# Topic 3 – Thermal Physics

## Temperature and Thermal Energy

### Temperature

Temperature is the degree of hotness of a substance. On a microscopic level, temperature is a measure of the average kinetic energy of the particles within a substance.

We can therefore say that if a substance is hotter then each particle will (on average) have a greater kinetic energy (so gas particles will be moving – or vibrating – faster)

This kinetic energy can be vibrational motion, in the case of solids, or translational motion, in the case of liquids or gases.

### Thermal contact

Two objects are said to be in thermal contact if it is possible for thermal energy to be transferred directly from one object to the other as a result of the ***temperature difference*** between the two objects.

### Heat (Thermal Energy)

Thermal energy is often also called heat energy.

If two objects are in thermal contact, thermal energy will transfer from one to the other, and vice versa. Thermal energy ("heat") is thus the energy transfer that results when two objects are in thermal contact with each other and one is hotter (at a higher temperature than) the other.

### Thermal Equilibrium

The net, (overall) transfer of thermal energy is always from the object with the highest temperature to the object with the lowest temperature. Therefore the hottest object will cool down and the coolest object will warm up until they both reach the same temperature. At this point the two objects are said to be in thermal equilibrium.

If two objects are in thermal contact and they are both at the same temperature, it does not mean that no thermal energy is being transferred from one object to the other, but that there is no overall transfer of energy. For this to be the situation, it must be that thermal energy is flowing equally in both directions. This situation is described as thermal equilibrium. So objects in thermal contact and at the same temperature are said to be in thermal equilibrium.

## Temperature Scales

The two common temperature scales are the celsius temperature scale and the kelvin temperature scale.

The kelvin scale is also referred as the absolute temperature scale.

The absolute (kelvin) temperature scale starts at the lowest possible temperature – zero kelvin (0 K – degrees word and sign is omitted).

This equates to a temperature of $-273\,°C$. Since an increment of 1°C is the same as an increment of 1 K, converting from °C to K or visa versa is very easy.

| | | |
|---|---|---|
| To convert from °C to K: | Add | 273 |
| To convert from K to °C: | Subtract | 273 |

Examples:

| | | |
|---|---|---|
| 0 K | = | $-273\,°C$ |
| 0 °C | = | 273 K |
| 100 °C | = | 373 K |
| 150 K | = | $-123\,°C$ |

## Internal Energy

Internal Energy = Potential Energy + Kinetic Energy

The potential energy of a substance increases if the attractive bonds between the atoms are weakened (by increasing the average distance between adjacent molecules)

The kinetic energy of a substance increases if the motion (translational or vibrational) is increased

Increasing the temperature of a substance is effected by increasing the average kinetic energy of the molecules

Changing the state of a substance (from solid to liquid or liquid to gas) is effected by increasing the potential energy of the molecules

Adding energy to a substance (by heating it or doing work on it) can result in one of the following:

- The temperature can increase (KE increases)
- The state can change (PE increases)
- Energy can be lost by the substance at an equal rate (equilibrium is said to occur)
- The substance can chemically change (e.g. burn, decompose)

**Key point:** Temperature of a substance is a measure of the average kinetic energy of molecules in that substance

The rate (°C per second) at which the **temperature** changes depends on:

- The rate at which net energy is added
- The mass of substance
- The specific heat capacity of the substance

The rate (kg per second) at which the **state** changes depends on:

- The rate at which net energy is added
- The specific latent heat of fusion/vaporization of the substance

## Thermal Energy Transfer

To understand thermal energy transfer it is best to think of thermal energy as "molecular motion" (vibrational or translational)
Thermal energy (heat energy) is transferred from one place to another by three ways:

1. Conduction - thermal energy (vibrations) is passed on by molecules colliding with their neighbouring molecules – neighbouring molecules therefore move more, increasing their thermal energy, and so on
2. Convection - thermal energy is moved simply by molecules containing thermal energy moving
3. Radiation - thermal energy is transferred from a "hot" body by infra-red (heat) radiation. This radiation can then be absorbed by another body, whose internal energy would then increase.

### Some characteristics of thermal energy transfer

- The only type of heat transfer in solids is conduction
  The main type of heat transfer in liquids and gases is convection
- Radiation is most effective when there are no particles in the way – i.e. in a vacuum
- Conduction and convection require matter
- Heat transfer by convection is usually in the upwards direction, since hotter particles move more, take up more space and make that part of the fluid (liquid or gas) less dense
- All objects radiate heat – the hotter, the greater the amount of radiation
- Conduction can and does take place in fluids, although generally only to a minor extent since the particles are not in close proximity to each other, as in solids.
- Metals are good conductors of heat, since they contain free electrons that assist the passage of heat through the substance
- Non-metals are classed as thermal insulators
- Good conductors that are hot *feel* hot to touch because they quickly transfer heat to the contact point, whilst hot insulators don't feel so hot – the contact point cools on contact and the thermal energy is not quickly replaced. (the same applies to cold objects)

***Temperature, internal energy and thermal energy (heat) – differences explained:***

Temperature is a measure of the average kinetic energy of a substance.
The internal energy of a substance is the total kinetic and potential energy of the substance
Thermal energy (heat) is the energy transfer that results when a high temperature body is placed in thermal contact with a low temperature body.
It is incorrect to talk about the thermal energy of a substance, as it is incorrect to talk about temperature transfer.

## Amount of Substance (The mole)

Gas pressure does not depend on mass of particles, but rather, the number of particles of a given gas. For example 1000 molecules per cubic metre of hydrogen gas at room temperature will exert the same pressure as 1000 molecules per cubic metre of oxygen molecules – even though oxygen molecules are 16 times more massive than hydrogen molecules.

The above example uses simple, but unrealistic numbers. At room temperature and pressure, one cubic metre will contain about $2.5\times10^{25}$ molecules! We use a more convenient unit to measure "number of particles" – the mole.

The mole is thus defined as An amount of substance such that it contains the same number of molecules as there atoms in exactly 12g of carbon-12

## Avogadro Constant

This number is called the Avogadro constant, $N_A$, where
$N_A = 6.02\times10^{23} mol^{-1}$

## Molar mass

The molar mass of a substance is the mass of one mole of a particular substance. Molar masses of elements can easily found on the periodic table. For example, the molar mass of helium gas (consists of helium atoms) is 4g and the molar mass of oxygen gas (consists of $O_2$ molecules) is 16g x 2 = 32g

## Thermal Properties of Matter

### Specific Heat Capacity

The energy required to increase the temperature of 1 kilogram of a substance by 1 °C varies from one substance to another. This property is known as the specific heat capacity of the substance.

**Equation:** $$c=\frac{Q}{m\times\Delta T}$$

$c = \text{specific heat capacity}$

$Q = \text{energy required / released as a consequence of temperature change (joules)}$

$m = \text{mass of substance (kilograms)}$

$\Delta T = \text{temperature change} (^\circ C)$

***Example T3.1***

27 KJ of energy is needed to warm up 3 kg of a substance by 12 °C.
Find its specific heat capacity.

***Example T3.2***

When 500 grams of water cools down by 5°C it is found that approximately 10.5kJ of energy is given out – heating the cooler surroundings. Find an approximate value for the specific heat capacity of water

***Example T3.3***

Ice has a specific heat capacity of 2100 $Jkg^{-1}{}^{\circ}C^{-1}$ How much energy is needed to increase the temperature of a block of ice with a mass of 7.5kg from –18°C to –5°C?

**Variation in Specific Heat Capacity**

Different substances have different specific heat capacities because, per kilogram, they contain different numbers of molecules and because the chemical (bonding) properties are different for different substances

Water has an extremely high specific heat capacity. This makes it a very useful substance for cooling systems for car engines and other machinery. One kilogram of water will absorb a lot of energy whilst only increasing by a small temperature. (4200 J for 1 kg to increase by 1°C)

**Heat Capacity (Thermal Capacity)**

***Specific heat capacity*** relates to ***substances***. ***Heat capacity*** relates to ***objects***.

The heat capacity (thermal capacity) of an object is the energy needed to increase the temperature of the object by 1°C. (This quantity is not as useful as specific heat capacity)

Equation: $C = \dfrac{Q}{\Delta T}$

$C = heat\ capacity$

$Q = energy\ required/released\ as\ a\ consequence\ of\ temperature\ change\ (joules)$

$\Delta T = temperature\ change\ (^{\circ}C)$

***Example T3.4***

A wood-burning stove (fire) is used to heat up a room. The oven, which has a mass of 220kg, requires 1.66 MJ of heat energy for it to warm up, on a cold morning, from 9°C to 21°C.

(a) Find the heat capacity of the oven
(b) Assuming that the oven is made of only one material, find the specific heat capacity of this material.

**Change of state/phase**

*solid ↔ liquid*

$$\begin{pmatrix} solid \rightarrow liquid = "melting" \\ liquid \rightarrow solid = "freezing"\ or\ "solidification"\ or\ "fusion" \end{pmatrix}$$

Energy is required to change the state, or phase, of a substance from a solid to a liquid, and energy is released when a substance changes from a liquid to a solid. The energy needed to melt one kilogram of a substance is equal to the energy released when one kilogram of the same substance, in its liquid phase, freezes at constant temperature.

This energy is known as the latent heat of fusion. (Fusion is another word for freezing)

**Equation** $Q = ml$

$Q = \text{energy needed to melt the substance}$

$(\text{or energy released when substance freezes})$

$m = \text{mass of substance changing state}$

$l = \text{specific latent heat of fusion}$

***Example T3.5***

An electrical heater is used to melt 5 Kg of ice, which has already been warmed up to its melting point (0°C). It is found that 1.7 MJ is needed. Find the specific latent heat of fusion of water using this information.

$liquid \rightarrow gas\,(vapour)$ $\left(\begin{array}{l} liquid \rightarrow gas = \text{"vaporisation"} \\ gas \rightarrow liquid = \text{"condensation"} \end{array}\right)$

Energy is required to change the state, or phase, of a substance from a liquid to a gas, and energy is released when a substance changes from a gas to a liquid
The energy needed to vaporize one kilogram of a substance is equal to the energy released when one kilogram of the same substance, in its gas phase, condenses.

This energy is known as the latent heat of vaporization.

**Equation:** $Q = ml$

$Q = \text{energy needed to vaporize the substance}$

$(\text{or energy released when substance condenses})$

$m = \text{mass of substance changing state}$

$l = \text{specific latent heat of vaporization}$

***Example T3.6***

Given that the latent heat of vaporization of water is $2.26 \times 10^6\ Jkg^{-1}$ how much energy is needed to vaporize 500 grams of water?

## Molecular Structure of the Phases

Solid substances contain atoms or molecules that are fixed in one place. The particles do not move from one place to another (translate), but vibrate. Particles are fixed in place because of the attractive forces holding them together. The (vibrational) motion of the particles gives them their kinetic energy. The position of the particles, in an attractive field, gives the particles their potential energy (which is negative).

Liquid substances contain atoms or molecules that are able to move, but are still attracted to each other. The kinetic energy of the particles is now attributable to their translational motion. Motion is impeded by attractive forces between particles and by particle collisions. Since the particles are still in an attractive field, they still have potential energy (which is negative, but closer to zero than in solids).

Gaseous substances contain atoms or molecules that are completely separated and move around quickly, in straight lines until they collide with each other or an object and then they bounce. The kinetic energy of these particles is high because of their very high speeds (translational motion). Forces between particles are negligible (effectively zero), so the potential energy of a gas is usually assumed to be zero (unless under very high pressure, or very low temperature).

## Heating a Substance through its phase changes

At this level, for calculations, we generally assume:

- that a solid must be heated to its melting/freezing point before it begins to melt
- that the solid substance at its melting/freezing point completely melts before any of it increases in temperature
- that the melted, now liquid, substance must be heated to its boiling point before it begins to vaporize
- that the boiling liquid then continues to vaporize as more energy is added
- (it is then possible to heat up the vapour above the boiling point, but this is uncommon in practice since the vapour leaves the container and moves away from the heat source)

The energy changes occurring are as follows:

***Increasing the temperature of the solid:***

Energy needed $= mc\Delta T$
This energy results in an increase in the kinetic energy of the particles
The greater average separation of the particles means that there is also a slight increase in their potential energy

***Changing the state of the solid (at melting point) into a liquid (at same temperature)***

Energy needed $= ml$ ($l$ is specific latent heat of fusion)
This results in an increase in the potential energy of the particles to a point where the attractive forces are weak enough to allow translational movement of the particles.

***Increasing the temperature of the liquid:***

Energy needed $= mc\Delta T$ (note that the value for c is different to the solid substance)
This energy results in an increase in the kinetic energy of the particles
The greater average separation of the particles means that there is also a slight increase in their potential energy

***Changing the state of the liquid (at boiling point) into a gas (at same temperature)***

Energy needed $= ml$ ($l$ is specific latent heat of vaporization)
This results in an increase in the potential energy of the particles to a point where there are no longer attractive forces between them. The potential energy of the particles is now zero.

If the vapour (gas) is heated further, the particles move faster, their kinetic energies are increased and the temperature continues to increase.

**Evaporation of a liquid below its boiling point**

A liquid will evaporate at temperatures below its boiling point – for example a puddle evaporates without boiling.
The particles that escape from the liquid are those closest to the surface. They have to first gain kinetic energy, which is then converted into potential energy (as they separate from other particles). Once their potential energy has been increased to zero (and they no longer attract each other) they escape. The energy comes from either the surroundings, above the liquid, or from the particles below, or both. Particles below the surface transfer energy to the particles on the surface by colliding with them. If the surface particles gain enough speed from one or more such collisions they will escape.

The rate of evaporation of a liquid depends upon:

- The temperature of the liquid
- The temperature of the surroundings
- The amount of vapour already in the surroundings (if the gas above the liquid is saturated with vapour, no further ***net*** evaporation can take place – equilibriumis reached – rate of evaportaion = rate of condensation)
- The surface area of the liquid
- The nature of the liquid (volatility of liquid)

**Evaporation and Boiling – differences**

A liquid evaporates continually, even at low temperatures. Surface molecules gain sufficient energy from the bulk of the liquid to become gas molecules.

A liquid boils at a certain temperature (which depends on the external air pressure and on the substance). When this happens, molecules within the bulk of the liquid (not just at the surface) gain sufficient energy from surrounding molecules to become gas molecules, and hence form bubbles.

Water can be made to boil at quite low temperatures by decreasing air pressure (e.g. at top of mountains). Conversely, water boils at a higher temperature when external pressure is increased (e.g. pressure cookers)

## Kinetic Model of an Ideal Gas

The kinetic model of an ideal gas is a model that explains the macroscopic (bulk) properties of a gas, like temperature, pressure and volume.

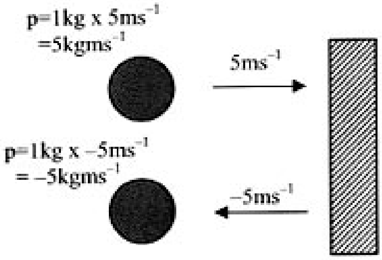
The assumptions of the model are:

Molecules are point molecules – they occupy no space
Molecules have random motion – so they tend to spread out evenly in a container
Collisions between pairs of molecules and between the walls of the container are elastic – so that the total kinetic energy of a gas left undisturbed will remain constant

These assumptions apply to an "ideal gas" – one that behaves perfectly. In reality, under normal conditions of temperature and pressure, gases do approximate closely to these assumptions and behave in a very similar way to an ideal gas.

## Pressure

We can explain how pressure arises on the walls of a container filled with gas by considering each gas particle as an elastic ball, perhaps like a billiard ball.
To keep numbers simple, imagine such a ball has a mass of 1kg and is travelling at a speed of $5ms^{-1}$ towards a wall. The diagram below shows the arrangement:
As the ball hits the wall its momentum must be rapidly changed (from $5kgms^{-1}$ to $-5kgms^{-1}$ in the example on the right). A force is required to do this. The force is provided by the wall. Newton's Third Law also applies here – the ball applies a force on the wall, and the wall applies a force on the ball.




If we assume that the time between collisions is 0.2 seconds – so that each collision takes, on average 0.2 seconds, then we could find the average force of this particle exerted on the container walls by as follows:

$$F = \frac{\Delta p}{\Delta t} = \frac{(-5-5)}{0.2} = -50N$$ (ignoring the minus, 50N)

This is the way that kinetic theory assumes gases to behave – ie. that gases are made up of many tiny spheres, each of which behaves as has just been described.

**Pressure - Definition**

Pressure is defined to be force per unit area ($P = \frac{F}{A}$) so it can be explained by the average force of all collisions, such as the one described above, acting over the surface area of the inside of the container.

Using this model it is easy to see that pressure is increased by:

- increasing the speed of the particles
- increasing the mass of the particles
- decreasing the area of the collision surface, by decreasing the volume of the gas (whilst maintaining the number of particles).

It also explains that for a fixed mass of (an ideal) gas:

| | | |
|---|---|---|
| Increasing volume at constant temperature | $\Rightarrow$ | pressure decreases |
| Increasing temperature at constant volume | $\Rightarrow$ | pressure increases |
| Increasing temperature at constant pressure | $\Rightarrow$ | volume increases |

**Temperature**

Temperature is a measure of the average kinetic energy of the molecules of an ideal gas.

This means that if gas molecules are made to increase in speed, the gas will increase in temperature.

Thus, if a syringe of gas is reduced in volume by pushing in the plunger, we can explain its temperature increase by the fact that the gas molecules will collide with the now moving container wall and will rebound at a faster speed that its speed of approach. Since it gains speed, it has increased in kinetic energy and the temperature of the gas will increase. The temperature increase can also be explained directly in terms of energy arguments: work is done on the gas (a force is applied through a distance) and so the gas must have gained energy.