Edexcel IAL Physics A-level

Topic 5.3: Thermodynamics

Notes

5.3 - Thermodynamics

5.3.125 - Thermal energy transfer

You can measure the amount of energy required to change the temperature of a substance using the following formula:

$$\Delta E = mc\Delta\theta$$

Where **ΔE** is energy required, **m** is the mass, **c** is the specific heat capacity, and **Δθ** is the change in temperature.

The **specific heat capacity (c)** of a substance is the amount of energy required to increase the temperature of 1 kg of a substance by 1 °C/1 K, **without** changing its state.

You can measure the amount of energy required to change the state of a substance using the following formula:

$$\Delta E = L\Delta m$$

Where **ΔE** is energy required, **L** is the specific latent heat and **m** is the mass.

The **specific latent heat (L)** of a substance is the amount of energy required to change the state of 1 kg of material, **without** changing its temperature. There are two types of specific latent heat:
the **specific latent heat of fusion** (when solid changes to liquid) and **specific latent heat of vaporisation** (when liquid changes to gas).

Below are some example questions using the above equations.

A kettle has a power of 1200 W, and contains 0.5 kg of water at 22°C, how long will it take for the water in the kettle to reach 100°C? (specific heat capacity of water = 4200 J/kg°C)

Firstly, you must find the energy required to increase the temperature of the water to 100°C using $\Delta E = mc\Delta\theta$.

$\Delta E = 0.5 \times 4200 \times (100 - 22) = 2100 \times 78 =$ **163800 J**

Power is the energy transferred over time, therefore to find the value of time taken we must divide the energy required by the power.

$P = \frac{Q}{t} \rightarrow t = \frac{Q}{P}$ $\quad\quad$ $t = \frac{163800}{1200} =$ **136.5 s**

An ice cube of mass 0.01 kg at a temperature of 0°C is dropped into a glass of water of mass 0.2 kg, at a temperature of 19°C. What is the final temperature of the water once the ice cube has fully melted? (specific heat capacity of water = 4200 J/kg°C, specific latent heat of fusion of ice = 334×10^3 J/kg)

Firstly, find the energy required to change the state of the ice.

$\Delta E = L\Delta m$ $\quad\quad$ $\Delta E = 0.01 \times 334 \times 10^3 =$ **3340 J**

Next, you must set up a pair of simultaneous equations to show the energy transfer in the water and in the ice separately. As we know that the energy transfer is the same in both as the system is closed, we can equate these values to find the final temperature (T).

For ice: $\Delta E = L\Delta m + mc\Delta\theta$ (because the ice changes state **and** temperature)

$\Delta E = 3340 + 0.01 \times 4200 \times (T - 0)$ $\quad \Delta E = 3340 + 42T$

For water: $\Delta E = mc\Delta\theta$

$\Delta E = 0.2 \times 4200 \times (19 - T)$ $\quad \Delta E = 15960 - 840T$

Set them equal: $3340 + 42T = 15960 - 840T$

$882T = 12620$

$T =$ **14.3 °C**

5.3.126 - Internal energy

The **internal energy** of a body is equal to the sum of all of the kinetic energies and potential energies of **all** its particles. The kinetic and potential energies of a body are **randomly distributed**.

When the state of a substance is changed, its internal energy also changes, this is because the **potential energy of the system changes, while the kinetic energy of the system is kept constant**.

5.3.127 - Absolute zero

Absolute zero (- 273°C), also known as 0 K, is the lowest possible temperature, and is the temperature at which particles have **no kinetic energy** and the volume and pressure of a gas are zero.

The absolute scale of temperature is the **kelvin scale**. A change of 1 K is equal to a change of 1°C, and to convert between the two you can use the formula:

$$K = C + 273$$

Where **K** is the temperature in kelvin and **C** is the temperature in Celsius.

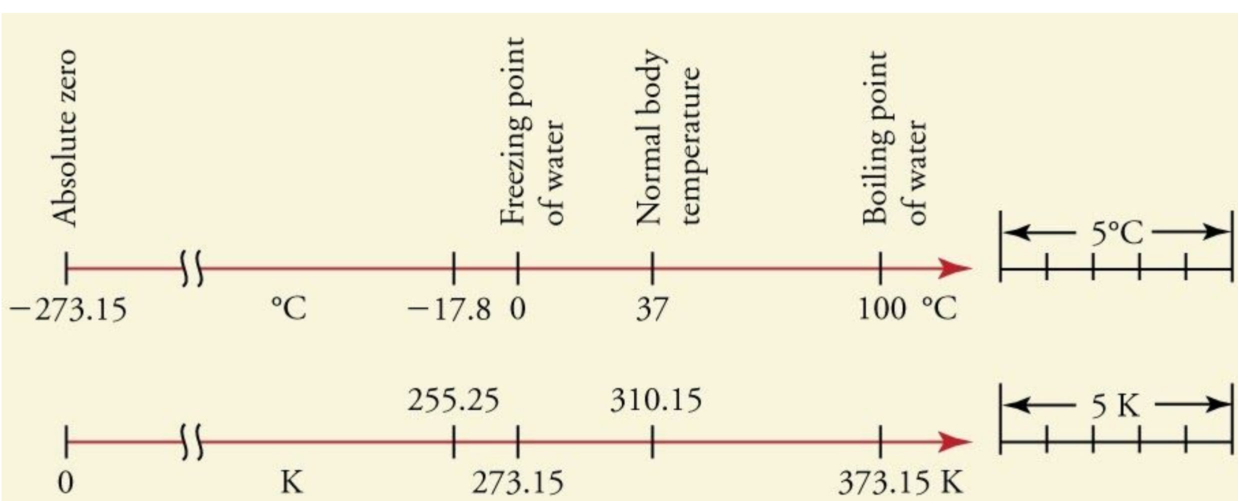


Image source: OpenStax College, CC BY 4.0, Image is cropped and fahrenheit scale is removed

The average kinetic energy of molecules and their absolute temperature are related by the following equation:

$$\text{Average molecule kinetic energy} = \frac{3}{2}kT$$

Where **k** is the Boltzmann constant and **T** is the temperature in kelvin.

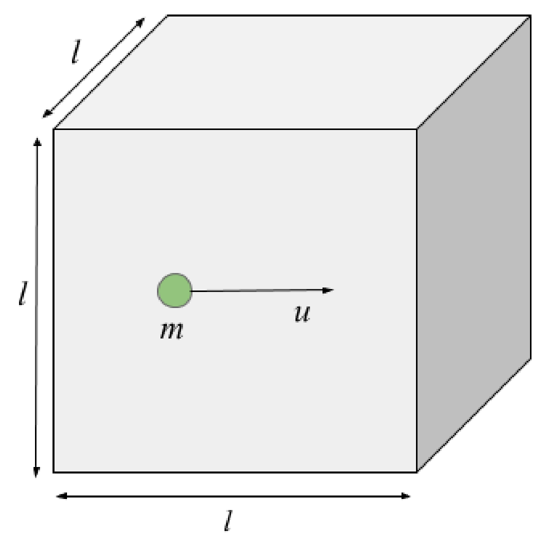
As you can see, the average kinetic energy of a gas molecule is **directly proportional** to temperature (in Kelvin).

5.3.128 - Kinetic theory model

The **kinetic theory model** equation relates several features of a fixed mass of gas, including its pressure, volume and mean kinetic energy. There are several underlying **assumptions**, which lead to the derivation of this equation, these assumptions and the derivation are outlined below.

Assumptions -

- **No intermolecular forces** act on the molecules
- The **duration of collisions is negligible** in comparison to time between collisions
- The motion of molecules in **random**, and they experience **perfectly elastic collisions**
- The motion of the molecules follows **Newton's laws**
- The molecules **move in straight lines** between collisions



Derivation -

1. First, you must consider a cube with side lengths l, full of gas molecules. One of these molecules, has a mass m and is travelling towards the right-most wall of the container, with a velocity u. Assuming it collides with this wall elastically, its **change in momentum** is $mu - (-mu) = 2mu$.
2. Before this molecule can collide with this wall again it must travel a distance of $2l$. Therefore the time between collisions is t, where $t = \frac{2l}{u}$.

3. Using these two bits of information we can find the **impulse**, which is the rate of change of momentum of the molecule. As impulse is equal to the **force** exerted, we can find **pressure** by dividing our value of impulse by the area of one wall: l^2 .

$$F = \frac{2mu}{\frac{2l}{u}} = \frac{mu^2}{l} \qquad P = \frac{\frac{mu^2}{l}}{l^2} = \frac{mu^2}{l^3} = \frac{mu^2}{V}$$

As shown, the above equation can be further simplified because l^3 is equal to the cube's volume (V).

4. The molecule we have considered is one of many in the cube, the total pressure of the gas will be the sum of all the individual pressures caused by each molecule

$$P = \frac{m((u_1)^2+(u_2)^2+...+(u_n)^2)}{V}$$

5. Instead of considering all these speeds separately, we can define a quantity known as **mean square speed**, which is exactly what it sounds like, the mean of the square speeds of the gas molecules. This quantity is known as $\overline{u^2}$, and we multiply it by N, the number of particles in the gas, to get an estimate of the sum of the molecules' speeds.

$$P = \frac{Nm\overline{u^2}}{V}$$

6. The last step is to consider all the directions the molecules will be moving in. Currently we have only considered one dimension, however the particles will be moving in all 3 dimensions. Using pythagoras' theorem we can work out the speed the molecules will be travelling at:

$$\overline{c^2} = \overline{u^2} + \overline{v^2} + \overline{w^2}$$

Where u, v, and w are the components of the molecule's velocity in the x, y and z directions. As the motion of the particles is random we can assume the mean square speed in each direction is the same.

$$\overline{u^2} = \overline{v^2} = \overline{w^2} \quad \therefore \quad \overline{c^2} = 3\overline{u^2}$$

The last thing to do now it put this into our equation and rearrange:

$$pV = \tfrac{1}{3}Nm\overline{c^2} \quad \text{or} \quad pV = \tfrac{1}{3}Nm< c^2 >$$

As $\overline{c^2}$ and $< c^2 >$ are equivalent

5.3.128 - Ideal gases

In an **ideal gas** there is no other interaction other than **perfectly elastic collisions** between the gas molecules, which shows that no intermolecular forces act between molecules. As potential energy is associated with intermolecular forces, an ideal gas has **no potential energy**, therefore its internal energy is equal to the sum of the kinetic energies of all of its particles.

The following equation describes the relation between the pressure (p), volume (V), number of molecules (N) and absolute temperature (T) of an **ideal gas**:

$$pV = NkT$$

Where **k** is the boltzmann constant.

5.3.129 - Average kinetic energy of molecules

By using the kinetic theory model equation and the ideal gas equation (from above), you can **derive** the equation for the average kinetic energy of a molecule (mentioned in 5.3.148).

$$pV = \frac{1}{3}Nm< c^2 > \qquad\qquad pV = NkT$$

First, set the above equations equal to each other and simplify.

$$\frac{1}{3}Nm< c^2 > = NkT$$
$$\frac{1}{3}m< c^2 > = kT$$

Finally, make the left hand side of the equation resemble the equation for the kinetic energy of an object (E_k = ½ mv^2), by multiplying both sides by 3/2.

$$\frac{3}{2} \times \frac{1}{3}m< c^2 > = \frac{3}{2}kT$$
$$\frac{1}{2}m< c^2 > = \frac{3}{2}kT$$