UNIT 8

HEAT AND THERMODYNAMICS

How thermodynamics plays its role in the human bodies, in terms of work and energy?

Student Learning Outcomes (SLOs)

The students will:

- State that regions of equal temperatures are in thermal equilibrium.
- Relate a rise in temperature of an object to an increase in its internal energy.
- Apply the equation of state for an ideal gas.
- State that the Boltzmann constant is given by: $k = R/N_A$
- Describe the basic assumptions of the kinetic theory of gases.
- Use $W = p\Delta V$ for the work done when the volume of a gas changes at constant pressure.
- Describe the difference between the work done by a gas and the work done on a gas.
- Define and use first law of thermodynamics.
- Explain qualitatively, in terms of particles, the relationship between the pressure, temperature and volume of a gas.
- Use the equation, including a graphical representation of the relationship between pressure and volume for a gas at constant temperature.
- Justify how the first law of thermodynamics expresses the conservation of energy.
- Relate a rise in temperature of a body to an increase in its internal energy.
- State the working principle of a heat engine.
- Describe the concept of reversible and irreversible processes.
- State and explain the second law of thermodynamics.
- State the working principle of Carnots' engine.
- Describe that refrigerator is a heat engine operating in reverse as that of an ideal heat engine.
- Explain that an 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 tends to become less orderly over time.
- Explain that Entropy, S, is a thermodynamic quantity that relates to the degree of disorder of the particles in a system.
- State that the Carnot cycle sets a limit for the efficiency of a heat engine at the temperatures of its heat reservoirs given by: $\text{Efficiency} = 1 - \frac{T_{\text{cold reservoir}}}{T_{\text{hot reservoir}}}$

UNIT 8 HEAT AND THERMODYNAMICS

The concept of temperature is rooted in qualitative ideas of "hot" and "cold" based on our sense of touch. A body that feels hot usually has a higher temperature than a similar body that feels cold. However, many properties of matter that we can measure depend on temperature. The length of a metal rod, steam pressure in a boiler, the ability of a wire to conduct an electric current, and the color of a very hot glowing object—all these depend on temperature. Temperature is also related to the kinetic energies of the molecules of a material.

Heat is the form of energy associated with the kinetic energies of all the molecules in a substance and its unit is joule. Temperature describes the degree of hotness and coldness of an object and it is the measure of average kinetic energy of the molecules and its unit is kelvin.

8.1 THERMAL EQUILIBRIUM

Two systems are in thermal equilibrium with each other, if they are at the same temperature.

The temperature is the main property that determines whether two systems will be in thermal equilibrium or not. When two bodies at different temperatures are connected by a **diathermic substance**, heat starts flowing between them from the higher temperature body to the lower temperature body until their temperatures become equal and after that no net heat flow takes place between them, as shown in the Fig 8.1 (a). They are now said to be in thermal equilibrium. Thus, we can state that when two bodies are in thermal equilibrium (at same temperature), no net heat flow takes place between them. A system is said to be in thermal equilibrium with the surroundings, if each part of the system and the surrounding are at the same temperature.

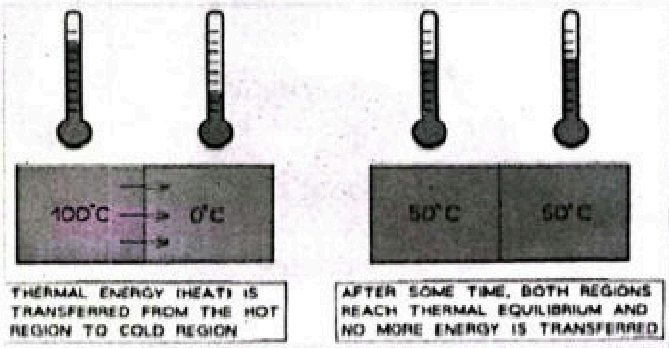


Figure 8.1(a): Thermal equilibrium.

Do You Know?

Diathermic substances are those substances that allow heat to pass through them and the process is called a diathermic process.

For Your Information

System: The matter or space region that is being studied is called a "system." For example, a gas in a cylinder, etc.

Surroundings of the system: The term "surroundings" refers to everything outside the system.

Boundary of the system: A system is separated from the surroundings by its boundary. All energy changes, caused by the work done or heat exchange between the system and its surroundings, take place through this boundary.

Types of the systems:

Closed system: It is a system in which heat energy can enter or leave the system but mass cannot do either. An example of a closed system is a container sealed on all sides.

Open system: A system in which both heat energy and mass can enter or leave it, is called open system. An example of open system is a glass beaker with an open top which allows matter (i.e., water) to be added or removed, as well as, heat to be added or removed.

Isolated system: A system in which there is no transfer of mass and heat energy across its boundary is called an isolated system. An example of it is a thermos flask filled with hot water.

8.1.1 Internal Energy

The sum of all the forms of molecular energies (such as kinetic and potential energy) of a substance is called internal energy. An ideal gas is one in which all collisions between atoms or molecules are perfectly elastic and there are no intermolecular attractive forces between them. The internal energy of an ideal gas system is generally the translational K.E of its molecules. Molecules of a gas are always in random motion. According to the kinetic theory of gases, the average kinetic energy of gas molecules is given by:

$$<\frac{1}{2}mv^2> = \frac{3}{2}kT \quad \text{(8.1)}$$

Do You Know?
When a substance melts or boils, energy is required to break the bonds holding the particles together, which increases the potential energy.

Where k is Boltzmann's constant. If temperature increases, the average kinetic energy of gas molecules also increases. Therefore, the internal energy increases with rise in temperature.

Since temperature is directly proportional to average kinetic energy of gas molecules, i.e. $T \propto <K.E>$. Therefore, the internal energy of an ideal gas is directly proportional to its temperature.

The internal Energy of a system can be increased by heating and doing mechanical work. When we heat a substance, energy associated with its atoms or molecules increases. i.e., heat is converted into internal energy. Similarly, when two objects are rubbed together, their internal energy increases due to the mechanical work. The increase in temperature of the object indicates an increase in its internal energy. Likewise, when an object slides over a surface and comes to rest due to frictional forces, the mechanical work done on or by the system is partially converted into internal energy. In study of heat changes and heat flow, we focus on the changes in the internal energy of a substance with changes in temperature indicating these changes in internal energy.

DO YOU KNOW?
A piece of metal is hammered. Does its internal energy increases?

In thermodynamics, internal energy is function of state. Consequently, it does not depend on the path but depends on initial and final states of the system.

Consider a system which undergoes a pressure and volume change from P_1 and V_1 to P_2 and V_2, regardless of the process by which the system changes from initial to final state, as shown in the Fig. 8.1 (b). The change in internal energy is the same and is independent of the paths C_1 and C_2 and it depends on the temperature difference between two points. Like the gravitational P.E we take the change in internal energy and not its absolute value, which is important.

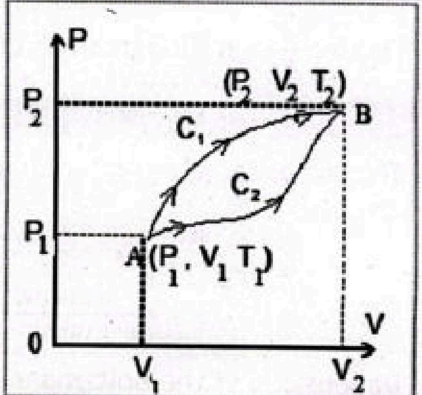


Figure 8.1 (b): PV graph of a system.

In case of real gases, the molecules exert mutual force of attraction on one another. The internal energy of real gas is partially kinetic energy and partially intermolecular potential energy and hence it is function of temperature and volume.

Sign Conventions: If initial internal energy is U_1 at initial temperature T_1 and final internal energy U_2 at final temperature T_2, then change in internal energy = $\Delta U = U_2 - U_1$.

- When the temperature of a system increases then its internal energy increases ($U_2 > U_1$) and the change in internal energy ΔU is positive.
- When the temperature of a system decreases then its internal energy decreases ($U_2 < U_1$) and the change in internal energy ΔU is negative.
- When the temperature of a system remains constant then its internal energy remains constant (i.e., $U_2 = U_1$) and the change in internal energy ΔU is zero.

8.1.2 Ideal Gas Equation and its Applications

It is an equation of state of an ideal gas that relates pressure, volume, quantity of gas, and temperature. The ideal gas equation is written as:

$$PV = nRT \quad \text{\_\_\_\_\_ (8.2)}$$

In this equation, P refers to the pressure of the ideal gas, V is its volume, n is its number of moles, R is the universal gas constant (R = 8.314 $J\,mol^{-1}K^{-1}$), and T is its temperature.

Do You Know?

What are ideal gas conditions?

There are some assumptions that must hold true for a gas to be "ideal.":

- The gas particles have negligible volume.
- The gas particles are equally sized and do not have intermolecular forces (attraction or repulsion) with other gas particles.
- The gas particles undergo perfectly elastic collisions with no energy loss.

If N_A is Avogadro number and N is total number of gas molecules, then number of moles can be expressed as: $n = \frac{N}{N_A}$

For Your Information

Unit of Boltzmann constant is same as that of entropy J K^{-1}.

Hence, equation (8.2) can be written as:

$$PV = \frac{NRT}{N_A} \quad \text{or} \quad PV = N\left(\frac{R}{N_A}\right)T$$

Putting $\frac{R}{N_A}$ = k (Boltzmann's constant), we get:

$$PV = NkT \quad \text{\_\_\_\_\_ (8.3)}$$

The numerical value of Boltzmann constant k can be estimated as:

$$k = \frac{R}{N_A}$$

$$k = \frac{8.314\ J\,K^{-1}mol^{-1}}{6.022140857 \times 10^{23} mol^{-1}.} = 1.3806452 \times 10^{-23}\ J\,K^{-1}$$

Dimensions of the Boltzmann constant are $[ML^2T^{-2}K^{-1}]$.

Example: 8.1: Calculate the average translational kinetic energy of molecules in a gas at room temperature.

Given: Temperature = T = 25 C° = 25 + 273 = 298 K

To Find: Average translational kinetic energy = <K.E> =?

Solution: As $\langle K.E.\rangle = \frac{3}{2} kT$

Where k = Boltzmann constant = 1.38×10^{-23} J K^{-1}

Thus, $\langle K.E.\rangle = \frac{3}{2} \times 1.38 \times 10^{-23} \times 298$

$\langle K.E.\rangle = 6.17 \times 10^{-21}$ J

Assignment: 8.1

Estimate the total number of air molecules (including molecules of oxygen, nitrogen, water vapour and other constituents) in a room of capacity 20.0 m^3 at a temperature of 27 °C and 1 atm pressure.

8.2 KINETIC THEORY OF GASES

In the 19th century, James Clark Maxwell, Rudolph, Clausius and others developed the kinetic theory of gases to explain the behaviour of gases. According to the theory, a gas is composed of a number of tiny, hard spheres (molecules) that collide with one another and with the container walls. These molecules move in accordance with Newton's laws of motion. It explains how the motion of molecules influences the macroscopic properties of gases, such as temperature and pressure. It relates macroscopic properties (T, P, and V etc.) of gases to microscopic properties (K.E etc.).

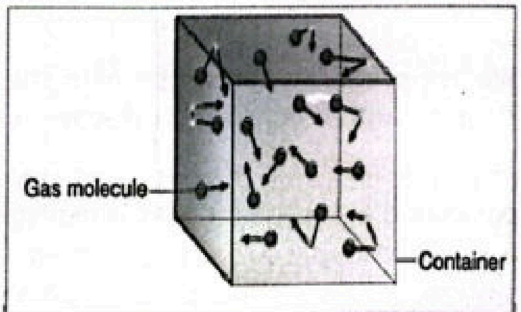


Figure 8.2: Gas molecules in a container.

Assumptions of Kinetic Theory of Gases: The following are the assumptions of the kinetic theory of gases:

- A finite volume of gas consists of a very large number of molecules.
- The size of the molecules is much smaller than the separation between them.
- The gas molecules are in random motion and may change their direction of motion after every collision. Collisions between gas molecules and with the walls of the container are assumed to be perfectly elastic.
- Molecules exert no force on each other except during a collision.

Condition for Real Gas to Behave as an Ideal Gas: According to general gas equation:

$$PV = n\,RT$$

Putting, $n = \frac{Mass\ of\ gas}{moler\ mass} = \frac{m}{M}$, we get:

$$PV = \left(\frac{m}{M}\right) RT \quad \text{or} \quad PM = \left(\frac{m}{V}\right) RT$$

Putting, $\frac{m}{V} = \rho$ (density of gas), we get:

$$PM = \rho\, RT$$

Do You Know?

Work is a form of energy, and it has units of joule (where 1 J = kg m^2 s^{-2}). You may also see other units used, such as atmospheres for pressure and liters (l) for volume, resulting in l-atm (liter atmosphere) as the unit for work.

or $$\rho = \frac{PM}{RT} \qquad (8.4)$$

For given mass of the gas, we can write above equation as: $\rho \propto \frac{P\,M}{T}$

This equation suggests that at low pressure and high temperature, the density of gas will be low. Moreover, the distance between gas molecules becomes large, leading to the negligible intermolecular forces. In this situation, a real gas behaves as an ideal gas. Conversely, at high pressure and low temperature, the density of gas will be high while the distance between gas molecules will be small and intermolecular forces will be stronger; therefore, a real gas cannot behave as an ideal gas.

8.2.1 Work in Thermodynamics

Both heat and work correspond to the transfer of energy by some means. One of the main ways, energy enters or leaves a system is through work. To calculate the work done by a constant force, we can use the following general equation:

Work = Force × Displacement

We are primarily concerned with the work that gases do when they expand or contract in thermodynamics.

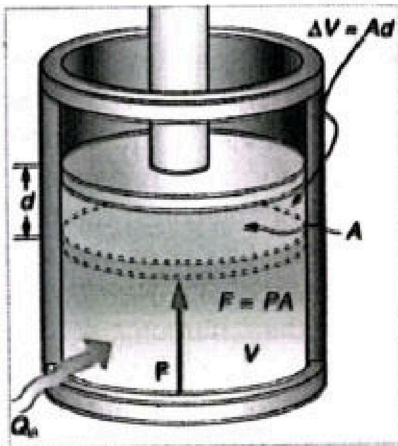


Figure 8.3: Work done by the gas

Pressure-Volume Work: Let us consider a gas that is contained in a cylinder with a movable, frictionless piston with a cross-sectional area A, as shown in the Fig. 8.3. When the system is in equilibrium, it occupies a volume "V" and exerts pressure "P" on the cylinder's walls and the piston, i.e.,

$$P = F/A \quad \text{Or} \quad F = PA$$

This is the force exerted by the gas on the piston. The gas gradually expands by ΔV in order to maintain equilibrium. A little distance = d = Δy is covered by the piston as it rises. The work done by the gas is given by: $W = F\,\Delta y$

Putting F = PA, we get: $W = P\,A\,\Delta y$

Since $A\,\Delta y = \Delta V$ (change in volume), so

$$W = P\Delta V \qquad (8.5)$$

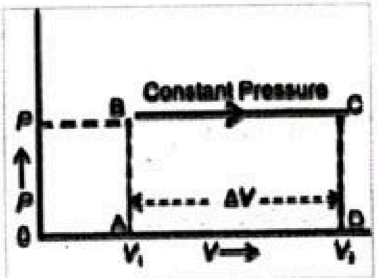


Figure 8.4: Area of P-V graph equals Work done.

This is the work done by gas on piston. Where P is the external pressure (as opposed to the pressure of the gas in the system) and ΔV is the change in the volume of the gas, which can be calculated from the initial and final volumes of the gas:

$$\Delta V = V_{final} - V_{initial}$$

Graphical Representation: Work done can be calculated from the area under a P-V graph. From Fig. 8.4 the area under the P-V graph = P ΔV = work.

Example 8.2: A 2 kg of argon gas is heated to a temperature of 30 °C. If the gas is contained in a cylinder of radius 1 m and height 2 m, what is the pressure of the gas?

Given: mass = m = 2 kg Temperature = T = 30 °C = 30 + 273 = 303 K

r = 1 m h = 2 m

To Find: Pressure = P = ?

Solution: Volume = V = (πr^2)h

$V = 3.142\,(1)^2 \times 2 = 6.284\ m^3$

$n = \frac{mass\ of\ gas}{molar\ mass} = \frac{2000\ g}{40\ g\ mol^{-1}} = 50$ mol

From general gas equation PV= n RT (where, $R = 8.314\ JK^{-1}\ mol^{-1}$)

$P = \frac{nRT}{V}$ or $P = \frac{50 \times 8.314 \times 303}{6.284} = 20044$ Pa

Assignment 8.2

A sample of gas is compressed to one third of its initial volume at constant pressure of $2.25 \times 10^5\ N\ m^{-2}$. During the compression, 200 J of work is done on the gas. Determine the final volume of the gas.

8.2.2 Difference between Work Done by the Gas and on the Gas

In thermodynamics, work done is given by:

$$W = P\Delta V$$

Positive Work Done: When gas expands, it is said that work is done by the gas (system) on the surroundings. Due to the expansion of gas, the final volume will be greater than the initial volume. So, the change in volume of the gas is positive, i.e., $\Delta V > 0$, as shown in the Fig. 8.5. Therefore,. the work done by the gas on the surroundings is positive. Mathematically,

$$W = +P\Delta V$$

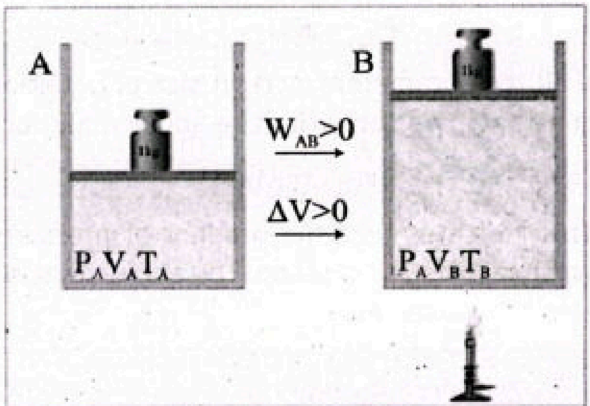


Figure 8.5: Work done by the system.

Therefore, when a gas expands, we can say that the work done by the system on the surroundings is positive.

Negative Work Done: When gas contracts, the final volume of the gas is smaller than the initial volume. So, the change in volume of the gas is negative, i.e. $\Delta V < 0$, as shown in the Fig. 8.6. Therefore, the work done on the gas by the surroundings is negative. Mathematically,

$$W = -P\Delta V$$

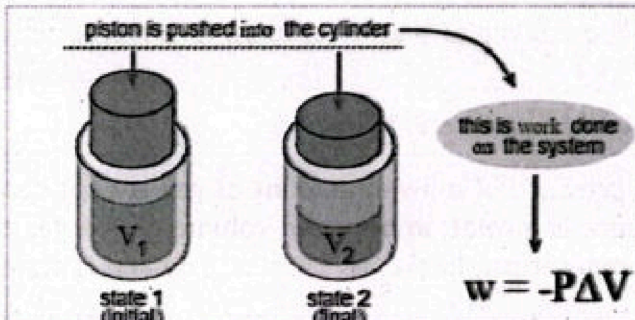


Figure 8.6: Work done on the system.

Therefore, when a gas contracts, we can say that the work done by the surroundings on the system is negative.

Zero Work Done: If volume remains constant, then change in volume is zero (i.e., $\Delta V = 0$), and the work done is zero.

$$W = P\Delta V$$

or $$W = P(0) = 0.$$

8.3 THE GAS LAWS

It is a common observation that whenever we change the external conditions like temperature and pressure, the volume of a given quantity of any gas is affected. Gas laws provide the relationships between the volume of given amount of a gas and variables like temperature or pressure.

8.3.1 Boyle's Law

For an ideal gas system with fixed quantity at constant temperature, the pressure and volume are related by the Boyle's law. This relationship can be derived from ideal gas equation:

$$PV = nRT \quad \_\_\_\_\_ \quad (8.6)$$

If all the parameters on right side of equation are constants, we can write the above equation as:

$$PV = \text{Constant}$$

This indicates that the product of pressure and volume remains constant. The above relation can also be written as:

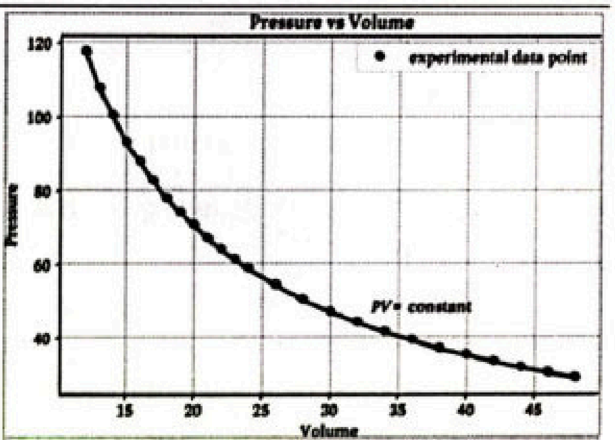


Figure 8.7: Boyle's law.

$$V \propto \frac{1}{P}$$

As the pressure increases, volume of the gas decreases and vice versa, graphically it is shown in Fig. 8.7. Therefore, Boyle's law can be stated as:

The volume of a given amount of a gas at constant temperature is inversely proportional to the pressure applied.

8.3.2 Charles's Law

If pressure of a given amount of gas is kept constant, there is a relation between volume of the gas and its temperature, known as Charles' law and is stated as:

The volume of a given amount of a gas at constant pressure is directly proportional to the absolute temperature.

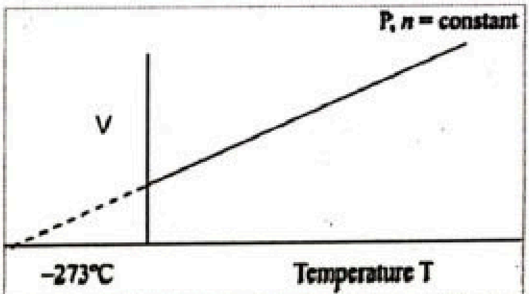


Figure 8.8: Charles's law.

The general gas law can then be expressed as:

$$V \propto T \quad \text{or} \quad \frac{V}{T} = \text{constant}$$

Graphically, it is shown in Fig. 8.8. This graph also indicates that at temperature -273 °C the volume of all gases reduces to zero showing that a gas cannot exist at such a low temperature.

8.3.3 Gay Lussac's Law

To find the relation between pressure and temperature of given amount of a gas at constant volume, we refer Amontons's law, also called as Gay Lussac's law, which can be stated as:

The applied pressure of a given amount of a gas at constant volume is directly proportional to the absolute temperature.

Mathematically:

$$P \propto T \quad \text{or} \quad \frac{P}{T} = \text{constant}$$

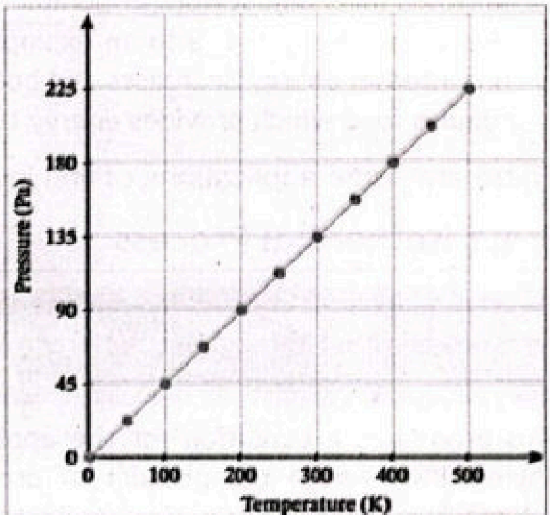


Figure 8.9: Gay Lussac's law.

Graphically, the Gay Lussac's law is shown in Fig. 8.9. For all gas laws, the temperature is expressed in Kelvin scale.

8.4 FIRST LAW OF THERMODYNAMICS

Whenever heat is added to a system, the internal energy of the system increases due to the rise in temperature of the system. At the same time, if the system is allowed to expand, it may do work on its environment. First law of thermodynamics is based on law of conservation of energy applied on thermodynamic process. The first law of thermodynamics can be stated as:

When heat (Q) is added to a system, it increases the internal energy (ΔU) of the system along with doing work done (W) by the system on the environment.

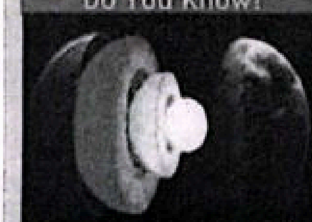
Mathematically, it is written as:

$$Q = \Delta U + W \quad \text{\_\_\_\_\_\_} \quad (8.7)$$

Similarly, when heat is removed from the system, its internal energy decreases and the work will be done on the system due to compression in a gas (system).

The change in internal energy $\Delta U = U_f - U_i$ of the system depends only on the initial and the final states of the system; it is independent of the path followed. It is the change in internal energy which is important, that is why we use change in internal energy in spite of absolute value of internal energy.

Do You Know?



How can you measure the temperature of core of Earth?

Examples: First law of thermodynamics dictates the behavior of heat energy:

- Melting of ice cubes is an example of first law of thermodynamics.
- Sweating in a crowded room is also an example of first law of thermodynamics, in which heat from a person's body transfers to sweat, which take away heat of the body but warms the *room* by increasing the temperature of atmosphere in the room.
- Filling the air in the tube of a car wheel is also an example of first law of thermodynamics, in which mechanical work of pumping the gas increases internal energy of system.
- Human metabolism is also an example of first law of thermodynamics, when we do work our internal energy decreases and body temperature falls. To maintain internal energy, we require food which provides energy to our bodies.

There are some applications of first law of thermodynamics, which are given below.

8.4.1 Isothermal Process

A thermodynamic process in which temperature remains constant throughout the process is called isothermal process.

This process is a condition for the application of Boyle's law, where the product of pressure and volume remains constant. For understanding the process, consider an ideal gas, as shown in Fig. 8.10. Initially at pressure P_1 and volume V_1. After heating the system, the moveable piston moves outward by increasing the volume to V_2 and decreasing the pressure to P_2, while temperature of gas remains constant. Hence, such that product of pressure and volume will remain same for both initial and final values. In this example, as the gas expands, work is done by the gas, if gas compresses the work will be done on the gas. Furthermore, the internal energy of the system remains constant, i.e., $\Delta U = 0$, due to constant temperature. Hence, for isothermal process, the first law of thermodynamics is written as:

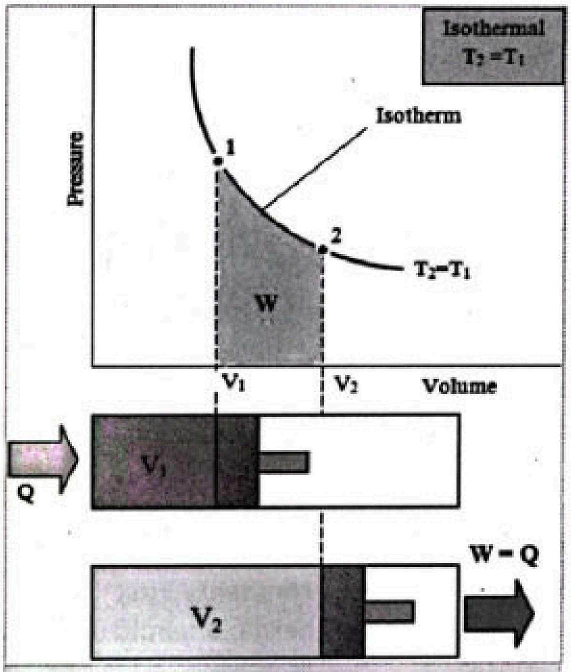


Figure 8.10: Iso-thermal process.

$$Q = 0 + W$$

or $$Q = W \qquad (8.8)$$

The above equation shows that for a gas to expand isothermally, some amount of heat Q is to be given to the system to do work. As heat takes time to move from one place to another, hence isothermal process should be carried out slowly to keep the temperature constant.

The curve representing isothermal process is called isotherm.

Do You Know?

Humans learnt to use of fire to raise the temperature much earlier than use of heat for mechanical work, e.g., like in steam engines. Do you know of a reason why this could be true?

Isotherm is represented in the graph of Fig. 8.10, whereas the shaded area represents work done. Some common examples of isothermal process include:

- Melting of ice at zero degrees centigrade is an example of isothermal process.
- Changing states of different liquids through the process of melting and evaporation.
- Reaction in a heat pump is also an example of isothermal process.

Do You Know?

How clouds are formed in the atmosphere?

8.4.2 Adiabatic Process

If we do not supply or remove heat from the system, can the system still perform work? Yes, when a system expands without addition of heat, it still does work.

A process in which no heat or mass transfers between a thermodynamic system and its surroundings is called an adiabatic process.

In adiabatic process, the system transfers energy only to the surroundings as work. Hence, for adiabatic process, the first law of thermodynamics is written as:

For $Q = 0$, $W = -\Delta U$

This equation shows that if no heat is supplied to the system and system still expands and perform work, this work is done at the expense of internal energy.

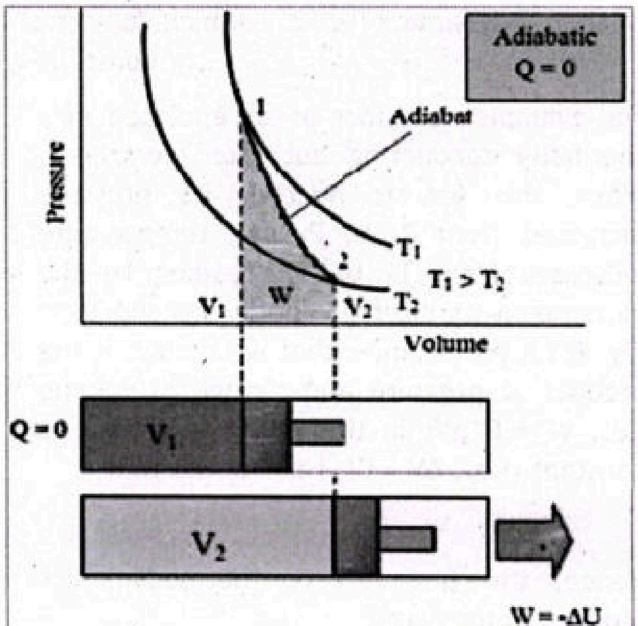


Figure 8.11: Adiabatic process.

In adiabatic process, if gas expands and does work, its temperature and internal energy decreases. While if gas is compressed adiabatically, its temperature and internal energy increases. In an adiabatic process, the gas expands or compresses rapidly.

The curve representing adiabatic process is called adiabat.

Adiabat is represented in the graph in Fig. 8.11. Some examples of adiabatic process are:

- The rapid compression and expansion of air as sound wave passes through the it.

For Your Information

Blow air onto your hand with your mouth wide open and then with your lips puckered. When does the air feel cooler and why? Assume the process is so fast that $Q = 0$.

- The vertical flow of air in the atmosphere, air expands and cools as it rises, and contracts and gets warms as it descends.
- Expansion and contraction of gas cloud in interstellar regions.

In case of adiabatic process, Boyle's law gets the form:

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

8.4.3 Isochoric Process

When you heat a gas in closed container, what will happen? There are some thermodynamic processes in which system does not change its volume; such a process is called isochoric process.

A thermodynamic process in which volume of the system remains constant is called isochoric or constant-volume process.

For example, consider a gas enclosed in a thermally conducting but fixed container. When this gas is heated, its pressure increases from P_1 to P_2 and temperature increases from T_1 to T_2, leading to the increase in its internal energy, as shown in Fig. 8.12. As we know that work done is the product of pressure and change in volume i.e., $W = P\,\Delta V$. In this case, as volume is constant (i.e., $\Delta V = 0$), this implies that

$$W = 0$$

Hence, the first law of thermodynamics reduces to the form:

$$Q = \Delta U$$

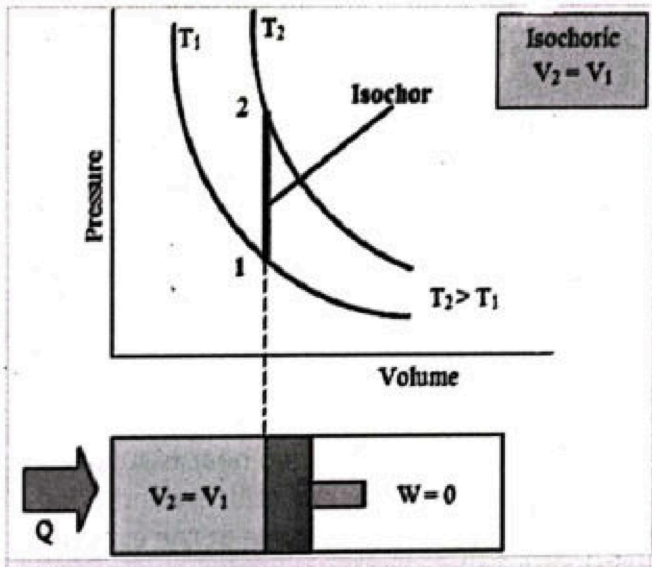


Figure 8.12: Iso-choric process.

This means that in isochoric process, all the heat given to the system will be utilized in increasing its internal energy. On the other hand, if heat is removed from the system in isochoric process, both temperature and pressure of the system decrease. The P-V graph of isochoric process is a vertical line and called "isochor". Examples of isochoric process include:

- Cooking food in a pressure cooker: a closed container where when heat is supplied the temperature and pressure get increased.
- When gasoline-air mixture is burnt in the engine of a car, it increases the pressure and temperature of the gas but volume of a gas remains constant.

8.4.4 Isobaric Process

The term isobaric is derived from the Greek word 'iso' meaning same and 'baros' meaning pressure. In isobaric process, when heat is transferred to the system, some work is done, and there is also a change in internal energy of the system. It is the process in which no quantities in the first law of thermodynamics becomes zero.

A thermodynamic process in which pressure of the system remains constant is called isobaric.

Do You Know?

How a balloon under varying atmospheric temperature may be in isobaric state?

When a gas expands slowly due to heat being supplied while keeping the pressure constant, it is an example of isobaric process.

Let's consider a gas in the container with a cross-sectional area A, as shown in Fig. 8.13, with initial pressure, temperature and volume P, T_1 and V_1 respectively. When this gas is supplied a certain amount of heat Q, its temperature and volume changes to T_2 and V_2 respectively, while pressure remains constant. As the gas expands, it does work and its internal energy also increases. Mathematically, the force is expressed as:

$$F = P A$$

If the gas undergoes a displacement Δy, then work done by the gas is expressed as:

$$\text{Work} = (\text{Force})\ (\text{Displacement})$$

$$W = P A \Delta y = P \Delta V$$

$$Q = \Delta U + W$$

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

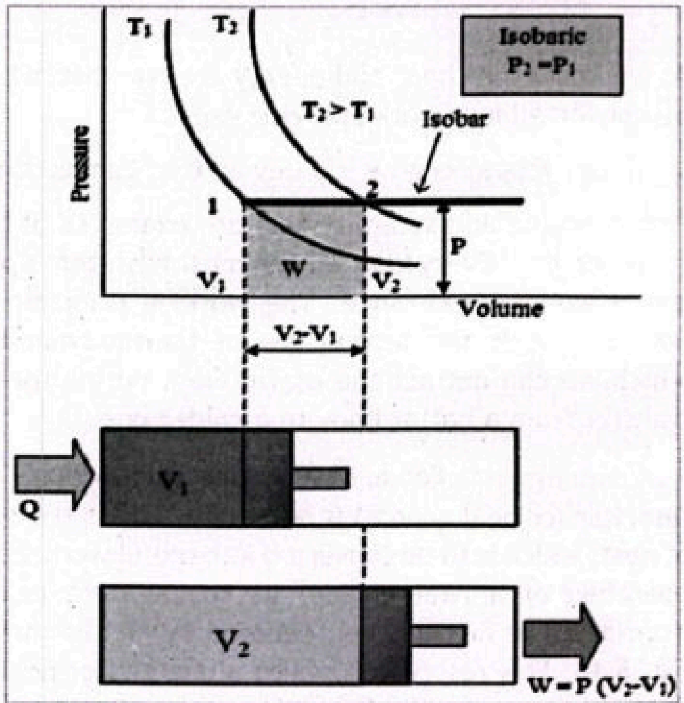


Figure 8.13: Iso-baric process.

The P-V graph of an isobaric process is a horizontal line, called 'isobar'. The area under isobar is equal to work done. Examples of isobaric process include:

- Boiling of water to steam in an open container.
- Solid moth ball (made of solid material which, at room temperature slowly changes to gas and becomes fumes in air) in your linen closet sublimating into an insect repelling gas.
- Ice formation in nature in which volume changes to compensate energy removal, while pressure remains constant.

Example 8.3: If the internal energy of a gas decreased by 200 J, while 50 J work is done by the gas. How much energy is transferred as heat? Is the work done positive or negative?

Given: $\Delta U = 200\ kJ$ $W = 50\ J$

To Find: Heat $Q = ?$

Solution: By using first law of thermodynamics, we have:

$$Q = \Delta U + W = -200\ J + 50\ J = -150\ J$$

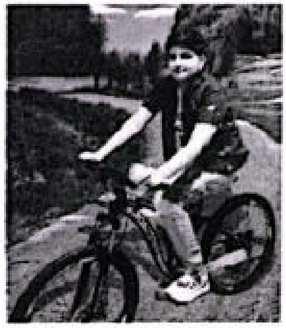
Negative sign shows that heat is given out of the system.

Assignment 8.3

A cup is filled with hot tea and a spoon is used for stirring purpose. Initially the tea has an internal energy of 200 kJ. On cooling, it loses 150 kJ of heat. The spoon does 25 kJ of work while stirring. Find the change in the internal energy of the tea and the final internal energy of the tea.

Do You Know?

How thermodynamics plays a role in the human bodies, in terms of work and energy? Thermodynamics also applies to the living bodies like human. This forms the basis of the biological thermodynamics. As in the cover picture of this chapter, a boy is eating an apple and also riding a bicycle. When he rides a bicycle, heat (Q) is transferred out of the body and work (W) is done by him which removes the internal energy (U). Do you know from where human gets the energy for all this process? Human and other living things get energy from the food intake which may be considered as work done on the body (system).



8.5 HEAT ENGINE

As we know that heat and energy are two distinct quantities but are closely related; heat can be converted into work and vice versa.

A heat engine is a device that converts heat energy into mechanical work.

Petrol engine and steam engine are examples of heat engine. The earliest heat engine was a steam engine. Every heat engine must have three parts, namely a hot reservoir, a cold reservoir and a working substance. The working principle of a heat engine is the second law of thermodynamics in which we can extract the useful work during the heat transfer from a hotter body to a colder one.

Hot Reservoir: For a heat engine to function, a hot reservoir (or heat source) is necessary. This is the source of heat, which is to be converted into useful work. For the operation of a heat engine, its temperature must be maintained at higher level, denoted by 'T_1' as shown in Fig. 8.14. This reservoir supplies a quantity of heat 'Q_1' flowing towards low temperature.

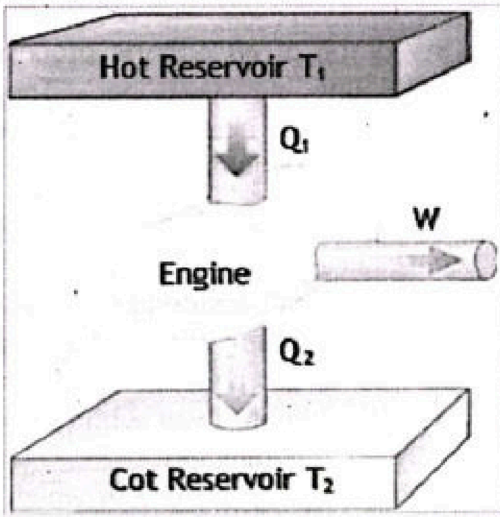


Figure 8.14: Heat engine.

Cold Reservoir: For a heat engine, a cold reservoir (or heat sink) is another necessary part. The difference between the temperatures of both reservoirs is responsible for the heat flow. Heat sink absorbs heat 'Q_2' at temperature 'T_2' from heat source. Cold reservoir is essential for the operation of heat engine, as heat can only flow when there is a difference.

Working Substance: In a heat engine, a working substance is the main part which practically converts heat into useful mechanical work. Working substance in most of the heat engines is a gas. It performs work due to the heat flowing from heat source to the heat sink. Mathematical relation for work done for heat engine is given as:

$$W = Q_1 - Q_2$$

For continues operation of the heat engine, it is made cyclic. Leonard Sadi Carnot invented the first heat engine. It was a type of hot air engine.

Thermodynamics and Auto-engine

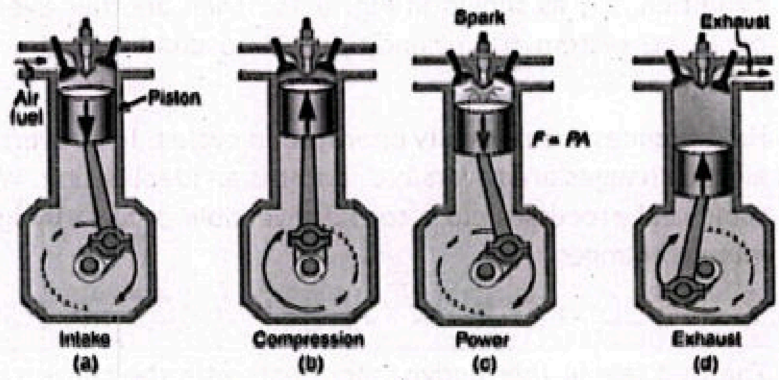
A petrol engine of a car extracts heat from burning fuel and converts some of its energy into mechanical work. The engine expels rest of energy to the atmosphere. A petrol engine roughly has efficiency of about 25% to 30%. Motorbikes normally has two cylinders whereas cars have four cylinders on the same crankshaft timed to fire turn by turn in succession for smooth running of car. It has four steps of working.

Intake Stroke: In this stroke, the piston moves downward and petrol-air mixture is drawn through inlet valve, as shown in figure (a).

Compression Stroke: In this stroke, piston moves upward, inlet valve closed and petrol-air mixture compresses adiabatically, as shown in figure (b).

Power Stroke: A spark ignites the mixture, causing a rapid increase in temperature and pressure, expands adiabatically, and hence forces the piston to move downwards. This is the stroke which delivers the power to the engine and hence called power stroke, as shown in figure (c).

Exhaust Stroke: in this stroke piston moves upward. Outlet valve opens and residual gases are expelled out into the atmosphere as shown in figure (d).



8.6 REVERSIBLE AND IRREVERSIBLE PROCESSES

In thermodynamics, a process occurs, when exchange of energy takes place between the system and its surroundings. There are mainly two types of processes in thermodynamics: reversible and irreversible processes.

Reversible Process:

A process which can be retraced in exactly reverse order without causing any change to its surroundings is called reversible process.

For example, if heat is absorbed in a direct process, it will be evolved in the reverse process. If work is done by the system in direct process, it will be done on the system in reverse process. In reality, no actual change is exactly reversible but some changes can be taken as reversible if done slowly. Some examples of reversible process are:

- The transformation between water and ice.
- Liquefaction and evaporation of a substance performed slowly.

Thermodynamics and Thermometry

A thermodynamic scale of temperature is a scale which has two fixed points. One is absolute zero (0 K) and the other is the triple point of water. The triple point of water is the temperature at which water co-exists in all three states i.e. solid (ice), liquid and gas (vapors). Its value is 273.16 K.

- Melting, freezing, boiling, and condensing are the reversible processes.

Irreversible Process:

A process which cannot be retraced in exactly the reverse order without causing a change into its surroundings is called irreversible process.

Examples of irreversible processes include:

- Any process involving friction or dissipation of energy.
- Decaying of animals and plants.
- Convection, conduction and radiation are irreversible process.

Cyclic Process:

A succession of events which bring the system back to its initial condition is called cyclic process.

For example, an event 'A' brings the system from condition '1' to condition '2', as shown in Fig. 8.15. Then another event B brings back the system from condition '2' to condition '1', is a cyclic process.

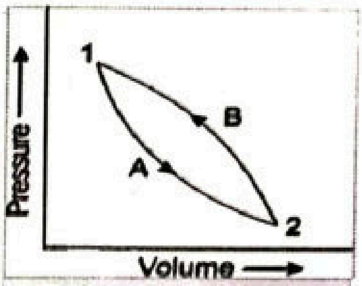


Figure 8.15: A cyclic process.

Heat engines are normally operated in cycles. In a reversible cycle, all the changes are reversible, but it is an idealization. We can take some real processes close to the reversible process by ignoring the minute changes.

8.7 SECOND LAW OF THERMODYNAMICS

The first law of thermodynamics deals with the conversion of heat into work and vice versa; it is simply law of conservation of energy. However, it does not address the conditions under which this conversion takes place. For finding this condition, we require another law, the second law of thermodynamics. This law deals with the circumstances under which heat can be converted into work and also the direction heat flow. It can be stated in two different ways as:

Lord Kelvin's Statement:

It is impossible for a heat engine to convert heat taken from single reservoir entirely into work without leaving any change in the working system.

Do You Know?
What may be the net change in internal energy in cyclic process?

It is clear that in any heat engine, a single heat reservoir, no matter how much energy it contains, cannot be made to perform any work. This is why heat content of our atmosphere cannot be utilized for work, as it is a single source and there is no sink relative to it.

Rudolf Clausius's Statement:

It is impossible to cause heat to flow from cold body to hot body without the expenditure of work.

Second law of thermodynamics explains that both a hot and a cold reservoir are essential for a working substance to do work. As from Fig. 8.14, a heat source Q_1 rejects heat towards a heat sink Q_2 at lower temperature, while some of the heat is converted into mechanical work W, which can be given as:

$$W = Q_h - Q_c$$

In a cyclic process, the substance eventually returns to its initial state, so the change in internal energy is equal to zero i.e., $\Delta U = 0$.

For Your Information

The second law of thermodynamics is a fundamental principle in physics that addresses the direction of natural processes and even the concept of entropy. This law explains the heat naturally flows from hot objects to cold ones and not the opposite way i.e. from cold to hot one. This can be explained if you put a cup of hot tea in a room with air-conditioner is running the tea will cool down due to low temperature of the room but when you switch off the A.C and after sometime the temperature of the room increases but the tea will not get warm up to the initial level. This shows that naturally heat can only flow in one direction i.e. from hotter body to colder one.

8.8 CARNOT'S ENGINE

A Carnot heat engine is a theoretical engine that operates on the principle of Carnot cycle. This concept was introduced by Sadi Carnot in 1824. A heat engine operating in an ideal reversible cycle between a heat source and a heat sink would be the most efficient engine. For the operation of Carnot engine, we consider Carnot cycle using an ideal gas as working substance. The working principle of Carnot's engine is the isothermal and adiabatic processes. Carnot's engine works in a cycle on the isothermal expansion, adiabatic expansion, isothermal compression and finally adiabatic compression to reach the initial state while taking some useful work at output. This working process in the form of P-V diagram is shown in Fig. 8.16. This cycle can be explained in four steps as:

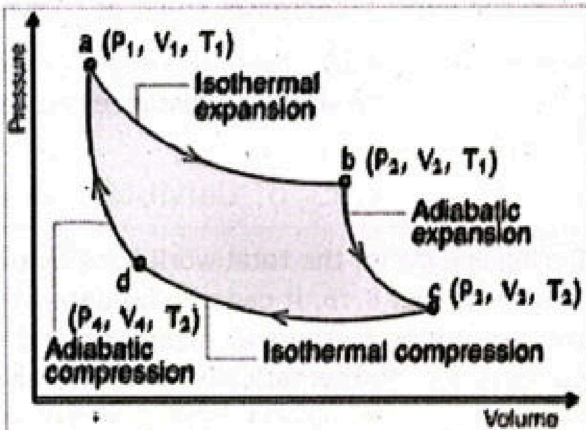


Figure 8.16: P-V diagram for Carnot cycle.

1) Isothermal Expansion: In the first step, the gas is allowed to expand isothermally at pressure P_1 and volume V_1. The temperature of the gas remains high at this moment, represented by T_1. Absorbing heat Q_1 from hot reservoir, the pressure of gas decreases to P_2 and volume increases to V_2. Hence, work is done by the gas, while temperature remains constant. The isotherm expansion is represented by portion 'ab' in Fig. 8.16 and mechanically shown in Fig. 8.17 (A).

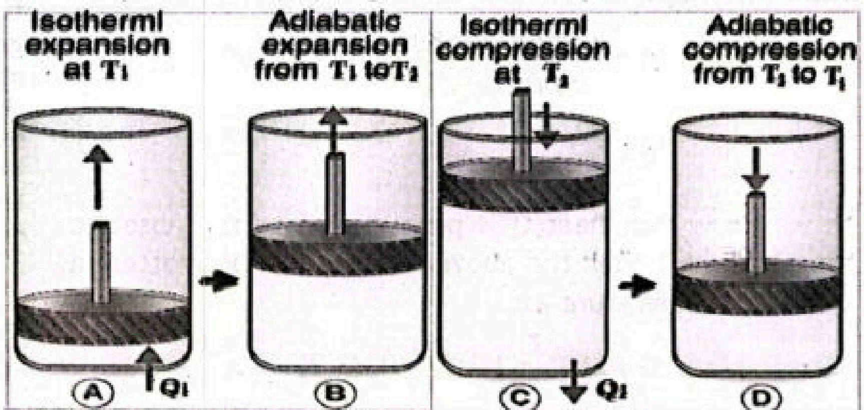


Figure 8.17: Working of Carnot engine.

2) Adiabatic Expansion: In this step, the cylinder is insulated so that gas neither absorbs nor releases the heat, as shown in Fig. 8.17 (B). The gas expands adiabatically, causing the temperature of the gas drops from high temperature T_1 to a low temperature T_2. As shown in adiabat (the portion of cycle represented by 'bc' in Fig. 8.16), the pressure further decreases to P_3 and volume further increases to V_3, causing the piston moves outwards by doing work, as shown in Fig. 8.17 (B).

3) Isothermal Compression: In this process, the gas is kept at low temperature T_2 and it compresses by rejecting heat Q_2, as shown in Fig. 8.17 (C). The pressure in this case increases to P_4 while volume decreases to V_4 and hence work is done on the gas. The isotherm for this case is represented by curve 'cd' in Fig. 8.16.

Adiabatic Compression: Finally, the gas is once again placed in insulated cylinder, ensuring that no heat enters or leaves the gas. The gas is compressed adiabatically to increase its temperature from T_2 to T_1, as shown in Fig. 8.17 (D). During this step, the pressure increases to P_1 and volume decreases to V_1, as shown in Fig. 8.16 represented by curve 'da'.

Thermal and mechanical equilibrium is maintained throughout the process to make it perfectly reversible. As the working substance returns to its initial state, so there is no change in internal energy i.e., $\Delta U = 0$.

8.8.1 Efficiency of Carnot Engine:

During one cycle, the total work done by the gas can be found by the area enclosed by the path 'abcda' in Fig. 8.16. It can also be determined by the difference of heat absorbed Q_1 (input) by the gas during isothermal expansion and the heat rejected Q_2 by the gas during isothermal compression. Mathematically, it can be given as:

$$W = Q_1 - Q_2 \quad \text{\_\_\_\_\_ (8.8)}$$

The above expression comes from the fact that in the first law of thermodynamics, $Q = \Delta U + W$, while $\Delta U = 0$, it simplifies to:

$$W = Q \qquad W = Q_1 - Q_2$$

The efficiency η of heat engine can be given as:

$$\eta = \frac{output(work)}{input(heat)}$$

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

As we know that heat Q is proportional to the absolute temperature T then the above relation can be written in terms of temperature as:

$$\eta = (1 - \frac{T_2}{T_1}) \quad \text{\_\_\_\_\_ (8.9)}$$

Efficiency is usually expressed in percentage, so:

Do You Know?

Does internal energy of an ideal gas depend on pressure? What about a real gas?

Out of solid, liquid and gas of same mass and temperature, which one has greatest internal energy? And which one has the least internal energy?

$$\text{Percentage Efficiency} = \eta = (1 - \frac{T_2}{T_1}) \times 100\ \%$$

Conclusion: From above result, it is clear that efficiency of Carnot engine is independent of nature of working substance. It depends only on the temperatures of hot and cold reservoirs. For the efficiency to be 100 % the ratio of temperatures should be zero. This will only happen if $T_2 = 0$ or $T_1 = \infty$, which is impossible because we do not have reservoir at absolute zero temperature or infinite temperatures. Therefore, it is impossible for a real engine to have an efficiency of 100 %.

8.8.2 Carnot Theorem

Carnot's theorem states that no heat engine can be more efficient than a Carnot engine operating between the same two temperatures.

In most of the cases, the cold reservoir is our atmosphere. In order to increase the efficiency of heat engine, we have to increase the temperature of hot reservoir. All real heat engines are less efficient than Carnot's engine due to heat losses.

Example 8.4: Find the efficiency of a heat engine operating between 400 °C and 30 °C.

Given: $T_1 = 400 + 273 = 673\ K$ $\quad T_2 = 30 + 273 = 303\ K$

To Find: Percentage Efficiency = ?

Solution: $\text{Percentage Efficiency} = (1 - \frac{T_2}{T_1}) \times 100\ \%$

$$\eta = (1 - \frac{303}{673}) \times 100\ \% = (1 - 0.45) \times 100\ \% = 55\ \%$$

Assignment: 8.4

A heat engine is working with thermal efficiency of 40%. It receives 4 kJ of heat from a furnace. What amount of waste heat does it reject?

8.9 REFRIGERATOR

We know that in nature, heat flows from hotter body towards colder body. If we want to move heat from a colder to a hotter body, we need to reverse the working of heat engine, and work is to be done on the system.

A refrigerator is a device designed to remove heat from a region that is at lower temperature than its surroundings.

The same device can be used to heat a space that is at higher temperature than the surroundings. In this case, the device is called **Heat Pump**, as shown in Fig. 8.18. In refrigerators, heat flows from lower temperature source to higher temperature sink. In other words, we can also define refrigerator as:

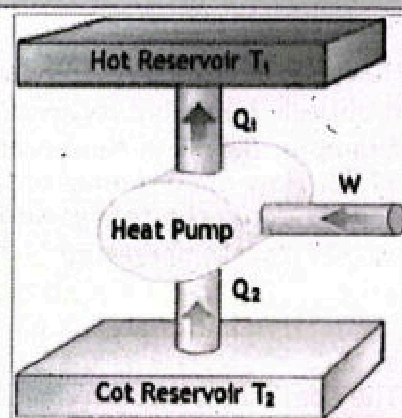


Figure 8.18: Schematic diagram of heat pump.

A device in which the working substance performs cycle in a direction opposite to that of a heat engine is called refrigerator.

Refrigerator removes some amount of heat Q_2 from a cold reservoir at low temperature T_2. Some work W is performed by the compressor of the refrigerator on the working substance. The quantity of heat Q_1 is rejected to a hot reservoir at higher temperature T_1. The working substance in this case is usually a gas called the refrigerant.

Co-efficient of Performance (CP) of Refrigerator: The coefficient of performance for cooling or cooling energy ratio can be defined as:

The ratio of the amount of heat removed from the cold reservoir to the work required to do so.

Mathematically, it can be written as:

$$\text{Coefficient of performance for cooling} = CP_{Cooling} = \frac{Q_2}{W}$$

As we know that: $W = Q_1 - Q_2$ by using this value in above equation, we get:

$$CP_{Cooling} = \frac{Q_2}{Q_1 - Q_2} \quad \text{\_\_\_\_\_\_ (8.10)}$$

As we know that heat Q is proportional to temperature T, we can express the $CP_{Cooling}$ as:

$$CP_{Cooling} = \frac{T_2}{T_1 - T_2}$$

Similarly, coefficient of performing for heating, or heating energy ratio can be expressed as:

$$\text{Coefficient of Performance for Heating} = CP_{Heating} = \frac{Q_1}{W}$$

As we know that: $W = Q_1 - Q_2$ by using this value in above equation, we get:

$$CP_{Heating} = \frac{Q_1}{Q_1 - Q_2} \quad \text{\_\_\_\_\_\_ (8.11)}$$

As we know that heat Q is proportional to temperature T.

$$CP_{Heating} = \frac{T_1}{T_1 - T_2}$$

No cyclic device has ever been built that can extract heat 'Q_2' from a cold reservoir and reject it entirely into a hot reservoir without expenditure of work.

Example: 8.5: The temperature inside a refrigerator is 6 °C and the room temperature is 37 °C. How many joules of heat will be delivered to the room for each joule of electricity consumed by the refrigerator? Assume the refrigerator is ideal.

Given: Low temperature 'T_2' = 6 °C High temperature 'T_1' = 37 °C

To Find: Quantity of heat pumped out in the room 'Q_1' = ?

Solution: First of all, we have to convert the temperatures into the Kelvin scales as:

$T_1 = 37°C + 273°C = 310\ K$ $T_2 = 6°C + 273°C = 279\ K$

The coefficient of performance of the refrigerator for cooling is:

$$CP_{cooling} = \frac{T_2}{T_1 - T_2}$$

$$CP_{cooling} = \frac{279}{310-279} = 9$$

The coefficient of performance of the refrigerator for cooling can also be expressed as:

$$CP_{cooling} = \frac{Q_2}{W} \quad \Rightarrow \quad Q_2 = W\,CP_{cooling}$$

$$Q_2 = 9\ W$$

Where 'W' is the work done by the pump, and then heat can be given as:

$$Q_1 = Q_2 + W$$

$$Q_1 = 9W + W = 10W$$

So, for each joule of work done (for each joule of electricity consumed), the quantity of heat pumped out in the room will be:

$$Q_1 = 10\ J$$

This shows that the refrigerator has to perform significant work to expel heat from its interior into the room on a hot summer day when the outside temperature is 37 °C.

Assignment 8.5

The temperature inside a refrigerator is t_2 °C and the room temperature is t_1 °C. Find the amount of heat delivered to the room for each joule of electricity consumed ideally.

8.10 ENTROPY

The concept of entropy was introduced into the study of thermodynamics by Rudolph Clausius in 1856 to provide a quantitative statement to second law of thermodynamics. It introduced another state variable, along with temperature, pressure, volume and internal energy. Entropy can be defined in many ways.

A thermodynamic quantity that represents the unavailability of a system's thermal energy for conversion into mechanical work is called entropy.

It is simply the **degree of disorder or randomness in a system**. For mathematical derivation of entropy, consider a system undergoes a reversible process during which it absorbs an amount of heat ΔQ at an absolute temperature T. The increase in state variable called entropy S of the system is given by:

$$\Delta S = \frac{\Delta Q}{T} \quad \text{———} \quad (8.12)$$

From this equation, we find that:

Entropy is the measure of a system's thermal energy per unit temperature that is unavailable for doing useful work.

Like potential energy and internal energy, it is change in entropy which is important rather than the absolute value of entropy. Examples of entropy changes include:

- Burning of wood, as wood converts into ash, smoke and gases, releasing the stored energy within the wood.

- Melting of ice, as the molecules of ice lose their order during melting, as shown in Fig. 8.19. If we place some ice in the bucket for some time in a room, we notice that with the passage of time the ice is converting into liquid water by releasing the heat. As we know that molecules are ordered in ice while in water the molecules are moving randomly. This activity shows that with time the entropy of the system decreases in this natural process. In all natural processes the entropy of the system as well as the universe is increasing and hence the universe is going from an order to disorder state with time.

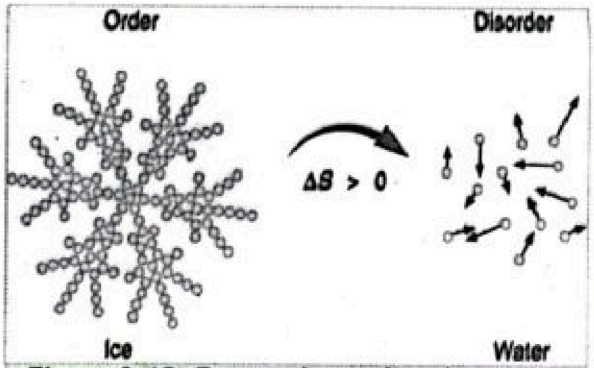


Figure 8.19: From order to disorder.

8.10.1 Sign Convention for Entropy

During a change, the sign of entropy is important consider. It depends on the direction of heat flow, i.e., whether heat is added to the system or removed from the system.

- The change in entropy is positive if heat is added to the system.
- The change in entropy is negative if heat is removed from the system.

Suppose heat Q flows from a heat source at temperature T_1 to a heat sink at temperature T_2. The change in entropy of the heat source can be given as $-Q/T_1$, as the source loses heat, so its entropy is negative. The entropy of sink is given as $+Q/T_2$. As $T_1 > T_2$, the net change in entropy will be positive:

$$\Delta S = \frac{Q}{T_2} - \frac{Q}{T_1}$$

This equation shows that in all natural processes where heat flows from hotter body to colder body, there is a net increase in entropy. We can define second law of thermodynamics in terms of entropy as follows:

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

It is observed that all natural processes tend to proceed towards a state of greater disorder. There is a relation between entropy and molecular disorder, as shown in the Fig. 8.20.

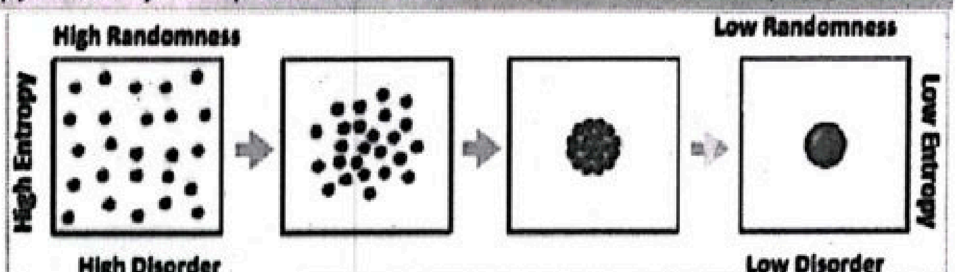


Figure 8.20: Randomness of molecules.

Entropy requires a particular direction for time, known as **"Arrow of Time"**. As one goes 'forward' in time the entropy of isolated system increases, hence entropy measurement is a way of distinguishing the past from the future.

8.10.2 Entropy and Energy

In nature only those processes are more likely to occur where the entropy of the system increases or remains constant.

- For all reversible processes, entropy of the system remains constant.
- Entropy increases for irreversible process.

Do You Know?
Does the entropy of a star increase or decrease as it radiates? What will be the effect of this radiation on space around it and on the universe?

Every time entropy increases the opportunity to convert some heat into work is lost.

An increase in entropy means the degradation of energy.

For example, in a car engine the burning of fuel produces some work while the remaining heat energy is released into the atmosphere. The heat energy released into the atmosphere is no longer available for work. Before entropy change, all the heat from this process was available for work, but after the process a major part of heat energy is lost into the atmosphere.
Even in the case of reverse processes such as in refrigerator or air conditioner, the temperature of one system decreases at the expense of an increase in the temperature of another system. When these systems are considered together as universe, the entropy of universe always increases.

Example: 8.6: Calculate entropy change when 700 g of ice melts at 0 °C. Latent heat of fusion for ice is $L_f = 3.36\times10^5\ J\ kg^{-1}$. Also discuss the sign of the entropy changes.

Given: m = 700 g = 0.7 kg T = 0 °C = 273 K $L_f = 3.36\times10^5\ J\ kg^{-1}$

To Find: $\Delta S = ?$

Solution: The relation for heat 'ΔQ' in this case can be given as:

$$\Delta Q = m L_f$$

Here 'm' is the mass and 'L_f' is the latent heat of fusion.

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

$$\Delta S = \frac{0.7\ \text{kg} \times 336000\ \text{J kg}^{-1}}{273\ K} = 861.5\ J\ K^{-1}$$

The positive value of entropy indicates that entropy increases in melting of ice, as molecules are loosing order to become orderless liquid.

Assignment 8.6:

A body at 150 °C undergoes a reversible isothermal process. The heat energy removed in the process is 7373 J. Find the entropy change of the body.

For Your Information

Second law of thermodynamics gives us clues to tackle with environmental crisis we are facing right now. In fact, environmental crisis arises due to our efforts to bring order to the nature for our comforts, which is against law of nature that is why we can say that environmental crisis is entropy crisis.
The energy processes we use are not efficient, as a result most of the energy is lost to the environment, causing thermal pollution, as heat is the ultimate death of any form of energy i.e., whenever any type of energy is converted completely into heat energy it is now no longer available for doing useful work. With thermal pollution most of the heat engines we use cause air pollution.

HEAT AND THERMODYNAMICS

SUMMARY

- **Thermodynamics** is that branch of physics in which we study the transformation of heat into other forms of energy.
- **Thermal energy** is the energy possessed by a system due to movement of its particles.
- **Internal energy** is the energy associated with the random and disordered motion of molecules of a substance.
- In thermodynamics, **work** is the product of pressure and change in volume of the system.
- **First law of thermodynamics** states that when heat is added to a system, it increases the internal energy of the system plus work is done on the environment.
- An **isothermal process** is a thermodynamic process in which temperature remains constant throughout the process.
- An **adiabatic process** is a thermodynamic process in which no heat or mass transfers between the system and the surroundings.
- An **isochoric** or **constant volume process** is a thermodynamic process in which volume of the system remains constant.
- An **isobaric** or **constant pressure process** is a thermodynamic process in which pressure of the system remains constant.
- A **heat engine** is a device that converts heat energy into mechanical work.
- **Second law of thermodynamics** states that it is impossible for a heat engine to convert heat taken from a single reservoir entirely into work without leaving any change in the working substance.
- **Carnot's theorem** states that, no heat engine can be more efficient than a Carnot engine operating between the same two temperatures.
- **Entropy** is a measure of the degree of disorder or randomness in a system.

EXERCISE

Multiple Choice Questions

Encircle the Correct option.

1) A real gas can be approximated to as ideal gas at:

A. low density B. high pressure C. high density D. low temperature

2) A thermos flask containing milk as a system is shaken vigorously, temperature of milk rises due to process called:

A. isochoric B. isothermal C. isobaric D. adiabatic

3) Considering your metabolism as a system, during fasting in Ramadan, it is a/an _______ process.

A. isochoric B. isothermal C. isobaric D. adiabatic

4) Change in internal energy of a gas kept in rigid container when 'Q' J energy is added to it is:

A. $\frac{Q}{2}$ B. $\frac{Q}{3}$ C. Q D. 2Q

5) The volume of an ideal gas increases from 5 m^3 to 20 m^3 under a constant pressure of $6x10^5$ Pa. work done by the gas is:

A. $5x10^5$ J B. 6 $x10^6$ J C. 9 $x10^6$ J D. 9 $x10^7$ J

6) Which process involves an increase in entropy?

A. crystallization B. sublimation C. freezing D. condensation

7) A Carnot engine working between 300 K and 600 K has work output 800 J/cycle, the heat supplied is:

A. 1000 J/cycle B. 1600 J/cycle C. 1800 J/cycle D. 2000 J/cycle

8) A Carnot engine working between 0 ^{0}C to 200 ^{0}C has efficiency η_1. Then same engine working between 0 ^{0}C to -200 ^{0}C has efficiency η_2. Ratio of its efficiencies is.

A. 0.577 B. 0.638 C. 0.733 D. 0.85

9) Maximum work is obtained by a process called:

A. isochoric B. isothermal C. isobaric D. adiabatic

10) The coefficient of performance of a refrigerator operating at room temperature is 5. The temperature inside the refrigerator is:

A. 150 K B. 200 K C. 250 K D. 300 K

11) If the temperature of heat source is doubled than before, the efficiency increases by:

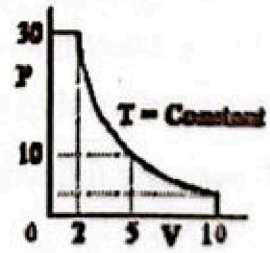
A. 1.5times B. 2 times C. 2.5 times D. 3 times

12) Thermodynamics is that branch of physics in which we study:

A. No heat transfers to the environment.
B. Neither heat nor any mass are transferred to the environment.
C. No dissipated energy and heat transferred to the environment.
D. No mass transfers to the environment.

13) If two objects are in thermal equilibrium with each other, they cannot:

A. be moving.
B. be undergoing an elastic collision.
C. have different pressures.
D. be at different temperatures.



14) What is change in internal energy in the figure?

A. zero B. 20 J C. 40 J D. 160 J

15) The change in internal energy is independent of pathstaken, similar to:

A. K.E. B. wave energy C. gravitational P.E. D. solar energy

16) Boltzmann constant k is equal to:

A. $\frac{N_A}{R}$ B. $\frac{R}{N_A}$ C. $\frac{R}{N_o}$ D. $\frac{N_o}{R}$

17) Two spheres of same size are made of the same material, but one is hollow and the other is solid. They are heated to the same temperature. Then:

A. Both spheres will expand equally.
B. The hollow sphere will expand more than the solid one.
C. The solid sphere will expand more than the hollow one.

D. No conclusion can be drawn about their relative expansions unless the nature of the material is known.

18) Expansion during heating:

A. occurs at the same rate for all materials.
B. increases the weight of a material.
C. occurs at different rates for different materials.
D. increases the density of material.

Short Questions

Give short answers to the following questions:

8.1 Why does the gas pressure in the tires rise when a car runs on a road through some distance?

8.2 When the internal energy of a system rises, can its temperature remain the same?

8.3 Can the temperature of an isolated system change? Explain.

8.4 The internal energy of a system is increased as a result of some process, how can one tell that the increase was due to orderly macroscopic work W or due to the flow of disorderly microscopic energy 'Q'?

8.5 At what temperature (in °C) does the volume of a gas at 0°C becomes double, while pressure remains constant?

8.6 Should the internal energy of a system necessarily increase if heat is added to it?

8.7 Why is the slope of an adiabatic curve steeper than the slope of isothermal curve?

8.8 Why isothermal processes typically slow and adiabatic processes fast?

8.9 Can a process be both adiabatic and isothermal? Explain.

8.10 Does the entropy of a Carnot engine increases for each cycle?

8.11 Does entropy of a system increases or decreases due to friction?

8.12 What are the similarities and dissimilarities in the working of refrigerator and air conditioner?

8.13 When a coffee filled thermos is vigorously shaken: (i) is the work done on coffee? (ii) Does the internal energy of coffee increase? (iii) Does the temperature of coffee rise? (iv) Does the coffee get heat from outside?

Comprehensive Questions

Answer the following questions in detail.

8.1 Define internal energy of a system and find its relation with absolute temperature.

8.2 Explain the gas laws.

8.3 Explain first law of thermodynamics.

8.4 Define and explain: (a) Isothermal process (b) Isobaric process (c) adiabatic process (d) isochoric process.

8.5 Explain the working of a heat engine.

8.6 Define and explain second law thermodynamics.

8.7 Define and explain Carnot's Engine, also discuss the relation for the efficiency of Carnot's engine.

8.9 Explain the working of a refrigerator.

8.10 What is entropy? Explain.

8.11 Explain that entropy is the degradation of energy.

Numerical Problems

8.1 Calculate number of moles of air in an inflated balloon of radius 10 cm and pressure 180 kPa at room temperature. **(Ans: 0.3 moles)**

8.2 A heat engine operating between the freezing and boiling point of water. Find its efficiency. **(Ans: 27%)**

8.3 One mole of a perfect gas in a cylinder with a piston has pressure P, volume V and temperature T. If its temperature is increased by 1 K. Find the increase in volume, if initial volume was 100 m^3. **(Ans: 0.37 m^3)**

8.4 The high temperature of Carnot engine is 600 K. If engine absorbs 600 J of heat at low temperature of 400 K. Find the work done by the engine. **(Ans: 200 J)**

8.5 A 220 W electric immersion heater is used to boil 136 g of water. Calculate the time required to bring this water from 23.5 ^{0}C to its boiling point, ignoring any heat loss.

(Ans: 198 s)

8.6 If a heat engine at room temperature has an efficiency 50 %, you change the heat source to increase the efficiency up to, 70 %. Find the temperature difference between the two heat sources. **(Ans: 397 K)**

8.7 A Carnot engine absorbs an amount Q of heat at temperature T. Find the amount of heat rejected at temperature T/3. **(Ans: Q/3)**

8.8 Energy 500 J is required to melt 2 g of ice at 0 ^{0}C. Find the change in entropy of 70 g water at 0 ^{0}C, if it changes into ice in a refrigerator. **(Ans: -64 J K^{-1})**

8.9 A gas expands from volume $1m^3$ to $2m^3$ at constant atmospheric pressure.

(a) Calculate the work done by the gas.

(b) Represent the work done in PV diagram. **(Ans: 1.013×10^5 J)**