



HEAT AND THERMODYNAMICS

LEARNING OBJECTIVES

At the end of this chapter the students will be able to:

- State the basic postulates of kinetic theory of gases.
- Derive gas laws on the basis of kinetic theory.
- Describe that the internal energy of an ideal gas is due to kinetic energy of its molecules.
- Understand and use the terms work and heat in thermodynamics.
- Differentiate between isothermal and adiabatic processes.
- Explain the molar specific heats of a gas.
- Apply first law of thermodynamics to derive $C_p - C_v = R$.
- Explain the second law of thermodynamics and its meaning in terms of entropy.
- Understand the concept of reversible and irreversible processes.
- Define the term heat engine.
- Understand and describe Carnot theorem.
- Describe the thermodynamic scale of temperature.
- Explain the term entropy.

INTRODUCTION

Thermodynamics deals with various phenomena of energy and related properties of matter, especially the transformation of heat into other forms of energy. An example of such transformation is the process converting heat into mechanical work. Thermodynamics thus plays central role in technology, since almost all the raw energy available for our use is liberated in the form of heat. In this

Q.1 Define thermodynamics.**Ans. THERMODYNAMICS**

“Thermodynamics is the branch of physics, which deals with transformation of heat energy into mechanical energy (work).”

Q.2 What are the basic assumption of kinetic molecular theory of gases?**Ans. KINETIC THEORY OF GASES**

Matter is composed of tiny molecules which are not in the state of rest. These molecules move in different direction and make collision with each other as well as with the walls of the container. The molecular kinetic theory of gases based on the following postulates.

1. A finite volume of gas consists of a very large number of molecules.
2. The size of the molecule is much smaller than the separation between molecules.
3. The gas molecules are in random motion and may change their direction of motion after every collision.
4. Collision between gas molecules themselves and with walls of container are assumed to be perfectly elastic.
5. Molecules do not exert force on each other except during a collision.

Q.3 Define pressure. Also derive the expression for the pressure of a gas.**Ans. PRESSURE OF GAS**

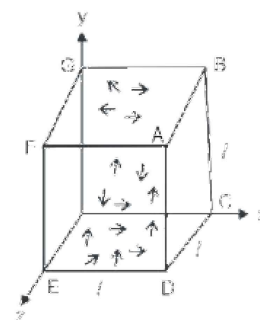
According to kinetic theory of gas,

Molecules collide with the walls of container and exert pressure on the walls. An expression for this can be obtained as follow

Consider a cubical container of side of length ‘ l ’, which has ‘ N ’ number of molecules moving in random motion as shown in figure.

$$\text{Area of each face} = A = l \times l = l^2$$

$$\begin{aligned} \text{Volume of container} &= V = A \times l \\ &= l^2 \times l = l^3 \end{aligned}$$



Consider a single molecule of mass ‘ m ’ moving with velocity ‘ \vec{V} ’, which has three components \vec{V}_{1x} , \vec{V}_{1y} , \vec{V}_{1z} along x , y and z axes.

Momentum of molecule before striking the face

$$ABCD = P_i = m V_{1x}$$

If collision is assumed to be perfectly elastic, the molecule will rebound from this face with same velocity

$$\Delta P = -m V_{1x} - m V_{1x}$$

$$\Delta P = -2m V_{1x} \quad \dots\dots\dots (1)$$

After recoil the molecule travels to the opposite face EFGHE and collides with it, rebounds and travels back to the face 'ABCD' after covering a distance $2l$. The time ' Δt ', between two successive collision with face 'ABCD' is

$$\text{As,} \quad S = V t$$

$$2l = V_{1x} \Delta t$$

$$\Delta t = \frac{2l}{V_{1x}} \quad \dots\dots\dots (2)$$

So, the number of collisions per-second that the molecule will make with this face is;

$$\Delta t = \frac{\Delta V_{1x}}{2l} \quad \left(\because f = \frac{1}{\Delta t} \right)$$

$$\left(f = \frac{1}{\frac{2l}{V_{1x}}} \right)$$

$$\left(f = \frac{V_{1x}}{2l} \right)$$

Now according to Newton's 2nd law, in term of momentum, the force ' F_m ' exerted on the molecule by the wall, is equal to rate of change of momentum i.e.,

$$F_m = \frac{\Delta P}{\Delta t}$$

Putting value of ΔP .

$$\therefore F_m = -\frac{2m V_{1x}}{\Delta t} \quad \dots\dots\dots (3)$$

According to Newton's 3rd law of motion force F_{1x} exerted by the molecule on the face ABCD is equal but opposite so,

$$F_{1x} = -F_m$$

Putting value of F_m from equation (3)

$$\therefore F_{1x} = -\left(-\frac{2m V_{1x}}{\Delta t} \right)$$

$$F_{1x} = \frac{2m V_{1x}}{\Delta t}$$

Putting value of Δt .

$$\therefore F_{1x} = \frac{2m V_{1x}}{2l/V_{1x}}$$

Similarly the forces due to all other molecule can be determined. Thus the total x-directed force F_x due to 'N' number of molecules moving with velocities V_1, V_2, \dots, V_N is

$$\begin{aligned} F_x &= F_{1x} + F_{2x} + \dots + F_{Nx} \\ \therefore F_x &= \frac{m}{l} V_{1x}^2 + \frac{m}{l} V_{2x}^2 + \dots + \frac{m}{l} V_{Nx}^2 \\ F_x &= \frac{m}{l} (V_{1x}^2 + V_{2x}^2 + \dots + V_{Nx}^2) \end{aligned}$$

As pressure is normal force per unit area, hence pressure P_x , on the face perpendicular to x-axis is

$$\begin{aligned} P_x &= \frac{F_x}{A} = \frac{F_x}{l^2} \\ P_x &= \frac{1}{l^2} \left(\frac{m V_{1x}^2}{l} + \frac{m V_{2x}^2}{l} + \frac{m V_{3x}^2}{l} + \dots + \frac{m V_{Nx}^2}{l} \right) \\ P_x &= \frac{m}{l^3} (V_{1x}^2 + V_{2x}^2 + V_{3x}^2 + \dots + V_{Nx}^2) \quad \dots\dots\dots (4) \end{aligned}$$

As the mass of single molecule is m , the mass of N molecule will be $m N$

Since density;

$$\rho = \frac{\text{Mass}}{\text{Volume}} = \frac{m N}{l^3}$$

Hence,
$$\frac{m}{l^3} = \frac{\rho}{N}$$

Substituting the value of $\frac{m}{l^3}$ in equation (4).

$$\begin{aligned} \therefore P_x &= \frac{\rho}{N} (V_{1x}^2 + V_{2x}^2 + V_{3x}^2 + \dots + V_{Nx}^2) \\ \text{or } P_x &= \rho \left(\frac{V_{1x}^2 + V_{2x}^2 + V_{3x}^2 + \dots + V_{Nx}^2}{N} \right) \quad \dots\dots\dots (5) \\ \text{where} &= \left(\frac{V_{1x}^2 + V_{2x}^2 + V_{3x}^2 + \dots + V_{Nx}^2}{N} \right) \end{aligned}$$

is called the mean of squared velocities of the molecules moving along 'x' direction, known as mean square velocity, represented by $\langle V_x^2 \rangle$.

\therefore equation (5) becomes

$$P_x = \rho \langle V_x^2 \rangle \quad \dots\dots\dots (6)$$

Similarly pressure on the faces perpendicular to 'y' and 'z' axes will be

$$P_y = \rho \langle V_y^2 \rangle \quad \text{and} \quad P_z = \rho \langle V_z^2 \rangle$$

The mean square of all the component velocities will be equal. Hence,

$$\langle V_x^2 \rangle = \langle V_y^2 \rangle = \langle V_z^2 \rangle$$

$$\langle V^2 \rangle = \langle V_x^2 \rangle + \langle V_x^2 \rangle + \langle V_x^2 \rangle$$

thus, $\langle V^2 \rangle = 3 \langle V_x^2 \rangle$

or $\langle V_x^2 \rangle = \frac{1}{3} \langle V^2 \rangle$

Putting this value of $\langle V_x^2 \rangle$ in equation (6).

$$\therefore P_x = \frac{\rho}{3} \langle V^2 \rangle$$

By Pascal's law the pressure on the other sides and everywhere inside the vessel will be the same provided the gas is of uniform density. So,

$$P_x = P_y = P_z = \frac{\rho}{3} \langle V^2 \rangle$$

Thus in general,

$$P = \frac{1}{3} \rho \langle V^2 \rangle$$

Since Density = $\rho = \frac{m N}{V}$

Hence, $P = \frac{m N}{V} \langle V^2 \rangle$

Multiply and divide by (2)

$$P = \frac{2 N}{3 V} \langle \frac{1}{2} m V^2 \rangle$$

$$P = \frac{2}{3} N_0 \langle \frac{1}{2} m V^2 \rangle$$

Where ' N_0 ' is the number of molecules per unit volume.

Thus, $P = \text{Constant} \langle \text{K.E.} \rangle$

$\therefore P \propto \langle \text{K.E.} \rangle$

Hence pressure exerted by the gas is directly proportional to the average translational K.E. of the gas molecules.

INTERPRETATION OF TEMPERATURE

Q.4 Show that absolute temperature is directly proportional to average translational K.E.

Ans. From ideal gas law;

$$PV = nRT \quad \dots\dots\dots (1)$$

$$n = \frac{N}{N_A}$$

∴ equation (1) becomes

$$PV = \frac{N}{N_A} RT$$

$$PV = N \frac{R}{N_A} T$$

$$PV = N k T \quad \dots\dots\dots (2)$$

Where $k = \frac{R}{N_A}$ is the Boltzman constant and has the value $= 1.38 \times 10^{-23} \text{ J K}^{-1}$

As,
$$P = \frac{2}{3} \frac{N}{V} < \frac{1}{2} m V^2 >$$

$$PV = \frac{2}{3} N < \frac{1}{2} m V^2 > \quad \dots\dots\dots (3)$$

Comparing (2) and (3)

$$NkT = \frac{2}{3} N < \frac{1}{2} m V^2 >$$

$$kT = \frac{2}{3} < \frac{1}{2} m V^2 >$$

$$T = \frac{2}{3k} < \frac{1}{2} m V^2 >$$

$$T = \text{Constant} < \frac{1}{2} m V^2 >$$

or
$$T \propto < \text{K.E.} >$$

DERIVATION OF GAS LAWS

Q.5 *Derive Boyle's law from the kinetic molecules theory of gases.*

Ans. **BOYLE'S LAW**

As,
$$P = \frac{2}{3} \frac{N}{V} < \frac{1}{2} m V^2 >$$

$$PV = \frac{2}{3} N < \frac{1}{2} m V^2 >$$

If we keep the temperature constant.

∴ $< \frac{1}{2} m V^2 >$ is constant ($\because T \propto \text{K.E.}$)

Thus pressure 'P' is inversely proportional to volume V at constant temperature of gas, which is Boyle's law.

Q.6 *Derive Charles's from the kinetic molecular theory of gases.*

Ans. CHARLES'S LAW

$$\text{As,} \quad P = \frac{2}{3} \frac{N}{V} < \frac{1}{2} m V^2 >$$

$$V = \frac{2}{3} \frac{N}{P} < \frac{1}{2} m V^2 >$$

If pressure is kept constant.

$$\therefore V = \text{Constant} < \frac{1}{2} m V^2 >$$

$$\therefore V \propto < \frac{1}{2} m V^2 >$$

$$\text{or} \quad V \propto T \quad \left(\because T \propto < \frac{1}{2} m V^2 > \right)$$

Thus volume is directly proportional to absolute temperature of gas, provided pressure is kept constant.

Q.7 *What is internal energy?*

Ans. INTERNAL ENERGY

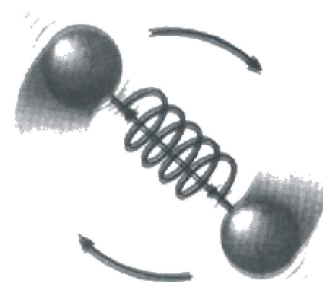
"The sum of all forms of molecular energies (K.E. and P.E.) of a substance is termed as its internal energy."

In the study of thermodynamics, usually ideal gas is considered as a working substances. The molecules of an ideal gas are mere mass points, which exert forces on one another. So the internal energy of an ideal gas system is generally the translational K.E. of its molecules. Since the temperature of a system is defined as the average K.E. of its molecules, thus for an ideal gas system, the internal energy is directly proportional to its temperature.

When we heat a substance, energy associated with its atoms or molecules is increased i.e., heat is converted to internal energy.

It is important to note that energy can be added to a system even though no heat transfer takes place. For example, when two objects are

Do You Know?



A diatomic gas molecule has both translational and rotational energy. It also has vibrational energy associated with the spring like

increase in the internal energy. Similarly, when an object slides over any surface and comes to rest because of frictional forces, the mechanical work done on or by the system is partially converted into internal energy.

In thermodynamics, internal energy is a function of state. Consequently, it does not depend on path but depends on initial and final states of the system. consider a system, which undergoes a pressure and volume change from P_a and V_a to P_b and V_b respectively, regardless of the process by which

System

It is the collection of matter, which has distinct boundaries.

For example a gas enclosed in a cylinder.

Q.8 What is the relation between work and heat?

Ans. WORK AND HEAT

Heat is the form of energy, which can travel from one body to another.

Its unit is joule (J).

Consider the gas enclosed in a cylinder with a movable frictionless piston of cross-sectional area A . In equilibrium the system occupies volume ' V ', and exerts a pressure ' P ' on the walls of the cylinder and its piston. The force ' F ' exerted by the gas on the piston is PA .

We assume that the gas expands through ΔV very slowly, so that it remains in equilibrium. As the piston moves up through a small distance ΔY , the work (W) done by the gas is;

$$W = F \Delta Y = PA \Delta Y$$

$$\text{Since } A \Delta Y = \Delta V \quad (\text{Change in volume})$$

$$\text{Hence } W = P \Delta V$$

The work done can also be calculated by area of the curve under $P - V$ graph, as shown in figure.

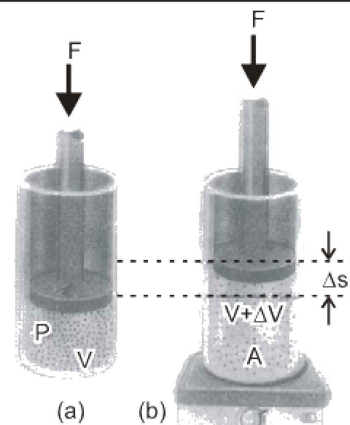
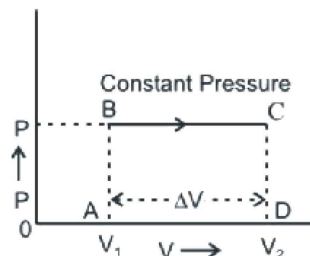


Fig. A gas sealed in a cylinder by a weightless, frictionless piston. The constant downward applied force F equals PA , and when the piston is displaced, downward work is done on the gas.



Q.9 State and explain first law of thermodynamics.

Ans. FIRST LAW OF THERMODYNAMIC

“In any thermodynamic process, when heat ‘Q’ is added to the system, this energy appears as an increase in the internal energy ‘ ΔU ’ stored in the system plus the work ‘W’ done by the system on its surroundings.”

Let ‘Q’ be the heat supplied to the system, so that the change in internal energy is ΔU and total work done by the system is ‘W’, so

$$Q = \Delta U + W \quad \dots\dots\dots (1)$$

$$(\Delta U = U_2 - U_1)$$

When heat supplied to the system then K.E. of molecules increases, so internal energy increase. Also molecules push the piston upward and work is done by the system.

From equation (1).

$$\Delta U = Q - W \quad \dots\dots\dots (2)$$

So, change in internal energy is defined as;

“The heat supplied to the system–work done by the system.”

This law is the extended form of the law of conservation of energy.

Examples

- (1) Heat engine (2) A bicycle pump (3) Human metabolism

Q.10 Describe the isothermal process and also draw P-V diagram.

Ans. ISOTHERMAL PROCESS

“The process, in which temperature of the system remains constant is called an isothermal process.”

Consider a system consisting of an ideal gas, in a cylinder having conducting base and non-conducting walls and piston. The piston is frictionless and moveable.

The cylinder is placed on heat reservoir. In order to keep the temperature of the gas constant, the expansion or compression must take place slowly because transfer of heat requires time. In case of an ideal gas potential energy associated with its molecules is zero. Hence the internal energy of an ideal gas depends only on its temperature, which is constant

$$\therefore \Delta U = 0$$

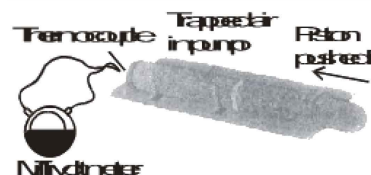
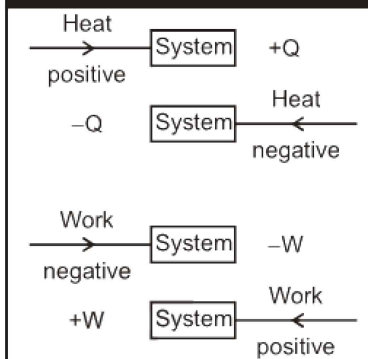
Hence 1st law of thermodynamics becomes;

$$Q = \Delta U + W$$

$$Q = 0 + W$$

$$Q = W$$

For Your Information

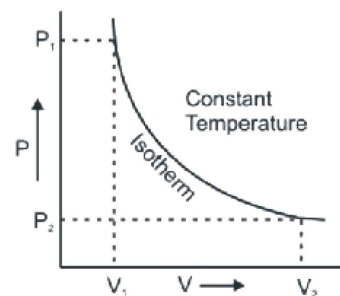


This shows that if the gas expands and does an external work 'W', then an amount of heat 'Q', has to be supplied to keep the temperature constant. Conversely, if the gas is compressed i.e., work is done on the system, then heat 'Q' should leave the system to keep the temperature constant.

"The curve representing an isothermal process is called an isotherm."

The relation for isothermal process is;

$$PV = \text{Constant}$$



Q.11 Describe adiabatic process and also draw P-V diagram.

Ans. ADIABATIC PROCESS

"An adiabatic process is the one, in which no heat enters or leaves, the system."

i.e., $Q = 0$

This prevention of heat may be achieved either by surrounding the system with a layer of insulating material or by performing expansion or compression process quickly, because heat flow require finite time and any process performed quickly is practically adiabatic.

- e.g.,
1. The rapid escape of air from a burst tyre.
 2. The rapid expansion and compression of air through, which a sound wave is passing.
 3. Cloud formation in the atmosphere.

Consider a system consisting of a gas enclosed in a heat insulator. For adiabatic process;

$$Q = 0$$

∴ 1st law of thermodynamics becomes;

$$Q = \Delta U + W$$

$$0 = \Delta U + W$$

$$W = -\Delta U$$

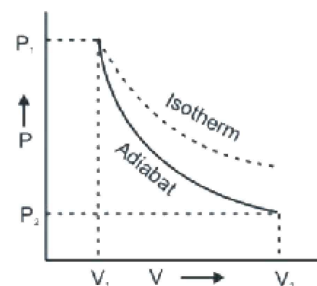
In this case work is done by the system and is equal to decrease in internal energy i.e., work is done at the cost of internal energy.

or $\Delta U = -W$

In this case work is done on the system and is equal to increase in internal energy.

The curve is called adiabatic and is obtained by

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



Isochoric Process

Such a process in which volume is constant.

Isobaric Process

Such a process in which pressure is constant.

Q.12 Define molar specific heat of a gas.

Ans. MOLAR SPECIFIC HEAT OF A GAS

“The amount of heat required to raise the temperature of one mole of the substance through 1K, is called molar specific heat of a gas.”

Consider ‘n’ number of moles of a substance. The amount of heat ‘Q’, absorbed by it depends on;

1. Number of moles i.e. $Q \propto n$ (1)
2. Temperature difference i.e., $Q \propto \Delta T$ (2)

Combining (1) and (2).

$$Q \propto n \Delta T$$

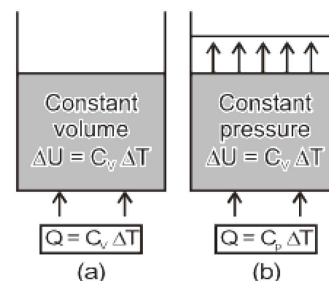
$$Q = C_m n \Delta T$$

$$\therefore C_m = \frac{Q}{n \Delta T}$$

where C_m is the molar specific heat.

Unit

$$\text{J/mole K or J mole}^{-1} \text{K}^{-1}$$



Q.13 Define molar specific heat at constant volume.

Ans. MOLAR SPECIFIC HEAT AT CONSTANT VOLUME

“The amount of heat required to raise the temperature of one mole of the gas through 1K, at constant volume, is called molar specific heat at constant volume.”

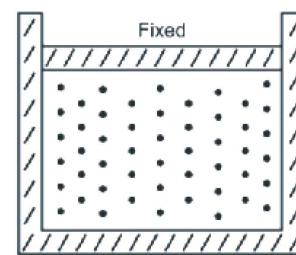
It is represented by C_v .

For ‘n’ moles

$$C_v = \frac{Q_v}{n \Delta T}$$

For 1 mole

$$C_v = \frac{Q_v}{\Delta T}$$



$$\text{As, } W = P \Delta V$$

Since piston is fixed

$$\therefore \Delta V = 0$$

$$\therefore W = P(0)$$

$$W = 0$$

Now applying 1st law of thermodynamics, at constant volume;

$$\therefore Q_V = \Delta U + W$$

$$C_V \Delta T = \Delta U + 0$$

$$\therefore \Delta U = C_V \Delta T$$

Q.14 Define molar specific heat at constant pressure.

Ans. MOLAR SPECIFIC HEAT AT CONSTANT PRESSURE

“The amount of heat required to raise the temperature of one mole of a gas, through 1K at constant pressure, is called molar specific heat at constant pressure.”

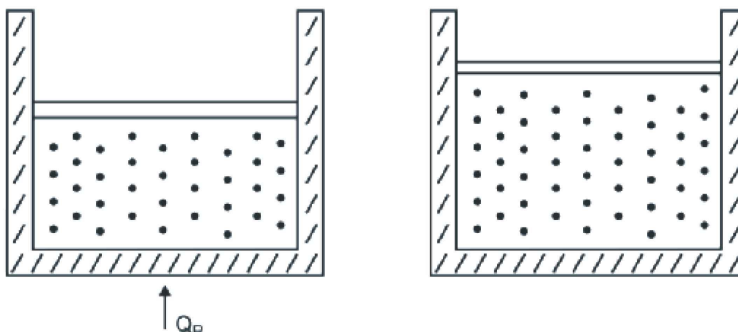
For ‘n’ moles;

$$C_P = \frac{Q_P}{n \Delta T}$$

For 1 mole

$$C_P = \frac{Q_P}{\Delta T}$$

$$Q_P = C_P \Delta T$$



Q.15 Prove that molar heat capacity at constant pressure is greater than molar heat capacity at constant volume. Show that $C_P - C_V = R$.

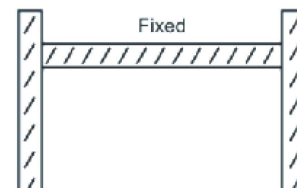
Ans. Consider one mole of an ideal gas, contained in a cylinder, fitted with a fixed piston. As the piston is fixed and the gas is heated, its volume remains constant and all heat supplied goes to increase K.E. of gas molecules due to which temperature of gas increase. If ‘ Q_V ’ is heat supplied and ‘ Δt ’ is rise in temperature, then by the definition of ‘ C_V ’ we have,

$$Q_V = C_V \Delta T \quad \dots\dots\dots (1)$$

As piston is fixed

$$\therefore \Delta V = 0$$

$$\therefore W = P \Delta V$$



Now applying 1st law of thermodynamics at constant volume;

$$Q_V = \Delta U + W$$

$$C_V \Delta T = \Delta U + 0$$

$$\Delta U = C_V \Delta T \quad \dots\dots (2)$$

Now if the piston is free to move through small distance, when ' Q_P ' is supplied, from definition of ' C_P '.

$$Q_P = C_P \Delta T \quad \dots\dots (3)$$

When gas is heated, its temperature rises and doing some work in pushing the piston upward at constant external pressure.

$$\text{As} \quad W = P \Delta V \quad \dots\dots (4)$$

Using ideal gas equation for one mole.

$$\therefore PV = RT \quad \left(\begin{array}{l} PV = n RT \\ n = 1 \end{array} \right) \dots\dots (5)$$

At constant pressure ' P ', amount of work done by one mole of a gas due to expansion ' ΔV ' caused by the rise in temperature ΔT so equation (5) becomes.

$$P \Delta V = R \Delta T \quad \dots\dots\dots (6)$$

Comparing (4) and (6).

$$W = R \Delta T \quad \dots\dots\dots (7)$$

Now using 1st law of thermodynamics at constant pressure.

$$Q_P = \Delta U + W \quad \dots\dots\dots (8)$$

When one mole of a gas is heated at constant pressure, the internal energy increases, by the same amount, as at constant volume for the same rise in temperature ' ΔT '.

$$\text{i.e., } (\Delta U = \Delta U_P = \Delta U_V = C_V \Delta T)$$

Putting values of Q , ΔU , W from equation (3), (2) and equation (7) in equation (8).

$$\therefore C_P \Delta T = C_V \Delta T + R \Delta T$$

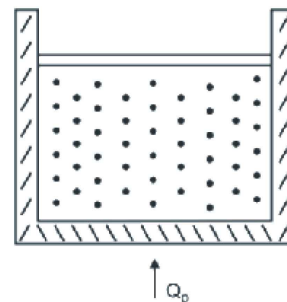
$$C_P \Delta T = \Delta T (C_V + R)$$

$$C_P = C_V + R$$

$$C_P - C_V = R$$

As R is positive

$$\therefore C_P > C_V$$



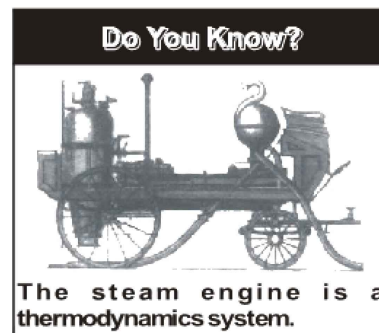
heat is absorbed in the direct process, it will be given out in the reverse process and if work is done by the substance in the direct process, work will be done on the substance in the reverse process. Hence, the working substance is restored to its original conditions.

A succession of events which bring the system back to its initial condition is called a cycle. A reversible cycle is the one in which all the changes are reversible.

Although no actual change is completely reversible but the processes of liquefaction and evaporation of a substance, performed slowly, are practically reversible. Similarly the slow compression of a gas in a cylinder is reversible process as the compression can be changed to expansion by slowly decreasing the pressure on the piston to reverse the operation.

If a process cannot be retraced in the backward direction by reversing the controlling factors, it is an irreversible process.

All changes which occur suddenly or which involve friction or dissipation of energy through condition, convection or radiation are irreversible. An example of highly irreversible process is an explosion.



Q.16 What is heat engine?

***Ans.* HEAT ENGINE**

A heat engine converts some thermal energy to mechanical work. Usually the heat comes from the burning of a fuel. The earliest heat engine was the steam engine. It was developed on the fact that when water is boiled in a vessel covered with a lid, the steam inside tries to push the lid off showing the ability to do work. This observation helped to develop a steam engine.

Basically a heat engine (figure) consists of hot reservoir or source which can supply heat at high temperature and a cold reservoir or sink into which heat is rejected at a lower temperature. A working substance is needed which can absorb heat Q_1 from source, converts some of it into work W by its expansion and rejects the rest heat Q_2 to the cold reservoir or sink. A heat engine is made cyclic to provide a continuous supply of work.

Q.17 State second law of thermodynamics.

Ans. SECOND LAW OF THERMODYNAMICS

First law of thermodynamics tells us that heat energy can be converted into equivalent amount of work, but it is silent about the conditions under which this conversion takes place. The second law is concerned with the circumstances in which heat can be converted into work and direction of flow of heat.

Before initiating the discussion on formal statement of the second law of thermodynamics, let us analyze briefly the factual operation of an engine. The engine or the system represented by the block diagram absorbs a quantity of heat Q_1 from the heat source at temperature T_1 . It does work W and expels heat Q_2 to low temperature reservoir at temperature T_2 . As the working substance goes through a cyclic process, in which the substance eventually returns to its initial state, the change in internal energy is zero. Hence from the first law of thermodynamics, net work done should be equal to the net heat absorbed.

$$W = Q_1 - Q_2$$

In practice, the petrol engine of a motor car extracts heat from the burning fuel and converts a fraction of this energy to mechanical energy or work and expels the rest to atmosphere. It has been observed that petrol engines convert roughly 25% and diesel engines 35 to 40% available heat energy into work.

The second law of thermodynamics is a formal statement based on these observations. It can be stated in a number of different ways.

According to Lord Kelvin's statement based on the work of a heat engine.

It is impossible to devise a process which may convert heat, extracted from a single reservoir, entirely into work without leaving any change in the working system.

This means that a single heat reservoir, no matter how much energy it contains, cannot be made to perform any work. This is true for oceans and our atmosphere which contain a large amount of heat energy but cannot be converted into useful mechanical work. As a consequence of second law of thermodynamics, two bodies at different temperatures are essential for the conversion of heat into work. Hence for the working of heat engine there must be a source of heat at a high temperature and a sink at low temperature to which heat may be expelled. The reason for our inability to utilize the heat contents of

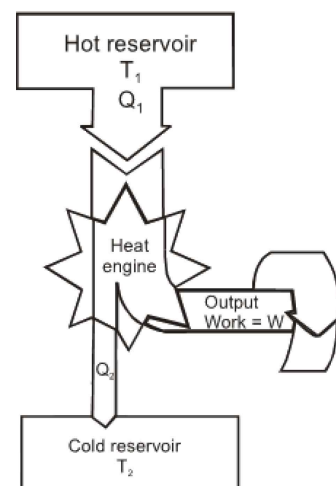
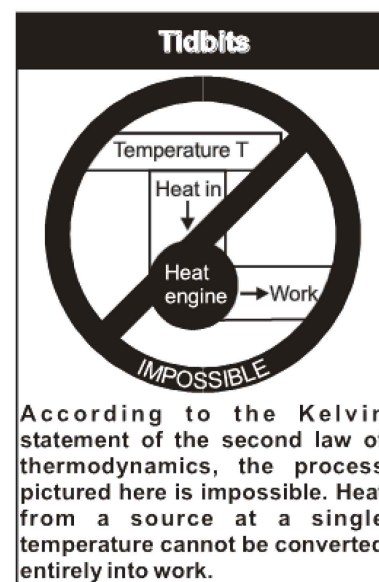


Fig. Schematic representation of a heat engine. The engine absorbs heat Q_1 from the hot reservoir, expels heat Q_2 to the cold reservoir and does work W .



According to the Kelvin statement of the second law of thermodynamics, the process pictured here is impossible. Heat from a source at a single temperature cannot be converted entirely into work.

Q.18 *What is Carnot engine? Describe the four processes (steps) of the operating cycle of the Carnot engine.*

Ans. **CARNOT ENGINE**

It is an ideal heat engine, whose efficiency is nearly 100%.

In 1840 CARNOT described an ideal engine using isothermal and adiabatic processes, he showed that a heat engine operating in an ideal reversible cycle, between two heat reservoirs, of different temperatures, would be the most efficiency engine.

Working Principle

It absorbs some heat from H.T.R., convert a part of it into work and reject the remaining part to L.T.R.

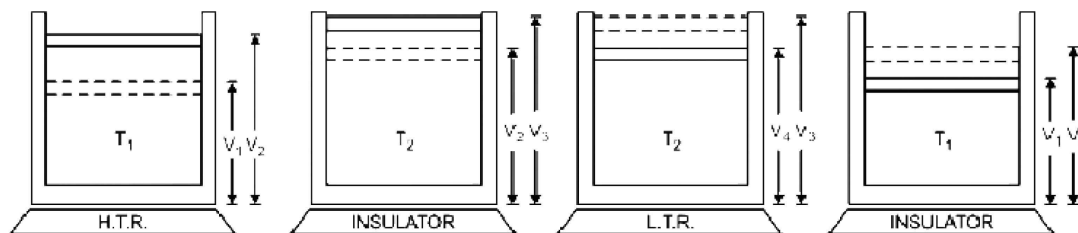
Construction

It consists of an ideal gas, enclosed in a cylinder, provided by a frictionless, movable and non-conducting piston. The walls of the cylinder are non-conducting, while the base is conducting to heat.

The operating cycle of CARNOT engine is called CARNOT cycle.

Carnot Cycle

It consist of 4 processes, which are shown on PV diagram, as shown in Fig.



Process 1

The cylinder is placed on H.T.R. and the gas is allowed to expand isothermally of temperature T_1 .

Heat Q_1 flows into the cylinder due to conduction through base and the gas does some work on piston. The process is represented by curve AB.

Process 2

The cylinder is placed on an insulator and the gas is allowed to expand.

As no heat can enter or leave the system, the expansion is adiabatic and the temperature of gas fall from T_1 to T_2 , the gas does work on the piston. The process is represented by curve BC.

Process 3

The cylinder is placed on a L.T.R. and the gas is compressed slowly.

During this compression temperature of gas rises, but heat Q_2 is rejected to L.T.R. making temperature constant, some work is done on the gas. The process is represented by curve CD.

Process 4

During this compression, temperature of the gas increases from T_2 to T_1 . The process is represented by curve DA.

Q.19 *What is Carnot's theorem? Also calculate the efficiency of such a engine in terms of temperature of source and sink.*

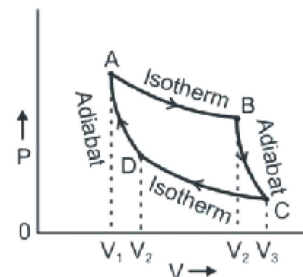
Ans. **CARNOT'S THEOREM**

“No heat engine can be more efficient than a CARNOT engine operating between the same two temperature.”

The Carnot's theorem can be extended to state that all Carnot's engines operating between the same two temperatures have the same efficiency, irrespective of the nature of working substance.

All real heat engines are less efficient than Carnot engine due to friction and other heat losses.

As the working substance returns to the initial state, there is no change in its internal energy i.e., $\Delta U = 0$.



The net work done during one cycle equals to the area enclosed by the path ABCDA of the PV diagram. It can also be estimated from net heat ' ΔQ ', absorbed in one cycle.

$$\Delta Q = Q_1 - Q_2$$

From 1st law of thermodynamics;

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

$$\Delta W = Q_1 - Q_2 \quad (\because \Delta U = 0)$$

The efficiency η of the heat engine is defined as;

$$\eta = \frac{(\text{Output})}{(\text{Input})}$$

$$\text{thus, } \eta = \frac{Q_1 - Q_2}{Q_1}$$

$$\text{or, } \eta = 1 - \frac{Q_2}{Q_1}$$

The energy transfer in an isothermal expansion or compression turns out to be proportional to Kelvin temperature. So Q_1 and Q_2 are proportional to Kelvin temperature, T_1 and T_2 respectively and hence

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

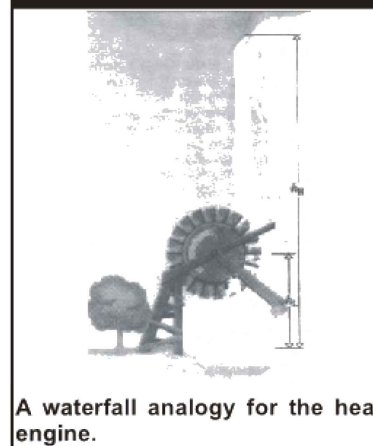
The efficiency in % age.

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

Thus the efficiency of CARNOT engine depends on the temperature of hot and cold reservoirs. It is independent of the nature of working substance. The larger the temperature difference of two reservoirs, the greater is the efficiency. But it can never be one or 100% unless cold reservoir is at absolute zero temperature.

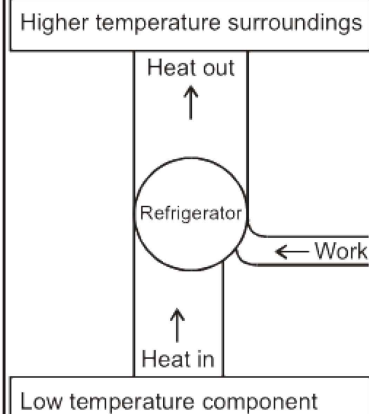
$$\text{i.e., } T_2 = \text{OK}$$

Interesting Information



A waterfall analogy for the heat engine.

Do You Know?



A refrigerator transfers heat from a low-temperature compartment to higher-temperature surroundings with the help of external work. It is a heat engine operating in reverse order.

Q.20 What is thermodynamic scale of temperature?

Ans. THERMODYNAMIC SCALE OF TEMPERATURE

The CARNOT cycle provides us the basis to define a temperature scale which is independent of material properties of the working substance.

The thermodynamic scale of temperature is defined by choosing 273.16 K as absolute temperature of the triple point of water as one fixed point and absolute zero as the other.

Unit

The unit of thermodynamic scale is Kelvin.

Kelvin

As, 273.16 K = Thermodynamic temperature of the triple point of water.

$$\therefore 1\text{K} = \frac{1}{273.16} \times \text{Thermodynamic temperature of the triple point of water.}$$

Triple Point of Water

“It is a state in which ice, water and vapour co-exists in equilibrium and it occurs uniquely, at one particular pressure (0.61 K pa) and temperature (273.16 K).”

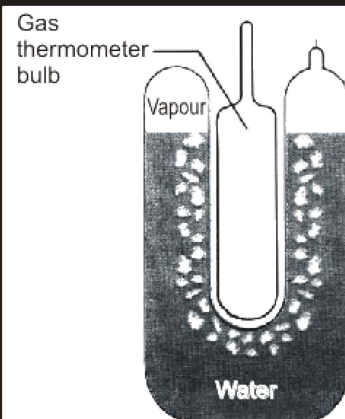
If heat Q is absorbed or rejected by system at T and Q_3 is heat absorbed or rejected by system when it is at temperature of triple point of water then unknown temperature T is given by

$$\frac{Q}{Q_3} = \frac{T}{273.16}$$

$$\therefore T = \frac{Q}{Q_3} (273.16)$$

Since this scale is independent of working substance hence can be applied at very low temperature.

For Your Information



A triple-point cell, in which solid ice, liquid water, and water vapour coexist in thermal equilibrium. By international agreement, the temperature of the mixture has been defined to be 273.16 K. The bulb of a constant-volume gas thermometer is shown inserted into the well of the cell.

Q.21 What is the principle, construction and working of a petrol engine?

Ans. PETROL ENGINE

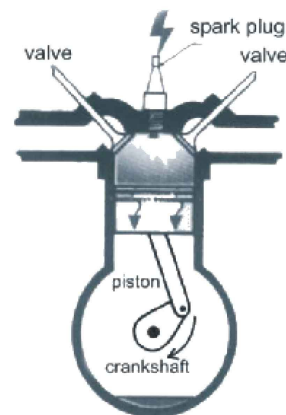
Although different engines may differ in their construction technology but they are based on principle of a Carnot cycle. A typical four stroke petrol engine also under goes four successive processes in each cycle.

Construction

It consists of pistons, crankshaft, sparking plug and valves, as shown in figure.

(1) Intake Stroke

The cycle starts on intake stroke in which piston moves outward and petrol air mixture is drawn through an inlet valve into the cylinder



On the compression stroke, the inlet valve is closed and the mixture is compressed adiabatically by inward movement of the piston.

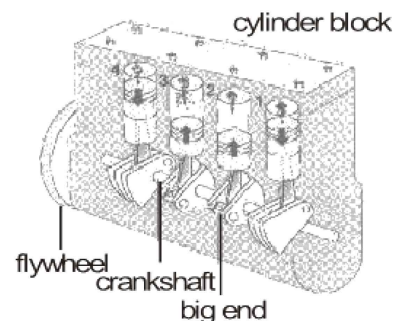
(3) Power Stroke

An electric spark is produced by the sparking plug. On the power stroke a spark fires the mixture causing a rapid increase in pressure and temperature. The burning mixture expands adiabatically and forces the piston to move outward. This is the only working stroke in the cycle which delivers power to crank shaft to derive the fly wheel.

(4) Exhaust Stroke

On the exhaust stroke, the outlet valve opens. The residual gases are expelled and piston moves inward.

The cycle then begins again. Most motor bikes have one cylinder engine but cars usually have four cylinders on the same crankshaft. The cylinders are timed to fire turn by turn in succession for smooth running of the car. The actual efficiency of properly tuned engine is not more than 25% to 30% due to friction and other heat losses.



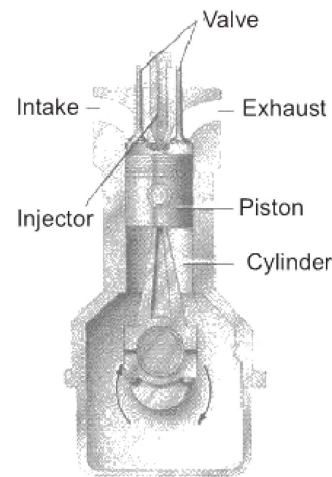
Q.22 What is diesel engine?

Ans. DIESEL ENGINE

No spark plug is needed in diesel engine. Diesel is sprayed into the cylinder but maximum compression by a strong compression pump.

Because air is at very high temperature immediately after compression, the fuel mixture ignites on contact with the air in the cylinder and pushed the piston upward.

The operation of diesel engine is very easy and its efficiency is greater than that of petrol engine which is about 35% to 40%.



Q.23 What is entropy? Explain it with examples.

Ans. ENTROPY

The concept of entropy was introduced into the study of thermodynamics by **Rudolph Clausius** in 1856 to give a quantitative basis for the second law. It provides another variable to describe the state of a system to go along with pressure, volume, temperature and internal energy. If a system undergoes a reversible process during which it absorbs a quantity of heat ΔQ at absolute temperature T , then the increase in the state variable called entropy ΔS of the system is given by

Like potential energy or internal energy, it is the change in entropy of the system which is important. Change in entropy is positive when heat is added and negative when heat is removed from the system. Suppose, an amount of heat Q flows from a reservoir at temperature T_1 through a conducting rod to a reservoir at temperature T_2 when $T_1 > T_2$. The change in entropy of the reservoir, at temperature T_1 , which loses heat, decreases by Q/T_1 and of the reservoir at temperature T_2 , which gains heat, increases by Q/T_2 . As $T_1 > T_2$ so Q/T_2 will be greater than Q/T_1 i.e., $Q/T_2 > Q/T_1$.

Hence, net change in entropy $= \frac{Q}{T_2} - \frac{Q}{T_1}$ is positive.

It follows that in all natural processes where heat flows from one system to another, there is always a net increase in entropy. This is another statement of 2nd law of thermodynamics. According to this law

If a system undergoes a natural process, it will go in the direction that causes the entropy of the system plus the environment to increase.

It is observed that a natural process tends to proceed towards a state of greater disorder. Thus, there is a relation between entropy and molecular disorder. For example an irreversible heat flow from a hot to a cold substance of a system increases disorder because the molecules are initially sorted out in hotter and cooler regions. This order is lost when the system comes to thermal equilibrium. Addition of heat to a system increases its disorder because of increase in average molecular speeds and therefore, the randomness of molecular motion. Similarly, free expansion of gas increases its disorder because the molecules have greater randomness of position after expansion than before. Thus in both examples, entropy is said to be increased.

We can conclude that only those processes are probable for which entropy of the system increases or remains constant. The process for which entropy remains constant is a reversible process; whereas for all irreversible processes, entropy of the system increases.

Every time entropy increases, the opportunity to convert some heat into work is lost. For example there is an increase in entropy when hot and cold waters are mixed. Then warm water which results cannot be separated into a hot layer and a cold layer. There has been no loss of energy but some of the energy is no longer available for conversion into work. Therefore, increase in entropy means degradation of energy from a higher level where more work can be extracted to a lower level at which less or no useful work can be done. The energy in a sense is degraded, going from more orderly form to less orderly form, eventually ending up as thermal energy.

In all real processes where heat transfer occurs, the energy available for doing useful work decreases. In other words the

Do You Know?	
Approximate efficiencies of various devices	
Device	Efficiency (%)
Electric generator	70-99
Electric motor	50-93
Dry cell battery	90
Domestic gas furnace	70-85
Storage battery	72
Hydrogen-oxygen fuel cell	60
Liquid fuel rocket	47
Steam turbine	35-46
Fossil-fuel power plant	30-40
Nuclear reactor	39
Aircraft gas turbine engine	36
Solid-state laser	30
Internal combustion gasoline engine	20-30
Gallium arsenide solar cells	>20
Fluorescent lamp	20
Silicon solar cell	12-15
Steam locomotive	8

ENVIRONMENTAL CRISIS AS ENTROPY CRISIS

The second law of thermodynamics provides us the key for both understanding our environmental crisis, and for understanding how we must deal with this crisis.

From a human standpoint the environmental crisis results from our attempts to order nature for our comforts and greed. From a physical standpoint, however, the environmental crisis is an entropy or disorder crisis resulting from our futile efforts to ignore the second law of thermodynamics. According to which, any increase in the order in a system will produce an even greater increase in entropy or disorder in the environment. An individual impact may not have a major consequence but an impact of large number of all individuals disorder producing activities can affect the overall life support system.

The energy processes we use are not very efficient. As a result most of the energy is lost as heat to the environment. Although we can improve the efficiency but 2nd law eventually imposes an upper limit on efficiency improvement. Thermal pollution is an inevitable consequence of 2nd law of thermodynamics and the heat is the ultimate death of any form of energy. The increase in thermal pollution of the environment means increase in the entropy and that causes great concern. Even small temperature changes in the environment can have significant effects on metabolic rates in plants and animals. This can cause serious disruption of the overall ecological balance.

In addition to thermal pollution, the most energy transformation processes such as heat engines used for transportation and for power generation cause air pollution. In effect, all forms of energy production have some undesirable effects and in some cases all problems can not be anticipated in advance.

The imperative from thermodynamics is that whenever you do anything, be sure to take into account its present and possible future impact on your environment. This is an ecological imperative that we must consider now if we are to prevent a drastic degradation of life on our beautiful but fragile Earth.

For Your Information



The jet engines on this aircraft convert thermal energy to work, but the visible exhaust clearly shows that a considerable amount of thermal energy is lost as waste heat.