Heat and Thermodynamics

Unit: 7.1

Heat:

Heat is one of the forms of energy that flows from one body to another by virtue of temperature difference between them.

Temperature:

The degree of hotness or coldness of a body is measured by temperature. *The temperature of a body can be defined as the property that determines whether or not the body is in thermal equilibrium with the neighbouring systems.* If two systems are not in thermal equilibrium, they are at different temperatures.

Measurement of temperature:

The branch of heat relating to the measurement of temperature of a body is called *thermometry*. *Thermometer* is an instrument used to measure temperature.

In order to measure temperature, some standard reference temperatures are required that can easily be reproduced in any laboratory. For example, we take the melting point of ice (*ice point*) as lower fixed point and the boiling point of water (*steam point*) as upper fixed point of a thermometer.

Different scales to measure temperature:

1. Celsius (or Centigrade scale):

In this scale, the temperature is measured in *degree Celsius* (°C). Here, the lower fixed point is taken as 0° C for ice point while the upper fixed point is taken as 100° C for steam point. The interval is divided into 100 equal parts and each part represents 1^o C.

2. Fahrenheit scale:

In this scale, the temperature is measured in *degree Fahrenheit* (°F). Here, the lower fixed point (ice point) is marked as 32° F and the upper fixed point (steam point) is marked as 212° F. The interval is divided into 180 equal parts and each part represents 1^o F.

3. Reaumur scale:

In this scale, lower fixed point, i.e. ice point is marked as 0° R while upper fixed point i.e. steam point is marked as 80° R. The interval is divided into 80 equal parts and each part represents 1^o R.

4. Absolute scale or Kelvin scale:

In this scale, the temperature is measured by the unit *kelvin* (K). Here 0 K corresponds to 273.15° C.

Relation between Celsius, Fahrenheit and Reaumur scales of temperature:

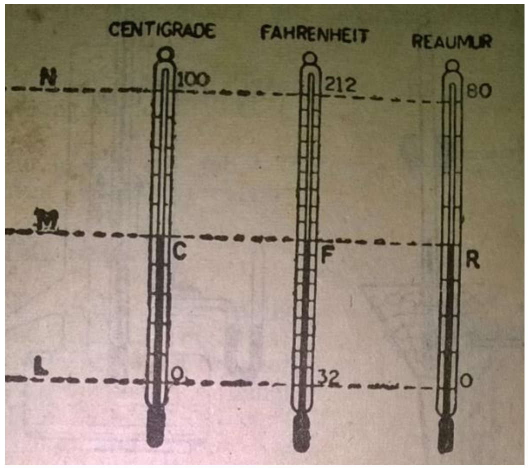


Fig.7.1.1

If the level of mercury in each thermometer stands up to the same level M (Fig. 7.1.1), then

$$\frac{\boldsymbol{ML}}{\boldsymbol{NL}} = \frac{\boldsymbol{C-0}}{\boldsymbol{100-0}} = \frac{\boldsymbol{F-32}}{\boldsymbol{212-32}} = \frac{\boldsymbol{R-0}}{\boldsymbol{80-0}}$$

Or

$$\boxed{\frac{C}{100} = \frac{F-32}{180} = \frac{R}{80}}$$

Relation between Celsius, Fahrenheit and Kelvin scales of temperature:

$$\boxed{\frac{C}{100} = \frac{F-32}{180} = \frac{K-273.15}{100}}$$

Example 1 Convert 40^0 C to Fahrenheit scale.

Solution: Given, C= 40^0 centrigrade

We know that,

$$\frac{C}{5} = \frac{F-32}{9}$$

$$=> \frac{40}{5} = \frac{F-32}{9}$$

$$=> F - 32 = 72 => F = 104$$

Therefore, the temperature on Fahrenheit scale is 104^0 F.

Q.1 The reading of a certain temperature on the Centigrade scale is half the reading on the Fahrenheit scale. Find the reading on the Centigrade scale.

Unit: 7.2

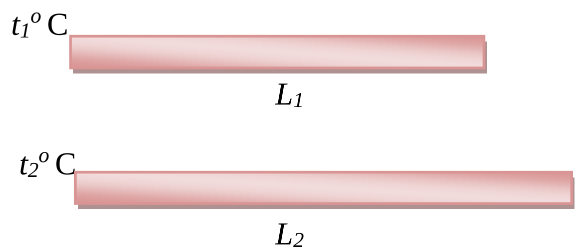
Thermal expansion

Matter can expand when it is heated. In case of solids, the expansion will be in length, area or volume. On the other hand, in liquids or gasses, only expansion in volume is possible as they do not possess any fixed shape. The property of thermal expansion of substances is different for different substances and also depends on the state of the substance.

Expansion of solids:

1. Linear expansion:

Let L_1 and L_2 be the length of solid rod at t_1^o C and t_2^o C respectively. Then



change in length $= L_2 - L_1$

increase in temperature= $t_2 - t_1$

$\therefore\ L_2 - L_1 \propto$ original length (L_1)

$\propto$ raise in temperature ($t_2 - t_1$)

=> $L_2 - L_1 = \alpha L_1 (t_2 - t_1)$

Or

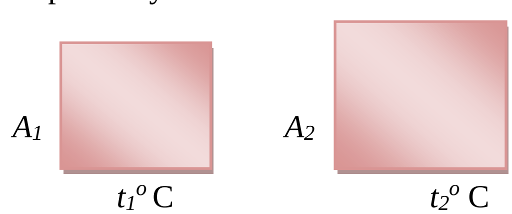
$\alpha = \frac{L_2 - L_1}{L_1(t_2 - t_1)}$

where α is called *coefficient of linear expansion* of the material of the body.

Coefficient of linear expansion (α): The coefficient of linear expansion of the material of a body is defined as the increase in length per unit length per unit degree rise of temperature.

2. Superficial or areal expansion:

Let A_1 and A_2 be the area of a solid at t_1^o C and t_2^o C respectively. Then



increase in area $= A_2 - A_1$

increase in temperature= $t_1 - t_2$

$\therefore\ A_2 - A_1 \propto$ original area (A_1)

$\propto$ raise in temperature ($t_2 - t_1$)

$$=> A_2 - A_1 = \beta A_1(t_2 - t_1)$$

Or

$$\beta = \frac{A_2 - A_1}{A_1(t_2 - t_1)}$$

where β is called *coefficient of superficial expansion* of the material of the solid.

Coefficient of superficial expansion (β): The coefficient of superficial expansion of the material of a body is defined as the increase in area per unit area per unit degree rise of temperature.

3. Cubical or volume expansion:

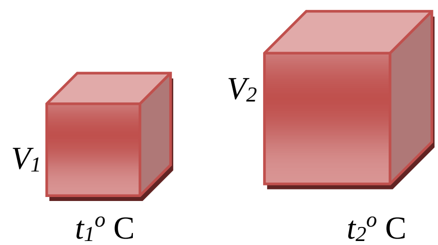
Let V_1 and V_2 be the volume of a solid at t_1^o C and t_2^o C respectively. Then

increase in volume $= V_2 - V_1$

increase in temperature= $t_2 - t_1$

$\therefore\ V_2 - V_1 \propto$ original volume (V_1)

$\propto$ raise in temperature ($t_2 - t_1$)



$$=> V_2 - V_1 = \gamma V_1(t_2 - t_1)$$

Or

$$\gamma = \frac{V_2 - V_1}{V_1(t_2 - t_1)}$$

where γ is called *coefficient of cubical expansion* of material of the solid.

Coefficient of cubical expansion (γ): The coefficient of cubical expansion of the material of a body is defined as the increase in volume per unit volume per unit degree rise of temperature.

Relation between $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$:

It can be shown that

$\beta = 2\alpha => \alpha = \frac{\beta}{2}$ and $\gamma = 3\alpha => \alpha = \frac{\gamma}{3}$

$\therefore\ \alpha = \frac{\beta}{2} = \frac{\gamma}{3}$ => $\boxed{\alpha : \beta : \gamma = 1 : 2 : 3}$

Expansion of liquids:

The volume of a liquid changes when it is heated. When a liquid is heated, the containing vessel also expands and hence the measured increase in volume of the liquid is the apparent increase in volume. The real increase in volume of the liquid is equal to the sum of the apparent increase in volume of the liquid and increase in volume of the containing vessel. Consequently, a liquid has the following two coefficients of expansion.

Coefficient of apparent expansion (γ_a): It is defined as the apparent increase in volume per unit volume per unit degree rise in temperature when the liquid is heated in a vessel that expands on heating.

Coefficient of real expansion (γ_r): It is defined as the actual increase in volume of a liquid per unit volume per unit degree rise in temperature of the liquid.

Relation between γ_r and γ_a:

The coefficient of real expansion (γ_r) of a liquid is approximately equal to the sum of the coefficient of apparent expansion (γ_a) of the liquid and the coefficient of the cubical expansion (γ_g) of the containing vessel.

$$\gamma_r = \gamma_a + \gamma_g$$

If α_g is the coefficient of linear expansion of the material of the containing vessel, then $\gamma_g = 3\alpha_g$.

Variation of density of a substance with temperature:

When a solid is heated, its volume increases due to expansion and consequently the density of the substance decreases.

Let ρ_1 and ρ_2 be the densities of the solid at temperatures t_1^o C and t_2^o C respectively. Then it can be shown that

$$\boxed{\rho_2 = \frac{\rho_1}{1 + \gamma(t_2 - t_1)}}$$

Anomalous expansion of water:

Most of the liquid expand uniformly over moderate ranges of temperature. However, water shows a marked exception when it is heated from 0^0 C to 10^0 C. The variation of volume of water with temperature is shown in the Fig. 7.2.1. It is seen from the figure that the volume of water decreases with the rise of temperature from 0^0 C to 4^0 C. At 4^0 C, water occupies its minimum volume or its density becomes maximum. Above 4^0C, the volume water increases with the rise of temperature.

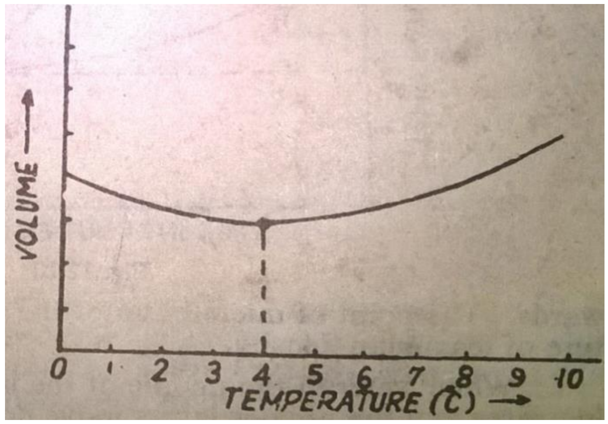


Fig.7.2.1

Unit: 7.3

Calorimetry

This is the branch of heat transfer that deals with the measurement of heat. The heat is usually measured in calories or kilo calories.

Principle of calorimetry:

When a hot body is brought in contact with a cold body, then heat lost by the hot body is equal to the heat gained by the cold body.

Heat lost = Heat gain

Heat:

Heat is a form of energy called thermal energy which flows from a higher temperature body to a lower temperature body when they are placed in contact.

Heat or thermal energy of a body is the sum of kinetic energies of all its constituent particles on account of translational, vibrational and rotational motion.

The SI unit of heat energy is **joule (J).**

The practical unit of heat energy is **calorie**.

1 cal = 4.18 J

Calorie: 1 calorie is the quantity of heat required to raise the temperature of 1 gm of water by 1°C.

Specific heat:

The amount of heat required to raise the temperature of unit mass of a substance through 1°C is called its specific heat.

It is denoted by *c* or *s*.

Its SI unit is **joule kilogram^{-1} kelvin^{-1}** (**J kg^{-1} K^{-1}**).

The specific heat of water is 4200 J kg^{-1} K^{-1} or 1 cal g^{-1} ^{0}C^{-1}, which is high compared with most other substances.

Thermal (Heat) capacity:

Heat capacity of any body is equal to the amount of heat energy required to increase its temperature through 1°C.

Heat capacity = *mc*,

where *c* = specific heat of the substance of the body and *m* = mass of the body.

Its SI unit is **joule/kelvin (J K^{-1})**.

Water equivalent:

It is the amount of water that will absorb the same quantity of heat as the substance for the same rise in temperature.

Q.1 A piece of lead of mass 500 g gives out 1200 cal of heat when it is cooled from 90^{0} C to 10^{0} C. Find its specific heat, thermal capacity and water equivalent.

Q.2 40 g of water at 60^{0} C is poured into a calorimeter whose temperature is 20^{0} C. The final temperature of the two is 45^{0} C. Find the water equivalent of the calorimeter.

Unit: 7.4

Hygrometry

Hygrometry is that branch of physics which deals with the study of water vapours in the atmosphere.

Relative humidity:

It is defined as the ratio of the mass of water vapour (m) actually present in a certain volume of air at room temperature to the mass of water vapour (M) required to saturate the same volume of air at the same temperature.

Relative humidity (RH) $=\frac{m}{M}$

Relative humidity is normally expressed as a percentage.

Dew point: It is the temperature at which the water vapour actually present in the atmosphere is just sufficient to saturate it.

Absolute humidity:

It is the mass of water vapour actually present in unit volume of moist air.

Unit: 7.5

Change of state

We are familiar with that a substance exists in three states, e.g. solid, liquid and gas. The particular state of the substance depends on its temperature. Ice is the solid state of water. By supplying heat (i.e. increasing temperature) to ice, it can be changed its state to water. Further, by heating water, it can be converted into the gaseous state (steam). For a given substance, the change of state takes place at a fixed temperature and pressure.

Latent heat of fusion:

It has been found that one gram of ice takes 80 calories of heat to get converted into water. This heat is called the latent heat of fusion of ice.

Latent heat of fusion of a substance is defined as the amount of heat required to change the state of one gram of a substance from solid to liquid without any change in its temperature.

Laws of fusion:

(1) Every substance changes its state from solid to liquid at a particular temperature (under normal pressure) called the **melting point**.

e.g. the melting point of ice is 0^0 C at a pressure of 76 cm of Hg.

(2) As long as the change of state takes place, there is no change in temperature.

(3) Latent heat of fusion is different for different substances.

(4) Some substances show increase in volume on melting (e.g. wax) while some other substances show decrease in volume on melting (e.g. ice)

(5) The melting point of those substances which decreases in volume on melting is lowered with increase in pressure.

(6) The melting point of those substances which increase in volume on melting is increased with increase in pressure.

Effect of pressure on melting point of ice:

The melting point of ice is lowered with increase in pressure. Let us take an ice slab and a wire with its ends fixed with heavy weights. We put the wire over the slab as shown in the Fig. 7.4.1. Just below the wire, ice melts at a lower temperature due to increase in pressure. When the wire has passed, the water, above the wire, freezes again. Thus the wire passes through the slab and the slab does not split. This phenomenon of refreezing is called *Regelation.*

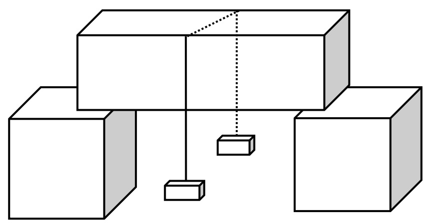


Fig. 7.4.1

Vaporization:

The conversion of a substance from liquid state to vapour state is called vaporization. Conversion of water to steam is an example of vaporization.

On the other hand, *the conversion of a substance from vapour state to the liquid state is called condensation.* Conversion of steam into water is an example of condensation.

Latent heat of vaporization:

Latent heat of vaporization of a liquid is defined as the amount of heat required to convert one gram of the liquid into vapour without any change in its temperature.

Latent heat of vaporization for water is 537 cal/gm at a pressure of 76 cm of Hg.

Laws of ebullition or boiling:

(1) Every liquid changes its state from liquid to vapour at a particular temperature (under normal pressure) called the *boiling point*.

(2) As long as the change of state takes place, there is no change in temperature.

(3) Latent heat of vaporization is different for different substances.

(4) All liquids show increase in volume on vaporization.

(5) The boiling point of a liquid increases with increase in pressure on the liquid.

(6) The liquid can boil at a lower temperature at reduced pressure.

Q.1 Calculate the amount of heat required to convert 10 g of ice at -10^0 C completely into steam. Specific heat of ice is 0.5 cal/g ^{0}C.

Q.2 Find the amount of heat required to increase the temperature of 100 g water at 10^0 C to vapour at 100^0 C. Specific heat of water is 1 cal/ g ^{0}C and latent heat of vaporization of water is 540 cal/g.

Unit: 7.6

Transmission of heat

Heat can be transferred from one place to the other in the following three different ways.

Conduction:

The process in which heat is transmitted from one point to the other through a substance without the actual motion of the particles is called conduction. Heat transfer takes place by conduction from the hot end of a metallic rod through its different parts to the other end.

Convection:

The process in which heat is transmitted from one point to the other through a substance by the actual motion of the heated particles is called conduction. This mode of heat transfer is possible only in fluids, i.e. in air or in liquids.

Radiation:

The process in which heat is transferred from one place to the other directly without the necessity of the intervening medium is called radiation. We get heat radiation directly from the sun.

Thermal conductivity:

Let us consider a metal rod of length *l* and area of cross section *A*. At steady state, the quantity of heat conducted through the rod in time *t* when its ends are kept at temperatures θ_1 and θ_2 ($\theta_1 > \theta_2$) is given by

$$Q = \frac{KA(\theta_1 - \theta_2)t}{l}$$

where *K* is known as the coefficient of thermal conductivity of the material of the rod.

Coefficient of thermal conductivity is defined as the amount of heat flowing in one second across the opposite faces maintained at unit temperature difference of a rod of unit length and unit area of cross section.

The SI unit of *K* is **J s^{-1} m^{-1} K^{-1}** or **W m^{-1} K^{-1}**.

Unit: 7.7

First law of thermodynamics:

It states that the amount of heat supplied to a system is equal to the sum of the increase in its internal energy and the external work done by it.

Second law of thermodynamics:

Kelvin-Planck statement:

No process is possible whose sole result is the absorption of heat from a reservoir and complete conversion of it into work.

Clausius' statement:

No process is possible whose sole result is the transfer of heat from a colder to a hotter body.

Joule's law:

It states that if an amount of work W (or any other form of energy) disappears, a definite quantity of heat H is produced. That is

$$W \propto H$$

Or

$$W = JH$$

where J is a constant called the *mechanical equivalent* of heat.

The mechanical equivalent of heat (J) is defined as the amount of work done to produce a unit quantity of heat.

The value of J is **4.18 joule/cal**.