CHAPTER 11

TRANSFER OF THERMAL ENERGY

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- explain thermal conduction in all solids (in terms of atomic or molecular lattice vibrations and also in terms of the movement of free (delocalized) electrons in metallic conductors).
- analyze everyday applications of conduction, convection, and radiation. (a) Heating objects such as kitchen pans (b) Heating a room by convection (c) Measuring temperature using an infrared thermometer (d) Using thermal insulation to maintain the temperature of a liquid and to reduce thermal energy transfer in buildings (e) The mechanism of a household hot-water system.
- explain convection in liquids and gases [in terms of density changes]. Justify experiments to illustrate convection.
- explain convection in seawater to support marine life.
- describe the role of land breezes and sea breezes in maintaining moderate coastal climates.
- explain how birds are able to fly for hours without flapping their wings and gliders are able to rise by riding on thermal currents.
- describe the process of thermal energy transfer by radiation [and know that it does not require a medium].
- describe the effect of surface colour and texture on the emission, absorption, and reflection of infrared radiation.
- justify qualitatively how the rate of emission of radiation depends on the surface temperature and surface area of an object.
- analyze the consequence of heat radiation in the greenhouse effect and its effect on global warming.

Heat is an important form of energy that is essential for life. It plays a pivotal role in cooking, maintaining our body temperature, and supporting various industrial processes. Understanding how heat flow is important for protecting ourselves from extreme temperatures. In this chapter, we will look into the different methods of heat transfer. When two objects with different temperatures come into contact, thermal energy flows from the hotter object to the cooler one, a process known as heat transfer. This is a natural occurrence that continues as long as there is a temperature difference between the objects. Thermal energy constantly transfers from one object to another until thermal equilibrium is reached. Whether it is the Sun warming the Earth, a hot cup of coffee, or a metal rod heating when placed in a flame, heat transfer is a fundamental part of daily life. This chapter focuses on the three primary types of heat transfer conduction, convection, and radiation. Understanding of these processes is important not just in nature, but also in the fields like engineering, meteorology, and technology.

11.1 Conduction

Conduction is the process by which heat is transferred through direct contact between particles in a material, without any actual movement of the material. It happens when fast-moving (hotter) particles collide with slow-moving (cooler) particles, transferring their kinetic energy (Fig. 11.1). This method of heat transfer is most efficient in solids, especially in metals, as their particles are densely packed, and freely moving electrons facilitate the quick transfer of energy.

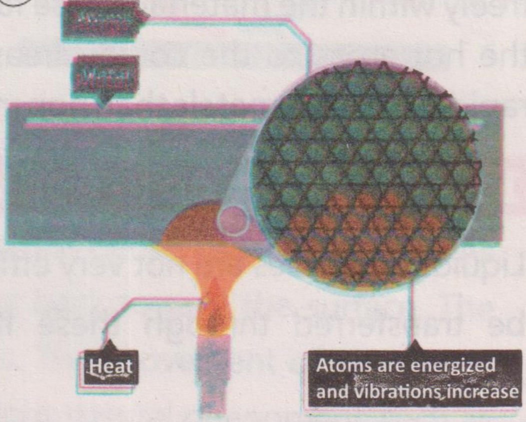


Fig. 11.1: Heat transfer in metals through conduction

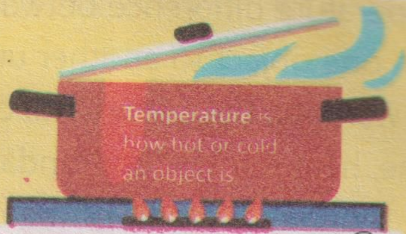
Thermal Conduction in Solids

When the handle of a metal spoon is placed in hot water, it quickly becomes warm, whereas the handle of a wooden spoon does not heat up. This difference highlights how materials transfer heat in different ways. Both metals and non-metals can conduct heat, but metals are typically much better at it. In solids, the atoms and molecules are tightly packed and constantly vibrate around their mean positions as shown in Fig. 11.1. When one end of the solid is heated, the particles at that end begin to vibrate more vigorously. These vibrating particles collide with nearby atoms or molecules, transferring some of their energy. This process causes the neighbouring particles to vibrate more rapidly and, in turn, pass some of their energy to other surrounding particles. Gradually, heat spreads throughout the solid, but the transfer is slow, with only a small amount of heat moving from the hotter to the cooler parts. In conduction, heat transfers through a solid medium due to a temperature difference.

Tidbit

Diamonds are the best heat conductors, far better than metals. A high quality diamond can conduct heat 4-5 times better than copper.

Do You Know?



Heat is transferred to an object, for example how the stove "heats" the pot.

why does heat travel more quickly in metals than in non-metals?

Metals have free electrons that can move freely within the material. These fast-moving electrons carry energy quickly from the hot areas to the cooler areas of the metal. This is why heat moves more rapidly through metals than non-metals.

11.2 Convection in liquids and Gases

Liquids and gases are not very efficient in conducting heat. However, heat can still be transferred through these fluids (liquids or gases) by a process called convection.

When a liquid or gas is heated, it becomes less dense (lighter) and expands. The heated liquid or gas rises above the heat source, and cooler fluid from the surrounding area moves in to take its place. This colder fluid then gets heated as well. In this way, heat is transferred through fluids by the movement of heated molecules from the hotter parts to the colder parts of the fluid.

Convection is the transfer of heat through the actual movement of molecules from a hot area to a cold area.

Experiment: (For Liquid Convection)

Fill a beaker two-thirds with water and heat it by placing a burner underneath. Now drop two or three potassium permanganate crystals into the water. We will notice coloured streaks moving upward above the flame, then flowing downward along the sides, as shown in Fig. 11.2. These coloured streaks reveal the movement of currents within the liquid. But why do these currents stop when the burner is removed? As the water at the bottom of the beaker heats up, it expands, becoming lighter and rising. Meanwhile, the cooler, denser water sinks to replace it.

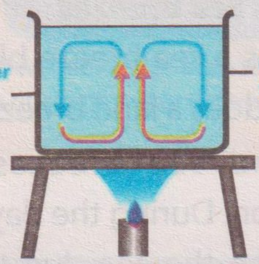


Fig. 11.2: Convection currents circulate heat as hot water rises and cold water sinks

Convection Currents in Air

When gases get heated, they expand, and this creates convection currents due to the differences in air density at various points in the atmosphere. This can be demonstrated with a simple experiment, as shown in Fig. 11.3. Can you explain the process?

Fig. 11.3: Convection currents drive air circulation as warm air rises and cool air sinks

This process begins when the Sun heats the Earth's surface, warming the air close to the ground. As the air warms up, it becomes lighter and less dense, causing it to rise. As it rises, it cools down, becomes denser, and sinks back toward the surface. The cooler air then gets heated, and the cycle repeats. This movement of air creates convection currents, which are responsible for various natural phenomena such as winds, sea breezes, and weather patterns. These currents help to distribute heat throughout the atmosphere, playing a vital role in regulating Earth's climate and weather.

Applications of Convection Currents

Convection currents created by electric, gas, or coal heaters are used to warm our homes and offices. Central heating systems also rely on convection to distribute heat throughout the buildings. On a larger scale, convection currents occur naturally in the environment. The daily changes in temperature in the atmosphere are caused by the movement of warm or cool air. Land and sea breezes are examples of convection currents in nature.

Land and Sea Breezes

Why does a sea breeze blow during the day, and why does a land breeze occur at night?

Land and sea breezes are caused by convection. During the day, the land heats up faster than the sea due to the land's lower specific heat capacity. The warm air above the land rises, and cooler air from the sea moves in to replace it, creating a sea breeze, as shown in Fig.11.4.

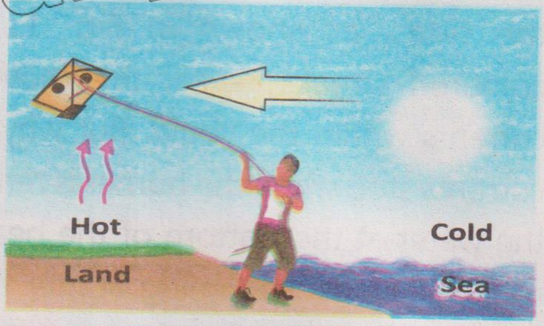


Fig. 11.4: Sea breeze blows from sea to land as warm air rises over heated land (day time)

At night, the land cools down more quickly than the sea. As a result, the air above the sea becomes warmer and rises, while cooler air from the land moves towards the sea, creating a land breeze, as illustrated in Fig. 11.5.

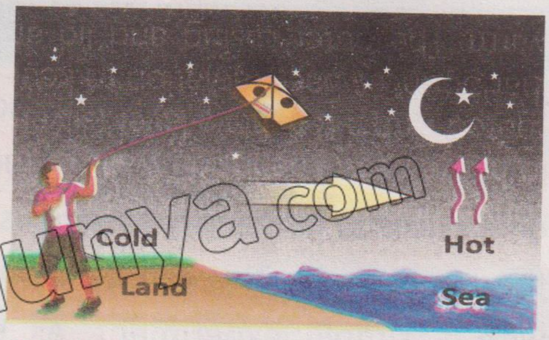


Fig. 11.5: Land breeze blows from land to sea as warm air rises over heated water (night time)

Gliding

What keeps a glider in the air?

A glider, which is like a small plane without an engine, relies on the upward movement of warm air currents, or thermals, created by convection (Fig. 11.6).

Fig. 11.6: A glider

Gliders take advantage of these rising currents of warm air to stay in the air for extended periods. Similarly, birds use thermals to stay aloft for hours without flapping their wings. They stretch their wings and circle in the thermals, allowing them to gain altitude as the warm air rises.

Birds such as eagles, hawks, and vultures are especially skilled at using thermals to glide over long distances with little effort, barely needing to flap their wings (Fig. 11.7).

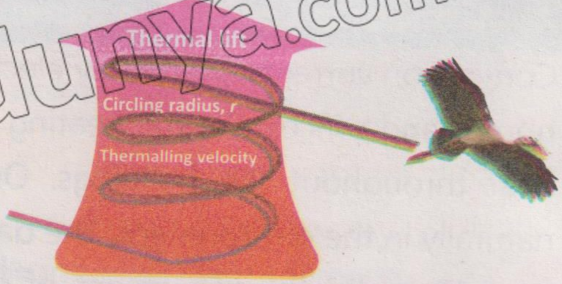


Fig. 11.7: Birds flying taking the advantage of thermal air currents

Convection in Seawater and Marine Life

Convection plays an important role in seawater and is important for supporting marine life. When sunlight heats the surface of the ocean, the warm water becomes lighter and stays at the top, while the cooler, denser water sinks to the bottom. This difference in temperature causes convection currents in the ocean. These currents continuously move water up and down, helping to mix oxygen from the surface into deeper layers and bringing nutrients from the ocean floor to the surface. This process is very important for the survival of marine animals and plants because it ensures that there is enough oxygen and food available at different depths. Without convection, the deep ocean would lack oxygen, and surface waters would lack nutrients, making it difficult for marine ecosystems to thrive.

Brain Teaser

Why do we feel a nice breeze coming from the sea during the day time at the beach?

Brain Teaser

How can birds fly for hours without moving their wings much in sunny weather?

Heating and cooling of Rooms by Convection

In winter, gas heaters are often used to warm rooms (Fig. 11.8). When the heater is turned on, it warms the air near it. This warm air becomes lighter (less dense) and rises toward the ceiling. As the hot air moves up, cooler, heavier air moves down to take its place near the heater. This process is called a convection current. Similar effect is applied during summer when air conditioning is used to cool the room. It keeps the air moving and helps in spreading the heat evenly throughout the room. That is why, rooms gradually become warmer without needing fans.

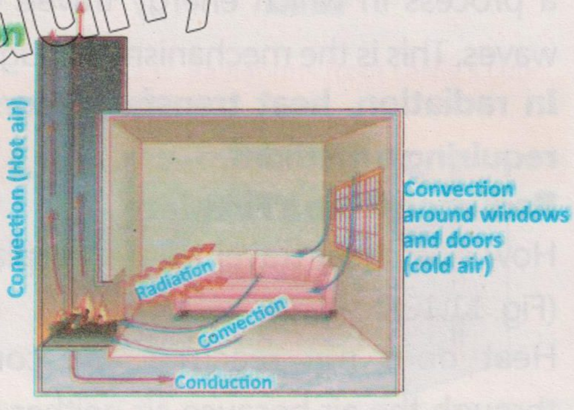


Fig. 11.8: Heating room by convection

The Mechanism of a Household Hot-Water System

In most homes, hot water is provided using a storage tank water heater. The system works by bringing cold water into the house through pipes, where it splits into two lines: one for cold water use and one that goes into the water heater. Inside the water heater, the cold water is heated using an electric heating element or a gas burner, depending on the type of system. As the water heats up, it becomes less dense and rises naturally to the top of the tank, while the cooler, denser water stays at the bottom. When someone turns on a hot water tap, the hot water from the top of the tank flows out easily, and new cold water enters from below to be heated. A thermostat inside the tank controls the heating element or gas burner, ensuring that the water stays at a set temperature (Fig. 11.9). This system ensures a steady supply of hot water.

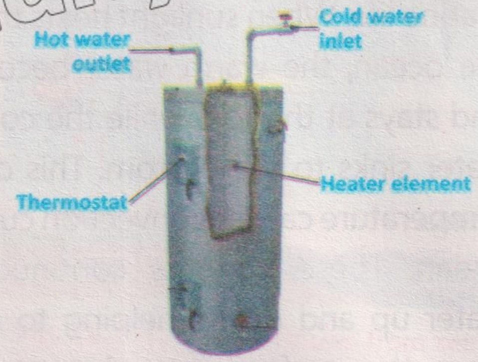


Fig. 11.9: Household hot-water system

11.3 Heat Transfer through Radiation

The Sun serves as the main source of heat for our planet. However, this heat does not reach the Earth through conduction or convection, as there is no medium between the Sun and Earth's atmosphere. Instead, heat is transferred via radiation, a process in which energy travels across space in the form of electromagnetic waves. This is the mechanism through which the Sun's heat reaches the Earth.

In radiation, heat transfer occurs through electromagnetic waves without requiring a medium.

Radiation from a Fireplace

How does heat travel from a fireplace to us (Fig. 11.10)?

Heat does not reach us via conduction through the air because air neither conducts heat efficiently nor transfers heat but radiation emitted is influenced by various factors, including:

- the colour and texture of the surface
- the temperature of the surface
- the surface area

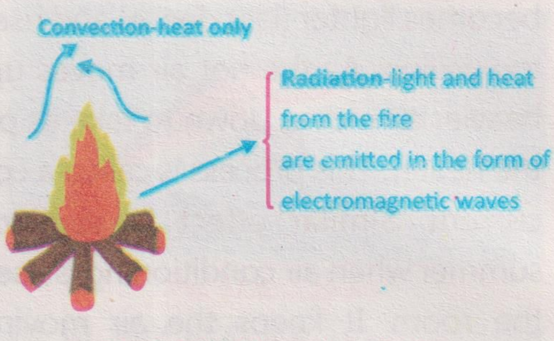


Fig. 11.10: Thermal radiations transform in form of E.M waves

Why Objects Cool or Warm Over Time?

Why does a hot cup of tea cool down over time, and why does a cold glass of water warm up? All objects in a room, including the walls, ceiling, and floor radiate heat while simultaneously absorbing it. If temperature of an object is higher than that of its

Do You Know?

- Convection is when liquid or gases get heated.
- Conduction is when something is hot and it touches another object and it becomes hot.
- Radiation is when energy travels through E.M. waves to heat something up.

surroundings, it radiates more heat than it absorbs. Consequently, its temperature decreases until it matches the temperature of the surrounding environment. On the other hand, if the temperature of the object is lower than its surroundings, it absorbs more heat than it radiates, causing its temperature to rise until it reaches equilibrium with the environment. The rate at which different surfaces emit heat depends on their characteristics. This phenomenon can be illustrated with Leslie's cube (Fig. 11.11).

Leslie's Cube – Emission and Absorption of Radiation

Leslie's cube is a metal box with faces of different materials, such as:

- a shiny silver surface
- a dull black surface
- a white surface
- a coloured surface

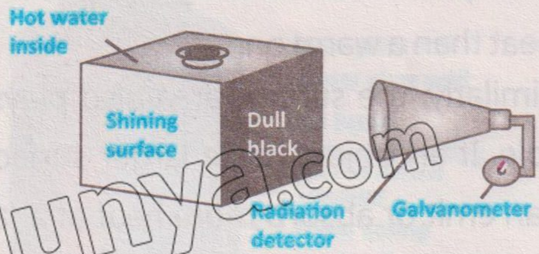


Fig. 11.11: Radiations from Leslie's cube

When the cube is filled with hot water and one face is directed towards a radiation detector, it is found that the dull black surface is the most effective emitter of heat (Fig. 11.11). The rate at which different surfaces absorb heat also varies based on their nature. For example, when comparing a dull black surface with a polished silver one, the dull black surface absorbs heat more rapidly, causing its temperature to rise quickly, while the polished silver surface absorbs heat more slowly and warms up at a much slower rate. These observations are recorded and compared for clarity (Fig.11.12).

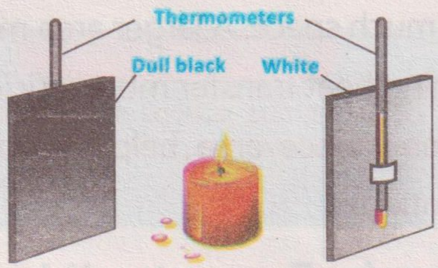


Fig. 11.12: A comparison of absorption of radiations

Effect of Surface Colour and Texture on Infrared Radiation

The colour and texture of a surface have a strong effect on how it emits, absorbs, and reflects infrared radiation. Dull and dark-coloured surfaces are very good at absorbing and emitting infrared radiation. That is why a dull black surface heats up quickly and cools down faster by giving off more heat. On the other hand, shiny and light-coloured surfaces are poor absorbers and emitters of radiation. Instead, they reflect most of the infrared radiation away. This is why shiny surfaces, like polished metals, stay cooler under the Sun compared to dark surfaces. The texture also matters. Rough surfaces absorb and emit radiation better, while smooth surfaces tend to reflect more radiation.

Impact of Surface Temperature and Surface Area on Heat Transfer

The rate of radiation emitted by an object depends greatly on two important factors: the surface temperature and the surface area. When the surface temperature of an object increases, it radiates more energy because hotter objects emit more heat compared to cooler ones. For example, a hot iron rod glows and emits more heat than a warm one.

Similarly, the surface area also plays a major role. If an object has a larger surface area, it can emit or absorb more heat at a faster rate. This is why radiators used for heating rooms are made with lots of thin slots or fins to increase the surface area without taking up too much space. A larger area means more radiation can happen at the same time, making heat transfer more efficient. Thus, both a higher surface temperature and a larger surface area help an object emit thermal energy more quickly through radiation.

Tidbit

Heat from the Sun reaches us through radiation, no air needed, just pure energy travelling across space.

Do You Know?

Dull black surfaces absorb and emit more heat than shiny surfaces that is why solar panels are black.

Measuring Temperature Using an Infrared Thermometer

An infrared thermometer (Fig. 11.13). measures the temperature of objects without touching them. It detects the heat (infrared radiation) emitted by the object. During the COVID-19 pandemic, these thermometers were used widely to check body temperatures safely. They are also useful for checking the heat of ovens, machines, or even dangerous radioactive materials. To use it, we point the thermometer at the object, press the trigger, and read the temperature on the screen.

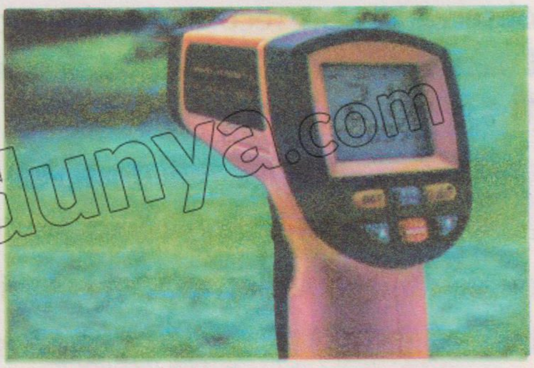


Fig. 11.13: Infrared thermometer

Applications of Heat Transfer

1. Heating Objects such as Kitchen Pans

One everyday application of heat transfer is when we cook food using kitchen pans. When a pan is placed on a stove, heat from the flame or heating element transfers to the pan mainly by conduction. The metal of the pan, being a good conductor, quickly absorbs the heat and passes it through the surface. This causes the entire pan to become hot, allowing food placed inside to cook evenly (Fig.11.14).

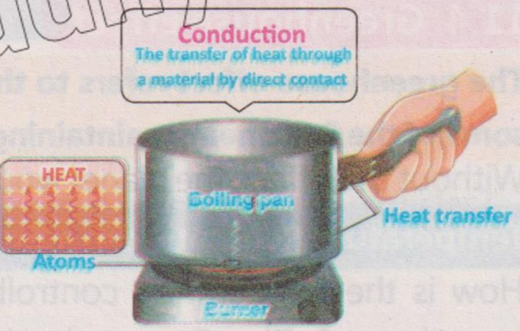


Fig. 11.14: Heat transfer through conduction in a boiling pan

2. Using Thermal Insulation to Maintain the Temperature of a Liquid

Thermal insulation helps to keep hot things hot and cold things cold. For example, a thermos flask (vacuum flask) has double walls with a vacuum between them (Fig. 11.15). The vacuum stops heat transfer by conduction and convection because there is no air or material to move heat. The inside walls of the flask are coated with a reflective layer (silvered coating) that bounces back radiation to keep the liquid warm. The outer casing and lid are made of insulating materials like plastic or stainless steel to prevent heat loss. This smart design helps liquids like tea, coffee, or soup to stay at the right temperature for many hours.

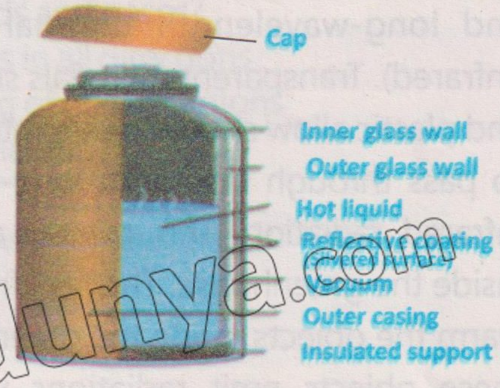


Fig. 11.15: Thermos flask

Tidbit

The handle of a cooking pan stays cool because it is made of poor conductors like wood or plastic.

3. Reducing Thermal Energy Transfer in Buildings

Thermal insulation in buildings helps to keep them warm in winter and cool in summer. By adding things like thick curtains, foam in the walls, double-glazed windows (Fig. 11.16-a), or false ceilings (Fig. 11.16-b). We can reduce heat loss through conduction, convection, and radiation. In cold weather, insulation stops warm indoor air from escaping. In hot weather, it prevents heat from entering from outside. This reduces the need for heaters and air conditioners, saving energy and lowering costs. Even simple ideas like using proper shading outside the windows or ensuring good ventilation can make a big difference in

(a) Doubled-glazed window (b) False cieling

Fig. 11.16: Reducing thermal energy transfer

11.4 Greenhouse Effect

The greenhouse effect refers to the process by which the Earth's atmosphere traps some of the Sun's heat, maintaining a temperature that is suitable for life. Without this effect, the planet would be too cold to support life as we know it.

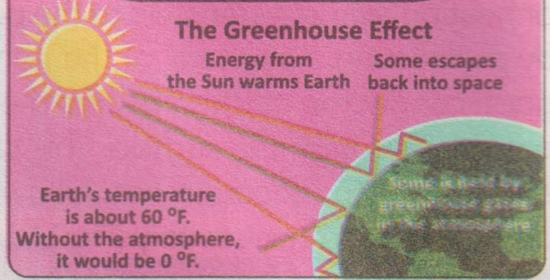
Temperature Regulation in a Greenhouse

How is the temperature controlled inside a greenhouse? The Sun emits both short-wavelength light and ultraviolet radiations and long-wavelength thermal radiations (infrared). Transparent materials such as glass and plastic allow short-wavelength radiations to pass through but block long-wavelength infrared radiation. This creates a heat trap inside the greenhouse. The rays from the Sun warm the objects inside the greenhouse, and these objects emit radiations with longer wavelengths. However, the glass or plastic sheets prevent this longer-wavelength radiations from escaping, reflecting it back into the greenhouse and maintaining a warm environment that benefits plant growth.

Greenhouse Effect on Earth

The Earth's atmosphere functions in a similar way to a greenhouse, trapping heat from the Sun with gases such as carbon dioxide and water vapours (Fig. 11.17). This helps to maintain the Earth's temperature. In recent years, the amount of carbon dioxide in the atmosphere has increased significantly, strengthening the greenhouse effect. As a result, more heat is trapped, leading to a rise in the Earth's average temperature, a phenomenon known as global warming. This increase in temperature has serious implications for global climate patterns.

For Your Information



Tidbit

The public has been led to believe that increased carbon dioxide from human activities in causing a green house effect that is heating the planet. But carbon dioxide comprises only 0.035% of our atmosphere and is a very week green-house gas.

Do You Know?

- Greenhouse gases absorb solar energy and trap it in the atmosphere.
- Without greenhouse gases creating what is known as the "Greenhouse Effect" the Earth would not be warm enough for human to live.

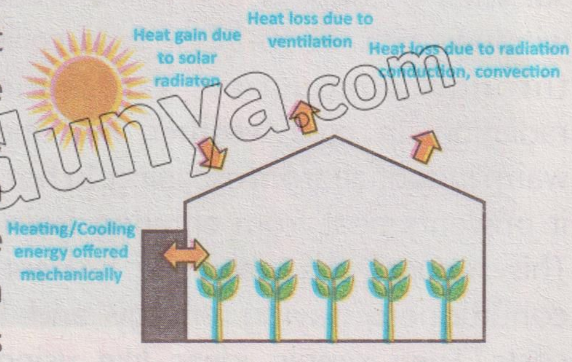


Fig. 11.17: Heat transfer mechanisms in a greenhouse

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

11.1 Which method of heat transfer requires direct contact between particles?
(a) Convection
(b) Radiation
(c) Conduction
(d) Evaporation

11.2 What causes convection currents in liquids and gases?
(a) The continuous movement of particles in all directions
(b) The rising of warm regions and sinking of cooler regions
(c) The conduction of heat through the medium
(d) The reflection of heat waves

11.3 The natural phenomenon caused by convection currents is:
(a) earthquakes
(b) land and sea breezes
(c) magnetic fields
(d) solar eclipses

11.4 How does heat transfer occur through radiation?
(a) Through direct contact between objects
(b) Through the movement of heated fluid
(c) Through electromagnetic waves without needing a medium
(d) Through the absorption of water molecules

11.5 The surface which absorbs and emits the most radiation is:
(a) smooth and shiny surfaces
(b) dark and rough surfaces
(c) transparent and thin surfaces
(d) polished and white surfaces

11.6 What is the role of the greenhouse effect in Earth's temperature regulation?
(a) It allows all heat to escape into space
(b) It blocks heat from entering the atmosphere
(c) It traps heat to maintain a stable temperature
(d) It causes immediate cooling of Earth's surface

11.7 The Sun's heat reaches the Earth:
(a) through conduction between air particles
(b) through convection in space
(c) through radiation via electromagnetic waves
(d) through reflection by the moon

B. Short Answer Questions

11.1 What are the three primary types of heat transfer?
11.2 Why does heat travel faster in metals compared to non-metals?
11.3 How does convection transfer heat in liquids and gases?
11.4 What natural phenomenon causes land and sea breezes?
11.5 How do birds and gliders take advantage of convection currents?
11.6 What is radiation, and how does it transfer heat?
11.7 Why does a dull black surface emit and absorb more radiation than a shiny silver surface?
11.8 How does the greenhouse effect help regulate Earth's temperature?

C. Constructed Response Questions

11.1 During the Leslie's Cube experiment, why does the dull black surface radiate more heat than the shiny silver one, even though they are at the same temperature?
11.2 How does the size (surface area) of a radiator affect the amount of heat it emits through radiation? Explain using a real-world example.
11.3 Why is convection not possible in solids, and how do convection currents in liquids and gases compensate for their poor thermal conductivity?
11.4 How do birds like eagles and gliders manage to stay aloft without flapping their wings for hours? Explain the scientific principle involved.
11.5 Why does a hot metal object placed in a cooler room eventually cool down? Explain using the concepts of radiation and thermal equilibrium.

D. Comprehensive Questions

11.1 Describe how convection occurs in fluids. How do convection currents contribute to natural phenomena such as sea breezes and wind patterns?
11.2 How does radiation differ from conduction and convection in terms of heat transfer? Give examples of radiation in everyday life and explain how different surfaces affect radiation absorption and emission.
11.3 Discuss the role of the greenhouse effect in regulating Earth's temperature. What are the potential consequences of an enhanced greenhouse effect due to human activities?
11.4 Compare the absorption and emission of heat by different surfaces. How does the colour and texture of a surface affect its ability to absorb and emit heat?
11.5 Analyze how uneven heating of Earth's surface leads to the formation of convection currents and influence with patterns.