

CHAPTER

10

Thermal Properties of Matter

Temperature and Thermal Expansion • Calorimetry and Change of State
• Heat Transfer

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
NOTESSHALA.IN • cm

What's inside

1	Temperature and Thermal Expansion	2	2	2	Calorimetry and Change of State	14
1.1	Temperature and Heat	2	2.1	Heat Capacity and Specific Heats	14	
1.2	Caloric and Dynamic Theory of Heat	3	2.2	Calorimetry and Calorimeter	16	
1.3	Measurement of Temperature	4	2.3	Change of State	18	
1.4	Constant-Volume Gas and Platinum Resistance Thermometers	6	2.4	Terms Related to Change of State	19	
1.5	Ideal Gas Equation	6	2.5	Triple Point	20	
1.6	Absolute Zero Temperature	7	2.6	Latent Heat	21	
1.7	Thermal Expansion	8	2.7	Mechanical Equivalent of Heat	22	
1.8	Linear Expansion	9	3	Heat Transfer	22	
1.9	Area Expansion	9	3.1	Modes of Heat Transfer	22	
1.10	Volume Expansion	10	3.2	Conduction and Thermal Conductivity	23	
1.11	Relation Among the Coefficients of Expansion	11	3.3	Heat Current and Thermal Resistance	24	
1.12	Anomalous Expansion of Water	12	3.4	Rods in Series and in Parallel	25	
1.13	Expansion of Solids, Liquids and Gases	12	3.5	Convection	26	
1.14	Thermal Strain and Thermal Stress	13	3.6	Radiation	28	
			3.7	Absorptive Power and Emissivity	29	
			3.8	Stefan-Boltzmann Law	29	
			3.9	Wien's Displacement Law	30	
			3.10	Newton's Law of Cooling	30	

READING KEY

DEFINITION

NOTE

REMEMBER

DERIVATION

STRATEGY

Formulas sit on graph paper • coloured words are the key terms

We all have a common-sense idea of **hot** and **cold**. When a body gets **heat**, its **size** or its **physical state** may change. These changes follow definite laws. All the properties of matter that change because of heat are called its **thermal properties**. This chapter covers **heat**, how heat is **measured** and how heat **moves** from one place to another.

1.1 Temperature and Heat

• TEMPERATURE

DEFINITION

Temperature is the **degree of hotness or coldness** of a body. It tells how hot or cold the body is. Temperature is always a **relative measure**.

Take two bodies at temperatures T_1 and T_2 , with $T_1 > T_2$.

i Body at T_1

It is the **hotter body** of the two.

ii Body at T_2

It is the **colder body** of the two.

NOTE

When a body is **heated**, it may **expand**. Its **physical state** may also change.

• HEAT

DEFINITION

Heat is the form of **energy** that flows from a **hotter body** to a **colder body** because of the **temperature difference** between them.

Heat transfer is a **non-mechanical process**. No mechanical work is done when heat flows.

Hotter body (T_1) → heat flows → Colder body (T_2)

SI unit of heat

joule (J)

CGS unit of heat (widely used)

calorie (cal)

Relation between the two units

1 cal = 4.2 J

DEFINITION

One Calorie

One calorie is the heat required to warm **1 g of water** by **1 °C**, from **14.5 °C to 15.5 °C**.

1.2 Caloric and Dynamic Theory of Heat

● CALORIC THEORY OF HEAT

This old theory treats heat as a **fluid** called **caloric**. Caloric was thought to be **invisible**, **weightless** and **odourless**.

Caloric is **added** to a body

Temperature rises ↑

Caloric is **taken out** of a body

Temperature falls ↓

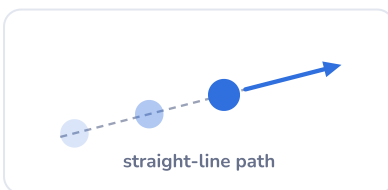
● DYNAMIC THEORY OF HEAT

Every substance is made of **molecules**. This is true for **solids**, **liquids** and **gases**. The molecules are always in **continuous random motion**.

A molecule can have **three types of motion**. Which types it has depends on the **nature** and the **temperature** of the substance.

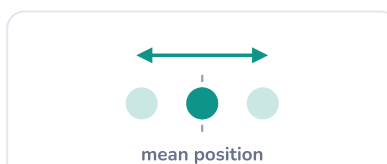
i Translatory Motion

The molecule moves along a **straight line**. It is common in **gases**.



ii Vibrational Motion

The molecule moves **to and fro** about its **mean position**. It is the main motion in **solids**. It also occurs in **liquids** and **gases**.



iii Rotational Motion

The molecule **spins about its own axis**. This motion usually occurs at **high temperature**.



NOTE

Each type of motion gives **kinetic energy** to the molecules. The **heat of a body** is its **total thermal energy**. It is the **sum of the kinetic energies** of all its molecules, due to their **translational**, **vibrational** and **rotational** motion.

1.3 Measurement of Temperature

Temperature is a **fundamental physical quantity**, so we need to measure it. It is measured on fixed **scales**.

DEFINITION

Thermometer

A **thermometer** is an instrument that measures temperature. It is **calibrated**, so that each temperature gets a **number**.

Temperature is measured in these units:

K kelvin (SI unit)

°C degree Celsius (centigrade)

°F degree Fahrenheit

Many **physical properties** of materials change enough with temperature. Such a property can be used to **make a thermometer**. The common ones are:

- ◆ change in the **volume of a liquid** with temperature
- ◆ change in the **pressure or volume of a gas** with temperature
- ◆ change in the **resistance of a metal** with temperature
- ◆ change in the **thermo-emf** of a **thermocouple junction** with temperature, etc.

NOTE

Fixed Reference Points

Every standard scale needs **two reference points**. For water, these are the **ice point** and the **steam point**. At these points pure water **freezes** and **boils**, under **standard pressure**.

Fahrenheit Scale

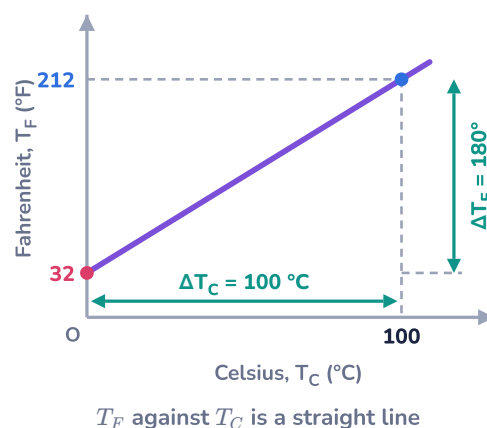
Ice point **32 °F**, steam point **212 °F**. The gap is split into **180 equal parts**.

Celsius Scale

Ice point **0 °C**, steam point **100 °C**. The gap is split into **100 equal parts**.

Plot the Fahrenheit temperature T_F against the Celsius temperature T_C . The graph is a **straight line**.

A change of **100 °C** on the Celsius scale is the same as a change of **180 °F** on the Fahrenheit scale. So $\Delta T_F = 180^\circ$ when $\Delta T_C = 100^\circ$.



$$T_F = \frac{9}{5} T_C + 32$$

NOTE

Kelvin and Celsius

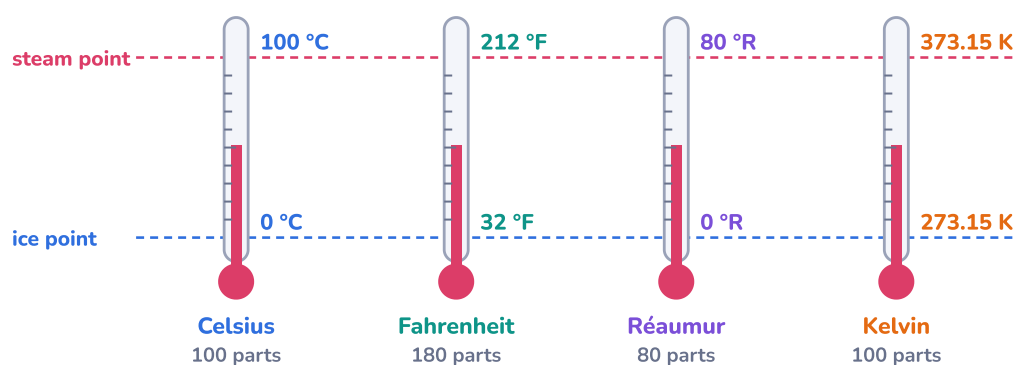
One **kelvin** and one **Celsius degree** have the **same size**. So the two scales differ only by a fixed number:

$$T_K = T_C + 273.15$$

• DIFFERENT SCALES TO MEASURE TEMPERATURE

S.NO.	SCALE	UNIT	ICE POINT (LOWER FIXED POINT)	STEAM POINT (UPPER FIXED POINT)
1.	Celsius scale	degree Celsius (°C)	0 °C	100 °C
2.	Fahrenheit scale	degree Fahrenheit (°F)	32 °F	212 °F
3.	Réaumur scale	degree Réaumur (°R)	0 °R	80 °R
4.	Kelvin scale	kelvin (K)	273.15 K	373.15 K

• RELATION AMONG THE DIFFERENT SCALES



The same two fixed points read on the four scales

RELATION AMONG THE SCALES

$$\frac{C - 0}{100} = \frac{F - 32}{180} = \frac{R - 0}{80} = \frac{K - 273.15}{100}$$

where, C , F , R and K are the readings of the same temperature on the Celsius, Fahrenheit, Réaumur and Kelvin scales.

1.4 Constant-Volume Gas and Platinum Resistance Thermometers

• CONSTANT-VOLUME GAS THERMOMETER

The **volume of the gas is kept constant**. Its pressure is noted at four temperatures:

p_0 at 0°C

p_{100} at 100°C

p_{tr} at the triple point of water

p at the unknown temperature t

UNKNOWN TEMPERATURE IN $^\circ\text{C}$

$$t = \left(\frac{p - p_0}{p_{100} - p_0} \times 100 \right) ^\circ\text{C}$$

IN KELVIN

$$T = \left(273.16 \frac{p}{p_{tr}} \right) \text{K}$$

• PLATINUM RESISTANCE THERMOMETER

Here the **resistance of a platinum wire** is noted at four temperatures:

R_0 at 0°C

R_{100} at 100°C

R_{tr} at the triple point of water

R_t at the unknown temperature t

UNKNOWN TEMPERATURE IN $^\circ\text{C}$

$$t = \left(\frac{R_t - R_0}{R_{100} - R_0} \times 100 \right) ^\circ\text{C}$$

IN KELVIN

$$T = \frac{R_t}{R_{tr}} T_{tr} = \left(273.16 \frac{R_t}{R_{tr}} \right) \text{K}$$

1.5 Ideal Gas Equation

i Liquid-in-Glass Thermometer

Different liquids **expand differently**. So two such thermometers give **different readings**, except at the fixed points.

ii Gas Thermometer

It gives the **same reading**, no matter **which gas** is used.

At **low density**, all gases **expand in the same way**. Three quantities describe the behaviour of a gas:

p pressure

V volume

T temperature

LAW

Boyle's Law

At **constant temperature**, the pressure of a given mass of gas is **inversely proportional** to its volume. So $p \propto 1/V$, that is, $pV = \text{constant}$.

Given by the English chemist Robert Boyle (1627–1691).

LAW

Charles' Law

At **constant pressure**, the volume of a given mass of gas is **directly proportional** to its temperature. So $V \propto T$, that is, $V/T = \text{constant}$.

Given by the French scientist Jacques Charles (1747–1823).

$$\text{Boyle's law} + \text{Charles' law} \rightarrow \frac{pV}{T} = \text{constant (for a given amount of gas)}$$

This relation is called the **ideal gas law**. For a given amount of gas, its general form is:

IDEAL GAS EQUATION

$$pV = \mu RT$$

where, μ = number of moles of the gas, R = universal gas constant = $8.31 \text{ J mol}^{-1} \text{ K}^{-1}$

NOTE

The ideal gas equation gives $pV \propto T$. If the **volume is kept constant**, then $p \propto T$. That is why a gas can measure temperature in a **constant-volume gas thermometer**.

1.6 Absolute Zero Temperature

DEFINITION

There is **no upper limit** to temperature. But there is a **sharp lower limit**. No body can be colder than this lowest temperature. It is called **absolute zero temperature**.

Maximum temperature

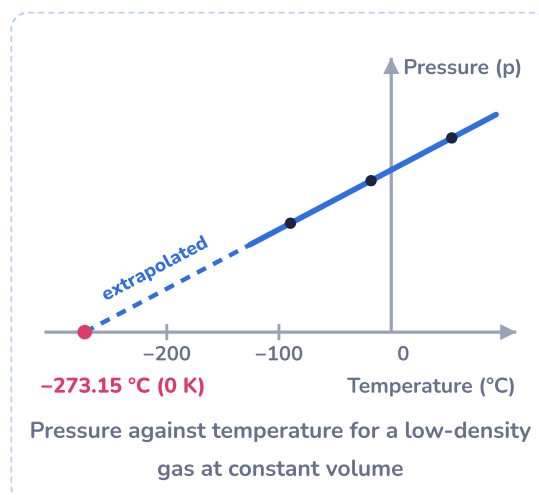
No limit

Minimum temperature

A sharp limit: absolute zero

• ABSOLUTE ZERO FROM THE P-T GRAPH

- ◆ Keep a **low-density gas** at **constant volume**. Plot its **pressure p** against its **temperature** in $^{\circ}\text{C}$.
- ◆ Extend the straight line backwards (**extrapolate** it). It meets the temperature axis at **-273.15°C** .
- ◆ The British scientist **Lord Kelvin** named this temperature **absolute zero**. It is written as **0 A** or **0 K**.
- ◆ At this temperature, the **pressure and volume of the gas would become zero**.



DEFINITION**Absolute Zero of Temperature**

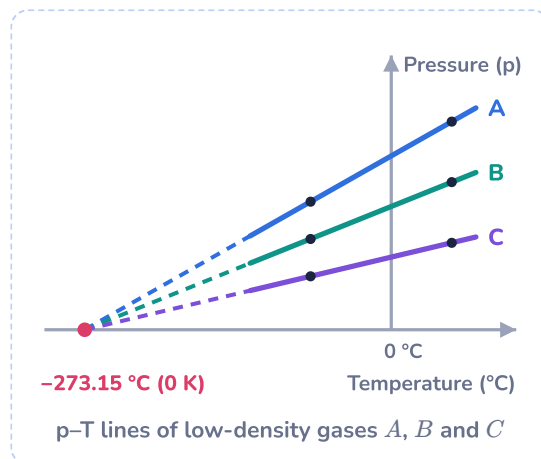
Absolute zero is the lowest temperature, $-273.15\text{ }^{\circ}\text{C}$. At this temperature a gas would have **zero volume** (or **zero pressure**), and **all molecular motion stops**.

REMEMBER**Why Is It the Lowest?**

Imagine a temperature **below** absolute zero. The volume of the gas would then be **negative**, which is **impossible**. So absolute zero is the **lowest temperature that can exist**.

Repeat the experiment with **different low-density gases** *A*, *B* and *C*. Each gas gives a straight line with its own slope.

When extended, **all the lines meet the temperature axis at the same point**, $-273.15\text{ }^{\circ}\text{C}$. So every gas gives the **same absolute zero**.



$$\text{Absolute zero} = 0\text{ K} = -273.15\text{ }^{\circ}\text{C} \Rightarrow 0\text{ }^{\circ}\text{C} = 273.15\text{ K}$$

Absolute Temperature

A temperature measured on the **Kelvin scale** is called the **absolute temperature**.

Absolute Scale

The **Kelvin scale itself** is called the **absolute scale**.

1.7 Thermal Expansion**EXAMPLE**

The **metal lid** of a glass bottle is sometimes screwed on very tightly. To open it, we dip the lid in **hot water** for a while. The metal lid **expands** and becomes loose. Now it unscrews easily.

Tight metal lid → dipped in hot water → lid expands → opens easily

So, when a material gets **heat**, its temperature rises. Then its **length**, **area** and **volume** can change.

DEFINITION

Thermal expansion is the change in the **size (dimensions)** of a body when it is **heated**.

Thermal expansion is of **three types**:

i Linear Expansion

Increase in **length**.

ii Area (Superficial) Expansion

Increase in **area**.

iii Volume (Cubical) Expansion

Increase in **volume**.

1.8 Linear Expansion

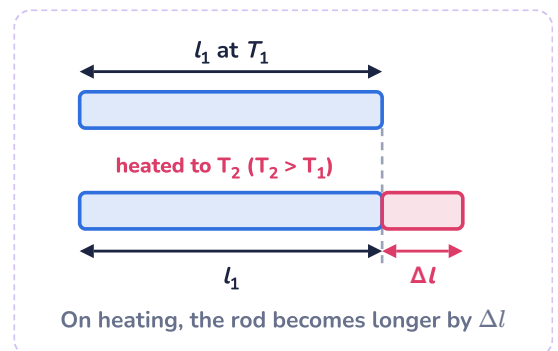
DEFINITION

Linear expansion is the **increase in the length** of a body when its **temperature rises**.

A rod has length l_1 at temperature T_1 . On heating to T_2 , its length becomes l_2 . The **fractional change in length** is:

$$\frac{\Delta l}{l_1} = \frac{l_2 - l_1}{l_1} = \alpha_l (T_2 - T_1) = \alpha_l \Delta T$$

The increase in length is proportional to the **original length**. It is also proportional to the **rise in temperature**.



$$\Delta l \propto l_1 \text{ and } \Delta l \propto \Delta T \Rightarrow \Delta l \propto l_1 \Delta T$$

EXPANSION IN LENGTH

$$\Delta l = \alpha_l l_1 \Delta T$$

where, α_l = coefficient of linear expansion, l_1 = original length, ΔT = rise in temperature

DEFINITION

Coefficient of Linear Expansion

The **coefficient of linear expansion** (α_l) of a solid is the **change in length of a rod of unit length** when its temperature **rises by one degree**. It is measured in **°C⁻¹ or K⁻¹**.

$$\alpha_l = \frac{\Delta l}{l_1 \Delta T} = \frac{\text{Increase in length}}{\text{Original length} \times \text{Rise in temperature}}$$

α_l depends on the **material** of the rod. **Metals expand more.**

Metals: high α_l

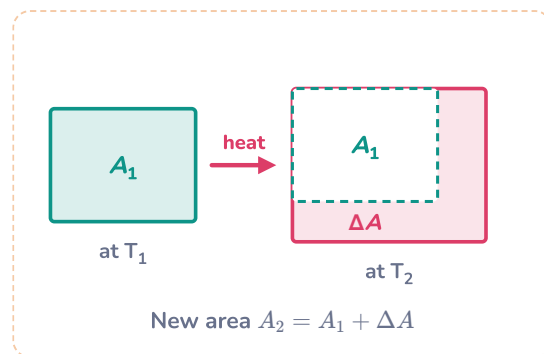
1.9 Area Expansion

DEFINITION

Area expansion is the **increase in the area** of a surface when its **temperature rises**.

A plate has area A_1 at temperature T_1 . On heating to T_2 , its area becomes A_2 . The **fractional change in area** is:

$$\frac{\Delta A}{A_1} = \frac{A_2 - A_1}{A_1} = \alpha_A (T_2 - T_1) = \alpha_A \Delta T$$



$$\Delta A \propto A_1 \text{ and } \Delta A \propto \Delta T \Rightarrow \Delta A \propto A_1 \Delta T$$

EXPANSION IN AREA

$$\Delta A = \alpha_A A_1 \Delta T$$

where, α_A = coefficient of area expansion. It depends on the nature of the material of the plate.

DEFINITION

Coefficient of Area Expansion

The **coefficient of area expansion** (α_A) of a metal sheet is the **change in area of a sheet of unit area** when its temperature **rises by one degree**. It is measured in $^{\circ}\text{C}^{-1}$ or K^{-1} .

$$\alpha_A = \frac{\Delta A}{A_1 \Delta T} = \frac{\text{Increase in surface area}}{\text{Original surface area} \times \text{Rise in temperature}}$$

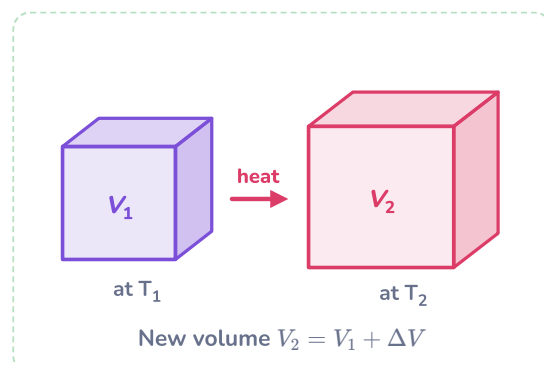
1.10 Volume Expansion

DEFINITION

Volume expansion is the **increase in the volume** of a body when its **temperature rises**.

A body has volume V_1 at temperature T_1 . On heating to T_2 , its volume becomes V_2 . The **fractional change in volume** is:

$$\frac{\Delta V}{V_1} = \frac{V_2 - V_1}{V_1} = \alpha_V (T_2 - T_1) = \alpha_V \Delta T$$



$$\Delta V \propto V_1 \text{ and } \Delta V \propto \Delta T \Rightarrow \Delta V \propto V_1 \Delta T$$

EXPANSION IN VOLUME

$$\Delta V = \alpha_V V_1 \Delta T$$

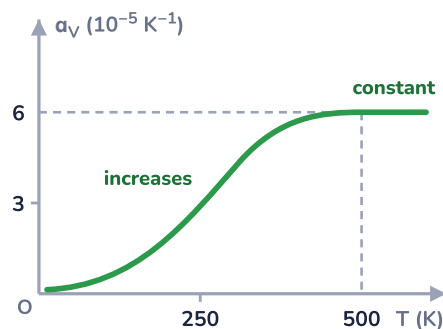
where, α_V = coefficient of volume expansion, so that $\alpha_V = \frac{\Delta V}{V_1 \Delta T}$

DEFINITION

Coefficient of Volume Expansion

The **coefficient of volume (cubical) expansion** (α_V) of a substance is the **change in volume of a body of unit volume** when its temperature **risks by one degree**. It is measured in $^{\circ}\text{C}^{-1}$ or K^{-1} .

- ◆ α_V is a **property of the material**. But it is **not strictly a constant**.
- ◆ In general, α_V **depends on temperature**. The graph shows this for **copper**.
- ◆ Its value first **increases** with temperature.
- ◆ It becomes **constant** at high temperature, above about **500 K**.



α_V of copper against temperature

NOTE

All coefficients of expansion have the **dimension** $[\text{K}^{-1}]$. Their **SI unit** is **per kelvin** (K^{-1}).

1.11 Relation Among the Coefficients of Expansion

Write the original size simply as l , A or V (that is, $l_1 = l$, $A_1 = A$ and $V_1 = V$). Then the three coefficients are:

LINEAR

$$\alpha_l = \frac{\Delta l}{l_1 \Delta T} = \frac{\Delta l}{l \Delta T}$$

AREA

$$\alpha_A = \frac{\Delta A}{A_1 \Delta T} = \frac{\Delta A}{A \Delta T}$$

VOLUME

$$\alpha_V = \frac{\Delta V}{V_1 \Delta T} = \frac{\Delta V}{V \Delta T}$$

RATIO OF THE COEFFICIENTS

$$\alpha_l : \alpha_A : \alpha_V = 1 : 2 : 3$$

So, $\alpha_A = 2\alpha_l$ and $\alpha_V = 3\alpha_l$

• COEFFICIENTS OF EXPANSION AT HIGH TEMPERATURE

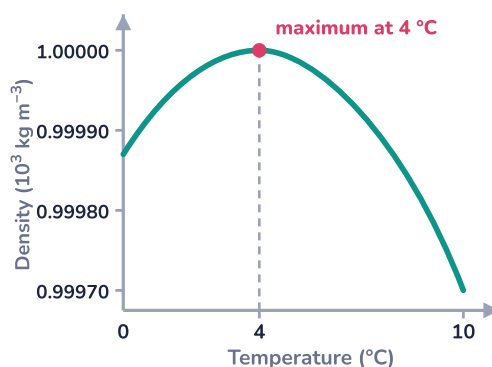
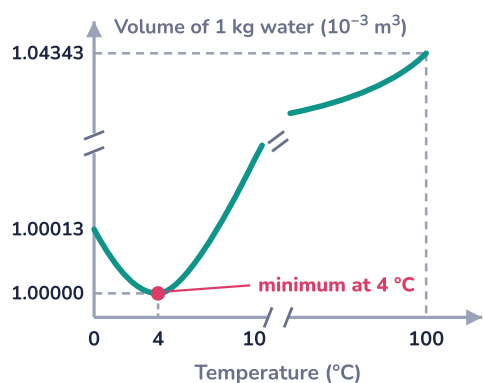
For a given solid, α_l , α_A and α_V are **constant only at a given temperature**.

When the **temperature range** changes

Their values change

1.12 Anomalous Expansion of Water

- Water behaves in an **unusual (anomalous)** way. Between **0 °C and 4 °C**, it **contracts on heating**.
- Cool some water below room temperature. Its **volume decreases** until it reaches **4 °C**.
- Below 4 °C**, its volume **increases**. So its **density decreases**.
- The second graph shows the **density of water** from **0 °C to 10 °C**. The density is **maximum at 4 °C**. It falls on both sides of 4 °C.



At 4 °C, water has **maximum density** and **minimum volume**

NOTE

A Lake in Winter

In winter, a lake cools towards **4 °C**. The surface water gives heat to the air. It becomes **denser and sinks**. The **warmer, lighter water** from the bottom rises up.

When the top water cools **below 4 °C**, it becomes **less dense**. So it stays at the **surface** and **freezes** there. The water below stays liquid. This lets **water animals stay alive** and move freely near the bottom.

1.13 Expansion of Solids, Liquids and Gases

i Solids and Liquids

At ordinary temperature, they expand **very little** compared with gases.

ii Liquids

For a liquid, α_V is **nearly independent of temperature**.

DERIVATION

Volume Expansion of an Ideal Gas

Keep the **pressure constant**. Start from the ideal gas equation:

1

$$pV = \mu RT \Rightarrow p \Delta V = \mu R \Delta T$$

2

Dividing by $pV = \mu RT$: $\frac{\Delta V}{V} = \frac{\Delta T}{T}$

FOR AN IDEAL GAS

$$\frac{\Delta V}{V} = \frac{\Delta T}{T} \Rightarrow \alpha_V = \frac{1}{T}$$

At **0 °C**, $\alpha_V = 3.7 \times 10^{-3} \text{ K}^{-1}$. This is far larger than for solids and liquids.

Gas » solid, liquid

A gas at **room temperature** and **constant pressure**

$$\alpha_V \approx 3300 \times 10^{-6} \text{ K}^{-1}$$

1.14 Thermal Strain and Thermal Stress

Fix both ends of a metal rod **rigidly**, so that it cannot expand or contract. Now change its temperature.

Thermal strain and **thermal stress** develop in the rod.

Why? When the temperature rises, the rod **tries to expand**. But both its ends are fixed. So the rod **pushes on the supports** with a force.

Temperature rises → rod tries to expand → ends are fixed → force on supports

DERIVATION

Let a rod of length l be heated through ΔT . If it were free, its length would increase by:

1

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

2

The ends are fixed, so the rod cannot expand. A **compressive thermal strain** develops in it:

$$\text{Thermal strain} = \frac{\Delta l}{l} = \alpha \Delta T$$

3

This strain produces a **thermal stress**:

$$\text{Thermal stress} = Y \times \text{thermal strain} = Y \alpha \Delta T$$

THERMAL (COMPRESSIVE) STRAIN

$$\text{Strain} = \frac{\Delta l}{l} = \alpha \Delta T$$

where, α = coefficient of linear expansion of the rod's material

THERMAL STRESS

$$\text{Stress} = Y \alpha \Delta T$$

where, Y = Young's modulus of the rod's material

Force exerted by the rod on the supports. Here A is the **area of cross-section** of the rod.

$$F = Y \alpha \Delta T A$$

$$\text{Strain} = \alpha \Delta T \times Y \rightarrow \text{Stress} = Y \alpha \Delta T \times A \rightarrow \text{Force} = Y \alpha \Delta T A$$

02

PART 2

Calorimetry and Change of State

2.1 Heat Capacity and Specific Heats

The heat needed to change the temperature of a substance **depends on** three things:

m mass

ΔT change in temperature

nature of the substance

A substance **absorbs** or **gives out** heat when its temperature changes. A quantity called **heat capacity** describes this.

DEFINITION

Heat Capacity

The **heat capacity** (S) of a body is the **amount of heat needed to change its temperature by one unit** (1 °C or 1 K). Its SI unit is **J K⁻¹**.

HEAT CAPACITY

$$S = \frac{\Delta Q}{\Delta T}$$

where, ΔQ = heat absorbed or given out by the body, ΔT = change in its temperature

Dimensional formula of heat capacity

$$[ML^2T^{-2}K^{-1}]$$

DEFINITION

Water Equivalent

The **water equivalent** of a body is the **mass of water** that has the **same heat capacity** as the body. Its unit is the **gram**.

• SPECIFIC HEAT CAPACITY

DEFINITION

The **specific heat capacity** (or **specific heat**) (s) of a substance is the **heat required to increase the temperature of unit mass (1 kg) of it by one unit (1 K)**. Its SI unit is $\text{J kg}^{-1} \text{K}^{-1}$.

SPECIFIC HEAT CAPACITY

$$s = \frac{S}{m} = \frac{1}{m} \frac{\Delta Q}{\Delta T}$$

where, m = mass of the substance, S = its heat capacity, ΔQ = heat given, ΔT = rise in temperature

NOTE

Water Has a Very High Specific Heat

Water has the **highest specific heat capacity** among common substances, $4.18 \times 10^3 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$. So water is used:

- ◆ as a **coolant** in **car radiators**, and
- ◆ as a **heater** in **hot-water bags**.

• MOLAR SPECIFIC HEAT CAPACITY

DEFINITION

The **molar specific heat capacity** (C) of a substance (gas) is the **heat required to increase the temperature of 1 mole of it by one unit (1 K)**. Its SI unit is $\text{J mol}^{-1} \text{K}^{-1}$.

MOLAR SPECIFIC HEAT CAPACITY

$$C = \frac{S}{\mu} = \frac{\Delta Q}{\mu \Delta T}$$

where, μ = number of moles of the substance (gas)

• RELATION BETWEEN SPECIFIC HEAT AND MOLAR SPECIFIC HEAT

DERIVATION

Number of moles $\mu = \frac{m}{M}$. Here m is the mass of the substance and M is its molecular mass. So $m = \mu M$.

- 1 Put $\mu = \frac{m}{M}$ in the formula for C :

$$C = \frac{1}{\mu} \left[\frac{\Delta Q}{\Delta T} \right] = M \left[\frac{\Delta Q}{m \Delta T} \right]$$

2 But $\frac{\Delta Q}{m \Delta T} = s$, the specific heat capacity. So:

$$C = Ms$$

RELATION

$$C = Ms$$

So C equals the molecular mass M multiplied by the specific heat s .

• TYPES OF MOLAR SPECIFIC HEAT CAPACITY

i At Constant Pressure, C_p

The heat needed to raise the temperature of **1 mole of a gas** by **one unit**, at **constant pressure**.

ii At Constant Volume, C_v

The heat needed to raise the temperature of **1 mole of a gas** by **1 °C**, at **constant volume**.

NOTE

Both kinds of heat capacity are very useful in **calorimetry**.

2.2 Calorimetry and Calorimeter

DEFINITION

Calorimetry is the branch of physics in which we **measure heat**.

Put a **hot body** in contact with a **cold body**. Heat flows from the hot body to the cold body. It keeps flowing until **both bodies reach the same temperature**.

Body at higher temperature → heat → Body at lower temperature • until both temperatures are equal

PRINCIPLE

Principle of Calorimetry

The **total heat given out by the hotter body** is equal to the **total heat taken in by the colder body**.

$$\text{Heat lost by the hotter body} = \text{Heat gained by the colder body}$$

Let body 1 (hotter) have mass m_1 and specific heat s_1 . Let body 2 (colder) have mass m_2 and specific heat s_2 . Then:

PRINCIPLE OF CALORIMETRY

$$m_1 s_1 \Delta T_1 = m_2 s_2 \Delta T_2$$

where, ΔT_1 = fall in temperature of the hot body, ΔT_2 = rise in temperature of the cold body

NOTE

Isolated System

A system is **isolated** when **no heat is exchanged** between the system and its **surroundings**. In calorimetry, we assume that **no heat escapes** to the surroundings.

• CALORIMETER

DEFINITION

A **calorimeter** is a device used to **measure quantities of heat**.

• CONSTRUCTION

- 1 It has a **cylindrical copper vessel** with a **stirrer**.
- 2 The vessel sits inside a **wooden jacket**. The gap between them is packed with a **heat-insulating material** such as **glass wool**. So the calorimeter is **thermally isolated** from the surroundings.
- 3 The **lid** has **holes**. A **thermometer** and the **stirrer** go into the vessel through them.

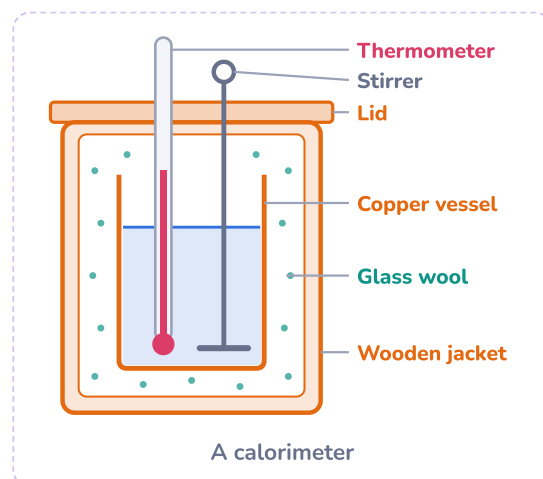
NOTE

Less Heat Lost by Radiation

Heat lost by **radiation** is cut down further by **polishing** two surfaces:

- ◆ the **outer surface** of the calorimeter, and
- ◆ the **inner surface** of the jacket.

Bodies at **different temperatures** are mixed in the calorimeter. Heat is exchanged among the **bodies** and also with the **calorimeter**. If no heat is lost to the surroundings, the principle of calorimetry gives:



Heat gained by the cold bodies = Heat lost by the hot bodies

2.3 Change of State

DEFINITION

Change of state is the process in which a substance changes from **one state to another**.

Matter usually exists in **three states**:

i Solid

e.g. ice

ii Liquid

e.g. water

iii Gas

e.g. steam

A substance can change from one state to another by **taking in heat** or **giving out heat**. The common changes of state are:

(i) Solid to liquid, and back

Solid $\rightleftharpoons$ Liquid

(ii) Liquid to gas, and back

Liquid $\rightleftharpoons$ Gas

These changes happen when **heat is exchanged** between the substance and its **surroundings**.

NOTE

Plasma, the Fourth State of Matter

Besides solid, liquid and gas, there is a **fourth state of matter**. It is called **plasma**.

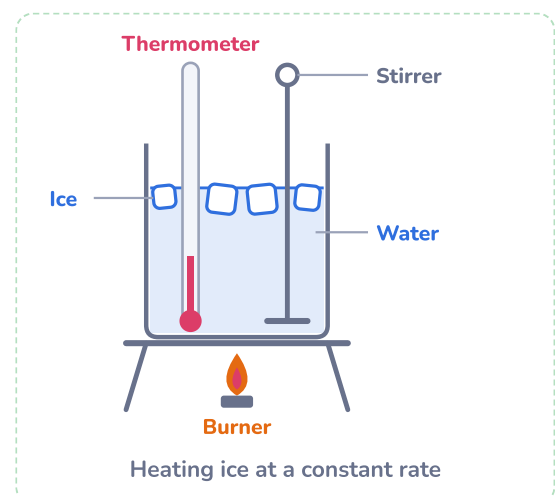
Heat a substance to a **very high temperature**. Many **electrons** of its atoms become **free** from the nucleus. The free electrons and the **positive ions** together form plasma.

Heat to a very high temperature → electrons set free → plasma

● EFFECT OF HEAT ON ICE

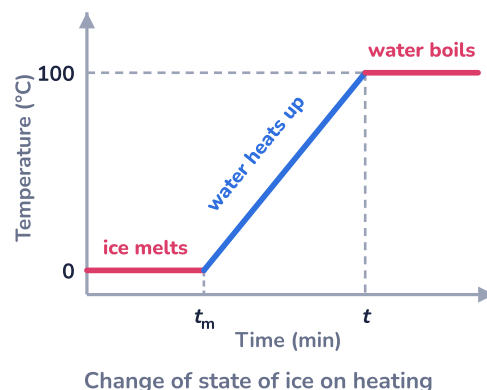
● EXPERIMENT

- ◆ Put a few **ice cubes at 0 °C** in a beaker. Heat them **slowly** on a source that gives heat at a **constant rate**.
- ◆ **Stir** the mixture of ice and water all the time. Note the **temperature every minute**.



OBSERVATIONS

- ◆ The **temperature–time graph** looks like the one shown.
- ◆ Heat is supplied all the time. Yet the temperature **does not change** as long as there is **ice in the beaker**.
- ◆ The temperature stays **constant** until **all the ice has melted**.
- ◆ So, during melting, the **solid and liquid states** exist together in **thermal equilibrium**.



- ◆ After **all the ice has melted**, keep heating. The temperature now **starts to rise**. It rises until it reaches about **100 °C**. Then it becomes **steady** again. This happens at time t on the graph.
- ◆ The heat now changes the water from **liquid to vapour**. The temperature stays **constant** until **all the water has turned into vapour**.

Ice (0 °C) → melts → Water → warms up → Water (100 °C) → boils → Steam

NOTE

With a **constant supply of heat**, a change of state takes place with **no change in temperature**.

2.4 Terms Related to Change of State

i Melting and Melting Point

The change from **solid to liquid** is called **melting**. The temperature at which a solid starts to turn into liquid is its **melting point**.

ii Fusion and Freezing Point

The change from **liquid to solid** is called **fusion** (freezing). The temperature at which a liquid starts to freeze is its **freezing point**.

iii Vaporisation and Boiling Point

The change from **liquid to vapour (gas)** is called **vaporisation**. During this change, the temperature stays **constant**. The liquid and vapour exist together in **thermal equilibrium**. This temperature is the **boiling point** of the liquid.

iv Sublimation

The change from **solid directly to vapour** is called **sublimation**. The substance does **not pass through the liquid state**. **e.g.** camphor, naphthalene balls.

DEFINITION

Normal Melting Point

The **normal melting point** of a substance is its melting point at **standard atmospheric pressure**.

• EFFECT OF PRESSURE ON THE BOILING POINT OF A LIQUID

When the **pressure increases**, the boiling point of a liquid

Increases ↑

Water at 1 atm

Boiling point = **100 °C**

Water at 2 atm

Boiling point = **128 °C**

2.5 Triple Point

The temperature of a substance stays **constant** during a **change of state (phase change)**.

DEFINITION

Phase Diagram

A graph between the **temperature and the pressure** of a substance is called its **phase diagram**, or **p-T diagram**.

The phase diagrams of **water** and **CO₂** divide the p-T plane into **three regions**: the **solid region**, the **liquid region** and the **vapour region**.

Three curves separate these regions: the **sublimation curve**, the **fusion curve** and the **vaporisation curve**. On these curves, two phases exist together: solid and vapour, solid and liquid, and liquid and vapour.

DEFINITION

Triple Point

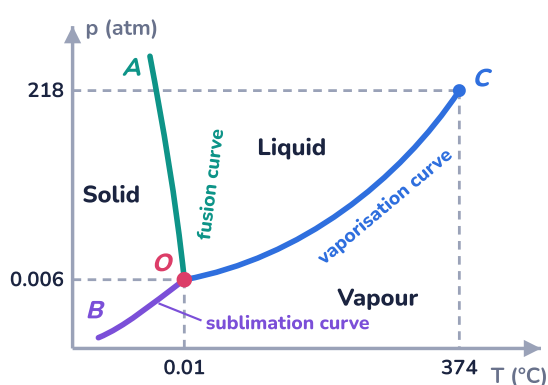
The **triple point** of a substance is the **temperature and pressure** at which **all three phases** (solid, liquid and vapour) **exist together**.

e.g. Triple point of **water**: temperature

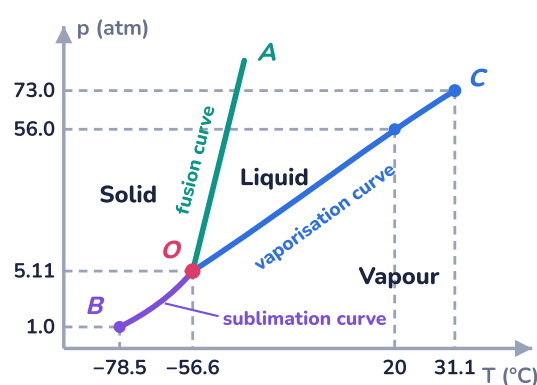
273.16 K

Triple point of **water**: pressure

6.11×10^2 Pa (≈ 0.006 atm)



(a) Water: triple point O



(b) CO₂: triple point O

A point on the **sublimation curve** BO

Solid + vapour exist together

A point on the **vaporisation curve** OC

Liquid + vapour exist together

A point on the **fusion curve** AO

Solid + liquid exist together

2.6 Latent Heat

DEFINITION

The **latent heat** of a substance is the **amount of heat per unit mass** transferred during a **change of state**, with **no change in temperature**.

Latent heat is written as L . Its SI unit is J kg^{-1} . Latent heat **depends on pressure**. So its value is usually given at **standard atmospheric pressure**.

Let a mass m of a substance change from one state to another. The heat needed is:

HEAT NEEDED FOR A CHANGE OF STATE

$$Q = mL \quad \text{or} \quad L = \frac{Q}{m}$$

where, Q = heat of transformation, m = mass of the substance, L = latent heat. So the heat needed depends on the mass and on the latent heat.

• TYPES OF LATENT HEAT

i Latent Heat of Fusion, L_f

The latent heat for the change between **solid and liquid**. It is also called the **heat of fusion**.

$$L_f = \frac{Q}{m} \quad (\text{SI unit J kg}^{-1})$$

ii Latent Heat of Vaporisation, L_V

The latent heat for the change between **liquid and gas**. It is also called the **heat of vaporisation**.

$$L_V = \frac{Q}{m} \quad (\text{SI unit J kg}^{-1})$$

EXAMPLE

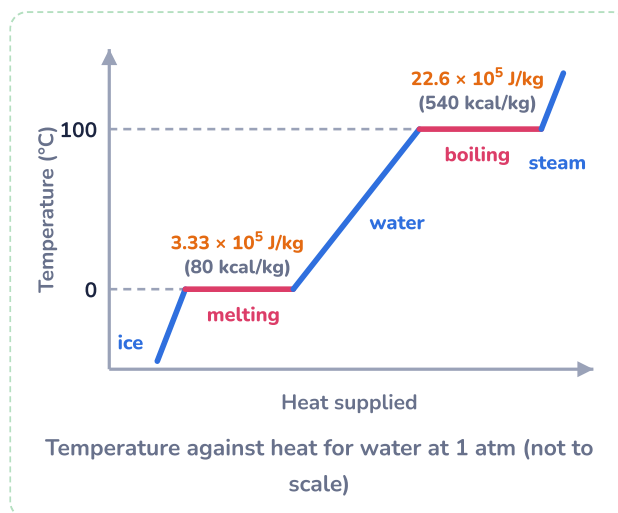
Water

For water, $L_f = 3.33 \times 10^5 \text{ J kg}^{-1}$ and $L_V = 22.6 \times 10^5 \text{ J kg}^{-1}$. This means:

- ◆ $3.33 \times 10^5 \text{ J}$ of heat melts **1 kg of ice at 0°C** .
- ◆ $22.6 \times 10^5 \text{ J}$ of heat changes **1 kg of water at 100°C** into steam.

● TEMPERATURE DURING A CHANGE OF STATE

- ◆ The graph shows that the temperature stays **constant** while heat is added (or removed) during a **change of state**.
- ◆ The sloping lines for ice, water and steam have **different slopes**. So the **specific heats** of the different states are **not equal**.



2.7 Mechanical Equivalent of Heat

We can also raise the temperature of a body by doing **mechanical work** on it.

DEFINITION

The **mechanical equivalent of heat** (J) is the number of **joules of mechanical work** needed to raise the temperature of **1 g of water by 1 °C**.

Its unit is **J/cal**. It is only a **number** that converts heat in calories into work in joules.

MECHANICAL EQUIVALENT OF HEAT

$$W = JH$$

where, W = work done, in joules (SI unit), J = mechanical equivalent of heat (J/cal), H = heat given or taken out, in calories (CGS unit)

03 PART 3 Heat Transfer

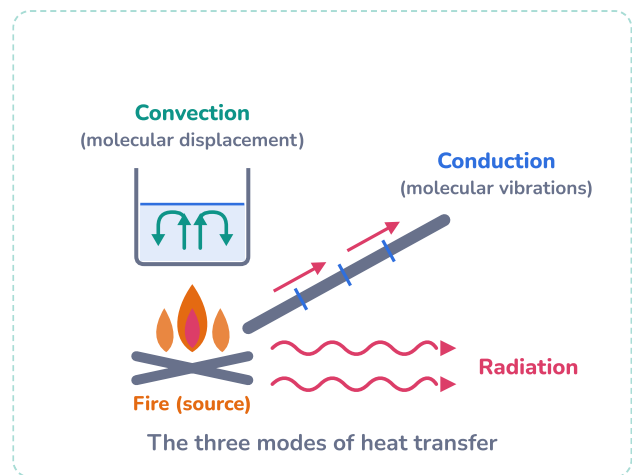
3.1 Modes of Heat Transfer

DEFINITION

Heat flows from one body to another because of a **temperature difference**. It can flow as **radiation**, through **molecular vibrations** or through **molecular displacement**. All these processes of heat flow together are called **heat transfer**.

There are **three modes** of heat transfer:

- (i) **Conduction** molecular vibrations
- (ii) **Convection** molecular displacement
- (iii) **Radiation** radiations



3.2 Conduction and Thermal Conductivity

DEFINITION

Conduction

Conduction is the transfer of heat through **molecular vibrations** (molecular collisions). The **average position of the molecules does not change**. So there is **no movement of matter** as a whole. In **solids**, heat is usually transferred by conduction.

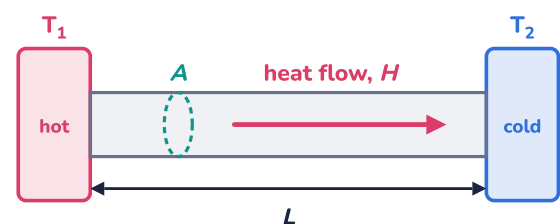
• THERMAL CONDUCTIVITY

DEFINITION

Thermal conductivity is the **ability of a material to conduct heat** through it. We measure it by the **heat that flows per second** through the material when a fixed **temperature difference** is kept across it.

SETUP – METAL ROD

- ◆ Length of the rod = L . Area of cross-section = A .
- ◆ Temperatures of its two ends = T_1 and T_2 ($T_1 > T_2$).
- ◆ The rod is in the **steady state**.



In the steady state, the **heat** Q that flows through any section of the rod is:

directly proportional to the **temperature difference** $\Delta T = T_1 - T_2$

$$Q \propto \Delta T$$

directly proportional to the **area of cross-section**

$$Q \propto A$$

directly proportional to the **time** of flow

$$Q \propto t$$

inversely proportional to the **length** of the rod

$$Q \propto \frac{1}{L}$$

So the **rate of heat flow** H does not depend on time. It is:

$$H = \frac{\Delta Q}{\Delta t} = \frac{KA(T_1 - T_2)}{L} \quad \text{i.e.} \quad H = KA \frac{\Delta T}{L}$$

Since $H = \frac{Q}{t}$, the total heat that flows in time t is:

HEAT CONDUCTED

$$Q = KA \frac{\Delta T}{L} t$$

where, K = coefficient of thermal conductivity of the material. A **larger** K means the material **conducts heat faster**.

SI unit of K

$\text{J s}^{-1} \text{m}^{-1} \text{K}^{-1}$ or $\text{W m}^{-1} \text{K}^{-1}$

Dimensions of K

$[\text{MLT}^{-3}\text{K}^{-1}]$

The ratio $\frac{\Delta T}{L}$ is called the

temperature gradient

The thermal conductivity of a material **changes slightly with temperature**. But over the **normal range of temperature**, we can take it as **constant**.

DEFINITION

Coefficient of Thermal Conductivity

Put $A = 1$, $\Delta T = T_1 - T_2 = 1$, $L = 1$ and $t = 1$. Then $Q = K$.

So the **coefficient of thermal conductivity** of a material is the **heat that flows in unit time through a unit cube** of it, when its opposite faces differ in temperature by **one degree**.

STEADY STATE The temperature of each part of the body stays constant while heat flows through it

NOTE

Metals and Non-metals

Metals conduct heat **much better** than non-metals. Metals have a **large number of free electrons**. These electrons carry heat from the **hotter part** to the **colder part**.

3.3 Heat Current and Thermal Resistance

DEFINITION

Heat Current

The **heat current** (H) is the **rate of flow of heat**. Its SI unit is **J/s or watt (W)**. Its dimensions are $[\text{ML}^2\text{T}^{-3}]$.

$$H = \frac{\Delta Q}{\Delta t} = KA \frac{(T_1 - T_2)}{L} = \frac{T_1 - T_2}{\left(\frac{L}{KA}\right)}$$

THERMAL RESISTANCE

$$R = \frac{\Delta T}{H} = \frac{T_1 - T_2}{H} = \frac{L}{KA}$$

• COMPARISON WITH ELECTRIC CURRENT

i Electric Current

$$i = \frac{V_1 - V_2}{R}$$

$V_1 - V_2$ = potential difference, R = electrical resistance

ii Heat Current

$$H = \frac{T_1 - T_2}{(L/KA)}$$

$T_1 - T_2$ = temperature difference, $\frac{L}{KA}$ = thermal resistance

So $\frac{T_1 - T_2}{(L/KA)}$ behaves like a **thermal current** (heat flow), and $\frac{L}{KA}$ behaves like a **thermal resistance**.

SI unit of thermal resistance R

K s/J or K/W

Dimensions of thermal resistance

$[M^{-1}L^{-2}T^3K]$

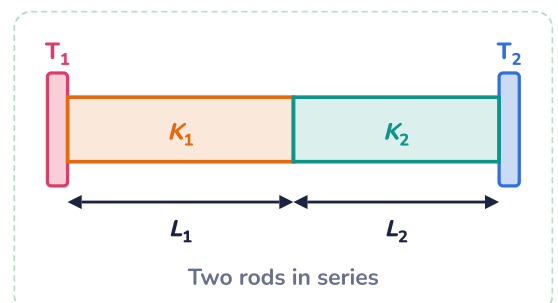
3.4 Rods in Series and in Parallel

When **two or more rods** are joined together, the **equivalent thermal conductivity** of the whole set-up changes.

• (A) SERIES COMBINATION OF TWO CONDUCTORS

For resistances in series, $R_{eq} = R_1 + R_2$. Use $R = \frac{L}{KA}$ for each rod:

$$\frac{L_1 + L_2}{K_{eq}A} = \frac{L_1}{K_1A} + \frac{L_2}{K_2A}$$



If the rods have equal lengths, $L_1 = L_2 = L$, then $\frac{2L}{K_{eq}A} = \frac{L}{K_1A} + \frac{L}{K_2A}$. This gives:

SERIES – EQUIVALENT THERMAL CONDUCTIVITY

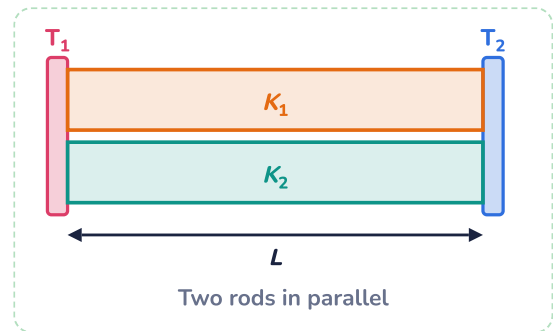
$$K_{eq} = \frac{2K_1K_2}{K_1 + K_2}$$

where, K_{eq} = equivalent thermal conductivity of the two rods joined end to end

• (B) PARALLEL COMBINATION OF TWO CONDUCTORS

For resistances in parallel, $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$. Take rods of **equal length and equal area**. Together they have area $2A$:

$$\frac{1}{\left(\frac{L}{K_{eq}2A}\right)} = \frac{1}{\left(\frac{L}{K_1A}\right)} + \frac{1}{\left(\frac{L}{K_2A}\right)}$$



$$\Rightarrow \frac{2AK_{eq}}{L} = \frac{K_1A}{L} + \frac{K_2A}{L}$$

PARALLEL – EQUIVALENT THERMAL CONDUCTIVITY

$$K_{eq} = \frac{K_1 + K_2}{2}$$

for two rods of equal length and equal area, placed side by side

3.5 Convection

DEFINITION

Convection is the transfer of heat by the **actual movement of matter** from a region of **higher temperature** to a region of **lower temperature**. It takes place only in **fluids**, that is, in **liquids and gases**.

Convection is of **two types**:

i Forced Convection

The heated material is **forced to move**, for example by a **blower or a pump**. It carries heat with it.

e.g. Heat transfer in the **human body**.

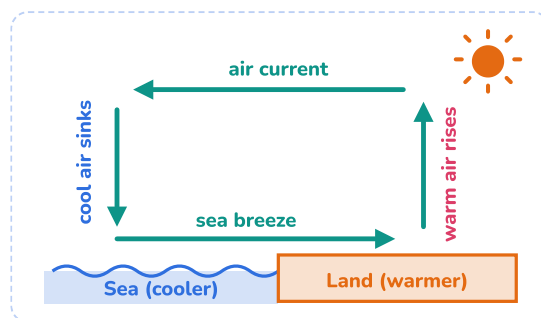
ii Natural (Free) Convection

The heated material moves because of a **difference in density**.

e.g. Heat transfer in **water** being heated.

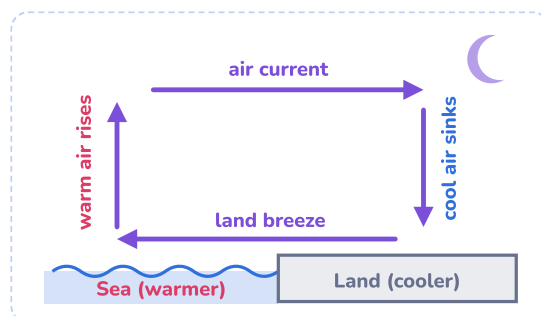
• SEA BREEZE (DURING THE DAY)

- ◆ In the day, the **land heats up faster than the sea**. Water has a **greater specific heat**. Mixing currents also spread the heat through its **large volume**.
- ◆ The **hot air above the land expands**, becomes less dense and **rises**. **Cooler air from the sea** takes its place. The warm air from the land moves towards the sea and completes the cycle.
- ◆ So a breeze blows from the **sea to the land**. It is called a **sea breeze**.



• LAND BREEZE (DURING THE NIGHT)

- ◆ At night, the **opposite happens**. The **land cools faster than the sea**.
- ◆ The **warm air above the sea rises**. **Cooler air from the land** takes its place.
- ◆ So a breeze blows from the **land to the sea**. It is called a **land breeze**.



• FORMATION OF TRADE WINDS

- ◆ The **equator** and the **poles** of the Earth get **unequal heat** from the Sun. Air near the surface at the equator is **hot**. Air in the upper atmosphere at the poles is **cool**.
- ◆ So a **convection current** forms between them. Air at the equator **rises** and moves out towards the **poles**. It then **comes down** and flows back towards the **equator**.
- ◆ The **rotation of the Earth** changes this convection current. Air near the equator has an **eastward speed of 1600 km/h**. Close to the poles, this speed is **zero**.
- ◆ So the air comes down **not at the poles** but at about **30° N latitude**. It then returns to the equator. This is called the **trade wind**.

Equator: hot air rises → moves towards the poles → comes down at 30° N → returns to the equator

DEFINITION

Trade Wind

The **trade wind** is the **steady wind** that blows near the Earth's surface from the **north-east towards the equator**. It is an example of **natural convection**.

3.6 Radiation

DEFINITION

Radiation is the transfer of heat from one point to another **without warming the medium in between**. The heat travels as **thermal radiation**, also called **radiant energy** or simply **radiation**.

The word **radiation** has **two meanings**:

i The Process

A body **gives out** energy. The energy **travels through space** and **falls on another body**.

ii The Energy

The **energy itself** that travels through space.

EXAMPLE

From the Sun to the Earth

Heat from the **Sun** reaches the **Earth** by **radiation**. It crosses **millions of kilometres of empty space**, with **no material medium** in between.

• THERMAL RADIATION

DEFINITION

Thermal radiation is the **electromagnetic radiation** given out by a body **because of its temperature**.

e.g. Radiation from a **red-hot iron**. Light from a **filament lamp**.

• COLOUR OF A BODY

Thermal radiation falling on a body is **partly reflected** and **partly absorbed**.

- ◆ The heat a body **absorbs by radiation** depends on its **colour**.
- ◆ A body has a particular colour because it **reflects back radiation of that wavelength**.

• BLACK BODY RADIATION

DEFINITION

Black Body

A **black body** is a body that **absorbs all the radiation falling on it**. The radiation given out by a black body is called **black body radiation**.

absorbs all the radiation falling on it

emits at the fastest rate

also called an ideal radiator

A body that absorbs **100% of the radiation** is only an **ideal idea**. A perfect black body does not exist in the universe.

Ideal only

Lamp black reflects only **1%** of the radiation falling on it. So it is close to a black body.

≈ Black body

3.7 Absorptive Power and Emissivity

DEFINITION

Absorptance (Absorptive Power)

The **absorptance** (a), or **absorptive power**, of a body is the **ratio of the thermal radiation it absorbs** in a given time **to the total thermal radiation falling on it** in the same time.

$$a = \frac{\text{Energy absorbed}}{\text{Energy incident}}$$

DEFINITION

Emissive Power

The **emissive power** of a body is the **radiant energy it gives out per unit time per unit surface area**, within a **unit wavelength range** around a wavelength λ . It is taken at a fixed temperature.

DEFINITION

Emissivity

The **emissivity** (ϵ) of a body is the **ratio of its emissive power (e) to the emissive power of a perfect black body (E) at the same temperature**.

EMISSIVITY

$$\epsilon = \frac{e}{E}$$

where, e = emissive power of the body, E = emissive power of a perfect black body at the same temperature

3.8 Stefan–Boltzmann Law

LAW

Stefan–Boltzmann Law

The **total energy emitted per second per unit area** of a **perfect black body** is **directly proportional to the fourth power of its absolute temperature**.

$$E \propto T^4$$

STEFAN–BOLTZMANN LAW

$$E = \sigma T^4$$

where, E = total energy emitted per second per unit area, T = absolute temperature, σ = Stefan–Boltzmann constant
(a universal constant) = $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

NOTE

A Body That Is Not a Perfect Black Body

Suppose the body is **not a perfect black body**. Let its emissivity be ε . Then the law becomes:

PERFECT BLACK BODY

$$E = \sigma T^4$$

BODY WITH EMISSIVITY ε

$$E = \varepsilon \sigma T^4$$

3.9 Wien's Displacement Law

LAW

Wien's Displacement Law

The **wavelength** (λ_m) at which a black body **emits the maximum energy** is **inversely proportional to its absolute temperature** (T).

$$\lambda_m \propto \frac{1}{T}$$

WIEN'S DISPLACEMENT LAW

$$\lambda_m T = b$$

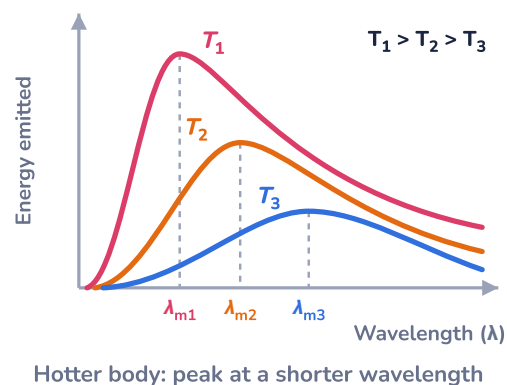
where, b = Wien's constant = 2.9×10^{-3} m K

Temperature T **increases** $\uparrow$

λ_m **decreases** $\downarrow$

Temperature T **decreases** $\downarrow$

λ_m **increases** $\uparrow$

**3.10 Newton's Law of Cooling**

LAW

Newton's Law of Cooling

The **rate at which a body loses heat** is **directly proportional** to the **difference between its temperature and the temperature of its surroundings**. This is true only when the **difference is small**.

Rate of loss of heat $\propto$

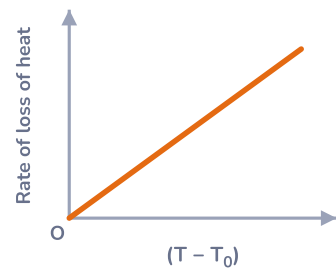
Temperature difference between the body and its surroundings

$$-\frac{dQ}{dt} \propto (T - T_0)$$

NEWTON'S LAW OF COOLING

$$-\frac{dQ}{dt} = k(T - T_0)$$

where, $-\frac{dQ}{dt}$ = rate of loss of heat, T = temperature of the body, T_0 = temperature of the surroundings, k = a constant



Straight line through the origin