OCR A Physics A-level

Topic 5.1: Thermal physics

Notes

Temperature

Scales of temperature

Temperature is a number used to indicate the **level of hotness** of an object on some scale. The **Celsius scale** is commonly used to measure temperature. It marks the melting point of pure ice as 0°C, and the boiling point of water as 100°C, under atmospheric pressure. The **thermodynamic scale** of temperature uses the triple point of pure water, 273.16K and absolute 0 as its fixed points, and it is measured in **kelvin**. A temperature increase of 1 kelvin is equal to an increase of 1 Celsius, but the 0 point is absolute 0, so T(K) = T(°C) + 273.16

Thermal equilibrium

If two substances are in contact, and one is hotter than the other, then there will be a **net flow** of thermal energy from the hotter object to the cooler object. The hotter object will cool down and the cooler one will warm up, until they are at the same temperature, where there will be no net energy transfer. Two objects are in **thermal equilibrium** when there is no net transfer of thermal energy between them.

Solids, liquids, and gases

The kinetic model

In **solids**, atoms are closely packed together. There are **strong electrostatic forces of attraction** between molecules, and the molecules also have negative electrostatic potential energy (negative because external energy is required to separate the molecules). The molecules have kinetic energy, which allows them to **vibrate around their fixed positions**.

In the **liquid** phase, the molecules are still have a **greater mean separation** than in solids, but are still close together. They have more kinetic energy, so they can move around. There is still electrostatic attraction, but it is weaker than in solids. The negative electrostatic potential energy value is greater (less negative).

In the **gaseous** phase, the molecules have the most kinetic energy, allowing them to move freely and rapidly, and collide elastically with each other. These collisions result in the molecules travelling with **random speed and direction**. The electrostatic attraction between molecules is negligible, and the electrostatic potential energy is at a maximum, of 0J.

Brownian motion

The molecules of a gas travel in random directions with random velocity. This is called **Brownian motion**, and can be seen by looking at smoke particles in air. The smoke particles are visible under a microscope, and exhibit random motion because of their collisions with the molecules in air, which result in a transfer of momentum in random ways.

Internal energy

Internal energy

The **internal energy** of a substance is defined as the sum of the randomly distributed kinetic and potential energies associated with the atoms or molecules which make up the substance. When a substance is heated, but remains in the same state, the kinetic energy of the molecules increases, but the potential energy remains the same. When a substance changes state (from solid -> liquid -> gas) the potential energy increases, but the kinetic energy remains the same. The temperature of the substance will also stay the same whilst it changes phase, because the thermal energy is being used to **overcome electrostatic bonds** between molecules.

Absolute zero

Absolute zero is 0K, and is the point where all molecules in a substance **stop moving completely**. This is also where the substance has minimal internal energy. The internal energy here is entirely due to the electrostatic potential energy, as the molecules do not have any kinetic energy.

Thermal properties of materials

Specific heat capacity

The **specific heat capacity**, c of a substance is defined as the energy required per unit mass to increase the temperature by 1K. The specific heat capacity is given by the equation

$$E = mc\Delta\theta$$

where E is the energy supplied to the substance, m is the mass of the substance, and $\Delta\theta$ is the change in temperature of the substance. It has the units $\mathrm{Jkg^{-1}K^{-1}}$.

The **method of mixtures** can be used to determine specific heat capacity. Known masses of two substance at different known temperatures are mixed together until they reach **thermal equilibrium**, at which point the final temperature is measured. The energy transfer from the hotter substance is the same as the energy transfer to the cooler substance, so the equation $E = mc\Delta\theta$ can be equated for both substances. If the specific heat capacity of one of the substances is known, then it can be determine for the other substance.

The specific heat capacity of a substance can be calculated more accurately by using an **electrical heater** to heat a substance. A known mass of a substance is heated by an electrical heater with known power (or measured p.d. and current) for a given time. The initial and final temperatures of the substance are measured. As energy transfer is equal to power (VI) multiplies by time, we can use the equation $VI = \frac{mc\Delta\theta}{t}$, and rearrange to find c. An **insulator** is used around the substance to minimise external energy transfer, increasing accuracy.

Specific latent heat

Energy is required in order for a substance to **change phase**. The specific latent heat of fusion, L_f, is the energy required per unit mass to change the phase of a substance from **solid to liquid**. The specific latent heat of vaporisation, L_v, is the energy required per unit mass to change the phase of a substance from **liquid to gas**. The formula

$$E = mL$$

can be used to determine specific latent heat, L, where E is the energy required to change the phase of a substance of mass m. The units for L are Jkg^{-1}.

The specific latent heat of a substance can be determined using a similar set-up to the experiment for specific heat capacity. An electrical heater with known power heats the object. When an object is changing phase, the temperature remains constant, so the temperature is monitored and the duration where the **temperature is constant** is used as the time when calculating the energy transferred to the substance.

Kinetic theory of gases

Amount of substance

The amount of a substance can be measured in the SI base unit of the **mole**. One mole is the amount of substance containing 6.02×10^{23} particles (atoms or molecules). This value is **Avogadro's constant**. The number of particles in a substance can be determined by multiplying the number of moles of the substance by Avogadro's constant. The number of moles, n, of a given substance can by determined using the formula

$$n = \frac{m}{M}$$

where m is the mass of the substance, and M is the **molar mass** (in grams, which is the same as the nucleon number for the atom/molecule) of the particles that make up the substance.

The kinetic theory of gases

The kinetic theory of gases is a model which can be used to describe how particles within in **ideal gas** behave. Certain assumptions are made in order to model a gas as an ideal gas.

- The gas contains a large number of atoms which move with random, rapid motion.
- The volume of the gas atoms is negligible when compared to the total volume of the gas.
- All collisions between atoms, with other atoms and with the walls of the container they are in, are perfectly elastic.
- The time taken for atoms to collide is negligible compared to the time between collisions.
- The electrostatic forces between atoms are negligible, except for when the atoms are colliding.

Pressure

The kinetic theory of gases can be used to understand how gas in a container produces **pressure**. As the collisions between atoms and the wall of the container are **perfectly elastic**, the atoms rebound from the wall at the same speed they travel in at. This makes their change in momentum, p, (given by p = m(v-u)) equal to 2mv. As the change in momentum is equal to force multiplied by time, the average force exerted on the atom by the wall is given by $F = \frac{2mv}{t}$. Using Newton's third law, the atom also exerts an equal and opposite force on the wall of the container. The total pressure on the wall is equal to the sum of the force of each collision between atoms in the gas and the wall, and the area of the wall.

Ideal gas laws

There are two ideal gas laws which can be used to derive the equation of state for ideal gases. **Boyle's law** states that *for a fixed mass of gas at constant temperature, the pressure is inversely proportional to the volume.* **Charles' law** states that *for a fixed mass of gas at a constant pressure, the volume is directly proportional to temperature*. These laws can be combined to show that $\frac{pV}{T} = k$, where k is a constant. From this we can derive:

$$pV = nRT$$

where p is the pressure of the gas (Pa), V is the volume the gas is contained in (m^3), n is the number of moles of gas (mol), R is the molar gas constant (8.31 $Jmol^{-1}K^{-1}$), and T is the temperature of the gas (Kelvin).

Investigating Boyle's law

Boyle's law states that the pressure exerted by a fixed amount of gas is inversely proportional to its volume at a constant temperature. To investigate this experimentally, a **sealed syringe** can be filled with gas and connected to a **pressure gauge**. The syringe can be used to vary the volume of the container, and the values for volume and pressure recorded. When a graph of pressure against 1/volume is plotted, a **straight line** should be produced, showing a constant relationship. To increase accuracy in this experiment, the syringe should be lowered **slowly** so that no heat is produced from friction.

Estimating absolute zero using gas

To determine the value of absolute zero in °C, a **sealed container** of air, connected to a pressure gauge, is placed in a water bath. The temperature of the water is varied, and the values of temperature and pressure and recorded. When pressure is plotted against temperature, a linear graph will be produced. At absolute zero, the gas molecules will have **no kinetic energy**, so there will be no collisions with the container walls, resulting in there being no gas pressure. By extrapolating the graph back the **x intercept** can be found, and this is equal to absolute 0.

Root mean square speed

Root mean square speed

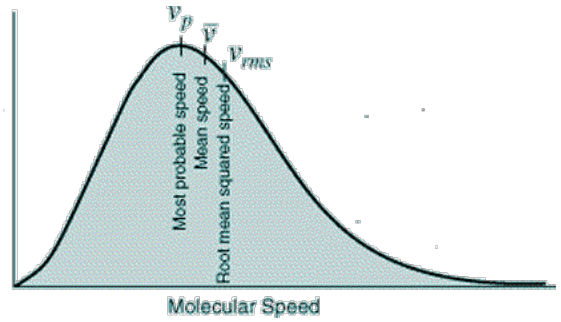
The pressure exerted by a gas, and the mean kinetic energy of molecules in the gas, are related to the **root mean squar**e (r.m.s.) speed of the molecules. The root mean square speed, *c*, is determined by summing the square of all of the individual velocities of molecules, dividing by the number of molecules, N, and then finding the square root of this value.

The root mean square speed can be used to find the **pressure** of a gas at the microscopic level, using the equation

$$pV = ⅓Nm\overline{c^2}$$

where *p* is the pressure, *V* is the volume, *N* is the number of molecules, *m* is the mass of a single molecule, and $\overline{c^2}$ is the r.m.s

The Maxwell-Boltzmann distribution



Particles in a gas move with random velocities, in random directions. This means some of the molecules are moving very fast, whilst other molecules are barely moving at all. **The Maxwell-Boltzmann distribution** shows the number of molecules with each speed, against speed *c*. The area under the graph represents the total number of molecules. As the temperature of the gas increases, the peak of the graph shifts to a **higher speed**, and the distribution becomes **more spread out**.

The Boltzmann constant

The **Boltzmann constant** (*k*) is equal to the molar gas constant (*R*), divided by Avogadro's Constant (N_A). Its value is $1.38\text{x}10^{-23}$ JK^{-1}. It can be used derive a second equation for the state of an ideal gas. The equation pV = nRT can be written as

$$\mathrm{pV} = \frac{\mathrm{NRT}}{N_A}$$

because *n*, the number of moles, is equal to N, the number of molecules, divided by Avogadro's constant. As $k = R/N_A$, we can then write this equation as

$$pV = NkT$$

Mean kinetic energy and temperature

The **kinetic energy** of gas molecules in an ideal gas is proportional to the **temperature** (which must be measured in kelvin). At a given temperature, every gas molecule has the same mean kinetic energy, so more massive molecules have lower r.m.s. speeds.

We can relate the two pressure equations, $pV = NkT$ and $pV = ⅓N m\overline{c^2}$ to produce the equation

$$kt = \frac{1}{3} m\overline{c^2}$$

The equation for kinetic energy is 1/2mv2, so by adjusting the equation, we can produce

$$\frac{3}{2} kt = \frac{1}{2} m\overline{c^2}$$

This shows that $E_k = \frac{3}{2} kt$, where E_k is the mean kinetic energy of the gas molecules

Internal energy of an ideal gas

The internal energy of an ideal gas is the sum of the kinetic and potential energies. Since we assume there are no electrostatic forces between molecules in an ideal gas, there is **no potential energy**. This means that for an ideal gas, the kinetic energy is equal to the total internal energy, hence the internal energy is proportional to temperature.