SHORT NOTES: CLASS 11

CHAPTER 10: THERMAL PROPERTIES OF MATTER

HEAT: Heat is a form of energy transferred between two bodies due to differences in temperature. Heat energy always flows from a body at high temperature to a body at low temperature. The unit of heat is Joule or Calorie.

TEMPERATURE: Temperature is a scalar physical quantity. Temperature is a physical quantity that measures the degree of hotness or coldness of a body. When two bodies are at the same temperature, then they are said to be in a **thermal equilibrium** with each other. The unit of temperature is Celsius, Kelvin, or Fahrenheit.

MEASUREMENT OF TEMPERATURE: The science of temperature and its measurement is called **thermometry.** An instrument designed to measure temperature is called a **thermometer.**

Types of thermometers:

(i) Liquid in glass thermometer

(ii) Constant volume gas thermometer

(iii) Resistance thermometer

Note:

(i) Among the thermometers with cylindrical and spherical bulbs, the cylindrical is more sensitive because the cylindrical shape has more surface area.

(ii) An alcohol thermometer is more sensitive than a mercury thermometer as the expansion of alcohol is more than that of mercury.

(iii) **Mercury is used as liquid in thermometers because ….**

(a) Mercury has low specific heat, low heat capacity, and low vapour pressure.
(b) The coefficient of real expansion is more.
(c) Mercury is opaque and shines like silver.
(d) Mercury does not wet the glass.

(iv) **Gas thermometers are more sensitive than liquid thermometers because,**

(a) All gases have the same temperature coefficients.
(b) For slight variation of temperature there will be a large expansion.
(c) Even though there is an impurity in it, it does not affect temperature.

(v) Nitrogen is used as a thermometric substance for measuring temperatures up to 1500^{0}C.

(vi) Helium is used as a thermometric substance for measuring low temperatures below -200^{0}C.

Measurement of temperature requires:

(i) The construction of an instrument. (i.e., thermometer)

(ii) The calibration of the thermometer.

Note:

(i) Calibration of the thermometer depends on fixing certain points on the thermometer.

(ii) The ice point and the steam point of water are known as freezing and boiling points of water.

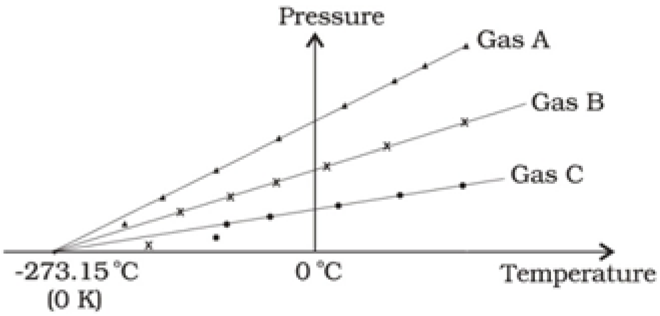
(iii) Ice point is taken as Lower Fixed Point (LFP). Steam point is taken as the Upper Fixed Point (UFP).

(iv) Fundamental interval = UFP – LFP

General formula: $\frac{\textit{Unknown tempwerature on the scale} - \textit{ice point}}{\textit{steam point} - \textit{ice point}}$

Celsius scale	Kelvin scale	Fahrenheit scale	Reaumur scale	Rankine scale
$\frac{C}{100}$	$\frac{k-273}{100}$	$\frac{F-32}{180}$	$\frac{R}{80}$	$\frac{R_a-492}{180}$

Zero point of the Kelvin temperature scale: Absolute zero is the lowest possible temperature, at -273.15 degrees on the Celsius scale. It's the zero point of the Kelvin temperature scale. At absolute zero, the particles in a gas would have some energy, but it would be zero kinetic energy.



IDEAL GAS EQUATION:

(i) BOYLE'S LAW: At constant temperature, the volume of a given mass of a gas is inversely proportional to its pressure. Let P and V be the pressure and volume of a given mass of a gas at constant temperature. According to Boyle's Law,

$V \alpha 1/P$ at a constant temperature

PV = constant

The curve is isothermal.

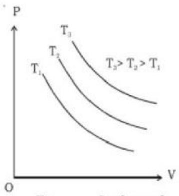


Fig. Isothermal process

Boyle's law in terms of density:

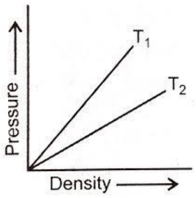
Consider a gas of mass m, pressure P, volume V density ρ then $V = m/\rho$

But from Boyle's law

PV=constant or $P.\ m/\rho$ =constant.

At constant temperature, for a given mass of a gas, pressure is directly proportional to its density

$P_1/P_2 = \rho_1/\rho_2$



(ii) CHARLE'S LAW:

Charles' law at constant pressure: At constant pressure, the volume of a given mass of gas is directly proportional to its temperature on the Kelvin scale.

$V \alpha T$ $\quad$ V = KT $\quad$ V/T = constant.

Let V_0 and V_t be the volumes of the given mass of gas at 0^0C and t^0C respectively at constant pressure. From the definition of the volume coefficient of the gas,

$V_t = V_0 [1+\alpha t]$ $\quad$ **$V_t = V_0\left[1 + \frac{t}{273.15}\right]$**

Charles' law at constant volume: At constant volume, the pressure of a given mass of gas is directly proportional to its temperature on the Kelvin scale.

$P \alpha T$ $\quad$ P = KT $\quad$ P/T = constant

Let P_0 and P_t be the pressure of the given mass of gas at 0^0C and t^0C respectively at constant volume. From the definition of the pressure coefficient of a gas

$$P_t = P_0 [1 + \beta t] \qquad P_t = P_0\left[1 + \frac{t}{273.15}\right]$$

(iii) IDEAL GAS: A gas that obeys Boyle’s law and Charles's law strictly at all temperatures and pressure is called a perfect or an ideal gas.

1. The ideal gas has molecules of point size.
2. Total internal energy (U) of an ideal gas: U =Σ K.E of all the gas molecules.

For ‘n’ moles of a gas, the ideal gas equation is :

PV = nRT

SI unit of R is $J\ mol^{-1}\ K^{-1}$

Dimensional formula of R is $[ML^2T^{-2}K^{-1}mol^{-1}]$.

(iv) IDEAL GAS EQUATION IN TERMS OF BOLTZMANN CONSTANT:

Boltzmann constant (k) is defined as the universal gas constant per molecule. i.e. $K = \frac{R}{N_A}$

We know, PV = nRT

n = Total number of molecules (N)/Avogadro’s number of molecules (N_A)

(v) REAL GAS: The gas that obeys Boyle’s law at low pressure and high temperature is called real gas.

1. Real gas has molecules of finite size
2. The total internal energy (U): U =ΣP.E + ΣK.E of all molecules.

THERMAL EXPANSION OF SOLIDS:

Note:

(i) The solids that expand uniformly in all directions when heating are called isotropic solids.

(ii) Anisotropic solids have different thermal expansions in various directions. Examples: Cristiana ($CaCo_3$), and Galena.

(iii) Solid substances such as cast iron, silver iodine, silica glass, rubber, leather, ice, lead, etc., contract on heating.

COEFFICIENT OF LINEAR EXPANSION

- When a solid is heated, the increase in length is called linear expansion.
- The ratio of the increase in length of a solid per degree rise in temperature to its original length is called the coefficient of linear expansion (α).
- If l_1 and l_2 are the lengths of a rod at two temperatures $t_1{}^0C$ and $t_2{}^0C$ respectively, and the rise in temperature of the rod is $(t_2\text{-}t_1)\ ^0C$ then the coefficient of linear expansion is,

$$\alpha = \frac{l_2 - l_1}{l_1(t_2 - t_1)} \qquad\qquad \alpha = \frac{\Delta l}{l\Delta t}$$

- The SI unit of α is K^{-1} and its CGS unit is $(^0C)^{-1}$.
- The dimensional formula of α is $[M^0L^0\,T^0\,K^{-1}]$.
- The coefficient of linear expansion of a solid depends on the nature of the material and the scale of temperature.
- The linear expansion of a solid depends on three factors.
  - (i) Its original length (l_1)
  - (ii) The nature of the material (α)
  - (iii) Change in temperature ($t_2 - t_1$)
- Final length $\boldsymbol{l_2 = l_1[1 + \alpha (t_2 - t_1)]}$
- Change in length $\boldsymbol{l_2 - l_1 = \Delta l = \alpha l_1 (t_2 - t_1)}$
- Final temperature $\mathbf{t_2} = \frac{l_2 - l_1}{\alpha l_1} + t_1$
- Percentage change in length: $\frac{\Delta l}{l} \times 100 = \alpha\Delta t \times 100$

COEFFICIENT OF AREAL/SUPERFICIAL EXPANSION

- It is defined as the increase in the area of a solid per unit original area per unit rise in temperature.
- If A_1 and A_2 are the areas of a solid at temperatures t_1 and t_2 respectively, then coefficient of areal expansion is given by

$$\boldsymbol{\beta = \frac{A_2 - A_1}{A_1(t_2 - t_1)}} \qquad \boldsymbol{\beta = \frac{\Delta A}{A\Delta t}}$$

- The SI unit β is K^{-1} and its CGS unit is $(^0C)^{-1}$.
- The dimensional formula of β is $[M^0L^0T^0K^{-1}]$
- Final area $\mathbf{A_2 = A_1[1 + \beta\ (t_2-t_1)]}$
- Final change in area $\mathbf{\Delta A = \beta A_1(t_2-t_1)}$
- Final temperature $\mathbf{t_2 = \frac{A_2 - A_1}{A_1\,\beta} + t_1}$
- Change in area $\mathbf{\Delta A = \beta\ A_1(t_2-t_1)}$
- Percentage of fractional change in area $\mathbf{\Delta a/a \times 100 = \beta(\Delta t) \times 100}$

COEFFICIENT OF CUBICAL/VOLUME EXPANSION:

- It is defined as the increase in volume of a solid per unit original volume per unit rise in temperature.
- If V_1 and V_2 are the volumes of a solid at temperature t_1 and t_2 respectively, then the coefficient of cubical expansion is given by,

$$\boldsymbol{\gamma = \frac{V_2 - V_1}{V_1(t_2 - t_1)}} \qquad \boldsymbol{\gamma = \frac{\Delta V}{V\Delta t}}$$

- The SI unit of γ is K^{-1} and its CGS unit is $(^0C)^{-1}$.
- The dimensional formula of γ is $[M^0\ L^0\ T^0\ K^{-1}]$.
- Final volume $\mathbf{V_2 = V_1[\ 1 + \gamma\ (\ t_2 - t_1\ )]}$
- Final temperature, $\boldsymbol{t_2 = \frac{V_2 - V1}{V_1\gamma} + t_1}$
- Change in volume $\mathbf{\Delta V = \gamma\ V\ (t_2 - t_1)}$
- Percentage change in volume $= \boldsymbol{\frac{\Delta V}{V} \times 100 = \gamma\Delta t \times 100}$

Note: For an **anisotropic solid**, if α_x, α_y and α_z are coefficients of linear expansions along x, y, and z directions respectively then the coefficient of cubical expansion is

$$\boldsymbol{\alpha = \frac{\alpha_x + \alpha_y + \alpha_z}{3}}$$

For **isotropic solids**, **γ=3α** $(\because \alpha_x = \alpha_y = \alpha_z = \alpha)$

RELATION BETWEEN α, β AND γ:

(i) $\boldsymbol{\beta = 2\alpha}$

(ii) $\boldsymbol{\gamma = 3\alpha}$

(iii) $\boldsymbol{\alpha + \beta = \gamma}$

(iv) $\boldsymbol{\alpha : \beta : \gamma = 1 : 2 : 3}$

(v) $\boldsymbol{\frac{\alpha}{1} = \frac{\beta}{2} = \frac{\gamma}{3}}$

The values of α, β and γ are independent of units of length, area, and volume respectively.

VARIATION OF THE DENSITY OF A SUBSTANCE WITH TEMPERATURE:

The volume of a solid increases on heating while its mass remains constant, hence the density of the substance decreases.

Let a solid of mass 'm' have volumes V_1 and V_2 and densities d_1 and d_2 at temperatures $t_1{}^0C$ and $t_2{}^0C$ respectively.

Hence, $m = V_1d_1 = V_2d_2$

Therefore, $V_1d_1 = V_1\,[1+ \gamma\ (t_2 - t_1)]\ d_2$ (because, $V_2 = V_1\ [1+ \gamma\ (t_2 - t_1)]$)

$d_1 = d_2\,[1+\gamma\ (t_2 - t_1)]$

$$\gamma = \frac{d_1 - d_2}{d_2(t_2 - t_1)}$$

If the solid is heated from 0^0C to t^0C, its density changes from d_0 to d_t.

$$\therefore \gamma = \frac{d_0 - dt}{d_t(t)}$$

$$d_0 = d_t [1+\gamma t]$$

APPLICATIONS OF THERMAL EXPANSION: Examples of thermal expansion of solids in daily life:

- While laying the railway tracks, small gaps are left between adjacent rails to prevent the line from buckling or even breaking due to changes in temperature.
- Gaps are left along the length of cement roads to allow for expansion during summer.
- To fix an iron tyre onto the wooden rim of a cartwheel, the iron tyre is heated so that it slips onto the wooden rim. On cooling the iron tyre contracts and grips the wheel firmly.
- Platinum wires are fused into the glass without any risk of a crack developing since the coefficient of linear expansions of platinum and glass are the same.
- Wires between two electrical poles are loosely stretched to allow for contraction during the winter season.
- The expansion of steel is equal to that of concrete for the same rise in temperature. Hence steel and concrete are used in the construction of buildings.
- When hot water is taken in a glass tumbler it breaks due to uneven expansion.
- When cold water drops on a hot chimney it breaks due to uneven contraction.

BIMETALLIC STRIP: A bimetallic strip consists of two strips made of two different metals with different coefficients of expansion riveted together.

- It works on the principle that different metals expand differently for the same rise in temperature.

Uses:

- For continuous recording of temperature
- As a thermostat to control the temperature of a body (in refrigerator, iron box).
- As a fire alarm.

MEASURING TAPES:

- Measuring tapes are made of invar steel because of its least coefficient of linear expansion.
- Measuring tapes made of metals show correct readings only at the temperature at which they are constructed.
- A metal tape is graduated at $t_1{}^0C$. If the measurement is taken at temperature $t_2{}^0C$ then the distance between the divisions changes due to linear expansion of scale.
- Thus, the measured reading will be different from the correct reading.
- If l_m is the measured reading of the length of a body and l_o is the correct length of the body at $t_1{}^0C$ then, $l_0 = l_m [1 + (\alpha_s - \alpha_b)(t_2 - t_1)]$

PENDULUM CLOCK:

- The period of a pendulum of length l is given by: $T = 2\pi\sqrt{\frac{l}{g}}$
- In summer length of a pendulum increases so that its time period increases and it makes less number of oscillations than the required oscillations per day.
- In winter length of a pendulum decreases so that its time period decreases and it makes more oscillations than the required oscillations per day.
- Pendulum clocks are made of invar steel because of its least coefficient of linear expansion.

THERMAL STRESS

- A metal rod is rigidly fixed at its ends to prevent it from expansion and contraction. When it is heated, thermal stress is developed in the rod.
- Tension on the rod or thermal force: $F = YA\alpha(t_2 - t_1)$

  Thermal Stress=$Y\alpha(t_2-t_1)$
- For the same rise of temperature, if the same thermal stress is developed in two different rods,

then $Y_1\alpha_1 = Y_2\alpha_2$.

- If a cube of coefficient of cubical expansion γ is heated, then the pressure to be applied to prevent its expansion is given by, $P = K\gamma\,(t_2 - t_1)$ or $P = 3K\,\alpha\,(t_2 - t_1)$

THERMAL EXPANSION OF LIQUIDS

- Liquids have only volume but no definite shape of their own. So liquids have only volume expansion on heating.
- Solids can be heated directly, but liquids cannot be heated directly. Liquids are to be taken in a container and then heated.
- When a liquid in a container is heated, both the liquid and the container expand.
- Hence, in the case of liquids there are two types of expansions. They are

1) Apparent expansion. **2) Absolute or real expansion.**

APPARENT EXPANSION:

- When a liquid is heated in a container the observed change in volume of the liquid relative to the container is called the apparent expansion of the liquid.
- Apparent expansion of the liquid depends on
  a) Nature of liquid.
  b) Nature of material of container.
  c) Initial volume of the liquid.
  d) Change in temperature.

REAL OR ABSOLUTE EXPANSION:

- When a liquid is heated in a container the real change in volume of the liquid is called the real or absolute expansion of the liquid.
- The real expansion of the liquid depends on
  a) Nature of liquid.
  b) Initial volume of the liquid.
  c) Change in temperature.

COMPARISON OF EXPANSIONS OF SOLID AND LIQUID:

a) Expansion of solids is almost uniform in any temperature range whereas liquids expand at different rates in different ranges of temperature.
b) Solids can have linear, superficial, and volume expansions but liquids have only volume expansion.
c) The coefficient of volume expansion of liquids is generally several hundred times greater than that of solids.

ANOMALOUS EXPANSION OF WATER:

- Generally, liquids expand on heating and contract on cooling.
- But water contracts on heating from 0^0C to 4^0C and expands with a further rise in temperature.
- On cooling it contracts from 100^0C to 4^0C and expands from 4^0C to 0^0C.
- This peculiar behaviour of water in the range from 0^0C to 4^0C is called the anomalous expansion of water.
- The curve shows that the volume of water decreases from 0^0C to 4^0C and then increases. At 4^0C volume of water is minimal.

Cause of anomalous expansion:

The anomalous behaviour of water is explained on the assumption that there are three types of water molecules: H_2o, $(H_2o)_2$, $(H_2o)_3$

Significance of anomalous expansion of water:

- Water has maximum density at 4^0C.
- Anomalous expansion of water plays a very important role in the life of animals in lakes, ponds, seas, etc.

- During winter in cold countries, water in ponds, lakes, and rivers cools to 4^0C due to atmospheric temperature.
- Ice is a bad conductor of heat, so the lower layer of water is protected against freezing.
- So, the lower layers of water remain at 4^0C while the upper layers further cool down to 0^0C and freeze into ice.
- Hence, the aquatic animals can survive in lower layers of water at 4^0C.

EXPANSION OF GASES:

- Gases have no definite shape and size, therefore, for gases, the coefficients of linear and areal expansions have no significance.
- When gas is heated, its pressure and volume change simultaneously. This is not convenient to measure the two variations at a time.

Gas has two coefficients:

a) **Volume co-efficient of Gas (α):** Volume co-efficient of Gas is defined as the increase in the volume of a given mass of a gas per volume at 0^0C per degree Celsius rise in temperature keeping pressure constant.

b) **Pressure co-efficient of Gas (β):** The pressure co-efficient of a gas is defined as the increase in pressure of a given mass of a gas per pressure at 0^0C per degree Celsius rise in temperature, keeping the volume constant.

HEAT CAPACITY OR THERMAL CAPACITY:

The quantity of heat required to raise the temperature of a body by one degree is called the heat capacity (S) of the body.

Let ΔQ be the quantity of heat given to the substance and let the rise in its temperature be Δt.

Heat capacity $S = \Delta Q/\Delta t$

Unit in C.G.S system: Cal/^{0}C **SI unit: JK^{-1}** **Dimensional formula: $[M^0 L^2 T^{-2} K^{-1}]$**

- When some quantity of heat is given to the bodies of the same mass but of different substances, it is observed that the rise in temperature is different for different substances.
- So, the heat capacity of a body depends on the nature of the substance and also the mass of the body.

SPECIFIC HEAT CAPACITY:

The specific heat of a material is defined as the quantity of heat required by the unit mass of the material to raise temperature by one degree.

$\Delta Q \propto m. \Delta T$ **$\Delta Q = s\, m. \Delta T$**

's' is called the specific heat of the material of the body.

C.G.S unit: Cal $gm^{-1}\,{}^0C^{-1}$ **SI unit: $J\, kg^{-1}\, K^{-1}$**

1Cal/g ^{0}C = 4186 J/kg K $\approx$ 4200 J/ kg K **1 Cal = 4.186 J** **1 gm = 10^{-3} kg**

- **The dimensional formula of specific heat is $[M^0 L^2 T^{-2} K^{-1}]$**
- Specific heat depends only on the nature of the substance. It does not depend on the mass of the substance.
- The ratio of the universal gas constant per unit mass is called the specific gas constant.
- $r = \frac{R}{M}$, r= specific constant, R = universal gas constant
- The value of r changes from one gas to another gas.
- 'R' same for all gases.

<u>RELATION BETWEEN HEAT CAPACITY (S) AND SPECIFIC HEAT (s):</u> When a quantity of heat ΔQ is given to a body of mass 'm'. Let the rise in temperature of the body be Δt.

Then $S = \Delta Q/\Delta T$ ....(1)

But specific heat $s = \Delta Q/m.\Delta T$ ....(2)

$\Delta Q = m\, s\Delta T$ $\therefore S = m\, s\Delta T/\Delta T$ $\Rightarrow$ $\therefore$ **S = ms.**

MOLAR SPECIFIC HEAT CAPACITY: $C = \frac{S}{\mu} = \frac{1}{\mu}\frac{\Delta Q}{\Delta T}$, μ: number of moles

C: Molar-specific heat capacity

It depends upon the nature of the substance and its temperature. The SI unit of C is J $mol^{-1}K^{-1}$.

Molar specific heat capacity at constant pressure: C_P: Molar specific heat capacity at constant pressure is the amount of heat required to raise the temperature of one mole of a substance by 1 Kelvin at constant pressure. It is denoted by the symbol C_p. Its unit is $J/mol{\cdot}K$

Molar specific heat capacity at constant volume: C_v: Molar specific heat at constant volume is the amount of heat required to raise the temperature of one mole of a substance by 1 Kelvin at constant volume. It is denoted by the symbol C_v. Its unit is $J/mol{\cdot}K$

WATER EQUIVALENT OF A BODY: The water equivalent of a body is defined as the mass of water which absorbs the same quantity of heat for the same rise in temperature.

The mass of water whose thermal capacity is equal to that of a given body is called the water equivalent of that body.

Water equivalent of a given body,

$$w = \frac{\text{Heat capacity of a given body}}{\text{Specific heat of water}}$$

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

$\Delta Q = w\, \Delta T$

$\Rightarrow$ $w = sm$

CALORIMETRY:

- The branch of science which deals with the measurement of heat is called calorimetry.
- A perfect calorimeter completely prevents heat from flowing to its surroundings.
- At thermal equilibrium all the materials reach the same temperature.
- Because no energy flows into or out of the container.
- The Law of conservation of energy leads to the principle of calorimetry.
- The apparatus used for this purpose is called a calorimeter.

PRINCIPLE OF CALORIMETRY:

- If two bodies at two different temperatures are brought into thermal contact, then heat is lost by the hot body, and heat is gained by the cold body until they attain thermal equilibrium if heat is not lost by any other process
- heat lost by hot body=heat gained by cold body

  Explanation:

  Consider a hot body of mass m_1. Specific heat S_1 at $t_1{}^0C$ is kept in thermal constant with another cold body of mass m_2, specific heat S_2, and at temperature t_2. Let t_3 be the common temperature attained.

  Heat lost by hot body=$m_1s_1(t_1-t_3)$ **Heat gained by cold body=$m_2s_2(t_3-t_2)$**

LATENT HEAT: The amount of heat absorbed or given out by the unit mass of a substance during the change of state is called latent heat.

Latent Heat $L = Q/m$

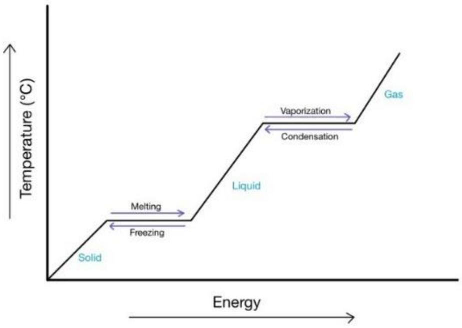
Units: Cal/gm or J / kg.

- The latent heat of fusion of ice is: $L_f = 3.35\times10^5$ J kg^{-1} or 80 Cal g^{-1}
- The latent heat of vaporization of water is: $L_v = 2.26\times10^6$ J kg^{-1} or 540 Cal g^{-1}.
- Liquids with low latent heat of vaporization are called **volatile liquids**. Ether and petrol are examples of volatile liquids.

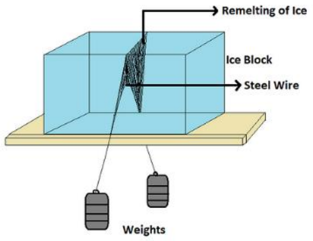
THREE PHASES OF MATTER:

- The substances can exist in three states of matter i.e., solid, liquid, and gas at different temperatures and pressures.

- Any phase of a substance can be changed into another phase on heating or cooling.
- The process of converting one phase of a substance into another phase is called “phase change”.
- The process of changing the liquid phase into a solid phase is called freezing or fusion.
- The process of changing the gaseous phase into the liquid phase is called as condensation.
- The process of changing the liquid phase into the gaseous phase is known as vaporization.



1) **Melting:** Heat supplied to the system
2) **Vaporization or boiling:** Heat supplied to the system
3) **Solidification or freezing:** Heat is given out by the system
4) **Condensation:** Heat is given out by the system
5) **Sublimation:** Heat supplied to the system
6) **Hoarfrost:** Heat is given out by the system

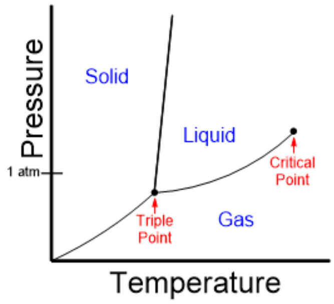


REGELATION: Regelation is the phenomenon of ice melting under pressure and refreezing when the pressure is reduced.

Just below the wire, ice melts at a lower temperature due to an increase in pressure. When the wire has passed, water above the wire freezes again. Thus, the wire passes through the slab and the slab does not split.

TRIPLE POINT OF WATER

- The temperature and pressure at which three states (solid, liquid, and vapour) of water are in thermal equilibrium is called the triple point of water.
- All these temperatures change with pressure. So, a phase diagram is obtained as shown in the figure.



- With the increase in pressure, the melting point of ice decreases, which is shown by the negative slope of the curve.

HEAT TRANSFER: Heat is transferred from a higher temperature to a lower temperature region by three different processes.

(i) Convection
(ii) Conduction
(iii) Radiation

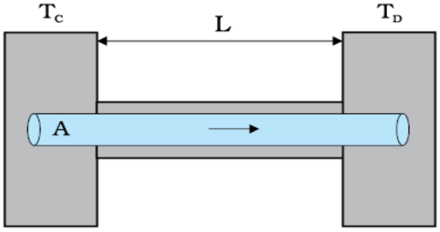
CONDUCTION:

- The transmission of heat energy from one place to another without movement of the particles of the medium is called conduction.
- In this process heat transfer takes place by molecular vibrations.

Coefficient of thermal conductivity:

- In the steady state, the temperature at any point of a slab or rod does not change as time passes.
- But along the slab or rod from the high-temperature end to the low-temperature end temperature decreases from point to point.
- The change in temperature with distance is called the temperature gradient.

Temperature gradient = $\theta_2 - \theta_1/d$ **SI unit: K m^{-1}**



Consider a metallic bar of length, L, and a uniform cross-section A with its two ends maintained at different temperatures, T_C and T_D respectively. The reservoir at C supplies heat at a constant rate, which transfers through the bar and is given out at the same rate to the reservoir at D.

It is found experimentally that 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.

$$H = KA\frac{T_C - T_D}{L}$$

K: Thermal conductivity of the material, the greater the value of K, the more rapidly will it conduct heat.

SI unit of K: $Wm^{-1}K^{-1}$ or $J\,s^{-1}m^{-1}K^{-1}$. **Dimensional formula K is $[M\,L\,T^{-3}k^{-1}]$.**

- In general, solids are better conductors than liquids and gases.

For metals K = ∞ **For insulators K = 0**

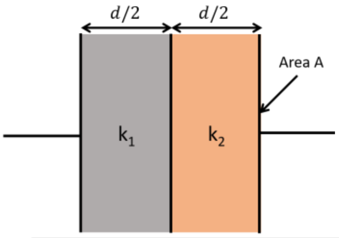
- Copper is used at the bottom of cooking utensils because it is a good conductor of heat.
- Houses made of concrete roofs get very hot during summer days.
- In nuclear reactors, a heat transfer system needs to be installed, it prevents the core from overheating.

SLABS IN COMBINATION: In parallel slabs, the area is different but the length is the same. In series slabs, the length is different but the area is the same.

Heat flow through the slabs in series: Two or more slabs that are joined together side by side and conduct heat from one substance to another.

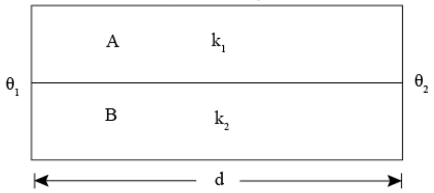
The junction temperature, T of the two bars:

$$T = \frac{k_1T_1 + k_2T_2}{k_1 + k_2}$$



Heat flow through the slabs in parallel: If two slabs of the same thickness have thermal conductivities K_1 and K_2

$$k_{eq} = \frac{2k_1k_2}{k_1 + k_2}$$



CONVECTION: The process of heat transfer from one place to another by actual movement of particles of the medium due to difference in density is called convection.

- Natural convection
- Forced convection

The rate of heat flow (P = Q/t) is directly proportional to the area A and temperature difference (ΔT).

$P \propto A\,\Delta T$ $\therefore P = hA\,\Delta T$

Where A is the surface area over which fluid moves and h is the coefficient of convection.

Natural Convection: The transfer of heat due to the movement of fluid resulting from the differences in density is called natural convection.

Examples:

- Hot air rises by natural convection.
- Sea breeze: Cold breeze moves from the sea to the land during the day by natural convection.
- Land breeze: Cold breeze moves from the land to the sea during the night by natural convection.
- When a vessel containing water is placed on a fire then, water is heated by natural convection.
- Trade winds: The winds that blow from east to West near the equator and from the northeast in the northern hemisphere and southeast in the southern hemisphere. Trade winds are caused by several factors including:
  - *(i)* *unequal heating:* The earth's Equatorial and polar regions are heated differently.
  - *(ii)* *Hadley cells:* These low-latitude circulations cause air to rise at the equator and sink at around 30°latitude.
  - *(iii)* *Coriolis force:* This phenomenon causes things like wind to appear to move in a curve as they travel around the earth.

  Note: The trade winds help ships travel west, and have been used by sailors for centuries.

Forced convection: The transfer of heat due to the forced movement of the fluid by mechanical means, such as a fan or pump, is known as forced convection.

Examples:

- The hot air in contact with the radiator of a car will be thrown away by forcing air using a fan.
- Cooling rooms in summer by pumping cold air by mechanical means (air coolers).
- Exhaust fans drive out the hot air from an auditorium or a big crowded hall.
- Ventilation in houses is an example of forced convection.
- The hot air in contact with the radiator of a car will be thrown away by forcing air using a fan.

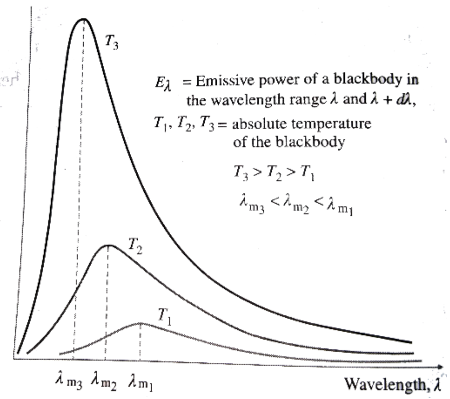
RADIATION: The transmission of heat from one place to another without the necessity of a materialistic medium is called radiation.

- In this process, heat transmits in the form of electromagnetic radiation.
- The radiation by virtue of its temperature is thermal radiation.
- All bodies emit thermal radiation except at absolute zero.

BLACK BODY RADIATION: Black body radiation is the thermal radiation emitted by an idealized object that absorbs all electromagnetic radiation that falls on it:

Definition: A black body is an object that absorbs all light that falls on it and does not reflect any. The radiation emitted by a black body is called black body radiation.

Properties: Black body radiation has a continuous spectrum of wavelengths that depends only on the body's temperature. The hotter the black body, the more intense the radiation and the shorter the peak wavelength.



(i) WIEN'S DISPLACEMENT LAW

- The wavelength of maximum radiation (λ_{min}) is inversely proportional to the absolute temperature of the black body.
- λ_{min} T = constant, b, b = 2.89×10^{-3}mK.
- At two different temperatures T_1K and T_2K of a black body, the wavelengths corresponding to maximum radiations are λ_{1m} and λ_{2m} respectively.$\lambda_m T_1 = \lambda_m T_2$

(ii) STEFAN'S BOLTZMANN LAW: proved experimentally by Stefan, later theoretically by Boltzmann

- The total electromagnetic energy radiated by a body at absolute temperature T is proportional to its size, its ability to radiate (emissivity), and temperature.
- The radiation emitted by a black body per unit area per unit of time (The emissive power of a black body) is proportional to the fourth power of the absolute temperature of a body.
- **E:** Energy per unit area per unit of time, **H:** Energy per unit of time and **Q:** Energy
- **E = H/A = Q/At**

  $E \propto T^4$

⇨ **$E = \sigma T^4$** ⇨ **$H = A\sigma T^4$** ⇨ **$Q = At\sigma T^4$**

Where**, σ is Stefan's constant = 5.67×10^{-8} $Wm^{-2}K^{-4}$**

Energy gained = energy emitted (for a perfectly black body)

But, bodies - not perfectly black

Therefore, the radiant power, **$E = e\sigma AT^4$**

When a body of radiant power E is kept in an enclosure of power E_0 at temperature T_0.

Rate of heat lost **$(E-E_0) = e\sigma A\,(T^4 - T_0^4)$.**

The rate of fall of temperature of a body at temperature T kept in surroundings of temperature T_0 is obtained by substituting the rate of heat lost R =ms dθ/dt.

Therefore, $ms\frac{d\theta}{dt} = \sigma eA\,(T^4 - T_0^4)$

GREENHOUSE EFFECT: Carbon dioxide and water do not allow the larger wavelengths' radiations (IR radiations) in the glass to escape from it.

(iii) NEWTON'S LAW OF COOLING: The rate of loss of heat to the surroundings is directly proportional to the mean excess temperature (temperature difference) of the body above that of the surroundings, provided the difference in temperature between the body and that of the surroundings is small (not more than 40°C).

If T and T_s are the temperatures of the body and surroundings.

$$-\frac{dQ}{dt} \propto (T - T_s) \qquad\qquad -\frac{d}{dt}(msT) = k(T - T_s)$$

$$\frac{-dT}{dt} = \frac{k}{ms}(T - T_s)$$, -dT/dt: rate of fall of temperature

$$-\frac{dT}{dt} = K(T - T_s)$$, K = k/ms (another constant)

$$\frac{dT}{T - T_s} = -K\,dt$$

$$\ln(T - T_s) = -Kt + C$$, C is the constant of integration

0 to t : T_1 to T_2

$$\int_{T_1}^{T_2} \frac{dT}{T - T_s} = -\int_0^t K\,dt$$

⇨ $\ln\left(\frac{T_2 - Ts}{T_1 - T_s}\right) = -Kt$

Limitations of the law of cooling:

- The surface of the body must be black.
- The loss of heat must take place only through the radiation process.
- The excess of temperature $(T - T_s)$ must not be large i.e. $(T - T_s) \leqslant 32^0C$ to 35^0C.
- The surface $\left(T = \frac{T + Ts}{2}\right)$ must remain constant.
- The air must be still.
- Newton's law of cooling is a special case of Stefan's law.
- Newton's law of cooling is applicable when the heat lost by conduction is negligible and the heat lost by the body is mainly by radiation.
- Normally, Newton's law holds good for small temperature differences up to 20K or 20^0C
- This law holds good even for large temperature differences in the case of forced convection.