Unit 10

THERMODYNAMICS

Major Concepts (22 PERIODS)

- Thermal equilibrium
- Heat and work
- Internal energy
- First law of thermodynamics
- Molar specific heats of a gas
- Heat engine
- Second law of thermodynamics
- Carnot's cycle
- Refrigerator
- Entropy

Conceptual Linkage

This chapter is built on
Heat Physics IX
Thermo Chemistry XI

Students Learning Outcomes

After studying this unit, the students will be able to:

- Describe that thermal energy is transferred from a region of higher temperature to region of lower temperature.
- Describe that regions of equal temperatures are in thermal equilibrium.
- Describe that heat flow and work are two forms of energy transfer between systems and calculate heat being transferred.
- Define thermodynamics and various terms associated with it.
- Relate a rise in temperature of a body to an increase in its internal energy.
- Describe the mechanical equivalent of heat concept, as it was historically developed, and solve problems involving work being done and temperature change.
- Explain that internal energy is determined by the state of the system and that it can be expressed as the sum of the random distribution of kinetic and potential energies associated with the molecules of the system.
- Calculate work done by a thermodynamic system during a volume change.
- Describe the first law of thermodynamics expressed in terms of the change in internal energy, the heating of the system and work done on the system.
- Explain that first law of thermodynamics expresses the conservation of energy.
- Define the terms, specific heat and molar specific heats of a gas.
- Apply first law of thermodynamics to derive $C_p - C_v = R$.
- State the working principle of heat engine.
- Describe the concept of reversible and irreversible processes.
- State and explain second law of thermodynamics.

- Explain the working principle of Carnot's engine
- Explain that the efficiency of a Carnot engine is independent of the nature of the working substance and depends on the temperatures of hot and cold reservoirs.
- Describe that refrigerator is a heat engine operating in reverse as that of an ideal heat engine.
- Derive an expression for the coefficient of performance of a refrigerator.
- Describe that change in entropy is positive when heat is added and negative when heat is removed from the system.
- Explain that increase in temperature increases the disorder of the system.
- Explain that increase in entropy means degradation of energy.
- Explain that energy is degraded during all natural processes.
- Identify that system tend to become less orderly over time.

INTRODUCTION

In the past, the scientists believed in the caloric theory of heat. According to this theory, heat is a fluid called caloric which flows from the hot body to the cold body. After the development of kinetic theory, it has become a well known fact that heat is a form of energy called thermal energy and it flows from the hot body to the cold body till the two bodies attain the same temperature. This state of the same temperature of the bodies is called thermal equilibrium.

The kinetic theory also explains the random motion of atoms and molecules of matter. Such motion of atoms and molecules depends upon the temperature. The sum of kinetic energies and potential energies of the moving atoms and molecules of a substance is called its internal energy.

Thermodynamics is the study of heat energy and its transformation into other forms of energy and vice versa. It is an experimental science based on the study of the behaviour of solids, liquids and gases using the concepts of heat and temperature. In this chapter, thermodynamics can be explained under the following two laws. The first law of thermodynamics is based upon law of conservation of energy and it deals with the relationship between work and heat energy, that is, how the heat energy is converted into the other forms of energy and vice versa. The second law of thermodynamics explains not only the proper method of conversion of heat energy into mechanical work but also a specific direction of flow of heat.

We will study the efficiency of a heat engine, theory of Carnot engine, Carnot theorem, working of a refrigerator and the concept of entropy in this chapter.

10.1 THERMAL EQUILIBRIUM

We have studied mechanical equilibrium in unit 2 titled as 'Vectors and Equilibrium'. But in this chapter we deal with thermal equilibrium. The thermal equilibrium can be explained by an example of two bodies at different temperatures which are made in thermal contact. If both the bodies are good conductor of heat, then there is a transfer of heat energy from the hotter body to the cooler body as shown in Fig. 10.1.

In other words, the hotter body loses thermal energy whereas cooler body gains thermal energy. This process of transfer of heat energy continues till both the bodies attain the same temperature. This state of the same temperature of the bodies is termed as thermal equilibrium which is stated as,

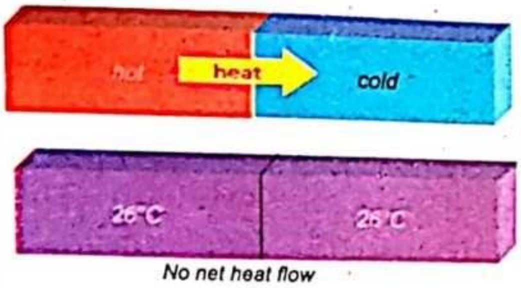


Fig.10.1: A state of Thermal Equilibrium of the two bodies having same temperature and there is no transfer of heat between them.

The bodies are said to be in thermal equilibrium when they have same temperature and there is no transfer of heat energy between them

For example, if we feel that we have fever, we might place a thermometer in our mouth and wait for a few minutes. There is transfer of heat energy between the thermometer and our body. Because our body is hot as compared to the thermometer, therefore, the reading of the thermometer increases. After some time, the rate of transfer of energy between the thermometer and our body becomes equal and our body and the thermometer are then at the same temperature. At this point our body and the thermometer are said to be in the thermal equilibrium.

10.2 INTERNAL ENERGY

All matter is made up of atoms and molecules. According to the kinetic theory, these atoms and molecules are always in motion. For example, atoms in solids vibrate back and forth about their equilibrium positions. In liquids, the molecules wander around the other molecules. In gases, the molecules are in random motion with high speeds and have frequent elastic collisions with one another. The motion may be translational, vibrational and rotational.

> **POINT TO PONDER**
> Normal temperature of a man is 37°C. What will be the temperature of a dead body?

The atoms and molecules of a gas possess both kinetic energy due to their translational, rotational and vibrational motion and potential energy associated with the forces between molecules.

Thus, the internal energy of the gas is defined in terms of the sum of the random distribution of kinetic and potential energies of its atoms or molecules.

It is stated as the sum of all kinds of kinetic and potential energies of the system, comprising of gas molecules, is called its internal energy

In the study of thermodynamics, usually ideal gas (mono-atomic gas) is considered as a working substance. The molecules of an ideal gas do not exert inter molecular forces, therefore, its molecules do not possess potential energy. So, the internal energy of an ideal gas is only due to the translational kinetic energy of the molecules. In case of diatomic gas, the molecules possess transitional, vibrational and rotational kinetic energy as well as potential energy. Therefore, the internal energy of dia-atomic gas is a sum of all kinds of kinetic and potential energies of their molecules.

10.2.1 Thermodynamics Systems

Thermodynamics is a branch of physics in which we study about the heat energy and its conversion into other forms of energy and vice versa. For example, the conversion of heat energy into mechanical. This conversion of energy from one form to another can be studied by making a separate environment within a boundary has its own specific values, as shown in Fig.10.2. The boundary may enclose a solid, liquid or gas. This is called system and defined as; **The collection of matter within a distinct boundary is called system.**

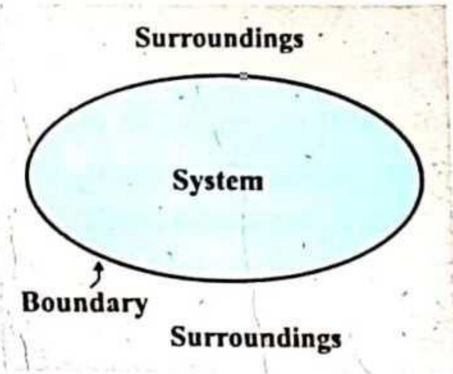


Fig.10.2: A thermodynamics system which is surrounded by a distinct boundary.

Everything outside the boundaries of the system which has a direct bearing on its behaviour is known as surrounding. A system may have the potential to exchange energy with its surrounding. Because the values of thermodynamics variables pressure, volume and temperature of a system are different from the values of the surrounding.

There are three types of systems as shown in Fig.10.3. These are explained as;

(i) Open System

A system which can interact with its surroundings both in terms of heat energy and matter is called open system e.g. plants and animals.

(ii) Closed System

A system which can interact with its surroundings only in terms of heat energy is called closed system e.g. balloon and cylinder.

(iii) Isolated System

A system which has no interaction with its surroundings in terms of heat energy and matter is called isolated system e.g. thermos flask.

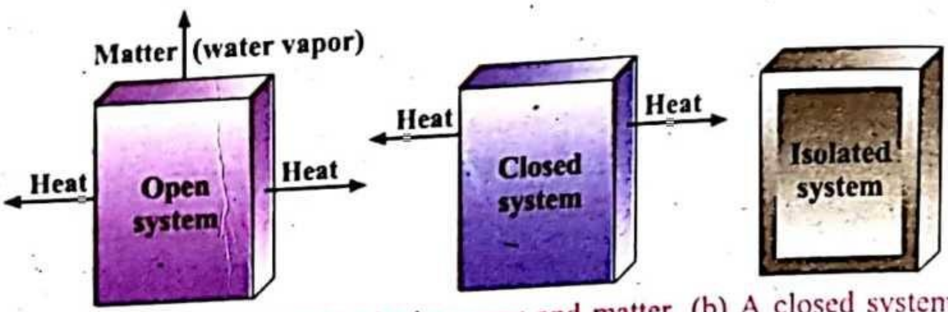


Fig.10.3: (a) An open system which transfer both energy and matter, (b) A closed system which transfers only energy, (c) An isolated system which transfers neither energy nor matter.

10.3 WORK AND HEAT

Work and heat are two different quantities but they are related to each other. A heat engine is a good example to explain such relationship between work and heat. For example, in heat engine, heat energy serves as input and its output is work done. Similarly, when an amount of heat energy in a heat engine enters into a thermodynamics system, it increases the internal energy of this system and work is done by the system. The work done by the system is considered as positive, while work done on the system is considered as negative.

A British engineer Count Rumford observed that a large amount of heat was liberated during boring the barrel of cannon. He concluded from this experiment that heat can also be produced by friction and its amount depends upon the mechanical work against the friction. Later on Joules did a series of experiments and established a relationship between mechanical work and heat energy. According to his results, work done is directly proportional to the amount of heat generated.

$$W \propto Q$$

$$W = J\,Q$$

where J is a mechanical equivalent of heat and its value is 4.186 joule per caloric.

Now we study further the relationship between work and heat by an example of a system (Cylinder) which contains gas at pressure P. The cylinder has a moveable piston of cross-sectional area 'A' and at equilibrium state. The volume occupied by gas is 'V'.

When the pressure is reduced, the volume of the system is increased from V_1 to V_2 at a distance 'Δx' as shown in Fig.10.4. It means that work is done by the system which is given as;

$$W = F\Delta x$$

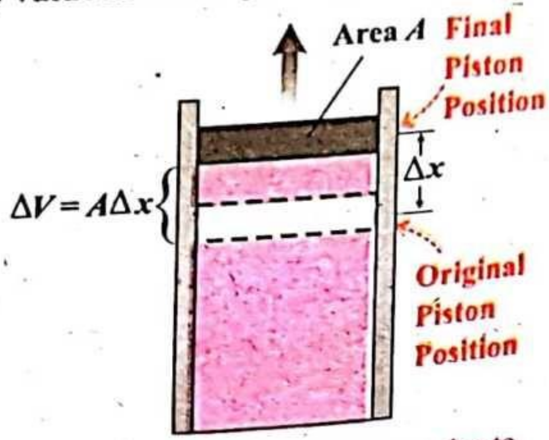


Fig.10.4: Work done by a system due to the expansion of volume by reducing the pressure.

But $$F = PA$$
$$W = PA\Delta x$$
$$W = P\Delta V \quad \because \Delta V = A\,\Delta x = \text{(Change in volume)}$$
$$W = P(V_2 - V_1) \quad \ldots\ldots(10.1)$$

This is a work done by the system. The work done at constant and at variable pressure can be represented graphically on a PV-diagram in the form of a straight horizontal line and a curved line respectively as shown in Fig.10.5. The area under these lines is equal to work done on the system.

Thus, these graphs show that the work done on or by the system depends upon the limiting values and the path followed.

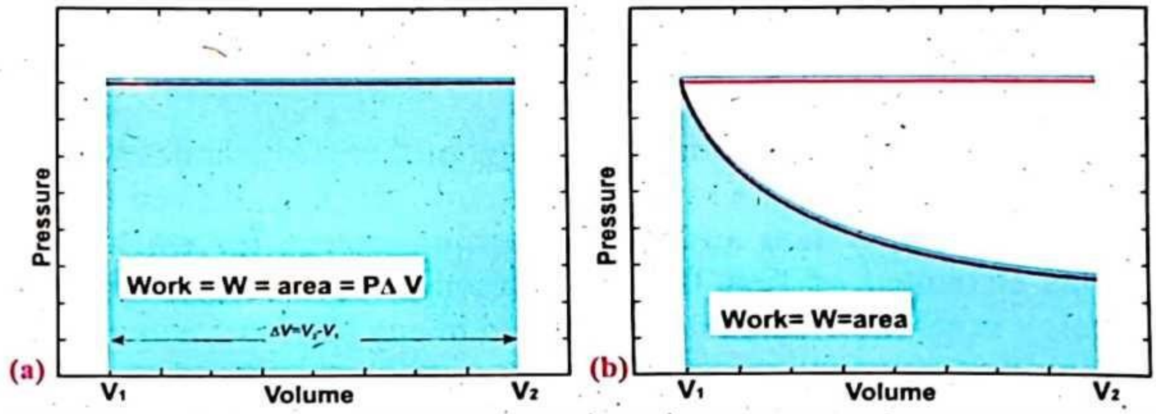


Fig.10.5: Thermodynamics work (a) The area under the straight line in PV-graph shows the work done at constant pressure (b) The area under a curved line shows the work done at variable pressure

Example 10.1

How much work is done by an ideal gas during expansion from its initial volume of 4 litres to a final volume of 24 litres at constant pressure of 8.08×10^5 Nm^{-2}?

Solution:

$$\text{Work} = W = ?$$
$$\text{Initial Volume} = V_1 = 4 \text{ litres} = 4\times10^{-3}\,m^3$$
$$\text{Final Volume} = V_2 = 24 \text{ litres} = 24\times10^{-3}\,m^3$$
$$\text{Change in volume} = \Delta V = V_2 - V_1$$
$$\text{Change in volume} = \Delta V = 20\times10^{-3}m^3$$
$$\text{Pressure} = P = 8.08\times10^5 Nm^{-2}$$
$$\text{Work} = P\Delta V$$
$$\text{Work} = 8.08\times10^5\times20\times10^{-3}$$
$$= 16.2\times10^3\,J$$
$$= 16.2\,kJ$$

10.4 FIRST LAW OF THERMODYNAMICS

First law of thermodynamics is based upon the law of conversion of energy i.e. when heat energy is transformed into other forms of energy or when the other forms of energy is transformed into heat energy, then the total energy of the closed system remains constant. Let heat energy 'Q' is added into a thermodynamic system and the system does not work during the process of transfer of heat but the internal energy of the system increases from its initial state $\mathbf{U_i}$ to its final state $\mathbf{U_f}$. This change in internal energy ΔU is equal to **Q**, that is, $\Delta \mathbf{U} = \mathbf{Q}$.

When a system does work 'W' due to its expansion but no heat is added during the process then internal energy decreases that is, when 'W' is positive, ΔU is negative and vice versa. Now when heat transfers and both change in internal energy and work done by the system occur then the heat Q is given as;

$$Q = \Delta U + W \quad ......(10.2)$$

This is the mathematical form of first law of thermodynamics which is stated as; **"When heat Q is added to a system, a part of this heat is used to change the internal energy of the system and the remaining energy for work done by the system"**. This statement of first law of thermodynamics also provides universal truth that energy is neither created nor destroyed in any thermodynamic system.

In using first law of thermodynamics, a proper sign should be used. That is, Q is taken as positive when heat energy is supplied to the system and negative when heat energy is taken from the system. Similarly, W is taken as positive when the work is done by the system and negative when it is done on the system.

Example 10.2

When 400 J heat is transferred to the system during expansion then 350 joules of work is done by the system. What is the change in its internal energy?

Solution:

Heat energy added to system $= \Delta Q = 400\text{ J}$

Work done by the system $= \Delta W = 350\text{ J}$

Internal energy $= \Delta U = ?$

From first law of thermodynamics $\Delta Q = \Delta V + \Delta W$

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

$$\Delta U = 400 - 350$$

$$\Delta U = 50\,\text{J}$$

10.4.1 Applications of first law of thermodynamics

The first law of thermodynamics can be studied under the following four processes; each has its different conditions and properties.

(a) Isochoric Process

It is a process in which the volume of gas of the given system remains constant.

Consider a finite volume of gas enclosed in cylinder which has non-conducting walls and piston but a conducting base. Let an amount of heat 'Q' is supplied to the system. When gas is heated at constant volume (fixed piston) its pressure increases from P_1 to P_2 but the work is neither done by the system nor on the system because there is no expansion or compression of the system that is $\Delta V = 0$ as shown in Fig.10.6.

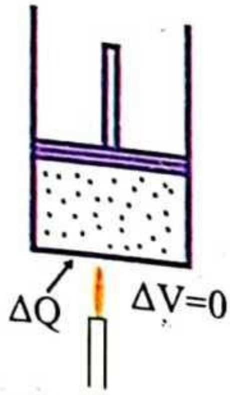


Fig.10.6: Isochoric Process, when volume remains constant and no work is done on or by the system.

Thus the first law of thermodynamics becomes,

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

As $\quad \Delta V = 0$ therefore

$$\Delta Q = \Delta U \quad ......(10.3)$$

This result shows that under isochoric process all the supplied energy is used to increase the internal energy of the system.

Graphically, a straight vertical line in P–V graph represents first law of thermodynamics under isochoric process as given in Fig. 10.7.

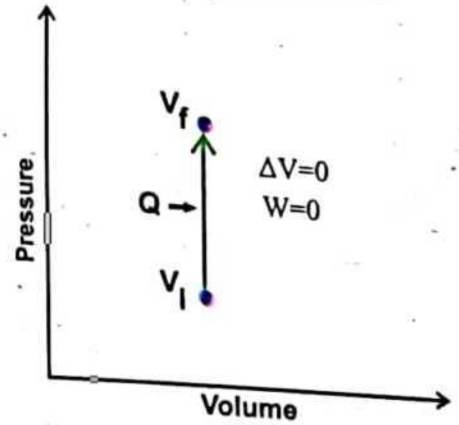


Fig.10.7: A straight vertical line in P-V graph shows isochoric process

(b) Isobaric Process

A process in which the pressure of the gas of the given system remains constant is known as isobaric process.

Consider a finite volume of gas is enclosed in cylinder with moveable piston. The walls and piston of the cylinder are insulator whereas its base is conductor as shown in Fig.10.8. Let an amount of heat 'Q' is added to the system at constant pressure then its temperature increases from T_1 to T_2. As a result, gas is expanded from V_1 to V_2 due the increase in its internal energy. If the piston moves slowly and the displacement of the piston is kept very small, the pressure of the gas will not change much and can be considered constant, and some work is done by the system. Thus first law of thermodynamics under these conditions becomes,

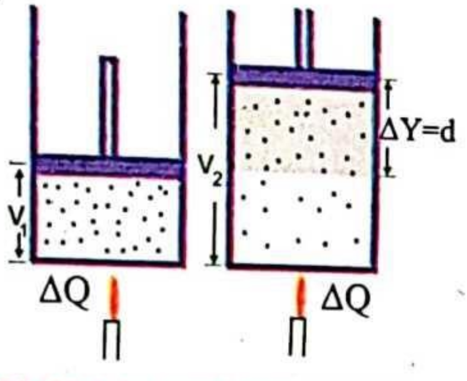


Fig.10.8: Isobaric Process, where pressure remains constant and work is done on the system.

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

As $\quad W = Fd$

$$W = F\Delta y$$

$$W = PA\Delta y = P\Delta V \qquad \because \Delta V = A\,\Delta y = \text{change in volume}$$

$$\Delta Q = \Delta U + P\Delta V \text{......(10.4)}$$

Under isobaric process, all the supplied heat energy of the system is converted into work done and increase in internal energy.

Graphically, a straight horizontal line in P–V graph represents first law of thermodynamics under isobaric process as shown in Fig.10.9. The P–V graph of isobaric process is called Isobar.

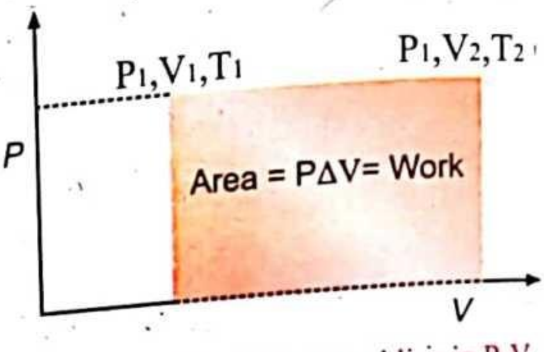


Fig.10.9: A straight horizontal line in P-V graph shows isobaric process

(c) Isothermal Process

A process in which the temperature of gas of the given system remains constant is known as isothermal process.

Consider a gas which is enclosed in a cylinder that has non-conducting walls and piston but its base is conducting as shown in Fig. 10.10. When heat energy ΔQ is added to the system then the temperature of the gas increases. To keep temperature constant, the system is allowed to expand slowly from V_1 to V_2.

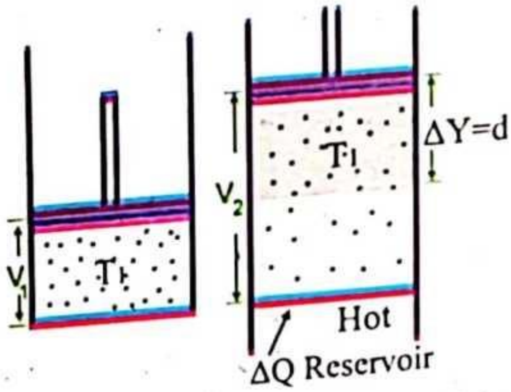


Fig.10.10: Isothermal Process in which temperature remains constant

The internal energy of the gas does not change during this isothermal expansion, as the temperature of the gas remains constant. So, $\Delta U = 0$ and hence at constant temperature, the first law of thermodynamics is written as;

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

$$\Delta Q = P\Delta V \text{ ......(10.5)}$$

This equation shows that the heat energy supplied appears in the form of work. Since the work is done by the system, so ΔW is positive.

Graphically, a curved line called isotherm represents the first law of thermodynamics under isothermal process as shown in Fig. 10.11.

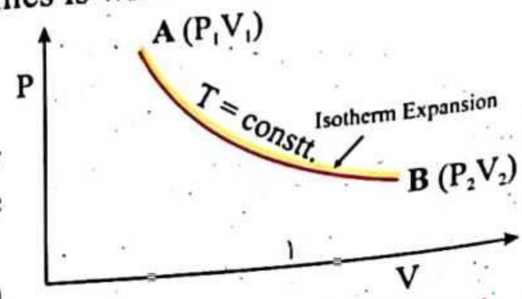


Fig.10.11: A curved line in P-V graph represents the isothermal process.

Conversely, if the gas is compressed, the work is being done on the system and an amount of heat ΔQ has to be allowed to leave the system.

(d) Adiabatic Process

A process in which heat energy neither enters nor leaves the system is called adiabatic process.

Considering a gas which is enclosed in a cylinder that has non-conducting walls and piston as shown in Fig. 10.12. When the system is placed on an insulator stand then there is no transfer of heat into or out of the system, that is $\Delta Q = 0$.

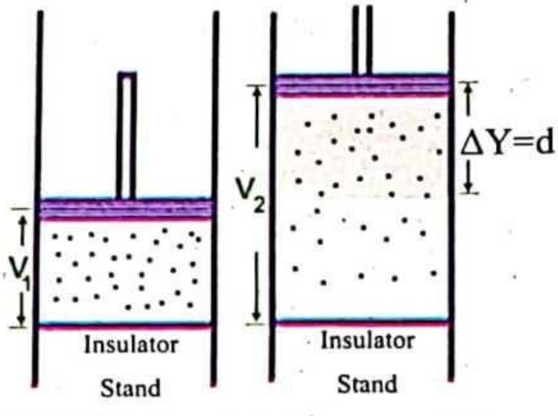


Fig.10.12: Adiabatic Process in which heat energy is not transferred.

Now when the system is allowed to expand by reducing the pressure the internal energy of the system decreases due to decrease in temperature. Similarly, when the system is compressed by applying pressure the internal energy of the system increases by increasing the temperature. Now first law of thermodynamics under the adiabatic process becomes

$$0 = \Delta U + \Delta W$$

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

$$\Delta U = -P\Delta V \text{ ......(10.6)}$$

In adiabatic process, the work is done at the cost of internal energy of the system. In other words, if the gas expand it will be cooled and it will be heated on compression. Graphically, a curved line in P–V graph shows adiabatic process, but the curve of adiabatic is steeper than that of the curve of isothermal as shown of Fig.10.13, because of the rapid variations in temperature in adiabatic process take place during its expansion or compression.

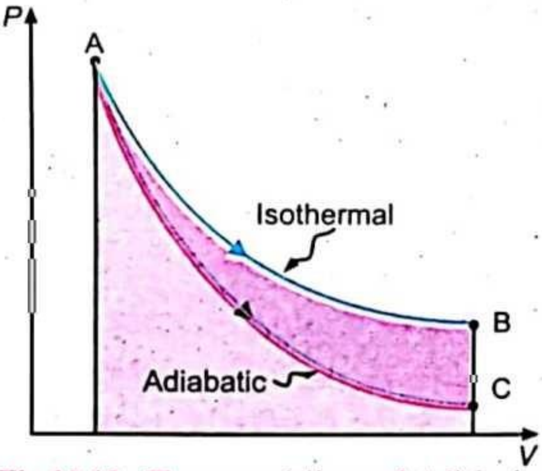


Fig.10.13: The curved lines of Adiabatic and Isothermal P-V graph, where the cure of Adiabatic is faster.

Example 10.3

A gas is enclosed in a cylinder with a moveable piston of cross-section area $0.1\ m^2$. If the piston of the cylinder is allowed to expand through a distance of 5 cm by adding heat energy of 45 J to the gas, then what is the change in internal energy inside the cylinder at constant pressure of $8000\ Nm^{-2}$.

Solution:

Cross-sectional area of the piston $= A = 0.1\ m^2$

Distance covered by the piston $= \Delta x = 5\ cm = 5\times10^{-2}\ m$

Heat energy added to system $= \Delta Q = 45\ J$

Internal energy $= \Delta U = ?$

Pressure $= P = 8000\ Nm^{-2}$

Work done by the system

$$Work = P\Delta V$$

$$Work = PA\Delta x$$

$$Work = 8000 \times 0.1 \times 5 \times 10^{-2}$$

$$Work = 40\ J$$

According to first law of thermodynamics

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

$$\Delta U = 45 - 40$$

$$\Delta U = 5\ J$$

10.5 SPECIFIC HEAT AND MOLAR SPECIFIC HEAT

If a substance is heated then its temperature raises. This raise in temperature of a substance depends upon its mass i.e., more is the mass of the substance, more heat is required to raise its temperature. Thus, **the amount of heat energy required to raise the temperature of any substance through a unit degree is called heat capacity.** The experiment shows that the heat energy is directly proportional to the temperature, that is

$$\Delta Q \propto \Delta T$$

$$\Delta Q = C\Delta T$$

$$\text{Heat capacity } (C) = \frac{\Delta Q}{\Delta T} \quad \text{......(10.7)}$$

Some materials are easier to heat than the others. For example, it takes more energy to raise the temperature of 1kg of aluminum through 1°C, than to raise the temperature of 1kg iron by the same temperature. Therefore, **the amount of heat required to raise the temperature of unit mass of a substance through a unit degree is called specific heat** and its value can be calculated as;

$$\Delta Q \propto \Delta T$$

Molar Specific Heats of Various Gases

Gas	C_P	C_V	$C_P - C_V$	$\gamma = C_P/C_V$
	Molar Specific Heats (J/mol. K)			
Monoatomic gases				
He	21	13	8.33	1.67
Ar	21	13	8.33	1.67
Ne	21	13	8.12	1.64
Kr	21	12	8.49	1.69
Diatomic gases				
H_2	29	20	8.33	1.41
N_2	29	21	8.33	1.4
O_2	29	21	8.33	1.4
CO_2	29	21	8.33	1.4
Cl_2	35	26	8.96	1.4
Polyatomic gases				
CO_2	37	29	8.5	1.3
SO_2	40	31	9	1.29
H_2O	35	27	8.37	1.3
CH_2	36	27	8.41	1.31

$$\Delta Q \propto m$$
$$\Delta Q \propto m\Delta T$$
$$\Delta Q = cm\Delta T$$
$$c = \frac{\Delta Q}{m\Delta T} \quad ......(10.8)$$

The unit of specific heat 'c' is $J kg^{-1}K^{-1}$. As one kilogram mass of different substances contains different number of molecules and has different specific heats so mass of substance is replaced by mole because one mole of any substance contains the same number of molecules. Thus the specific heat capacity in term of moles is known as molar specific heat. It is stated as; **"the amount of heat energy required to raise the temperature of one mole of a substance through one kelvin is called molar specific heat"**. The equation for molar specific heat is given by,

$$C = \frac{\Delta Q}{n\Delta T} \quad ......(10.9)$$

where 'n' is the number of moles of the given sample.

In case of solids and liquids, the change in their volume and pressure due to increase in temperature are very small and can be neglected. In case of gases the situation is different, because there is variation in pressure as well as in volume of gas with the raise in temperature. To study the heating effect of the gas, either volume or pressure of the gas should be constant. Thus, molar specific heat of a gas is defined under the following two ways.

1) Molar specific heat of gas at constant volume

The amount of heat required to raise the temperature of one mole of gas through 1 K at constant volume is called its molar specific heat at constant volume. It is denoted by C_V and it is expressed as;

$$C_V = \frac{\Delta Q}{n\Delta T} \quad ......(10.10)$$

2) Molar specific heat of gas at constant pressure

The amount of heat required to raise the temperature of one mole of gas through 1 K at constant pressure is called its molar specific heat at constant pressure. It is denoted by C_P and it is expressed as;

$$C_P = \frac{\Delta Q}{n\Delta T} \quad ......(10.11)$$

10.5.1 Prove that $C_P - C_V = R$

Consider two systems that contain equal amount of gas but heat is added to first at constant volume and heat is added to the second at constant pressure as shown in Fig. 10.14. When both systems are heated to raise their temperatures then the heat energy increases their internal energy. But the experiment shows that the system at constant pressure requires more heat than the system at constant volume for the same temperature increase. That is,

$$\Delta Q_P > \Delta Q_V$$

$$\Delta Q_P = \Delta Q_V + \text{Work done due to expansion of the system}$$

$$nC_P\Delta T = nC_V\Delta T + P\Delta V$$

As $$PV = nRT$$

$$P\Delta V = nR\Delta T$$

$$nC_P\Delta T = nC_V\Delta T + nR\Delta T$$

$$nC_P\Delta T = n\Delta T(C_V + R)$$

$$C_P = C_V + R$$

$$C_P - C_V = R \text{......(10.12)}$$

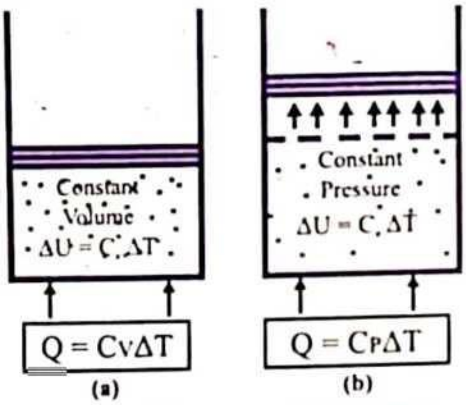


Fig.10.14: Heat transfer into the system (a) at constant volume and (b) at constant pressure

Equation (10.12) shows that $C_P > C_V$ by an amount equal to universal gas constant 'R'.

Example 10.4

The temperature of a silver bar rises by 10°C when it absorbs 1.23 kJ of heat energy. The mass of the bar is 525 g. Determine the specific heat of the silver.

Solution:

$$\Delta T = 10^\circ C - 0^\circ C = 10^\circ C$$

$$\Delta Q = 1.23\text{ kJ} = 1.23 \times 10^3\text{ J}$$

$$m = 525\text{ g} = 0.525\text{ kg}$$

$$c_{silver} = ?$$

$$c_{silver} = \frac{\Delta Q}{m\Delta T}$$

$$c_{silver} = \frac{1.23 \times 10^3}{0.525 \times 10} = 234\text{ Jkg}^{-1}\text{C}^{o-1}$$

10.5.2 Adiabatic Equation

Consider a system (container) which contains a gas. The walls and moveable piston of the container are perfectly insulated from the surroundings. So heat energy neither enters nor leaves the system and $\Delta Q = 0$. It means the work done under adiabatic process is possible only at the cost of its internal energy during the compression and expansion of the system. Thus, 1st law of thermodynamics under adiabatic process is given by;

$$0 = \Delta U + P\Delta V$$

$$\Delta U = -P\Delta V \quad ......(10.13)$$

According to molar specific heat at constant volume

$$\Delta Q = nC_v\Delta T$$

But 1st law of thermodynamics under isochoric process

$$\Delta Q = \Delta U$$

$$\Delta U = nC_v\Delta T$$

Putting the value of ΔU in equation (10.13), we get

$$nC_v\Delta T = -P\Delta V \quad ......(10.14)$$

As $\qquad PV = nRT$

$$\Rightarrow V\Delta P = nR\Delta T \text{ (at constant volume)}$$

$$\Rightarrow \Delta T = \frac{V\Delta P}{nR}$$

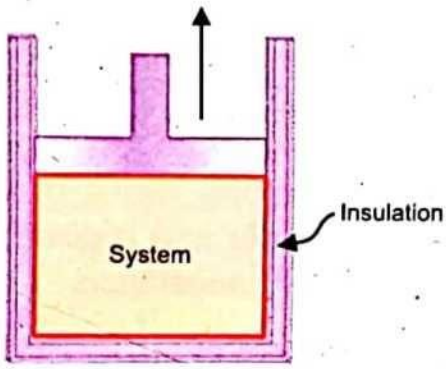
Substitute this value of ΔT in equation (10.14)

$$nC_v \cdot \frac{V\Delta P}{nR} = -P\Delta V$$

$$\frac{\Delta P}{P} = -\frac{R}{C_v} \times \frac{\Delta V}{V}$$

POINT TO PONDER

Why there is space between the two walls of a thermo flask?



An diabatic process is that process in which the heat energy neither enters not leaves the system..

But, $\qquad C_P - C_v = R$

$$\frac{\Delta P}{P} = -\left(\frac{C_P - C_v}{C_v}\right)\frac{\Delta V}{V}$$

$$\frac{\Delta P}{P} = -\left(\frac{C_P}{C_v} - 1\right)$$

But, $\qquad \because \frac{C_P}{C_v} = \gamma = \text{Ratio of specific heats}$

$$\frac{\Delta P}{P} = -(\gamma - 1)\frac{\Delta V}{V}$$

$$\frac{\Delta P}{P} = -\gamma\frac{\Delta V}{V} + \frac{\Delta V}{V}$$

As $\frac{\Delta V}{V}$ is very small so it can be neglected.

$$\frac{\Delta P}{P} = -\gamma\frac{\Delta V}{V}$$

$$\frac{\Delta P}{P}+\gamma\frac{\Delta V}{V}=0$$

By the operation of integration, the following result is obtained as;

$\therefore \quad PV^{\gamma} = \text{Constant} \quad ......(10.15)$

This is known as adiabatic equation and 'γ' is adiabatic constant.

10.6 REVERSIBLE AND IRREVERSIBLE

When a thermodynamic process is operated by changing the values of the given system then there are two possibilities, the state of the system remains same due to the reverse direction of the process after the succession of an event or the state of the system changes due to proceeding the process in one direction. Thus on the basis of these two reasons, a process of thermodynamics is defined under the following two ways such as reversible and irreversible process.

1) Reversible Process

When a thermodynamics system operates such that a change takes place and it returns to its initial state after a certain fixed interval of time then the process is called a reversible process.

For example, motion of a piston in a heat engine when it completes one cycle under four steps is a reversible process as shown in Fig.10.15. Similarly, the conversion of ice into water then water into ice is also an example of the reversible process. In other word, a reversible process is one which can be retraced in exactly reverse order and it does not produce any change in the surrounding if the work is done by the substance.

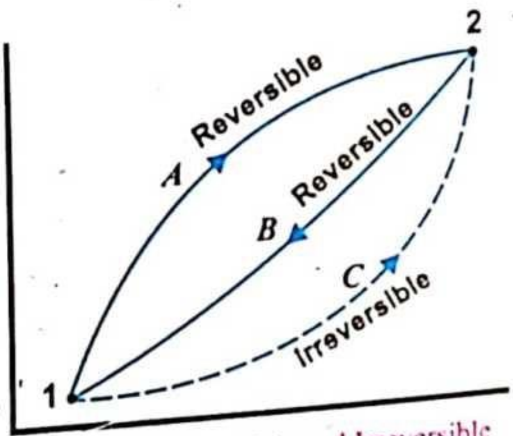


Fig.10.15: Reversible and Irreversible process in one cycle

2) Irreversible Process:

When a thermodynamic system operates such that its function changes from its initial value to its final value but does not returns to its initial value then the process is called irreversible process. For example, the flow of heat from a hot body to a cold body is an irreversible process because heat never flow from a cold body to a hot body. Similarly, burning of fuel and burst tyre are also irreversible process.

10.7 HEAT ENGINE

A heat engine is an important device which converts heat energy into mechanical energy or work. In the beginning a steam heat engine was introduced. In this engine water was boiled in a vessel called steam boiler and engine took heat from this steam boiler and converted a part of it into work. Now in the present age, petrol engines and diesel engines are being used at large scale. These engines consist of a cylinder which contains a gas such as air with a moveable piston, hot reservoir (source) and cold reservoir (sink).

Working of heat engine

A schematic diagram of a heat engine is shown in Fig. 10.16. It shows that a heat engine that works between hot and cold reservoirs. That is, the engine gains heat energy from a source at a high temperature and converts a part of this heat energy into a mechanical work and the remaining part of energy is rejected through a sink as shown in Fig.10.16.

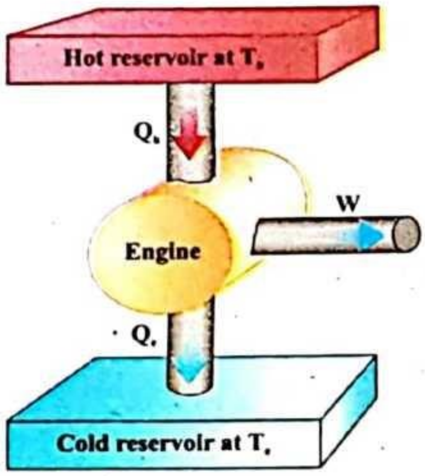


Fig.10.16: Schematic diagram of heat engine, where engine is working between hot and cold reservoirs

In order to get a continuous steady mechanical energy, the heat engine is made to operate in a cyclic process which absorbs heat Q_1 and rejects heat Q_2. The initial and final internal energies of the system under this cyclic process remain same.

Thus first law of thermodynamics becomes

$$\Delta Q = \Delta U - \text{Work}$$

But $$\Delta U = U_2 - U_1 = 0$$

$$Q_1 - Q_2 = \text{Work} \quad ......(10.16)$$

The efficiency of a heat engine is defined as the ratio between the work done by the engine to the supplied heat energy.

POINT TO PONDER
What is the main difference between steam and diesel engine?

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

$$\text{Efficiency}\ (\eta) = \frac{\text{Work done}}{\text{Supplied energy}}$$

$$\text{Efficiency}\ (\eta) = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta = 1 - \frac{Q_2}{Q_1} \quad ...... (10.17)$$

This result shows that the efficiency of a heat engine depends upon the absorbed heat Q_1 and discarded heat Q_2. As heat energy is proportional to the temperature, so the efficiency of heat engine can also be expressed as;

$$\eta = 1 - \frac{T_2}{T_1} \quad ......(10.18)$$

If $T_2 = 0K$ (−273°C) called absolute temperature then the efficiency of heat engine would be 100% but this is an ideal or a theoretical case.

Example 10.4

Compute the maximum possible efficiency of a heat engine operating between the temperature limits of 150°C and 450°C.

Solution:

Efficiency (η) = ?

Initial temperature = $T_1 = 450°C = 450 + 273 = 723\ K$

Final temperature = $T_2 = 150°C = 150 + 273 = 423\ K$

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

$$\eta = 1 - \frac{423}{723}$$

$$\eta = 1 - 0.585$$

$$\eta = 0.415$$

Percentage Efficiency = $\eta = 0.415 \times 100 = 41.5\%$

10.8 SECOND LAW OF THERMODYNAMICS

In first law of thermodynamics, we have discussed the conversation of heat energy into a useful work. Now second law of thermodynamics not only verifies the first law of thermodynamics, but it also explains the proper method of conversion of heat into mechanical work and the specific direction of flow of heat.

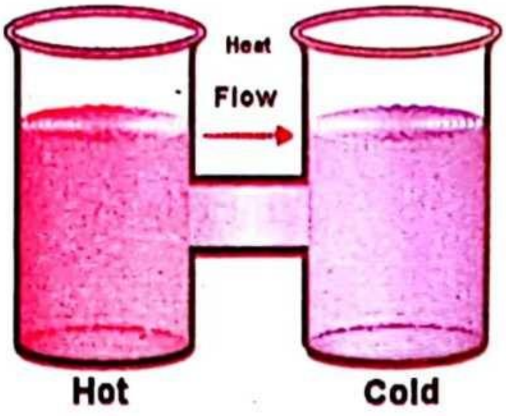


Fig.10.17: Two reservoirs at different temperature where, heat flows from hot body to cold body.

This law is based upon law of nature that is the experimental evidences about the nature show that water flow from higher level to lower level. Similarly, heat energy flows from hot body to cold body and work can be performed as shown in Fig. 10.17. It may be noted that it is impossible to have a cold reservoir at 0K. Based upon these notions, the second law of thermodynamics can be defined under the following two statements.

Lord Kelvin Statement

According to this statement, "it is impossible to construct a heat engine operating in a cycle which absorbs heat energy from a hot reservoir and converts it completely into the mechanical".

Rudolf Clausius Statement

This is another statement of the second law of thermodynamics. According to this statement "Heat energy cannot flow from cold body to hot body without expenditure of energy ". It can be studied in the working principle of refrigerator.

10.9 CARNOT ENGINE AND CARNOT CYCLE

In order to improve the efficiency of a heat engine, French military engineer Sadi Carnot in 1824 introduced a theoretical engine which is known as Carnot engine. It consists of a cylinder that contains gas with a moveable piston. The walls and piston of the cylinder are insulators but its base is conductor. It is assumed that there is no friction between walls and piston. The Carnot engine operates in a cycle known as Carnot cycle which is completed in four steps; two under isothermal and two under adiabatic conditions as shown in Fig.10.18. Here three parameters of gas i.e. P,V and T are considered which control the behaviour of gas contained in the cylinder.

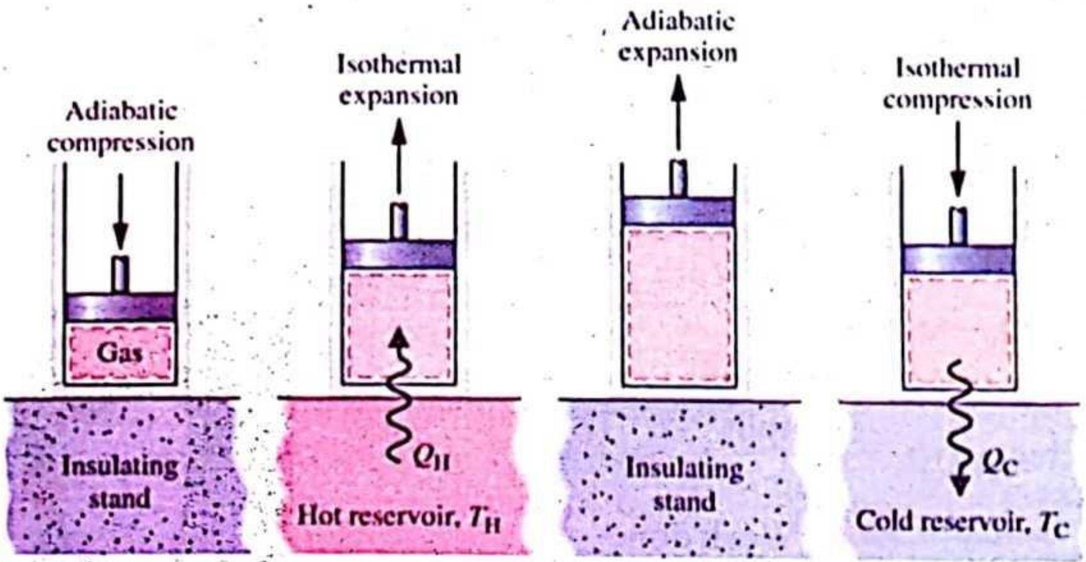


Fig.10.18: Schematic diagrams which explain the operation of a Carnot engine and it completes one cycle in four steps.

(i) Isothermal Expansion

When the system is allowed to expand by reducing the pressure on the piston then the temperature decreases but temperature should remain constant in isothermal process. Therefore, heat energy Q_1 is supplied from the hot reservoir.

Thus, the values of parameters change from $P_1V_1T_1$ to $P_2V_2T_1$. Graphically it is represented by curve AB in P-V graph as shown in Fig.10.19.

(ii) Adiabatic Expansion

When the system is further allowed to expand this time it follows adiabatic process. Therefore, the temperature decreases and thus the values of parameters change from $P_2V_2T_1$ to $P_3V_3T_2$. It is represented by curve BC in Fig.10.19.

(iii) Isothermal Compression

After the expansion, when the system is compressed by applying the pressure on the piston then the temperature should increase but to keep temperature constant heat energy Q_2 is released to the cold reservoir and the values of parameters change from $P_3V_3T_2$ to $P_4V_4T_2$.

Graphically it is represented by curve CD in P–V graph as shown in Fig.10.19.

(iv) Adiabatic Compression

Finally, when the system is further compressed, increased and the reversible cycle is completed.

Thus, the system returns back to its initial stage $P_4V_4T_2$ to $P_1V_1T_1$. Graphically it is represented by curve

Carnot engine operates under reversible p equilibrium is maintained in the whole process by ab rejecting heat energy Q_2.

Thus the internal energy of the system remains c first law of thermodynamics becomes

$$\Delta Q = \Delta U + \text{Work}$$

$$Q_1 - Q_2 = \text{Work}$$

The efficiency of a Carnot engine is defined as:

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

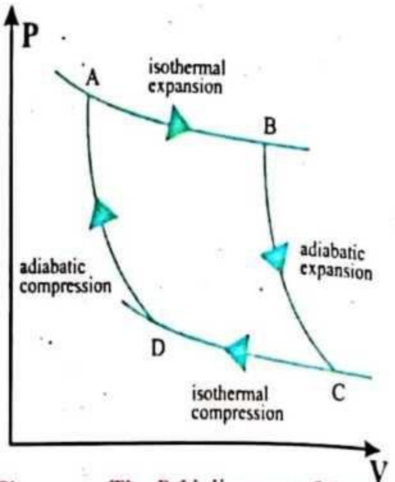
$$\text{Efficiency}\ (\eta) = \frac{\text{Work done}}{\text{Supplied energy}}$$

$$\text{Efficiency}\ (\eta) = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta = 1 - \frac{Q_2}{Q_1} \quad \text{......(10.19)}$$

As heat energy is proportional to the temperature so efficiency in terms of temperature is given as;

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



[The P-V diagram of Carnot
engine executing a Carnot cycle

d, this time the temperature is

ge and the values change from
ve DA in Fig.10.19.
process, therefore, thermal
absorbing heat energy Q_1 and

s constant that is $\Delta U = 0$. Now

Nicolas Leonard Sadi Carnot (1796 – 1832)

French military engineer and
hysicist known as "Father of
hermodynamics" His excellent
orks are Carnot cycle, Carnot
eorem and Carnot heat engine.

The efficiency in percentage is given as

$$\eta = \left(1 - \frac{T_2}{T_1}\right) \times 100\% \quad ......(10.20)$$

This shows that the efficiency of a Carnot engine depends on temperature of hot and cold reservoirs.

It is clear from Eq.(10.20) that efficiency of Carnot engine will be 100 percent if either the temperature of hot reservoir is at infinity or the temperature of cold reservoir is 0K. These two conditions cannot be met experimentally. Hence, the efficiency of Carnot engine is always less than 100 percent and depends on the temperature of hot and cold reservoirs.

Carnot Theorem

After the drawing of the nomenclature of a heat engine, Carnot derived the following two results called Carnot's theorems. That is;

1) No heat engine can be more efficient than a reversible engine working between the same two temperatures.
2) All the reversible engines have the same efficiency when they are working between the same two temperatures.

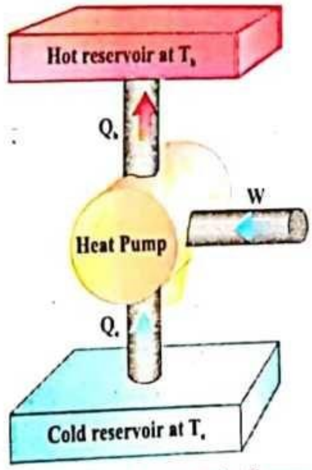


Fig.10.20: A Schematic diagram of a refrigerator which shows that the refrigerator is working between the cold and hot reservoirs.

10.10 REFRIGERATOR

It is a device which maintains the temperature of a body below that of its surrounding. It operates in a cyclic process but in reverse as that of the heat engine as shown in Fig.10.20.

A refrigerator absorbs heat from a cold reservoir and gives it off to a hot reservoir. This shows that in a refrigerator, the work is done on the system while in a heat engine work is done by the system.

A refrigerator consists of a compressor, condenser, expansion valve, exporter and a gas as the working substance which is called refrigerant as shown in Fig.10.21.

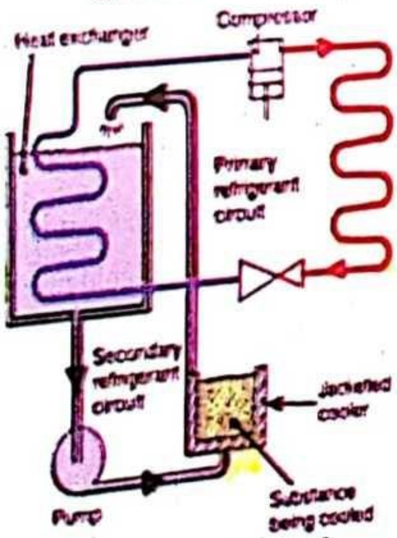


Fig.10.21: A cyclic process of a refrigerator under various steps.

The refrigerant at low pressure and at low temperature from the cold reservoir is compressed by the compressor and the compression is adiabatic. So both pressure and temperature are increased as compared to its surrounding. Now the refrigerant at high pressure and at high temperature passes through the condenser where it loses some of its heat to the surrounding and partly condenses to liquid. The refrigerant now expands adiabatically into the evaporator at a rate controlled by the expansion valve. This adiabatic expansion causes cooling of refrigerant in the evaporator coil, which is cooler than its surrounding. Finally, the refrigerant again enters the compressor to start the next cycle.

Refrigerator operates in a cyclic process; it takes heat energy Q_1 from cold reservoir and leaves heat energy Q_2 to hot reservoir due to work done on the system with constant internal energy $\Delta U = 0$. Now according to first law of thermodynamics

$$\Delta Q = \Delta U + \text{Work}$$

$$Q_2 - Q_1 = 0 + W \qquad \text{...... (10.21)}$$

Co-efficient of performance of a refrigerator is defined as the ratio of heat extracted from reservoir at low temperature to the work done on the system. That is

$$\text{Co-efficient of performance} = \frac{Q_1}{W}$$

$$\text{Co-efficient of performance} = \frac{Q_1}{Q_2 - Q_1} \qquad \text{...... (10.22)}$$

Co-efficient in terms of temperature, where $Q \propto T$

$$\text{Co-efficient of performance} = \frac{T_1}{T_2 - T_1} \qquad \text{......(10.23)}$$

Example 10.5

A refrigerator has a Co-efficient of performance 8. If temperature in the freezer is $-23^{\circ}C$ then what is the temperature at which it rejects the heat?

Solution:

Co-efficient of performance = 8

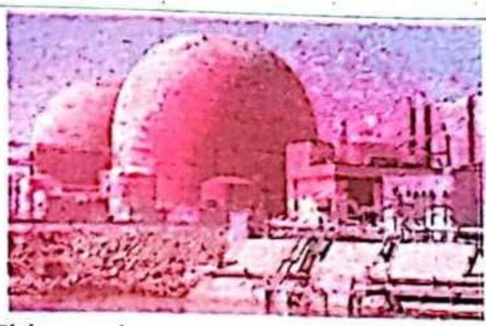
Temperature of cold reservoir (freezer) = $T_1 = -23^{\circ}C = -23 + 273 = 250$ K

Temperature of hot reservoir (room) = T_2 = ?

$$\text{Co-efficient of performance} = \frac{T_1}{T_2 - T_1}$$

$$8 = \frac{250}{T_2 - 250}$$

$$8(T_2 - 250) = 250$$
$$8T_2 - 8\times 250 = 250$$
$$8T_2 = 250 + 8\times 250$$
$$= 250 + 2000$$
$$= 2250$$
$$T_2 = \frac{2250}{8}$$
$$T_2 = 281.25\,\text{K}$$
$$T_2 = 8.1^\circ\text{C}$$



This nuclear power plant generates electric energy at the rate of 1000 MW. At the same time, by design, it discards energy into the nearby river at the rate of 2000 MW. This plant and all others like it throw away more energy than they deliver in useful form. They are real counterparts of the ideal engine.

10.11 ENTROPY

In the laws of thermodynamics, a state of a function has been explained by variables such as pressure, volume, temperature and internal energy. Rudolf Clausius in 1856 introduced another variable named as entropy which describes the state of the system as well as providing a quantitative relationship to the second law of thermodynamics and it is always being used as the measurement of disorder of the system. For example, if a system undergoes a reversible process by taking heat energy ΔQ from a hot reservoir at the thermodynamic temperature 'T' then the increase in the state variable called entropy. It is represented by 'S' and its value is given by;

$$\Delta S = \frac{\Delta Q}{T} \quad ......(10.26)$$

The unit of entropy is J K^{-1}. Change in entropy of the system is positive when heat is added and is negative when heat is removed. It is explained by an example of two reservoirs at different temperatures T_1 and T_2 such that $T_1 > T_2$ as shown in Fig.10.22(a). When both reservoirs are made in thermal contact with each other then there is flow of heat 'Q' from hot reservoir to cold reservoirs, i.e., Heat is lost in hot reservoir with negative entropy $\left(-\frac{Q}{T_1}\right)$ while heat is added in cold reservoir with positive entropy $\left(\frac{Q}{T_2}\right)$.

Fig.10.22(a): Two reservoirs at different temperature where heat flows from hot to cold reservoir performs work.

Thus change in entropy $= \frac{Q}{T_2} - \frac{Q}{T_1}$

When the temperature of both reservoirs becomes equal as shown in Fig.10.22(b), flow of heat stops and no work is possible. It means the heat energy which is present in the system but not available for useful work. Hence entropy can also be defined as, "the unavailability of energy for useful work".

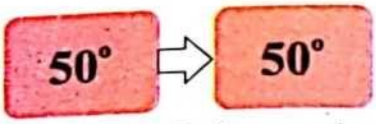


Fig.10.22(b): Both reservoirs have same temperature. There is no flow of heat and no work performs.

Entropy of reversible and irreversible process

Let a system undergoes a reversible process absorbs heat Q_1 at temperature T_1 and releases heat Q_2 at temperature T_2. Then its total entropy as shown in Fig. 10.23 is given as.

$$S = S_1 + S_2 + S_3 + S_4$$

$$S = \frac{Q_1}{T_1} + 0 - \frac{Q_2}{T_2} + 0$$

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

Entropy differs from energy, which does not obey law of conservation of energy.

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

Therefore, $$S = 0$$

This shows that entropy of a system under reversible process remains constant.

When the system undergoes an irreversible process at temperatures T_1 and T_2then according to Carnot theorem the efficiency of irreversible is less than that of the efficiency of the reversible i.e.

$$\eta_{irrev} < \eta_{rev}$$

$$1 - \frac{Q_2}{Q_1} < 1 - \frac{T_2}{T_1}$$

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

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

$$\frac{Q_2}{T_2} - \frac{Q_1}{T_1} > 0$$

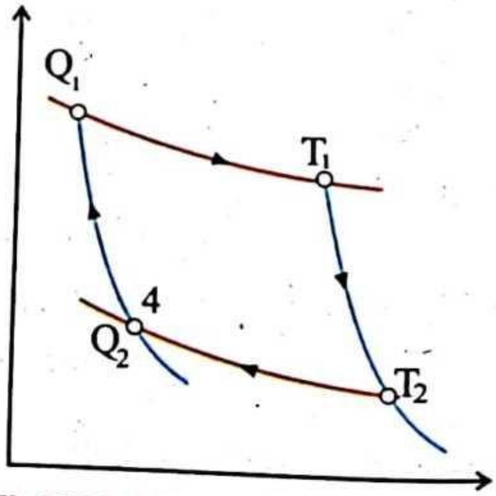


Fig.10.23: Entropy of a cycle reversible

The above results show that entropy of a system under irreversible process increases. By applying these two results of reversible and irreversible process to the universe or a natural process we conclude the entropy of the universe either remains constant or increases. This is called law of increase of entropy and this is another statement of second law of thermodynamics which is stated as **"in any natural process the entropy increases and the available energy for doing work decreases"**.

Entropy and Heat Death

It is a universal truth that hot places are becoming cold and cold places are becoming hot. This is according to law of nature. This process is continued till the temperatures will become same everywhere. At this stage, where the temperature difference for useful work is not available and entropy will be maximum. This is termed as heat death i.e., the available energy could not be brought in its respective function i.e. it could not be used for useful work.

Example 10.6

Calculate the entropy change when 1 kg of ice at $0^{\circ}C$ melts into water at $0^{\circ}C$. Latent heat of fusion of ice is $3.36 \times 10^5\ J \cdot Kg^{-1}$.

Solution:

Mass = m = 1 Kg

Temperature = T = $0^{\circ}C$ = 273 K

Latent heat of fusion = $L_f = 3.36 \times 10^5\ J \cdot Kg^{-1}$

Entropy = ΔS=?

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

$$\Delta S = \frac{1 \times 3.36 \times 10^5}{273}$$

$$\Delta S = 1.23 \times 10^3\ JK^{-1}$$

SUMMARY

- **Thermal equilibrium**: The condition of a system in which the flow of heat between the bodies is zero called thermal equilibrium.
- **Internal energy:** The sum of all forms of molecular energies of a substance is known as its internal energy.
- **First law of thermodynamics:** This law states that "When heat energy is converted into other form of energies or other form of energies are converted into heat energy but total energy remains constant" Mathematically $\Delta U = \Delta Q + \Delta W$.

- **Molar specific heat:** It is the amount of heat required to raise the temperature of one mole of a gas through one Kelvin.

  Molar specific heat at constant volume is the amount of heat required to raise the temperature of one mole of a gas through one Kelvin keeping volume constant.

  Molar specific heat at constant pressure is the amount of heat required to raise the temperature of one mole of a gas through one Kelvin keeping volume constant.
- **Reversible process:** A process in which the system is in equilibrium at any instant due to its reverse direction is a reversible process.
- **Irreversible process:** A process which cannot be retraced in the reverse direction and the system does not remain in equilibrium is an irreversible process.
- **Heat engine**: It is a device which converts heat energy into mechanical energy.
- **Second law of thermodynamics**: This law is stated as "There is no heat engine which takes heat and converts it completely into mechanical work".
- **Carnot cycle**: It is a reversible cycle which is completed under four steps, two for expansion and two for compression.
- **Carnot theorem**: According to this theorem there is no heat engine which is more efficient than reversible engine working between the same two temperatures.
- **Refrigerator**: It is a device to maintain the temperature of a body below than the temperature of its surrounding.
- **Entropy:** Measurement of disorder is called entropy.
- **Degradation of energy**: It is the transfer of heat energy from hot reservoir to cold reservoir.

EXERCISE

Multiple choice questions.

1. When two bodies are made at thermal contact having the same temperature then they are at:

(a) Physical equilibrium (b) Thermal equilibrium
(c) Mechanical equilibrium (d) Chemical equilibrium

2. Normal temperature of a human body is 98.6°F while its atmosphere temperature is 84.6°F. What will be the temperature of the dead body in such atmosphere

(a) 84.6°F (b) 98.6°F (c) 92.5°F (d) 185°F

3. When the system is expanded by adding heat energy then the work done is:

(a) Positive and on the system (b) Negative and on the system
(c) Positive and by the system (d) Negative and by the system

4. Which substance possesses the largest internal energy at $t^{\circ}C$
(a) Solid (b) Liquid (c) Gas (d) All of these

5. Internal energy of a substance is defined in terms of
(a) P and V (b) P and T (c) T and V (d) P, V and T

6. The ratio between work done and heat energy is equal to:
(a) Adiabatic constant (b) Joul's constant
(c) Specific heat constant (d) Real gas constant

7. A system which transfers neither mass not energy is called;
(a) Open system (b) Close system
(c) Isolated system (d) Non-cyclic system

8. First law of thermodynamics is based upon law of conservation of;
(a) Mass (b) Energy (c) Momentum (d) Charges

9. A process in which all the heat energy is used for increasing internal energy of the system is known as:
(a) Isobaric (b) Isochoric (c) Isothermal (d) Adiabatic

10. In which process the internal energy is used for doing work:
(a) Isobaric (b) Isochoric (c) Isothermal (d) Adiabatic

11. Specific heat of a gas in an isothermal process is:
(a) Zero (b) Remains constant
(c) Negative (d) Infinite

12. A process in which the system remains at thermal equilibrium is known as:
(a) Isobaric (b) Isochoric (c) Isothermal (d) Adiabatic

13. The value of adiabatic constant for mono-atomic gas is;
(a) 1.40 (b) 1.44 (c) 1.60 (d) 1.66

14. The efficiency of a heat engine will be 100% when
(a) Engine takes huge amount of heat from source
(b) Engine exhaust a very small amount of heat from sink
(c) The temperature of cold reservoir is $0^{\circ}C$
(d) The temperature of cold reservoir is 0 K

15. Second law of thermodynamics provides the proper direction of;
(a) Temperature (b) Force (c) Pressure (d) Flow of heat

16. A device which converts mechanical energy into heat energy is known as:
(a) Heat engine (b) Carnot Engine (c) Refrigerator (d) Turbine

17. Entropy of a system in a reversible process;
(a) Decreases (b) Increases (c) Infinite (d) Zero

18. Entropy remains constant in the process of;
(a) Isochoric (b) Isobaric (c) Isothermal (d) Adiabatic

SHORT QUESTIONS

- **Give the short answers of the following questions.**

1. What is the condition of perfect thermal equilibrium?
2. Why is the earth not in thermal equilibrium with the sun?
3. What is the difference between the work done on the system and work done by the system?
4. In which process the internal energy of the system remains constant?
5. Which variable remains constant in adiabatic process?
6. Why the curve of adiabatic is steeper than isothermal process?
7. Why the measurement of molar specific heat is being preferred than specific heat?
8. Why molar specific heat at constant pressure is greater than molar specific heat at constant volume?
9. What is the difference between reversible and irreversible process?
10. Why the construction of a heat engine with 100% efficiency is impossible?
11. What is the difference between heat engine and refrigerator?
12. How can a Carnot cycle be completed?
13. What do you know about the heat death?
14. What will be the work done by a system when its hot and cold reservoirs are at same temperature?

COMPREHENSIVE QUESTIONS

1. What is thermal equilibrium? Discuss the condition of perfect thermal equilibrium.
2. Define internal energy of the given system in terms of the kinetic energies of the molecules of the gas.
3. State and explain thermodynamics system with all its kinds such as; open system, closed system and isolated system.
4. Explain that how did Rumford observe the relation between work and heat? Also show the graphical representation of the work done.
5. State and explain first law of thermodynamics and discuss its four applications.
6. Compare specific heat and molar specific heat. Also prove that $C_P - C_V = R$.
7. State and prove adiabatic equation, $PV^{\gamma} =$ Constant.
8. Explain reversible and irreversible processes with examples.
9. What is heat engine? Show the working principle and efficiency of a heat engine.
10. State and explain the second law of thermodynamics with examples.

11. Define Carnot engine, Carnot cycle, efficiency of Carnot engine and Carnot theorem.
12. What is refrigerator? Explain the working principle and co-efficient of performance of a refrigerator.
13. State and explain entropy. Calculate entropy of reversible and irreversible process. Also discuss the condition of heat death.

NUMERICAL PROBLEMS

1. How much work is done by an ideal gas in expanding from a volume of 3 litres to a volume of 33 litres at constant pressure of 2.5 atm.? **(7.6 kJ)**
2. A sample of gas is compressed to one half of its initial volume at constant pressure of 1.25×10^5 Nm^{-2}. During the compression, 100 J of work is done on the gas; determine the final volume of the gas. **(8×10^{-4} m^3)**
3. An ideal gas undergoes an isobaric expansion at 2.5 kPa. If the volume increases from $2m^3$ to $5m^3$ and 13 kJ of energy is transferred to the gas by heat, what is the change in its internal energy. **(5.5 kJ)**
4. The temperature of 2 kg metal block is raised from 15°C to 90°C by absorbing heat energy 86 kJ. Calculate the specific heat of the metal block. **(5735 J/kg °C)**
5. A mechanical engineer develops an engine, working between 327°C and 27°C and claims to have an efficiency of 50%. Does he claim correctly? Explain. **(Yes)**
6. A heat engine has a power output of 6 kW and an efficiency of 30%. Assume that the engine exhausts 8 kJ of heat energy in each cycle. Find (a) energy absorbed in each cycle and (b) the time for each cycle. **(11.4 kJ, 0.55s)**
7. In a refrigerator, heat from inside at 277 K is transferred to a room at 300 K. How much joule of heat will be delivered to the room for each joule of electrical energy consumed ideally? **(12 J)**
8. A Carnot engine utilizes an ideal gas. The source temperature is 227°C and the sink temperature is 127°C. Find the efficiency of the engine. Also find the heat input from the source and heat rejected to the sink when 10000 J of work is done. **(20%, 5×10^4 J, 4×10^4 J)**
9. How much work does on ideal Carnot refrigerator require to remove 1 J of energy from liquid helium at 4K and rejects this thermal energy to a room temperature 293 K environment. **(72.3 J)**
10. 336 J of energy is required to melt 1 g of ice at 0°C. What is the change in entropy of 30 g of water at 0°C as it is changed to ice at 0°C by a refrigerator? **(-36.8 J K^{-1})**