Matter and material: States of matter and the kinetic molecular theory

Objectives

- Understand the concept of standard temperature and pressure and how this affects melting and boiling points of substances.
- List and characterize the three states of matter.
- Describe a solid, a liquid and a gas according to the particle model of matter.
- Define melting, boiling, evaporation, solidification, condensation, sublimation and deposition/reverse sublimation.
- Identify the physical state of a substance at a specific temperature, given its melting point and the boiling point.
- Interpret and draw the heating and cooling curves, and explain the graph based on kinetic molecular theory.
- Describe Brownian motion and diffusion based on kinetic molecular theory.

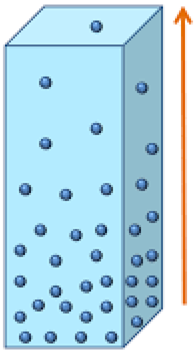
Standard temperature and pressure (STP)

Air particles move quickly and randomly over large distances. These air particles press against objects when they hit them and bounce off them and therefore exert air pressure or atmospheric pressure. Standard temperature and pressure (STP) is the atmospheric pressure that's exerted by air particles when:

- The surrounding temperature is at standard temperature of 0°C or 273 K.
- At sea level where the surrounding pressure is 1 atm or 101 kPa.

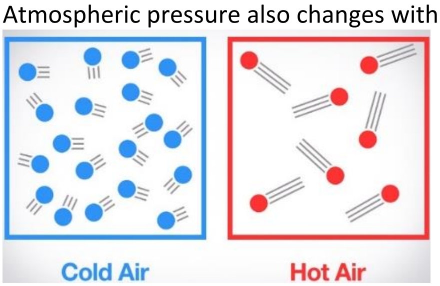
So, for example when we say that water boils at 100°C, what we mean is that this is the boiling temperature of the water at STP. This means that water will boil at this temperature if the surrounding temperature is 0°C and the surrounding pressure is 1 atm.

Atmospheric pressure changes with a changing elevation or altitude. Elevation or altitude means the height above or below sea level. Consider the diagram below:



As we can see, air becomes thinner with elevation. This means that as elevation **increases**, atmospheric pressure **decreases**.

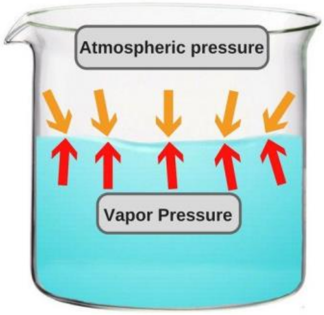
Atmospheric pressure also changes with a changing temperature. Consider the diagram below:



As we can see, the air particles move faster and further apart as temperature increases. This means that as temperature **increases**, atmospheric pressure **decreases**.

What is the boiling point of a liquid? *D It is the temperature at which vapour pressure of a liquid equals the atmospheric pressure.

What does this mean? As already discussed, the atmospheric pressure is the air pressure that's exerted by the surrounding air particles. The vapor pressure is the pressure exerted by the liquid particles that may have enough energy to escape the liquid as gas particles. For a liquid to boil, the vapour pressure of the liquid needs to overcome the atmospheric pressure of the surrounding air.



Vapour pressure of a liquid and atmospheric pressure from the surrounding atmosphere

As already mentioned, when we talk about water having a boiling point of 100°C or iron having a melting point of 1538°C, this is true only at STP. If the surrounding conditions are not at STP, then the boiling point and the melting point of a substance will deviate from the standard boiling point and the standard melting point experienced at STP.

If the atmospheric pressure is greater (e.g. on a cold day or at low elevation), then the vapour pressure will be **greater**. This means that the boiling point will be **higher**. If the atmospheric pressure is lower (e.g. on a hot day or at high elevation), then the vapour pressure will be **lower**. This means that the boiling point will be **lower**. Johannesburg is approximately 1700 m (1.7 km) above sea level. On a warm day in Johannesburg, water will boil at around 94°C. At the top of Mount Everest, where it is very cold and approximately 8800 m (8.8 km) above sea level, water boils at around 70°C.

It works similarly for melting. Imagine a high atmospheric pressure on a solid. This keeps the particles that make up the solid close together and in an organised pattern. If the atmospheric pressure decreases, the particles that make up the solid can move further apart from each other, turning the substance into a liquid. Therefore, if the atmospheric pressure is greater, the melting point of the substance will be **higher**. If the atmospheric pressure is lower, the melting point of the substance will be **lower**.

The three states of matter

Solid is a state in which matter keeps a fixed volume and shape. Liquid is a state in which matter keeps a fixed volume, but because of gravity, it takes on the shape of the container. Gas is a state in which matter distributes itself spontaneously and uniformly across the entire volume of the container it is in. In the figure below water exists in all three states: as ice in the solid state, as water and clouds in the liquid state, as water vapour in the gas state.

*D represents a definition. Definitions need to memorised word for word.

Whatever the state, the water molecules remain chemically identical as H_2O. Only the state or the phase of the water molecules has changed. Other substances can also change their state. For example, metals are melted to be moulded. Solid rock melts to form molten lava which feeds volcanos. A nuclear explosion can cause rocks not only to melt but also to evaporate. In all these examples, the physical state of the substance changes, but the chemical composition of the substance remains the same.

The most common way of changing the state of a substance is by heating it up or cooling it down. However, with a changing pressure (pressure that is higher or lower than standard pressure), we can also influence the melting and boiling points of substances. For example, at STP oxygen (O_2) will solidify at –219°C. At STP, the atmospheric pressure is 1 atm. If we increase the atmospheric pressure to 10 atm, we can solidify O_2 at –8°C. This is because along with a decrease in temperature, which decreases the kinetic energy of the particles, we also increase the pressure, which physically forces the particles closer together.

The particle model of matter is a model that explains the arrangement of particles in solids, liquids and gases. Whether in the solid, liquid or gas phase, the particles are always moving. There is **kinetic** energy associated with that movement. Particles of a solid are associated with the lowest kinetic energy, and particles of a gas are associates with the highest kinetic energy.

Because we cannot see the particles that make up matter and are unable to record their speeds, we measure the **kinetic energy** of a substance based on its **temperature**. At room temperature (23°C), the air you breathe is a gas. The water in your bottle is a liquid. The iron leg of your desk is a solid. Because the air, water and iron are all at the **same temperature**, the particles that make them up all have the **same kinetic energy**. This is because the particles all move at the same speed (even though there is a different distance between collisions).

However, for any given substance, the gas phase of that substance has the most kinetic energy, and the solid phase of that substance has the least kinetic energy. For example, iron in the gas phase has more kinetic energy than iron in the solid phase. Water in the gas phase has more kinetic energy than in the solid phase.

Here are some important definitions for changes of state:

- Melting is the change of state from solid to liquid. For example, ice melts to form water.
- Boiling is the change of state from liquid to gas. For example, water boils to form H_2O gas.
- Condensation is the change of state from gas to liquid. For example, H_2O gas condenses to form water.
- Solidification is the change of state from liquid to solid. For example, water solidifies to form ice.
- Sublimation is the changing state from a solid to a gas (skipping the liquid phase). For example, dry ice (CO_2) and iodine (I_2) sublime from solid to gas.
- Deposition or reverse sublimation is the changing state from a gas to a solid (again, skipping the liquid phase). For example, dry ice (CO_2) and iodine (I_2) depose from gas to solid.

Another very important concept is the fact that:

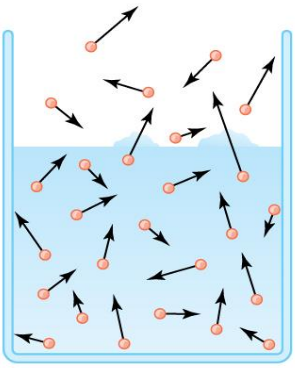
- The solidification point and the melting point of a substance is the same temperature.
- The condensation point and the boiling point of a substance is the same temperature.

So at STP, water has a solidification (freezing) **and** melting point of 0°C; and a condensation **and** boiling point of 100°C. What does this mean? At 0°C, water may exist as a solid or as a (cold) liquid. At 100°C, water may exist as a gas or as a (hot) liquid:

- If we start with ice and increase the temperature, at 0°C it will exist as a solid, and just above 0°C it will start to melt.
- If we start with liquid water and decrease the temperature, at 0°C it will exist as a liquid, and just below 0°C it will start to solidify.
- If we start with liquid water and increase the temperature, at 100°C it will exist as a liquid, and just above 100°C it will start to boil.
- If we start with gas and decrease the temperature, at 100°C it will exist as a gas, and just below 100°C it will start to condense.

Lastly, we need to understand the difference between boiling and evaporation. Boiling takes place at the boiling point of a liquid when bubbles of vapour form in the liquid. However, liquids evaporate at all temperatures, not just at the boiling point. For example, clothes dry when hanging on the line. If you leave water in an open container, after a few days the water level drops. Eventually there will be no water left in the container.

The process of evaporation takes place at the surface of the liquid as you can see in the diagram below. The particles at the surface get “bumped off” by the particles below them. This gives the surface particles enough energy to escape the liquid as gas as demonstrated in the picture below.



The particles at the surface get “bumped off” the liquid by the energy of the particles below them

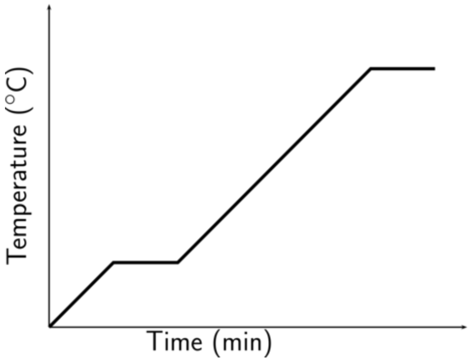
The difference between evaporation and boiling is summarised in this table:

Evaporation	Boiling
Takes place at all temperatures.	Takes place at the boiling point.
Takes place only at the surface of the liquid.	Forms bubbles of vapour within the body of the liquid.

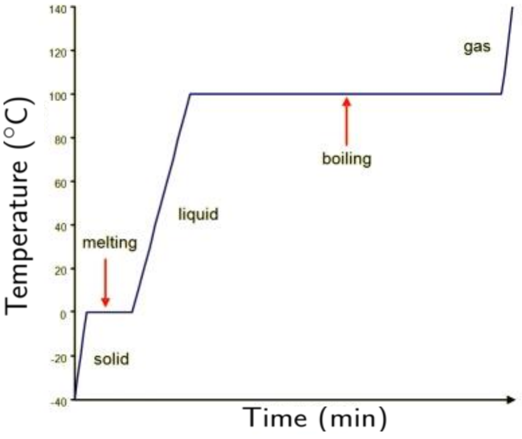
Heating and cooling curve

Heating curve

The heating curve of a substance is a time of heat absorption vs temperature graph that shows the temperature as the substance is heated (heat is absorbed) and changes phase from a solid to a liquid to a gas. The graph below represents a general heating curve:



This graph represents the heating curve of water:



From –40°C to 0°C: Water exists in the solid phase with an increasing temperature. This means that the kinetic energy of the particles that make up the solid increases from -40°C to 0°C.

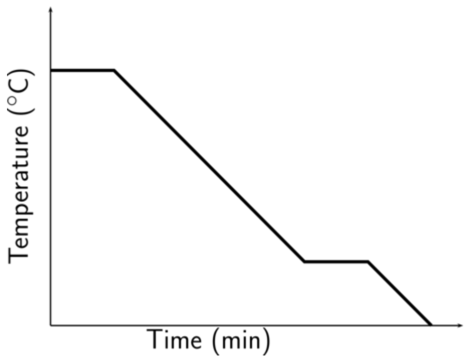
At 0°C: Once the first drops of liquid appear, the ice begins to melt. The graph is flat during the process of melting, meaning that the temperature remains the same. This also means that the kinetic energy of the particles remains the same. The heat absorbed is going into weakening the intermolecular forces of attraction between the particles. The particles move further apart from each other, increasing their potential energy.
From 0°C to 100°C: Once the entire solid has melted, water now exists in the liquid phase with an increasing temperature. This means that the kinetic energy of the particles that make up the liquid increases from 0°C to 100°C.

At 100°C: Once the first bubbles of gas appear, the water begins to boil. The graph is flat during the process of boiling, meaning that the temperature remains the same. This also means that the kinetic energy of the particles remains the same. The heat absorbed is going into weakening the intermolecular forces of attraction between the particles. The particles move further apart from each other, increasing their potential energy.

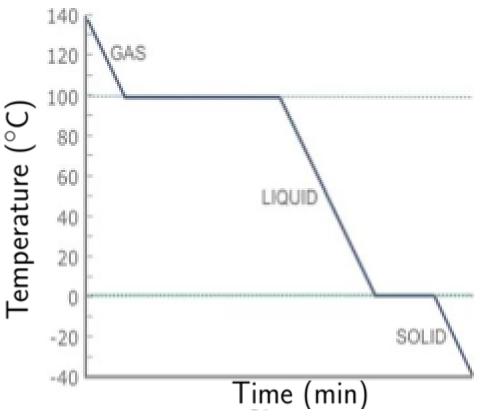
Above 100°C: Once the entire liquid has boiled, water now exists in the gas phase. We may increase the temperature of the gas. This means that the kinetic energy of the particles that make up the gas increases above 100°C.

Cooling curve

The cooling curve of a substance is a time of heat loss vs temperature graph that shows the temperature as the substance is cooled (heat is released) and changes phase from a gas to a liquid to a solid. The graph below represents a general cooling curve:



This graph represents the cooling curve of water:



From 140°C to 100°C: Water exists in the gas phase with a decreasing temperature. This means that the kinetic energy of the particles that make up the gas decreases from 140°C to 100°C.

At 100°C: Once the first droplets of liquid appear, the gas begins to condense. The graph is flat during the process of condensation, meaning that the temperature remains the same. This also means that the kinetic energy of the particles remains the same. The heat lost is going into strengthening the intermolecular forces of attraction between the particles. The particles move closer together, decreasing their potential energy.

From 100°C to 0°C: Once the entire gas has condensed, water now exists in the liquid phase with a decreasing temperature. This means that the kinetic energy of the particles that make up the liquid decreases from 100°C to 0°C.

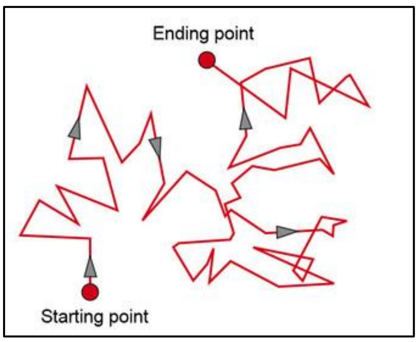
At 0°C: Once the first crystals of ice appear, the water begins to solidify. The graph is flat during the process of solidification, meaning that the temperature remains the same. This also means that the kinetic energy of the particles remains the same. The heat lost is going into strengthening the intermolecular forces of attraction between the particles. The particles move closer together, decreasing their potential energy.

Below 0°C: Once the entire liquid has solidified, water now exists in the solid phase. We may decrease the temperature of the solid. This means that the kinetic energy of the particles that make up the solid decrease below 0°C.

Brownian motion and diffusion

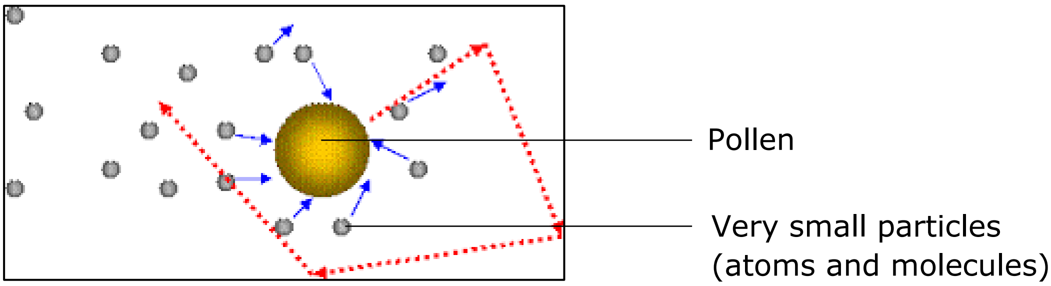
Brownian motion

In the 1800s, Robert Brown, a botanist, observed that pollen, when viewed under a microscope, undergoes sudden erratic jumps in random directions.



The random movement of pollen

He theorised that the pollen was alive, but later it was understood that the pollen was experiencing random collisions with the very small particles that make up air. These small air particles cannot be observed under a microscope, but their effect on pollen can be observed.



Pollen being bumped by air particles

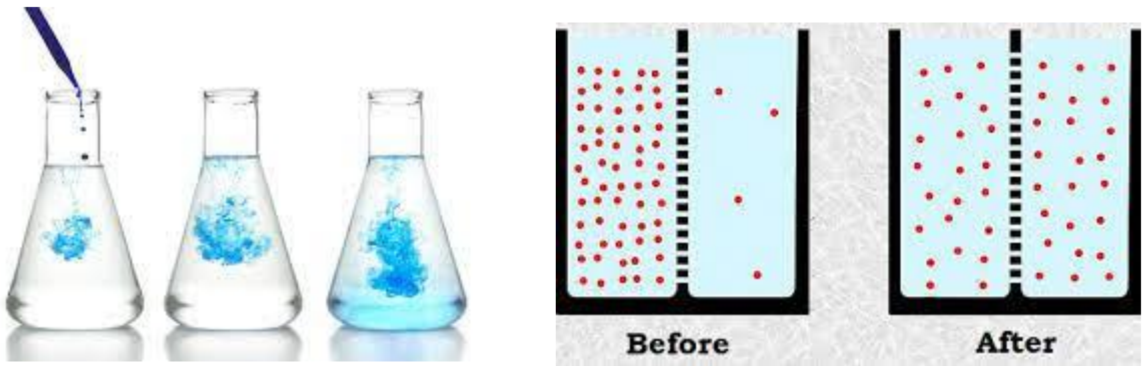
Brownian motion is the random movement of microscopic matter (such as dust and pollen) suspended in a fluid (liquid or gas). This random movement is caused by the microscopic particles in the surrounding <u>medium</u> that are colliding with the microscopic matter. This was the first evidence that matter exists as discrete and separate particles that are very small, which we now know to be atoms and molecules.

Videos on Brownian Motion: **https://www.youtube.com/watch?v=ygiCHALySmM**
https://www.youtube.com/watch?v=4m5JnJBq2AU

<u>Diffusion</u>

Diffusion [D] is the random movement of particles of a fluid (liquid or gas) from an area of higher concentration to an area of lower concentration until they are evenly distributed.

The particles of fluids are constantly and randomly moving due to their kinetic energy. This is the reason that fluids mix without any outside influence. Eventually the particles will get distributed evenly all the way through. This is called diffusion. For example, smoke from a chimney will diffuse into the air. If you pour a few drops of food colouring into a glass of water, you will see the colour diffuse into the water as shown in the diagram below:



The process of diffusion. The process ends when the particles are evenly distributed

We may speed up the process of diffusion by increasing the kinetic energy of the particles, for example by stirring or heating up the mixture. However, diffusion will take place even without any outside interference. Diffusion is further evidence that matter exists of discrete and separate particles that are very small.

Video on diffusion: **https://www.youtube.com/watch?v=_oLPBnhOCjM**

The <u>kinetic molecular theory</u> is a model that explains our macroscopic observations at a microscopic level. Kinetic molecular theory compares the movement of atoms and molecules in their different states. It also explains our macroscopic observations (e.g. the heating and cooling curves of substances, Brownian motion and diffusion) by describing what happens at the microscopic level, i.e. the behaviour of atoms and molecules.

Practice questions and answers

Practice questions

1. The table below shows the boiling points and melting points of substances A-D.

Substances	Boiling point (°C)	Melting point (°C)
A	78	–117
B	444	133
C	–188	–220
D	184	90

1.1 From the above table, write down the letter (A-D) that represents the substance that is a:

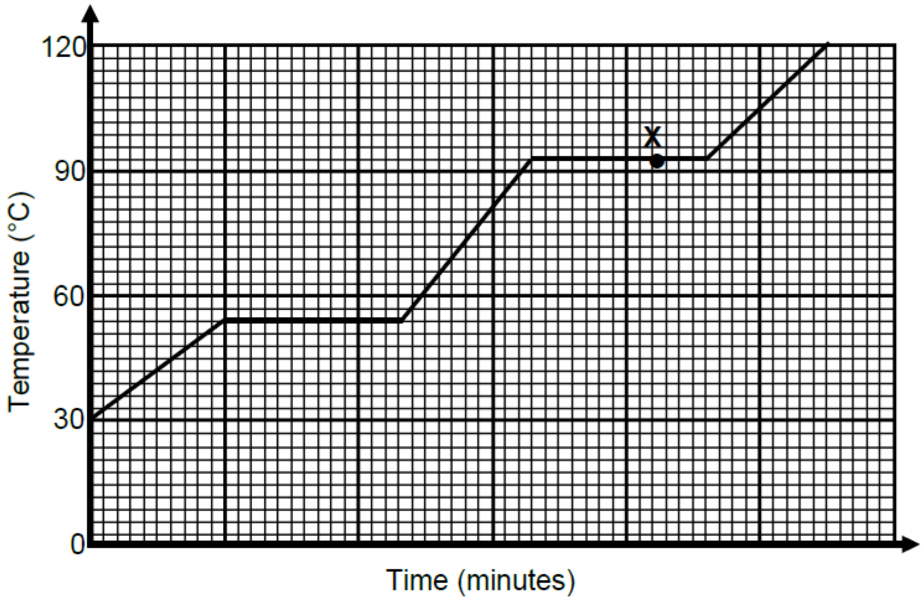
1.1.1 Liquid at 100°C.

1.1.2 Solid at 100°C.

1.1.3 Gas at room temperature

1.2 From the above table, which substance has the strongest forces of attraction between particles. Explain.

2. The heating curve for a pure substance at STP is shown in the graph below:



2.1 What is the boiling point of this substance?

2.2 What is the melting point of this substance?

2.3 Is this substance water? Provide a reason for your answer.

2.4 What is the physical state of the substance at room temperature?

2.5 What is the physical state of the substance at point X?

2.6 At a macroscopic level, what happens to the temperature while the substance melts?

2.7 Explain the above observation microscopically.

Practice question answers

1.

1.1

1.1.1 D

1.1.2 B

1.1.3 C

1.2 Substance B. It has the highest boiling point, so it takes more energy to weaken the forces of attraction.

2.

2.1 93°C

2.2 54°C

2.3 No. It does not have a melting point of 0°C / boiling point of 100°C.

2.4 Solid

2.5 Liquid and gas

2.6 The temperature remains the same.

2.7 The temperature remains the same because the kinetic energy of the particles remains the same. The energy is going into weakening the intermolecular forces of attraction between the particles. The particles move further apart from each other, meaning that their potential energy increases.