Notes

11

# THERMODYNAMICS

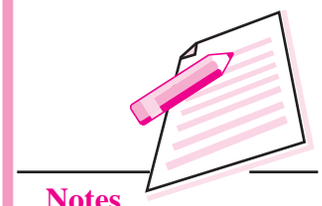
You are familiar with the sensation of hotness and coldness. When you rub your hands together, you get the feeling of warmth. You will agree that the cause of heating in this case is mechanical work.This suggests that there is a relationship between mechanical work and thermal effect. A study of phenomena involving thermal energy transfer between bodies at different temperatures forms the subject matter of thermodynamics, which is a phenomenological science based on experience. A quantitative description of thermal phenomena requires a definition of temperature, thermal energy and internal energy. And the laws of thermodynamics provide relationship between the direction of flow of heat, work done on/by a system and the internal energy of a system.

In this lesson you will learn three laws of thermodynamics : the zeroth law, the first law and the second law of thermodynamics. These laws are based on experience and need no proof. As such, the zeroth, first and second law introduce the concept of temperature, internal energy and entropy, respectively. While the first law is essentially the law of conservation of energy for a thermodynamic system, the second law deals with conversion of heat into work and vice versa.You will also learn that Carnot's engine has maximum efficiency for conversion of heat into work.

## OBJECTIVES

After studying this lesson, you should be able to :

- *draw indicator diagrams for different thermodynamic processes and show that the area under the indicator diagram represents the work done in the process;*
- *explain thermodynamic equilibrium and state the Zeroth law of thermodynamics;*





- *explain the concept of internal energy of a system and state first law of thermodynamics;*
- *apply first law of thermodynamics to simple systems and state its limitations;*
- *define triple point;*
- *state the second law of thermodynamics in different forms; and*
- *describe Carnot cycle and calculate its efficiency.*

## 11.1 CONCEPT OF HEAT AND TEMPERATURE

### 11.1.1 Heat

Energy has pervaded all facets of human activity ever since man lived in caves. In its manifestation as heat, energy is intimate to our existence. The energy that cooks our food, lights our houses, runs trains and aeroplanes originates in heat released in burning of wood, coal, gas or oil. You may like to ask : What is heat? To discover answer to this question, let us consider as to what happens when we inflate the tyre of a bicycle using a pump. If you touch the nozzle, you will observe that pump gets hot. Similarly, when you rub you hands together, you get the feeling of warmth. You will agree that in these processes heating is not caused by putting a flame or something hot underneath the pump or the hand. Instead, heat is arising as a result of mechanical work that is done in compressing the gas in the pump and forcing the hand to move against friction. These examples, in fact, indicate a relation between mechanical work and thermal effect.

We know from experience that a glass of ice cold water left to itself on a hot summer day eventually warms up. But a cup of hot coffee placed on the table cools down. It means that energy has been exchanged between the sysem – water or coffee – and its surrounding medium. This energy transfer continues till thermal equilibrium is reached. That is until both – the system and the suroundings – are as the same temperature. It also shows that the direction of energy transfer is always from the body at high temprature to a body at lower temperature. You may now ask : In what form is energy being transferred? In the above examples, energy is said to be transfered in the form of heat. So we can say that heat is the *form of energy transferred between two (or more) systems or a system and its surroundings because of temperature difference.*

You may now ask. What is the nature of this form of energy? The answer to this question was provided by Joule through his work on the equivalence of heat and mechanical work : Mechanical motion of molecules making up the system is associated with heat.

The unit of heat is calorie. One calorie is defined as the quantity of heat energy required to raise the temperature of 1 gram of water from 14.5°C to 15.5°C. It is denoted as cal.

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Kilocalorie (k cal) is the larger unit of heat energy :

$$1 \text{ kcal} = 10^3 \text{ cal.}$$

Also $$1 \text{ cal} = 4.18 \text{ J}$$

### 11.1.2 Concept of Temperature

While studying the nature of heat, you learnt that energy exchange between a glass of cold water and its surroundings continues until thermal equilibrium was reached. All bodies in thermal equilibrium have a common property, called temperature, whose value is same for all of them. Thus, we can say that temperature of a body is the property which determines whether or not it is in thermal equilibrium with other bodies.

### 11.1.3 Thermodynamic Terms

(i) **Thermodynamic system :** A thermodynamic system refers to a definite quantity of matter which is considered unique and separated from everything else, which can influence it. Every system is enclosed by an arbitrary surface, which is called its boundary. The boundary may enclose a solid, a liquid or a gas. It may be real or imaginary, either at rest or in motion and may change its size and shape. The region of space outside the boundary of a system constitutes its surroundings.

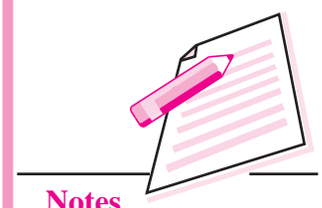
(a) **Open System :** It is a system which can exchange mass and energy with the surroundings. A water heater is an open system.

(b) **Closed system :** It is a system which can exchange energy but not mass with the surroundings. A gas enclosed in a cylinder fitted with a piston is a closed system.

(c) **Isolated system :** It is a system which can exchange neither mass nor energy with the surrounding. A filled thermos flank is an ideal example of an isolated system.

(ii) **Thermodynamic Variables or Coordinates :** In module–1, we have studied the motion of a body (or a system) in terms of its mass, position and velocity. To describe a thermodynamic system, we use its physical properties such on temperature (T), pressure (P), and volume (V). These are called thermodynamic variables.

(iii) **Indicator diagram :** You have learnt about displacement–time and velocity–time graphs in lesson 2. To study a thermodynamic system, we use a pressure-volume graph. This graph indicates how pressure (P) of a system varies with its volume (V) during a thermodynamic process and is known as an indicator diagram.





The indicator diagram can be used to obtain an expression for the work done. It is equal to the area under the P-V diagram (Fig. 11.1). Suppose that pressure is P at the start of a very small expansion $\Delta V$. Then, work done by the system.

$$\Delta W = P \Delta V \qquad (11.1)$$

= Area of a shaded strip ABCD

Now total work done by the system when it expands from $V_1$ to $V_2$ = Area of $P_1P_2V_2V_1P_1$ Note that the area depends upon the shape of the indicator diagram.

The indicator diagram is widely used in calculating the work done in the process of expansion or compression. It is found more useful in processes where relationship between P and V is not known. The work done on the system increases its energy and work done by the system reduces it. For this reason, work done on the system is taken as negative. You must note that the area enclosed by an isotherm (plot of p versus V at constant temperature) depends on its shape. We may conclude that work done by or on a system depends on the path. That is, work does not depend on the initial and final states.

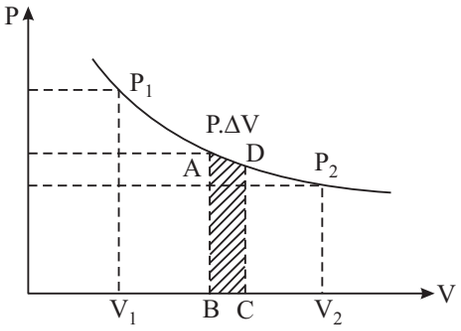



**Fig. 11.1 :** Indicater Diagram

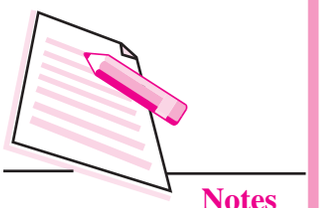
## 11.2 THERMODYNAMIC EQUILIBRIUM

Imagine that a container is filled with a liquid (water, tea, milk, coffee) at 60° C. If it is left to itself, it is common experience that after some time, the liquid attains the room temperature. We then say that water in the container has attained thermal equilibrium with the surroundings.

If within the system, there are variations in pressure or elastic stress, then parts of the system may undergo some changes. However, these changes cease ultimately, and no unbalanced force will act on the system. Then we say that it is in mechanical equilibrium. Do you know that our earth bulged out at the equator in the process of attaining mechanical equilibrium in its formation from a molten state?

If a system has components which react chemically, after some time, all possible chemical reactions will cease to occur. Then the system is said to be in chemical equilibrium.

A system which exhibits thermal, mechanical and chemical equilibria is said to be in thermodynamic equilibrium. The macroscopic properties of a system in this state do not change with time.



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### 11.2.1 Thermodynamic Process

If any of the thermodynamic variables of a system change while going from one equilibrium state to another, the system is said to execute a thermodynamic process. For example, the expansion of a gas in a cylinder at constant pressure due to heating is a thermodynamic process. A graphical representation of a thermodynamic process is called a path.

Now we will consider different types of thermodynamic processes.

**(i) Reversible process :** If a process is executed so that all intermediate stages between the inital and final states are equilibrium states and the process can be executed back along the same equilibrium states from its final state to its initial state, it is called reversible process. A reversible process is executed very slowly and in a controlled manner. Consider the following examples :

- Take a piece of ice in a beaker and heat it. You will see that it changes to water. If you remove the same quantity of heat of water by keeping it inside a refrigerator, it again changes to ice (initial state).
- Consider a spring supported at one end. Put some masses at its free end one by one. You will note that the spring elongates (increases in length). Now remove the masses one by one. You will see that spring retraces its initial positions. Hence it is a reversible process.

  As such, a reversible process can only be idealised and never achieved in practice.

**(ii) Irreversible process :** A process which cannot be retraced along the same equilibrium state from final to the initial state is called irreversible process.

All natural process are irrerersible. For example, heat poduced during friction, sugar dissolved in water, or rusting of iron in the air. It means that for irrerersible process, the intermediate states are not equilibrium states and hence such process can not be represented by a path. Does this mean that we can not analyse an irrerersible process? To do so, we use quasi-static process, which is infinitesimally close to the equilibrium state.

**(iii) Isothermal process :** A thermodynamic process that occurs at constant temperature is an isothermal process. The expansion and compression of a perfect gas in a cylinder made of perfectly conducting walls are isothermal processes. The change in pressure or volume is carried out very slowly so that any heat developed is transferred into the surroundings and the temperature of the system remains constant. The thermal equilibrium is always maintained. In such a process, $\Delta Q$, $\Delta U$ and $\Delta W$ are finite.

**(iv) Adiabatic process :** A thermodynamic process in which no exchange of thermal energy occurs is an adiabatic process. For example, the expansion

and compression of a perfect gas in a cylinder made of perfect insulating walls. The system is isolated from the surroundings. Neither any amount of heat leaves the system nor enters it from the surroundings. In this process, therefore $\Delta Q = 0$ and $\Delta U = -\Delta W$.

The change in the internal energy of the system is equal to the work done on the system. When the gas is compressed, work is done on the system. So, $\Delta U$ becomes positive and the internal energy of the system increases. When the gas expands, work is done by the system. It is taken as positive and $\Delta U$ becomes negative. The internal energy of the system decreases.

(v) **Isobaric process :** A thermodynamic process that occurs at constant pressure is an isobaric process. Heating of water under atmospheric pressure is an isobaric process.

(vi) **Isochoric process :** A thermodynamic process that occurs at constant volume is an isochoric process. For example, heating of a gas in a vessel of constant volume is an isochoric process. In this process, volume of the gas remains constant so that no work is done, i.e. $\Delta W = 0$. We therefore get $\Delta Q = \Delta U$.

In a **Cyclic Process** the system returns back to its initial state. It means that there is no change in the internal energy of the system. $\Delta U = 0$.

$$\therefore \Delta Q = \Delta W.$$

### 11.2.2 Zeroth Law of Thermodynamics

Let us consider three metal blocks A, B and C. Suppose block A is in thermal equilibrium with block B. Further suppose that block A is also in thermal equilibrium with block C. It means the temperature of the block A is equal to the temperature of block B as well as of block C. It follows that the temperatures of blocks B and C are equal. We summarize this result in the statement known as Zeroth Law of Thermodynamics :

***If two bodies or systems A and B are separately in thermal equilibrium with a third body C, then A and B are in thermal equilibrium with each other.***

**Phase Change and Phase Diagram**

You have learnt that at STP, matter exists in three states : solid, liquid and gas. ***The different states of matter are called its phases.*** For example, ice (solid), water (liquid) and steam (gas) are three phases of water. We can discuss these three phases using a three dimensional diagram drawn in pressure (P), temperature (T) and volume (V). It is difficult to draw three dimensional diagram. Thus, we discuss the three phases of matter by drawing a pressure-temperature diagram. This is called ***phase diagram.***

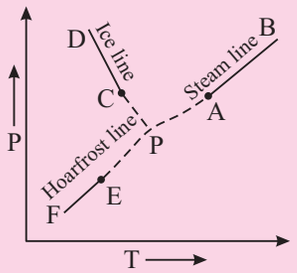


**Fig. 11.2:** Phase diagram of water

Refer to Fig. 11.2, which shows phase diagram of water. You can see three curves CD; AB and EF. Curve CD shows the variation of melting point of ice with pressure. It is known as a ***fusion curve***. Curve AB shows variation of boiling point of water with pressure. It is known as ***vaporization curve***. Curve EF shows change of ice directly to steam. It is known as a ***sublimation curve.*** This curve is also known as ***Hoarfrost Line.***

If you extend the curve AB, CD and EF (as shown in the figure with dotted lines), they meet at point P. This point is called ***triple point.*** At triple point, all three phases co-exist.

When we heat a solid, its temperature increases till it reaches a temperature at which it starts melting. This temperature is called **melting point** of the solid. During this change of state, we supply heat continuously but the temperature does not rise. The heat required to completely change unit mass of a solid into its corresponding liquid state at its melting point is called **latent heat of fusion of the solid.**

On heating a liquid, its temperature also rises till its **boiling point** is reached. At the boiling point, the heat we supply is used up in converting the liquid into its gaseous state. The amount of heat required to convert unit mass of liquid in its gaseous state at constant temperature is called **latent heat** of vaporization of the liquid.

### 11.2.3 Triple Point of Water

Triple point of a pure substance is a very stable state signified by precisely constant temperature and pressure values. For this reason, in kelvin's scale of thermometry, triple point of water is taken as the upper fixed point.

On increasing pressure, the melting point of a solid decreases and boiling point of the liquid increases. It is possible that by adjusting temperature and pressure, we can obtain all the three states of matter to co-exist simultaneously. These values of temperature and pressure signify the **triple point.**

## INTEXT QUESTIONS 11.1

1. Fill in the blanks

   (i) Zeroth law of thermodynamics provides the basis for the concept of .....

   (ii) If a system A is in thermal equilibrium with a system B and B is in thermal equilibrium with another system C, then system A will also be in thermal equilibrium with system.....

   (iii) The unit of heat is

2. Fig. 11.3 is an indicator diagram of a thermodynamic process. Calculate the work done by the system in the process :

   (a) along the path ABC from A to C

   (b) If the system is returned from C to A along the same path, how much work is done by the system.

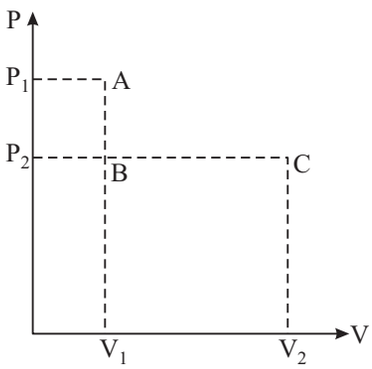


Fig. 11.3

3. Fill in the blanks.

   (i) A reversible process is that which can be ..... in the opposite direction from its final state to its initial state.

   (ii) An ..... process is that which cannot be retraced along the same equilibrium states from final state to the initial state.

4. State the basic difference between isothermal and adiabatic processes.

5. State one characteristic of the triple point.

## 11.3 INTERNAL ENERGY OF A SYSTEM

Have you ever thought about the energy which is released when water freezes into ice ? Don't you think that there is some kind of energy stored in water. This energy is released when water changes into ice. This stored energy is called the **internal energy**. On the basis of kinetic theory of matter, we can discuss the concept of internal energy as sum of the energies of individual components/ constituents. This includes kinetic energy due to their random motion and their potential energy due to interactions amongst them. Let us now discuss these.

**(a) Internal kinetic energy :** As you now know, according to kinetic theory, matter is made up of a large number of molecules. These molecules are in a state of constant rapid motion and hence possess kinetic energy. The **total**

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**kinetic energy of the molecules constitutes the internal kinetic energy of the body.**

**(b) Internal potential energy :** The energy arising due to the inter-molecular forces is called the internal potential energy.

The internal energy of a metallic rod is made up of the kinetic energies of conduction electrons, potential energies of atoms of the metal and the vibrational energies about their equilibrium positions. The energy of the system may be increased by causing its molecules to move faster (gain in kinetic energy by adding thermal energy). It can also be increased by causing the molecules to move against inter-molecular forces, i.e., by doing work on it. **Internal energy** is denoted by the letter U.

*Internal energy of a system = Kinetic energy of molecules + Potential energy of molecules*

Let us consider an isolated thermodynamic system subjected to an external force. Suppose W amount of work is done on the system in going from initial state *i* to final state *f* adiabatically. Let $U_i$ and $U_f$ be internal energies of the system in its initial and final states respectively. Since work is done on the system, internal energy of final state will be higher than that of the initial state.

According to the law of conservation of energy, we can write

$$U_i - U_f = -W$$

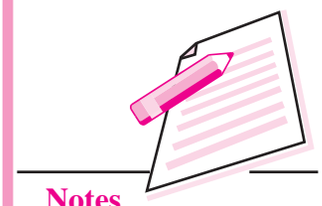
Negative sign signifies that work is done on the system.

We may point out here that unlike work, internal energy depends on the initial and final states, irrespective of the path followed. We express this fact by saying that U is a function of state and depends only on state variables P, V, and T. Note that if some work is done by the system, its internal energy will decrease.

## 11.4 FIRST LAW OF THERMODYNAMICS

You now know that the zeroth law of thermodynamics tells us about thermal equilibrium among different systems characterised by same temperature. However, this law does not tell us anything about the non-equilibrium state. Let us consider two examples : (i) Two systems at different temperatures are put in thermal contact and (ii) Mechanical rubbing between two systems. In both cases, change in their temperatures occurs but it cannot be explained by the Zeroth law. To explain such processes, the first law of thermodynamics was postulated.

*The first law of thermodynamics is, in fact, the law of conservation of energy for a thermodynamic system. It states that change in internal energy of a system during a thermodynamic process is equal to the sum of the heat given to it and the work done on it.*





Suppose that $\Delta Q$ amount of heat is given to the system and $-\Delta W$ work is done on the system. Then increase in internal energy of the system, $\Delta U$, according to the first law of thermodynamics is given by

$$\Delta U = \Delta Q - \Delta W \qquad (11.3\ a)$$

This is the mathematical form of the first law of thermodynamics. Here $\Delta Q$, $\Delta U$ and $\Delta W$ all are in SI units.

The first law of thermodynamics can also be written as

$$\Delta Q = \Delta U + \Delta W \qquad (11.3\ b)$$

The signs of $\Delta Q$, $\Delta U$ and $\Delta W$ are known from the following sign conventions :

1. Work done ($\Delta W$) by a system is taken as positive whereas the work done on a system is taken as negative. The work is positive when a system expands. When a system is compressed, the volume decreases, the work done is negative. The work done does not depend on the initial and final thermodynamic states; it depends on the path followed to bring a change.
2. Heat gained by (added to) a system is taken as positive, whereas heat lost by a system is taken as negative.
3. The increase in internal energy is taken as positive and a decrease in internal energy is taken as negative.

If a system is taken from state 1 to state 2, it is found that both $\Delta Q$ and $\Delta W$ depend on the path of transformation. However, the difference ($\Delta Q - \Delta W$) which represents $\Delta U$, remains the same for all paths of transformations.

We therefore say that the change in internal energy $\Delta U$ of a system does not depend on the path of the thermodynamic transformations.

### 11.4.1 Limitations of the First Law of Thermodynamics

The first law of thermodynamics asserts the equivalence of heat and other forms of energy. This equivalence makes the world around us work. The electrical energy that lights our houses, operates machines and runs trains originates in heat released in burning of fossil or nuclear fuel. In a sense, it is universal. It explains the fall in temperature with height; the adiabatic lapse rate in upper atmosphere. Its applications to flow process and chemical reations are also very interesting. However, consider the following processes :

- You know that heat always flows from a hot body to a cold body. But first law of thermodynamics does not prohibit flow of heat from a cold body to a hot body. It means that this law fails to indicate the direction of heat flow.
- You know that when a bullet strikes a target, the kinetic energy of the bullet is converted into heat. This law does not indicate as to why heat developed

in the target cannot be changed into the kinetic energy of bullet to make it fly. It means that this law fails to provide the conditions under which heat can be changed into work. Moreover, it has obvious limitations in indicating the extent to which heat can be converted into work.

Now take a pause and answer the following questions :

## INTEXT QUESTIONS 11.2

1. Fill in the blanks
   (i) The total of kinetic energy and potential energy of molecules of a system is called its .....
   (ii) Work done = – W indicates that work is done ..... the system.
2. The first law of thermodynamics states that .....

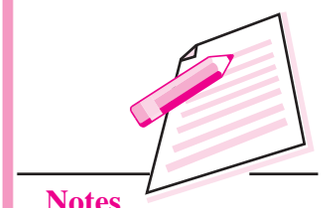
## 11.5 SECOND LAW OF THERMODYNAMICS

You now know that the first law of thermodynamics has inherent limitations in respect of the direction of flow of heat and the extent of convertibility of heat into work. So a question may arise in your mind : Can heat be wholly converted into work? Under what conditions this conversion occurs? The answers of such questions are contained in the postulate of *Second law of thermodynamics.* The second law of thermodynamics is stated in several ways. However, here you will study Kelvin-Planck and Clausius statements of second law of thermodynamics.

***The Kelvin-Planck's statement*** is based on the experience about the performance of heat engines. (Heat engine is discussed in next section.) In a heat engine, the working substance extracts heat from the source (hot body), converts a part of it into work and rejects the rest of heat to the sink (environment). There is no engine which converts the whole heat into work, without rejecting some heat to the sink. These observations led Kelvin and Planck to state the second law of thermodynamics as

**It is impossible for any system to absorb heat from a reservoir at a fixed temperature and convert whole of it into work.**

***Clausius statement of second law of thermodynamics*** is based on the performance of a refrigerator. A refrigerator is a heat engine working in the opposite direction. It transfers heat from a colder body to a hotter body when external work is done on it. Here concept of external work done on the system is important. To do this external work, supply of energy from some external source is a must. These observations led Clausius to state the second law of thermodynamics in the following form.





**It is impossible for any process to have as its sole result to transfer heat from a colder body to a hotter body without any external work.**

Thus, the second law of thermodynamics plays a unique role for practical devices like heat engine and refrigerator.

### 11.5.1 Carnot Cycle

You must have noticed that when water is boiled in a vessel having a lid, the steam generated inside throws off the lid. This shows that high pressure steam can be made to do useful work. ***A device which can convert heat into work is called a heat engine.*** Modern engines which we use in our daily life are based on the principle of heat engine. These may be categorised in three types : steam engine, internal combustion engine and gas turbine. However, their working can be understood in terms of Carnot's reversible engine. Let us learn about it now.

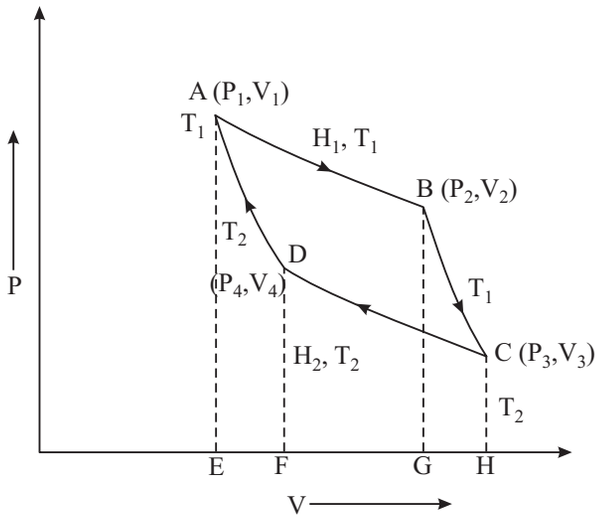



**Fig. 11.4 :** Indicator diagram of Carnot cycle

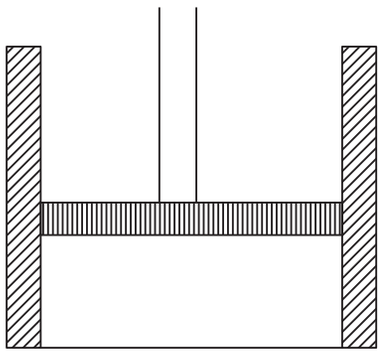
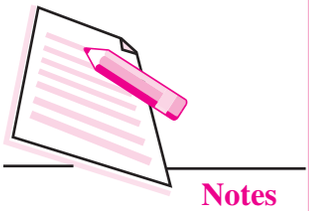


**Fig. 11.5 :** The cylinder with working substance



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In Carnot cycle, the working substance is subjected to four operations : (a) isothermal expansion, (b) adiabatic expansion, (c) isothermal compression and (d) adiabatic compression. Such a cycle is represented on the P-V diagram in Fig. 11.4. To describe four operations of Carnot's cycle, let us fill one gram. mol. of the working substance in the cylinder (Fig. 11.5). Original condition of the substance is represented by point A on the indicator diagram. At this point, the substance is at temperature $T_1$, pressure $P_1$ and volume $V_1$.

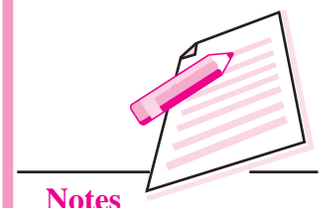
(a) **Isothermal expansion :** The cylinder is put in thermal contact with the source and allowed to expand. The volume of the working substance increases to $V_2$. Thus working substance does work in raising the piston. In this way, the temperature of the working substance would tend to fall. But it is in thermal contact with the source. So it will absorb a quantity of heat $H_1$ from the source at temperature $T_1$. This is represented by the point B. At B, the values of pressure and volume are $P_2$ and $V_2$ respectively. On the indicator diagram (Fig. 11.4), you see that in going from A to B, temperature of the system remains constant and working substance expands. We call it ***isothermal expansion process.*** $H_1$ is the amount of heat absorbed in the isothermal expansion process. Then, in accordance with the first law of thermodynamics, $H_1$ will be equal to the external work done by the gas during isothermal expansion from A to B at temperature $T_1$. Suppose $W_1$ is the external work done by the gas during isothermal expansion AB. Then it will be equal to the area ABGEA. Hence

$$W_1 = \text{Area ABGEA}$$

(b) **Adiabatic expansion :** Next the cylinder is removed from the source and placed on a perfectly non-conducting stand. It further decreases the load on the piston to $P_3$. The expansion is completely adiabatic because no heat can enter or leave the working substance. Therefore, the working substance performs external work in raising the piston at the expense of its internal energy. Hence its temperature falls. The gas is thus allowed to expand adiabatically until its temperature falls to $T_2$, the temperature of the sink. It has been represented by the adiabatic curve BC on the indicator diagram. We call it ***adiabatic expansion.*** If the pressure and volume of the substance are $P_3$ and $V_3$, respectively at C, and $W_2$ is the work done by the substance from B to C, then

$$W_2 = \text{Area BCHGB.}$$

(c) **Isothermal compression :** Remove the cylinder from the non-conducting stand and place it on the sink at temperature $T_2$. In order to compress the gas slowly, increase the load (pressure) on the piston until its pressure and volume become $P_4$ and $V_4$, respectively. It is represented by the point D on the indicator diagram (Fig. 11.4). The heat developed ($H_2$) due to compression will pass to the sink. Thus, there is no change in the temperature of the system. Therefore, it is called an isothermal compression process. It is shown





by the curve CD (Fig. 11.4). The quantity of heat rejected ($H_2$) to the sink during this process is equal to the work done (say $W_3$) on the working substance. Hence

$$W_3 = \text{Area CHFDC}$$

(d) **Adiabatic compression :** Once again place the system on the non-conducting stand. Increase the load on the piston slowly. The substance will under go an adiabatic compression. This compression continues until the temperature rises to $T_1$ and the substance comes back to its original pressure $P_1$ and volume $V_1$. This is an adiabatic compression process and represented by the curve DA on the indicator diagram (Fig. 11.4). Suppose $W_4$ is the work done during this adiabatic compression from D to A. Then

$$W_4 = \text{Area DFEAD}$$

During the above cycle of operations, the working substance takes $H_1$ amount of heat from the source and rejects $H_2$ amount of heat to the sink. Hence the net amount of heat absorbed by the working substance is

$$\Delta H = H_1 - H_2$$

Also the net work done (say W) by the engine in one complete cycle

$$W = \text{Area ABCHEA} - \text{Area CHEADC}$$

$$= \text{Area ABCD}$$

Thus, the work done in one cycle is represented on a P-V diagram by the area of the cycle.

You have studied that the initial and final states of the substance are the same. It means that its internal energy remains unchanged. Hence according to the first law of thermodynamics

$$W = H_1 - H_2$$

Therefore, heat has been converted into work by the system, and any amount of work can be obtained by merely repeating the cycle.

### 11.5.2 Efficiency of Carnot Engine

Efficiency is defined as the ratio of heat converted into work in a cycle to heat taken from the source by the working substance. It is denoted as $\eta$:

$$\eta = \frac{\text{Heat converted into work}}{\text{Heat taken from source}}$$

or

$$\eta = \frac{H_1 - H_2}{H_1} = 1 - \frac{H_2}{H_1}$$

It can be shown that for Carnot's engine,

$$\frac{H_2}{H_1} = \frac{T_2}{T_1}$$

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

Note that efficiency of carnot engine does not depend on the nature of the working substance. Further, if no heat is rejected to the sink, $\eta$ will be equal to one. But for $H_2$ to be zero, $T_2$ must be zero. It means that efficiency $\eta$ can be100% only when $T_2 = 0$. The entire heat taken from the hot source is converted into work. This violates the second law of thermodynamics. Therefore, a steam engine can operate only between finite temperature limits and its efficiency will be less than one.

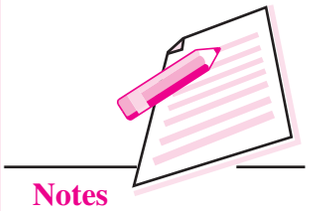
It can also be argued that the Carnot cycle, being a reversible cycle, is most efficient; no engine can be more efficient than a Carnot engine operating between the same two temperatures.

### 11.5.3 Limitation of Carnot's Engine

You have studied about Carnot's cycle in terms of isothermal and adiabatic processes. Here it is important to note that the isothermal process will take place only when piston moves very slowly. It means that there should be sufficient time for the heat to transfer from the working substance to the source. On the other hand, during the adiabatic process, the piston moves extremely fast to avoid heat transfer. In practice, it is not possible to fulfill these vital conditions. Due to these very reasons, all practical engines have an efficiency less than that of Carnot's engine.

## INTEXT QUESTIONS 11.3

1. State whether the following statements are true or false.
   (i) In a Carnot engine, when heat is taken by a perfect gas from a hot source, the temperature of the source decreases.
   (ii) In Carnot engine, if temperature of the sink is decreased the efficiency of engine also decreases.
2. (i) A Carnot engine has the same efficiency between 1000K and 500K and between TK and 1000K. Calculate T.
   (ii) A Carnot engine working between an unknown temperature T and ice point gives an efficiency of 0.68. Deduce the value of T.



Notes

## WHAT YOU HAVE LEARNT

- Heat is a form of energy which produces in us the sensation of warmth.
- The energy which flows from a body at higher temperature to a body at lower temperature because of temperature difference is called heat energy.
- The most commonly known unit of heat energy is calorie. 1 cal = 4.18 J and 1k cal = $10^3$ cal.
- A graph which indicates how the pressure (P) of a system varies with its volume during a thermodynamic process is known as indicator diagram.
- Work done during expansion or compression of a gas is $P\Delta V = P(V_f - V_i)$.
- Zeroth law of thermodynamics states that if two systems are separately in thermal equilibrium with a third system, then they must also be in thermal equilibrium with each other.
- The sum of kinetic energy and potential energy of the molecules of a body gives the internal energy. The relation between internal energy and work is $U_i - U_f = -W$.
- The first law of thermodynamics states that the amount of heat given to a system is equal to the sum of change in internal energy of the system and the external work done.
- First law of thermodynamics tells nothing about the direction of the process.
- The process which can be retraced in the opposite direction from its final state to initial state is called a reversible process.
- The process which can not be retraced along the same equilibrium state from final to the initial state is called an irreversible process. A process that occurs at constant temperature is an isothermal process.
- Any thermodynamic process that occurs at constant heat is an adiabatic process.
- The different states of matter are called its phase and the pressure and temperature diagram showing three phases of matter is called a phase diagram.
- Triple point is a point (on the phase diagram) at which solid, liquid and vapour states of matter can co-exist. It is characterised by a particular temperature and pressure.
- According to Kelvin-Planck's statement of second law, it is not possible to obtain a continuous supply of work from a single source of heat.

Notes



- According to Clausius statement of second law, heat can not flow from a colder body to a hotter body without doing external work on the working substance.
- The three essential requirements of any heat engine are :
  (i) source from which heat can be drawn
  (ii) a sink into which heat can be rejected.
  (iii) working substance which performs mechanical work after being supplied with heat.
- Carnot's engine is an ideal engine in which the working substance is subjected to four operations (i) Isothermal expansion (ii) adiabatic expansion (iii) isothermal compression and (iv) adiabatic compression. Such a cycle is called a Carnot cycle.
- Efficiency of a Carnot engine is given only

  $\eta = 1 - \frac{H_2}{H_1}$, $H_1$ = Amount of heat absorbed and $H_2$ = Amount of heat rejected.

  $= 1 - \frac{T_2}{T_1}$, $T_1$ = Temperature of the source, and $T_2$ = Temperature of the sink.
- Efficiency does not depend upon the nature of the working substance.

## TERMINAL EXERCISE

1. Distinguish between the terms internal energy and heat energy.
2. What do you mean by an indicator diagram. Derive an expression for the work done during expansion of an ideal gas.
3. Define temperature using the Zeroth law of thermodynamics.
4. State the first law of thermodynamics and its limitations.
5. What is the difference between isothermal, adiabetic, isobaric and isochoric processes?
6. State the Second law of thermodynamics.
7. Discuss reversible and irreversible processes with examples.
8. Explain Carnot's cycle. Use the indicator diagram to calculate its efficiency.
9. Calculate the change in the internal energy of a system when (a) the system absorbs 2000J of heat and produces 500 J of work (b) the system absorbs 1100J of heat and 400J of work is done on it.

10. A Carnot's engine whose temperature of the source is 400K takes 200 calories of heat at this temperature and rejects 150 calories of heat to the sink. (i) What is the temperature of the sink. (ii) Calculate the efficiency of the engine.

## ANSWERS TO INTEXT QUESTIONS

### 11.1

1. (i) Temperature (ii) C (iii) Joule or Calorie
2. (a) $P_2 (V_2 - V_1)$ (b) $-P_2 (V_2 - V_1)$
3. (i) retrace (ii) irreversible
4. An isothermal process occurs at a constant temperature whereas an adiabatic process occurs at constant heat.
5. At triple point all three states of matter i.e. solid, liquid and vapour can co-exist.

### 11.2

1. (i) Internal energy (ii) on
2. It states that the amount of heat given to a system is equal to the sum of the change in internal energy of the system and the external energy.

### 11.3

1. (i) False (ii) True
2. (i) 2000 K (ii) 8583.1K

### Answers to Terminal Problems

9. (a) 1500 J (b) 1500 J.
10. 300K, 25%