1. Details of Module and its structure

Module Detail	
Subject Name	Physics
Course Name	Physics 02(Physics Part 2, Class XI)
Module Name/Title	Unit 8, Module 6, Questions based on thermodynamics Chapter 12, Thermodynamics
Module Id	keph_201206_eContent
Pre-requisites	First law of thermodynamics, Thermodynamic processes, Second law of thermodynamics, Entropy, heat engine, refrigerator, Carnot cycle.
Objectives	After going through this module, the learners will be able to: • Apply laws of thermodynamics to daily life situations.
Keywords	Thermodynamic processes: Isothermal process, Adiabatic process, Isobaric process, Isochoric process, Entropy, heat engine, refrigerator, Carnot cycle.

2. Development Team

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TABLE OF CONTENTS:

1. UNIT SYLLABUS
Unit 8: Thermodynamics

Chapter 12: Thermodynamics

Thermal equilibrium and definition of temperature (zeroth law of thermodynamics), heat, work and internal energy. First law of thermodynamics, isothermal and adiabatic processes. Second law of thermodynamics: reversible and irreversible processes, Heat engine and refrigerator.

2. MODULE-WISE DISTRIBUTION OF UNIT SYLLABUS   6 Modules

The above unit is divided into six modules for better understanding.

Module 1	**Thermal equilibrium** **Heat exchange** **Zeroth law of thermodynamics** **Daily life observations**
Module 2	**Relation between work and internal energy** **Work on solids, liquids & gas** **Relation between heat and internal energy** **Molecular nature of heat and work**
Module 3	**First law of thermodynamics** **Relation between internal energy work and heat absorbed or released by a body** **Relevance of first law to gases** **P-V indicator diagram** **Thermodynamical processes Isothermal, adiabatic, isobaric, isochoric, reversible and irreversible**

Module 4	- Second law of thermodynamics - Heat engines - Carnot cycle - Efficiency of engines
Module 5	- Refrigerator - Heat machines -devices that produce heat geyser, toaster, stove –devices that operate on using internal energy
Module 6	- Understanding the thermal effect of heat and thermodynamics - Problem solving in thermodynamics

3. WORDS YOU MUST KNOW

- **First law of thermodynamics:** The change in internal energy of a system is equal to the difference in the heat given to the system and the work done by the system.

- **Thermodynamic processes:**
  a) Isothermal process: Process taking place at constant temperature
  b) Isobaric process: Process taking place at constant pressure
  c) Isochoric process: Process taking place at constant volume
  d) Adiabatic process: Process in which there is no transfer of heat

- **Heat engine:** A device which converts heat energy into mechanical energy in a cyclic process.

- **Carnot engine:** An ideal, reversible engine in which there are no dissipative forces. The ideal gas used as a working substance is always in equilibrium as it goes through the four processes of isothermal expansion, adiabatic expansion, isothermal compression and adiabatic compression and returns back to its initial state to complete the cycle.

- **Efficiency of the Carnot engine (η):**
  It depends only on the temperature of the source (hot reservoir) T_1 and the sink (cold reservoir) T_2 and it is equal to

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

- **Carnot theorem:**
  'No engine working between two given heat reservoirs can be more efficient than the Carnot's reversible engine working between those two reservoirs'

- **Carnot cycle: :** An ideal, reversible thermodynamic cycle in which there are no dissipative forces

- **Refrigerator:** It is a device which transfers heat from a cold reservoir to a hot reservoir when work is done on it.

- **Coefficient of performance of refrigerator:** It is the ratio of heat extracted from the cold reservoir to the work done on it

$$\text{Coefficient of performance (COP)} = \frac{Heat\ extracted\ from\ the\ cold\ reservoir}{Work\ done\ on\ the\ system}$$

- **Second law of thermodynamics**:

  No heat engine working in a cyclic process can have a hundred percent efficiency

  No refrigerator can have its coefficient of performance equal to infinity.

4. INTRODUCTION

In modules 1-5 of this unit on thermodynamics we considered many new ideas and concepts. We will now take up examples to help us understand them better. The analysis with every example will clarify many doubts that you might have.

5. QUESTION BASED ONTHERMODYNAMICS:

EXAMPLE 1

(i) Internal energy of a gas

1. **A container of volume 1 m^3 is divided into two equal parts by a partition. One part has an ideal gas at 320K and the other part is vacuum. The whole system is thermally isolated from the surroundings. When the partition is removed, the gas expands to occupy the whole volume.**
   a. **What will be the new temperature?**
   b. **How would the answer be modified if instead of an ideal gas we had a real gas?**
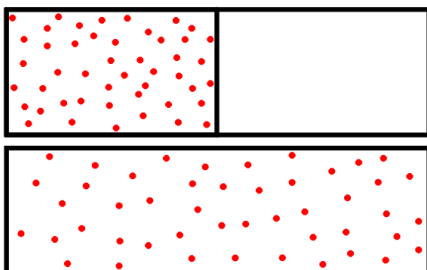
ANALYSIS:

a. As the system is thermally isolated from the surroundings, no heat can either go or come out of the system.

When the partition is removed the gas expands into the empty compartment. This is known as free expansion. Now since the other compartment is vacuum, the gas does not have to push against anything to expand, so no work is done by the gas in the expansion. Similarly nothing pushes on the gas in the expansion, so no work is done on the gas in the expansion.

So there is no heat exchange with the surroundings and there is no work done by gas or on the gas. By the first law of thermodynamics, this means that there will be no change in the internal energy of the gas.

Now for an ideal gas, the force between the molecules of the gas is considered to be zero, so the potential energy of the gas is zero and the internal energy is only due to the kinetic energy of the gas. A constant internal energy of the ideal gas therefore implies a constant kinetic energy. Since the temperature of a gas depends on the kinetic energy, **the temperature of the ideal gas will remain the same.**

b. For a real gas, the attractive forces between the molecules of the gas are not absent. So the gas possesses a potential energy due to these forces. The internal energy of a real gas is a sum of the potential energy and the kinetic energy. During the expansion of the real gas, the volume increases and the separation between the molecules increase. This increases the potential energy of the gas. Since the total internal energy remains conserved, the kinetic energy of the gas decreases. **This causes a decrease in the temperature of a real gas in free expansion.**

EXAMPLE 2

(ii) Thermodynamic processes

An ideal monoatomic gas at initial temperature To (in K) expands from initial volume Vo to volume 2Vo by each of the three processes indicated in the T-V diagram. In which of the process is the expansion
a. **Isothermal**
b. **Isobaric**
c. **Adiabatic**
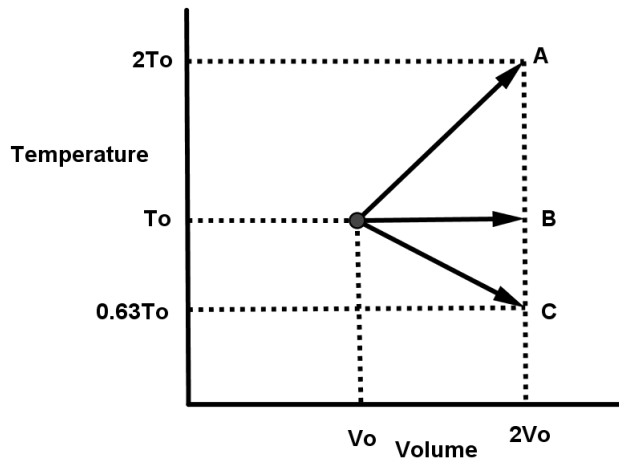
ANALYSIS:

a. **Isothermal process**: In this process the temperature of the thermodynamic system remains constant. In the given situations, in process B although the volume is increasing from Vo to 2Vo, the temperature remains constant

Answer: Process B

b. **Isobaric process:** In this process the pressure of the thermodynamic system remains constant. So the Charles law for gases is followed which says that " Pressure remaining constant, the temperature of a gas is directly proportional to the volume of the gas"
In the given situations, in process A as the volume of the gas doubles, the temperature of the gas also doubles which shows a direct proportionality.

Answer: Process A

c. **Adiabatic process:** In this process there is no exchange of heat between the system and the surrounding. So by the first law of thermodynamics, work is done by the gas in expansion at the expense of the internal energy. Hence the internal energy of the gas will decrease causing a drop in the temperature. The exact thermodynamic equation for adiabatic process is given by

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

$$T_o V_o^{1.66-1} = T_2 (2V_o)^{1.66-1}$$

$$T_2 = 0.63 T_o$$
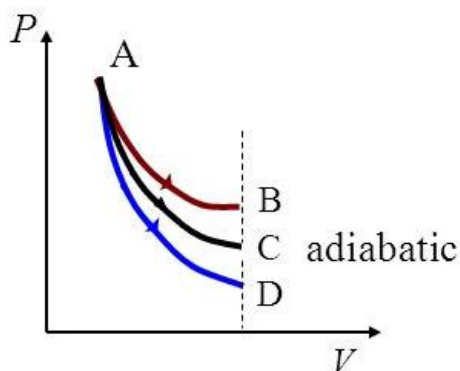
This result matches with the process C.

Answer: Process C

EXAMPLE 3

ADIABATIC PROCESSES

The figure shows adiabatic processes for samples of equal moles of three gases.

Write the name of one possible gas for each of the three processes.

ANALYSIS:

The P-V diagram shows adiabatic expansion. The adiabatic process follows the adiabatic equation

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

Differentiating this equation with respect to the volume gives the slope of the PV curve

$$\text{Slope} = -\gamma P/V$$

So the steepness of the curve depends on the value of γ

Value of γ which is ratio of the molar specific heats of gases at constant pressure and constant volume is maximum for mono atomic gases

γ for monoatomic gases = 1.66
γ for diatomic gases = 1.4
γ for triatomic gases = 1.33

So the steepness of the curve is maximum for monoatomic gases and hence

Process D is for a monoatomic gas like Helium gas

Process B will be for a triatomic gas like Carbon dioxide

Process C will be for diatomic gases like Oxygen or Nitrogen

EXAMPLE 4

A given volume of dry air at NTP is allowed to expand two times its original volume under

- **(i)** **isothermal conditions**
- **(ii)** **adiabatic conditions**
  Calculate the final temperature and pressure in each of above given cases. Given that the ratio $C_p/C_V = \gamma = 1.4$

ANALYSIS:

At NTP the temperature is taken to be 273K and the pressure is equal to 1 atmospheric pressure or 76cm of Hg.

i)   In isothermal conditions

$$PV = nRT = \text{constant}$$

or $P_1V_1 = P_2V_2$

$V_2 = 2V_1$, $P_1 = 76\text{cm of Hg}$

Hence

$$P_2 = P_1V_1 / V_2 = 76 / 2 = 38\text{cm of Hg}$$

Temperature will remain the same = 273K

ii)   In adiabatic conditions

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

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

$$P_2 = P_1\left(\frac{V_1}{V_2}\right)^\gamma = 76\,(1/2)^{1.4}$$

$$= 29 \text{ cm of Hg}$$

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

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

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

$$= 273 \, (1/2)^{1.4-1}$$

$$= 207K$$

EXAMPLE 5

WORK DONE IN THERMODYNAMIC PROCESSES

Two moles of helium gas are taken over the cycle ABCDA, as shown in the P-T diagram. Assuming the gas to be ideal, what is the

a. Work done on the gas in taking it from A to B

b. Work done on the gas in taking it from D to A

c. Net work done on the gas in the cycle ABCDA
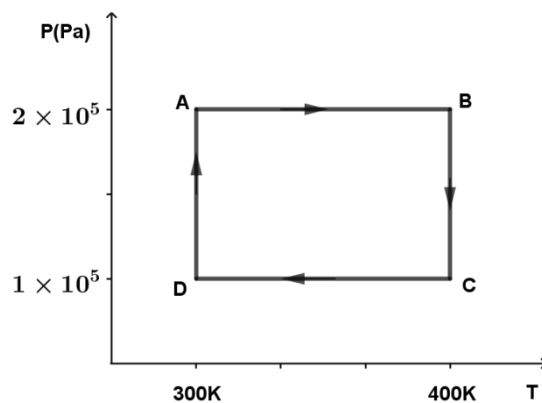
ANALYSIS:

a. Process AB is a isobaric process since it is taking place at a constant pressure of 2×10^5 Pa. So the increase in temperature is accompanied by an increase in the volume of the gas {V α T (Charles law)}.

$$\text{Hence} \quad W_{AB} = P(V_B - V_A) = nR(T_B - T_A)$$

$$= 2R(400 - 300)$$

$$= 200R = 200 \text{ x } 8.31 = 1662J$$

b. Process DA is an isothermal process since it is taking place at a constant temperature of 300K. So the increase in the pressure of the gas is accompanied by a decrease in the volume of the gas {P α 1/V (Boyles law)}

Hence $W_{DA} = nRT \ln(V_A/V_D)$

But by Boyles law

$$P_A V_A = P_D V_D$$

Hence $\quad V_A / V_D = P_D / P_A$

$$W_{DA} = nRT \ln(P_D/P_A)$$

$$= 2R \text{x} 300 \text{x} 2.303 \log_{10} (1/2)$$

$$= -2 \text{ x } 8.31 \text{ x } 300 \text{ x } 2.303 \text{ x } 0.3010$$

$$= -3456 \text{ J}$$

c. Net work done in the complete cycle is
$W_{net} = W_{AB} + W_{BC} + W_{CD} + W_{DA}$

We know that the work W_{AB} = 1662J and W_{DA} = -3440J

Process CD is also an isobaric process and work done in taking the gas along CD

$$W_{CD} = P (V_D - V_C) = nR(T_D - T_C)$$

$$= 2R(300 - 400)$$

$$= -200R$$

$$= -1662 \text{ J}$$

Note: Work done in this process is negative of the work done in process AB. The magnitude of the work done is independent of the pressure at which the process is happening. It only depends on the final and initial temperature

Process BC is an isothermal process so the work done
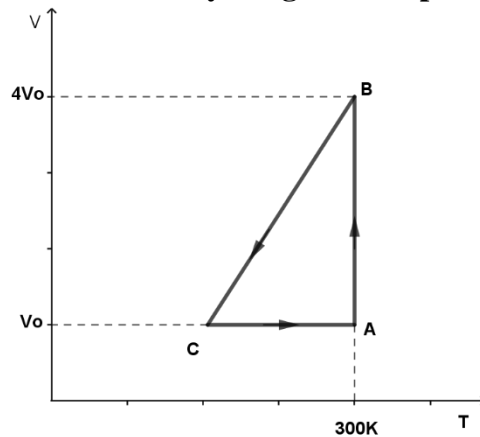
$$W_{BC} = nRT \ln(V_C/V_B)$$

$$= nRT \ln(P_B/P_C)$$

$$= 2R \times 400 \times 2.303 \log_{10} (2)$$

$$= 2 \times 8.31 \times 400 \times 2.303 \times 0.3010$$

$$= 4608 \text{ J}$$

$$W_{net} = W_{AB} + W_{BC} + W_{CD} + W_{DA}$$

$$= 1662J + 4608J - 1662J - 3456J = 1152J$$

EXAMPLE 6

One mole of an ideal gas in initial state A undergoes a cyclic process ABCA, as shown in figure. Its pressure at A is Po and its internal energy at A is U_o.
a. What is the internal energy at B
b. What is the work done by the gas in the process AB.

ANALYSIS:

a. Internal energy at B is same as A and is equal to U_o, since internal energy is constant for a given temperature in an ideal gas.
b. Process AB is a isothermal process. So the work done will be

$$W = nRT_o \ln(4V_o/V_o)$$

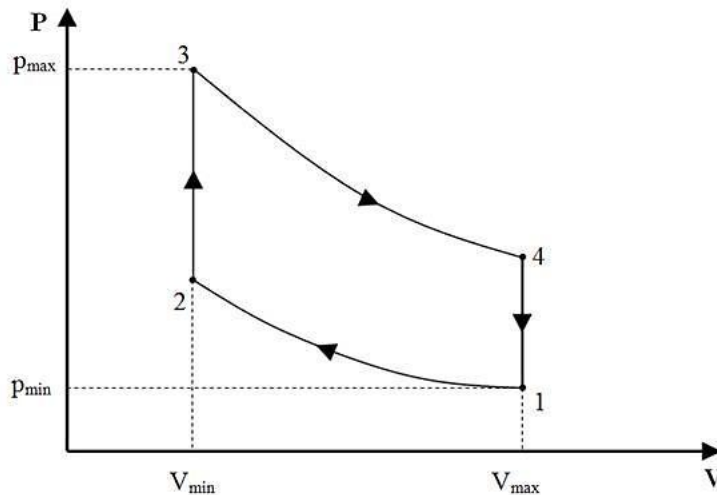$$= nRT_o \ln (4)$$

Also $P_oV_o = nRT_o$

Hence $W = P_oV_o \ln(4)$

EXAMPLE 7

(iii)Heat engine

The P-V diagram shows a gasoline internal combustion. Assuming the gasoline-air intake mixture is an ideal gas and $P_{max} = 3P_{min}$, $V_{max} = 4V_{min}$. The process 3 to 4 and the process 1 to 2 are adiabatic processes.

What will be the efficiency of the cycle?

ANALYSIS:

In the adiabatic process from 1 to 2 and from 3 to 4 there is no exchange of heat with the surroundings. The heat transfer takes place only in the isochoric process from 2 to 3 and from 4 to 1. Heat goes into the system from 2 to 3 and some heat is rejected by the system from 4 to 1.

Heat absorbed in the process from 2 to 3 $= mC_v(T_3 - T_2)$

Heat rejected in the process from 4 to 1 $= mC_v(T_1 - T_4)$

$$\text{Efficiency} = \frac{\text{Heat absorbed} - \text{Heat rejected}}{\text{Heat absorbed}}$$

$$= \frac{mC_v(T_3 - T_2) - mC_v(T_1 - T_4)}{mC_v(T_3 - T_2)}$$

$$= 1 - \frac{(T_1 - T_4)}{(T_3 - T_2)}$$

And in the adiabatic process from 1 to 2 we have

$$T_1 V_{max}{}^{\gamma-1} = T_2 V_{min}{}^{\gamma-1}$$

$$T_1 (4V_{min})^{\gamma-1} = T_2 V_{min}{}^{\gamma-1}$$

$$T_2/ T_1 = 4^{\gamma-1}$$

During the adiabatic expansion from 3 to 4 is given by

$$T_3 V_{min}^{\gamma-1} = T_4 V_{max}^{\gamma-1}$$

$$T_3 V_{min}^{\gamma-1} = T_4 (4V_{min})^{\gamma-1}$$

$$\frac{T_3}{T_4} = 4^{\gamma-1}$$

Hence
$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$

$$= (T_2 - T_3)/ (T_1 - T_4) = 4^{\gamma-1}$$

So efficiency $= 1 - \dfrac{(T_1 - T_4)}{(T_3 - T_2)}$

$$= 1 - \frac{1}{4^{\gamma-1}}$$

$$= 1 - 4^{1-\gamma}$$

Conclusion: Efficiency of this engine depends only on the compression ratio V_{max}/V_{min}

EXAMPLE 8

(iv) Refrigerator:

You have called guests at your place to celebrate your birthday. But half an hour before the party you realise that there is no ice in the refrigerator. So you quickly put one litre of water at 25°C into your ice cube trays of the freezer. The refrigerator has a coefficient of performance of 10 and a power rating of 500 W. Estimating that only 10 per cent of the power goes to freezing the ice, will you have ice in time for your guests?

ANALYSIS:

Mass of 1 litre of water = 1kg

Heat lost by water at 25°C to fall to 0°C = mc $(T_2 - T_1)$ = 1 x 4200 x 25 = 105000J = 105kJ

Latent heat of fusion of ice (L) = 336 kJ /kg

Latent heat lost in converting 1 kg of water into ice = mL = 336kJ

So total heat that should be extracted to convert 1kg of water into ice = (336 + 105) kJ

$$= 441 \text{ kJ}$$

For a refrigerator:

Coefficient of performance (COP) = $\dfrac{Heat\ extracted\ from\ the\ cold\ reservoir}{Work\ done\ on\ the\ system}$

Hence the work that should be done on the system to convert 1kg of water into ice

$$= \dfrac{Heat\ extracted\ from\ the\ cold\ reservoir}{Coefficient\ of\ perfomance} = \dfrac{441kJ}{10} = 44.1kJ$$

Refrigerator's power rating of 500W means that 500J of work is done on the refrigerator in one second

Since only 10% of this power is used in freezing the ice = 500 x 0.1 = 50W

$$Power\ (P) = Work(W)\ /\ time(t)$$

So the time taken to convert the water into ice = W/P = 44100/50 = 882 sec

$$= (882/60)\ min = 14.7min$$

Ice will be ready much before the guests arrive for the birthday party!

EXAMPLE 9

(v) Carnot engine

A Carnot engine works between the ice point and the steam point. We want the efficiency of this engine to increase by 10% keeping

    i)   **Temperature of the source constant**
    ii)   **Temperature of the sink constant**

        Find the change in temperature of the sink and the source respectively in the two cases given above. Which one is preferred?

    ANALYSIS:

Temperature of the source $(T_1) = 100^oC = 373K$

Temperature of the sink (T_1) = $0^oC = 273K$

Efficiency of the Carnot engine $\eta = (T_1 - T_2)\ /\ T_1$

$$= 100/373$$

10% increase in this efficiency makes the efficiency $\eta' = 110/373$

i)   Temperature of the source is kept constant

$\eta' = 110/373 = (373 - T_2')/373$

$T_2' = 373 - 110 = 263K$

Change $= T_2' - T_2 = 263 - 273 = -10K$

So the sink temperature has to be decreased by 10K or 10^oC

ii)   Temperature of the sink is kept constant

$\eta' = 110/373 = (T_1' - 273)/T_1' = 1 - (273/T_1')$

$T_1' = 387.2K$

Change $= T_1' - T_1 = 387.2 - 373 = 14.2K$

So the source temperature has to be increased by 14.2K or 14.2^oC

CONCLUSION: To achieve the same result the temperature of the sink had to decreased by 10^oC while the temperature of the source had to be increased by 14.2^oC. So decreasing the temperature of the sink is more preferable.