider in a Heat engine, the thermal energy is converted into mechanical energy and the process also is vice versa. Heat engines are mostly categorized as open systems. The basic working principle of a heat engine is that it makes use of the different relationships between heat, pressure and volume of a working fluid which is usually a gas. Sometimes phase changes might also occur involving a gas to liquid and back to gas. Thus, the First Law of Thermodynamics states that heat is a form of energy, and thermodynamic processes are therefore subject to the principle of conservation of energy. This means that heat energy cannot be created or destroyed. It can, however, be transferred from one location to another and converted to and from other forms of energy.*

**(A) Assertion (A): Zeroth law of thermodynamics explain the concept of energy.**

**Reason (R): Energy is independent of temperature.**

**(a) Both A and R are true and R is the correct explanation of A.**

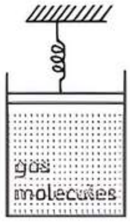
**(b) Both A and R are true and R is not correct explanation of A.**

**(c) A is true but R is false.**

**(d) A is false and R is also false.**

**[Delhi Gov. QB 2022]**

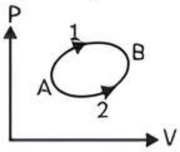
(B) The gas molecules in the given system receive 20 J of heat. Initially, the spring is neither elongated nor compressed. If the spring is compressed by one centimetre. Calculate the change in the system's internal energy. The spring constant is 200 N/m. Assume that the piston moves slowly.




(C) An electric kettle provides 120 W of heat to a system. If the system performs work at a rate of 80 $Js^{-1}$, the rate of internal energy increase is:

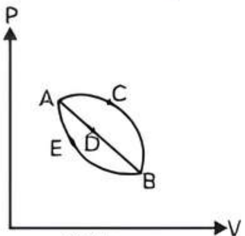
(a) 30 $Js^{-1}$ (b) 40 $Js^{-1}$
(c) 50 $Js^{-1}$ (d) 60 $Js^{-1}$

(D) In the P-V diagram shown in the figure, a system travels from A to B via two distinct paths. The heat given to the system in path 1 is 1100 J, and the work done by the system along path 1 is 150 J greater than that of path 2. Heat exchanged of path 2 by the system is:




(a) 800 J (b) 750 J
(c) 1050 J (d) 950 J

(E) A certain mass of gas is carried from A to B, along three paths via ACB, ADB and AEB.




P-V curve

Which one of the following is correct?

(a) Work done via path ACB is minimum.
(b) Work done via path ADB is maximum.
(c) Work done via path ACB is maximum.
(d) Work done via path AEB is maximum.

**Ans.** (A) *(a) Both A and R are true and R is the correct explanation of A.*

**Explanation:** As it relates to heat energy, the zeroth law of thermodynamics of energy.

According to the Zeroth Law of Thermodynamics, two bodies are in equilibrium with one another if they are both in thermal equilibrium with a third body. In essence, this indicates that the temperatures of the three bodies are equal.

(B) The work done by the piston will be stored in the spring.

The energy stored in spring

$$= \frac{1}{2}kx^2$$
$$= 0.5 \times 200 \times 0.01$$
$$= 1\ J$$

The work done by the piston

$$= 0.01\ J$$
$$\Delta U = \Delta Q - \Delta W$$
$$= 20 - 1 = 19\ J.$$

(C) *(b) 40 J $s^{-1}$*

**Explanation:** According to the first Law of thermodynamics,

$$\Delta Q = \Delta U + \Delta W$$
$$\frac{\Delta Q}{\Delta t} = \frac{\Delta U}{\Delta t} + \frac{\Delta W}{\Delta t}$$
$$\frac{\Delta Q}{\Delta t} = 120\ W$$
$$\frac{\Delta W}{\Delta t} = 80\ Js^{-1}$$
$$\frac{\Delta U}{\Delta t} = 120 - 80$$
$$= 40\ Js^{-1}$$

(D) *(d) 950 J*

**Explanation:** The change in internal energy of the system will be the same for both paths 1 and 2.

Along path 1,

$$\Delta Q_1 = \Delta U + \Delta W_1 \quad \text{...(i)}$$

Along path 2,

$$\Delta Q_2 = \Delta U + \Delta W_2 \quad \text{...(ii)}$$

Subtract (ii) from (i), we get P,

or $$\Delta Q_1 - \Delta Q_2 = \Delta W_1 - \Delta W_2$$
$$1100 - \Delta Q_2 = 150$$
$$\Delta Q_2 = 1100 - 150 = 950\ J$$

(E) *(c) Work done via path ACB is maximum.*

**Explanation:** Work done by a gas depends on the area enclosed between the P-V curve and the volume axis. The area enclosed by curve ACB is maximum. Hence, work done is maximum along path ACB.

The area enclosed by curve AEB is minimum. Hence, work done is minimum along path AEB.

## TOPIC 4

# HEAT CAPACITY

If $\Delta Q$ is the amount of heat required to change its temperature by $\Delta T$, then the heat capacity can be defined as,

$$S = \frac{\Delta Q}{\Delta T}$$

Heat capacity is numerically equal to the heat energy required to change the temperature of a body by unity.

The amount of heat required to raise the temperature of one gram of a substance through a unit is called the molar specific heat capacity of the substance. If the amount of substance is specified in terms of moles μ (instead of mass *m* in kg), we can define heat capacity per mole of the substance by,

$$C = \frac{S}{\mu} = \frac{1}{\mu}\frac{\Delta Q}{\Delta T}$$

Here, C is known as the molar specific heat capacity of the substance.

Both S and C are independent of the amount of the substance.

Value of specific heat may vary from 0 to ∞ (infinity).

Specific heat capacity depends on the process or the conditions under which heat transfer takes place.

## Specific heat capacity of solids

In solids, there is a very minor difference between heat capacity at constant pressure and constant volume. Therefore, we do not differentiate between $C_P$ and $C_V$ for solids.

$$S = \frac{\Delta Q}{\Delta T} = \frac{\Delta U}{\Delta T}$$

{As solids hardly expand or expansion is negligible}.

Now in a solid, the atoms are arranged in an array structure and they are not free to move independently like in gases.

Therefore, the atoms do not possess any translational or rotational degree of freedom.

On the other hand, the molecules do possess vibrational motion along three mutually perpendicular directions.

Hence for 1 mole of a solid, there is $N_A$ number of atoms.

The energy associated with every molecule

$$= 3[2 \times \frac{1}{2}k_B T] = 3k_B T$$

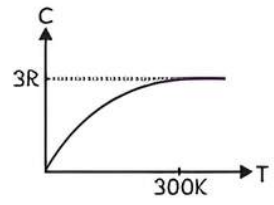
U = 3 RT for one mole

$$S = \frac{\Delta Q}{\Delta T} = \frac{\Delta U}{\Delta T} = 3R$$

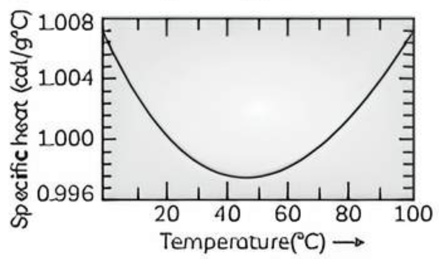
C = 3 E

The above equation is called Dulong and Petit's Law.

At low temperatures, the vibrations made may not be that active. Hence, heat capacity is low at low temperatures for solids.




## Specific heat capacity of water




*Variation of specific heat capacity of water with temperature*

Water is treated like a solid.

Water has three atoms, 2 of hydrogen and one of oxygen

∴ Total degree of freedom for every atom

$$= 3 \times 2 = 6$$

∴ Total degree of freedom for every molecule of water

$$= 3 \times 2 = 18$$

$$S = \frac{\Delta Q}{\Delta T} = \frac{\Delta U}{\Delta T}$$

$$= \frac{(18 \times \frac{1}{2} R\Delta T)}{\Delta T}$$

C = 9R

### ⚠ Caution

➥ *Students must know that the specific heat of all substances approaches zero as T → 0. This is related to the fact that degrees of freedom get frozen and ineffective at low temperatures.*

**Example 1.7:** Explain why:

**(A) Two bodies at different temperatures $T_1$ and $T_2$, if brought in thermal contact do not necessarily, settle to the mean temperature $\frac{T_1 + T_2}{2}$.**

(B) The coolant in a chemical or a nuclear plant (*i.e.*, the liquid used to prevent the different parts of a plant from getting too hot) should have high specific heat.

(C) Air pressure in a car tyre increases during driving.

(D) The climate of a harbour town is more temperate than that of a town in a desert at the same latitude. [NCERT]

**Ans.** (A) In thermal contact, heat from the body at higher temperature transfers to the body at the lower temperature, till the temperature of both becomes equal. Final temperature can be mean temperature $\frac{T_1 + T_2}{2}$ only when the thermal capacities of two bodies are equal.

(B) Because the heat absorbed $\mu$ specific heat of the substance.

(C) Temperature of air inside the tyre increases due to motion during driving. Air pressure, therefore, increases inside the tyre (by Charle's law, $P \propto T$).

(D) In a harbour town, the relative humidity is more than in a desert town. Hence, the climate of a harbour town is without extremes of hot and cold.

**Example 1.8:** **A 1 kg piece of hot copper is allowed to cool to 100°C. What was the initial temperature of the copper if it gave off 231 kJ of energy? Copper has a specific heat of 0.385 J/g°C.** [NCERT]

**Ans.** Given,

$$m = 1 \text{ kg},$$
$$T_{final} = 100\ °C$$
$$Q = -231 \text{ kJ}$$

(The negative sign is because the copper is cooling and losing energy.)

$$c = 0.385 \text{ J/g°C}$$

We need to make our units consistent with the specific heat units, so let's convert the mass and energy units.

$$m = 1 \text{ kg} = 1000 \text{ grams}$$
$$1 \text{ kJ} = 1000 \text{ J}$$
$$Q = -231 \text{ kJ} \times (1000 \text{ J/kJ})$$
$$= -231000 \text{ J}$$

The specific heat formula is:

$$Q = mc\Delta T$$
$$-231000\text{J} = 1000\text{g} \times (0.385 \text{ J/g°C}) \times \Delta T$$
$$-231000 \text{ J} = 385 \text{ J/°C} \times \Delta T$$
$$\frac{-231000}{385 \text{J/°C}} = \Delta T$$
$$\Delta T = -600\ °C$$
$$\Delta T = (T_{final} - T_{initial})$$

Putting in the values for $\Delta T$ and $T_{final}$.

$$-600°C = (100°C - T_{initial})$$

Subtract 100 °C from both sides of the equation.

$$-600°C - 100°C = -T_{initial}$$
$$-700°C = -T_{initial}$$
$$T_{initial} = 700\ °C$$

The initial temperature of the copper chunk was 700°C.

## Specific Heat Capacity of Gases

For gases, their specific heat capacities depend on the process or under which condition heat exchange between the gases and the surrounding is taking place.

There are two main specific heat capacities for a gas which are defined as:

### Molar Heat Capacity at Constant Volume

The amount of heat required to increase the temperature of one mole of gas by 1°C at constant volume is known as molar heat capacity at constant volume. It is denoted by $C_V$.

### Molar Heat Capacity at Constant Pressure

The amount of heat required to increase the temperature of one mole of gas by 1°C at constant pressure is known as molar heat capacity at constant pressure. It is denoted by $C_P$.

# TOPIC 5

# THERMODYNAMIC PROCESSES

The branch of physics which deals with the interconversion between heat energy and any other form of energy is known as thermodynamics. In this branch of physics, we deal with the processes involved in heat, work and internal energy. In this branch of science, the conversion of heat into mechanical work and vice versa is studied.

## Thermodynamic system

The system which can be represented in terms of pressure (P), volume (V) and temperature (T) is known as a thermodynamic system. A specified portion of matter consisting of one or more substances on which the effects of thermodynamics variables such as temperature, volume and pressure are to be studied, is called a thermodynamic system. E.g., A gas enclosed in a cylinder, fitted with a piston is a system.

### Thermodynamic state

The state of a system can be described completely by composition, temperature, volume and pressure.

If a system is homogenous and has definite mass and composition, then the state of the system can be described by the remaining three variables namely temperature, pressure and volume.

These variables are interrelated by the equation

$$PV = \mu RT.$$

The thermodynamics of the system in its condition is identified by two independent thermodynamics variables (P, V or P, T or V, T).

**Internal energy**

The internal energy of a system is the energy possessed by the system due to molecular motion and molecular configuration. The energy due to molecular motion is called internal kinetic energy ($U_k$) and that is due to molecular configurations is called internal potential energy ($U_p$).

$$dU = dU_k + dU_p$$

If there are no intermolecular forces,

then $dU_p = 0$ and (Ideal Gas)

$C_v$ = specific heat at constant volume and

$dT$ = infinitesimal change in temperature

$m$ = mass of system,

M = Molecular weight

Molar heat capacity,

$$C_V = MC_V$$

For $\mu$–moles of the ideal gas

$$dU = \mu C_v dT = \frac{m}{M} C_V \, dT$$

Internal energy in the absence of intermolecular forces is simply the function of temperature and state only, it is independent of the path followed.

$U_i$ = internal energies in initial state

and $U_f$ = internal energies in the final state.

### Thermodynamic State Variables

Thermodynamic state variables describe the equilibrium states of systems. The connection between the state variables is called the equation of state. For an ideal gas, the equation of state is the ideal gas equation

$$PV = nRT$$

**(A)** Extensive variables indicate the 'size' of the system. *i.e.*, volume.

**(B)** Intensive variables are the variables that do not indicate the size of the system such as pressure and temperature.

## Thermodynamic Processes

A thermodynamic process is said to occur when there are changes in the state of a thermodynamic system, *i.e.*, the thermodynamic parameters of the system change over time.

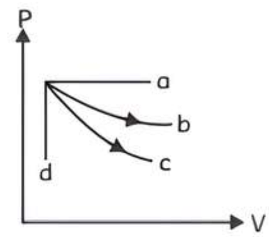
These thermodynamic processes are classified as isothermal, adiabatic, isobaric, and isochoric.

### Quasi-static process

Quasi-static is a thermodynamics process which proceeds extremely slowly such that at every instant of time, the temperature and pressure are the same in all parts of the system.

### Indicator P-V Diagram

A graph between the pressure and volume of a gas under thermodynamic operation is called a P-V diagram.




$a \rightarrow$ Isobaric

$b \rightarrow$ Isothermal

$c \rightarrow$ Adiabatic

$d \rightarrow$ Isochoric

The area under the P–V diagram gives us work done by a gas.

## Isothermal Process

In this process, pressure and volume of the system change but the temperature remains constant. In an isothermal process, the exchange of heat between the system and the surroundings is allowed. Isothermal process is carried out by either supplying heat to the substance or by extracting heat from it. A process has to be extremely slow to be isothermal.

### Equation of state

$$PV = \text{constant}$$

$$PV = \mu RT \text{ (T is constant)}$$

### Work done

Consider $\mu$ moles of an ideal gas, enclosed in a cylinder, at absolute temperature T, fitted with a frictionless piston. Suppose that gas undergoes an isothermal expansion from the initial state ($P_1$, $V_1$) to the final state. ($P_2$, $V_2$).

Then work done.

$$W = \int_{V_1}^{V_2} PdV$$

$\therefore$ $PV = \mu RT$

then $P = \frac{\mu RT}{V}$

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

$$\because = \mu RT \left[\log_e V\right]_{V_1}^{V_2}$$

$$= \mu RT \left[\log_e V_2 - \log_e V_1\right]$$

$$= \mu RT \log_e \left[\frac{V_2}{V_1}\right]$$

$$W = 2.303\ \mu RT \log_{10}\left[\frac{P_2}{P_1}\right]$$

**Form of First law0**

There is no change in temperature and the internal energy of the system depends on temperature only.

So, $W = 2.303\ \mu RT \log_{10}\left[\frac{P_2}{P_1}\right]$

It is clear that all of the heat energy supplied to the system is utilized by the system in doing external work. There is no change in the internal energy of the system.

**Slope of isothermal curve**

For an isothermal process,

$$PV = \text{constant}$$

Differentiating,

$$PdV + VdP = 0$$

$$VdP = -PdV$$

$$\frac{dP}{dV} = -\frac{P}{V}$$

Slope of the isothermal curve,

$$\left[\frac{dP}{dV}\right]_{\text{isothermal}} = -\frac{P}{V}$$

## Adiabatic Process

It is a thermodynamic process in which the pressure, volume and temperature of the system do change but there is no exchange of heat between the system and the surroundings.

A sudden and quick process will be adiabatic since there is no sufficient time available for the exchange of heat so the process is adiabatic.

**Equation of state**

$$PV = \mu RT$$

Equation for adiabatic process,

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

**Work done**

Let initial state of system is ($P_1$, $V_1$, $T_1$) and after adiabatic change final state of system is ($P_2$, $V_2$, $T_2$) then

$$P_1V_1^{\gamma} = P_2V_2^{\gamma} = K \quad \text{(Here, K is constant)}$$

$$\because W = \int_{V_1}^{V_2} PdV = K\int_{V_1}^{V_2} V^{-\gamma} dV$$

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

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

$$(\because P_1V_1^{\gamma} = P_2V_2^{\gamma})$$

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

$$= \frac{1}{(\gamma-1)}\left[P_1V_1 - P_2V_2\right]$$

$$W = \frac{\mu R}{(\gamma-1)}(T_1 - T_2)$$

$$\because PV = \mu RT$$

(1) It means the work done by an ideal gas during adiabatic expansion (or compression) is on the cost of change in internal energy proportional to the fall (or rise) in the temperature of gas.

(2) If the gas expands adiabatically, work is done by the gas. So, $W_{adia}$ is positive.

(3) The gas cools during adiabatic expansion and $T_1 > T_2$.

(4) If the gas is compressed adiabatically, work is done on the gas. So, $W_{adia}$ is negative.

(5) The gas heats up during adiabatic compression and $T_1 < T_2$.

**Slope of Adiabatic curve**

For an adiabatic process,

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

Differentiating,

$$\gamma PV^{\gamma-1} dV + V^{\gamma} dP = 0$$

$$V^{\gamma} dP = -\gamma PV^{\gamma-1} dV$$

$$\frac{dP}{dV} = \frac{-\gamma PV^{\gamma-1}}{V^{\gamma}} = \frac{-\gamma P}{V}$$

Slope of adiabatic curve,

$$\left[\frac{dP}{dV}\right]_{\text{adiabatic}} = -\frac{\gamma P}{V}$$

## Isochoric process

Isochoric process is a thermodynamic process that takes place at a constant volume of the system but pressure and temperature vary for change in the state of the system.

#### Equation of state

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

(P and T are variable, and V is constant).

#### Work done

In this process, volume remains constant.

So,

$$dV = 0$$

$$W = \int_{V_1}^{V_2} P.dV = 0$$

#### Form of First Law

It means the whole of the heat supplied is utilized for change in internal energy of the system.

$$Q = \Delta U = \mu C_v \Delta T$$

#### Slope of PV curve

$$\frac{dP}{dV} = \infty$$

### Isobaric Process

Isobaric process is a thermo-dynamic process that takes place at constant pressure but volume and temperature vary for change in the state of the system.

#### Equation of state

$$\frac{V}{T} = \text{Constant or } V \propto T$$

#### Work done

In this process, pressure remains constant.

$\therefore$ $dP = 0$

$$\text{Work done, } W = \int_{V_1}^{V_2} PdV$$

$$= P(V_2 - V_1)$$

Fraction of heat given, which:

(1) is converted into internal energy $\frac{\Delta U}{\Delta Q} = \frac{1}{\gamma}$

(2) does work against external pressure,

$$\frac{\Delta W}{\Delta Q} = 1 - \frac{1}{W}$$

#### Form of First Law

$$Q = \Delta u + P(V_f - V_i)$$

$$\mu C_P(T_f - T_i) = \mu C_v(T_f - T_i) + P(V_f - V_i)$$

It's clear that heat supplied to the system is utilized for:

(1) Increasing Internal energy

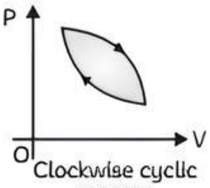
(2) Work done against the surrounding atmosphere.

#### Slope of PV curve

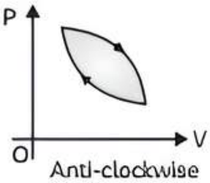
$$\frac{dP}{dV} = 0$$

### Cyclic process

A process that eventually returns a system to its initial state is called a cyclic process. Since the final state is the same as the initial state and so the total internal energy change must be zero because internal energy is a state variable.




Clockwise cyclic process

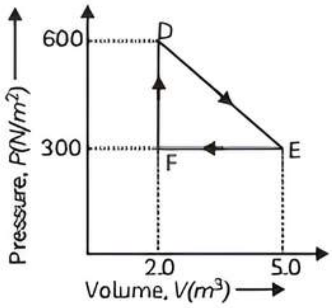



Anti-clockwise cyclic process

### Non-cyclic process

Non-cyclic process is a process in which the system does not return to its initial stage.

**Example 1.9: A thermodynamic system is taken from an original state to an intermediate state by the linear process shown in the figure:**




**Its volume is then reduced to the original value from E to F by an isobaric process. Calculate the total work done by the gas from D to E to F.**

**[NCERT]**

**Ans.** Work done from D to E

$$W_{DE} = \frac{1}{2} \times (5 - 2)(600 - 300) + (5 - 2)(300)$$

$$= 450 + 900$$

$$= 1350 \text{ J}$$

Work done from E to F,

$$W_{EF} = 300 (2 - 5)$$

$$= -900 \text{ J}$$

Work done from D to E to F

$$\therefore \quad W_{DEF} = W_{DE} + W_{EF}$$

$$= (1350 - 900) \text{ J}$$

$$= 450 \text{ J}$$

**Example 1.10: At 27°C and atmospheric pressure, a volume of air is suddenly compressed to half its original volume. Find out what are the final pressure and temperature. Given that, $g$ for air is 1.42.**

**[NCERT]**

**Ans.** Given:

$$T_1 = 27 + 273$$

$$= 300 \text{ K},$$

$$P_1 = 1 \text{ atm},$$

$$V_2 = \frac{1}{2} V_1,$$

$$P_2 = ?,$$

$$T_2 = ?, g = 1.42$$

The process is adiabatic.

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

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

$$= 1 \times (2)^{1.42}$$

$$= 2.675 \text{ atm}$$

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

$$= 300 \times (1.42 - 1) = 401.3 \text{ K}$$

$$T_2 = 401.3 \text{ K}$$

$$K = 401.3 - 273 = 128.3°C$$

**Example 1.11:** **At 127°C, one gram mole of gas expands isothermally until its volume is doubled. Determine the amount of work done and the amount of heat absorbed. [NCERT]**

**Ans.** Given:

$$T = 273 + 127$$

$$= 400 \text{ K.}$$

Let $V_1 = V$

and $V_2 = 2V$

$$\text{Work done, } W = 2.303RT \log_{10}\frac{V_2}{V_1}$$

$$= 2.303 \times 8.3 \times 400 \times \log_{10}\frac{2V}{V}$$

$$= 2.303 \times 8.3 \times 400 \times 0.3010$$

$$= 2.3 \times 10^3 \text{ J}$$

Amount of heat absorbed,

$$H = \frac{W}{J}$$

$$= \frac{(2.3 \times 10^3)}{4.2} = 548 \text{ cal}$$

# OBJECTIVE Type Questions

[ 1 mark ]

## Multiple Choice Questions

1. **A process that applies 500 calories of heat to a system while performing 100 joules of work on it. An increase in the system's internal energy is:**

**(a) 40 calories** **(b) 2193 calories**

**(c) 1993 calories** **(d) 4293 calories**

**Ans.** *(b) 2193 calories*

**Explanation:** As heat is given to the system,

So,

$$Q = +500 \text{ calories}$$

$$= 500 \times 4.186 \text{ Joules}$$

$$= +2093 \text{ Joules}$$

And work done on the system so,

$$W = -100 \text{ Joules}$$

By the first law of thermodynamics,

$$Q = \Delta U + W$$

$$2093 = \Delta U + (-100)$$

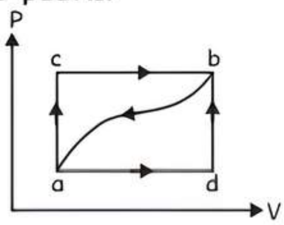
Change in internal energy,

$$\Delta U = 2093 + 100 = 2193$$

### Caution

➥ *Students must know that the internal energy of a system does not depend on the motion of a system as a whole, i.e., the sum of the kinetic energy of only the constituent molecules due to their randomness inside the system is considered.*

2. **When a system moves from state '*a*' to state '*b*' along the path '*acb*,' it absorbs 200 J of heat and performs 80 J of work. Q = 144 J along the '*adb*' path. The work completed on the '*adb*' path is:**




**(a) 24 J** **(b) 18 J**

**(c) 12 J** **(d) 6 J**

**Ans.** *(a) 24 J*

**Explanation:** A system is taken from the state '*a*' to state '*b*' along the path '*acb*', it is found that a quantity of heat, Q = 200 J is absorbed by the system and work, W = 80 J is done by it. Along the path '*adb*',

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

The net heat in the process is

$$Q = 200 - 144 = 56 \text{ J}$$

The work done along path '*abd*'

$$= \text{Work done by system-heat}$$

$$W_{abd} = 80 - 56 = 24 \text{ J}$$

### Related Theory

➥ *In the thermodynamic process the pressure, volume, temperature and entropy of the system change with time. Thermodynamic process is said to take place if the change occurs in the state of a thermodynamics system.*

3. **Consider two identical gas containers A and B at the same pressure, volume and**

temperature. The gas in container A is isothermally compressed to half its original volume, while the gas in container B is adiabatically compressed to half its original value. The final pressure ratio of gas in B to gas in A is:

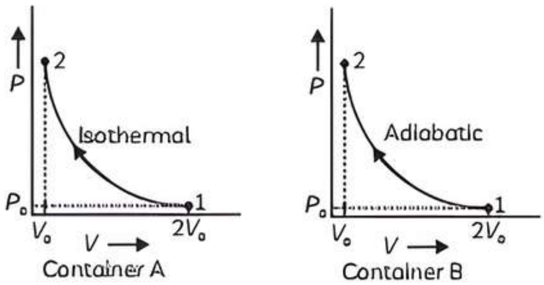
(a) $2^{\gamma-1}$ (b) $\left(\frac{1}{2}\right)^{\gamma-1}$

(c) $\left(\frac{1}{1-\gamma}\right)^{\gamma-1}$ (d) $-\left(\frac{1}{1-\gamma}\right)^{2}$

[NCERT Exemplar]

**Ans.** *(a)* $2^{\gamma-1}$

**Explanation:** Consider the P–V diagram shown for container A and container B.




Both process involves compression of the gas.

(1) Isothermal compression (Gas A)

(During $1 \rightarrow 2$)

$$P_1V_1 = P_2V_2$$
$$P_0(2V_0)^{\gamma} = P_2(V_0)^{\gamma}$$
$$P_0(2V_0) = P_2(V_0)$$

(2) Adiabatic compression (Gas B)

(During $1 \rightarrow 2$)

$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$
$$P_0(2V_0)^{\gamma} = P_2(V_0)^{\gamma}$$
$$P_2 = \left(\frac{2V_0}{V_0}\right)^{\gamma}P_0$$
$$P_2 = (2)^{\gamma}P_0$$
$$\frac{(P_2)_B}{(P_2)_A} = \text{ratio of final pressure}$$

Hence, $\frac{(2)^{\gamma}P_0}{2P_0} = 2^{\gamma-1}$

Where $\gamma$ is the ratio of specific heat capacities for the gas.

### Caution

*Students should know that when a gas expands, its volume increases, and then final pressure is less for adiabatic expansion. But when gas compresses, its volume decreases, and then the final pressure is more in the case of adiabatic compression.*

4. When an ordinary person jogs, he expends $14.5 \times 10^4$ cal $min^{-1}$. Sweat evaporates, which removes this. The amount of sweat evaporated per minute (assuming 1 kg of evaporation requires $580 \times 10^3$ cal) is:

(a) 0.25 kg (b) 2.25 kg

(c) 0.05 kg (d) 0.20 kg

**Ans.** *(a) 0.25 kg*

**Explanation:** Given,

Calories produced per minute

$$= 14.5 \times 10^3 \text{ cal/min}$$

$$\text{Latent heat} = 580 \times 10^3 \text{ cal/kg}$$

Amount of sweat evaporated per minute =

$$\frac{\text{sweat produces/minute}}{\text{Number of calories required of evaporation/kg}}$$

$$= \frac{\text{calories produces (heat produced)/minute}}{\text{Latent heat}\left(\text{in}\frac{\text{cal}}{\text{kg}}\right)}$$

$$= \frac{14.5 \times 10^3}{580 \times 10^3}$$

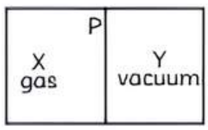
$$= \frac{14.5}{580}$$

$$= 0.25 \text{ kg}$$

### Related Theory

*Temperature of a body is that the parameter which determines the degree of hotness or coldness of a body. It also determines the flow of heat when the body is brought in contact with another body.*

5. A confined flask is completely sealed off from the outside world. As shown in the diagram, one half of it is filled with an ideal gas X, separated from the other half Y by a plate P, which contains a vacuum. X enters Y when O is removed. Which of the following statements is NOT correct?




(a) No work is done by X

(b) X decreases in temperature

(c) X increases in internal energy

(d) X doubles in pressure

**Ans.** *(a) No work is done by X*

**Explanation:** Work done by a gas is given by:

$$W = \int PdV$$

Work done by X is against vacuum.

Hence, $P = 0$;

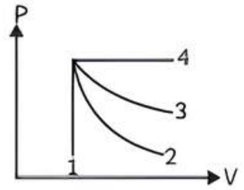
$$W = \int PdV$$
$$= \int 0dV = 0$$

Hence, no work is done by or done on X.

### ⚠ Caution

➥ *Students should know that most of the heat transfer that is taking place on earth is by convection, the contribution due to conduction and radiation is very small.*

**6. An ideal gas undergoes four different processes from the same initial state (figure). Four processes are adiabatic, isothermal, isobaric and isochoric. Out of 1, 2, 3, and 4, which one is adiabatic?**




**(a)** 4 **(b)** 3
**(c)** 2 **(d)** 1

[NCERT Exemplar]

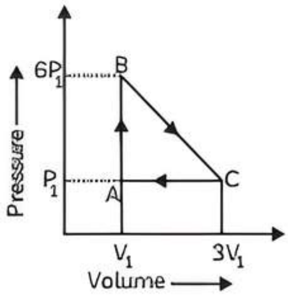
**Ans.** *(c) 2*

**Explanation:** 4 is an isobaric process and 1 is an isochoric process. Out of 3 and 2, 3 has a smaller slope (magnitude). Hence, it is isothermal. Remaining process 2 is adiabatic.

### Related Theory

➥ *For a gas, $C_P > C_V$ always, because at constant pressure, more heat is required to increase the temperature at one mole of the gas by 1°C as compared to that of at constant volume.*

**7. As shown in the P-V diagram, an ideal gas is taken around the cycle ABCA. The network created by the gas during the cycle equals:**




**(a)** 6PV **(b)** 12PV
**(c)** 2PV **(d)** 5PV

**Ans.** *(d) 5PV*

**Explanation:** Work done = Area of triangle

$$= \frac{1}{2}(3V - V)(6P - P)$$

$$= 5PV$$

### ⚠ Caution

➥ *Students should know that when a gas expands its volume increases, and then the final pressure is less for adiabatic expansion but when a gas compresses its volume decreases, then the final pressure is more in a case of adiabatic compression.*

**8. The molar specific heat capacity of an ideal gas at constant volume is $\frac{3}{2}$ R. The molar specific heat capacities, at constant pressure, is:**

**(a)** $\frac{1}{2}$ R **(b)** $\frac{5}{2}$ R
**(c)** $\frac{7}{2}$ R **(d)** $\frac{9}{2}$ R

**Ans.** *(b) $\frac{5}{2}R$*

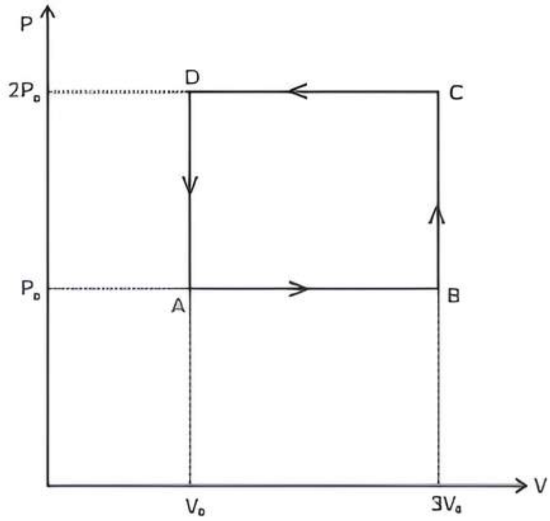
**Explanation:** As we know,

$$C_p - C_v = R$$

$$C_p - \frac{3}{2}R = R$$

$$C_p = \frac{5}{2}R$$

**9. An ideal gas undergoes the cyclic process ABCDA as shown in given PV diagram.**




**The amount of work done by the gas is:**

**(a)** $6\,P_0V_0$ **(b)** $-2\,P_0V_0$
**(c)** $+2P_0V_0$ **(d)** $+4\,P_0V_0$

[Delhi Gov. QB 2022]

**Ans.** *(b) $-2\,P_0V_0$*

**Explanation:** Let P be the pressure of the gas in the cylinder, then the force exerted by the gas on the piston of the cylinder,

$$F = PA$$

In a small displacement of the piston through *dc*, work done by the gas,

$$dW = F.dx = PA\,dx = P\,dV$$

∴ Total amount of work done

$$\Delta W = \int dW = \int_{V_i}^{V_f} P\,dV = P(V_f - V_i)$$

In P - V diagram or indicator diagram, the area under P - V curve represents work done.

$$W = \text{Area under } P - V \text{ diagram}$$

According to the P – V diagram given in the question.

Work done in the process ABCD

= Area of rectangle ABCDA

$= AB \times BC = (3V_o - V_o) \times (2P_o - P_o)$

$= 2V_o \times P_o = 2\,P_oV_o$

Since the cyclic process is anti-clockwise, work done by the gas is negative.

That is, $-2P_oV_o$. Hence, there is a net compression in the gas.

**10. Which of the process described below are irreversible?**

**(a) The increase in temperature of an iron rod by hammering it.**

**(b) A gas in a small container at a temperature $T_1$ is brought in contact with a big reservoir at a higher Temperature. $T_2$ which inverses the temperature of the gas.**

**(c) An ideal gas is enclosed in a piston-cylinder arrangement with adiabatic Walls. A weight W is added to the piston, resulting in the compression of a gas.**

**(d) All of the above [Delhi Gov. QB 2022]**

**Ans.** *(d) All of the above*

**Explanation:** During hammering, work is done on the rod, which turns into heat and raises the temperature of the rod. Because this heat energy cannot be transformed back into work, the process is irreversible.

The heat from the larger container is transferred to the smaller container until their temperatures are equal, which is the average of both. Heat cannot move from a smaller container to a larger container because heat travels from a higher temperature to a lower temperature.

When weight is added to a piston, the pressure and volume rise, but the process cannot be reversed.

Hence, all the given options are correct.

## Assertion – Reason Questions

**Two statements are given one labelled Assertion (A) and the other labelled Reason (R). Select the correct answer to these questions from the codes (a), (b), (c) and (d) as given below:**

**(a) Both A and R are true and R is the correct explanation of A.**

**(b) Both A and R are true and R is not the correct explanation of A.**

**(c) A is true but R is false.**

**(d) A is false and R is also false.**

**11. Assertion (A): Specific heat capacity and molar heat capacity both have the same units.**

**Reason (R): Specific heat capacity and molar heat capacity both depend on mass.**

**Ans.** *(d) A is false and R is also false.*

**Explanation:** Specific heat capacity,

$$S = \frac{\Delta Q}{m\Delta T}$$

Where $m$ is the mass of a substance.

Molar-specific heat capacity,

$$C = \frac{\Delta Q}{\mu\Delta T}$$

Wheres $\mu$ is the number of moles.

Both of these are constant characteristics of a substance and are independent of mass.

**12. Assertion (A): The first law of thermodynamics is the restatement of the conservation of energy. Mathematically, it reads $\Delta Q = \Delta U + \Delta W$, where $\Delta Q$ is the heat energy supplied to the system, $\Delta U$ is the change in the internal energy, and $\Delta W$ is the work done by the system against external forces.**

**Reason (R): The Fundamental quantity is a physical quantity that cannot be expressed in any other physical quantity. For example, energy is a fundamental quantity.**

**Ans.** *(c) A is true but R is false.*

**Explanation:** The first law of thermodynamics states that heat is a form of energy and thermodynamic processes are subject to the principle of conservation of energy. This means that heat energy cannot be created or destroyed. "So, it's a restatement of conservation of energy."

According to the first law, $\Delta Q = \Delta U + \Delta W$

that is, heat supplied to a system is equal to the amount of work done by the system plus the increase in its internal energy. So, it's the same as the law of conservation of energy.

**13. Assertion (A): Rotating the blade in a liquid stops after a certain time is an irreversible process.**

**Reason (R): Irreversibility arises as the system attains a non-equilibrium state.**

**Ans.** (b) *Both A and R are true and R is not the correct explanation of A.*

**Explanation:** Irreversibility mainly arises due to:

(1) Dissipative factors like friction, viscosity etc.

(2) And as many processes take the system to an equilibrium state.

So, when the blade is rotated in a liquid, then due to viscosity, the system becomes irreversible as it stops after a certain time. Thus it's an irreversible process.

**14. Assertion (A):** The specific heat of a gas in an adiabatic process is zero and in an isothermal process is infinite.

**Reason (R):** Specific heat of gas is directly proportional to the change of heat in the system and inversely proportional to the change in temperature.

[Delhi Gov. QB 2022]

**Ans.** (c) *A is true but R is false.*

**Explanation:** Assertion is true, since in the adiabatic process there is no transfer of heat,

therefore, $c = \frac{Q}{\Delta T} = 0$

Since, $Q = 0$ therefore, $c = 0$

In isothermal process, $\Delta T = 0$

therefore, $c = \infty$

Whereas specific heat is constant for a material, therefore the reason is false.

**15. Assertion (A):** Work and heat are two equivalent forms of energy.

**Reason (R):** Work is the transfer of mechanical energy irrespective of the temperature difference, whereas heat is the transfer of thermal energy because of temperature difference only.

[Delhi Gov. QB 2022]

**Ans.** (a) *Both A and R are true and R is the correct explanation of A.*

**Explanation:** Heat and work are comparable in that they both represent methods of transmitting energy. We cannot state that a system includes a given amount of heat or work since neither is a fundamental attribute of a system.

# CASE BASED Questions (CBQs)

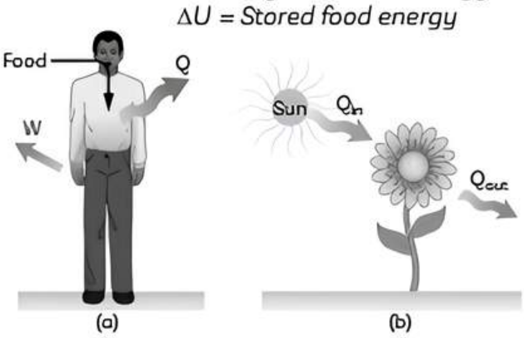
[ 4 & 5 marks ]

Read the following passages and answer the questions that follow:

**16.** *The first law of thermodynamics simply states that energy can be neither created nor destroyed (conservation of energy). Thus, power generation processes and energy sources involve the conversion of energy from one form to another, rather than the creation of energy from nothing. Thus, the energy of the universe is constant. However, energy can be transferred from one part of the universe to another. To work out thermodynamic problems we will need to isolate a certain portion of the universe, the system, from the remainder of the universe, the surroundings.*

$$\Delta U = -Q - W + \text{food energy}$$

$$\Delta U = \text{Stored food energy}$$




**(A)** It's a hot summer day, and your air conditioning system isn't working. You have a working refrigerator and an ice chest full of ice in your kitchen. Which should you open and which should you leave open to effectively cool the room?

**(B)** Can a gas be liquefied at any temperature by the increase of pressure alone?

**(C)** State the first law of thermodynamics.

**Ans.** (A) The high-temperature reservoir for your kitchen refrigerator is the air in the kitchen. If the refrigerator door were left open, energy would be drawn from the air in the kitchen passed through the refrigeration system and transferred right back into the air. The result would be that the kitchen would become warmer, due to the addition of the energy coming in by electricity to run the refrigeration system. If the ice chest were opened, energy in the air would enter the ice, raising its temperature and causing it to melt. The transfer of energy from the air would cause its temperature to drop. Thus, it would be more effective to open the ice chest.

(B) No, a gas can be liquefied by pressure alone, only when the temperature of the gas is below its critical temperature.

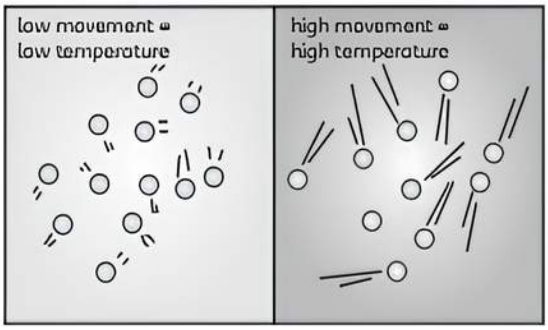
(C) If some quantity of heat is supplied to a system capable of doing work. Then the quantity of heat absorbed by the system is equal to the sum of the increase in the internal energy of the system and the external work done by the system.

$$\delta Q = \delta U + \delta W$$

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

**17.** *Water's high specific heat is a result of hydrogen bonds. The molecules must vibrate in order to raise the temperature of the water due to the multitude of joined hydrogen bonds. Because there are so many hydrogen bonds, it takes more energy to break the water molecules by vibrating them.*

*Similarly, it takes some time for hot water to cool down. Temperature drops as heat are dissipated, and the vibrational movement of water molecules slows. The heat emitted compensates for the cooling effect of heat loss from liquid water.*




*Heat can be transferred from one place to another by three different methods. These are conduction, convection and radiation. Solids are usually heated by the process of conduction. Liquid and gases are heated by the process of convection. The process of radiation requires no medium. Conduction and convection are slow processess while radiation is a very fast process.* **[Delhi Gov. QB 2022]**

**(A) Which of the following processes depends on gravity?**

(a) Conduction (b) Convection

(c) Radiation (d) None of these

**(B) Woolen cloths keep the body warm because wool:**

(a) is a bad conductor

(b) increases the temperature

(c) decreases the temperature

(d) generates heat energy

**(C) On a cold morning, a metal surface will feel colder to touch than a wooden surface because:**

(a) metal has a high specific heat

(b) metal has a high thermal conductivity

(c) metal has a low specific heat

(d) metal has a low thermal conducting

**(D) Earth receive heat from the sun by the method of:**

(a) conduction (b) convection

(c) radiation (d) all of these

**(E) A slab consists of two portions of different materials of the same thickness and having the thermal conductivities $K_1$ and $K_2$. The equivalent thermal conducting of the slab is:**

(a) $K_1 + K_2$ (b) $\frac{K_1K_2}{K_1+K_2}$

(c) $\frac{2K_1K_2}{K_1+K_2}$ (d) $\sqrt{K_1+K_2}$

**Ans.** (A) *(b) Convection*

**Explanation:** Convection occurs when heated lighter particles move upwards and colder heavier particles move downwards to their respective positions. This is determined by weight, and thus by gravity.

(B) *(a) is a bad conductor*

**Explanation:** Woolen cloths keep the body warm because it is a poor conductor of heat. As a result, the body stays warm.

(C) *(b) metal has high a thermal conductivity*

**Explanation:** The metal has a high thermal conductivity, which means it conducts heat more quickly. Metal is also a good heat conductor. As a result, it absorbs your body heat as you touch it, causing your body temperature to drop and you to feel cold when you touch a piece of metal.

(D) *(c) radiation*

**Explanation:** The majority of the energy received by the earth's surface is in short wavelengths. Incoming solar radiation, also known as insolation, is the energy received by the Earth.

(E) *(c)* $\frac{2K_1K_2}{K_1+K_2}$

**Explanation:** The thermal rate for the first conductor is given as,

$$\frac{H_1}{t} = \frac{K_1A(T-T_1)}{L}$$

The thermal rate for the second conductor is given as,

$$\frac{H_2}{t} = \frac{K_2A(T_2-T)}{L}$$

Since they are counted in series,

$$H_1 = H_2$$

$$K(T-T_1) = K_2(T_2-T)$$

Let K be the equivalent conductance

Hence,

$$\frac{KA(T_2-T_1)}{2L} = \frac{K_1A(T-T_1)}{L} + \frac{K_2A(T_2-T)}{L}$$

$$K = \frac{2K_1K_2}{K_1+K_2}$$

## VERY SHORT ANSWER Type Questions (VSA)

[ 1 mark ]

**18. A gas-filled cylinder is enclosed in a heat-resistant jacket. How will the temperature of the gas change as the cylinder's volume is gradually increased?**

**Ans.** When the volume of the gas is increased in a heat-proof jacket, the work is done by the gas at the expense of its internal energy. Due to a decrease in internal energy, the temperature of the gas will decrease.

**19. Why can't heat naturally flow from a low-temperature body to a high-temperature body?**

**Ans.** First law of thermodynamics simply tells about the conversion of mechanical energy into heat energy and vice versa. It does not put any condition as to why heat cannot flow from a lower temperature to a higher temperature.

**Caution**

➥ *Students should know that although the temperature of a body can be raised without limit, it can not be lowered without limit and theoretically limiting low temperature is taken to be zero on the Kelvin scale (i.e., no negative temperature on The Kelvin scale is possible).*

**20. Can a system be heated and its temperature remains constant? [NCERT Exemplar]**

**Ans.** It is given that,

$$\Delta T = 0,$$
$$\Delta U = 0$$
$$\Delta Q = \Delta U + \Delta W$$
$$\Delta Q = \Delta W$$

So, heat supplied to the system is utilised in the expansion, the system is isothermal.

**21. For which thermodynamic process entropy is zero? [Diksha]**

**Ans.** Entropy is zero in a reversible process, it increases in an irreversible process. The ultimate fate of the universe is likely to be thermodynamic equilibrium, where the universal temperature is constant and no energy is available to do work.

**22. Out of the parameters: temperature, pressure, work and volume, which parameter does not characterise the thermodynamics state of matter? [Delhi Gov. QB 2022]**

**Ans.** Since we know that the parameter pressure, volume and temperature are characterise the thermodynamic state of matter.

Since, work is both function, it gives only a specific relationship between two different thermodynamic states.

So, work does not characterise the thermodynamic state of matter.

**23. Heat is supplied to a system, but its internal energy does not increase. What is the process involved? [Delhi Gov. QB 2022]**

**Ans.** Isothermal expansion is the process involved. The internal energy of the system remains constant in the isothermal, free expansion, and cyclic processes because the system's temperature remains constant. Because internal energy is a function of temperature, there is no change in the system's internal energy.

## SHORT ANSWER Type-I Questions (SA-I)

[ 2 marks ]

**24. A 100 W electric heater provides heat to a system. If the system operates at 75 joules per second. What is the rate of increase in internal energy?**

**Ans.** By the law of conservation of energy,

$$\text{Total energy} = \text{Work done} + \text{Internal Energy}$$

$$100 = 75 + U = 25 \text{ J/s}$$

Hence, internal energy is increasing at the rate of 25 W.

**25. In accordance with the first law of thermodynamics under which condition the law can be violated? [Diksha]**

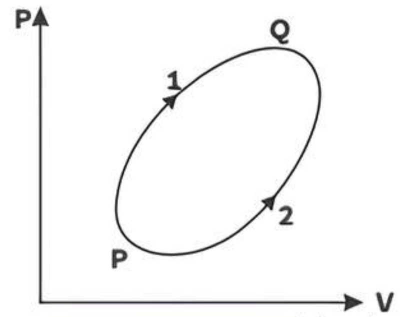
**Ans.** In accordance to the first law of thermodynamics, for a thermodynamic system, in which internal energy is the only type of energy the system may have the law of conservation of energy may be expressed as,

$$Q + W = \Delta E_{int}$$

Here, Q is the energy transferred (as heat) between the system and environment, W is the work done on (or by) the system and $\Delta E_{int}$ is the change in the internal energy of the system. By convention, we have chosen Q to be positive when heat is transferred into the system and W to be positive when work is done on the system.

When $W > 0$ and $Q > 0$ and putting this condition in the left-hand side of the equation $Q + W = \Delta E_{int}$, then the right-hand side of the equation must be greater than zero ($\Delta E_{int} > 0$). Thus $W > 0$, $Q > 0$, and $\Delta E_{int} < 0$ must violate the first law of thermodynamics.

**26.** **A system goes from P to Q by two different paths in the P-V diagram as shown in the figure. Heat given to the system in path 1 is 1000 J. The work done by the system along path 1 is more than path 2 by 100 J. What is the heat exchanged by the system in path 2?**




(given)

**[NCERT Exemplar]**

**Ans.** For path 1

$$Q_1 = +1000 \text{ J}$$

$$\text{Work Done} = W_1 - W_2 = 100$$

$$W_1 = \text{Work done through path 1}$$

$$W_2 = \text{Work done through path 2}$$

$$\therefore \quad W_2 = W_1 - 100$$

As change in internal energy by paths 1 and 2 are the same

$$\Delta U = Q_1 - W_1 = Q_2 - W_2$$

$$1000 - W_1 = Q_2 - (W_1 - 100)$$

$$1000 = Q_2 + 100$$

$$Q_2 = 900 \text{ J.}$$

**27.** **Heat system based on the circulation of steam is more efficient in warming a building than those based on the circulation of hot water why?** **[Delhi Gov. QB 2022]**

**Ans.** At 100°C, steam has more heat than the equivalent quantity of water at 100°C. One gram of steam at 100°C has 540 calories more heat than one gram of water at 100°C. As a result, heating systems based on steam circulation are more efficient than those based on hot water circulation.

**28.** **Write the expressions for $C_v$ and $C_p$ of a gas in terms of gas constant R and $\gamma$. Where,**

$$\gamma = \frac{C_p}{C_v}$$

**[Delhi Gov. QB 2022]**

**Ans.** $C_P \rightarrow$ Specific heat capacity at constant pressure;

$C_V \rightarrow$ Specific heat capacity at constant volume;

$R \rightarrow$ Molar gas constant;

$\gamma \rightarrow$ Atomicity of an ideal gas

We know $\quad C_P - C_V = R \quad$ ...(i)

and $\quad \gamma = \frac{C_p}{C_v} \quad$ ...(ii)

From eqn (i) and (ii)

$$C_V = C_P - R$$

$$\Rightarrow \quad C_P = C_V + R$$

$$\text{So,} \quad \gamma = \frac{C_V + R}{C_V}$$

$$\Rightarrow \quad C_V\gamma = C_V + R$$

$$\Rightarrow \quad C_V\gamma - R = C_V$$

$$\Rightarrow \quad \gamma - \frac{R}{C_V} = 1$$

$$\Rightarrow \quad \frac{R}{C_V} = (\gamma - 1)$$

$$\Rightarrow \quad C_V = \frac{R}{(\gamma - 1)}$$

## **SHORT ANSWER** Type-II Questions **(SA-II)**

[ **3** marks ]

**29.** **The volume of some air assumed to be an ideal gas, in the cylinder of a car engine in cylinder of a car engine is 540 $cm^3$ at a pressure of $1.1 \times 10^5$ Pa and a temperature of 27°C. The air is suddenly compressed so that no thermal energy enters or leaves the gas, to a volume of 30 $cm^3$. The pressure rises to $6.5 \times 10^6$ Pa.**

**(A) Determine the temperature of the gas after the compression**

**(B) Use the first law of thermodynamics to explain why the temperature of the air changed during the compression.**

**Ans.** (A) Here

$$P_1 = 1.1 \times 10^5 \text{ Pa,}$$

$$V_1 = 540 \text{ cm}^3,$$

$$T_1 = 27°C$$

$$= 27 + 273$$

$$= 300 \text{ K.}$$

$P_2 = 6.5 \times 10^6$ Pa.

$V_2 = 30$ cm$^3$

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

$$T_2 = \frac{P_2V_2}{P_1V_1} \times T_1$$

$$= \frac{6.5 \times 10^6}{1.1 \times 10^5} \times 300$$

$$= 984.8 \text{ K}$$

(B) Here, no thermal energy enters or leaves the air, $dQ = 0$.

From the first law of the thermodynamics we have

$$0 = dU + dW$$

$$dU = -dW$$

Since the air is compressed, work is done on the air *i.e.*, dW is negative.

$$dU = -(-dW)$$

$$= +dW = \text{Positive}$$

As $dU$ is positive the temperature of the air increases.

**30. A spherical constant temperature heat source of radius $r_1$ is at the center of a uniform solid sphere of radius $r_2$. Calculate the rate at which heat is transferred through the surface of the sphere. [Diksha]**

**Ans.** The rate H at which heat is transferred through the slab is:

(1) Directly proportional to the area (A).

(2) Inversely proportional to the thickness of the slab $\Delta x$.

So, $$H = KA\frac{\Delta T}{\Delta x}$$

Where K is the proportionality constant which is called the thermal conductivity of the material.

The rate H at which heat is transferred through the slab is directly proportional to the area (A) available.

Area of a solid sphere is defined as $A = 4\pi r^2$ $r$ is the radius of the sphere.

So, the area $A_1$ of the uniform large sphere having radius $r_1$ is,

$$A_1 = 4\pi r_1^2$$

and the area $A_2$ of the uniform large sphere having radius $r_2$ is,

$$A_2 = 4\pi r_2^2$$

Thus, the area A from which heat is transferred through the surface of the solid sphere will be the difference between area of uniform large solid sphere $A_2$ and small solid sphere $A_1$.

So, $$A = A_2 - A_1$$

$$= 4\pi r_2^2 - 4\pi r_1^2$$

$$= 4\pi(r_2^2 - r_1^2)$$

Since the rate H at which heat is transferred through the slab is directly proportional to the area (A). Therefore, the rate at which heat is transferred through the surface of the sphere is proportional to $r_2^2 - r_1^2$.

**31. Consider a cycle tyre being filled with air by a pump. Let V be the volume of the tyre (fixed) and at each stroke of the pump $\Delta V (<<V)$ of air is transferred to the tube adiabatically. What is the work done when the pressure in the tube is increased from $P_1$ to $P_2$? [NCERT Exempler]**

**Ans.** Air is transferred into the tyre adiabatically let the initial volume of air in the tyre is $V$ and after pumping one stroke, it becomes $(V + dV)$ and pressure increased from P to $(P + dP)$ then.

$$P_1V_1^\gamma = P_2V_2^\gamma$$

$$P(V + dV)^\gamma = (P + dP)V^\gamma$$

$$PV^\gamma\left[1 + \frac{dV}{V}\right]^\gamma = P\left(1 + \frac{dP}{P}\right)V^\gamma$$

as volume of tyre V remains constant

$$PV^\gamma\left[1 + \frac{dV}{V}\right]^\gamma = PV^\gamma\left[1 + \frac{dP}{P}\right]$$

[on expanding by binomial theorem neglecting the higher terms of $\Delta V$ as $\Delta V << V$]

$$1 + \gamma\frac{dV}{V} = 1 + \frac{dP}{P}$$

$$dV = \frac{VdP}{\gamma P}$$

Integrating both side in limits $W_1$ to $W_2$ and $P_1 \to P_2$

$$\int PdV = \int_{P_1}^{P_2} \frac{VdP}{\gamma}$$

$$\int_{W_1}^{W_2} dw = \frac{V}{\gamma}(P_2 - P_1)$$

$$V = \text{constant}$$

$$W = \frac{(P_2 - P_1)V}{\gamma}$$

**32.** **(A) Why a gas has two principal specific heat capacities?**

**(B) Which one is greater and why?**

**[Delhi Gov. QB 2022]**

**Ans.** (A) Because a gas may be heated under two distinct situations, it has two primary specific heats:

(i) Specific heat at constant volume.

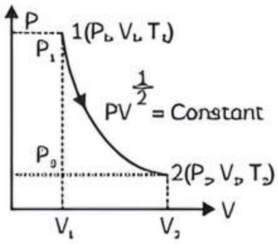
(ii) Specific heat at constant pressure.

(B) A gas expands when heated at a steady pressure. The heat given to it is utilized to raise its temperature and to conduct work against external pressure. When the gas, on the other hand, is heated at a fixed volume, no work is done. As a result, the heat delivered should only be utilized to raise the temperature. As a result, the amount of heat necessary to increase the temperature of a gas by 1°C (say) under constant pressure will be more than the amount required at constant volume.

## LONG ANSWER Type Questions (LA)

[ 4 & 5 marks ]

**33.** **Consider a P-V diagram in which the path followed by one mole of a perfect gas in a cylindrical container is shown in the figure.**




**(A) Find work done when the gas is taken from the state (1) to state (2).**

**(B) What is the ratio of temperature $\frac{T_1}{T_2}$, if $V_2 = 2V_1$?**

**(C) Given the internal energy for one mole of gas at temperature T is (3/2) RT, find the heat supplied to the gas when it is taken from the state (1) to (2) with $V_2 = 2V_1$.**

**[NCERT Exemplar]**

**Ans.**

$$PV^{1/2} = \text{Constant}$$
$$= K \text{(given)}$$

or $$P_1V_1^{1/2} = P_2V_2^{1/2} = K$$

and $$P = \frac{K}{V^{1/2}} \quad \text{...(i)}$$

(A) Work done for the process from 1 to 2,

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

$$= \int_{V_1}^{V_2} \frac{K}{V^{1/2}}.dV$$

$$= K\int_{V_1}^{V_2} V^{-1/2}.dV$$

$$W = K\left[\frac{V^{1/2}}{\frac{1}{2}}\right]_{V_1}^{V_2}$$

$$= 2K\left[\sqrt{V_2} - \sqrt{V_1}\right]$$

W from $V_1$ to $V_2$,

i.e., $$dW = 2P_1 V_1^{1/2}\left[\sqrt{V_2} - \sqrt{V_1}\right]$$

$$= 2P_2 V_2^{1/2}\left[\sqrt{V_2} - \sqrt{V_1}\right]$$

(B) From the gas equation of ideal gas:

$$PV = nRT$$

$$T = \frac{PV}{nR}$$

$$T = \frac{P\sqrt{V}\sqrt{V}}{nR}$$

$$T = \frac{K\sqrt{V}}{nR} \quad \text{[from eqn. (i)]}$$

$$T_1 = \frac{K\sqrt{V_1}}{nR}$$

$$T_2 = \frac{K\sqrt{V_2}}{nR}$$

$$\frac{T_1}{T_2} = \frac{\frac{K\sqrt{V_1}}{nR}}{\frac{K\sqrt{V_2}}{nR}}$$

$$= \frac{\sqrt{V_1}}{\sqrt{V_2}}$$

$$= \sqrt{\frac{V_1}{2V_1}} \quad (\because V_2 = 2V_1)$$

$$\frac{T_1}{T_2} = \sqrt{\frac{1}{2}}$$

Required ratio is $1 : \sqrt{2}$

(C) Given that, internal energy U of gas is,

$$U = \left(\frac{3}{2}\right) RT$$

$$\Delta U = \frac{3}{2} R dT$$

$$= \frac{3}{2} R(T_2 - T_1)$$

$$T_2 = \sqrt{2}\, T_1, \qquad \text{[from part (B)]}$$

$$\Delta U = \frac{3}{2} R\left[\sqrt{2}T_1 - T_1\right]$$

$$= \frac{3}{2} RT_1\left[\sqrt{2} - 1\right]$$

from part (A)

$$dW = 2P_1V^{1/2} (\sqrt{V_2} - \sqrt{V_1})$$

$$V_2 = V_1 \qquad \text{(Given)}$$

$$dW = 2P_1V_1^{1/2} (\sqrt{2}\sqrt{V_1} - \sqrt{V_1})$$

$$= 2P_1V_1^{1/2} \sqrt{V_1}\, [\sqrt{2} - 1]$$

$$dW = 2P_1V_1\, [\sqrt{2} - 1]$$

$$dW = 2nRT_1\, [\sqrt{2} - 1]$$

$$n = 1,$$

$$dW = 2nRT_1\, [\sqrt{2} - 1]$$

$$dQ = dW + dU$$

$$= 2RT_1 (\sqrt{2} - 1) + \frac{3}{2} RT_1 (\sqrt{2} - 1)$$

$$= RT_1 (\sqrt{2} - 1) \left[2 + \frac{3}{2}\right]$$

$$dQ = \frac{7}{2} RT_1 (\sqrt{2} - 1)$$

**34. An amount of work equal to 22.3 J is done on the system when changing the state of a gas adiabatically from one equilibrium state A to another state B. How much net work is done by the system in the latter case if the gas is transferred from state A to B via a process in which the net heat absorbed by the system is 9.35 cal? (One calorie equals 4.19 J.)**

**Ans.** The work done (W) on the system while the gas changes from state A to state B is 22.3 J.

This is an adiabatic process. Hence, the change in heat is zero.

$$\therefore \quad \Delta Q = 0$$

$$\Delta W = -22.3 \text{ J}$$

(Since the work is done on the system)

From the first law of thermodynamics,

We have:

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

Where, $\Delta U$ = Change in the internal energy of the gas

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

$$= -(-22.3 \text{ J})$$

$$\Delta U = +22.3 \text{ J}$$

When the gas goes from state A to state B via a process, the net heat absorbed by the system is:

$$\Delta Q = 9.35 \text{ cal}$$

$$= 9.35 \times 4.19$$

$$= 39.1765 \text{ J}$$

Heat absorbed,

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

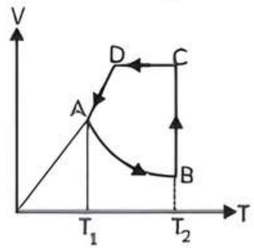
$$\therefore \quad \Delta W = \Delta Q - \Delta U$$

$$= 39.1765 - 22.3$$

$$= 16.8765 \text{ J}$$

Therefore, 16.88 J of work is done by the system.

**35. The diagram depicts a cycle ABCDA undergone by two moles of an ideal diatomic gas. $T_1$ = 300 K, $T_2$ = 500 K and the curve AB is a rectangular hyperbola. Ascertain the following:**




**(A) Work done by the gas in the process $A \rightarrow B$.**

**(B) Heat has given to the gas in the process $A \rightarrow B$.**

**(C) Molar heat capacity of the gas in the process $A \rightarrow B$.**

**Ans.** Evidently, for the process $A \rightarrow B$,

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

or $VT = \text{constant (say, } k)$

or $TdV + VdT = 0$

or $dV = -\frac{VdT}{T}$

(A) Now, work done by the gas in a process is given by,

$$W = \int PdV$$

$$W_{AB} = \int \frac{nRTdV}{V}$$

$$W_{AB} = \int (-nRdT)$$

$$W_{AB} = \int_{300}^{500} -nRdT$$

$$= (-2 \text{ mol})\left(8.314 \frac{1}{\text{mol}-\text{K}}\right)[500-300]$$

(B) Heat has given to the gas in the process $A \rightarrow B$,

$$Q_{AB} = W_{AB} + \Delta U_{AB}$$

$$= -3.326 \text{ kJ} + (2 \text{ mol}) \frac{5 \times 8.314 \text{J}}{2 \text{mol K}} (200 \text{ K})$$

$$= 5 \text{ kJ}$$

(C) Molar heat capacity C is given by

$$C = \frac{Q}{n\Delta T}$$

$$= \frac{5 \times 10^3}{(2 \text{ mol})(200 \text{ K})}$$

$$= \frac{12.5 \text{ J}}{\text{mol K}}$$

**36. Is it a violation of the second law of thermodynamics to convert:**

**(A) Work completely into heat**

**(B) Heat completely into work**

**Why or why not? [Delhi Gov. QB 2022]**

**Ans.** Converting, work totally into heat or heat totally in work, is not a violation of the second rule of thermodynamics. According to the second rule of thermodynamics, energy cannot be moved from one form to another without changing the entropy.

## NUMERICAL Type Questions

**37. A room has a concrete roof that measures 4 m × 4 m × 10 cm ($K_1$ = 1.26 w/m/°C). Outside, the temperature is 46°C and the radius is 32°C.**

**(A) Determine the amount of heat flowing into the room per second through the roof.**

**(B) If 7.5 cm thick bricks ($K_2$ = 0.56 w/m/°C) are laid down on the roof, what is the new rate of heat flow under the same temperature conditions? (3m)**

**Ans.** (A) Area of roof

$$A = 4 \times 4 = 16 \text{ m}^2$$

Thickness of roof,

$$x_1 = 10 \text{ cm} = 0.1 \text{ m}.$$

Thermal resistance of the roof is given by:

$$R_1 = \frac{X_1}{K_1 A_1}$$

$$= \frac{0.1}{1.26 \times 16}$$

$$= 4.96 \times 10^{-3} \text{ °C/W}$$

Rate of heat flow through the roof is:

$$H_1 = \frac{\theta}{t} = \frac{\theta_1 - \theta_2}{R}$$

$$= \frac{46-32}{4.96 \times 10^{-3}}$$

$$= 2.822 \times 10^3 \text{ W}$$

$$= 2822 \text{ W}$$

(B) The thermal resistance of the brick is given by:

$$R_2 = \frac{X_2}{K_2 A_2}$$

$$= \frac{7.5 \times 10^{-2}}{0.65 \times 16}$$

$$= 7.2 \times 10^{-3} \text{ °C/W}$$

The equivalent thermal resistance of the roof now is:

$$R = R_1 + R_2$$

$$= (4.96 + 7.2) \times 10^{-3}$$

$$= 1.216 \times 10^{-2} \text{ °C/W}$$

Rate of heat through the roof is:

$$H_2 = \frac{\theta}{t} = \frac{\theta_1 - \theta_2}{R}$$

$$= \frac{46-32}{1.216 \times 10^{-2}} = 1152 \text{ W}$$

**38. A steam engine's boiler generates $5.4 \times 10^8$J of work per minute and $3.6 \times 10^9$ heat per minute. How efficient is the engine? How much heat is wasted each minute? (3m)**

**Ans.** Work done by the steam engine per minute.

$$W = 5.4 \times 10^8 J$$

Heat supplied from the boiler.

$$H = 3.6 \times 10^9 J$$

$$\text{Efficiency of the engine} = \frac{\text{Output energy}}{\text{Input Energy}}$$

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

$$= \frac{5.4 \times 10^8}{3.6 \times 10^9} = 0.15$$

Hence, the percentage efficiency of the engine is 15 %.

Amount of heat wasted

$$= 3.6 \times 10^9 - 5.4 \times 10^8$$
$$= 30.6 \times 10^8$$
$$= 3.06 \times 10^9$$

Therefore, the amount of heat wasted per minute is $3.06 \times 10^9$ W.

**39. At the same temperature, 1 kg of water at 373K is converted into steam. Boiling one cubic centimeter of water expands it to 1671 cubic centimeters. What happens to the system's internal energy if water's latent heat of vaporization is $5.4 \times 10^5$ cal $kg^{-1}$? (3m)**

**Ans.** Volume of 1 kg of water

$$= 1000 \text{ cm}^3$$

Volume of 1 kg of steam

$$= 1000 \text{ cm}^3$$
$$= 10^{-3} \times 1671 \text{ cm}^3$$
$$= 1.671 \text{ m}^3$$

Change in volume.

$$\Delta V = (1.671 - 10^{-3})\ m^3$$

Pressure P = 1 atm $= 1.01 \times 10^5$ $Nm^{-2}$

In expansion, work done.

$$W = P\Delta V$$
$$= 1.01 \times 105 \times 1.67 J$$
$$= \frac{1.686 \times 10^5}{4.2} \text{ cal}$$
$$= 4.015 \times 10^4 \text{ cal}$$

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

(first law of thermodynamics)

or $\Delta U = (5.4 \times 10^5 - 4.015 \times 10^4)$ cal

$$= 4.9985 \times 10^5 \text{ cal.}$$

**40. $\frac{1}{2}$ mole of helium is contained in a container at S.T.P. How much heat energy is needed to double the pressure of the gas, keeping the volume constant? Heat capacity of gas is 3 J $g^{-1}$ $K^{-1}$. [Delhi Gov. QB 2022](3m)**

**Ans.** Here, $n = \frac{1}{2}$, $C_V = 3$ J$g^{-1}K^{-1}$, M = 4 g $mol^{-1}$

$$\therefore \quad C_V = M_{C_V}\ 4 \times 3 = 12 \text{ J mol}^{-1}\text{K}^{-1}$$

At constant volume P ∝ T.

$$\therefore \quad \frac{P_2}{P_1} = \frac{T_2}{T_1} = 2.$$

$$T_2 = 2T_1$$

Rise in temperature.

$$\Delta T = T_2 - T_1 = 2T_1 - T_1$$
$$= T_1 = 273 \text{ K}$$

Heat required.

$$\Delta Q = NC_V\Delta T = \frac{1}{2} \times 12 \times 273$$
$$= 1638 \text{ J}$$

# SECOND LAW OF THERMODYNAMICS AND CARNOT ENGINE

2

TOPIC 1

## SECOND LAW OF THERMODYNAMICS

The first law of thermodynamics is the principle of conservation of energy. Common experience shows that many conceivable processes are perfectly allowed by the first law and yet are never observed. For example, nobody has ever seen a book lying on a table, jumping to a height by itself. It would be possible if the principle of conservation of energy were the only restriction. This principle which disallows many phenomena consistent with the first law of thermodynamics is known as the second law of thermodynamics. The second law of thermodynamics gives a fundamental limitation to the efficiency of a heat engine and the co-efficient of performance of a refrigerator.

Second law of thermodynamics states that "the entropy in an isolated system always increases. Any isolated system spontaneously evolves towards thermal equilibrium—the state of maximum entropy of the system".

**Kelvin Planck Statement:** No process is possible whose sole result is the absorption of heat from a reservoir and the complete conversion of the heat into work.

**Clausius Statement:** No process is possible whose sole result is the transfer of heat from a colder object to a hotter object.

It can be proved that the two statements above are completely equivalent.

The second law of thermodynamics is a general principle that places constraints upon the direction of heat transfer and the attainable efficiencies of heat engines.

**Entropy statement of the second law of thermodynamics:**

The entropy of the universe never decreases. It either increases (for irreversible processes) or remains the same (for reversible processes ).

### Reversible and Irreversible Processes

#### Reversible processes

A Reversible process is defined as a process that can be reversed without leaving any trace on the surroundings. Both, the system and the surroundings, are returned to their initial states at the end of the reversible process.

Conditions for Reversible processes:

(1) The processes should take place very slowly *i.e.*, quasi-statically or seemingly static so that it satisfies the following requirements at each stage of the process:

- The system should be in mechanical equilibrium.
- The system should be in thermal equilibrium.
- The system should be in chemical equilibrium.

(2) There should be no friction losses etc. It should be remembered that a completely reversible process or cycle of operation is only an ideal case. In actual practice, there is always the loss of heat due to friction, conduction and radiation. However, it is possible to approximate reversible processes through carefully controlled procedures but they can never be achieved.

#### Irreversible processes

A process that is not reversible is called an irreversible process.

The spontaneous processes occurring in nature are irreversible. In fact, irreversibility is a rule rather than an exception in nature.

Examples:

(1) Sudden unbalanced expansion of a gas.

(2) Heat produced by friction.

(3) Heat is generated when a current flows through an electric resistance in any direction.

(4) Cooking gas leaking from a cylinder.

(5) Diffusion of liquids or gases.

(6) Breaking of an egg.

(7) The growth of a plant.

A system can be restored to its initial state following a process, regardless of whether the process is reversible or irreversible. But for reversible processes, this restoration is made without leaving any net change on the surroundings whereas, for irreversible processes, the surroundings usually do some work on the system and therefore will not return to their original state.

**Example 2.1:** **Dry ice is carbon dioxide in solid form. At normal atmospheric pressure and room temperature, dry ice undergoes sublimation**

(changes from solid to gas phase). Now According to the second law of thermodynamics, what is the entropy change in this process?

**Ans.** Dry ice sublimes at room temperature by taking in heat and the process is irreversible process. Since, the given room temperature is much higher than the freezing point of carbon dioxide.

The entropy of a gas is always higher than the entropy of a solid. Hence, the entropy of the surrounding after the sublimation of dry ice increases.

Hence, $\Delta S_{sys} + \Delta S_{surr} > 0$

**Example 2.2:** A heat exchanger performs 300 J of work in order to remove 400 J of heat from a low-temperature reservoir. How much heat is delivered to a higher-temperature reservoir?

**Ans.**

$$W = 300\text{ J}$$
$$Q_C = 400\text{ J}$$
$$Q_H = W + Q_C$$
$$Q_H = 300\text{ J} + 400\text{ J}$$
$$Q_H = 700\text{ J}$$

Heat delivered to the higher temperature reservoir is 700 J.

## TOPIC 2

# CARNOT ENGINE

Heat engine is a device which converts heat into work.

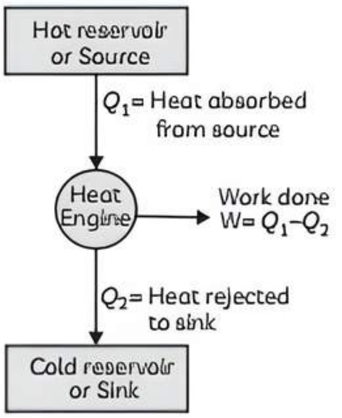
There are three parts of heat engine:

(1) Source of high-temperature reservoir at temperature $T_1$.

(2) Sink of high-temperature reservoir at temperature $T_2$.

(3) Working substance.

In a cycle of heat engines the working substance extracts heat $Q_1$ from the source, do some work W and rejects the remaining heat $Q_2$ to the sink.




Efficiency of heat engine,

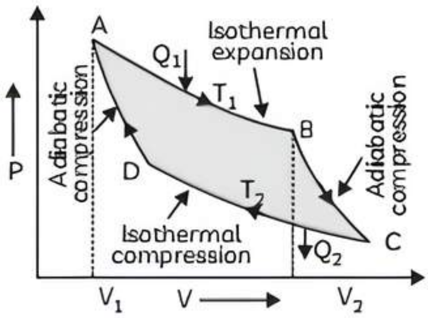
$$\eta = \frac{\text{Work done (W)}}{\text{Heat taken from source } (Q_1)}$$

$$\eta = \frac{T_1 - T_2}{T_1} = \frac{Q_1 - Q_2}{Q_1}$$

Sadi Carnot developed a hypothetical, idealized heat engine that has the maximum possible efficiency consistent with the second law of thermodynamics. For maximum heat engine efficiency, the processes should be reversible. So, we must avoid all irreversible processes.

A reversible heat engine operating between two temperatures is called a Carnot engine and the sequence of steps constituting one cycle are called the Carnot cycle.

Carnot devised an ideal engine which is based on a reversible cycle of four operations in succession: isothermal expansion, adiabatic expansion, isothermal compression and adiabatic compression.




## Main parts of Carnot's engine

### Source of heat

It is a hot body of high-temperature $T_1$ from which the heat can be drawn. It is a hot body of very large heat capacity kept at a constant high-temperature $T_1$ K. Its upper surface is perfectly conducting so that working substances can take the heat.

### Working substance

A cylinder, whose walls are perfectly non-conducting but the base is perfectly conducting, fitted with non-conducting piston which can move without any frictional losses. Ideal gas is enclosed in these systems as a working substance.

### Heat sink

A cold body at low-temperature $T_2$ K to which the heat can be rejected. It is a body of large heat capacity. Its upper surface is highly conducting so that a working substance can reject heat to it.

### Stand

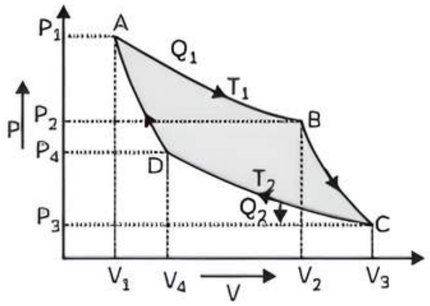
It is made of perfectly insulating material so that when a cylinder is placed on it, the working substance can expand or compress adiabatically.

## Working of Carnot's Engine

To get maximum work from this type of ideal engine, there is a set of reversible processes through which the working substance is taken back to the initial condition.

Complete Carnot cycle is divided Into four steps.

Processes of Carnot's cycle can be denoted by an indicator diagram as shown. The variation of pressure (P) and volume (V) of the working substance (ideal gas), are plotted.




**(1) Isothermal expansion A → B**

Initially the cylinder is taken to be in thermal equilibrium with the high-temperature $T_1$ represented by point A ($P_1$, $V_1$, $T_1$). This is the initial state of the working substance. Then the piston is allowed to move outward slowly. With the movement of the piston, the temperature of the gas tends to fall. The process is very slow, so it is isothermal. Heat from the reservoir flows into the gas and the temperature of the gas remains $T_1$. In this expansion, gas receive heat $Q_1$ from the source and gets state B ($P_2$, $V_2$, $T_1$).

The total heat input $Q_1$ to the gas occurs over the path from A to B and comes from a large reservoir of heat (source) at temperature $T_1$ and is utilized for doing work $W_1$.

Over the path from A to B, the heat input to the gas is equal to the work done against the external pressure.

$$Q_1 = \int_{V_1}^{V_2} PdV$$

$$Q_1 = \int_{V_1}^{V_2} \frac{\mu RT_1}{V} dV$$

$$Q_1 = \mu RT_1 ln\left(\frac{V_2}{V_1}\right)$$

$$W_1 = \mu RT_1 ln\left(\frac{V_2}{V_1}\right)$$

$$(\therefore W_1 = Q_1)$$

**(2) Adiabatic expansion B → C**

Now the contact of the cylinder with the source is removed and the cylinder is put in contact with a non-conducting stand. The piston is allowed to move outward the gas, now expands adiabatically because no heat can enter in or leave out. The temperature falls to $T_2$ and gas describes the adiabatic BC to point C ($P_3$, $V_3$, $T_2$) during which more work is done ($W_2$) at the expense of the internal energy.

Work done over this adiabatic path BC,

$$W_2 = \frac{\gamma R}{\gamma - 1}(T_1 - T_2)$$

**(3) Isothermal compression C → D**

The gas cylinder is placed in contact with the sink at temperature $T_2$. The piston is moved slowly inward, so that heat produced during compression passes to the sink. The gas is isothermally compressed to point D. ($P_4$, $V_4$, $T_2$)

The heat rejected $Q_2$ to the cold reservoir (sink) at $T_2$ occurs over the path from C to D. The amount of work done on the gas $W_3$ is equal to the amount of heat rejected to the sink $W_3 = Q_2$ and

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

or

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

**(4) Adiabatic compression D → A**

The cylinder is removed from the sink and put in contact with the insulating stand and the piston moves inward. Heat is not allowed to go out and it increases the internal energy of the system. Then work is done on the gas during adiabatic compression from state D to initial point A ($P_1$, $V_1$, $T_1$).

No heat exchanges occur over the adiabatic path.

Work done on the system is,

$$W_4 = \frac{\gamma R}{\gamma - 1}(T_1 - T_2)$$

**This cycle of operations is called a Carnot cycle.** In the first two steps work is done by the engine ($W_1$ and $W_2$ are positive) and in the last two steps work is done on the gas ($W_3$ and $W_4$ are negative). The work done in complete cycle W is equal to the area of the closed part of the P–V cycle.

$$W = W_1 + W_2 + W_3 + W_4$$

$$W = \mu RT_1 \, ln\left(\frac{V_2}{V_1}\right) + \frac{\gamma R}{\gamma - 1}(T_1 - T_2)$$

$$+ \mu RT_2 \, ln\left(\frac{V_4}{V_3}\right) + \frac{\gamma R}{\gamma - 1}(T_1 - T_2)$$

$$= \mu RT_1 \, ln\left(\frac{V_2}{V_1}\right) + \mu RT_2 \, ln\left(\frac{V_4}{V_3}\right)$$

Efficiency of Carnot engine,

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

$$= \frac{\mu RT_1 \ln\left(\frac{V_2}{V_1}\right) + \mu RT_2 \ln\left(\frac{V_4}{V_3}\right)}{\mu RT_1 \ln\left(\frac{V_2}{V_1}\right)}$$

Points B and C are connected by an adiabatic path as are points D and A. Hence, by using this equation and the adiabatic gas equation.

$$T_1 V_2^{(\gamma-1)} = T_2 V_3^{(\gamma-1)}$$

and $T_1 V_1^{(\gamma-1)} = T_2 V_4^{(\gamma-1)}$

Combination of the above equations gives:

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

$$\eta = \frac{T_1 - T_2}{T_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta = \left(1 - \frac{Q_2}{Q_1}\right) \times 100\%$$

$$= \left(1 - \frac{T_2}{T_1}\right) \times 100\%$$

**Important**

➥ *The Carnot engine is the most efficient engine which is theoretically possible. The efficiency depends only upon the absolute temperatures of the hot and cold heat reservoirs between which it operates.*

## Efficiency of Cyclic Process

When a system is subjected to a cyclic process, heat is supplied during some parts of the process, while heat is abstracted during other parts.

Evidently, the net heat supplied will be the work done by the system.

$\therefore \qquad \Delta Q = \Delta W$

However, the gross heat supplied will be more than that of the net heat.

Efficiency ($\eta$) of a cycle, is defined as the ratio of the work performed (net heat given) to the gross heat supplied to the system, per cycle.

Thus, $$\eta = \frac{\text{Work done per cycle}}{\text{Gross heat supplied per cycle}}$$

**The percentage efficiency of Carnot's engine:**

$$\eta = \frac{T_1 - T_2}{T_1} \times 100\%$$

or $$\eta = \frac{Q_1 - Q_2}{Q_1} \times 100\%$$

It can be shown that the efficiency for the Carnot engine is the best that can be obtained for any heat engine and the equation gives an upper limit to the efficiency of any heat engine operating between temperatures $T_1$ and $T_2$.

The efficiency depends upon the temperatures $T_1$ and $T_2$ which approaches unity only when the temperature of the cold reservoir approaches absolute zero. A steam engine using steam at 373 K and with a cold reservoir at 273 K has the best possible efficiency,

$$\eta \equiv 1 - \frac{273}{373} \equiv 27\%.$$

The efficiency of a Carnot engine is never 100% because it has 100% efficiency only if the temperature of the sink would be $T_2 = 0$ which is almost impossible.

In a Carnot cycle,

$$\frac{Q_2}{Q_1} = \frac{T_2}{T_1}$$

or $$\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$$

## Carnot Theorem

No irreversible engine (I) can have an efficiency greater than Carnot reversible engine (R) working between the same hot and cold reservoirs.

*i.e.*, $\eta_R > \eta_I$.

**Example 2.3: Two Carnot engines, A and B, are used sequentially. Engine A absorbs heat from the source at $T_1$ = 800 K and releases it to the sink at $T_2$K. Second engine B absorbs the heat released by the first engine at ($T_2$K) and releases it at another sink at temperature $T_3$ = 300 K. Calculate the value of $T_2$ if the work done by the two engines is the same.**

**Ans.** As $W_A = Q_1 - Q_2$

$W_B = Q_2 - Q_3$

$$\frac{W_A}{W_B} = \frac{Q_1 - Q_2}{Q_2 - Q_3} = \frac{T_1 - T_2}{T_2 - T_3}$$

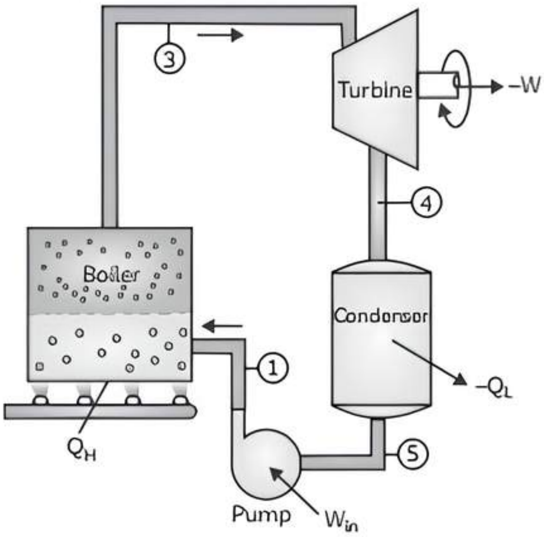
$$= \frac{800 - T_2}{T_2 - 300} = 1$$

$$800 - T_2 = T_2 - 300$$

$$T_2 = 550 \text{ K}$$

**Example 2.4:** Case Based:

*Carnot assumed that the steam engine was nothing but a water wheel for this caloric fluid, so the most efficient engine would have minimal friction, but also, in analogy with the water entering and leaving the wheel gently with no intermediate loss of height, the heat would enter and leave the gas in the engine isothermally (remember the temperature is analogous to the gravitational potential, thus the height). Therefore, by analogy with gh, the drop in temperature $T_H - T_C$ measures the potential energy given up by a unit amount of the "heat fluid".*




(A) A Carnot engine has an efficiency of 40% and temperature of sink 300 K to increase efficiency up to 60%. Calculate the change in temperature of source.

(B) Assertion (A): Efficiency of Carnot engine increases on reducing the temperature of sink.

Reason (R): The efficiency of Carnot engine is defined as ratio of net mechanical work done per cycle by the gas to the amount of heat energy absorbed per cycle from the source.

(a) Both A and R are true and R is the correct explanation of A.
(b) Both A and R are true and R is not the correct explanation of A.
(c) A is true but R is false.
(d) A is false and R is also false.

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(C) A Carnot engine with ideal gas is used for freezing water, which is at 0°C. The engine is operated by a 600 W electric motor having an efficiency of 50%. Find the time to freeze 25 kg of water. (Take 25°C and 0°C as the source and sink temperature respectively and latent heat of Ice = $3.33 \times 10^{-3}$ Jkg$^{-1}$).

(D) A Carnot refrigerator has to transfer an average of 263 J of heat per second from temperature 10°C to 25°C. Calculate the average power consumed. (Assuming no energy losses in the process).

(E) An ideal refrigerator runs between –23°C and 27°C. The heat rejected to the atmosphere for every joule of work input will be:

(A) 10 J (B) 6 J
(C) 2 J (D) 4 J

**Ans.** (A) Carnot engine efficiency,

$$\eta_1 = 40\%$$

Temperature of sink,

$$T_2 = 300 \text{ K}$$

Efficiency increased to

$$\eta_2 = 60\%$$

Change in temperature of the source.

$$T_1 = ?$$

We know the efficiency of the Carnot engine is,

$$\eta = \frac{T_1 - T_2}{T_1}$$

$$\frac{40}{100} = \frac{T_1 - 300}{T_1}$$

$$4T_1 = 10T_1 - 3000$$

$$6T_1 = 3000$$

$T_1$ = 500 K is the source temperature initially. Now to increase efficiency to 60%.

*i.e.,*

$$\eta_2 = \frac{T_1 - T_2}{T_1}$$

$$\frac{60}{100} = \frac{T_1 - 300}{T_1}$$

$$6T_1 = 10T_1 - 3000$$

$T_1$ = 750 K, is the new source temperature. Hence the change in temperature of the source is 250 K.

(B) *(b) Both A and R are true but R is not correct explanation of A.*

**Explanation:** Efficiency of Carnot cycle $\eta = \frac{W}{Q_1} = 1 - \frac{T_2}{T_1}$, for Carnot engine when $T_2$ decrease $\eta$ increases.

(C) Given,

$$Q_2 = 263 \text{ J/s}$$

$$T_2 = -10°\text{C}$$

$$T_2 = -10 + 273 = 298 \text{ K}$$

$$\beta = \frac{Q_2}{W} = \frac{T_2}{T_1 - T_2}$$

Average power,

$$P = \frac{Q_2(T_1 - T_2)}{T_2}$$

$$= \frac{263(298-263)}{263}$$

$$= \frac{35\text{J}}{s} = 35\text{ W}$$

(D) $T_1 = 273$ K

$T_2 = 25 + 273 = 298$ K

$L = 333 \times 10^3$

Efficiency of electric motor = 50%

The used power of the engine

= 50% of 500 W = 250 W

Coefficient of performance,

$$\beta = \frac{Q_2}{W} = \frac{T_2}{T_1 - T_2}$$

Heat extracted from water in unit time,

$$Q_2 = \frac{T_2}{T_1 - T_2} \times W$$

$$= \frac{273}{298-273} \times 250$$

$$= 2730.0\text{ Js}^{-1}$$

Total heat extracted from 25 kg water to freeze it into ice

$$Q = mL$$

$$= 25 \times 333 \times 10^3\text{J}$$

Total time taken in freezing water into ice

$$t = \frac{Q}{Q_2} = \frac{25 \times 333 \times 10^3}{2730}$$

$$= 3049.45\text{ s}$$

(E) *(b)* 6 J

**Explanation:** Let the heat be rejected by the atmosphere

$Q_1 = x$

and given W = 1 joule.

Now, $Q_2 = Q_1 - W$

$= x - 1.$

Given, the hot temperature,

$T_1 = 273 + 27$

$= 300$ K

and cold temperatures,

$T_2 = 273 - 23$

$= 250$ K

For the ideal process,

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$

$$\frac{x}{x-1} = \frac{300}{250}$$

$x = 6$ joule

# OBJECTIVE Type Questions

[1 mark]

## Multiple Choice Questions

1. The efficiency of the Carnot engine is 50% and the temperature of the sink is 500K. If the temperature of the source remains constant and its efficiency is increased to 60%, the required temperature of the sink will be:

(a) 100 K (b) 400 K

(c) 500 K (d) 600 K

**Ans.** *(b)* 400 K

**Explanation:** When efficiency is 50%,

Outlet temperature,

$T_2 = 500$ K

We know, $\eta = 1 - \frac{T_2}{T_1}$

$$\frac{50}{100} = 1 - \frac{500}{T_1}$$

$$\frac{500}{T_1} = \frac{100-50}{100}$$

$T_1 = 1000$ K

To increase the efficiency up to 60%, with

$T_1 = 1000$ K,

then $\eta = 1 - \frac{T_2}{T_1}$

$$\frac{60}{100} = 1 - \frac{T_2}{1000}$$

$$\frac{T_2}{1000} = \frac{100-60}{100}$$

$T_1 = 400$ K

Which is the required outlet temperature.

**2.** **The efficiency of a Carnot engine operating between temperatures $T_1$ and $T_2$ is $\frac{1}{6}$. When $T_2$ is reduced by 62 K, its efficiency rises to $\frac{1}{3}$ then compute $T_1$ and $T_2$ values:**

**(a) 372 K and 310 K (b) 372 K and 330 K**
**(c) 330 K and 268 K (d) 310 K and 248 K**

**Ans.** *(a) 372 K and 310 K*

**Explanation:** Efficiency,

$$\eta = 1 - \frac{T_2}{T_1}$$

In the first case,

$$\eta_1 = 1 - \frac{T_2}{T_1} = \frac{1}{6}.$$

$$\frac{T_2}{T_1} = \frac{5}{6}$$

In the second case,

$$\eta_2 = 1 - \frac{T_2 - 62}{T_1} = \frac{1}{3}.$$

$$\frac{T_2 - 62}{T_1} = \frac{2}{3}$$

$$\frac{T_2 - 62}{\left(\frac{6}{5}\right)T_2} = \frac{2}{3}$$

$$T_2 - 62 = \frac{2}{3} \times \left(\frac{6}{5}\right) \times T_2$$

$$T_2 - 62 = \left(\frac{4}{5}\right)T_2$$

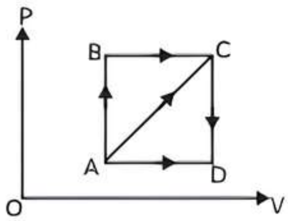
$$T_2 = 310 \text{ K}$$

$$T_1 = \frac{6}{5} \times 310 = 372 \text{ K}$$

$$T_1 = 372 \text{ K.}$$

$$T_2 = 310 \text{ K}$$

**3.** **Figure depicts a thermodynamic process. 600 J of heat is added in process AB and 200 J of heat is added in process BD. The total heat added in process ACD is:**




**(a) 560 J (b) 800 J**
**(c) 600 J (d) 640 J**

**Ans.** *(a) 560 J*

**Explanation:** In the process AB,
We have work done zero (isochoric process).
Using First law, we get,

$$\Delta U = \Delta Q - 0 = 600 \text{ J}$$

In the process BC,
The work done is calculated as,

$$P\Delta V = 8 \times 10^4 \times 3 \times 10^{-3}$$
$$= 240 \text{ J}$$

Thus we get

$$\Delta U = 200 - 240 = -40 \text{ J}$$

Thus the total change in internal energy is given as,

$$600 - 40 = 560 \text{ J}$$

**4.** **One-sixth of the heat input is converted into work by a reversible engine. The engine's efficiency is doubled when the temperature of the sink is reduced by 62°C. The temperature differences between the source and sink are:**

**(a) 99°C, 37°C (b) 80°C, 37°C**
**(c) 95°C, 37°C (d) 90°C, 37°C**

**Ans.** *(d) 90°C, 37°C*

**Explanation:** Efficiency,

$$\eta = 1 - \frac{T_2}{T_1}$$

$$\eta = \frac{T_1 - T_2}{T_1} = \frac{1}{6}$$

$$6T_2 - 6T_1 = T_2$$

$$T_2 = 1.2\, T_1 \quad \text{...(i)}$$

Where $T_2$ is the source temperature and $T_1$ is the sink temperature. If the sink temperature is reduced by 62°C, the efficiency gets doubled *i.e.*,

$$\eta = \frac{T_2 - (T_1 - 62)}{T_1}$$

$$= 2 \times \frac{1}{6} = \frac{2}{6}$$

$$6T_2 - 6T_1 + 372 = 2T_2$$

$$6T_2 - 2T_2 - 6T_1 + 372 = 0$$

$$4T_2 - 6T_1 + 372 = 0$$

Substituting the value of $T_2$ from equation (i), we will get,

$$4(1.2T_1) - 6T_1 + 372 = 0$$

$$4.8T_1 - 6T_1 + 372 = 0$$

$$372 = 1.2T_1$$

$$T_1 = 310\text{K} = 37°\text{C}$$

Therefore,

$$T_2 = 1.2 \times 310$$
$$= 372 \text{ K} = 99°\text{C}$$

Hence, the temperature of the source and the sink is 99°C and 37°C respectively.

**5.** The efficiency of a Carnot engine operating between temperatures $T_1$ and $T_2$ is 0.2. When $T_2$ is lowered by 60 K, the efficiency rises to 0.4. $T_1$ and $T_2$ are respectively:

(a) 300 K, 240 K (b) 240 K, 300 K

(c) 150 K, 300 K (d) 300 K, 150 K

**Ans.** *(a) 300 K, 240 K*

**Explanation:** Maximum efficiency of an engine working between temperatures $T_1$ and $T_2$ is given by the fraction of the heat absorbed by an engine which can be converted into work is known as the efficiency of the heat engine.

Mathematically,

Efficiency, $\eta = \dfrac{(T_1 - T_2)}{T_1}$

Substituting value of $\eta = 0.2$,

We get $0.8\,T_1 = T_2$

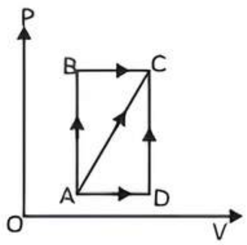
Now substituting value of $\eta = 0.4$ and sink temperature as,

$$T_2 = 60, \text{ we get}$$

$$0.6T_1 + 60 = T_2$$

Solving both we get $T_1 = 300$ K and $T_2 = 240$ K

**6.** Figure depicts a thermodynamic process. The pressures and volumes corresponding to some points in the figure are $P_A = 5 \times 10^4$ Pa, $P_B = 9 \times 10^4$ Pa, and $V_A = 4 \times 10^{-3}$ m$^3$, $V_D = 5 \times 10^{-3}$ m$^3$. Process AB adds 800 J of heat to the system, while Process BC adds 300 J of heat to the system. The change in the system's internal energy in process AC would be:




(a) 1000 J (b) 1020 J

(c) 1050 J (d) 1090 J

**Ans.** *(d) 1090 J*

**Explanation:** No work is done during isochoric process A $\rightarrow$ B.

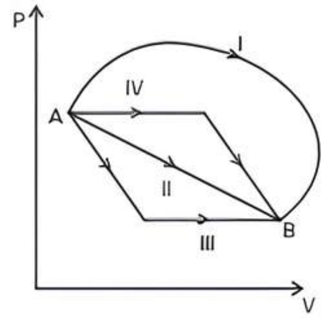
Work done during isobaric process B $\rightarrow$ C,

$$= P_B(V_C - V_B)$$
$$= P_B(V_D - V_A)$$
$$= 90 \text{ J}$$

From the conservation of energy,

$$Q = U + W$$
$$U = Q - W = (800 + 300)\text{ J} - 90\text{ J}$$
$$= 1090 \text{ J}$$

**7.** Figure shows the P-V diagram of an ideal gas undergoing a change of state from A to B. From the different processes I, II, III and IV as shown in the figure may lead to the same change of state.




Change in internal energy is:

(a) Change in internal energy is same in IV and III cases but not in I and II

(b) Change in internal energy is the same in all the four cases

(c) Work done is maximum in Case I

(d) Work done is minimum in case II

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**Ans.** *(b) Change in internal energy is the same in all the four cases*

**Explanation:** Internal energy is a function of a system's state and is independent of the route. As a result, internal energy will be the same.

**8.** During an adiabatic process, the increase of gas is found to be proportional to the cube of its temperature. The ratio of $\dfrac{C_P}{C_V}$ for the gas is:

(a) $\dfrac{3}{2}$ (b) $\dfrac{4}{3}$

(c) 2 (d) $\dfrac{5}{3}$

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**Ans.** *(a) $\dfrac{3}{2}$*

**Explanation:** $P \propto T^3$,

$$PV = nRT$$
$$P \propto T^3$$
$$P \propto (PV)^3$$
$$P^2V^3 = \text{constant}$$
$$PV^{\frac{3}{2}} = \text{constant}$$
$$\gamma = \frac{3}{2}$$

## Assertion–Reason Questions

Two statements are given one labelled Assertion (A) and the other labelled Reason (R). Select the correct answer to these questions from the codes (a), (b), (c) and (d) as given below:

(a) Both A and R are true and R is the correct explanation of A.

(b) Both A and R are true and R is not the correct explanation of A.

(c) A is true but R is false.

(d) A is false and R is also false.

**9.** Assertion (A): In an adiabatic process, the temperature of the gas remains constant.

Reason (R): An ideal gas's work equals a change in its internal energy in an adiabatic process.

**Ans.** (c) *A is true but R is false.*

**Explanation:** In an adiabatic process, no exchange of heat takes place.

Therefore the reason is incorrect.

From the first law of thermodynamics,

$$Q = U + W$$
$$0 = U + W$$
$$|W| = |U|$$

**10.** Assertion (A): The process in which a high-pressure fluid is converted to low-pressure by using a throttle valve is Throttling. In the process of throttling, temperature neither increases nor decreases.

Reason (R): For ideal gas, throttling process is isothermal and for real gases.

**Ans.** (c) *A is true but R is false.*

**Explanation:** In the throttling process enthalpy remains constant, and work done is zero. For ideal gas throttling process is isothermal and for real gases, due to throttling the temperature may increase decrease or remain constant. Throttling process is the process in which a high-pressure fluid is converted to low-pressure fluid at constant pressure using a throttle value. In the throttling process, work done is 0 and enthalpy is constant. It is an irreversible process.

Joule's Thompson coefficient,

$$(\mu) = \frac{dT}{dP} \text{ at constant H.}$$

**11.** Assertion (A): In a thermoflask, inner surface is shiny.

Reason (R): Shiny surface is a poor radiator of heat.

**Ans.** (a) *Both A and R are true and R is the correct explanation of A.*

**Explanation:** The wall of thermoflask is polished because shiny surfaces are good radiators of heat. Since we intend to keep it in the vacuum flask and not have it radiated, Outside the shiny surface is the best option. A black wall is a bad option as they are good emitters and absorbers of heat radiation. As on shiny objects heat is incident, due to the polishing most of the heat energy gets reflected back and as a result, very less energy (heat) is absorbed. So we can say that shiny bodies are only good radiators of heat, not good absorbers.

**12.** Assertion (A): A room can be cooled by opening the door of a refrigerator in a closed room.

Reason (R): Heat flows from a lower temperature (refrigerator) to a higher temperature (room).

[Delhi Gov. QB 2022]

**Ans.** (d) *A is false and R is also false.*

**Explanation:** The cooler inside of the refrigerator absorbs heat from the room when the door is initially opened. Overall, the heat pump turns electrical energy into heat. As a result, once the temperature within the refrigerator reaches the ambient temperature, the temperature of the room rises.

**13.** Assertion (A): It is not possible for a system, unaided by an external agency to transfer heat from a body at a lower temperature to another body at a higher temperature.

Reason (R): According to Clausius's statement, no process is possible whose sole result is the transfer of heat from a cooled object to a hotter object. [Delhi Gov. QB 2022]

**Ans.** (a) *Both A and R are true and R is the correct explanation of A.*

**Explanation:** The second rule of thermodynamics may be taught using the refrigerator as an example.

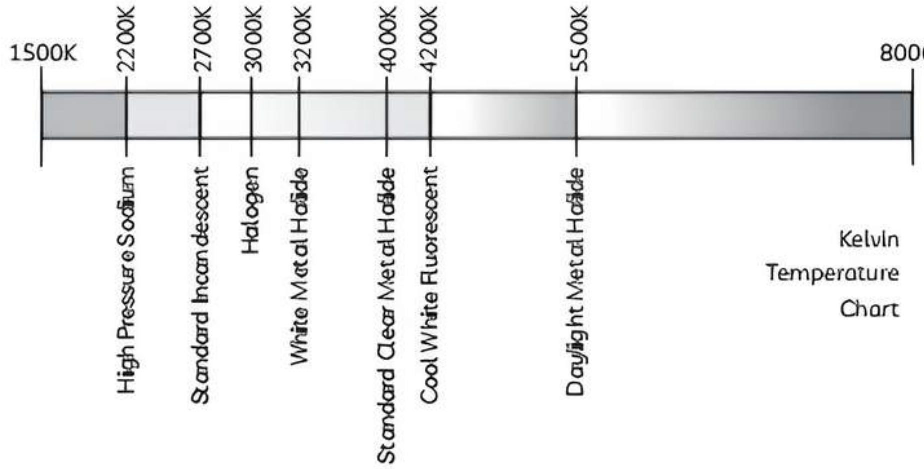
The cooler inside of the refrigerator absorbs heat from the room when the door is initially opened. Overall, the heat pump transforms electrical energy into heat, so once the temperature inside the refrigerator reaches the ambient temperature, the room temperature rises.

# CASE BASED Questions (CBQs)

[ 4 & 5 marks ]

**Read the following passages and answer the questions that follow:**

**14.** *Carnot cycle is particularly significant for a number of reasons. This cycle serves as a useful representation of a reversible steam power plant and refrigerator or heat pump model. However, it is also crucial from a theoretical standpoint since it helped formulate a crucial part of the second law of thermodynamics. Finally, it is possible to define an absolute temperature scale using the second law of thermodynamics and only two reservoirs, which is really independent of any material used to measure temperature. The Kelvin (or absolute) temperature scale was considered a "Universal" scale because every constant volume gas thermometer containing dilute gas gave rise to the same absolute scale, irrespective of the type of gas involved and defined as T=273.16K (PPtr) where Ptr is the pressure of any dilute constant volume gas thermometer and P is the pressure of same thermometer at T.*




**(A)** **Find the efficiency of the Carnot engine that operates between two reservoirs at temperatures of 1000 K and 330 K respectively and if the engine absorbs 5000 J of heat from the hot reservoir in a cycle, how much heat is ejected to the cool reservoir?**

**(B)** **Compare different thermodynamic processes.**

**(C)** **Mention two important results given by Carnot.**

**Ans.** (A) For ideal gas, all Carnot engines operating between the same two temperatures have the same efficiency and given as $e_C = 1 - T_C T_H = 1 - 330 \times 1000 = 0.670 = 67.0\%$.

$$Q_{out} Q_{in} = T_c T_H,$$

$$Q_{out} \times 5000 = 330 \times 1000$$

$$Q_{out} = 0.330 \times 5000 \text{J}$$

$$= 1650 \text{ J}$$

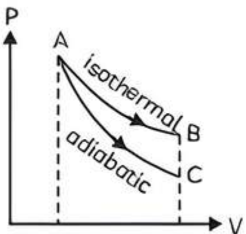
(B) An adiabat, is steeper than an isothermal *i.e.*, the slope of an adiabatic is greater than the slope of an isothermal.

Slope of isothermal $\left(\frac{dP}{dV}\right) = \frac{P}{V}$

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

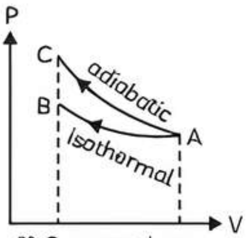
Slope of an adiabatic process = $\gamma$ × (slope of the isothermal process)

In expansion, the adiabatic curve lies below the Isothermal




(i) Expansions

In compression, the adiabatic curve lies above isothermal

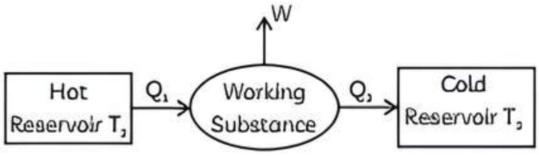



(ii) Compressions

(C) No engine can have efficiency more than that of the Carnot engine and the efficiency of the Carnot engine is independent of the nature of the working substance.

**15.** *A heat engine is a device by which a system is made to undergo a cyclic process that results in the conversion of heat into work. Basically, a heat engine consists of (i) a hot reservation maintained at a higher temperature $T_1$ (ii) a cold reservation maintained at a lower temperature $T_2$ and (iii) a working substance. If in one cycle of its operation the system draws, $Q_1$ heat from the hot reservoir does W work and releases $Q_2$ heat to the cold reservoir than*

*Efficiency of engine,* $\eta_1 = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$




**[Delhi Gov. QB 2022]**

(A) The area enclosed by a Carnot cycle represents:

(a) heat absorbed

(b) heat released

(c) amount of work done

(d) none of these

(B) A reversible heat engine 'A' operates between 223°C and −123°C. The efficiency of the engine is:

(a) 15% (b) 20%

(c) 25% (d) 30%

(C) Another reversible engine 'B' operates between temperatures 123° and T°C and has an efficiency 30%. The value of 'T' will be:

(a) 19.8°C (b) 10°C

(c) 280°C (d) 320°C

(D) Even the Carnot engine cannot give 100% efficiency, because we cannot:

(a) prevent radiation

(b) find ideal source

(c) eliminate friction

(d) reach absolute zero temperature

(E) The efficiency of Carnot engine does not depends on:

(a) temperature of source

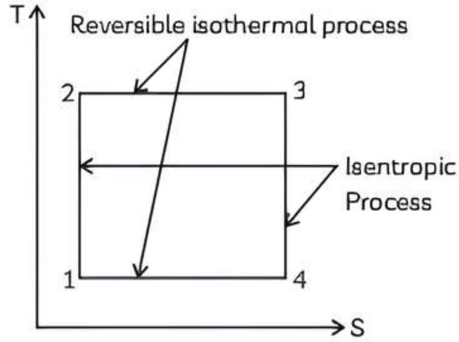
(b) temperature of sink

(c) nature of working substance

(d) temperature difference of source and sink temperature

**Ans.** (A) *(c) amount of work done*

**Explanation:** Carnot cycle consists of two reversible isothermal and two isentropic process.




Carnot cycle is one of the best-known reversible cycles. The Carnot cycle is composed of four reversible processes.

- Reversible Isothermal Expansion (process 1- 2)
- Reversible adiabatic expansion (Process 2-3)
- Reversible isothermal compression (process 3-4)
- Reversible adiabatic compression (process 4-1)

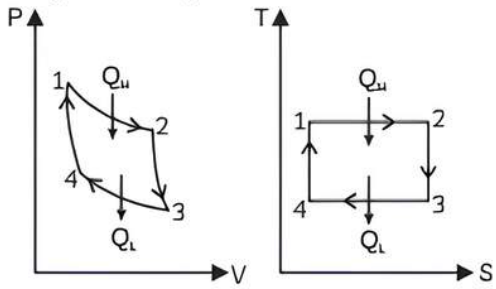



Fig. P-V and T-S diagrams of Carnot Cycle

∵ We know that

work done (W) = PΔV

□ The area under the PV diagram represents the work done.

(B) *(b) 20%*

**Explanation:** Using the relation for efficiency of Carnot's engine

$$\eta = \frac{T_1 - T_2}{T_1}$$

$$= \frac{396 - 496}{396}$$

$$= \frac{-100}{396}$$

$$= \frac{-100}{396} \times 100$$

$$= 20.155\% \simeq 20\%$$

(C) *(a) 19.8°C*

**Explanation:** We know that Efficiency of Carnot Engine,

$$\eta = \frac{T_1 - T_2}{T_1}$$

$$30\% = 1 - \frac{T_2}{T_1}$$

$$\Rightarrow \quad 0.3 = 1 - \frac{123+273}{T+273}$$

$$\Rightarrow \quad 0.7 = \frac{123+273}{T+273}$$

$$\Rightarrow \quad 0.7(T + 273) = 123 + 273$$

$$\Rightarrow \quad T = 292.8$$

$$K = 19.8°C$$

(D) *(d) reach absolute zero temperature*

**Explanation:** Even the Carnot engine is not 100% efficient. 100% efficiency ($\eta$ =1) requires that $Q_2$ be equal to 0, which indicates that all of the heat from the source has been turned to work. The term "temperature of sink" refers to a negative temperature that is larger than unity on an absolute scale.

(E) *(d) temperature difference of source and sink temperature*

**Explanation:** The efficiency of the cycle is given as $\eta = 1 - \frac{T_2}{T_1}$. Here $T_1$ is the temperature of the source and $T_2$ is the temperature of the sink.

If the difference between temperature of the source and the sink is increased (*i.e.*, temperature of source increase or temperature of sink decreases), the $\frac{T_2}{T_1}$ value decreases and thus efficiency increases.

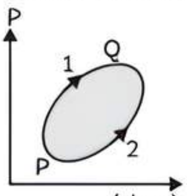
## VERY SHORT ANSWER Type Questions

[ 1 mark ]

**16. Would a Carnot engine be completely efficient if all deceleration was eliminated?**

**Ans.** No. Friction is one factor that reduces the efficiency of an engine, but even a frictionless engine is restricted to an efficiency less than or equal to that of the Carnot engine, which is less than 100%.

**17. A system goes from P to Q by two different paths in P–V diagram as shown in the figure. Heat given to the system in path 1 is 1000 J. The work done by the system along path 1 is more than path 2 by 100 J. What is the heat exchanged by the system in path 2?**



(given)

[NCERT Exemplar]

**Ans.** For path (1)

$$Q_1 = +1000 \text{ J}$$

$$\text{Work Done} = W_1 - W_2 = 100$$

$$W_1 = \text{Work Done through path 1}$$

$$W_2 = \text{Work Done through path 2}$$

$$\therefore \quad W_2 = W_1 - 100$$

As change in internal energy by paths 1 and 2 are the same

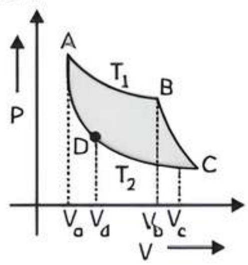
$$\Delta U = Q_1 - W_1 = Q_2 - W_2$$

$$1000 - W_1 = Q_2 - (W_1 - 100)$$

$$1000 = Q_2 + 100$$

$$Q_2 = 900 \text{ J}$$

**18. The P–V diagram shows that two adiabatic parts of the same gas intersect two isothermals at $T_1$ and $T_2$. How the ratio $(V_a/V_d)$ and $(V_b/V_c)$ are related to each other?**




[Diksha]

**Ans.** For adiabatic process

$$PV^{\gamma} = \text{Constant and}$$

$$PV = nRT$$

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

BC is adiabatic,

$$T_1V_b^{\gamma-1} = T_2V_c^{\gamma-1}$$

AD is adiabatic,

$$T_1V_a^{\gamma-1} = T_2V_d^{\gamma-1}$$

So, $$\left(\frac{V_a}{V_d}\right)^{\gamma-1} = \left(\frac{V_b}{V_d}\right)^{\gamma-1}$$

$$\frac{V_a}{V_d} = \frac{V_b}{V_d}$$

**19.** **On what factors, does the efficiency of the Carnot engine depend? [Delhi Gov. QB 2022]**

**Ans.** We know that $\eta = 1 - \frac{T_2}{T_1}$

$\therefore$ It depends on the temperature of the source and sink.

**20.** **Refrigerator transfers heat from a cold body to a hot body. Does this violate the second law of thermodynamics?**

**[Delhi Gov. QB 2022]**

**Ans.** No. External work is done. Hence, there is no violation of the second law of thermodynamics.

## SHORT ANSWER Type-I Questions (SA-I)

[ 2 marks ]

**21.** **Consider a Carnot's cycle operating between $T_1$ = 500 K and $T_2$ = 300 K producing 1 kJ of mechanical work per cycle. Find the heat transferred to the engine by the reservoirs.**

**[NCERT Exemplar]**

**Ans.** Efficiency of Carnot's engine,

$$\eta = 1 - \frac{T_2}{T_1}$$

Temperature of source or reservoir

$$T_1 = 500 \text{ K}$$

Temperature of sink

$$T_2 = 300 \text{ K}$$

$$\eta = 1 - \frac{T_2}{T_1}$$

$$\frac{\text{Output work}}{\text{Input work (E)}} = 1 - \frac{300}{500}$$

$$\frac{100\text{J}}{x} = 1 - 0.6$$

$$\frac{100\text{J}}{x} = 0.4$$

$$x = \frac{1000}{0.4}$$

$$= 2500 \text{ J}$$

**22.** **How much heat is extracted from a high-temperature reservoir per cycle for a Carnot engine if a real heat engine has an efficiency of 43%? The engine has a work output of 34 J per cycle.**

**Ans.** The efficiency of the Carnot engine is defined as:

$$\eta = |Q_H| - \left|\frac{Q_L}{Q_H}\right| = \frac{\Delta W}{|Q_H|}$$

Since $|Q_H| - |Q_L| = \Delta W$

To obtain the amount of heat energy extracted from the higher temperature $|Q_H|$ substitute 33% for $\eta$ and 34 J for $\Delta W$ in the equation

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

we get, $$\frac{43}{100} = \frac{34\text{J}}{|Q_H|}$$

Or $$|Q_H| = \frac{3400}{43}$$

$$= 79.07\text{J}$$

Rounding off the significant figure the amount of heat energy extracted from the higher temperature $|Q_H|$ would be 79 J.

**23.** **No real engine can have an efficiency greater than that of a Carnot engine working between the same low temperatures. Why?**

**[Delhi Gov. QB 2022]**

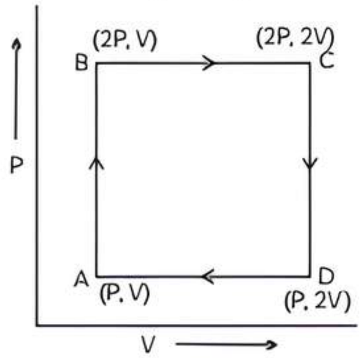
**Ans.** A Carnot engine is an excellent heat engine in the following ways:

(1) There is no friction between the cylinder and piston walls.

(2) The working component is an ideal gas.

These parameters cannot be met in a practical engine, hence no heat engine operating between the same two temperatures may have a higher efficiency than Carnot engines.

**24.** **An ideal monoatomic gas is taken around the cycle ABCDA as shown. Calculate the work done during the cycle.**




**[Delhi Gov. QB 2022]**

**Ans.** Here, A → B and C → D are isobaric processes.

$$\therefore \quad \Delta P = 0$$
$$W_{AB} = -P\Delta V$$
$$= -P(2V - V)$$
$$= -PV$$
$$W_{CD} = -P\Delta V$$
$$= -2P(V - 2V)$$
$$= +2PV$$
$$W_{BC} = W_{AD} = 0$$

∴ Total work done,

$$W = W_{AB} + W_{BC} + W_{CD} + W_{DA}$$
$$= -PV + 0 + 2PV + 0$$
$$= PV$$

## SHORT ANSWER Type-II Questions (SA-II)

[ 3 marks ]

**25. In a Carnot engine operating between 200 and 60 degrees Celsius, six moles of an ideal gas are taken. The useful work performed in one cycle is 402 J. Determine the volume ratio of the gas at the end and beginning of the isothermal expansion.**

**Ans.** Given: R = 8.31 J/mol K

$$e^{0.14} = 1.5$$

High temperature,

$$T_H = 200°C$$
$$= 200 + 273 = 473 \text{ K}$$

Low temperature,

$$T_L = 60°C = 60 + 273 = 333 \text{ K}$$

Amount of the gas, $n$ = 5 moles use for work done per cycle,

$$W = Q_H - Q_L$$

Now, $W = 402$ J,

So $Q_H - Q_L = 402$ J

$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$$
$$= \frac{473}{333} \quad \text{...(i)}$$

or

$$Q_H = \frac{473}{333} Q_L \text{ in equation (i)}$$
$$\frac{473}{333} Q_L - Q_L = 402 \text{ J}$$
$$\frac{473Q_L - 333Q_L}{333} = 402 \text{ J}$$
$$\frac{140Q_L}{333} = 402$$
$$Q_L = \frac{402 \times 333}{140}$$
$$= 956.18 \text{ J}$$

So, $Q_H - Q_L = 402$ J,

$$Q_H - 956.18 = 402 \text{ J},$$
$$Q_H = 1358.18 \text{ J}$$

When the gas is carried through the Carnot cycle, the heat absorbed $Q_H$ during isothermal expansion is equal to the work done by gas.

$V_1$ = Initial Value,

$V_2$ = Final Value

In isothermal expansion

$$Q_H = 2.303\eta RT_H \log_{10}\frac{V_2}{V_1}$$
$$\log_{10}\frac{V_2}{V_1} = \frac{1358.18}{2.303 \times 6 \times 8.4 \times 473}$$
$$= 0.0247$$
$$\frac{V_2}{V_1} = -3.7009$$

**26. Two samples of gas initially at the same temperature and pressure are compressed from volume V to V/2 one sample is compressed isothermally and the other adiabatically in which case the pressure will be higher? Explain. [Delhi Gov. QB 2022]**

**Ans.** For the isothermal process, PV = Constant

$$\Rightarrow \quad P_1V_1 = P_2V_2$$
$$P_2 = 2P_1$$

For adiabatic process,

$$PV^{\square} = \text{Constant}$$
$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$
$$\Rightarrow \quad P_2 = P_1\left(\frac{V_1}{V_2}\right)^{\gamma}$$
$$P_2 = 2P_1^{\gamma}$$

Since, γ is always greater than 1, for the same change in volume, there will be a greater change in pressure for the adiabatic process than that for the isothermal process.

# LONG ANSWER Type Questions (LA)

[4 & 5 marks]

**27.** A system consists of a sealed steel cylinder containing a volatile gas mixture. The system is surrounded by a thermally insulating material such as asbestos so that no heat can enter or leave the system (assuming radiative losses are negligible). The mixture explodes, but the cylinder stays intact and the system is allowed to settle down.

(A) How has the temperature of the system changed?

(B) What is the change in the internal energy of the system as a consequence of the explosion?

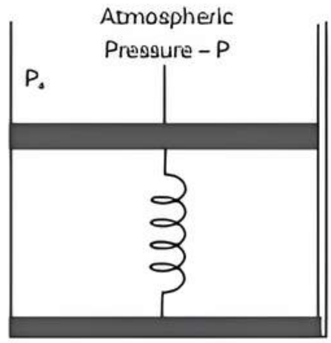
(C) How would one describe the overall process on a P-V diagram?

**Ans.** (A) In the explosion, stored chemical potential energy has been converted into thermal energy. Unless this thermal energy leaves the system or is converted to another form of energy, there will be a rise in temperature.

(B) Since, the sealed cylinder stays intact, there is essentially no change in volume and consequently, no work done. Similarly, the insulation stops any transfer of heat to the outside world. From the first law, the amount of internal energy must be unchanged. Of course, the form of the internal energy has changed as described in part (A).

(C) The change in the system cannot be plotted on a P-V diagram because the explosion is not quasi static. One may be tempted to say that the system is describable by a vertical line on the diagram corresponding to a constant volume (isovolumic process) but that would be wrong. The process is indeed isovolumic but there is no well-defined "systemwide" pressure at any moment of the explosion. All one can do is to represent the initial and final states by two points (one directly above the other) on a P-V diagram. Since, these are equilibrium states of the system.

**28.** Consider one mole of a perfect gas in a cylinder of the unit cross-section with a piston attached (figure). A spring (spring constant $k$) is attached (unstretched length L) to the piston and to the bottom of the cylinder. Initially, the spring is unstretched and the gas is in equilibrium. A certain amount of heat Q is supplied to the gas causing an increase in volume from $V_0$ to $V_1$.




(A) What is the initial pressure of the system?

(B) What is the final pressure of the system?

(C) Using the first law of thermodynamics, write down a relation between Q, $P_a$, $V_1$, $V_0$ and $k$.

**Ans.** (A) It is considered that the piston is massless and the piston is balanced by atmospheric pressure ($P_a$). So, the initial pressure of the system inside the cylinder = $P_a$.

(B) On supply heat Q, volume of gas increases from $V_0$ to $V_1$ and the spring stretches also.

So, an increase in volume

$$= V_1 - V_0$$

If the displacement of the piston is $x$ then the volume increase in the cylinder

$$= \text{Area of base} \times \text{height}$$

$$= A \times x$$

$$A \times x = V_1 - V_0$$

(A = area of cross-section of a cylinder)

$$x = \frac{V_1 - V_0}{A}$$

Force exerted by spring

$$F_S = Kx = \frac{K(V_1 - V_0)}{A}$$

as the piston is of unit area of cross-section.

$$A = 1$$

Force due to spring

$$= K(V_1 - V_0)$$

on unit area can be say press due to spring

$$= K(V_1 - V_0)$$

Final total pressure on gas

$$P_f = P_a + K(V_1 - V_0)$$

(C) By $I^{st}$ law of thermodynamics

$$dQ = dU + dW$$

$$dU = C_V(T - T_0)$$

$T$ = Final temperature of gas

$T_0$ = Initial temperature of gas

$n = 1$

$$T_f = T = \frac{P_1 V_1}{R}$$

$$= \frac{[P_a + k(V_1 - V_0)]V_1}{R}$$

Work done by gas = $p.\,dV$ + increase in PE of spring

$$dW = P_a(V_1 - V_0) + \frac{1}{2}kx^2$$

Now $dQ = dU + dW$

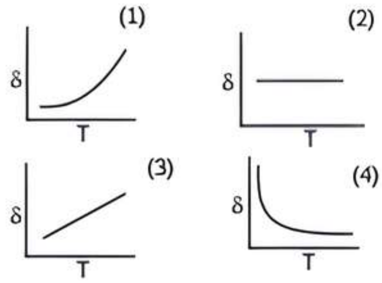
$$= C_v(T - T_0) + P_a(V_1 - V_0) + \frac{1}{2}kx^2$$

$$dQ = C_v(T - T_0) + P_a(V_1 - V_0) + \frac{1}{2}k(V_1 - V_0)^2$$

It is a required relation.

**29. (A) Describe the operation of the Carnot engine and calculate its efficiency.**

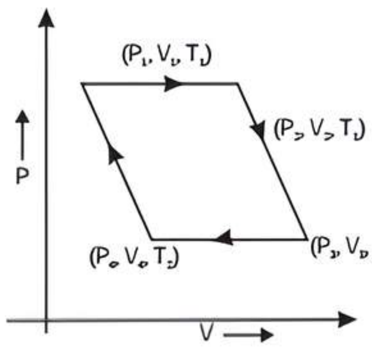
**(B) Which of the following graphs correctly represent the variation $\delta = \frac{dV}{VdT}$ for an ideal gas at constant pressure?**




**[Diksha]**

**Ans.** (A) A Carnot engine is a reversible heat engine operating between two temperatures.

The steps involved in a Carnot cycle are explained as follows:




Step 1: Isothermal expansion of gas from the state $(P_1, V_1, T_1)$ to state $(P_2, V_2, T_2)$ as shown in the given figure.

Step 2: Adiabatic expansion of gas from $(P_2, V_2, T_1)$ to $(P_3, V_3, T_2)$

Step 3: Isothermal compression of gas from $(P_3, V_3, T_2)$ to $(P_4, V_4, T_2)$

Step 4: Adiabatic compression of gas from $(P_4, V_4, T_2)$ to $(P_1, V_1, T_1)$

These steps constitute one Carnot cycle. The process is repeated thereafter.

The efficiency of the Carnot engine, η is defined as the ratio of net work done per cycle by the engine to the amount of heat absorbed per cycle by the working substance from the source.

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

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

$$\eta = 1 - \frac{T_1 - T_2}{T_1}$$

The efficiency of a Carnot engine depends upon the temperature of the source and sink. It is independent of the nature of the working substance. It is the same for all reversible engines that work between the same two temperatures. It is directly proportional to the temperature difference $T_1 - T_2$.

(B) Graph 4 represents the correct result.

$$PV = KT$$

$$PdV = KdT$$

$$\frac{dV}{dT} = \frac{k}{P}$$

$$\frac{dV}{VdT} = \frac{K}{PV}$$

Now as $PV = KT$

$$\frac{dV}{VdT} = \frac{K}{KT} = \frac{1}{T}$$

or $$\delta = \frac{dV}{VdT} = \frac{1}{T}$$

**30. Define adiabatic process. Derive an expression for work done during the adiabatic process. [Delhi Gov. QB 2022]**

**Ans.** The first law of thermodynamics, which relates the change in internal energy $dU$ to the work W done by the system and the heat $dQ$ given to it, may be used to construct the equation for an adiabatic process. $PdV$ is the work done $dW$ for the change in volume V by $dV$.

Adiabatic process :

$$PV^{\gamma} = K$$

So, $P = KV^{-\gamma}$

Work done $W = \int PdV$

Or $W = \int KV^{-\gamma}dV$

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

Or $W = \frac{K}{1-\gamma} \times \left[V_2^{-\gamma+1} - V_1^{-\gamma+1}\right]$

Or $W = \frac{1}{1-\gamma} \times \left[K V_2^{-\gamma+1} - K V_1^{-\gamma+1}\right]$

Or $W = \frac{1}{1-\gamma} \times \left[P_2 V_2^{\gamma} V_2^{-\gamma+1} - P_1 V_1^{\gamma} V_1^{-\gamma+1}\right]$

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

## NUMERICAL Type Questions

**31. A Carnot engine with a sink temperature of 500 K has a 60% efficiency. How much should the temperature of the source be raised to increase its efficiency by 70% of its original efficiency? (2m)**

**Ans.** Temperature of sink

$$T_L = 500 \text{ K}$$

Original efficiency

$$\eta = 60\% = 0.6$$

Let the Initial temperature of the source be $T_H$

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

$$0.6 = 1 - \frac{500}{T_H}$$

$$T_H = 1250 \text{ K}$$

Now the efficiency of the engine is increased by 70 % of the original efficiency.

∴ New efficiency

$$\eta' = 60\% + 70\% = 130\%$$

$$\eta' = 1 - \frac{T_L}{T'_H}$$

$$1.3 = 1 - \frac{500}{T'_H}$$

$$T'_H = 1666.66 \text{ K}$$

Increase in source temperature

$$\Delta T_H = T'_H - T_H$$

$$= 1666.66 - 1250$$

$$= 416.66 \text{ K}$$

**32. Refrigerator is to maintain eatables kept inside at 9°C. If the room temperature is 36°C. Calculate the coefficient of performance. [Delhi Gov. QB 2022](2m)**

**Ans.** Temperature inside the refrigerator,

$$T_1 = 9°C = 282 \text{ K}$$

Room temperature,

$$T_2 = 36°C = 309 \text{ K}$$

Coefficient of performance

$$= \frac{T_1}{T_2 - T_1}$$

$$= \frac{282}{(309 - 282)}$$

$$= 10.44$$

Therefore, the coefficient of performance of the given refrigerator is 10.44.