Revision Notes

Class – 11 Physics

Chapter 11 - Thermal properties of matter

1. THERMAL PROPERTIES OF MATTER

This topic discusses various thermal phenomena and how a matter behaves when subjected to the flow of thermal energy. We are specifically concerned in

• Thermal Expansion.

• Heat and Calorimetry

• Transfer of Heat

1.1 Temperature and Heat

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

SI Unit: Kelvin (K)

Commonly used unit: $^\circ C$ or $^\circ F$

Conversion: $t(K) = t\left(^\circ C\right) + 273.15$

Heat: Heat is a type of energy flow that occurs

(i) between two bodies or

(ii) between a body and its surroundings as a result of a temperature difference.

SI unit: Joule (J)

Commonly used unit: Calorie (Cal)

Conversion: $1\ cal = 4.186\ J$

• Heat is always transferred from a higher temperature system to a lower temperature system.

1.2 Measurement of Temperature

Principle: Thermometric properties are observed as temperature changes and compared to certain reference situations.

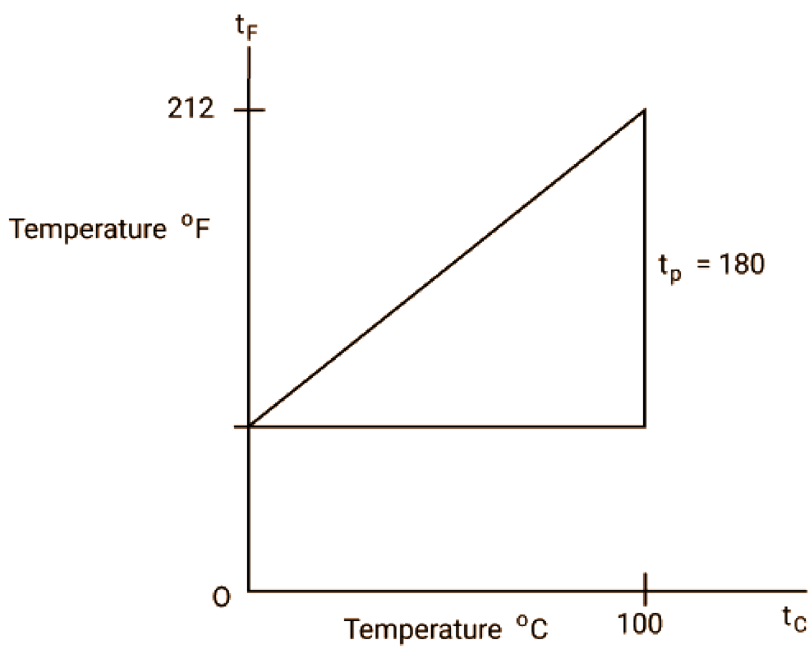
• Generally, the reference situation is ice point or steam point.

1.2.1 Celsius and Fahrenheit Temperature Scale

In Celsius Scale	In Fahrenheit Scale
Ice point $\rightarrow$ 0 $^\circ$ C Stream point $\rightarrow$ 1000 $^\circ$ C	Ice point $\rightarrow$ 32 $^\circ$ F Stream point $\rightarrow$ 212 $^\circ$ F

It implies that 100 divisions in Celsius are equivalent to 180 divisions in Fahrenheit.

Hence, $\frac{t_f - 32}{180} = \frac{t_c}{100}$



Note: Recreated the above diagram.

1.2.2 Absolute Temperature Scale

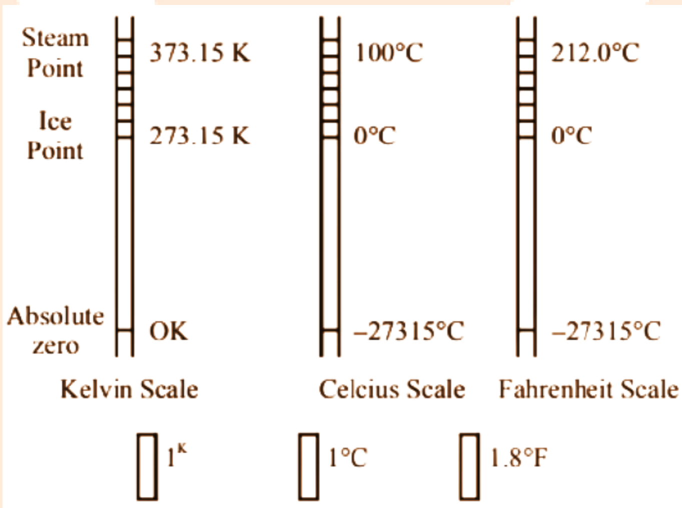
It is kelvin scale

Ice point $\rightarrow$ 273.15 K

Steam point $\rightarrow$ 373.15 K

When compared to the Celsius scale, the number of scale divisions in both scales is the same. $\frac{t_c - 0^\circ C}{100} = \frac{t_k - 273.15}{100}$

• The Kelvin scale is known as an absolute scale because it is nearly impossible to go beyond 0 K on the negative side.



Comparison of Temperature Scales

Note: Recreated the above diagram

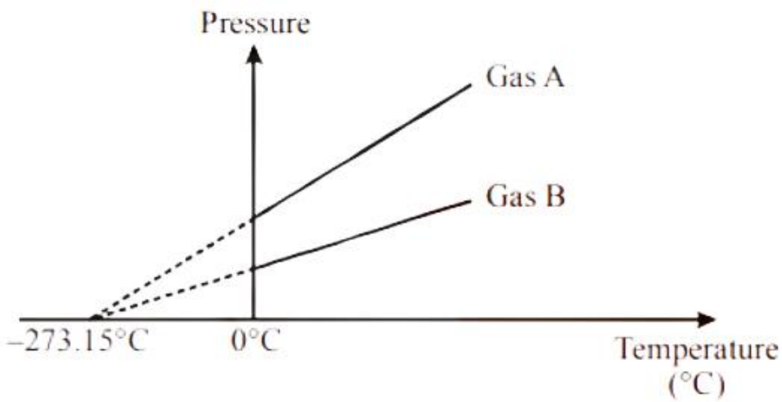
1.2.3 Thermometers

A thermometer is a device used to measure the temperature of any system.

Liquid in Glass thermometers, Platinum Resistance Thermometers, and Constant Volume Gas Thermometers are a few examples.

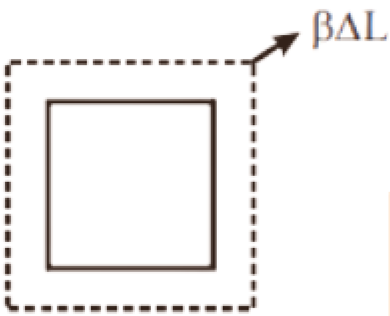
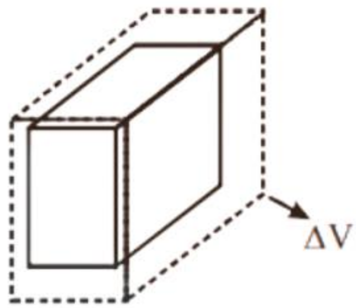
• The Liquid in Glass thermometer and the Platinum Resistance thermometer provide uniform readings for ice point and steam point but vary for different liquids and materials.

• A constant volume gas thermometer provides the same readings regardless of which gas is used. It is based on the fact that at low pressures and constant volume, $P \times T$ for a gas.



• All gases collide to absolute zero at zero pressure.

	$\frac{\Delta x}{x} = K\Delta T$	Constant (k)
Linear Expansion 	$\frac{\Delta L}{L} = \alpha \Delta T$	Coefficient of linear expansion: It rises in length per unit length per degree increase in temperature.
Area expansion	$\frac{\Delta A}{A} = \beta \Delta T$	Coefficient of area expansion: It rises in area per unit area per degree increase in temperature.

		
Volume Expansion 	$\frac{\Delta V}{V} = \gamma \Delta T$	Coefficient of volume expansion: It rises in volume per unit volume per degree increase in temperature.

Note: Recreated the above diagram.

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

In general, as the volume changes, the density changes as well.

• α is generally higher for metals than α for nonmetals

• γ is nearly constant at high temperatures but varies with temperature at low temperatures.

1.3 Thermal Expansion

Most materials, it has been observed, expands when heated and contract when cooled. This expansion is multidimensional.

It has been demonstrated experimentally that a fractional change in any dimension is proportional to a change in temperature.

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

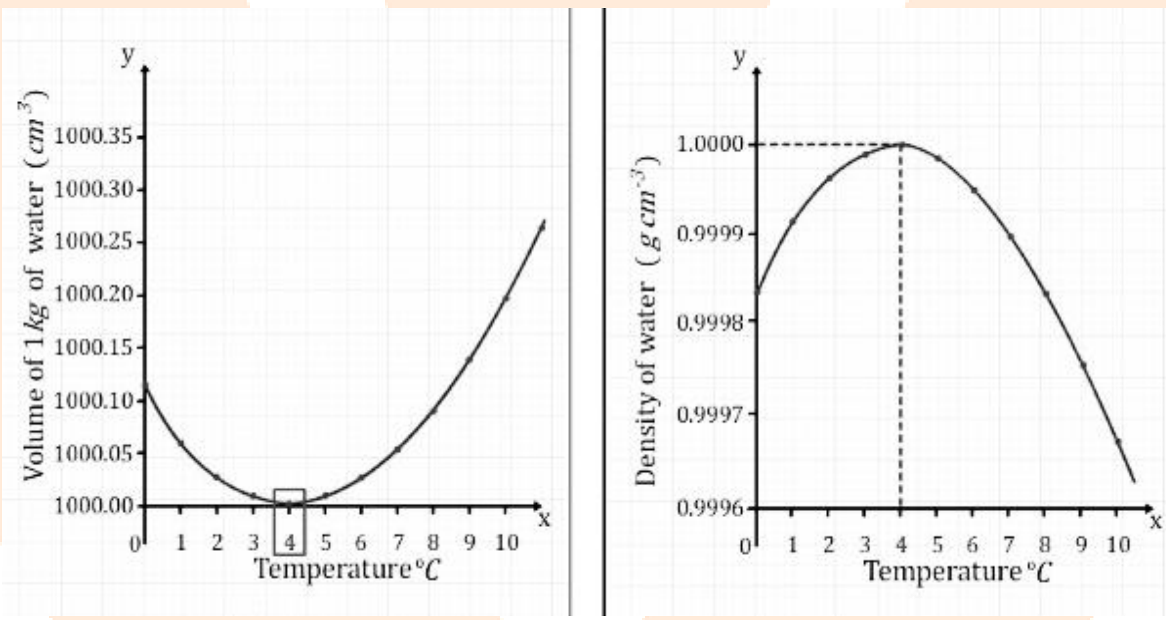
• For ideal gases, λ is inversely related to the temperature at constant pressure.

$$V = \frac{nRT}{P}$$

$$\Rightarrow \frac{\Delta V}{V} = \frac{\Delta T}{T}$$

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

Water, on the other hand, contracts when heated from $0\,^{\circ}C$ to $4\,^{\circ}C$ and thus its density rises from $0\,^{\circ}C$ to $4\,^{\circ}C$. This is known as anomalous expansion.



• In general $\gamma = 3\alpha = \frac{3}{2}\beta$

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

We have $\Delta l = \alpha l \Delta T$

Also

$$\Delta V = (l\Delta l)^3 \quad l^3$$

$= l^3 + 3l^2\Delta l + 3l\Delta l^2 + \Delta l^2 \ l^3$

$= 3l^2\Delta l \ ...(1)$

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

So,

$$\Delta V = \frac{3V}{l}\Delta l$$

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

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

$$\gamma = 3\,\alpha$$

Similarly, we can prove for area expansion coefficient of thermal expansion is prevented inside the rod by rigidly fixing its ends, then the rod acquires a compressive strain due to external fones at the ends. The corresponding stress set up in the rod is called thermal stress.

Hence, thermal stress $= \frac{F}{A} = Y\left(L - L_0\right)/L_0$ where Y is Young's modulus of the given material.

This can be simplified into $Y(\alpha\Delta T)/L_0$.

Practical applications include railway tracks, metal tyres on cart wheels, bridges, and a variety of other structures.

1.4 Heat and Calorimetry

When two systems at different temperatures are linked together, heat flows from the higher temperature to the lower temperature until their temperatures become the same.

The principle of calorimetry states that heat lost by a body at higher temperature equals heat gained by a body at lower temperature, ignoring heat loss to surroundings.

When heat is applied to anybody, either its temperature or its state changes.

1.4.1 Change in temperature

On heating, when the temp changes, then

$$\text{Heat supplied} \propto \text{change in temp} (\Delta T)$$
$$\propto \text{amount of substance} \left(m / n\right)$$
$$\propto \text{nature of substance} \left(s / C\right)$$

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

Here,

m is the mass of body,

s is specific heat capacity per kg,

ΔT is change in temp

or $\Delta H = nC \Delta T$

Here, n is the number of moles, C is the Specific/Molar heat Capacity per mole, ΔT is the change in temp.

Specific Heat Capacity: The amount of heat needed to increase the temperature of a substance's unit mass by one degree.

Units

$$SI \rightarrow J / KgK \qquad S_{H_2O(e)} = 1 \text{ cal} / g^{\circ}C$$
$$\text{Common} \rightarrow Cal / g^{\circ}C \qquad S_{H_2O(ice)} = 0.5 \text{ cal} / g^{\circ}C$$

Molar Heat Capacity: The amount of heat required to raise the temperature of a unit mole of a substance by one degree.

Units

$SI \rightarrow J / mol\ K$

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

Heat Capacity: The amount of heat needed to raise a system's temperature by one degree.

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

where S is heat capacity.

Units

SI $\rightarrow$ J / K

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

• For H_2O, the specific heat capacity varies, but only slightly.

• Materials with a higher specific heat capacity require a large amount of heat for a given temperature.

1.4.2 Change in state

On heating, when the phase changes then the heat supplied is directly related to the amount of substance which changes the state (M) and the nature of substance (L)

H = mL

Where L is the latent Heat of process

• **Latent Heat:** The amount of heat required to change the state of any substance per mass.

Units

SI $\rightarrow$ J/Kg

Common $\rightarrow$ Cal/g

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

For example

Solid $\rightleftharpoons$ Liq $\quad L_f$

Liq $\rightleftharpoons$ Gas $\quad L_v$

L_f = Latent Heat of fusion

L_v = Latent heat of vaporization

• If a material is not at its B.P. or M.P, heating will cause the temperature to change until a specific state change temperature is reached.

For Example: If water is initially at $50\ ^{\circ}C$ at 1 atm pressure in its solid state, then on heating

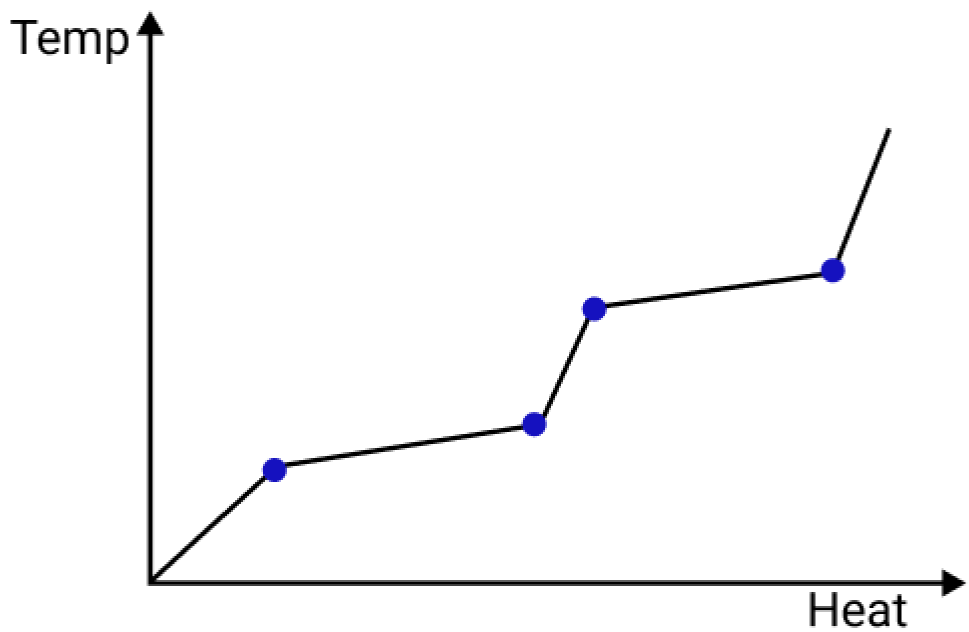
Step 1: Make a temperature change to the first to $0\ ^{\circ}C$

Step 2: The ice melts to $H_2O\ (l)$ while the temperature remains constant.

Step 3: The temperature is inverted to $100\ ^{\circ}C$.

Step 4: $H_2O\ (l)$ boils to steam while the temperature remains constant.

Step 5: Increase the temperature further.



Note: Recreated the above diagram.

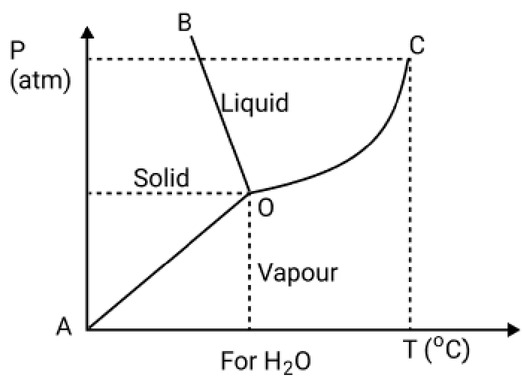
• The slope is inversely related to the heat capacity.

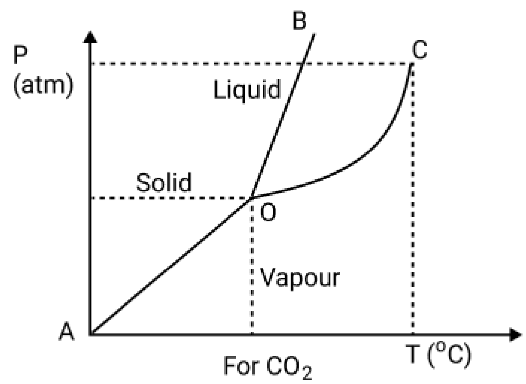
• The length of the horizontal line totally depends upon mL for the process.

1.4.3 Pressure dependence on melting point and boiling point

• Melting point decreases with increasing pressure for some substances and increases for others.

• Melting point increases with increasing temperature. The above results can be seen using phaser diagrams.





Line AO is the sublimation curve, line OB is the fusion curve, line OC is the vapourisation curve, point O is triple point, point C is critical temperature

Triple Point: The pressure and temperature combination at which all three states of matter (solids, liquids, and gases) coexist. Its value is 273.16 K and 0.006 atm for H_2O.

The combination of pressure and temperature beyond which a vapour cannot be liquified is referred to as the critical point. The corresponding temperature and pressure are referred to as the critical temperature and critical pressure.

• The phasor diagram shows that the melting point of H2O decreases as pressure increases. The concept of regulation is based on this.

• **Regulation:** The phenomenon of refreezing water that has melted below its normal melting point due to the addition of pressure. Cooking on mountains is difficult due to the pressure effect on melting point, whereas cooking in a pressure cooker is easier.

1.5 Heat Transfer

There are three modes of heat transfer.

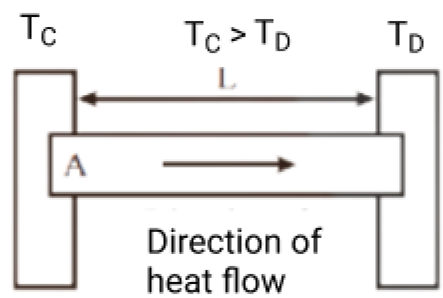
• Conduction

• Convection

• Radiation

1.5.1 Conduction

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



The rate of heat energy flowing through the rod becomes constant at steady state. It is given by,

$$Q = kA\frac{(T_C - T_D)}{L}$$

This is the rate for rods with a uniform cross-section.

Here, Q is rate of heat energy flow, A is area of cross-section, T_C and T_D are temperature of hot end and cold end respectively, L is length of the rod, K is coefficient of thermal conductivity.

Some of the examples of conduction which we experience in our day to day life are being burnt after touching a stove. Your hand is being cooled with ice. By putting a red-hot piece of iron into the water, it is brought to a boil.

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

Units

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

• The greater the thermal conductivity, the faster heat energy flows for a given temperature difference.

• Metals have higher thermal conductivity than nonmetals.

• Insulators have a very low thermal conductivity. As a result, heat energy cannot be easily conducted through air.

• The concept of equivalent thermal conductivity of the composite rod can be used for combinations of rods between two ends kept at different temperatures.

K_{eq} is the equivalent thermal conductivity of the composite.

• The term $\frac{(T_C - T_D)}{L}$ is known as temperature Gradient.

Temperature Gradient: Temperature Gradient refers to the decrease in temperature per unit length in the direction of heat energy flow.

Units SI $\rightarrow$ K/m

• The term Q is the rate of flow of heat energy can also be named as heat current

• The term (L / KA) is known as thermal resistance of any conducting rod.

Thermal Resistance: It is defined as the medium's obstruction of the flow of heat current.

Units SI $\rightarrow$ K/W

1.5.2 Convection:

Thermal convection is the process by which heat is transferred from one point to another by the actual movement of heated material particles from a higher temperature location to a lower temperature location.

• Forced convection occurs when the medium is forced to move by means of a fan or a pump. Natural or free convection occurs when a material moves due to differences in density in the medium.

• Examples of forced convection are circulatory system, cooling system, and heat connector of an automobile

• Examples of natural convection are trade winds, sea breeze/land breeze, monsoons, and tea burning.

1.5.3 Radiation

It is a method of heat transmission in which heat travels directly from one location to another without the use of an intermediary medium.

• This radiation of heat energy takes the form of EM waves.

• These radiators are emitted as a result of their temperature, similar to how a red-hot iron or a filament lamp emits light.

• Everybody both radiates and absorbs energy from its surroundings. The amount of energy absorbed is proportional to the color of the body.

•Black-body radiation is the thermal electromagnetic radiation emitted by a black body within or surrounding a body in thermodynamic equilibrium with its environment (an idealized opaque, non-reflective body). It has a specific spectrum of wavelengths that are inversely related to intensity and are only affected by the body's temperature, which is assumed to be uniform and constant for the sake of calculations and theory.

Stefan’s Law of Radiation:

Stefan's Law states that the radiated power density of a black body is directly related to its absolute temperature T raised to the fourth power.

Newton's Law of cooling:

According to Newton’s Law of cooling, the rate of loss of heat, that is, $-\frac{d}{dt}$ of the body is directly related to the temp difference.

Now,

$$-\frac{ds}{dt} = k\left(T_2 - T_1\right) \qquad \cdots\cdots(4)$$

Here, k is a positive constant which depends on the 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 temperature of surroundings if dT_2 the fall of temperature in time dt.

The amount of heat lost is given by,

$$dcs = msdT_2$$

Therefore, the rate of loss of heat is given by

$$\frac{dcs}{dt} = ms\frac{dT_2}{dt} \qquad \cdots\cdots(5)$$

From Equation 4 and 5

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

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

$$= -Kdt$$

Here,

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

On integrating,

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

$$T_2 = T_1 + C_1e^{-kt} \qquad \cdots\cdots(6)$$

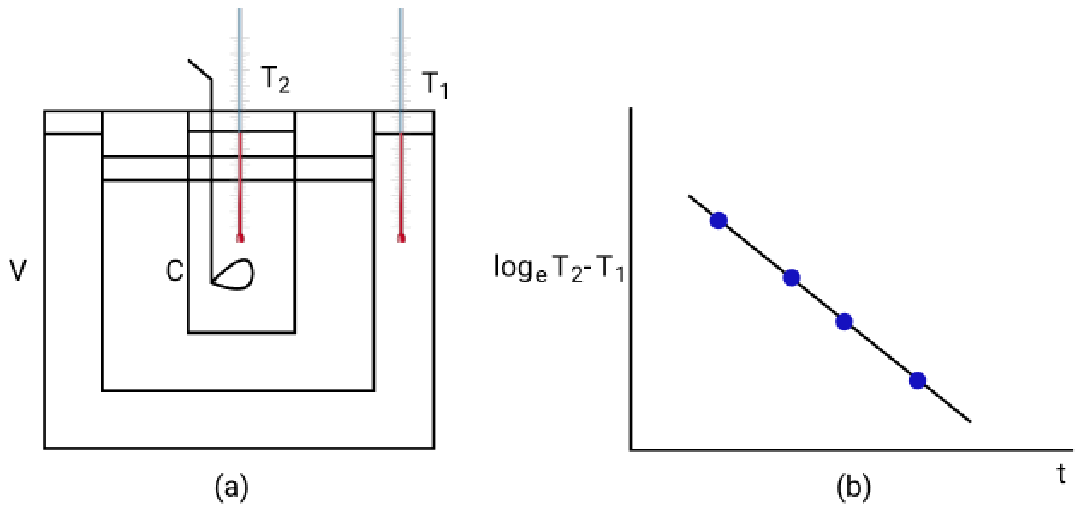
The equation (6) allows us to calculate the time it takes a body to cool through a given temperature range.

• For small temperature differences, the rate of cooling due to conduction, convection, and radiation combined is proportional to the temperature difference.

• Approximation: If a body cools from T_a to T_b in t times in a medium with a temperature of T_0, then

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

• Newton's law of cooling can be studied experimentally.



Configuration: A double-walled vessel (v) with water contained between two walls.

Inside the double-walled vessel is a copper calorimeter (c) containing hot water. Two thermometers threaded through the carbs are used to measure the temperature T_2 of H_2O in the calorimeter T of water in between the double walls.

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

As a result, A line graph is drawn between log $\left(T_2\ T_1\right)$ and time (t). The graph is observed to be a straight line, as predicted by Newton's law of cooling.