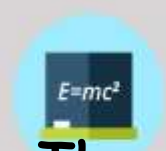




physics



## Chapter 12

# Thermometry, Thermal Expansion and Calorimetry

## Temperature



Temperature is defined as the degree of hotness or coldness of a body. The natural flow of heat is from higher temperature to lower temperature.

Two bodies are said to be in thermal equilibrium with each other, when no heat flows from one body to the other. That is when both the bodies are at the same temperature.

(1) Temperature is one of the seven fundamental quantities with dimension  $[\theta]$ . It is a scalar physical quantity with S.I. unit kelvin.

(2) When heat is given to a body and its state does not change, the temperature of the body rises and if heat is taken from a body its temperature falls i.e. temperature can be regarded as the effect of cause "heat".

(3) According to kinetic theory of gases, temperature (macroscopic physical quantity) is a measure of average translational kinetic energy of a molecule (microscopic physical quantity).

(4) Although the temperature of a body can be raised without limit, it cannot be lowered without limit and theoretically limiting low temperature is taken to be zero of the kelvin scale.

(5) Highest possible temperature achieved in laboratory is about  $10^8 K$  while lowest possible temperature attained is  $10^{-8} K$ .

(6) Temperature of the core of the sun is  $10^7 K$  while that of its surface is  $6000 K$ .

(7) Normal temperature of human body is  $310.15 K$  ( $37^\circ C = 98.6^\circ F$ ).

(8) NTP or STP implies  $273.15 K$  ( $0^\circ C = 32^\circ F$ )

## Scales of Temperature

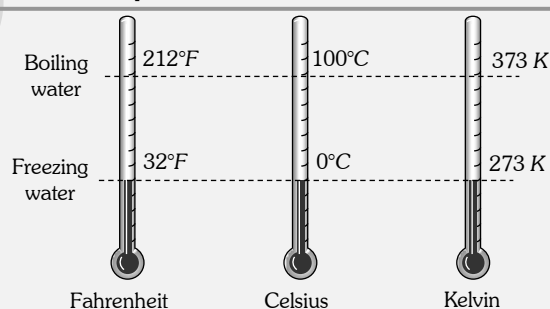


Fig. 12.1

The centigrade ( $^\circ C$ ), Fahrenheit ( $^\circ F$ ), Kelvin ( $K$ ), Reaumur ( $R$ ), Rankine ( $Ra$ ) are commonly used temperature scales.

(1) To construct a scale of temperature, two fixed points are taken. First fixed point is the freezing point (ice point) of water, it is called lower fixed point (LFP). The second fixed point is the boiling point (steam point) of water, it is called upper fixed point (UFP).

(2) **Celsius scale** : In this scale LFP (ice point) is taken  $0^\circ$  and UFP (steam point) is taken  $100^\circ$ . The temperature measured on this scale all in degree Celsius ( $^\circ C$ ).

(3) **Fahrenheit scale** : This scale of temperature has LFP as  $32^\circ F$  and UFP as  $212^\circ F$ . The change in temperature of  $1^\circ F$  corresponds to a change of less than  $1^\circ$  on Celsius scale.



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(4) **Kelvin scale** : The Kelvin temperature scale is also known as thermodynamic scale. The triple point of water is also selected to be the zero of scale of temperature. The temperature measured on this scale are in Kelvin (K).

The triple point of water is that point on a  $P$ - $T$  diagram where the three phases of water, the solid, the liquid and the gas, can coexist in equilibrium.

**Table 12.1 : Different measuring scales**

Scale	Symbol for each degree	LFP	UFP	Number of divisions on the scale
Celsius	$^{\circ}\text{C}$	$0^{\circ}\text{C}$	$100^{\circ}\text{C}$	100
Fahrenheit	$^{\circ}\text{F}$	$32^{\circ}\text{F}$	$212^{\circ}\text{F}$	180
Reaumer	$^{\circ}\text{R}$	$0^{\circ}\text{R}$	$80^{\circ}\text{R}$	80
Rankine	$^{\circ}\text{Ra}$	$460\text{ Ra}$	$672\text{ Ra}$	212
Kelvin	$\text{K}$	$273.15\text{ K}$	$373.15\text{ K}$	100

(5) Temperature on one scale can be converted into other scale by using the following identity.

$$\frac{\text{Reading on any scale} - \text{LFP}}{\text{UFP} - \text{LFP}} = \text{Constant for all scales}$$

(6) All these temperatures are related to each other by the following relationship

$$\frac{C-0}{100} = \frac{F-32}{212-32} = \frac{K-273.15}{373.15-273.15} = \frac{R-0}{80-0} = \frac{Ra-460}{672-460}$$

$$\text{or } \frac{C}{5} = \frac{F-32}{9} = \frac{K-273}{5} = \frac{R}{4} = \frac{Ra-460}{10.6}$$

(7) The Celsius and Kelvin scales have different zero points but the same size degrees. Therefore any temperature difference is the same on the Celsius and Kelvin scales  $(T_2 - T_1)^{\circ}\text{C} = (T_2 - T_1)\text{ K}$ .

### Thermometry

A branch of science which deals with the measurement of temperature of a substance is known as thermometry.

(1) The linear variation in some physical properties of a substance with change of temperature is the basic principle of thermometry and these properties are defined as thermometric property ( $x$ ) of the substance.

(2) Thermometric properties ( $x$ ) may be as follows

- Length of liquid in capillary
- Pressure of gas at constant volume.
- Volume of gas at constant pressure.
- Resistance of a given platinum wire.

(3) In old thermometry, freezing point ( $0^{\circ}\text{C}$ ) and steam point ( $100^{\circ}\text{C}$ ) are taken to define the temperature scale. So if the thermometric property at temperature  $0^{\circ}\text{C}$ ,  $100^{\circ}\text{C}$  and  $t^{\circ}\text{C}$  are  $x_0$ ,  $x_{100}$  and  $x$  respectively then

$$\frac{t-0}{100-0} = \frac{x-x_0}{x_{100}-x_0} \Rightarrow t^{\circ}\text{C} = \frac{x-x_0}{x_{100}-x_0} \times 100^{\circ}\text{C}$$

(4) In modern thermometry instead of two fixed points only one reference point is chosen (triple point of water  $273.16\text{ K}$ ) the other is itself  $0\text{ K}$  where the value of thermometric property is assumed to be zero.

So if the value of thermometric property at  $0\text{ K}$ ,  $273.16\text{ K}$  and  $T\text{ K}$  are  $0$ ,  $x_{Tr}$  and  $x$  respectively then

$$\frac{T}{273.16} = \frac{x}{x_{Tr}} \Rightarrow T = 273.16 \left[ \frac{x}{x_{Tr}} \right] \text{ K}$$

### Thermometers



An instrument used to measure the temperature of a body is called a thermometer

It works by absorbing some heat from the body, so the temperature recorded by it is lesser than the actual value unless the body is at constant temperature. Some common types of thermometers are as follows

(1) **Liquid (mercury) thermometers** : In liquid thermometers mercury is preferred over other liquids as its expansion is large and uniform and it has high thermal conductivity and low specific heat.

(i) Range of temperature :  $-50^{\circ}\text{C}$  to  $350^{\circ}\text{C}$   
(freezing point) (boiling point)

(ii) Upper limit of range of mercury thermometer can be raised upto  $550^{\circ}\text{C}$  by filling nitrogen in space over mercury under pressure (which elevates boiling point of mercury).

(iii) Mercury thermometer with cylindrical bulbs are more sensitive than those with spherical bulbs.

(iv) If alcohol is used instead of mercury then range of temperature measurement becomes  $-80^{\circ}\text{C}$  to  $350^{\circ}\text{C}$

(v) Formula :  $t = \frac{l-l_0}{l_{100}-l_0} \times 100^{\circ}\text{C}$

(2) **Gas thermometers** : These are more sensitive and accurate than liquid thermometers as expansion of gases is more than that of liquids. The thermometers using a gas as thermoelectric substance are called ideal gas thermometers. These are of two types

(i) **Constant pressure gas thermometers**

(a) Principle  $V \propto T$  (if  $P = \text{constant}$ )

(b) Formula :  $t = \frac{V - V_0}{V_{100} - V_0} \times 100^\circ\text{C}$  or  $T = 273.16 \frac{V}{V_{Tr}} K$

(ii) **Constant volume gas thermometers**

(a) Principle  $P \propto T$  (if  $V = \text{constant}$ )

(b) Formula :  $t = \frac{P - P_0}{P_{100} - P_0} \times 100^\circ\text{C}$  or  $T = 273.16 \frac{P}{P_{Tr}} K$

(c) Range of temperature :

Hydrogen gas thermometer :  $-200^\circ\text{C}$  to  $500^\circ\text{C}$

Nitrogen gas thermometer :  $-200^\circ\text{C}$  to  $1600^\circ\text{C}$

Helium gas thermometer :  $-268^\circ\text{C}$  to  $500^\circ\text{C}$

(3) **Resistance thermometers** : Usually platinum is used in resistance thermometers due to high melting point and large value of temperature coefficient of resistance.

Resistance of metals varies with temperature according to relation.  $R = R_0(1 + \alpha t)$  where  $\alpha$  is the temperature coefficient of resistance and  $t$  is change in temperature.

(i) Formula :  $t = \frac{R - R_0}{R_{100} - R_0} \times 100^\circ\text{C}$  or  $T = 273.16 \frac{R}{R_{Tr}} K$

(ii) Temperature range : For Platinum resistance thermometer it is  $-200^\circ\text{C}$  to  $1200^\circ\text{C}$

For Germanium resistance thermometer it is 4 to 77 K.

(4) **Thermoelectric thermometers** : These are based on "Seebeck effect" according to which when two distinct metals are joined to form a closed circuit called thermocouple and the difference in temperature is maintained between their junctions, an emf is developed. The emf is called thermo-emf and if one junction is at  $0^\circ\text{C}$ , thermoelectric emf varies with temperature of hot junction ( $t$ ) according to  $e = at + bt^2$ ; where  $a$  and  $b$  are constants.

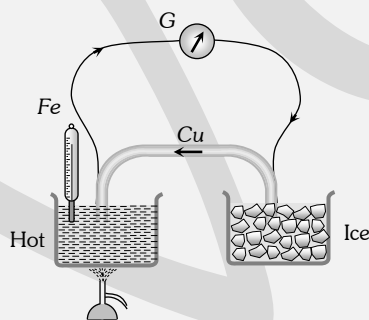


Fig. 12.2

Thermoelectric thermometers have low thermal capacity and high thermal conductivity, so can be used to measure quickly changing temperature

Table 12.2 : Different temperature range

Thermo couple	Temperature range
Copper-iron thermocouple	$0^\circ\text{C}$ to $260^\circ\text{C}$
Iron-constantan thermocouple	$0^\circ\text{C}$ to $800^\circ\text{C}$
Tungsten-molybdenum thermocouple	$2000^\circ\text{C}$ to $3000^\circ\text{C}$

(5) **Pyrometers** : These are the devices used to measure the temperature by measuring the intensity of radiations received from the body. They are based on the fact that the amount of radiations emitted from a body per unit area per second is directly proportional to the fourth power of temperature (Stefan's law).

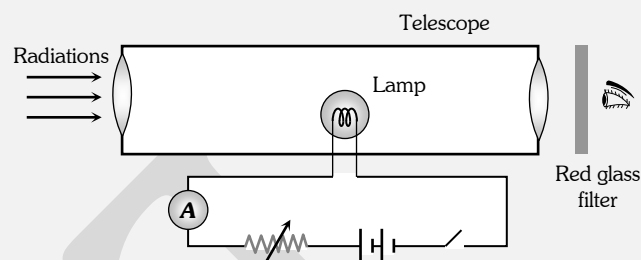


Fig. 12.3

(i) These can be used to measure temperatures ranging from  $800^\circ\text{C}$  to  $6000^\circ\text{C}$ .

(ii) They cannot measure temperature below  $800^\circ\text{C}$  because the amount of radiations is too small to be measured.

(6) **Vapour pressure thermometer** : These are used to measure very low temperatures. They are based on the fact that saturated vapour pressure  $P$  of a liquid depends on the temperature according to the relation  $\log P = a + bT + \frac{c}{T}$

The range of these thermometers varies from 0.71 K to 120 K for different liquid vapours.

## Thermal Expansion



When matter is heated without any change in its state, it usually expands. According to atomic theory of matter, a symmetry in potential energy curve is responsible for thermal expansion. As with rise in temperature the amplitude of vibration and hence energy of atoms increases, hence the average distance between the atoms increases. So the matter as a whole expands.

(1) 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.

(2) Solids can expand in one dimension (linear expansion), two dimension (superficial expansion) and three dimension (volume expansion) while liquids and gases usually suffers change in volume only.



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(3) **Linear expansion** : When a solid is heated and its length increases, then the expansion is called linear expansion.

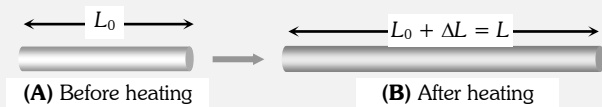


Fig. 12.4

(i) Change in length  $\Delta L = L_0 \alpha \Delta T$

( $L_0$  = Original length,  $\Delta T$  = Temperature change)

(ii) Final length  $L = L_0 (1 + \alpha \Delta T)$

(iii) Co-efficient of linear expansion  $\alpha = \frac{\Delta L}{L_0 \Delta T}$

(iv) Unit of  $\alpha$  is  $^{\circ}\text{C}^{-1}$  or  $\text{K}^{-1}$ . Its dimension is  $[\theta^{-1}]$

(4) **Superficial (areal) expansion** : When the temperature of a 2D object is changed, its area changes, then the expansion is called superficial expansion.

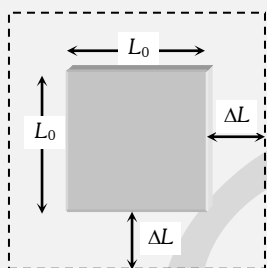


Fig. 12.5

(i) Change in area is  $\Delta A = A_0 \beta \Delta T$

( $A_0$  = Original area,  $\Delta T$  = Temperature change)

(ii) Final area  $A = A_0 (1 + \beta \Delta T)$

(iii) Co-efficient of superficial expansion  $\beta = \frac{\Delta A}{A_0 \Delta T}$

(iv) Unit of  $\beta$  is  $^{\circ}\text{C}^{-1}$  or  $\text{K}^{-1}$ .

(5) **Volume or cubical expansion** : When a solid is heated and its volume increases, then the expansion is called volume or cubical expansion.

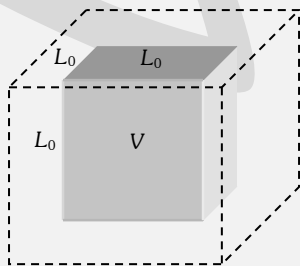


Fig. 12.6

(i) Change in volume is  $\Delta V = V_0 \gamma \Delta T$

( $V_0$  = Original volume,  $\Delta T$  = change in temperature)

(ii) Final volume  $V = V_0 (1 + \gamma \Delta T)$

(iii) Volume co-efficient of expansion  $\gamma = \frac{\Delta V}{V_0 \Delta T}$

(iv) Unit of  $\gamma$  is  $^{\circ}\text{C}^{-1}$  or  $\text{K}^{-1}$ .

(6) **More about  $\alpha$ ,  $\beta$  and  $\gamma$**  : The co-efficient  $\alpha$ ,  $\beta$  and  $\gamma$  for a solid are related to each other as follows

$$\alpha = \frac{\beta}{2} = \frac{\gamma}{3} \Rightarrow \alpha : \beta : \gamma = 1 : 2 : 3$$

(i) Hence for the same rise in temperature

Percentage change in area = 2 × percentage change in length.

Percentage change in volume = 3 × percentage change in length.

(ii) The three coefficients of expansion are not constant for a given solid. Their values depend on the temperature range in which they are measured.

(iii) The values of  $\alpha$ ,  $\beta$ ,  $\gamma$  are independent of the units of length, area and volume respectively.

(iv) For anisotropic solids  $\gamma = \alpha_x + \alpha_y + \alpha_z$  where  $\alpha_x$ ,  $\alpha_y$ , and  $\alpha_z$  represent the mean coefficients of linear expansion along three mutually perpendicular directions.

(7) **Contraction on heating** : Some rubber like substances contract with rising temperature, because transverse vibration of atoms of substance dominate over longitudinal vibration which is responsible for expansion.

Table 12.3 :  $\alpha$  and  $\gamma$  for some materials

Material	$\alpha [\text{K}^{-1} \text{ or } (^{\circ}\text{C})^{-1}]$	$\gamma [\text{K}^{-1} \text{ or } (^{\circ}\text{C})^{-1}]$
Steel	$1.2 \times 10^{-5}$	$3.6 \times 10^{-5}$
Copper	$1.7 \times 10^{-5}$	$5.1 \times 10^{-5}$
Brass	$2.0 \times 10^{-5}$	$6.0 \times 10^{-5}$
Aluminium	$2.4 \times 10^{-5}$	$7.2 \times 10^{-5}$

### Application of Thermal Expansion in Solids

(1) **Bi-metallic strip** : Two strips of equal lengths but of different materials (different coefficient of linear expansion) when join together, it is called “bi-metallic strip”, and can be used in thermostat to break or make electrical contact. This strip has the characteristic property of bending on heating due to unequal linear expansion of the two metal. The strip will bend with metal of greater  $\alpha$  on outer side i.e. convex side.



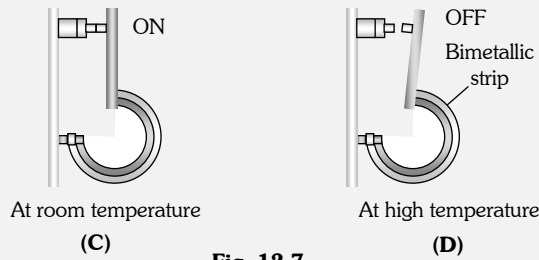


Fig. 12.7

(2) **Effect of temperature on the time period of a simple pendulum** : A pendulum clock keeps proper time at temperature  $\theta$ . If temperature is increased to  $\theta' (> \theta)$  then due to linear expansion, length of pendulum and hence its time period will increase.

$$\text{Fractional change in time period } \frac{\Delta T}{T} = \frac{1}{2} \alpha \Delta \theta$$

(i) Due to increment in its time period, a pendulum clock becomes slow in summer and will lose time.

$$\text{Loss of time in a time period } \Delta T = \frac{1}{2} \alpha \Delta \theta T$$

(ii) Time lost by the clock in a day ( $t = 86400 \text{ sec}$ )

$$\Delta t = \frac{1}{2} \alpha \Delta \theta t = \frac{1}{2} \alpha \Delta \theta (86400) = 43200 \alpha \Delta \theta \text{ sec}$$

(iii) The clock will lose time i.e. will become slow if  $\theta' > \theta$  (in summer)

and will gain time i.e. will become fast if  $\theta' < \theta$  (in winter).

(iv) The gain or loss in time is independent of time period  $T$  and depends on the time interval  $t$ .

(v) Since coefficient of linear expansion ( $\alpha$ ) is very small for invar, hence pendulums are made of invar to show the correct time in all seasons.

(3) **Thermal stress in a rigidly fixed rod** : When a rod whose ends are rigidly fixed such as to prevent expansion or contraction, undergoes a change in temperature, due to thermal expansion or contraction, a compressive or tensile stress is developed in it. Due to this thermal stress the rod will exert a large force on the supports. If the change in temperature of a rod of length  $L$  is  $\Delta \theta$  then

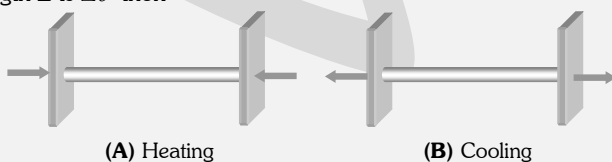


Fig. 12.8

$$\text{Thermal strain} = \frac{\Delta L}{L} = \alpha \Delta \theta$$

$$\left[ \text{As } \alpha = \frac{\Delta L}{L} \times \frac{1}{\Delta \theta} \right]$$

$$\text{So Thermal stress} = Y \alpha \Delta \theta$$

$$\left[ \text{As } Y = \frac{\text{stress}}{\text{strain}} \right]$$

$$\text{or Force on the supports } F = Y \alpha \Delta \theta$$

(4) **Error in scale reading due to expansion or contraction** : If a scale gives correct reading at temperature  $\theta$ , at temperature  $\theta' (> \theta)$  due to linear expansion of scale, the scale will expand and scale reading will be lesser than true value so that,

$$\text{True value} = \text{Scale reading} [1 + \alpha (\theta' - \theta)]$$

$$\text{i.e. } TV = SR [1 + \alpha \Delta \theta] \text{ with } \Delta \theta = (\theta' - \theta)$$

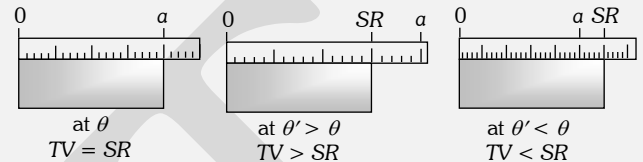


Fig. 12.9

However, if  $\theta' < \theta$ , due to contraction of scale, scale reading will be more than true value, so true value will be lesser than scale reading and will still be given by above equation with  $\Delta \theta = (\theta' - \theta)$  negative.

(5) **Expansion of cavity** : Thermal expansion of an isotropic object may be imagined as a photographic enlargement. So if there is a hole  $A$  in a plate  $C$  (or cavity  $A$  inside a body  $C$ ), the area of hole (or volume of cavity) will increase when body expands on heating, just as if the hole (or cavity) were solid  $B$  of the same material. Also the expansion of area (or volume) of the body  $C$  will be independent of shape and size of hole (or cavity), i.e., will be equal to that of  $D$ .

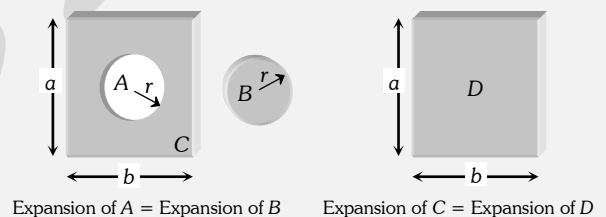


Fig. 12.10

(6) **Some other application**

(i) When rails are laid down on the ground, space is left between the ends of two rails.

(ii) The transmission cable are not tightly fixed to the poles.

(iii) Test tubes, beakers and crucibles are made of pyrex-glass or silica because they have very low value of coefficient of linear expansion.

(iv) The iron rim to be put on a cart wheel is always of slightly smaller diameter than that of wheel.

(v) A glass stopper jammed in the neck of a glass bottle can be taken out by warming the neck of the bottle

## Thermal Expansion in Liquids

(1) Liquids do not have linear and superficial expansion but these only have volume expansion.





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(2) Since liquids are always to be heated along with a vessel which contains them so initially on heating the system (liquid + vessel), the level of liquid in vessel falls (as vessel expands more since it absorbs heat and liquid expands less) but later on, it starts rising due to faster expansion of the liquid.

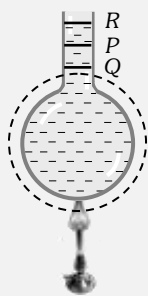


Fig. 12.11

PQ → represents expansion of vessel  
QR → represents the real expansion of liquid  
PR → Represent the apparent expansion of liquid

(3) The actual increase in the volume of the liquid = The apparent increase in the volume of liquid + the increase in the volume of the vessel.

(4) Liquids have two coefficients of volume expansion.

(i) **Co-efficient of apparent expansion ( $\gamma_a$ )** : It is due to apparent (that appears to be, but is not) increase in the volume of liquid if expansion of vessel containing the liquid is not taken into account.

$$\gamma_a = \frac{\text{Apparent expansion in volume}}{\text{Initial volume} \times \Delta\theta} = \frac{(\Delta V)_a}{V \times \Delta\theta}$$

(ii) **Co-efficient of real expansion ( $\gamma_r$ )** : It is due to the actual increase in volume of liquid due to heating.

$$\gamma_r = \frac{\text{Real increase in volume}}{\text{Initial volume} \times \Delta\theta} = \frac{(\Delta V)_r}{V \times \Delta\theta}$$

(iii) Also coefficient of expansion of flask  $\gamma_{\text{vessel}} = \frac{(\Delta V)_{\text{vessel}}}{V \times \Delta\theta}$

(iv)  $\gamma_{\text{Real}} = \gamma_{\text{Apparent}} + \gamma_{\text{Vessel}}$

(v) Change (apparent change) in volume in liquid relative to vessel is

$$\Delta V_{\text{app}} = V \gamma_{\text{app}} \Delta\theta = V(\gamma_{\text{Real}} - \gamma_{\text{Vessel}})\Delta\theta = V(\gamma_r - 3\alpha)\Delta\theta$$

$\alpha$  = Coefficient of linear expansion of the vessel.

Table 12.4 : Different level of liquid in vessel

$\gamma$	$\Delta V$	Level
$\gamma_{\text{Real}} > \gamma_{\text{Vessel}} (=3\alpha) \Rightarrow \gamma_{\text{app}} > 0$	$\Delta V_{\text{app}}$ is positive	Level of liquid in vessel will rise on heating.
$\gamma_{\text{Real}} < \gamma_{\text{Vessel}} (=3\alpha) \Rightarrow \gamma_{\text{app}} < 0$	$\Delta V_{\text{app}}$ is negative	Level of liquid in vessel will fall on heating.
$\gamma_{\text{Real}} = \gamma_{\text{Vessel}} (=3\alpha) \Rightarrow \gamma_{\text{app}} = 0$	$\Delta V_{\text{app}} = 0$	level of liquid in vessel will remain same.

(5) **Anomalous expansion of water** : Generally matter expands on heating 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.  $\gamma$  is negative. This behaviour of water in the range from 0°C to 4°C is called anomalous expansion.

This anomalous behaviour of water causes ice to form first at the surface of a lake in cold weather. As winter approaches, the water temperature increases initially at the surface. The water there sinks because of its increased density. Consequently, the surface reaches 0°C first and the lake becomes covered with ice. Aquatic life is able to survive the cold winter as the lake bottom remains unfrozen at a temperature of about 4°C.

At 4°C, density of water is maximum while its specific volume is minimum.

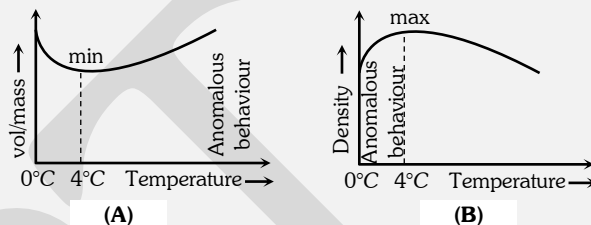


Fig. 12.12

(6) **Effect of temperature on upthrust** : The thrust on V volume of a body in a liquid of density  $\sigma$  is given by  $Th = V\sigma g$

Now with rise in temperature by  $\Delta\theta$  °C, due to expansion, volume of the body will increase while density of liquid will decrease according to the relations  $V' = V(1 + \gamma_S \Delta\theta)$  and  $\sigma' = \sigma / (1 + \gamma_L \Delta\theta)$

$$\text{So the thrust } Th' = V'\sigma'g \Rightarrow \frac{Th'}{Th} = \frac{V'\sigma'g}{V\sigma g} = \frac{(1 + \gamma_S \Delta\theta)}{(1 + \gamma_L \Delta\theta)}$$

and apparent weight of the body  $W_{\text{app}} = \text{Actual weight} - \text{Thrust}$

As  $\gamma_S < \gamma_L \therefore Th' < Th$  with rise in temperature thrust also decreases and apparent weight of body increases.

### Variation of Density with Temperature

Most substances (solid and liquid) expand when they are heated, i.e., volume of a given mass of a substance increases on heating, so the density should decrease  $\left( \text{as } \rho \propto \frac{1}{V} \right)$ . For a given

$$\text{mass } \rho \propto \frac{1}{V} \Rightarrow \frac{\rho'}{\rho} = \frac{V}{V'} = \frac{V}{V + \Delta V} = \frac{V}{V + \gamma V \Delta\theta} = \frac{1}{1 + \gamma \Delta\theta}$$

$$\Rightarrow \rho' = \frac{\rho}{1 + \gamma \Delta\theta} = \rho(1 + \gamma \Delta\theta)^{-1} = \rho(1 - \gamma \Delta\theta)$$

### Expansion of Gases

Gases have no definite shape, therefore gases have only volume expansion. Since the expansion of container is negligible in comparison to the gases, therefore gases have only real expansion.

(1) **Coefficient of volume expansion** : At constant pressure, the unit volume of a given mass of a gas, increases with 1°C rise of temperature, is called coefficient of volume expansion.

$$\alpha = \frac{\Delta V}{V_0} \times \frac{1}{\Delta\theta} \Rightarrow \text{Final volume } V' = V(1 + \alpha \Delta\theta)$$

(2) **Coefficient of pressure expansion** :  $\beta = \frac{\Delta P}{P} \times \frac{1}{\Delta \theta}$

$\therefore$  Final pressure  $P' = P(1 + \beta \Delta \theta)$

For an ideal gas, coefficient of volume expansion is equal to the coefficient of pressure expansion i.e.  $\alpha = \beta = \frac{1}{273} ^\circ\text{C}^{-1}$

## Heat

(1) The form of energy which is exchanged among various bodies or system on account of temperature difference is defined as heat.

(2) We can change the temperature of a body by giving heat (temperature rises) or by removing heat (temperature falls) from body.

(3) The amount of heat ( $Q$ ) is given to a body depends upon its mass ( $m$ ), change in its temperature ( $\Delta \theta = \Delta \theta$ ) and nature of material i.e.  $Q = mc \Delta \theta$ ; where  $c$  = specific heat of material.

(4) Heat is a scalar quantity. Its units are *joule, erg, cal, kcal etc.*

(5) The calorie (*cal*) is defined as the amount of heat required to raise the temperature of 1 gm of water from  $14.5^\circ\text{C}$  to  $15.5^\circ\text{C}$ .

Also  $1 \text{ kcal} = 1000 \text{ cal} = 4186 \text{ J}$  and  $1 \text{ cal} = 4.18 \text{ J}$

(6) **British Thermal Unit (BTU)** : One BTU is the quantity of heat required to raise the temperature of one pound (1 lb) of water from  $63^\circ\text{F}$  to  $64^\circ\text{F}$

$1 \text{ BTU} = 778 \text{ ft. lb} = 252 \text{ cal} = 1055 \text{ J}$

(7) In solids thermal energy is present in the form of kinetic energy, in liquids, in the form of translatory energy of molecules. In gas it is due to the random motion of molecules.

(8) Heat always flows from a body of higher temperature to lower temperature till their temperature becomes equal (Thermal equilibrium).

(9) The heat required for a given temperature increase depends only on how many atoms the sample contains, not on the mass of an individual atom.

## Specific Heat

When a body is heated its temperature rises (except during a change in phase).

(1) **Gram specific heat** : The amount of heat energy required to raise the temperature of unit mass of a body through  $1^\circ\text{C}$  (or  $\text{K}$ ) is called specific heat of the material of the body.

If  $Q$  heat changes the temperature of mass  $m$  by  $\Delta \theta$  then specific heat  $c = \frac{Q}{m \Delta \theta}$

(i) Units : *Calorie/gm*  $\times ^\circ\text{C}$  (practical), *J/kg*  $\times \text{K}$  (S.I.)  
Dimension :  $[L^2 T^{-2} \theta^{-1}]$

(ii) For an infinitesimal temperature change  $d\theta$  and corresponding quantity of heat  $dQ$ .

$$\text{Specific heat } c = \frac{1}{m} \cdot \frac{dQ}{d\theta}$$

(2) **Molar specific heat** : Molar specific heat of a substance is defined as the amount of heat required to raise the temperature of one gram mole of the substance through a unit degree it is represented by (capital)  $C$ .

Molar specific heat ( $C$ ) =  $M \times$  Gram specific heat ( $c$ )

( $M$  = Molecular mass of substance)

$$C = M \frac{Q}{m \Delta \theta} = \frac{1}{\mu} \frac{Q}{\Delta \theta} \quad \left( \text{where, Number of moles } \mu = \frac{m}{M} \right)$$

Units : *calorie/mole*  $\times ^\circ\text{C}$  (practical); *J/mole*  $\times \text{kelvin}$  (S.I.)

Dimension :  $[ML^2 T^{-2} \theta^{-1}]$

## Specific Heat of Solids

When a solid is heated through a small range of temperature, its volume remains more or less constant. Therefore specific heat of a solid may be called its specific heat at constant volume  $C_v$ .

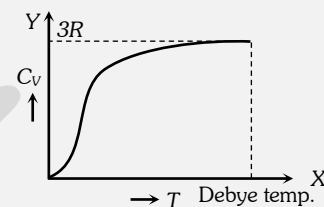


Fig. 12.13

(1) From the graph it is clear that at  $T = 0$ ,  $C_v$  tends to zero

(2) With rise in temperature,  $C_v$  increases and at a particular temperature (called Debye's temperature) it becomes constant =  $3R = 6 \text{ cal/mole} \times \text{kelvin} = 25 \text{ J/mole} \times \text{kelvin}$

(3) For most of the solids, Debye temperature is close to room temperature.

(4) **Dulong and Petit law** : Average molar specific heat of all metals at room temperature is constant, being nearly equal to  $3R = 6 \text{ cal. mole}^{-1} \text{ K}^{-1} = 25 \text{ J mole}^{-1} \text{ K}^{-1}$ , where  $R$  is gas constant for one mole of the gas. This statement is known as Dulong and Petit law.

(5) **Debye's law** : It was observed that at very low temperature molar specific heat  $\propto T^3$  (exception are *Sn, Pb* and *Pt*)

(6) **Specific heat of ice** : In C.G.S.  $c_{\text{ice}} = 0.5 \frac{\text{cal}}{\text{gm} \times ^\circ\text{C}}$

In S.I.  $c_{\text{ice}} = 500 \frac{\text{cal}}{\text{kg} \times ^\circ\text{C}} = 2100 \frac{\text{Joule}}{\text{kg} \times ^\circ\text{C}}$



## 8 Thermometry, Thermal Expansion and calorimetry

**Table 12.5 : Specific heat of some solids at room temperature and atmospheric pressure**

Substance	Specific heat (J·kg <sup>-1</sup> K <sup>-1</sup> )	Molar specific heat (J·g mole <sup>-1</sup> K <sup>-1</sup> )
Aluminium	900.0	24.4
Copper	386.4	24.5
Silver	236.1	25.5
Lead	127.7	26.5
Tungsten	134.4	24.9

### Specific Heat of Liquid (Water)

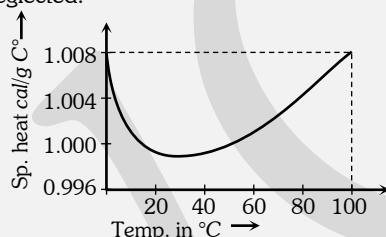
(1) Among all known solids and liquids specific heat of water is maximum i.e. water takes more time to heat and more time to cool w.r.t. other solids and liquids.

(2) It is observed that by increasing temperature, initially specific heat of water goes on decreasing, becomes minimum at 37°C and then it start increasing. Specific heat of water is –

$$\frac{1 \text{ cal}}{\text{gm} \times ^\circ\text{C}} = 1000 \frac{\text{cal}}{\text{kg} \times ^\circ\text{C}} = 4200 \frac{\text{J}}{\text{kg} \times ^\circ\text{C}}$$

(This value is obtained between the temperature 14.5°C to 15.5°C)

(3) The variation of specific heat with temperature for water is shown in the figure. Usually this temperature dependence of specific heat is neglected.



**Fig. 12.14**

(4) As specific heat of water is very large; by absorbing or releasing large amount of heat its temperature changes by small amount. This is why, it is used in hot water bottles or as coolant in radiators.

### Specific Heat of Gases

(1) In case of gases, heat energy supplied to a gas is spent not only in raising the temperature of the gas but also in expansion of gas against atmospheric pressure.

(2) Hence specific heat of a gas, which is the amount of heat energy required to raise the temperature of one gram of gas through a unit degree shall not have a single or unique value.

(3) If the gas is compressed suddenly and no heat is supplied from outside i.e.  $\Delta Q = 0$ , but the temperature of the gas raises on the account of compression.

$$\Rightarrow c = \frac{Q}{m(\Delta\theta)} = \frac{0}{m\Delta\theta} = 0$$

(4) If the gas is heated and allowed to expand at such a rate that rise in temperature due to heat supplied is exactly equal to fall in temperature due to expansion of the gas. i.e.  $\Delta\theta = 0$

$$\Rightarrow c = \frac{Q}{m(\Delta\theta)} = \frac{Q}{0} = \infty$$

(5) If rate of expansion of the gas were slow, the fall in temperature of the gas due to expansion would be smaller than the rise in temperature of the gas due to heat supplied. Therefore, there will be some net rise in temperature of the gas i.e.  $\Delta T$  will be positive.

$$\Rightarrow c = \frac{Q}{m(\Delta\theta)} = \text{Positive}$$

(6) If the gas were to expand very fast, fall of temperature of gas due to expansion would be greater than rise in temperature due to heat supplied. Therefore, there will be some net fall in temperature of the gas i.e.  $\Delta\theta$  will be negative.

$$\Rightarrow c = \frac{Q}{m(-\Delta\theta)} = \text{Negative}$$

Hence the specific heat of gas can have any positive value ranging from zero to infinity. Further it can even be negative. The exact value depends upon the mode of heating the gas. Out of many values of specific heat of a gas, two are of special significance, namely  $C_P$  and  $C_V$ , in the chapter “Kinetic theory of gases” we will discuss this topic in detail.

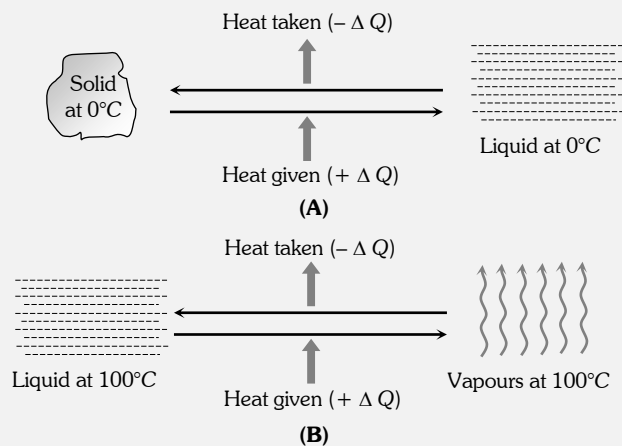
**Specific heat of steam :**  $c_{\text{steam}} = 0.47 \text{ cal / gm} \times ^\circ\text{C}$

### Phase Change and Latent Heat

(1) **Phase :** We use the term phase to describe a specific state of matter, such as solid, liquid or gas. A transition from one phase to another is called a phase change.

(i) For any given pressure a phase change takes place at a definite temperature, usually accompanied by absorption or emission of heat and a change of volume and density.

(ii) In phase change ice at 0°C melts into water at 0°C. Water at 100°C boils to form steam at 100°C.



**Fig. 12.15**



(iii) In solids, the forces between the molecules are large and the molecules are almost fixed in their positions inside the solid. In a liquid, the forces between the molecules are weaker and the molecules may move freely inside the volume of the liquid. However, they are not able to come out of the surface. In vapours or gases, the intermolecular forces are almost negligible and the molecules may move freely anywhere in the container. When a solid melts, its molecules move apart against the strong molecular attraction. This needs energy which must be supplied from outside. Thus, the internal energy of a given body is larger in liquid phase than in solid phase. Similarly, the internal energy of a given body in vapour phase is larger than that in liquid phase.

(iv) In case of change of state if the molecules come closer, energy is released and if the molecules move apart, energy is absorbed.

(2) **Latent heat** : The amount of heat required to change the state of the mass  $m$  of the substance is written as :  $Q = mL$ , where  $L$  is the latent heat. Latent heat is also called as Heat of Transformation. Its unit is  $\text{cal/gm}$  or  $\text{J/kg}$  and Dimension:  $[L^2T^{-2}]$

(i) **Latent heat of fusion** : The latent heat of fusion is the heat energy required to change 1 kg of the material in its solid state at its melting point to 1 kg of the material in its liquid state. It is also the amount of heat energy released when at melting point 1 kg of liquid changes to 1 kg of solid. For water at its normal freezing temperature or melting point ( $0^\circ\text{C}$ ), the latent heat of fusion (or latent heat of ice) is

$$L_F = L_{\text{ice}} \approx 80 \text{ cal / gm} \approx 60 \text{ kJ / mol} \approx 336 \text{ kilo joule / kg}$$

(ii) **Latent heat of vaporisation** : The latent heat of vaporisation is the heat energy required to change 1 kg of the material in its liquid state at its boiling point to 1 kg of the material in its gaseous state. It is also the amount of heat energy released when 1 kg of vapour changes into 1 kg of liquid. For water at its normal boiling point or condensation temperature ( $100^\circ\text{C}$ ), the latent heat of vaporisation (latent heat of steam) is

$$L_V = L_{\text{steam}} \approx 540 \text{ cal / gm} \approx 40.8 \text{ kJ / mol} \approx 2260 \text{ kilo joule / kg}$$

(iii) Latent heat of vaporisation is more than the latent heat of fusion. This is because when a substance gets converted from liquid to vapour, there is a large increase in volume. Hence more amount of heat is required. But when a solid gets converted to a liquid, then the increase in volume is negligible. Hence very less amount of heat is required. So, latent heat of vaporisation is more than the latent heat of fusion.

## Thermal Capacity and Water Equivalent

(1) **Thermal capacity** : It is defined as the amount of heat required to raise the temperature of the whole body (mass  $m$ ) through  $0^\circ\text{C}$  or  $1\text{K}$ .

$$\text{Thermal capacity} = mc = \mu C = \frac{Q}{\Delta\theta}$$

The value of thermal capacity of a body depends upon the nature of the body and its mass.

Dimension :  $[ML^2T^{-2}\theta^{-1}]$ , Unit :  $\text{cal}/^\circ\text{C}$  (practical) Joule/k (S.I.)

(2) **Water Equivalent** : Water equivalent of a body is defined as the mass of water which would absorb or evolve the same amount of heat as is done by the body in rising or falling through the same range of temperature. It is represented by  $W$ .

If  $m$  = Mass of the body,  $c$  = Specific heat of body,  $\Delta\theta$  = Rise in temperature.

$$\text{Then heat given to body } \Delta Q = mc\Delta\theta \quad \dots (i)$$

If same amount of heat is given to  $W$  gm of water and its temperature also rises by  $\Delta\theta$ . Then

$$\text{heat given to water } Q = W \times 1 \times \Delta\theta \dots (ii) \quad [\text{As } c_{\text{water}} = 1]$$

$$\text{From equation (i) and (ii) } \Delta Q = mc\Delta\theta = W \times 1 \times \Delta\theta$$

$$\Rightarrow \text{Water equivalent (W)} = mc$$

$$(i) \text{ Unit : Kg (S.I.)} \quad \text{Dimension : } [ML^0T^0]$$

(ii) Unit of thermal capacity is  $\text{J/kg}$  while unit of water equivalent is  $\text{kg}$ .

(iii) Thermal capacity of the body and its water equivalent are numerically equal.

(iv) If thermal capacity of a body is expressed in terms of mass of water it is called water-equivalent of the body.

## Some Important Terms

(1) **Evaporation** : Vaporisation occurring from the free surface of a liquid is called evaporation. Evaporation is the escape of molecules from the surface of a liquid. This process takes place at all temperatures and increases with the increase of temperature. Evaporation leads to cooling because the faster molecules escape and, therefore, the average kinetic energy of the molecules of the liquid (and hence the temperature) decreases.



Evaporation cools hot water produced by power plants

Fig. 12.16

(2) **Melting (or fusion)/freezing (or solidification)** : The phase change of solid to liquid is called melting or fusion. The reverse phenomenon is called freezing or solidification.



Fig. 12.17

When pressure is applied on ice, it melts. As soon as the pressure is removed, it freezes again. This phenomenon is called **regelation**.

(3) **Vaporisation/liquefaction (condensation)** : The phase change from liquid to vapour is called vaporisation. The reverse transition is called liquefaction or condensation.



## 10 Thermometry, Thermal Expansion and calorimetry

(4) **Sublimation** : Sublimation is the conversion of a solid directly into vapours. Sublimation takes place when boiling point is less than the melting point. A block of ice sublimates into vapours on the surface of moon because of very very low pressure on its surface. Heat required to change unit mass of solid directly into vapours at a given temperature is called heat of sublimation at that temperature.

(5) **Hoar frost** : Direct conversion of vapours into solid is called hoar frost. This process is just reverse of the process of sublimation, e.g., formation of snow by freezing of clouds.



Fig. 12.18

(6) **Vapour pressure** : When the space above a liquid is closed, it soon becomes saturated with vapour and a dynamic equilibrium is established. The pressure exerted by this vapour is called Saturated Vapour Pressure (S.V.P.) whose value depends only on the temperature – it is independent of any external pressure. If the volume of the space is reduced, some vapour liquefies, but the pressure is unchanged.

A saturated vapour does not obey the gas law whereas the unsaturated vapour obeys them fairly well. However, a vapour differs from a gas in that the former can be liquefied by pressure alone, whereas the latter cannot be liquefied unless it is first cooled.

(7) **Boiling** : As the temperature of a liquid is increased, the rate of evaporation also increases.

A stage is reached when bubbles of vapour start forming in the body of the liquid which rise to the surface and escape. A liquid boils at a temperature at which the S.V.P. is equal to the external pressure.



Fig. 12.19

It is a fast process. The boiling point changes on mixing impurities.

(8) **Dew point** : It is that temperature at which the mass of water vapour present in a given volume of air is just sufficient to saturate it, i.e. the temperature at which the actual vapour pressure becomes equal to the saturated vapour pressure.

(9) **Humidity** : Atmospheric air always contains some water vapour. The mass of water vapour per unit volume is called absolute humidity.

The ratio of the mass of water vapour ( $m$ ) actually present in a given volume of air to the mass of water vapour ( $M$ ) required to saturate the same volume at the same temperature is called the relative humidity (R.H.). Generally, it is expressed as a percentage,

$$\text{i.e., R.H.(\%)} = \frac{m}{M} \times 100(\%)$$

R.H. May also be defined as the ratio of the actual vapour pressure ( $p$ ) of water at the same temperature, i.e.

$$\text{R.H.(\%)} = \frac{p}{P} \times 100(\%)$$

Thus R.H. may also be defined as

$$\text{R.H.(\%)} = \frac{\text{S.V.P. at dew point}}{\text{S.V.P. at given temperature}} \times 100$$

(10) **Variation of melting point with pressure** : For those substances with contract on melting (e.g. water and rubber), the melting point decreases with pressure. The reason is the pressure helps shrinking and hence melting. Most substances expand on melting. (e.g. wax, sulphur etc.)

An increase of pressure opposes the melting of such substances and their melting point is raised.

(11) **Variation of latent heat with temperature and pressure** : The latent heat of vapourization of a substance varies with temperature and hence pressure because the boiling point depends on pressure. It increases as the temperature is decreased. For example, water at 1 atm boils at 100°C and has latent heat 2259 Jg<sup>-1</sup> but at 0.5 atm it boils at 82°C and has latent heat 2310 Jg<sup>-1</sup>

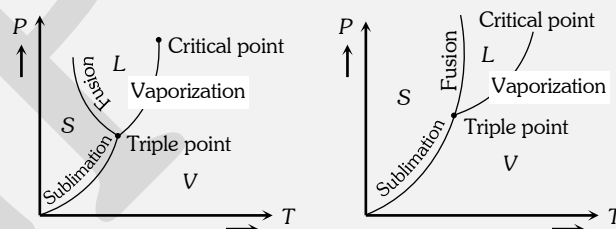


Fig. 12.20

The latent heat of fusion shows similar but less pronounced pressure dependence.

The figures show the  $P$ - $T$  graphs for (a) a substance (e.g., water) which contracts on melting and (b) a substance (e.g. wax) which expands on melting. The  $P$ - $T$  graph consists of three curves.

(i) Sublimation curve which connects points at which vapour (V) and solid (S) exist in equilibrium.

(ii) Vapourization curve which shows vapour and liquid (L) existing in equilibrium.

(iii) Fusion curve which shows liquid and solid existing in equilibrium.

The three curves meet at a single point which is called the triple point. It is that unique temperature-pressure point for a substance at which all the three phases exist in equilibrium.

(12) **Freezing mixture** : If salt is added to ice, then the temperature of mixture drops down to less than 0°C. This is so because, some ice melts down to cool the salt to 0°C. As a result, salt gets dissolved in the water formed and saturated solution of salt is obtained; but the ice point (freezing point) of the solution formed is always less than that of pure water. So, ice cannot be in the solid state with the salt solution at 0°C. The ice which is in contact with the solution, starts melting and it absorbs the required latent heat from the mixture, so the temperature of mixture falls down.

## Joule's Law (Heat and Mechanical Work)



Whenever heat is converted into mechanical work or mechanical work is converted into heat, then the ratio of work done to heat produced always remains constant. i.e.  $W \propto Q$  or  $\frac{W}{Q} = J$

This is Joule's law and  $J$  is called mechanical equivalent of heat.

(1) From  $W = JQ$  if  $Q = 1$  then  $J = W$ . Hence the amount of work done necessary to produce unit amount of heat is defined as the mechanical equivalent of heat.

(2)  $J$  is neither a constant, nor a physical quantity rather it is a conversion factor which used to convert Joule or erg into calorie or kilo calories vice-versa.

$$\begin{aligned} \text{(3) Value of } J &= 4.2 \frac{\text{Joule}}{\text{cal}} = 4.2 \times 10^7 \frac{\text{erg}}{\text{cal}} \\ &= 4.2 \times 10^3 \frac{\text{Joule}}{\text{kcal}} \end{aligned}$$

(4) When water in a stream falls from height  $h$ , then its potential energy is converted into heat and temperature of water rises slightly.

$$\text{From } W = JQ \Rightarrow mgh = J(mc \Delta\theta)$$

[where  $m$  = Mass of water,  $c$  = Specific heat of water,  $\Delta\theta$  = temperature rise]

$$\Rightarrow \text{Rise in temperature } \Delta\theta = \frac{gh}{Jc} ^\circ\text{C}$$

(5) The kinetic energy of a bullet fired from a gun gets converted into heat on striking the target. By this heat the temperature of bullet increases by  $\Delta\theta$ .

$$\text{From } W = JQ \Rightarrow \frac{1}{2}mv^2 = J(ms \Delta\theta)$$

[where  $m$  = Mass of the bullet,  $v$  = Velocity of the bullet,  $c$  = Specific heat of the bullet]

$$\Rightarrow \text{Rise in temperature } \Delta t = \frac{v^2}{2Jc} ^\circ\text{C}$$

If the temperature of bullet rises upto the melting point of the bullet and bullet melts then.

$$\text{From } W = J(Q_{\text{Temperature change}} + Q_{\text{Phase change}})$$

$$\Rightarrow \frac{1}{2}mv^2 = J(mc \Delta\theta + mL); \quad L = \text{Latent heat of bullet}$$

$$\Rightarrow \text{Rise in temperature } \Delta\theta = \left[ \frac{\left( \frac{v^2}{2J} - L \right)}{c} \right] ^\circ\text{C}$$

(6) If  $m$  kg ice-block falls down through some height ( $h$ ) and melts partially ( $m'$  kg) then its potential energy gets converted into heat of melting.

$$\text{From } W = JQ \Rightarrow mgh = Jm'L \Rightarrow h = \frac{m'}{m} \left( \frac{JL}{g} \right)$$

$$\text{If ice-block melts completely then } m' = m \Rightarrow h = \frac{JL}{g} \text{ meter}$$

## Principle of Calorimetry

Calorimetry means 'measuring heat'.

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

**Heat lost = Heat gained**

i.e. principle of calorimetry represents the law of conservation of heat energy.

(1) Temperature of mixture ( $\theta_{\text{mix}}$ ) is always  $\geq$  lower temperature ( $\theta_L$ ) and  $\leq$  higher temperature ( $\theta_H$ ), i.e.,  $\theta_L \leq \theta_{\text{mix}} \leq \theta_H$ .

It means the temperature of mixture can never be lesser than lower temperatures (as a body cannot be cooled below the temperature of cooling body) and greater than higher temperature (as a body cannot be heated above the temperature of heating body). Furthermore usually rise in temperature of one body is not equal to the fall in temperature of the other body though heat gained by one body is equal to the heat lost by the other.

(2) **Mixing of two substances when temperature changes only** : It means no phase change. Suppose two substances having masses  $m_1$  and  $m_2$ , gram specific heat  $c_1$  and  $c_2$ , temperatures  $\theta_1$  and  $\theta_2$  ( $\theta_1 > \theta_2$ ) are mixed together such that temperature of mixture at equilibrium is  $\theta_{\text{mix}}$

Hence, Heat lost = Heat gained

$$\Rightarrow m_1c_1(\theta_1 - \theta_{\text{mix}}) = m_2c_2(\theta_{\text{mix}} - \theta_2) \Rightarrow \theta_{\text{mix}} = \frac{m_1c_1\theta_1 + m_2c_2\theta_2}{m_1c_1 + m_2c_2}$$

**Table 12.6 : Temperature of mixture in different cases**

Condition	Temperature of mixture
If bodies are of same material i.e. $c_1 = c_2$	$\theta_{\text{mix}} = \frac{m_1\theta_1 + m_2\theta_2}{m_1 + m_2}$
If bodies are of same mass $m_1 = m_2$	$\theta_{\text{mix}} = \frac{\theta_1c_1 + \theta_2c_2}{c_1 + c_2}$
If $m_1 = m_2$ and $c_1 = c_2$	$\theta_{\text{mix}} = \frac{\theta_1 + \theta_2}{2}$



## 12 Thermometry, Thermal Expansion and calorimetry

(3) **Mixing of two substances when temperature and phase both changes or only phase changes:** A very common example for this category is ice-water mixing.

Suppose water at temperature  $\theta_w^\circ\text{C}$  is mixed with ice at  $0^\circ\text{C}$ , first ice will melt and then its temperature rises to attain thermal equilibrium. Hence; Heat given = Heat taken

$$\Rightarrow m_w C_w (\theta_w - \theta_{\text{mix}}) = m_i L_i + m_i C_w (\theta_{\text{mix}} - 0^\circ)$$

$$\Rightarrow \theta_{\text{mix}} = \frac{m_w \theta_w - \frac{m_i L_i}{C_w}}{m_w + m_i}$$

$$(i) \text{ If } m_w = m_i \text{ then } \theta_{\text{mix}} = \frac{\theta_w - \frac{L_i}{C_w}}{2}$$

(ii) By using this formulae if  $\theta_{\text{mix}} < \theta_i$  then take  $\theta_{\text{mix}} = 0^\circ\text{C}$

### Heating Curve

If to a given mass ( $m$ ) of a solid, heat is supplied at constant rate  $P$  and a graph is plotted between temperature and time, the graph is as shown in figure and is called heating curve. From this curve it is clear that

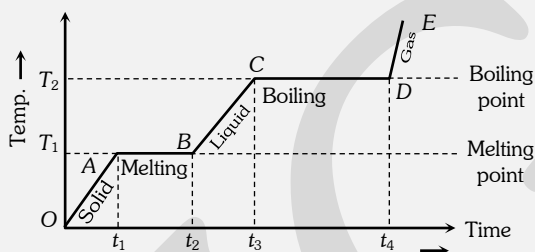


Fig. 12.21

(1) In the region OA temperature of solid is changing with time so,  $Q = mc_s \Delta T \Rightarrow P \Delta t = mc_s \Delta T$  [as  $Q = P \Delta t$ ]

But as  $(\Delta T / \Delta t)$  is the slope of temperature-time curve

$$c_s \propto \frac{1}{\text{Slope of line OA}}$$

i.e. specific heat (or thermal capacity) is inversely proportional to the slope of temperature-time curve.

(2) In the region AB temperature is constant, so it represents change of state, i.e., melting of solid with melting point  $T_1$ . At A melting starts and at B all solid is converted into liquid. So between A and B substance is partly solid and partly liquid. If  $L_F$  is the latent heat of fusion.  $Q = mL_F$  or  $L_F = \frac{P(t_2 - t_1)}{m}$  [as  $Q = P(t_2 - t_1)$ ]

$$\text{or } L_F \propto \text{length of line AB}$$

i.e. Latent heat of fusion is proportional to the length of line of zero slope. [In this region specific heat  $\propto \frac{1}{\tan 0} = \infty$ ]

(3) In the region BC temperature of liquid increases so specific heat (or thermal capacity) of liquid will be inversely proportional to the slope of line BC

$$\text{i.e., } c_L \propto \frac{1}{\text{Slope of line BC}}$$

(4) In the region CD temperature is constant, so it represents the change of state, i.e., boiling with boiling point  $T_2$ . At C all substance is in liquid state while at D in vapour state and between C and D partly liquid and partly gas. The length of line CD is proportional to latent heat of vaporisation

$$\text{i.e., } L_v \propto \text{Length of line CD [In this region specific heat } \propto \frac{1}{\tan 0} = \infty]$$

(5) The line DE represents gaseous state of substance with its temperature increasing linearly with time. The reciprocal of slope of line will be proportional to specific heat or thermal capacity of substance in vapour state.

## Tips & Tricks

✍ After snow falls, the temperature of the atmosphere becomes very low. This is because

the snow absorbs the heat from the atmosphere to melt down.

So, in the mountains, when

snow falls, one does not feel

too cold, but when ice melts, he feels too cold.

✍ There is more shivering effect of **ice-cream** on teeth as compared to that of water

(obtained from ice).

This is because, when ice-cream

melts down, it absorbs large

amount of heat from teeth.

✍ Branch of physics dealing with production and measurement of temperatures close to 0K is known as cryogenics while that dealing with the measurement of very high temperature is called as pyrometry.

✍ It is more painful to get burnt by steam rather than by boiling water at same temperature. This is so because when steam at  $100^\circ\text{C}$  gets converted to water at  $100^\circ\text{C}$ , then it gives out 536 calories of heat. So, it is clear that steam at  $100^\circ\text{C}$  has more heat than water at  $100^\circ\text{C}$  (i.e., boiling of water).





✍ A solid and hollow sphere of same radius and material, heated to the same temperature then expansion of both will be equal because thermal expansion of isotropic solids is similar to true photographic enlargement. It means the expansion of cavity is same as if it has been a solid body of the same material. But if same heat is given to the two spheres, due to lesser mass, rise in temperature of hollow sphere will be more  $\left\{ \text{As } \left( \Delta\theta = \frac{\Delta Q}{mc} \right) \right\}$ .

Hence its expansion will be more.

✍ Specific heat of a substance can also be negative. Negative specific heat means that in order to raise the temperature, a certain quantity of heat is to be withdrawn from the body.

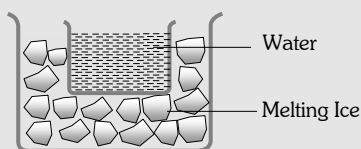
e.g. Specific heat of saturated vapours.

✍ Specific heat for hydrogen is maximum ( $3.5 \text{ cal/gm}^\circ\text{C}$ ) and it is minimum for radon and actinium ( $\approx 0.022 \text{ cal/gm}^\circ\text{C}$ ).

✍ The minimum possible temperature is 0 K.

✍ Amount of steam at  $100^\circ\text{C}$  required to just melt  $m \text{ gm}$  of ice at  $0^\circ\text{C}$  is  $m/8 \text{ gm}$ .

✍ If we put the beaker containing water in melting ice, the water in the beaker will cool to  $0^\circ\text{C}$  but will never freeze.



✍ A pressure in excess of 25 atm is required to make helium solidify. At 1 atm pressure, helium remains a liquid down to absolute zero.

✍ Boiling temperature of water, if pressure is different from normal pressure is  $t_{\text{Boiling}} = [100^\circ\text{C} - (760 - P \text{ in mm}) \times 0.037]^\circ\text{C}$

### ✍ Confusing S.I. and C.G.S. units

It is advised to do questions on calorimetry in C.G.S. as calculations becomes simple. If the final answer is in joules, then convert cal into joules.

✍ Invar and quartz have very small values of co-efficient of linear expansion.

✍ In S.I. nomenclature " degree" is not used with the kelvin scale; e.g.  $273^\circ\text{K}$  is wrong while  $273 \text{ K}$  is correct to write.

✍ Magnetic thermometer is recommended for measuring very low temperature (2K).

✍ The most sensitive thermometer is gas thermometer.

✍ Dew formation is more probable on a cloudiness calm night.

✍ In winters, generally fog disappear before noon. Because, the atmosphere warms up and tends to be unsaturated. The condensed vapours reevaporates and the fog disappears.

✍ Standardisation of thermometer is obtained with gas thermometer. Because coefficient of expansion of gas is very large.

✍ Dogs hang their tongues in order to expose a surface to the air for evaporation and hence, cooling. They do not sweat.



## Ordinary Thinking

### Objective Questions

#### Thermometry

- On the Celsius scale the absolute zero of temperature is at  
[CBSE PMT 1994]  
(a)  $0^\circ\text{C}$  (b)  $-32^\circ\text{C}$   
(c)  $100^\circ\text{C}$  (d)  $-273.15^\circ\text{C}$
- Oxygen boils at  $-183^\circ\text{C}$ . This temperature is approximately  
[CPMT 1992]  
(a)  $215^\circ\text{F}$  (b)  $-297^\circ\text{F}$   
(c)  $329^\circ\text{F}$  (d)  $361^\circ\text{F}$
- Recently, the phenomenon of superconductivity has been observed at 95 K. This temperature is nearly equal to  
[CPMT 1990]  
(a)  $-288^\circ\text{F}$  (b)  $-146^\circ\text{F}$   
(c)  $-368^\circ\text{F}$  (d)  $+178^\circ\text{F}$
- The temperature of a substance increases by  $27^\circ\text{C}$ . On the Kelvin scale this increase is equal to  
[CPMT 1993]  
(a) 300 K (b) 2.46 K  
(c) 27 K (d) 7 K
- The resistance of a resistance thermometer has values 2.71 and 3.70 ohm at  $10^\circ\text{C}$  and  $100^\circ\text{C}$ . The temperature at which the resistance is 3.26 ohm is  
[CPMT 1994]  
(a)  $40^\circ\text{C}$  (b)  $50^\circ\text{C}$   
(c)  $60^\circ\text{C}$  (d)  $70^\circ\text{C}$
- No other thermometer is as suitable as a platinum resistance thermometer to measure temperature in the entire range of  
[MNR 1993]  
(a)  $0^\circ\text{C}$  to  $100^\circ\text{C}$  (b)  $100^\circ\text{C}$  to  $1500^\circ\text{C}$   
(c)  $-50^\circ\text{C}$  to  $+350^\circ\text{C}$  (d)  $-200^\circ\text{C}$  to  $600^\circ\text{C}$