

HEAT & THERMODYNAMICS

1. THERMAL PROPERTIES OF MATTER

In this topic, we discuss various phenomena involving thermal and how does a matter behave on experiencing the flow of thermal energy. Primarily we study

- Thermal Expansion
- Heat & Calorimetry
- Heat Transfer

1.1 Temperature and Heat

Temperature : Temperature is a relative measure of hotness or coldness of a body.

SI Unit : Kelvin (K)

Commonly Used Unit : °C or °F

Conversion : $t_K = t_C + 273.15$

Heat : Heat is a form of energy flow (i) between two bodies or (ii) between a body and its surroundings by virtue of temperature difference between them

SI Unit : Joule (J)

Commonly Used Unit : Calorie (Cal)

Conversion : 1 cal = 4.186 J

- Heat always flows from a higher temperature system to a lower temperature & system.

1.2 Measurement of Temperature

Principle : Observation of Thermometric property with the change in temperature and comparing it with certain reference situations.

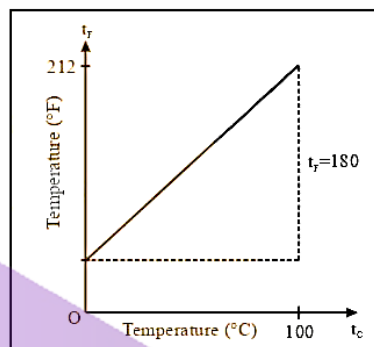
- Reference situation is generally ice point or steam point.

1.2.1 Celsius and Fahrenheit Temperature Scales

In Celsius Scale	In Fahrenheit Scale
Ice point → 0°C	Ice point → 32°F
Steam point → 100°C	Steam point → 212°F

It implies that 100 division in Celsius scales is equivalent to 180 scale divisions in Fahrenheit scale.

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



1.2.2 Absolute Temperature Scale

It is kelvin scale

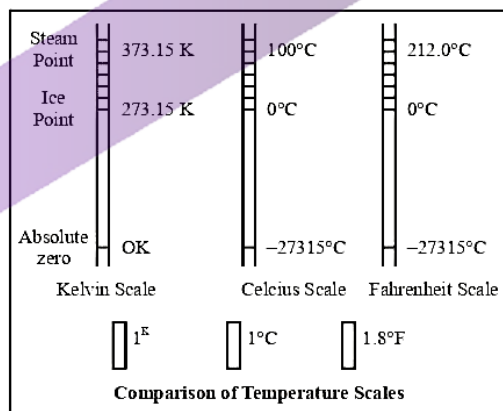
Ice point → 273.15 K

Steam point → 373.15 K

Comparing it with the Celsius scale, number of scale division in both the scales is same.

$$\frac{t_C - 0^\circ\text{C}}{100} = \frac{t_K - 273.15}{100}$$

- Kelvin scale is called as absolute scale, because it is practically impossible to go beyond OK in the negative side.

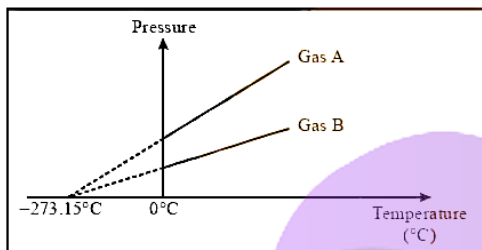


1.2.3 Thermometers

Instrument used to measure temperature of any system is called as **thermometer**.

Examples : Liquid in Glass thermometer, Platinum Resistance Thermometer, Constant Volume Gas Thermometers.

- Liquid in Glass thermometer and Platinum Resistance thermometer give uniform readings for ice point & steam point but go non uniform for different liquids and different materials.
- Constant volume gas thermometer gives same readings irrespective of which gas. It is based on the fact that at low pressures and constant volume, $P \propto T$ for a gas.



- All gases converge to absolute zero at zero pressure.

1.3 Thermal Expansion

It is widely observed, that most materials expand on heating and contract on cooling.

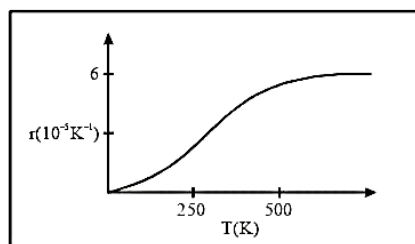
This expansion is in all dimensions.

Experimentally it has been observed that fractional change in any dimension is proportional to the change in temperature.

	$\frac{\Delta x}{x} = K \Delta T$	constant (k)
Linear Expansion 	$\frac{\Delta L}{L} = \alpha \Delta T$	Coefficient of Linear expansion (α) : Increase in length per unit length per degree rise in temp.
Area Expansion 	$\frac{\Delta A}{A} = \beta \Delta T$	Coefficient of Area Expansion (β) : Increase in area per unit area per degree rise in temp.
Volume Expansion 	$\frac{\Delta V}{V} = \gamma \Delta T$	Coefficient of volume expansion (γ) : Increase in area per unit volume per degree rise in temp.

Units of $\alpha, \beta, \gamma = /^{\circ}\text{C}$ or $/\text{K}$

- In general with change in volume the density will also change.
- α for metals generally higher than α for non-metals
- γ is nearly constant at high temperatures but at low temp it depends on temp.



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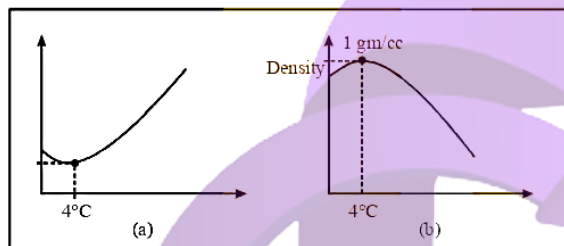
Coefficient of volume expansion of Cu as a function of temperature.

- For ideal gases γ is inversely proportional to temp. at constant pressure

$$v = \frac{nRT}{P} \Rightarrow \frac{\Delta V}{V} = \frac{\Delta T}{T}$$

$$\Rightarrow \gamma = \frac{1}{T}$$

- As an exception, water contracts on heating from 0°C to 4°C and hence its density increases from 0°C to 4°C . This is called as anomalous expansion



- In general

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

Proof: Imagine a cube of length, l that expands equally in all directions, when its temperature increases by small ΔT ;

We have

$$\Delta l = \alpha l \Delta T$$

Also

$$\Delta V = (l + \Delta l)^3 - l^3 = l^3 + 3l^2 \Delta l + 3l \Delta l^2 + \Delta l^3 - l^3 = 3l^2 \Delta l \quad \dots(1)$$

In Equation (1) we ignore $3l \Delta l^2$ & Δl^3 as Δl is very small as compared to l .

So

$$\Delta V = \frac{3V}{l} \Delta l = 3V\alpha \Delta T \quad \left[\text{Using } \frac{V}{l} = l^2 \right] \quad \dots(2)$$

$$\therefore \frac{\Delta V}{V} = 3\alpha \Delta T$$

$$\Rightarrow \gamma = 3\alpha$$

Similarly we can prove for area expansion coefficient

- In case, thermal expansion is prevented inside the rod by fixing its ends rigidly, then the rod acquires a compressive strain due to external forces at the ends corresponding stress set up in the rod is called thermal stress.

we know

$$\frac{\Delta V}{V} = \alpha \Delta T = \text{compressive strain}$$

$$\text{Also } \frac{\gamma \Delta l}{V} = \sigma = \text{Thermal stress}$$

$$\sigma_T = \gamma \alpha \Delta T \quad \dots(3)$$

- Practical applications in railway tracks metal tyres of cart wheels, bridges and so many other applications.

1.4 Heat & Calorimetry

When two systems at different temperatures are connected together then heat flows from higher temperature to lower temperature till the time their temperatures do not become same.

Principle of calorimetry states that, neglecting heat loss to surroundings, heat lost by a body at higher temperature is equal heat gained by a body at lower temperature.

$$\text{heat gained} = \text{heat lost}$$

Whenever heat is given to any body, either its temperature changes or its state changes.

1.4.1 Change in Temperature

When the temp changes on heating,

Then

Heat supplied \propto change in temp (ΔT)

\propto amount of substance (m/n)

\propto nature of substance (s/C)

$$\Rightarrow \Delta H = ms\Delta T$$

m = Mass of body

s = specific heat capacity per kg

ΔT = Change in temp

$$\text{or } \Delta H = nC\Delta T$$

n = Number of moles

C = Specific/Molar heat Capacity per mole

ΔT = Change in temp

- Specific Heat Capacity :** Amount of heat required to raise the temperature of unit mass of the substance through one degree.

Units

SI $\rightarrow \text{J/KgK}$

$S_{H_2O(l)} = 1 \text{ cal/g}^\circ\text{C}$

Common $\rightarrow \text{Cal/g}^\circ\text{C}$

$S_{H_2O(ice)} = 0.5 \text{ cal/g}^\circ\text{C}$

- Molar Heat Capacity** : Amount of heat required to raise the temperature of unit mole of the substance through one degree

Units

SI \rightarrow J/mol K

Common \rightarrow Cal/gc $^{\circ}$

- Heat Capacity** : Amount of heat required to raise the temperature of a system through one degree

$$\Rightarrow \Delta H = S \Delta T$$

where S = Heat Capacity

Units

SI \rightarrow J/K

Common \rightarrow Cal/C $^{\circ}$

- For H₂O specific heat capacity does change but fairly very less.
- Materials with higher specific heat capacity require a lot of heat for some a given in temperature

1.4.2 Change in state

When the phase changes on heating

Then

Heat supplied \propto amount of substance which changes the state (M)

\propto nature of substance (L)

$$\Rightarrow \Delta H = mL$$

Where L = Latent Heat of process

- Latent Heat** : Amount of heat required per mass to change the state of any substance.

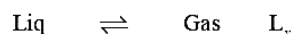
Units

SI \rightarrow J/Kg

Common \rightarrow Cal/g

- The change in state always occurs at a constant temperature.

For example



L_f = Latent Heat of fusion

L_v = Latent heat of vaporization

- In case any material is not at its B.P or M.P, then on heating the temperature will change till the time a particular state change temperature reaches.

For Example : If water is initially at -50°C at 1 Atm pressure in its solid state.

On heating.

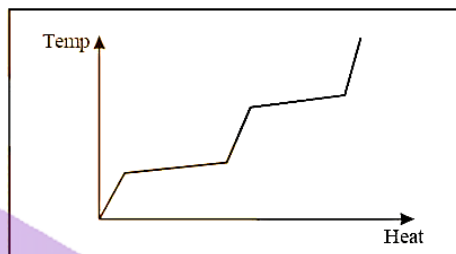
Step - 1 : Temp changes to 0°C first

Step - 2 : Ice melts to H₂O(l) keeping the temp constant

Step - 3 : Temp. increases to 100°C

Step - 4 : H₂O(l) boils to steam keeping the temp constant

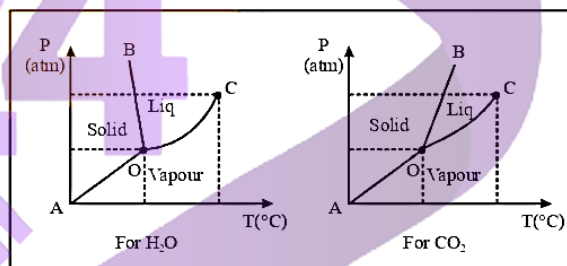
Step - 5 : Further temp increases



- The slope is inversely proportional to heat capacity.
- Length of horizontal line depends upon mL for the process.

1.4.3 Pressure dependence on melting point and boiling point

- For some substance melting point decreases with increases pressure and for other melting point increases
- Melting point increases with increase in temperature. We can observe the above results through phaser diagrams.



Line AO \rightarrow Sublimation curve

Line OB \rightarrow Fusion curve

Line OC \rightarrow Vapourization curve

Point O \rightarrow Triple Point

Point C \rightarrow Critical temperature

Triple Point : The combination pressure and temperature at which all three states of matter (i.e. solids, liquids gases co-exist.

For H₂O it is at 273.16K and 0.006 Atm.

Critical Point : The combination of pressure & temp beyond which a vapour cannot be liquified is called as critical point.

Corresponding temperature, pressure are called as critical temperature & critical pressure.

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- From the phasor diagram, we can see that melting point decreases with increases in pressure for H_2O .

Based on this is the concept of regelation.

Regelation : The phenomena of refreezing of water melted below the normal melting point due to addition of pressure.

- It is due to this pressure effect on melting point that cooking is tough on mountains and easier in pressure cooker.

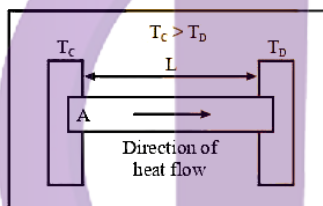
1.5 Heat Transfer

There are three modes of heat transfer.

- Conduction
- Convection
- Radiation

1.5.1 Conduction

Thermal conduction is the process in which thermal energy is transferred from the hotter part of a body to the colder one or from hot body to a cold body in contact with it without any transference of material particles.



At steady state,

The rate of heat energy flowing through the rod becomes constant.

$$\text{This is rate } Q = kA \frac{(T_c - T_d)}{L} \quad \dots(i)$$

for uniform cross-section rods

where Q = Rate of heat energy flow (J/s or W)

A = Area of cross-section (m^2)

T_c, T_d = Temperature of hot end and cold end respectively ($^{\circ}C$ or K)

L = Length of the rod (m)

K = coefficient of thermal conductivity

Coefficient of Thermal Conductivity : It is defined as amount of heat conducted during steady state in unit time through unit area of any cross-section of the substance under unit temperature gradient, the heat flow being normal to the area.

Units

SI $\rightarrow J/mSk$ or W/mK .

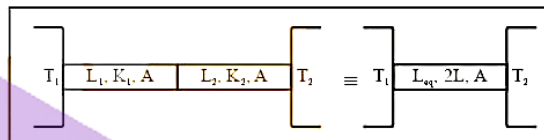
- Larger the thermal conductivity, the greater will be rate of heat energy flow for a given temperature difference.

$$K_{\text{metals}} > K_{\text{non metals}}$$

- Thermal conductivity of insulators is very low. Therefore, air does not let the heat energy to be conducted very easily.

- For combinations of rods between two ends kept at different temperatures, we can use the concept of equivalent thermal conductivity of the composite rod.

For example :



where K_{eq} for equivalent thermal conductivity of the composite.

- The term $\frac{(T_c - T_d)}{L}$ in the above equation is called as Temperature Gradient.

Temperature Gradient : The fall in temperature per unit length in the direction of flow of heat energy is called as Temperature Gradient

Units

SI $\rightarrow K/m$

- The term Q , (i.e.) rate of flow of heat energy can also be named as heat current
- The term (L/KA) is called as thermal resistance of any conducting rod.

Thermal Resistance : Obstruction offered to the flow of heat current by the medium

Units $\rightarrow K/W$

1.5.2 Convection

The process in which heat is transferred from one point to another by the actual movement of the heated material particles from a place at higher temperature to another place of lower temperature is called as thermal convection.

- If the medium is forced to move with the help of a fan or a pump, it is called as forced convection.

If the material moves because of the differences in density of the medium, the process is called natural or free convection.

- Examples of forced convection

Circulatory system, cooling system of an automobile heat connector

- Examples of natural convection
Trade winds, Sea Breeze/Land Breeze, Monsoons Burning of Tea.

1.5.3 Radiation

It is a process of transmission of heat in which heat travels directly from one place to another without the agency of any intervening medium.

- This radiation of heat energy occurs in the form of EM waves.
- These radiators are emitted by virtue of its temperature, like the radiation by a red hot iron or light from a filament lamp.
- Every body radiates energy as well as absorbs energy from surroundings.
- The proportion of energy absorbed depends upon the colour of the body.

(a) Newton's Law of cooling

Newton's Law of cooling states that, the rate of loss of heat

$-\frac{ds}{dt}$ of the body is directly proportional to the difference of temp difference

$$\text{Now } \frac{-ds}{dt} = k(T_2 - T_1) \quad \dots(4)$$

where k is a positive constant depending upon area and nature of the surface of the body. Suppose a body of mass m , specific heat capacity s is at temperature T_2 & T_1 be the temp of surroundings if dT_2 the fall of temperature in time dt .

Amount of heat lost is

$$dcs = msdT_2$$

\therefore Rate of loss of heat is given by

$$\frac{dcs}{dt} = ms \frac{dT_2}{dt} \quad \dots(5)$$

From Equation 4 and 5

$$-ms \frac{dT_2}{dt} = k(T_2 - T_1)$$

$$\Rightarrow \frac{dT_2}{T_2 - T_1} = \frac{-k}{ms} dt = -Kdt$$

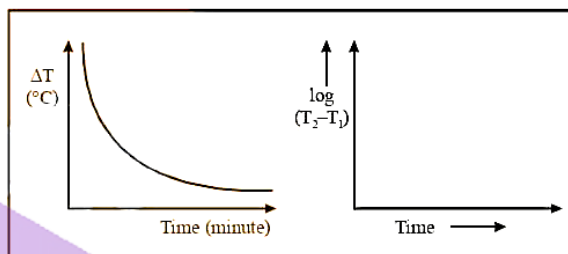
$$\text{where } K = \frac{k}{ms}$$

On integrating

$$\log(T_2 - T_1) = -Kt + C$$

$$\text{or } T_2 = T_1 + C_1 e^{-Kt} \text{ where } C_1 = e^C \quad \dots(6)$$

equation (6) enables you to calculate the time of cooling of a body through a particular range of temperature.

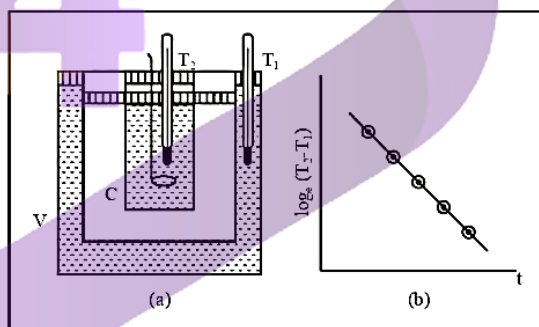


- For small temp diff, the rate of cooling, due to conduction, convection & radiation combined is proportional to difference in temperature.

- Approximation :** If a body cools from T_a to T_b in t times in medium where surrounding temp is T_0 , then

$$\frac{T_a - T_b}{t} = K \left(\frac{T_a + T_b}{2} - T_0 \right)$$

- Newton's Law of cooling can be verified experimentally.



Set Up : A double walled vessel (v) containing water in between two walls.

A copper calorimeter (c) containing hot water placed inside the double walled vessel. Two thermometers through the carbs are used to not the temperature T_2 of H_2O in calorimeter T_1 of water in between the double walls respectively.

Experiment : The temperature of hot water in the calorimeter after equal intervals of time.

Result : A graph is plotted between $\log(T_2 - T_1)$ and time (t). The nature of the graph is observed to be a straight line as it should be from Newton's law of cooling.