12 Thermodynamics

Facts that Matter

- The branch of physics which deals with the study of transformation of heat into other forms of energy and vice-versa is called thermodynamics.

Thermodynamics is a macroscopic science. It deals with bulk systems and does not go into the molecular constitution of matter.

- A collection of an extremely large number of atoms or molecules confined within certain boundaries such that it has a certain values of pressure (*P*), volume (*V*) and temperature (*T*) is called a thermodynamic system.

• Thermal Equilibrium

A thermodynamic system is in an equilibrium state if the macroscopic variables such as pressure, volume, temperature, mass composition etc. that characterise the system do not change in time. In thermal equilibrium, the temperature of the two systems are equal.

• Zeroth Law of Thermodynamics

This law identifies thermal equilibrium and introduces temperature as a tool for identifying equilibrium. According to this law "If two systems are in thermal equilibrium with a third system then those two systems themselves are in equilibrium."

• Heat, Work and Internal Energy

– Energy that is transferred between a system and its surroundings whenever there is temperature difference between the system and its surroundings is called heat.

– Work is said to be done if a body or a system moves through a certain distance in the direction of the applied force. It is given as

$$dW = PdV$$

where P is the pressure of the gas in the cylinder.

– If we consider a bulk system consisting of a large number of molecules, then internal energy of the system is the sum of the kinetic energies and potential energies of these molecules. This energy is possessed by a system due to its molecular motion and molecular configuration. The internal energy is denoted by U.

$$U = E_k + E_P$$

where E_k and E_P represent the kinetic and potential energies of the molecules of the system.

- Internal energy of a system is a macroscopic variable and it depends only on the state of the system. Its value depends only on the given state of the system and does not depend on the path taken to arrive that state.

• First Law of Thermodynamics

The first law of thermodynamics is simply the general law of conservation of energy applied to any system. According to this law, "the total heat energy change in any system is the sum of the internal energy change and the work done."

When a certain quantity of heat dQ is subjected to a system, a part of it is used in increasing the internal energy by dU and a part is used in performing external work dW, hence

$$dQ = dU + dW$$

• For gases, the specific heat capacity depends on the process or the conditions under which heat capacity transfer takes place. There are mainly two principal specific heat capacities for a gas. These are specific heat capacity at constant volume and specific heat capacity at constant pressure.

• From First Law of Thermodynamics we find a relation between two principal specific heats of an ideal gas. According to the relation

$$C_P - C_v = R$$

Here C_P and C_v are molar specific heats under constant pressure and constant volume condition respectively.

The specific heat capacity of a gas at constant pressure is greater than the specific heat capacity of the gas at constant volume i.e. $C_P > C_v$. Reason is that when heat supplied to a gas at constant volume, no work would be done by the gas against the external pressure and all the energy is used to raise the temperature of the gas. On the other hand when the heat is supplied to the gas at constant pressure, its volume increases and the heat energy supplied to it is used to increase the temperature of the gas as well as in doing the work against the external pressure.

The difference, between the two specific heats is the thermal equivalent of the work done in expanding the gas against the external pressure.

• Expression for the Relation between C_P and C_V

Let P, V and T be the pressure, volume and absolute temperature initially of one mole of an ideal gas.

Case (*i*) **:** The heat dQ is supplied to the gas at constant volume so that the temperature increases to $T + dT$.

$$\therefore \quad dQ = 1 \times C_V \times dT = C_V \times dT \qquad (i)$$

From the first law of Thermodynamics,

$$dQ = dU + dW \qquad (ii)$$

In this case, volume is constant

$$\therefore \quad dw = 0$$

$$\therefore \quad dQ = dU \qquad (iii)$$

From (*i*) and (*iii*) we get

$$dU = C_V \times dT \qquad (iv)$$

Case (*ii*) : When the heat is supplied to the same gas at constant pressure.

$$\therefore \quad dQ = 1 \times C_P \times dT \qquad (v)$$

Again applying first law of thermodynamics

$$C_P \times dT = dU + dW \;\Rightarrow\; C_P \times dT = dU + PdV$$

$$\Rightarrow \quad C_P \times dT = C_V \times dT + P \times dV \qquad (vi)$$

(Substituting the value of dU from (*v*))

But for one mole of an ideal gas

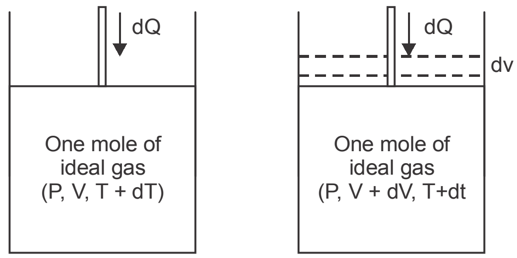
$$PV = RT \qquad (vii)$$

Differentiating both sides at constant P

$$P \times dV = R \times dT \qquad (viii)$$

From (*vi*) and (*viii*) we get $\quad C_P \times dT = C_V \times dT + R \times dT \quad$ or $\quad C_P = C_V + R$

$\therefore \quad C_P - C_V = R \quad$ (gas constant)



Heated at Constant volume   Heated at Constant pressure

• Thermodynamic State Variables

Thermodynamic state variables of a system are the parameters which describe equilibrium states of the system. For example, equilibrium state of gas is completely specified by the values of pressure, volume, temperature, mass and composition.

• Equation of State

The equation of state represents the connection between the state variables of a system. For example, the those equation of state of an ideal/perfect gas in represented as

$$PV = \mu RT$$

where μ is number of moles of the gas and R is gas constant for one mole of the gas.

• Thermodynamic state variables are of two kinds, extensive and intensive. Extensive variables indicate the size of the system but intensive variables do not indicate the size. Volume, mass, internal energy of a system are extensive variables but pressure, temperature and density are intensive variables.

• Thermodynamic Processes

Any process in which the thermodynamic variables of a thermodynamic system change is known as thermodynamic process.

• Quasi-Static Processes

Processes that are sufficiently slow and do not involve accelerated motion of piston and/or large temperature gradient are quasi-static processes.

In this process, the change in pressure or change in volume or change in temperature of the system is very small.

• Isothermal Process

A change in pressure and volume of a gas without any change in its temperature, is called an isothermal change. In such a change, there is a free exchange of heat between the gas and its surroundings.

• Adiabatic Process

A process in which no exchange of heat energy takes place between the gas and the surroundings, is called an adiabatic process.

- The work done dW under isothermal change is given by

$$dW = RT \log_e \frac{V_f}{V_i} \quad \text{or} \quad dW = RT \times 2.303 \log_{10} \frac{V_f}{V_i}$$

where V_i and V_f are the initial and final volumes of the gas under isothermal change.

- The work done dW under adiabatic change is given by

$$dW = \frac{R(T_2 - T_1)}{(\gamma - 1)} = \frac{P_2V_2 - P_1V_1}{(\gamma - 1)}$$

where T_1 and T_2 are initial and final temperatures.

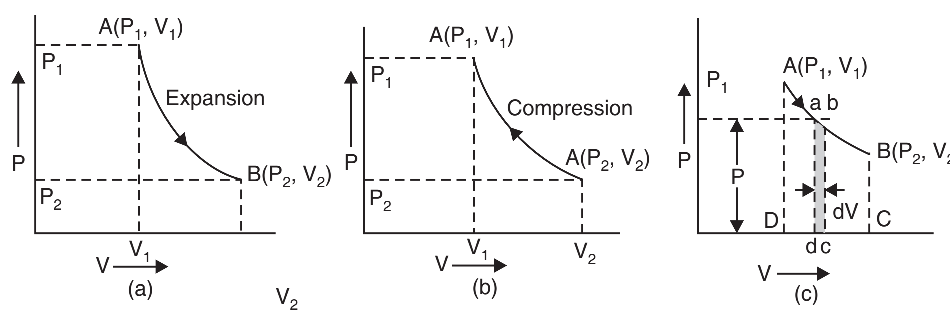
- Equation of state of an adiabatic process may be written in three different forms:
  (*i*) PV^{γ} = a constant or $P_1V_1^{\gamma} = P_2V_2^{\gamma}$
  (*ii*) $T.V^{\gamma-1}$ = a constant or $T_1V_1^{\gamma-1} = T_2V_1^{\gamma-1}$ and
  (*iii*) $P^{1-\gamma}.\,T^{\gamma}$ = a constant or $\left(\frac{P_1}{P_2}\right)^{1-\gamma} = \left(\frac{P_2}{P_1}\right)^{\gamma-1} = \left(\frac{T_2}{T_1}\right)^{\gamma}$

  Here γ is the ratio of two principal specific heats of gases *i.e.*, $\gamma = \frac{C_p}{C_v} = \frac{c_p}{c_v}$.

• P-V Diagram

A graph representing the variation of pressure with the variation of volume is called P–V diagram. The work done by the thermodynamic system is equal to the area under P–V diagram. It is given as

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



• Reversible Process

A process which can retrace so that the system passes through the same states is called a reversible process, otherwise it is irreversible.

Irreversibility arises mainly from two causes:

(*i*) Many processes like free expansion or an explosive chemical reaction take the system to non-equilibrium states.

(*ii*) Most processes involve friction, viscosity and other dissipative effects.

• Second Law of Thermodynamics

This principle which disallows certain phenomena consistent with the First law of thermodynamics is known as the second law of thermodynamics.

Following are the two statements of second law of thermodynamics.

Kelvin-Planck Statement: It is impossible to construct an engine, operating in a cycle, to extract heat from hot body and convert it completely into work without leaving any change anywhere *i.e.,* 100% conversion of heat into work is impossible.

Clausius Statement: It is impossible for a self acting machine, operating in a cycle, unaided by any external energy to transfer heat from a cold body to a hot body. In other words heat can not flow itself from a colder body to a hotter body.

- A heat engine is a device by which a system is made to undergo a cyclic process that results in conversion of heat to work. Basically, a heat engine consists of: (*i*) a heat source, (*ii*) a heat sink, and (*iii*) a working substance.

- **Carnot's Engine.** He proposed a hypothetical engine working on a cyclic/reversible process operating between two temperatures. Its efficiency is independent of the working substance and is given by, $\eta = 1 - \frac{T_2}{T_1}$, where T_1 is the temperature of source and T_2 is the temperature of sink.

- According to Carnot's theorem: (*a*) working between two given temperatures T_1 and T_2 of the hot and cold reservoirs respectively, no engine can have efficiency more than that of Carnot's engine, and (*b*) the efficiency of the Carnot engine is independent of the nature of the working substance.

• Refrigerator

The process of removing heat from bodies colder than their surroundings is called refrigeration and the device doing so is called refrigerator.

In the refrigerator, heat is absorbed at low temperature and rejected at higher temperature with the help of external mechanical work. Thus, a refrigerator is a heat engine working backward and hence it is also called heat pump.

Refrigerator works on the reverse process of Carnot engine. By the work done on the system, heat is extracted from low temperature sink T_2 and passed on to high temperature source T_1. The coefficient of performance is given by

$$\beta = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}.$$

• IMPORTANT TABLES

TABLE 12.1

Quantity	*Symbol*	*Dimensions*	*Unit*	*Remarks*
Co-efficiency of volume expansion	α_v	$[K^{-1}]$	K^{-1}	$\alpha_v = 3\,\alpha_1$
Heat supplied to a system	ΔQ	$[ML^2T^{-2}]$	J	Q is not a state variable
Specific heat	s	$[L^2T^{-2}K^{-1}]$	$J\ kg^{-1}\ K^{-1}$	
Thermal Conductivity	K	$[MLT^{-3}K^{-1}]$	$J\ s^{-1}\ K^{-1}$	$H = -KA\frac{dt}{dx}$

TABLE 12.2 Specific and molar heat capacities of some solids at room temperature and atmospheric pressure

Substance	*Specific heat ($J\ Kg^{-1}\ K^{-1}$)*	*Molar specific Heat ($J\ mol^{-1}\ K^{-1}$)*
Aluminium	900.0	24.4
Carbon	506.5	6.1
Copper	386.4	24.5
Lead	127.7	26.5
Silver	236.1	25.5
Tungsten	134.4	24.9

TABLE 12.3 Some special thermodynamic processes

Type of processes	*Feature*
Isothermal	Temperature constant
Isobaric	Pressure constant
Isochoric	Volume constant
Adiabatic	No heat flow between the system and the surroundings ($\Delta Q = 0$)

NCERT TEXTBOOK QUESTIONS SOLVED

12.1 *A geyser heats water flowing at the rate of 3.0 litres per minute 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?*

Ans. Volume of water heated = 3.0 litre per minute

Mass of water heated, m = 3000 g per minute

Increase in temperature,

$$\Delta T = 77°C - 27°C = 50°C$$

Specific heat of water, $c = 4.2\ Jg^{-1}\ °C^{-1}$

amount of heat used, $Q = mc\,\Delta T$

or $Q = 3000\ g\ min^{-1} \times 4.2\ Jg^{-1}\ °\ C^{-1} \times 50°C = 63 \times 10^4\ J\ min^{-1}$

Rate of combustion of fuel $= \dfrac{63 \times 10^4\ J\ min^{-1}}{4.0 \times 10^4\ Jg^{-1}} = 15.75\ g\ min^{-1}$.

12.2 *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? (Molecular mass of N_2 = 28; R = 8.3 J $mol^{-1}\ K^{-1}$.)*

Ans. Here, mass of gas, $m = 2 \times 10^{-2}$ kg = 20 g

rise in temperature, ΔT = 45°C

Heat required, $\Delta Q = ?$; Molecular mass, $M = 28$

Number of moles, $n = \frac{m}{M} = \frac{20}{28} = 0.714$

As nitrogen is a diatomic gas, molar specific heat at constant pressure is

$$C_P = \frac{7}{2}R = \frac{7}{2} \times 8.3 \text{ J mol}^{-1} \text{ K}^{-1}$$

As $\Delta Q = nC_P \, \Delta T$

$\therefore$ $\Delta Q = 0.714 \times \frac{7}{2} \times 8.3 \times 45 \text{ J} = 933.4 \text{ J}.$

12.3 *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 $(T_1 + T_2)/2$?

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

(c) Air pressure in a car tyre increases during driving. Why?

(d) The climate of a harbour town is more temperate (i.e., without extremes of heat and cold) than that of a town in a desert at the same latitude. Why?

Ans. (*a*) In thermal contact, heat flows from the body at higher temperature to the body at lower temperature till temperatures become equal. The final temperature can be the mean temperature $(T_1 + T_2)/2$ only when thermal capacities of the two bodies are equal.

(*b*) This is because heat absorbed by a substance is directly proportional to the specific heat of the substance.

(*c*) When car is driven, some work is being done on tyres in order to overcome dissipative forces of friction and air resistance etc. This work done is transformed into heat, due to which temperature of the car tyres increases.

(*d*) The climate of a harbour town is more temperate (neither too hot nor too cool) due to formation of sea breeze at day time and land breeze at night time as already explained in Chapter 11.

12.4 *A cylinder with a movable piston contains 3 moles of hydrogen at standard temperature and pressure. The walls of the cylinder are made of a heat insulator, and the piston is insulated by having a pile of sand on it. By what factor does the pressure of the gas increase if the gas is compressed to half its original volume?*

Ans. Here the process is adiabatic compression and $V_2 = \frac{V_1}{2}$, $P_2 = 1$ atm and for hydrogen (a diatomic gas) $\gamma = 1.4$.

$\because$ $P_1 V_1^\gamma = P_2 V_2^\gamma$, Hence $P_2 = P_1 \left(\frac{V_1}{V_2}\right)^\gamma = 1 \text{ atm} \left(\frac{V_1}{\frac{V_1}{2}}\right)^{1.4}$

$\Rightarrow$ $P_2 = (2)^{1.4} \text{ atm} = 2.64 \text{ atm}.$

12.5 *In changing the state of a gas adiabatically from an equilibrium state A to another equilibrium state B, an amount of work equal to 22.3 J is done on the system. If the gas is taken from state A to B via a process in which the net heat absorbed by the system is 9.35 cal, how much is the net work done by the system in the latter case? (Take 1 cal = 4.19 J)*

Ans. Here, when the change is adiabatic, $\Delta Q = 0$, $\Delta W = -22.3$ J

If ΔU is change in internal energy of the system, then

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

$0 = \Delta U - 22.3 \quad$ or $\quad \Delta U = 22.3$ J

In the second case, $\Delta Q = 9.35 \text{ cal} = 9.35 \times 4.2\text{J} = 39.3$ J

$\Delta W = ?$

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

$\therefore \quad \Delta W = \Delta Q - \Delta U = 39.3 - 22.3 = 17.0$ J.

12.6 *Two cylinders A and B of equal capacity are connected to each other via a stopcock. A contains a gas at standard temperature and pressure. B is completey evacuated. The entire system is thermally insulated. The stopcock is suddenly opened. Answer the following:*

(a) What is the final pressure of the gas in A and B?

(b) What is the change in internal energy of the gas?

(c) What is the change in the temperature of the gas?

(d) Do the intermediate states of the system (before settling to the final equilibrium state) lie of its P-V-T Surface?

Ans. (*a*) Since the final temperature and initial temperature remain the same,

$\therefore \quad P_2V_2 = P_1V_1$

But $\quad P_1 = 1$ atm, $\quad V_1 = V, \quad V_2 = 2V \quad$ and $\quad P_2 = ?$

$$\therefore \quad P_2 = \frac{P_1V_1}{V_2} = \frac{1 \times V}{2V} = 0.5 \text{ atm}$$

(*b*) Since the temperature of the system remains unchanged, change in internal energy is zero.

(*c*) The system being thermally insulated, there is no change in temperature (because of free expansion)

(*d*) The expansion is a free expansion. Therefore, the intermediate states are non-equilibrium states and the gas equation is not satisfied in these states. As a result, the gas can not return to an equilibrium state which lie on the P-V-T surface.

12.7 *A steam engine delivers 5.4×10^8 J of work per minute and services 3.6×10^9 J of heat per minute from its boiler. What is the efficiency of the engine? How much heat is wasted per minute?*

Ans. Work done per minute, output = 5.4×10^8 J

Heat absorbed per minute, input = 3.6×10^9 J

$$\text{Efficiency,} \quad \eta = \frac{\text{output}}{\text{input}} = \frac{5.4 \times 10^8}{3.6 \times 10^9} = 0.15$$

$\%\eta = 0.15 \times 100 = 15$

Heat energy wasted/minute

= Heat energy absorbed/minute – Useful work done/minute

= $3.6 \times 10^9 - 5.4 \times 10^8 = (3.6 - 0.54) \times 10^9 = 3.06 \times 10^9$ J.

12.8 *An electric heater supplies heat to a system at a rate of 100W. If system performs work at a rate of 75 Joules per second. At what rate is the internal energy increasing?*

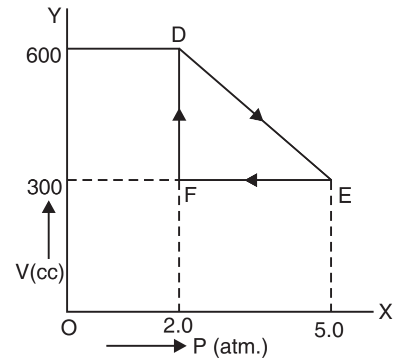
Ans. Here $\quad \Delta Q = 100 \text{ W} = 100$ J/s

$\Delta W = 75$ J/s

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

$\therefore$ Change in internal energy, $\Delta U = \Delta Q - \Delta W = 100 - 75 = 25$ J/s.

12.9 *A thermodynamic system is taken from an original state to an intermediate state by the linear process shown in Fig. 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.*



Ans. As is clear from Fig.

Change in pressure, $\Delta P = EF = 5.0 - 2.0 = 3.0$ atm $= 3.0 \times 10^5$ Nm^{-2}

Change in volume, $\Delta V = DF = 600 - 300 = 300$ cc $= 300 \times 10^{-6}$ m^3

Work done by the gas from D to E to F = area of ΔDEF

$$W = \frac{1}{2} \times DF \times EF$$

$$= \frac{1}{2} \times (300 \times 10^{-6}) \times (3.0 \times 10^5) = 45 \text{ J}$$

12.10 *A refrigerator is to maintain eatables kept inside at 9 °C, if room temperature is 36 °C. Calculate the coefficient of performance.*

Ans. Here, $T_1 = 36\ °C = (36 + 273)\ K = 309\ K$

$T_2 = 9\ °C = (9 + 273)\ K = 282\ K$

Coefficient of performance, $E = \dfrac{T_2}{T_1 - T_2} = \dfrac{282}{309 - 282} = \dfrac{282}{27} = 10.4.$

QUESTIONS BASED ON SUPPLEMENTARY CONTENTS

Q. 1. *Calculate the specific heat capacity at constant volume for a gas. Given specific heat capacity at constnat pressure is 6.85 cal mole^{-1} K^{-1}, R = 8.31 J mole^{-1} K^{-1} and J = 4.18 J cal^{-1}.*

Sol. We know that

$$C_P - C_V = \frac{R}{J}$$

$$6.85 - C_V = \frac{8.31}{4.18} \quad \Rightarrow \quad 6.85 - C_V = 1.988$$

$$\Rightarrow \quad C_V = 6.85 - 1.988 \quad \Rightarrow \quad C_V = 4.862 \text{ cal mole}^{-1}\text{ K}^{-1}$$

Q. 2. *The difference between the two specific heat capacities (at constant pressure and volume) of a gas is 5000 J kg^{-1} k^{-1} and the ratio of these specific heat capacities is 1.6. Find the two specific heat capacities i.e. C_P and C_V.*

Sol. We know that $C_P - C_V = R$

$$C_P - C_V = 5000$$

Dividing by C_V we get,

$$\frac{C_P}{C_V} - 1 = \frac{5000}{C_V}$$

$$1.6 - 1 = \frac{5000}{C_V}$$

$$0.6 = \frac{5000}{C_V}$$

$$\therefore \quad C_V = \frac{5000}{0.6} = 8333.33 \text{ J kg}^{-1}\text{k}^{-1}$$

Now $C_P - C_V = 5000$

$$C_P - 8333.33 = 5000$$

$$\therefore \quad C_P = 8333.33 + 5000 = 13333.33 \text{ J kg}^{-1} \text{ k}^{-1}$$

Q. 3. *Specific heat capacity of argon at constant pressure is 0.125 cal/g/k and at constant volume is 0.075 cal/g/k. Calculate the density of argon at STP. Given J = 4.18 J/cal and the normal pressure = $1.01 \times 10^5 \ Nm^{-2}$.*

Sol. Here, $C_P = 0.125$ cal/g/K

$C_V = 0.075$ cal/g/K

$J = 4.18$ J/cal or 4.18×10^7 ergs/cal

Normal pressure $= 1.01 \times 10^5 \text{ N/m}^2$ or $1.01 \times 10^6 \text{ dyne/cm}^2$

Absolute temperature $T = 273$ K

Let ρ be the density of argon at S.T.P. for one mole

$$\therefore \quad PV = RT \quad \text{(gas equation)}$$

$$\text{or} \quad R = \frac{PV}{T} = \frac{P}{\rho T} \quad \text{for 1 mole of gas}$$

Now $C_P - C_V = \dfrac{R}{J}$

$$R = J(C_P - C_V)$$

$$\frac{P}{\rho T} = 4.18 \times 10^7 \ (0.125 - 0.075)$$

$$\Rightarrow \quad \frac{1.01 \times 10^6}{\rho \times 273} = 4.18 \times 10^7 \times 0.05$$

$$\therefore \quad \rho = \frac{1.01 \times 10^6}{273 \times 4.18 \times 10^7 \times 0.05}$$

Hence $\rho = 1.77 \times 10^{-3} \text{ g/cm}^3$ or $1.77 \times 10^3 \text{ kg/m}^3$

Q. 4. *Find the value of C_V and C_P for nitrogen (given R = 8.3 J mole^{-1} K^{-1}, also for a diatomic gas, $C_V = \frac{5}{2} R$).*

Sol. As nirogen is a diatomic molecule,

$$\therefore \quad C_V = \frac{5}{2}R = \frac{5}{2} \times 8.3 \text{ J mol}^{-1} \text{ K}^{-1}$$

$$= 20.75 \text{ J mol}^{-1} \text{ K}^{-1}$$

But $C_P - C_V = R$

$$\therefore \quad C_P = C_V + R = (20.75 + 8.3) \text{ J mol}^{-1} \text{ K}^{-1}$$

$$= 29.05 \text{ J mol}^{-1} \text{ K}^{-1}$$

ADDITIONAL QUESTIONS SOLVED

I. VERY SHORT ANSWER TYPE QUESTIONS

Q. 1. *Can the temperature of an isolated system change?*

Ans. Yes, in an adiabatic process the temperature of an isolated system changes. It increases when the gas is compressed adiabatically.

Q. 2. *What is the nature of P-V diagram for isobaric and isochoric processes?*

Ans. The $P–V$ diagram for an isobaric process is a straight line parallel to volume axis while that for an isochoric process, it is a straight line parallel to pressure axis.

Q. 3. *Can we decide whether change in internal energy of a system is due to heating or performance of work?*

Ans. No, as internal energy might change due to both heating and performance of work.

Q. 4. *Does the internal energy of an ideal gas change in an isothermal process?*

Ans. No.

Q. 5. *Does the internal energy of an ideal gas change in an adiabatic process?*

Ans. *Yes.*

Q. 6. *What is the significance of Zeroth Law of Thermodynamics?*

Ans. It leads us to the concept of temperature.

Q. 7. *What is the change in internal energy of an ideal gas which is compressed/ expanded isothermally? Why?*

Ans. Zero, because for an ideal gas internal energy is wholly kinetic and it is a function of temperature. As temperature remains constant in an isothermal process, hence, internal energy of an ideal gas remains constant.

Q. 8. *Is coefficient of performance of a refrigerator constant?*

Ans. No, the coefficient of performance of refrigerator decreases with decrease in its inside temperature.

Q. 9. *Is it possible to convert internal energy into work or mechanical energy?*

Ans. Yes, for example in an adiabatic expansion and explosion of a bomb (chemical energy is converted into K.E.).

Q. 10. *Why can an engine working under isothermal conditions produce no useful work?*

Ans. We know that

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

For isothermal operation of the engine,

$$T_1 = T_2, \quad \text{so } \eta = 0$$

Hence an engine working under isothermal condition can do no useful work.

Q. 11. *Heat is being supplied to a system but the system does not perform any external work. Is it possible? If yes, how?*

Ans. Yes, it is possible. If total quantity of heat ΔQ supplied to a system is retained by it as its increase in internal energy ΔU *i.e.*, $\Delta Q = \Delta U$, then the external work done by the system ΔW is zero. Isochoric process is an example of this type of process.

Q. 12. *A sample of an ideal gas in a cylinder is compressed adiabatically to $\frac{1}{3}$rd of its volume. Will the final pressure be more or less than 3 times the initial pressure?*

Ans. Change in pressure will be more than 3 times the initial pressure.

Q. 13. *How is the efficiency of a Carnot engine affected by the nature of the working substance?*

Ans. The efficiency is independent of the nature of the working substance.

Q. 14. *Which one among a solid, liquid and gas of the same mass and at the same temperature has the greatest internal energy and which one has the least?*

Ans. A gas has greatest internal energy and a solid has the least internal energy.

Q. 15. *Why does a gas get heated on compression?*

Ans. Because work done in compressing the gas increases the internal energy of the gas.

Q. 16. *What is the efficiency of a Carnot engine operating between boiling and freezing points of water?*

Ans. $$\eta = 1 - \frac{T_2}{T_1} = 1 - \frac{273}{373} = 0.27$$

Q. 17. *What forbids the complete conversion of heat into work?*

Ans. Second law of thermodynamics, which says that 100% conversion of heat into work is impossible.

Q. 18. *What is an indicator diagram?*

Ans. An indicator diagram is a graphical representation of the state of a system with the help of two thermodynamic variables (generally pressure and volume). Work done by a system is numerically equal to area under the P–V indicator diagram.

Q. 19. *Can mechanical work be completely converted into heat? Is reverse also possible?*

Ans. The mechanical work can be completely converted into heat, but heat extracted from some body cannot be completely converted into useful work.

Q. 20. *Under what ideal condition can the efficiency of a Carnot engine be 100%?*

Ans. The efficiency of a carnot engine can be 100% if the temperature of sink is absolute zero.

Q. 21. *A piece of lead is hammered. Does its internal energy increase? Does the heat enter the lead from outside?*

Ans. Yes, internal energy of lead increases. No heat energy from outside enters the lead.

Q. 22. *Can the temperature of a system be increased without heating it?*

Ans. Yes, for example in adiabatic compression.

II. SHORT ANSWER TYPE QUESTIONS

Q. 1. *The temperature of 3 kg krypton gas is raised from –29 °C to 89 °C. (a) If this is done at constant volume, compute the heat added, the work done, and the change in internal energy (b) Repeat if the heating process is at constant pressure.*

For K_r, C_v = *0.0357 cal/gm °C and* C_p = *0.0595 cal/gm °C.*

Ans. (*a*) According to first law of thermodynamics

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

At constant volume, $\Delta W = 0$ so $\Delta Q = \Delta U$

(*i*) So heat added $\Delta Q = \Delta U = mc_v\, \Delta T. = (3 \times 10^3)\, 0.0357 \times 100$

= 10710 cal = **10.71 kcal.**

(*ii*) Work done $\Delta W = 0$

(*iii*) Change in internal energy = 10.71 × 4.184 = **44.8 KJ**

(*b*) (*i*) At constant pressure, $\Delta Q = mC_p\, \Delta T = (3 \times 10^3)\, 0.0595 \times 100$

= 17850 cal = **17.85 kcal.**

(*ii*) Change in the internal energy will be the same *i.e,*

$$\Delta U = \textbf{10.71 kcal}$$

Work done $\Delta W = \Delta Q - \Delta U = 17.85 - 10.71 = 7.14$ kcal

$$= 7.14 \times 4.184 \text{ kJ} = \textbf{29.9 kJ}$$

(*iii*) The change in internal energy is the same as in isochoric process = **44.8 kJ.**

Q. 2. *What are the limitations of the first law of thermodynamics?*

Ans. Following are the limitations of the first law of thermodynamics.

(*i*) It does not tell us about the direction of flow of heat.

(*ii*) It fails to explain why heat cannot be spontaneously converted into work.

Q. 3. *A 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 ideal reversible cycle and no other losses.*

Ans. Here $T_1 = 25 + 273 = 298$ K

$$T_2 = -10 + 273 = 263 \text{ K}$$

$$Q_2 = 263 \text{ Js}^{-1}$$

Since, $\frac{Q_1}{Q_2} = \frac{T_1}{T_2} \Rightarrow Q_1 = \frac{T_1}{T_2} \times Q_2 = \frac{298}{263} \times 263 = 298 \text{ Js}^{-1}$

$\therefore$ Average power consumed = $Q_1 - Q_2$

$$= (298 - 263) \text{ Js}^{-1} = 35 \text{ W}.$$

Q. 4. *One mole of an ideal gas requires 207 J heat to raise the temperature by 10 K when heated at constant pressure. Find the amount of heat required to heat the same gas to raise the temperature by same 10 K under constant volume conditions. Given R = 8.3 J mol^{-1} K^{-1}.*

Ans. Here heat required to raise temperature of 1 mole of gas through 10 K under constant pressure conditions $\Delta Q = 207$ J

$$\therefore \quad C_p = \frac{\Delta Q}{\mu \cdot \Delta T} = \frac{207}{1 \times 10} = 20.7 \text{ J mol}^{-1} \text{ K}^{-1}$$

$$\therefore \quad C_v = C_p - R = 20.7 - 8.3 = 12.4 \text{ J mol}^{-1} \text{ K}^{-1}$$

$\therefore$ Amount of heat required to raise the temperature of gas through 10 K under constant volume condition:

$$\Delta Q' = \mu \cdot C_v \cdot \Delta T = 1 \times 12.4 \times 10 = 124 \text{ J mol}^{-1} \text{ K}^{-1}.$$

Q. 5. *Two samples of gas initially at the same temperature and pressure are compressed from volume V to $\frac{V}{2}$. One sample is compressed isothermally and the other adiabatically. In which case will the pressure be higher? Explain.*

Ans. Let P_a and P_i be the final pressure during adiabatic and isothermal compression respectively. In case of isothermal compression

$$PV = P_i \left(\frac{V}{2}\right) \quad \text{or} \quad P_i = 2P \qquad ...(i)$$

In case of adiabatic compression

$$PV^\gamma = P_a \left(\frac{V}{2}\right)^\gamma \quad \text{or} \quad P_a = 2^\gamma P \qquad ...(ii)$$

$$\therefore \quad \frac{P_a}{P_i} = \frac{2^\gamma}{2} > 1, \quad \text{because } \gamma > 1 \quad \therefore \quad P_a > P_i$$

Hence, final pressure during adiabatic compression is greater than the pressure during isothermal compression.

Q. 6. *The volume of an ideal gas is V at a pressure P. On increasing the pressure by ΔP, the change in volume of the gas is (ΔV_1) under isothermal conditions and (ΔV_2) under adiabatic conditions. Is $\Delta V_1 > \Delta V_2$ or vice-versa and why?*

Ans. Under isothermal conditions, $K_i = \dfrac{\Delta P}{\Delta V_1 / V} = P$ ...(*i*)

under adiabatic condition, $K_a = \dfrac{\Delta P}{\Delta V_2 / V} = \gamma P$ ...(*ii*)

Dividing (*ii*) by (*i*), we get

$$\frac{\Delta V_1}{\Delta V_2} = \gamma. \text{ As } \gamma > 1,$$

$$(\Delta V_1) > (\Delta V_2).$$

Q. 7. *What is the coefficient of performance (β) of a Carnot refrigerator working between 30 °C and 0 °C?*

Ans. Here

$$T_2 = 0\text{ °C} = 273\text{ K}$$
$$T_1 = 30\text{ °C} = 273 + 30 = 303\text{ K}$$
$$\beta = ?$$

Using the relation, $\beta = \dfrac{T_2}{T_1 - T_2}$, we get

$$\beta = \frac{273}{303 - 273} = \frac{273}{30} = 9.1.$$

Q. 8. *A car tyre contains air at a pressure of 4 atm and its temperature is 27°C. The tyre suddenly bursts. Calculate the resulting temperature. (γ = 1.4)*

Ans. Here $P_1 = 4$ atm, $P_2 = 1$ atm, T_1 – 27°C = 300 K and γ = 1.4.

The sudden burst of tyre is an adiabatic process, in which

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

$$\therefore \quad T_2 = T_1 \left(\frac{P_1}{P_2}\right)^{\frac{1-\gamma}{\gamma}} = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 300 \left(\frac{4}{1}\right)^{\frac{1.4-1}{1.4}} = 201.9$$

$$= 202\text{ K or } -71\text{°C}.$$

Q. 9. *Why can't the efficiency of an internal combustion engine be raised beyond a limit?*

Ans. To increase the efficiency [$= 1 - (1/\rho)^{\gamma - 1}$], the compression ratio ρ has to be increased. ρ cannot be made greater than 10, because then the cylinder of the engine will have to be made very thick and heavy which will be unsuitable for lighter vehicles. Secondly, during the adiabatic compression, the temperature of the air-petrol mixture will be high enough to cause explosion.

Q. 10. *Calculate the efficiency of a Carnot's engine working between steam point and ice point.*

Ans. Here, steam point,

$$T_1 = 100\text{ °C} = 100 + 273 = 373\text{ K}$$

ice point, $T_2 = 0\text{ °C} = 0 + 273 = 273\text{ K}$

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

$\therefore$ $\eta = 1 - \frac{273}{373} = \frac{100}{373} = \frac{100}{373} \times 100\% = 26.81\%$

Q. 11. *The efficiency of heat engine cannot be 100%. Explain?*

Ans. The efficiency of heat engine is given by

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

Q_2 = Heat rejected to the sink,

Q_1 = Heat absorbed from the source

η = 1 or 100% if and only if $Q_2 = 0$.

This cannot happen because if $Q_2 = 0$, then the temperature of the working substance will go on increasing. A stage will come when the temperature of the working substance becomes equal to the temperature of the source. In this situation, there is no transfer of heat from source to the working substance. Hence, we will not get the output.

Q. 12. *A perfect Carnot engine utilizes an ideal gas. The source temperature is 500 K and sink temperature is 375 K. If the engine takes 600 K cal per cycle from the source, compute:*

(a) the efficiency of the engine. *(b) work done per cycle.*

(c) heat rejected to the sink per cycle.

Ans. Here T_1 = 500 K

T_2 = 375 K

Q_1 = Heat absorbed per cycle = 600 kcal

$\therefore$ (*a*) Using the relation,

$$\eta = 1 - \frac{T_2}{T_1}, \text{ we get}$$

$$\eta = \frac{T_1 - T_2}{T_1} = \frac{500 - 375}{500} = \frac{125}{500} = 0.25$$

$$\eta\% = 0.25 \times 100 = 25\%$$

(*b*) Let W = work done per cycle

$\therefore$ Using the relation

$$\eta = \frac{W}{Q_1}, \text{ we get}$$

$$W = \eta Q_1 = 0.25 \times 600 \text{ kcal} = 150 \text{ kcal}$$

$$= 150 \times 10^3 \times 4.2 \text{ J} = 6.3 \times 10^5 \text{ J.}$$

(*c*) Let Q_2 = heat rejected to the sink

$\therefore$ Using the relation

$$W = Q_1 - Q_2, \text{ we get}$$

$$Q_2 = Q_1 - W = 600 - 150 = 450 \text{ kcal}$$

Q. 13. *Write the expressions for C_v and C_P of a gas in terms of gas constant R and constant γ, where*

$$\gamma = \frac{C_P}{C_v}.$$

Ans. We know that $C_p - C_v = R$ ...(*i*)

and $\frac{C_P}{C_v} = \gamma$ ...(*ii*)

From eqn. (*ii*) $C_P = \gamma C_v$ and sustituting this value in (*i*),

We have $\gamma C_v - C_v = R \Rightarrow C_v = \frac{R}{(\gamma - 1)}$

$\therefore \quad C_p = \gamma \cdot C_v = \frac{\gamma R}{(\gamma - 1)}$

Q. 14. *No real engine can have an efficiency greater than that of a Carnot engine working between the same two temperatures, why?*

Ans. A Carnot engine is an ideal heat engine from the following points of view:

(*i*) There is absolutely no friction between the walls of cylinder and the piston.

(*ii*) The working substance is an ideal gas. In a real engine, these conditions cannot be fulfilled and hence no heat engine working between the same two temperatures can have efficiency greater than that of carnot engine.

Q. 15. *Calculate the fall in temperature when a gas initially at 72 °C is expanded suddenly to eight times its original volume. Given $\gamma = \frac{5}{3}$.* $\therefore \quad V_2 = 8x$ *c.c.*

Ans. Let, $V_1 = x$ *c.c.*; $T_1 = 273 + 72 = 345$ K; $\gamma = \frac{5}{3}$; $T_2 = ?$

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

$$\therefore \quad T_2 = T_1 \left(\frac{V_1}{V_2}\right)^{\gamma - 1} = 345 \times \left(\frac{x}{8x}\right)^{2/3} = 345 \times \left(\frac{1}{8}\right)^{2/3}$$

Taking log both sides, we get

$$\log T_2 = \log 345 - \frac{2}{3}\log 8 = 2.5378 - \frac{2}{3}(0.9031)$$

$$= 2.5378 - 0.6020 = 1.9358$$

or $T_2 = 86.26$ K

$\therefore$ Fall in temperature $= 345 - 86.26 = 258.74$ K.

Q. 16. *A Carnot engine whose heat sink is at 27 °C has an efficiency of 40%. By how many degrees should the temperature of source be changed to increase the efficiency by 10% of the original efficiency?*

Ans. Here, $T_2 = 27\ °C = 27 + 273 = 300$ K

$\eta = 40\%, \quad T_2 = ?$

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

$$\frac{T_2}{T_1} = 1 - \eta = 1 - \frac{40}{100} = \frac{60}{100} = \frac{3}{5}$$

$$T_1 = \frac{5}{3}T_2 = \frac{5}{3}\times 300 = 500 \text{ K}$$

Increase in efficiency = 10% of 40 = 4%

∴ New efficiency $\eta' = 40 + 4 = 44\%$

Let T'_1 be the new temperature of the source.

As $$\eta' = 1 - \frac{T_2}{T_1'},$$

∴ $$\frac{T_2}{T_1'} = 1 - \eta' = 1 - \frac{44}{100} = \frac{56}{100}$$

$$T'_1 = \frac{100}{56}\ T_2 = \frac{100}{56}\times 300 = 535.7 \text{ K}$$

∴ Increase in temp. of source = 535.7 – 500 = 35.7 K

Q. 17. *A steam engine intakes steam at 200 °C and after doing work exhausts it directly in air at 100 °C. Calculate the percentage of heat used for doing work. Assume the engine to be an ideal engine.*

Ans. Here, $T_1 = 200\ °C = 473$ K and $T_2 = 100\ °C = 373$ K

∴Efficiency of engine $$\eta = \frac{W}{Q_1} = \left(\frac{T_1 - T_2}{T_1}\right) = \frac{473 - 373}{473} = \frac{100}{473} = 0.21$$

∴ $W = 0.21\ Q_1 = 21\%$ of Q_1

Thus, engine will convert 21% of heat used for doing work.

Q. 18. *A refrigerator, whose coefficient of performance is 5, extracts heat from the cooling compartment at the rate of 250 J per cycle. How much heat per cycle is discharged to the room?*

Ans. $$\beta = \frac{Q_2}{Q_1 - Q_2} \quad \text{or} \quad 5 = \frac{250}{Q_1 - 250}$$

$$5Q_1 - 1250 = 250 \quad \text{or} \quad Q_1 = \frac{1500}{5}\text{ J} = 300 \text{ J}$$

∴ Heat discharged per cycle to the room = 300 J.

Q. 19. *Temperature in the freezer of a refrigerator is being maintained at –13 °C and room temperature on a particular day was 42 °C. Calculate the coefficient of performance of the refrigerator.*

Ans. Here, temperature of colder body T_2 = –13 °C = 260 K and temperature of hotter surroundings T_1 = 42 °C = 315 K.

∴ Coefficient of performance of refrigerator $$\beta = \frac{T_2}{T_1 - T_2} = \frac{260}{315 - 260} = \frac{260}{55} = 4.73.$$

Q. 20. *Find the pressure required to compress a gas adiabatically at atmospheric pressure to one fifth of its volume (γ = 1.4).*

Ans. Here, P_1 = 1 atm.

Let $V_1 = x$ *c.c.*; $V_2 = \frac{x}{5}$ *c.c.* ;

$\gamma = 1.4$; $P_2 = ?$

Using the relation $P_1V_1^\gamma = P_2V_2^\gamma$

$$\therefore \quad P_2 = P_1\left(\frac{V_1}{V_2}\right)^\gamma = 1\left(\frac{x}{\frac{x}{5}}\right)^{1.4} = (5)^{1.4}$$

Taking log both sides, we get

$$\log P_2 = 1.4 \log 5 = 1.4 \times 0.6990 = 0.97860$$

$$\therefore \quad P_2 = 9.519 \text{ atm.}$$

III. LONG ANSWER TYPE QUESTIONS

Q. 1. *State Carnot theorem. The motor in a refrigerator has power output 250 watt. The freezing compartment is at 270 K and outside air at 300 K. Assuming ideal efficiency, what is the amount of heat that can be extracted from the freezing compartment in 10 minutes? What is the shortest time in which 10 kg of water at 273 K can be converted into ice?* $J = 4.2 \times 10^3$ *J kcal*$^{-1}$.

Ans. For Carnot theorem, see the NCERT Textbook.

Numerical: We know that

$$\beta = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

Here, $T_1 = 300$ K, $T_2 = 270$K

$W = 250$ W $= 250$ Js^{-1}

$Q = ?, \quad t = ?$

$$\therefore \quad Q_2 = W\beta = W\left(\frac{T_2}{T_1 - T_2}\right) = 250\left(\frac{270}{300 - 270}\right)$$

$$= 250 \times \frac{270}{30} = 2250 \text{ J s}^{-1}$$

(*i*) Let Q be the heat extracted from the freezing compartment in 10 minutes

$$\therefore \quad Q = Q_2 \times 10 \text{ min} = 2250 \times 10 \times 60 = 1350000 \text{ J}$$

$$= \frac{135 \times 10^4}{4.2 \times 10^3} \text{ kcal} = 321.4 \text{ kcal.}$$

(*ii*) Heat required to convert 1 kg of water at 273 K into ice,

$$Q' = m \times L = 1 \times 80 \text{ kcal} = 80 \times 4.2 \times 10^3 \text{ J}$$

Let Q' be extracted in a time t.

$\therefore$ Rate of extraction of heat from freezing compartment

$$= \frac{80 \times 4.2 \times 10^3}{t} \text{ J s}^{-1}$$

This rate must be equal to Q_2.

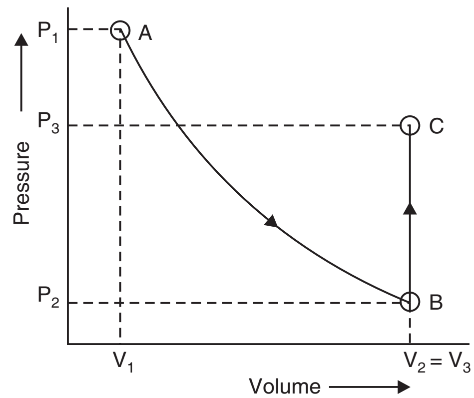
i.e.,
$$2250 = \frac{80 \times 4.2 \times 10^3}{t}$$

$$\therefore \quad t = \frac{80 \times 4.2 \times 10^3}{2250} = 149.33\text{s.}$$

Q. 2. *Explain what is meant by isothermal and adiabatic operations. A cylinder fitted with a movable piston contains hydrogen at a pressure of 3.5 × 10^5 N-m^2 and temperature 366 K. Hydrogen expands adiabatically until the pressure in the cylinder falls to 0.7 × 10^5 N-m^{-2}. The piston is then fixed and the gas is heated until the temperature becomes 366 K. The pressure in the cylinder is now found to be 1.1 × 10^5 N-m^{-2}. Determine the specific heats of hydrogen. (R = 8.3 J mol^{-1} K^{-1}).*

Ans. For isothermal and adiabatic operations, see the NCERT Textbook.

The processes are shown in Fig.



The process B to C is at constant volume, hence

$$\frac{P_3}{P_2} = \frac{T_3}{T_2}$$

or
$$T_2 = T_3 \times \frac{P_2}{P_3}$$

$$= 366 \times \frac{7 \times 10^4}{1.1 \times 10^5}$$

$$= 233 \text{ K.}$$

The process A to B is adiabatic, hence

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma} \quad \text{or} \quad \frac{366}{233} = \left(\frac{3.5\times10^5}{7\times10^4}\right)^{(\gamma-1)/\gamma}$$

Solving we get $\gamma = 1.39$

Now $\dfrac{C_P}{C_V} = 1.39 \quad (\because \gamma = C_P/C_V)$ ...(1)

Again $C_P - C_V = R$ or $C_P - C_V = 8.3$ ...(2)

From eq. (1) $C_P = 1.39\ C_V$.

Substituting the value of C_P in eq. (2), we have

$$1.39\ C_V - C_V = 8.3 \quad \text{or} \quad 0.39\ C_V = 8.3$$

$\therefore$ $C_V = \dfrac{8.3}{0.39} = 21.28$ J mol^{-1} K^{-1}

Now $C_P = 8.3 + C_V = 8.3 + 21.28 = 29.58$ J mol^{-1}.

Hence C_P = **29.58 J mol^{-1} K^{-1}** and C_V = **21.28 J mol^{-1} K^{-1}**

Q. 3. *A Carnot engine is working between ice point and steam point. It is desired to increase its efficiency by 20% (a) by changing temperature of hot reservoir alone, (b) by changing temperature of colder reservoir only. Calculate the change in temperature in each case.*

Ans. Here T_1 = 100 °C = 373 K and T_2 = 0 °C = 273 K

$$\eta = \frac{T_1 - T_2}{T_1} = \frac{373 - 273}{373} = \frac{100}{373} = 0.268$$

As we want to increase its efficiency by 20%, hence new efficiency is

$$\eta' = 26.8\% + 20\% = 46.8\%$$

(*a*) If keeping temperature of colder reservoir fixed the temperature of hot reservoir is changed to T_1', then

$$46.8 = \frac{T_1' - 273}{T_1'} \times 100 \quad \Rightarrow \quad 46.8\ T_1' = 100\ T_1' - 27300$$

$\Rightarrow$ $\quad 53.2\ T_1' = 27300 \quad$ or $\quad T_1' = \frac{27300}{53.2} = 513.2$ K

$\therefore$ $\quad T_1' - T_1 = 513.2 - 373 = 140.2$ K

It means that temperature of hot reservoir be raised by 140.2 K.

(*b*) If keeping temperature of hot reservoir fixed, the temperature of colder reservoir is changed to T_2', then

$$46.8 = \frac{T_1 - T_2'}{T_1} \times 100 = \frac{373 - T_2'}{373} \times 100$$

$\therefore$ $\quad 373 \times 46.8 = 373 \times 100 - 100\ T_2'$

$\Rightarrow$ $\quad 100\ T_2' = 373 \times (100 - 46.8) = 373 \times 53.2$

$\Rightarrow$ $\quad T_2' = \frac{373 \times 53.2}{100} = 198.4$ K

$\therefore$ $\quad T_2 - T_2' = 273 - 198.4 = 74.6$ K $= 74.6$ °C.

It means that temperature of colder reservoir be lowered by 74.6 °C.

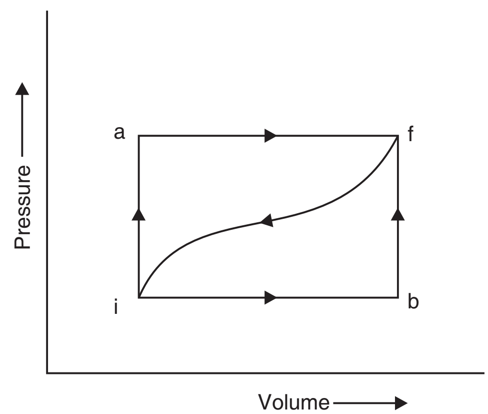
Q. 4. *When a system is taken from state i to state f along the path iaf (see fig. below), it is found that the heat Q absorbed by the system is 50 cal. and work done W by the system is equal to 20 cal. along the path ibf; Q = 36 cal.*

(i) What is W along the path ibf?

(ii) If W = –13 cal. for the curved return path fi, what is Q for this path?

(iii) Take $U_i = 10$ *cal, what is* U_f*?*

(iv) If $U_b = 22$ *cal. what are Q for the processes bf and ib?*



Ans. According to first law of thermodynamics

$$dQ = dU + dW \quad \text{or} \quad Q = U_f - U_i + W$$

U_f = internal energy in final state and U_i internal energy in initial state

For path *i a f*,

$$Q = +50 \text{ cal.} \quad \text{and} \quad W = 20 \text{ cal}$$

$\because$ $\quad U_f - U_i = Q - W = 50 - 20 = 30$ cal

Here it should be remembered that the change in internal energy between *i* and *f* state remains the same *i.e.,* 20 cal. whatever path is followed.

(*i*) For path *ibf*,

$$Q = 36 \text{ cal.} \quad \text{and} \quad dU = U_f - U_i = 30 \text{ cal}$$

$\therefore$ $\quad W = Q - (U_f - U_i) = 36 - 30 = 6$ cal.

(*ii*) For path *fi*, $\quad W = -13$ cal. $\quad dU = 30$ cal

$\therefore$ $\quad Q = W + (U_f - U_i) = .13 - 30 =$ **– 43 cal.**

(*iii*) $U_i = 10$ cal.

$dU = U_f - U_i = 30$

$\therefore \quad U_f = 30 + U_i = 30 + 10 = \mathbf{40\ cal.}$

(*iv*) For process *bf*, volume is constant *i.e.*, workdone is zero

$\therefore \quad Q = dU = U_f - U_b = 40 - 22 = 18$ cal.

For path *ib*,

$\therefore \quad Q = Q_{ibf} - Q_{bf} = 36 - 18 = \mathbf{18\ cal.}$

IV. MULTIPLE CHOICE QUESTIONS

1. The internal energy of an ideal gas depends on :

(*a*) Pressure (*b*) Volume (*c*) Temperature (*d*) Size of molecules

2. In an adiabatic change, the pressure P and temperature T of a diatomic gas are related by the relation $P \propto T^c$ where C equals :

(*a*) 5/3 (*b*) 2/5 (*c*) 3/5 (*d*) 7/2

3. An ideal heat engine exhosting heat at 27°C is to have 25% efficiency. It must take heat at:

(*a*) 127°C (*b*) 227°C (*c*) 327°C (*d*) 673°C

4. For a gas, $\gamma = 1.4$ then atomicity, C_P and C_V of the gas are :

(*a*) Monoatomic $\frac{5}{2}R, \frac{3}{2}R$ (*b*) Monoatomic $\frac{7}{2}R, \frac{5}{2}R$

(*c*) Diatomic $\frac{7}{2}R, \frac{5}{2}R$ (*d*) Triatomic $\frac{7}{2}R, \frac{5}{2}R$

5. The S.I. unit of mechanical equivelent of heat is

(*a*) Joule/Calorie (*b*) Calorie

(*c*) Calorie × erg (*d*) erg/calorie

6. The given quantity of an ideal gas is at pressure P and absolute Temperature T. The isothermal bulk Modulus of the gas is

(*a*) $\frac{2}{3}P$ (*b*) P (*c*) $\frac{3}{2}P$ (*d*) $2P$

7. Efficiency of an engine is η_1 at $T_1 = 200$°C and $T_2 = 0$°C and for η_2 at $T_1 = 0$°C and $T_2 = -200$ K, the ratio of $\frac{\eta_1}{\eta_2}$ is

(*a*) 1.00 (*b*) 0.721 (*c*) 0.577 (*d*) 0.34

8. A black body is at 727°C. It emits energy at a rate which is proportional to

(*a*) $(1000)^4$ (*b*) $(1000)^2$ (*c*) $(727)^4$ (*d*) $(727)^2$

9. An engine has an efficiency of $\frac{1}{6}$ when the temperature of sink is reduced by 62°C, its efficiency is doubled, temperature of the source is

(*a*) 37°C (*b*) 62°C (*c*) 99°C (*d*) 124°C

10. An ideal gas heat engine operates in a Carnot cycle between 227°C and 127°C. It absorbs 6 k cal of heat at higher temperature. The amount of heat in k cal rejected to sink is

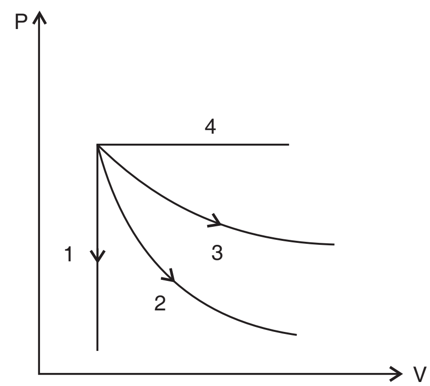
(*a*) 4.8 (*b*) 2.4 (*c*) 1.2 (*d*) 6.0

Answers

1. (*c*)	2. (*d*)	3. (*a*)	4. (*c*)	5. (*a*)
6. (*b*)	7. (*c*)	8. (*a*)	9. (*c*)	10. (*a*)

V. QUESTIONS ON HIGH ORDER THINKING SKILLS (HOTS)

Q. 1. *Identify and name the thermodynamic processes marked as 1, 2, 3 and 4 as shown in figure.*



Ans. 1. Isochoric process as it occurs at constant volume.

2. Adiabatic process because its slope is steeper than the process indicated by 3, which is isothermal process.
3. Isothermal process.
4. Isobaric process as it occurs at constant pressure.

Q. 2. *Three moles of an ideal gas of 300 K are isothermally expanded to five times its volume and heated at this constant volume so that the pressure is raised to its initial value before expansion. In the whole process 83.14 kJ heat is required. Calculate the ratio C_P/C_v of gas ($\log_e 5 = 1.61$).*

Ans. For isothermal expansion $P_1V_1 = P_2V_2$

$$\therefore \quad \frac{P_1}{P_2} = \frac{V_2}{V_1} = \frac{5V_1}{V_1} = 5$$

From gas law at constant volume

$$\frac{P_2}{T_2} = \frac{P_3}{T_3} = \frac{P_1}{P_3} \qquad \because (P_3 = P_1)$$

$$\therefore \quad \frac{P_2}{P_1} = \frac{T_2}{T_3} = \frac{T_1}{T_3} \quad \text{or} \quad \frac{T_3}{T_1} = \frac{P_1}{P_2} = 5$$

Now $\quad T_3 = 5\,T_1 = 5 \times 300 = 1500$ K

We know that $\quad dQ = dU + dW$

$$\therefore \quad dQ = nC_v\,\Delta T + \int_{V_1}^{V_2} PdV \quad \textit{where, } P = nRT_1/V$$

or $\quad dQ = nC_v\,\Delta T + nRT_1 \log_e (V_2/V_1)$

$$C_P - C_v = R \quad \text{and} \quad C_P/C_v = \gamma \qquad \therefore C_v = (R/\gamma - 1)$$

$$\therefore \quad dQ = \frac{nR}{\gamma-1}\Delta T + nRT_1 \log_e\left(\frac{V_2}{V_1}\right)$$

$$83.14 \times 10^3 = \frac{3\times 8.3}{\gamma-1} \times (1500 - 300) + 3 \times 8.3 \times \log_e 5$$

Solving we get $\gamma = \mathbf{1.42}$

Q. 3. *An ideal gas is taken through a cyclic thermodynamic process through four steps. The amount of heat involved in these steps are Q_1 = 5960 J, Q_2 = –5585 J. Q_3 = –2980 J and Q_4 = 3645 J respectively. The corresponding quantities of work involved are W_1 = 200 J, W_2 = –825 J, W_3 = –1100 J and W_4 respectively. Find the value of W_4. What is the efficiency of the cycle?*

Ans. As the process is cyclic, therefore, $\Delta U = 0$

According to first law of thermodynamics $\Delta Q = \Delta U + \Delta W = \Delta W$

i.e., $\Delta W = \Delta Q$ or $W_1 + W_2 + W_3 + W_4 = Q_1 + Q_2 + Q_3 + Q_4$

$$W_4 = (Q_1 + Q_2 + Q_3 + Q_4) - (W_1 + W_2 + W_3)$$

$$= (5960 - 5585 - 2980 + 3645) - (200 - 825 - 1100)$$

$$= 1040 - 275 = 765 \text{ J.}$$

$$\text{Efficiency} = \frac{\text{Net work done}}{\text{total heat absorbed}} = \frac{W_1 + W_2 + W_3 + W_4}{Q_1 + Q_4}$$

$$\eta = \frac{2200 - 825 - 1100 + 765}{5960 + 3645} = \frac{1040}{9605} = 0.1083$$

$$\eta = 0.1083 \times 100\% = 10.83\%$$

Q. 4. *One mole of an ideal gas is taken in a Carnot engine working between 27 °C and 227 °C. The useful work done in one cycle is 600 J. Calculate the ratio of the volume of the gas at the end and beginning of the isothermal expansion. Given R = 8.31 J mole^{-1} K^{-1}.*

Ans. Here, T_2 = 27 °C = (27 + 273) K = 300 K

T_1 = 227 °C = (227 + 273) K = 500 K

W = 600 J, R = 8.31 J mole^{-1} K^{-1}

As $$W = 2.303\, R\, (T_1 - T_2) \log_{10} \frac{V_2}{V_1}$$

$$\therefore \quad \log_{10}\frac{V_2}{V_1} = \frac{W}{2.303\, R\,(T_1 - T_2)} = \frac{600}{2.303 \times 8.31\,(500 - 300)} = 0.1568$$

$$\frac{V_2}{V_1} = \text{antilog } (0.1568) = 1.435$$

Q. 5. *Let the temperatures T_1 and T_2 of the two heat reservoirs in an ideal Carnot engine be 1500 °C and 500 °C respectively. Which of these, increasing T_1 by 100 °C or decreasing T_2 by 100 °C, would result in a greater improvement in the efficiency of the engine?*

Ans. The efficiency of Carnot engine is given by

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

(*i*) When T_1 is increased from 1500 °C to 1600 °C or 1600 + 273 = 1873 K and T_2 remains constant *i.e.,* 500 °C

or $\quad 500 + 273 = 773$ K, then

$$\eta_1 = \frac{1873 - 773}{1873} = \frac{1100}{1873} = \frac{1100 \times 100}{1873} = 58.73\%$$

(*ii*) When T_1 remains constant *i.e.,* 1500 °C or 1500 + 273 = 1773 K and T_2 is decreased by 100 °C *i.e.,* from 500 °C to 400 °C or 400 + 273 = 673 K then

$$\eta_2 = \frac{1773 - 673}{1773} = \frac{1100}{1773} = \frac{1100 \times 100}{1773} = 62.04\%$$

Thus, $\quad \eta_2 > \eta_1$.

Hence efficiency will be increased if T_2 is decreased from 500 °C to 400 °C

VI. VALUE-BASED QUESTIONS

Q. 1. *Shansher, a student of class X asked his physics teacher, "Why the refrigerator does not cool the room if it is kept open? Whereas the refrigerator cooles the eatables put in it. His teacher answered him that the refrigerator does not cool the room in which it is kept. When a refrigerator is working in a closed room with its door closed, it is rejecting heat from inside to the air in the room. So temperature increases gradually. When the door of the refrigerator is kept open, heat rejected by the refrigerator to the room will be more than the heat taken by the refrigerator from the room. Therefore the temperature of the room will increase at a slower rate compared to the first case. Shansher thanked his teacher for explaining it very well.*

(i) What values are shown by Shansher?

(ii) Calculate the efficiency of Carnot's engine working between steam point and ice point.

Ans. (*i*) The values shown by Shansher are : Sharp mind, visualisation, sharp observer, scientific attitude and awareness.

(*ii*) Here, steam point T_1 = 100°C = 100 + 273 = 373 K

and ice point T_2 = 0°C = 0 + 273 = 273 K

$$\therefore \quad \eta = 1 - \frac{T_2}{T_1} = 1 - \frac{273}{373} = \frac{100}{373}$$

$$\therefore \quad \eta = \frac{100}{373} \times 100\% = 26.81\%$$

Q. 2. *Anoop who is the student of class VIII went to a village in Rajasthan with his elder brother a science graduate. It was a month of June. He realised that during the day time, it was extreme hot but during the night it was too cold. He asked his elder brother the reason behind it. Anoop did not feel like it at his residence in Delhi. His brother explained him about Newton's cooling law that in desert places, the sand becomes too hot during day time and according to Newton's Law of cooling "The rate of heating is equal to rate of cooling". Anoop understood this reason very well and became happy.*

(i) What qualities, Anoop possess?

(ii) The climate of a harbour town is more temperate than that of a town in a desert at the same altitude. Why?

Ans. (*i*) Anoop possesses the qualities like having scientific attitude, awareness, intelligence and keen observer.

(*ii*) The relative humidity in a harbour town is more than that in a town in a desert. Hence the climate of a harbour town is more temperate than that of a town in a desert.

Q. 3. *Tajender was going to Agra with his father in the month of June. It was too hot to tolerate that day. His father was driving the car. He stopped on a petrol pump in the way and got filled the tank of the petrol in the car. He also checked the air in the tyres of the car at air pump. He asked the worker who was there to fill the air that fill the air in the tyre lesser than the normal air. Tajender immediately asked the reason behind it. His father explained that while driving, the air in the tyres expand due to the heat produced by the friction between the road and tyres. Tajender got the answer and became happy.*

(i) What values Tajender exhibit?

(ii) Can you design a heat Engine of 100% efficiency? Explain your answer.

Ans. (*i*) The values are : possessiveness, keen observer, sharp mind and intelligence.

(*ii*) The efficiency of a heat engine is

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

The efficiency of heat engine will be 100% or 1 if

$$T_2 = 0\text{K}$$

Since temperature equal to 0K can not be reached, so a heat engine cannot have 100 % efficiency.

TEST YOUR SKILLS

1. Differentiate among following thermodynamic processes.
(*a*) Isothermal, (*b*) Isobaric, (*c*) Isochoric and (*d*) Adiabatic.

2. What do you understand by cyclic process in thermodynamics? How does a heat engine work on the principle of cyclic process?

3. What do you understand about working of a refrigerator? How does the second law of thermodynamics explain the limitations of refrigerator?

4. What do you understand by reversible and irreversible processes in thermodynamics? What is the reason for irreversible nature of combustion reaction?

5. What is Carnot cycle?

6. What is a quasi-static process?

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