

# Thermal Physics and Kinetic Theory

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## Thermal Physics and Kinetic Theory

### The Nature of Heat

For most of the 18th century, scientists believed heat was an invisible, massless fluid called **caloric**. On this view, an object heated up when caloric flowed into it and cooled when caloric flowed out.

Two experiments demolished the caloric model.

### Rumford's Cannon-Boring Experiment

Benjamin Thompson (Count Rumford) observed that boring a brass cannon produced enormous amounts of heat, enough to boil water, and the heat continued as long as the boring continued. Under the caloric model, the caloric should have been exhausted. He also showed that the brass chips produced during boring had the same heat content as an equal mass of unbored brass, refuting the idea that caloric was being "squeezed out." He concluded that heat was generated by mechanical friction, not extracted from a finite store of fluid.

### Joule's Paddle Wheel Experiment

In 1843, James Prescott Joule dropped a measured mass through a measured height, causing paddles to churn water. The work done (

$$W = mgh$$

) produced a temperature rise in the water. Joule showed that a fixed amount of work always produced the same amount of heat:

$$4.2\text{J} \equiv 1\text{cal}$$

This **mechanical equivalent of heat** proved that heat is a form of energy, not a substance. The caloric theory was abandoned in favour of the **kinetic (energy transfer) theory** of heat.

## The Kinetic Theory of Heat

In the kinetic model:

- All matter is made of tiny particles (atoms and molecules) in constant random motion.
- **Temperature** is a measure of the average kinetic energy of these particles. Higher temperature means faster-moving particles.
- **Heat** is the net transfer of internal energy from a hotter body to a cooler body. Heat and temperature are not the same quantity.

## Phases of Matter

Matter exists in three phases. Their properties are explained by the kinetic model.

| Phase  | Particle arrangement                       | Motion                           | Compressible?         | Shape/Volume                    |
|--------|--|----------------------------------|-----------------------|---------------------------------|
| Solid  | Regular lattice; closely packed            | Vibrate about fixed positions    | No                    | Fixed shape; fixed volume       |
| Liquid | Irregular; closely packed but free to move | Slide past each other            | Nearly incompressible | No fixed shape; fixed volume    |
| Gas    | Far apart; disordered                      | Rapid, random, in all directions | Yes                   | No fixed shape; no fixed volume |

When a solid is heated, particles gain enough energy to break free of their lattice positions and the substance **melts** (solid to liquid). Further heating gives particles enough energy to escape the liquid surface entirely and the substance **boils** or **vaporises** (liquid to gas). Both changes happen at fixed temperatures for a pure substance at a given pressure.

## Temperature and Thermometers

**Temperature** is measured by finding a physical property of a substance that changes in a known, reproducible way with hotness. Common properties used include: volume of a liquid (liquid-in-glass thermometer), electrical resistance, and pressure of a gas at constant volume.

### Fixed Points on the Celsius Scale

Two reference temperatures define the Celsius scale:

| Fixed point | Definition | Celsius value | Kelvin value |
|-------------|------------|---------------|--------------|
|             |            |               |              |

|                                 |  |        |       |
|---------------------------------|--|--------|-------|
| Ice point (lower fixed point)   | Temperature of pure melting ice at standard pressure               | 0 °C   | 273 K |
| Steam point (upper fixed point) | Temperature of steam just above boiling water at standard pressure | 100 °C | 373 K |

The interval between the two fixed points is divided into 100 equal divisions, so each division is one degree Celsius (°C).

## Thermometer Types

| Thermometer               | Physical property used                 | Range              | Typical use                          |
|---------------------------|--|--------------------|--------------------------------------|
| Liquid-in-glass (mercury) | Volume of liquid                       | -39 °C to 360 °C   | Laboratory, general use              |
| Liquid-in-glass (alcohol) | Volume of liquid                       | -115 °C to 78 °C   | Cold-climate daily temperatures      |
| Clinical thermometer      | Volume of mercury (with constriction)  | 34 °C to 43 °C     | Body temperature                     |
| Thermocouple              | EMF produced at junction of two metals | -200 °C to 1500 °C | High-temperature industrial use      |
| Thermistor (electronic)   | Electrical resistance of semiconductor | Wide range         | Electronic thermometers, fire alarms |

### Thermometer types (2022 Paper 02, Q3)

A table in a 2022 exam asked students to identify three thermometer types, their uses, and ranges.

| Type | Use | Range |

|---|---|---|

| Thermocouple | Measures extremely high, rapidly changing temperatures | -200 °C to 1500 °C |

| Clinical thermometer | Measures body temperature | 34 °C to 43 °C |

| Liquid-in-glass | Measures boiling and freezing point of water and room temperature | -10 °C to 110 °C |

The ice point on the Celsius scale is **0 °C**. On the Kelvin scale it is **273 K**.

## Kelvin Scale

The Kelvin (absolute) scale uses the same size divisions as the Celsius scale but sets its zero at **absolute zero**, the temperature at which particles have minimum possible kinetic energy and all gas pressure would cease.

$$T(\text{K}) = \theta(^{\circ}\text{C}) + 273$$

$$\theta(^{\circ}\text{C}) = T(\text{K}) - 273$$

At absolute zero (0 K = -273 °C), molecular motion is at a minimum. Temperature in kelvin is always positive. Gas law calculations **must** use kelvin.

| Celsius | Kelvin |
|---------|--------|
| -273 °C | 0 K    |
| 0 °C    | 273 K  |
| 100 °C  | 373 K  |
| 27 °C   | 300 K  |

## Thermal Expansion

Most substances expand when heated because their particles gain kinetic energy and push further apart. The amount of expansion depends on the phase:


- **Solids** expand least, particles vibrate about fixed positions and cannot move far.
- **Liquids** expand more than solids, particles can slide past each other.
- **Gases** expand most, particles are far apart and free to move; pressure drives them further apart.

## Applications and Consequences of Thermal Expansion

| Application                               | Explanation  |
|---|--|
| Gaps in railway tracks and bridges        | Prevent buckling when the metal expands in hot weather                           |
| Bimetallic strip (thermostat, fire alarm) | Two metals with different expansion rates bond together; strip bends when heated |

|                                       |   |
|---------------------------------------|---|
| Riveting metal plates                 | Red-hot rivet is hammered in; on cooling it contracts and pulls plates tightly together |
| Fitting a steel tyre on a train wheel | Tyre is heated to expand, slid over wheel, then contracts as it cools to grip tightly   |
| Loosening a stuck metal lid           | Heating the metal lid causes it to expand more than the glass jar, loosening the fit    |

A bimetallic strip bends toward the metal that expands less when heated (because the metal that expands more is on the outer, longer side of the curve).

 **Exam Tip**

Temperature scale conversions are a guaranteed Paper 01 item. Remember:  $K = ^\circ C + 273$ .  
Absolute zero is  $0 K = -273 ^\circ C$ .

In thermal expansion questions, the comparison order is: gases expand most, liquids expand more than solids, solids expand least.