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HEAT AND THERMODYNAMICS

(THERMAL EXPANSION, CALORIMETRTY AND HEAT TRANSFER)

Temperature

(i) Temperature is a Macroscopic, physical quantity, basically a measure of degree of hotness or coldness of a body.

(ii) The natural flow of heat is from higher temperature to lower temperature.

(iii) The part of internal energy being transfered due to temperature difference is called heat energy.

(iii) Temperature of a body is directly proportional to the kinetic energy of the random motion of the molecules or atoms of the substance.

(iv) Two bodies are said to be a Thermal Equilibrium with each other, when no heat flows from one body of the other i.e., when both the bodies are at the same temperature.

$$\frac{\text{Reading on any scale} - \text{Melting point of water}}{\text{Boiling point of water} - \text{Melting point of water}} = \text{Constant for all scale}$$

$$\boxed{\frac{t^0C - 0}{100 - 0^0} = \frac{t^0F - 32}{212^0 - 32^0} = \frac{t^0R - 0}{80^0 - 0} = \frac{tK - 273.15}{373.15 - 273.15}}$$

Thermal Expansion

(i) When heat is supplied to matter and its state does not change, then it usually get expanded. There are also some such substances which contract on heating. Rubber is a very good example of it.

(ii) Thermal expansion is minimum in case of Solids but maximum in case of gases because intermolecular force is maximum in solids but minimum in gases.

(iii) Solids can have all the three types of thermal expansion i.e., one dimensional (Linear expansion), two dimensional expansion (superficial expansion) and three dimensional (volume expansion) while fluids (liquids and gases) usually posses only volume expansion.

Coefficient of Linear Expansion : Coefficient of linear expansion is defined as the increase in length (ΔL) per unit length (L) per unit rise in temperature. It is usually very small and hence may be expressed without much error by the equation

$$\alpha = \frac{\Delta L}{L(\Delta T)} \quad \text{So,} \quad L_{new} = L + \Delta L = L(1 + \alpha \Delta T)$$

Coefficient of Superficial / Areal Expansion : Coefficient of superficial expansion is defined as the increase in area (ΔA) per unit area (A) per unit rise in temperature. It is usually very small and hence may be expressed without much error by the equation.

$$\beta = \frac{\Delta A}{A(\Delta T)} \quad \text{So,} \qquad A_{new} = A + \Delta A = A(1 + \beta \Delta T)$$

Coefficient of Cubical / Volumetric Expansion : Coefficient of cubical expansion is defined as the increase in volume (ΔV) per unit volume (V) per unit rise in temperature It is usually very small and hence may be expressed without much error by the equation

$$\gamma = \frac{\Delta V}{V(\Delta T)} \quad \text{So,} \qquad V_{new} = V + \Delta V = V(1 + \gamma \Delta T)$$

Relation between α, β, γ : $\beta = 2\alpha, \ \gamma = 3\alpha$

Anomalous expansion of water : Generally on heating matter expands and contracts on cooling. In case of water, it expands on heating if its temperature is greater than 4°C. In the range 0°C to 4°C, water contracts on

heating and expands on cooling i.e., γ is negative. This behaviour of water in the range from 0°C to 4°C is called Anomalous Expansion.

Specific heat capacity c : $c = \frac{\Delta Q}{m\Delta T}$; Amount of energy exchange per unit mass per unit change in temperature

Molar Specific heat C : $C = \frac{\Delta Q}{n(\Delta T)}$; Amount of energy exchange per unit mole per unit change in temperature

Unit of Heat Energy : 1 cal = 4.18 J also W = JH where J = Mechanical equivalent of Heat

Water –Equivalent

(i) If thermal capacity of a body is expressed in terms of mass of water, it is called water – Equivalent of the body, i.e., water equivalent of a body is the mass of water which when given same amount of heat as to the body, changes the temperature of water through same range as that of body, i.e.,

$W = mc$ gram where c = specific heat of substance of body.

(ii) The unit of water equivalent W is gm while the dimensions [M]

Latent Heat, L

The heat of transformation during melting / freezing / vaporisation/condensation is called latent heat.The state of matter changes without changing temperature in such process. For H_2O (water),

$L_{ice} = L_{fusion} = L_{melting} = 80$ Cal/gram and $L_{steam} = L_{vaporisation} = 536$ Cal/gram $= L_{condensation}$

Principle of Calorimetry

When two bodies (one solid and other liquid or both being liquid) at different temperatures are mixed, heat will be transferred from body(s) at higher temperature to body(s) at lower temperature till both acquire same temperature. The body at higher temperature releases heat while that at lower temperature absorbs heat so that:

$$\boxed{\text{Heat lost} = \text{Heat gained}}$$

i.e. principle of calorimetry is an alternative form of the law of conservation of energy.

Important Conclusions

(i) Temperature of mixture (T) is always between lower temperature and higher temperature i.e, $T_L \le T \le T_H$

(ii) When temperature of a body changes, the body releases heat if its temperature falls and absorbs heat when its temperature rises. The heat released or absorbed by a body of mass m is given by:

$\boxed{Q = mc\Delta T}$ when c = specific heat of the substance of body.

(iii) When state of a body changes, change of state takes place at constant temperature (MP or BP) and heat released or absorbed is given by:

$\boxed{Q = mL}$ where L = Latent heat for the associated change of state.

(a) Heat is absorbed, if solid converts into liquid (at MP) or liquid converts into vapours (at BP) and

(b) Heat is released, if liquid converts into solid or vapours converts into liquid

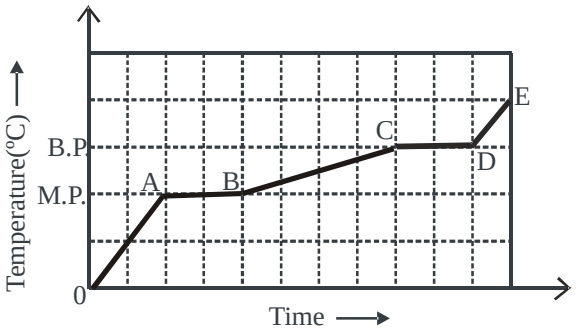
Heating Curve of a Solid

(i) If a given mass (m) of a solid is supplied heat continuously at a constant rate P and a graph is plotted between temperature and time, the graph so obtained is shown in the adjoining figure and is called as Heating Curve.

(ii) In the regions OA, the temperature of the solid is changing with time, so $\Delta Q = m \times c_{solid} \times \Delta T = P \times \Delta T$

In the region AB the solid is melting into liquid, So temperature does not change. Here $\Delta Q = m \times L$

In the region BC the temperature of the liquid is increasing and $\Delta Q = m \times c_{liquid} \times \Delta T$. Greater is the slope of BC, lesser will be the specific heat of the liquid because slope = $\frac{\Delta T}{\Delta t} = \frac{P}{mc}$



In region CD, vaporisation of liquid takes place and $\Delta Q = mL_{steam}$. In region DE, steam temperature is in increasing and $\Delta Q = m.c_{steam}.\Delta T$, In general, slope of BC is less than slope of OA and DE line.

HEAT TRANSFER

Conduction

(i) In conduction the molecules of the body transfer heat from a place at higher temperature to a place at lower temperature without actually moving in the body. i.e. energy transfer without bulk motion of material.

(ii) In steady state heat passing through a bar of length L and cross section A and time t when its ends are at temperature θ_1 and θ_2 is given by: $Q = \frac{KA(\theta_1 - \theta_2)t}{L}$

and rate of flow of heat will be $\boxed{\frac{dQ}{dt} = KA\frac{d\theta}{dx}}$, Here K = coefficient of thermal conductivity.

(iii) Flow of heat through multiple slabs: Suppose a compound slab consists of two rods of lengths L_1 and L_2 in series with common surface area A. Let K_1 and K_2 be the coefficient of thermal conductivities respectively. Let the ends of the slab be maintained at a temperature difference of $(\theta_1 - \theta_2)$. In the steady state, in such a case, the junction temperature is given by $\theta = \frac{K_1L_2\theta_1 + K_2L_1\theta_2}{K_1L_2 + K_2L_1}$ and rate of flow of heat $\frac{\Delta Q}{\Delta t} = \frac{A(\theta_1 - \theta_2)}{\left(\frac{L_1}{K_1} + \frac{L_2}{K_2}\right)}$

Applications

(a) Rods in series : Total equivalent thermal resistance (R) is equal to sum of individual thermal resistances i.e.,

$$R = R_1 + R_2 + ... = \left(\frac{1}{K_1} \times \frac{L_1}{A_1}\right) + \left(\frac{1}{K_2} \times \frac{L_2}{A_2}\right) + \left(\frac{1}{K_3} \times \frac{L_3}{A_3}\right) + ...$$

(b) Rods in parallel : In parallel, the total thermal resistance is given by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + ...$$

Convection

(i) Convection requires medium and it is the process in which heat is transferred from one place to the other by actual movement of heated substance (usually fluid)

(ii) The type of convection which results from difference in densities is called natural convection (for example, a fluid in a container heated through its bottom). However, if a heated fluid is forced to move (by a blower, fan or pump), the process is called forced convection.

Radiation

(i) The process through which heat is transferred directly from one body to another, without requiring any medium is called radiation. Heat from the Sun reaches the earth by radiation passing through several vacuums and transparent mediums.

(ii) Radiation is the fastest mode of heat transfer from one place to another as in this mode heat energy is propagated at speed of light in the form of electromagnetic wave.

(iii) All the bodies radiate energy at all temperatures and at all time. Radiation from a body can never be stopped but can be minimized.

(iv) Radiation does not affect the medium through which it passes.

(v) Rough and dark (i.e. black) surfaces are good absorbers while shining and smooth surfaces are good reflectors of heat radiations.

(vi) Heat radiations are invisible and like light, travel in straight lines, cast shadow, affect photographic plates and can be reflected by mirrors and refracted by lenses.

Black Body

(i) A body which absorbs all the radiations incident on it is called a perfectly black body.

(ii) A perfectly black body maintained at a suitable temperature emits radiations of all wavelengths.

(iii) A perfectly black body neither reflects nor transmits any radiation, it will always appear black whatever be the colour of the incident radiation.

Absorptive Power (a)

(i) Absorptive power of a surface is defined as the ratio of the radiant energy absorbed by it in a given time to the total radiant energy incident on it in the same time. $a = \frac{(\Delta Q)_{absorbed}}{(\Delta Q)_{incident}}$

(ii) For a perfectly black body, absorptive power is maximum and it is unity.

(iii) It has no units and dimensions.

Emissive Power (e or R)

(i) For a given surface it is defined as the radiant energy emitted per sec per unit area of the surface.

(ii) Emissive power of a surface depends on its nature and temperature. (as given by stafan's law)

Kirchhoff's Law

(i) According to Kirchhoff's law, the ratio of emissive power to absorptive power is same for all surfaces at the same temperature and is equal to the emissive power of a perfectly black body at that temperature.

(ii) If a and e represent absorptive and emissive power of a given surface while A and E for a perfectly black body then $\frac{e}{a} = \frac{E}{A}$ = constant for all surface

(iii) For a perfectly black body, A = 1 So, for any surface $\frac{e}{a} = E$.

For the radiation of a particular wavelength, $\frac{e_\lambda}{a_\lambda} = \frac{E_\lambda}{A_\lambda} \Rightarrow \frac{e_\lambda}{a_\lambda} = E_\lambda$

Since E_λ is constant at a given temperature, hence according to this law, if a surface is a good absorber of a particular wavelength, it is also a good emitter of that wavelength. Similarly, bad absorber are bad emitter.

Stefan's Law

(i) According to it, the radiant energy emitted by a perfectly black body per unit area per sec (i.e., emissive power of radiancy or intensity of black body radiation) is directly proportional to the fourth power of its absolute temperature,

i.e,. $e = \frac{\Delta Q}{A.\Delta t} = R \propto T^4$ or $R = \sigma T^4$ where σ is called Stefan's constant.

(ii) If a body is not a perfectly black body $R = \frac{\Delta Q}{A(\Delta t)} = \in \sigma T^4$ and hence $\frac{\Delta Q}{\Delta t} = e\sigma AT^4 = \in \sigma AT^4$

where $e = \in$ is called emissivity or relative emittance has value $0 < e < 1$ depending on the nature of surface. It has no units and dimensions. Emissivity is different from emissive power (represented by R).

Cooling by Radiation

Rate of cooling of a body at temperature T placed in an environment of temperature T_0< (T) is given by $\frac{\Delta Q}{\Delta t} = \sigma Ae\left(T^4 - T_0^4\right)$ where $T = (T_0 + \Delta T)$ and ΔT is the temperature difference between body and surrounding.

Newton's Law of Cooling

According to Newton's law of cooling, Rate of fall of temperature of a body with time is given by

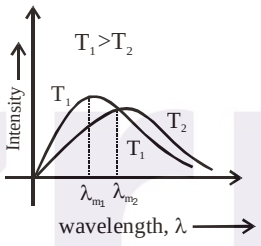
$$\frac{dT}{dt} = K(T - T_0) \text{ with } K = \frac{eA\sigma}{mc} 4T_0^3$$

where T = temperature of body and T_0 = temperature of surrounding.

i.e., rate of cooling of a hot body is directly proportional to temperature difference between the body and its surroundings provided the temperature of the body is not very different from the surroundings.

Wein's Displacement Law

(i) The quantity of energy radiated out by a body is not uniformly distributed over all the wavelengths emitted by it. It is maximum for a particular wavelength , which is different at different temperatures. As the temperature is increased, the value of wavelength which carries maximum energy is decreased.



(ii) According to this law, wavelength corresponding to maximum energy is inversely proportional to the absolute temperature of the body (i.e., $\lambda_m \propto 1/T$) or $\boxed{\lambda_m T = b}$, b = wein's constant = 2.89×10^{-3} mK.