Chapter 10
Thermal Properties of Matter

Temperature and Heat

Temperature

Temperature is a relative measure, or indication of hotness or coldness.
An object that has a higher temperature than another object is said to be hotter.

SI unit of temperature is kelvin (K).
° C(degree celsius) , ° F(degree fahrenheit) are other commonly used unit of temperature.

Heat

Heat is the form of energy transferred between two systems or a system and its surroundings by virtue of temperature difference.

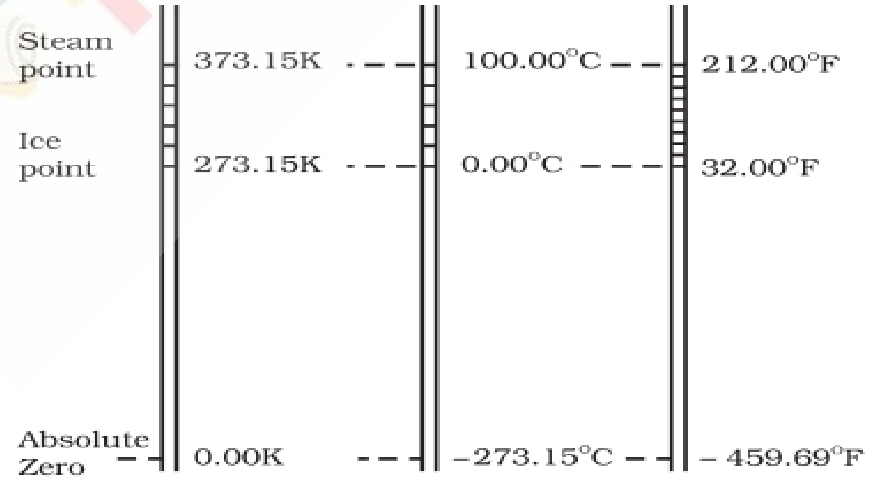
When the temperature of body and its surrounding medium are different, heat transfer takes place between the system and the surrounding medium, until the body and the surrounding medium are at the same temperature.

The SI unit of heat energy is joule (J)

Measurement of Temperature

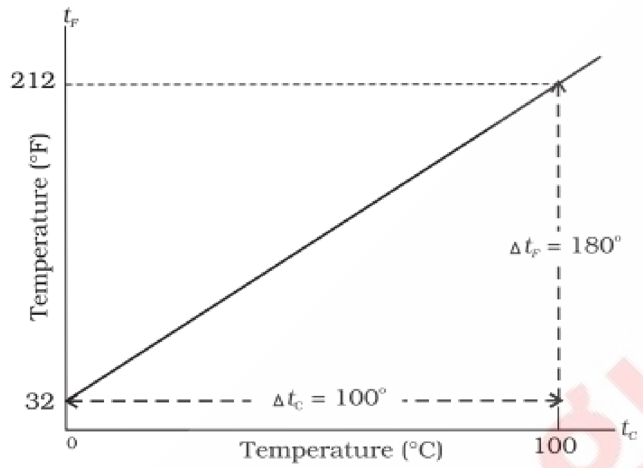
A measure of temperature is obtained using a thermometer.
Variation of the volume of a liquid with temperature is used as the basis for constructing thermometers.
Mercury and alcohol are the liquids used in most liquid-in-glass thermometers.

Comparison of the Kelvin, Celsius and Fahrenheit temperature scales.



- On Fahrenheit scale, there are 180 equal intervals between the ice and steam points.
- On Celsius scale, there are 100 equal intervals between the ice and steam points.
- On Kelvin scale, there are 100 equal intervals between the ice and steam points.

A plot of Fahrenheit temperature (t_F) versus Celsius temperature (t_C).



Temperature on Fahrenheit scale and Celsius scales are related by

$$\frac{t_F - 32}{180} = \frac{t_C}{100}$$

Temperature on Kelvin and Celsius scales are related by

$$T = t_C + 273.15$$

Ideal-Gas Equation and Absolute Temperature

Boyle's law

At constant temperature , the pressure of a quantity of gas is inversely proportional to volume.

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

$$PV = \text{constant.} \text{ --------------(1)}$$

Charles' law

At constant pressure , the volume of a quantity of gas is directly proportional to temperature .

$$V \propto T$$

$$\frac{V}{T} = \text{constant} \text{------------(2)}$$

Ideal gas law

Low density gases obey Boyle's law and Charles' law , which may be combined into a single relationship.

Combining eq(1) and (2)

$$\frac{PV}{T} = \text{constant}$$

For any quantity of any dilute gas the law can be generalised as

$$\frac{PV}{T} = \mu R$$

$$\mathbf{PV = \mu RT}$$

This is called ideal-gas equation

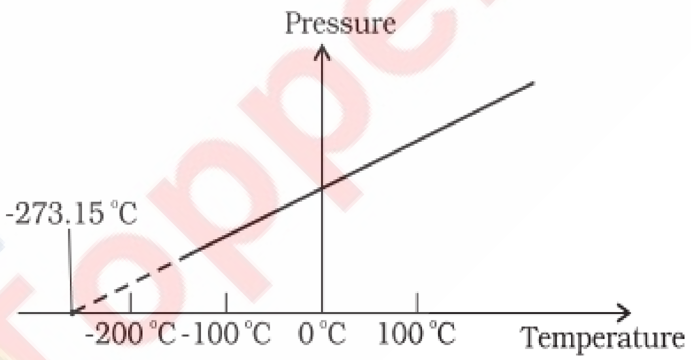
where, μ is the number of moles in the sample of gas.

R is called universal gas constant: $R = 8.31 \text{ J mol}^{-1} \text{ K}^{-1}$

Pressure versus temperature curve of a low density gas kept at constant volume

For ideal gas, $PV = \mu RT$

If volume of a gas is kept constant, it gives $P \propto T$. A plot of pressure versus temperature gives a straight line in this case.



Absolute zero Temperature or Zero kelvin (OK)

The minimum temperature for an ideal gas is called **Absolute temperature or zero kelvin(OK).** This temperature is found to be **– 273.15 °C**

It is obtained by extrapolating the straight line of Pressure – temperature (at constant V) to the axis.

Thermal Expansion

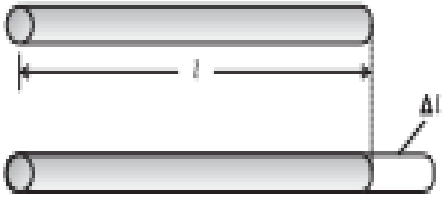
The increase in the dimensions of a body due to the increase in its temperature is called thermal expansion.

Three types of thermal expansions are

1.Linear expansion
2.Area expansion
3.Volume expansion

1.Linear Expansion

The expansion in length is called linear expansion.



If the substance is in the form of a long rod,

The fractional change in length, $\frac{\Delta l}{l} \propto \Delta T.$

$$\frac{\Delta l}{l} = \alpha_l \Delta T$$

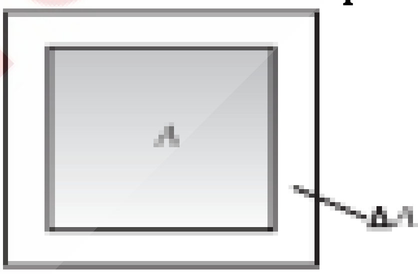
$$\boldsymbol{\alpha_l = \frac{\Delta l}{l\,\Delta T}}$$

where α_l is known as the **coefficient of linear expansion** and is characteristic of the material of the rod.

- Metals expand more and have relatively high values of α_l .
- Copper expands about five times more than glass for the same rise in temperature.

2.Area Expansion

The expansion in area is called area expansion



The fractional change in area, $\frac{\Delta A}{A} \propto \Delta T.$

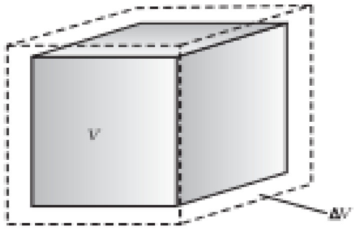
$$\frac{\Delta A}{A} = \alpha_a \Delta T$$

$$\boldsymbol{\alpha_a = \frac{\Delta A}{A\,\Delta T}}$$

where α_a is known as the **coefficient of area expansion .**

3. Volume Expansion

The expansion in volume is called volume expansion



The fractional change in volume, $\frac{\Delta V}{V} \propto \Delta T$

$$\frac{\Delta V}{V} = \alpha_V \Delta T$$

$$\boldsymbol{\alpha_V = \frac{\Delta V}{V\Delta T}}$$

where α_V is known as the **coefficient of volume expansion .**

The value of α_V for alcohol (ethyl) is more than mercury and it expands more than mercury for the same rise in temperature.

Relation between α_l and α_a

$$\alpha_a = \frac{\Delta A}{A\,\Delta T}$$

$$\Delta A = (l + \Delta l)^2 - l^2$$

$$\Delta A = 2\, l\, \Delta l \qquad (\text{Neglecting term } (\Delta l)^2)$$

$$A = l^2$$

$$\alpha_a = \frac{2\, l\, \Delta l}{l^2 \Delta T}$$

$$\alpha_a = 2\, \frac{\Delta l}{l\, \Delta T}$$

$$\frac{\Delta l}{l\, \Delta T} = \alpha_l$$

$$\boldsymbol{\alpha_a = 2\, \alpha_l} \text{ ---------(1)}$$

Relation between α_l and α_V

$$\alpha_V = \frac{\Delta V}{V \Delta T}$$

$$\Delta V = (l + \Delta l)^3 - l^3$$

$$\Delta V = 3\, l^2\, \Delta l \qquad (\text{Neglecting terms } (\Delta l)^2 \text{and } (\Delta l)^3)$$

$$\mathbf{V} = l^3$$

$$\alpha_v = \frac{3\, l^2\, \Delta l}{l^3 \Delta T}$$

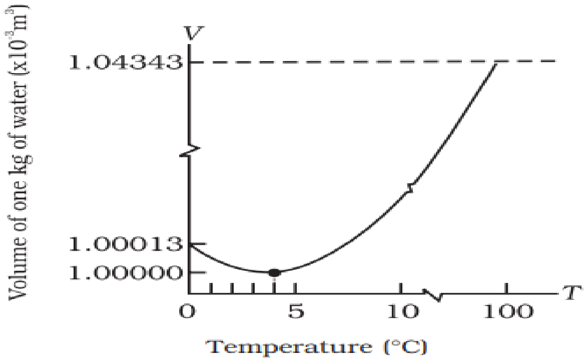
$$\alpha_v = 3\, \frac{\Delta l}{l\, \Delta T}$$

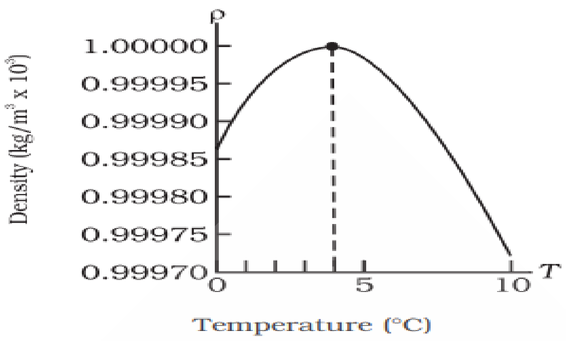
$$\frac{\Delta l}{l\, \Delta T} = \alpha_l$$

$$\boldsymbol{\alpha_v = 3\, \alpha_l} \text{ -----------(2)}$$

From eqs(1) and (2) $\boldsymbol{\alpha_l : \alpha_a : \alpha_v = 1 : 2 : 3}$

Thermal Expansion of Water(Or) Anomalous Behavour of Water





Water exhibits an anomalous behaviour; it contracts on heating from 0 °C to 4°C.When it is heated after 4°C ,it expands like other liquids. This means that **water has minimum volume and hence maximum density at 4 °C .**

Why the bodies of water, such as lakes and ponds, freeze at the top first?

This is due to anomalous expansion of water. As a lake cools toward 4 °C, water near the surface becomes denser, and sinks. Then the warmer, less dense water near the bottom rises. When this layer cools below 4 °C, it freezes, and being less dense, remain at the surfaces. Thus water bodies freeze at the top first. Water at the bottom protects aquatic animal and plant life.

The coefficient of volume expansion at constant pressure for an ideal gas

The ideal gas equation, $PV = \mu RT$ ------------------(1)

At constant pressure, $P\Delta V = \mu R\,\Delta T$

$$\frac{\Delta V}{V} = \frac{\mu R\,\Delta T}{P\,V}$$

From eq(1), $\frac{\mu R}{P\,V} = \frac{1}{T}$

$$\frac{\Delta V}{V} = \frac{\Delta T}{T}$$

$$\frac{\Delta V}{V\Delta T} = \frac{1}{T}$$

$$\alpha_V = \frac{1}{T}$$ (for an ideal gas at constant pressure)

Thermal Stress

If the thermal expansion of a rod is prevented by fixing its ends rigidly, the rod acquires a compressive strain. The corresponding stress set up in the rod is called thermal stress.

Heat Capacity

Heat capacity (S) of a substance is the amount of heat required to raise the temperature of the substance by one unit.

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

Unit is JK^{-1}

Heat capacity of a substance depends on its mass, temperature and the nature of substance.

Specific Heat capacity

Specific heat capacity (s) of a substance is the amount of heat required to raise the temperature of unit mass of the substance by one unit.

$$\text{Specific heat capacity} = \frac{\text{Heat capacity}}{\text{mass}}$$

$$s = \frac{S}{m}$$

$$\text{but,} \quad S = \frac{\Delta Q}{\Delta T}$$

$$s = \frac{1}{m}\frac{\Delta Q}{\Delta T}$$

Unit is $Jkg^{-1}K^{-1}$

It depends on the nature of the substance and its temperature. It is independent of mass of the substance.

From above equation, the amount of heat,

$$\Delta Q = m\, s\, \Delta T$$

Molar Specific Heat Capacity

Molar Specific heat capacity (C) of a substance is the amount of heat required to raise the temperature of one mole of the substance by one unit.

$$C = \frac{S}{m}$$

$$C = \frac{1}{\mu}\frac{\Delta Q}{\Delta T}$$

Unit is $Jmol^{-1}K^{-1}$

It depends on the nature of the substance and its temperature. It is independent of mass of the substance.

Specific Heat Capacities of Gases

As gas is compressible, heat transfer can be achieved by keeping either pressure or volume constant. So gases have two types of molar specific heat capacities.

Molar specific heat capacity at constant pressure C_p and

Molar specific heat capacity at constant volume C_v

Molar Specific Heat Capacity at Constant Pressure C_p

Molar specific heat capacity at constant pressure of a substance is the amount of heat required to raise the temperature of one mole of the substance by one unit keeping its pressure constant.

$$C_p = \frac{1}{\mu}\left(\frac{\Delta Q}{\Delta T}\right)_p$$

Molar specific heat capacity at constant volume C_v

Molar specific heat capacity at constant volume of a substance is the amount of heat required to raise the temperature of one mole of the substance by one unit keeping its volume constant.

$$C_v = \frac{1}{\mu}\left(\frac{\Delta Q}{\Delta T}\right)_v$$

Water has the highest specific heat capacity compared to other substances. Specific heat capacity of water is 4186 is $Jkg^{-1}K^{-1}$

- For this reason water is used as a coolant in automobile radiators as well as a heater in hot water bags.
- Owing to its high specific heat capacity, the water warms up much more slowly than the land during summer and consequently wind from the sea has a cooling effect.

In desert areas, the earth surface warms up quickly during the day and cools quickly at night.

Calorimetry: **Calorimetry means measurement of heat.**

Calorimeter: **A device in which heat measurement can be made is called a calorimeter.**

It consists a metallic vessel and stirrer of the same material like copper or alumiunium. The vessel is kept inside a wooden jacket which contains heat insulating materials like glass wool etc. The outer jacket acts as a heat shield and reduces the heat loss from the inner vessel. There is an opening in the outer jacket through which a mercury thermometer can be inserted into the calorimeter.

Change of State

Matter normally exists in three states: solid, liquid, and gas.

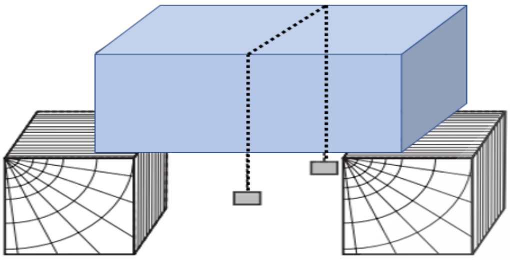
A transition from one of these states to another is called a change of state. The temperature of the system does not change during change of state.

Change of state from solid to liquid

The change of state from solid to liquid is called melting and from liquid to solid is called fusion.

- Both the solid and liquid states of the substance coexist in thermal equilibrium during the change of states from solid to liquid.
- **The temperature at which the solid and the liquid states of the substance in thermal equilibrium with each other is called its melting point.**
- **Melting point decrease with increase in pressure** . The melting point of a substance at standard atomspheric pressure is called its normal melting point.

Regelation



When the wire passes through the ice slab , ice melts at lower temperature due to increase in pressure. When the wire has passed, water above the wire freezes again. This phenomenon of refreezing is called **regelation.**

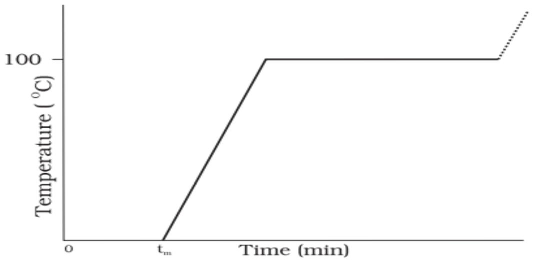
Skating is possible on snow due to the formation of water below the skates. Water is formed due to the increase of pressure and it acts as a lubricant.

The change of state from liquid to vapour

The change of state from liquid to vapour (or gas) is called vaporisation and from vapour to liquid is called condensation.

- The temperature remains constant until the entire amount of the liquid is converted into vapour
- **The temperature at which the liquid and the vapour states of the substance coexist is called its boiling point.**
- **The boiling point increases with increase in pressure and decreases with decreases in pressure.** The boiling point of a substance at standard atmospheric pressure is called its normal boiling point.
  - Cooking is difficult on hills. At high altitudes, atmospheric pressure is lower, boiling point of water decreases as compared to that at sea level.
  - Boiling point is increased inside a pressure cooker by increasing the pressure. Hence cooking is faster.

A plot of temperature versus time showing the changes in the state of ice on heating.



Sublimation

The change from solid state to vapour state without passing through the liquid state is called sublimation, and the substance is said to sublime.
Eg: Dry ice (solid CO2) , Iodine, Camphor

During the sublimation process both the solid and vapour states of a substance coexist in thermal equilibrium.

Change of state	
Solid to Liquid	Melting
Liquid to Solid	Fusion
Liquid to Gas	Vaporisation
Gas to Liquid	Condensation
Solid to Gas	Sublimation

Latent Heat

The amount of heat per unit mass transferred during change of state of the substance is called latent heat of the substance for the process.
The heat required during a change of state depends upon the heat of transformation and the mass of the substance undergoing a change of state.

$$Q = mL$$

$$L = \frac{Q}{m}$$

where L is known as latent heat and is a characteristic of the substance.

SI unit of Latent Heat is J kg^{-1}

The value of L also depends on the pressure. Its value is usually quoted at standard atmospheric pressure

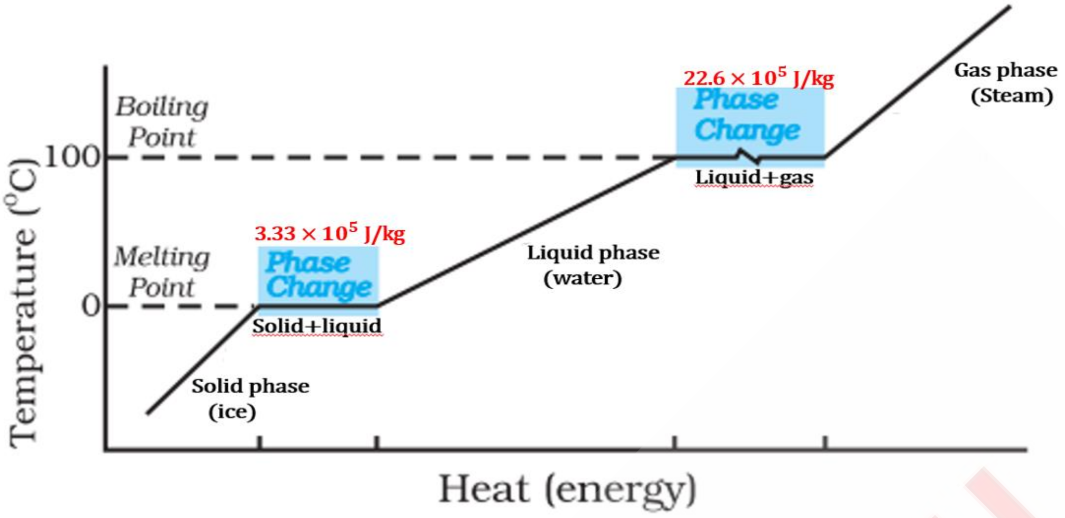
Latent Heat of Fusion (L_f)

The latent heat for a solid -liquid state change is called the latent heat of fusion (L_f) or simply heat of fusion.

Latent Heat of Vaporisation (L_v)

The latent heat for a liquid-gas state change is called the latent heat of vaporisation (L_v) or heat of vaporisation.

Temperature versus heat for water at 1 atm pressure (not to scale).



The slopes of the phase lines are not same, which indicate that specific heats of the various states are not equal.
When slope of graph is less, it indicates a high specific heat capacity .

- The specific heat capacity of water is greater than that of ice.

$$\Delta Q = m\, s\, \Delta T$$

  The amount of heat required ,ΔQ in liquid phase will be greater than that in solid phase for same ΔT.
  So slope of liquid phase is less than that of solid phase.
- For water, the latent heat of fusion is $\mathbf{L_f} = 3.33 \times 10^5$ J kg^{-1}.
  That is 3.33×10^5 J of heat are needed to melt 1 kg of ice at 0 °C.
  For water, the latent heat of vaporisation is $\mathbf{L_v} = 22.6 \times 105$ J kg^{-1}.
  That is 22.6×10^5 J of heat is needed to convert 1 kg of water to steam at 100 °C.

Why burns from steam are usually more serious than those from boiling water?

For water, the latent heat of vaporisation is $\mathbf{L_v} = 22.6 \times 10^5$ J kg^{-1}.
That is 22.6×10^5 J of heat is needed to convert 1 kg of water to steam at 100 °C. So, steam at 100 °C carries 22.6×10^5J kg^{-1}more heat than water at 100 °C. This is why burns from steam are usually more serious than those from boiling water.

Example

When 0.15 kg of ice at 0 °C is mixed with 0.30 kg of water at 50°C in a container, the resulting temperature is 6.7 °C. Calculate the heat of fusion of ice. (s_{water}= 4186 J $kg^{-1}\ K^{-1}$)

$$\Delta Q = m\, s\, \Delta T$$

Heat lost by water $= m s_{water}\ (T_f - T_i)$

$= 0.30 \times 4186 \times (50.0\ °C - 6.7\ °C) = 54376.14$ J

Heat required to melt ice $= m\, L_f$

$= (0.15$ kg$)\ L_f$

Heat required to raise temperature of ice water to final temperature

$= m\, s_{water}\ (T_f - T_i)$

$= 0.15 \times 4186\ \times (6.7\ °C - 0\ °C) = 4206.93$ J

Heat lost = heat gained

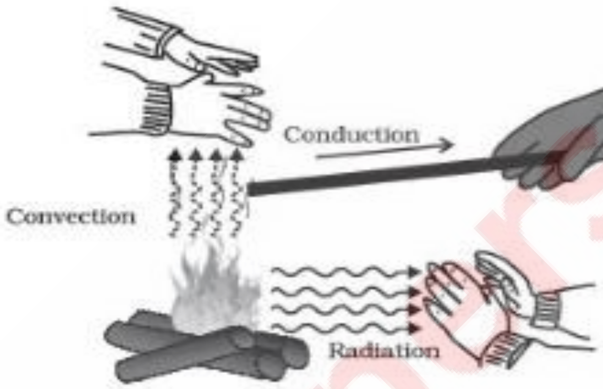
54376.14 J $= (0.15$ kg$)\ L_f + 4206.93$ J

$$\mathbf{L_f = 3.34 \times 105\ J\ kg^{-1}}$$

Heat Transfer

There are three distinct modes of heat transfer :

conduction, convection and radiation

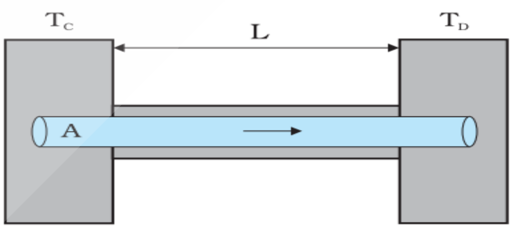


1.Conduction

Conduction is the mechanism of transfer of heat between two adjacent parts of a body because of their temperature difference.

If one end of a metallic rod is heated , heat transfer takes place by conduction from the hot end of the rod to the other end.

Consider a metallic bar of length L and uniform cross section A with its two ends maintained at different temperatures T_C and T_D; ($T_C > T_D$).



The rate of flow of heat H is proportional to the temperature difference (T_C - T_D) and the area of cross section A and is inversely proportional to the length L :

$$H = K A \frac{T_C - T_D}{L}$$

The constant of proportionality K is called the **thermal conductivity** of the material. The greater the value of K for a material, the more rapidly will it conduct heat. The SI unit of K is $Js^{-1}m^{-1}K^{-1}$ or $Wm^{-1}K^{-1}$

- Gases are poor thermal conductors while liquids have conductivities intermediate between solids and gases.
- Metals are good thermal conductors.
- Wood , glass and wool have small thermal conductivities.
- Some cooking pots have copper coating on the bottom. Being a good conductor of heat, copper promotes the distribution of heat over the bottom of a pot for uniform cooking.
- Plastic foams, on the other hand, are good insulators, mainly because they contain pockets of air.
- Houses made of concrete roofs get very hot during summer days, because thermal conductivity of concrete is moderately high. Therefore, people usually prefer to give a layer of earth or foam insulation on the ceiling so that heat transfer is prohibited and keeps the room cooler.

2.Convection

Convection is a mode of heat transfer by actual motion of matter. It is possible only in fluids.

Convection can be natural or forced.

Natural Convection

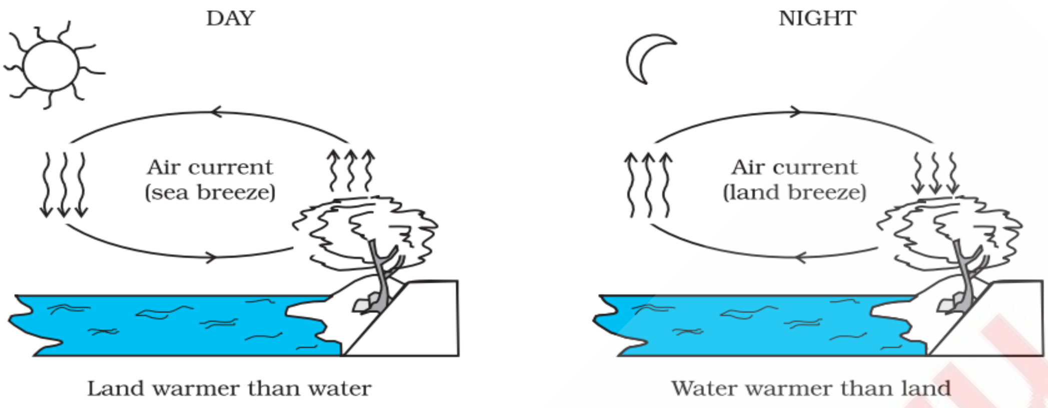
In natural convection, gravity plays an important part. When a fluid is heated from below, the hot part expands and, therefore, becomes less dense. Because of buoyancy, it rises and the upper colder part replaces it. This again gets heated, rises up and is replaced by the colder part of the fluid.**Eg: Sea breeze, Land breeze, Trade wind**

1.Sea breeze

During the day, the ground heats up more quickly than large water bodies. This is due to greater specific heat capacity of water. The air in contact with the warm ground is heated . It expands, becomes less dense and rises . Then cold air above sea moves to fill this space and is called as sea breeze .

2.Land breeze

At night, the ground loses its heat more quickly, and the water surface is warmer than the land. The air in contact with water is heated. It expands, becomes less dense and rises . Then cold air above the ground moves to fill this space and is called as land breeze .



3.Trade wind

The surface of the earth at the equator is heated more by sun rays than poles. The hot air at equator expands, becomes less dense and rises . Then cold air from poles moves to the equator. This is called trade wind.

Forced Convection

In forced convection, material is forced to move by a pump or by some other physical means.

Eg: Forced-air heating systems in home
The human circulatory system
The cooling system of an automobile engine.

In the human body, the heart acts as the pump that circulates blood through different parts of the body, transferring heat by forced convection and maintaining it at a uniform temperature.

3.Radiation

The mechanism for heat transfer which does not require a medium is called radiation.

The electromagnetic radiation emitted by a body by virtue of its temperature is called thermal radiation. The energy so radiated by electromagnetic waves is called radiant energy. All bodies emit radiant energy, whether they are solid, liquid or gases.

Heat is transferred to the earth from the sun through empty space as radiation.

Black bodies absorb and emit radiant energy better than bodies of lighter colours.

This fact finds many applications in our daily life.

- We wear white or light coloured clothes in summer so that they absorb the least heat from the sun.
- During winter, we use dark coloured clothes which absorb heat from the sun and keep our body warm.
- The bottoms of the utensils for cooking food are blackened so that they absorb maximum heat from the fire and give it to the vegetables to be cooked.

Principle of Thermo Bottles

Thermos bottle is a device to minimise heat transfer between the contents of the bottle and outside. It consists of a double-walled glass vessel with the inner and outer walls coated with silver. Radiation from the inner wall is reflected back into the contents of the bottle. The outer wall similarly reflects back any incoming radiation. The space between the walls is evacuated to reduce conduction and convection losses and the flask is supported on an insulator like cork. The device is, therefore, useful for preventing hot contents from getting cold, or alternatively to store cold contents (like ice).

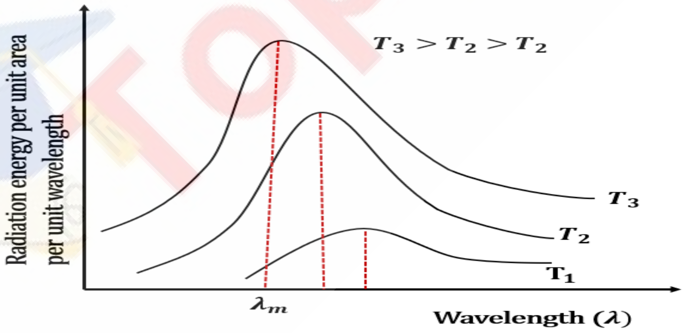
Blackbody

An object that absorbs all radiations falling on it at all wavelength is called a blackbody. A blackbody, also emits radiations of all possible wavelength.

Blackbody Radiation

The radiations emitted by blackbody are called blackbody radiations.

The variation of energy emitted by a blackbody with wavelength is is as shown in figure:



Wien's Displacement Law

The wavelength λ_m for which energy emitted by a blackbody is the maximum , is inversely proportional to the temperarure.This is known as Wien's Displacement Law.

$$\lambda_m \ \alpha \ \frac{1}{T}$$

$$\lambda_m T = \text{constant}$$

The constant is called Wien's constant and its value is 2.9 x 10^{-3}mK.

Stefan-Boltzmann Law

The energy emitted by a perfect radiator (black body) per unit time is given by $$\mathbf{H = A\sigma T^4}$$

This is called Stefan-Boltzmann Law.

where A - the area of the body
T - temperature of body
σ is called **Stefan-Boltzmann constant**
$\sigma = 5.67 \times 10^{-8} Wm^{-2}K^{-4}$

- If the body is not a perfect radiator

$$\mathbf{H = Ae\sigma T^4}$$

where e is the emissivity i.e, the ability to radiate.
For a perfect radiator,emissivity, e=1

- If T is the temperature of the body and T_s is the temperature of surroundings, then rate of loss of radiant energy is

$$\mathbf{H = Ae\sigma\, (T - T_s)^4}$$

Newton's Law of Cooling

Newton's Law of Cooling says that the rate of loss of heat(rate of cooling) of a body is proportional the difference of temperature of the body and the surroundings.

$$-\frac{dQ}{dT} = k(T_2 - T_1)$$

Where T_1 is the temperature of the surrounding medium
T_2 is the temperature of the body
k is a positive constant depending upon the area and nature of the surface of the body

Curve showing cooling of hot water with time.