

physics

Thermal

Name \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Teacher \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

# *Internal Energy*

Heat, temperature and internal energy

The internal energy of a substance is due to the vibrations/movement energy of the particles (kinetic) and the energy due to the bonds holding them together (potential).

***Solids:*** In a solid the particles are arranged in a regular fixed structure, they cannot move from their position in the structure but can vibrate. The internal energy of a solid is due to the kinetic energy of the vibrating particles and the potential energy from the bonds between them.

***Liquids:*** In a liquid the particles vibrate and are free to move around but are still in contact with each other. The forces between them are less than when in solid form. The internal energy of a liquid is due to the kinetic and potential energies of the particles but since they are free to slide past each other the potential energy is less than that of it in solid form.

***Gases:***  In a gas particles are free to move in all directions with high speeds. There are almost no forces of attraction between them. The internal energy of a gas is almost entirely due to the kinetic energy of the particles.



# *Temperature*

Temperature is a measure of the kinetic energies of the particles in the substance. As we can see from the graph something with a high temperature means the particles are vibrating/moving with higher average speeds that a substance at a lower temperature.

It is possible for two objects/substances to be at the same temperature but have different internal energies.

# *Heat*

Heat is the flow of thermal energy and it flows from a high temperature to a low temperature.

If two objects are at the same temperature we say that they are in thermal equilibrium and no heat flows.

*If object A is in thermal equilibrium with object B and object B is in thermal equilibrium with object C then A and C must be in thermal equilibrium with each other.*

Get into a hot or cold bath and energy is transferred:

In a cold bath thermal energy is transferred from your body to the water.

In a hot bath thermal energy is transferred from the water to your body.

As the energy is transferred you and the water become the same temperature. When this happens there is no longer a flow of energy 🡪 so no more heat. You both still have a temperature due to the vibrations of your particles but there is no longer a temperature difference so there is no longer a flow of energy.

# *Temperature Scale*

The Celsius scale was established by giving the temperature at which water becomes ice a value of 0 and the temperature at which it boils a value of 100. Using these fixed points a scale was created.

# *Absolute Zero and Kelvins*

In 1848 William Thomson came up with the Kelvin scale for temperature. He measured the pressure caused by gases at known temperatures (in °C) and plotted the results. He found a graph like this one.

By extrapolating his results he found the temperature at which a gas would exert zero pressure. Since pressure is caused by the collisions of the gas particles with the container, zero pressure means the particles are not moving and have a minimum internal energy. At this point the particle stops moving completely and we call this temperature absolute zero, it is not possible to get any colder. This temperature is -273°C.

1 Kelvin is the same size as 1 degree Celsius but the Kelvin scale starts at absolute zero.

°C = K – 273 K = °C + 273

**Temperature, internal energy and states of matter**

1. Describe the arrangement of atoms, the forces between the atoms and the motion of the atoms in:
2. A solid. [3]
3. A liquid. [3]
4. A gas. [3]
5. A small amount of gas is trapped inside a container. Describe the motion of the gas atoms as the temperature of the gas within the container is increased. [3]
6. a) Define the internal energy of a substance. [1]

b) The temperature of an aluminium block increases when it is placed in the flame of a Bunsen burner. Explain why this causes an increase in its internal energy. [3]

c) An ice cube is melting at a temperature of 0 °C. Explain whether its internal energy is increasing or decreasing as it melts at 0 °C. [4]

1. a) A glass of water is placed in direct sunlight during a hot summer’s day. The temperature of the water increases.
2. Describe the change in motion of the molecules of water. [1]
3. Explain whether or not there is a change in the internal energy of the water. [1]

b) Complete the table below for each of the processes shown. Write “increase”, “decrease” or “no change” as appropriate.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Kinetic energy of the particles.  | Potential energy of the particles.  | Internal energy.  |
| An aluminium block increasing its temperature from room temperature to 300 °C.  |  |  |  |
| Water boiling at 100 °C and changing into steam at 100 °C.  |  |  |  |
| Water at 0 °C changing into ice at ­15 °C |  |  |  |

**Temperature scale measurements**

Fill in the table below with the missing temperatures.

|  |  |  |
| --- | --- | --- |
|  | Absolute scale (K) | Celsius scale (°C) |
| Absolute zero | 0 |  |
| Boiling point of hydrogen |  | -252.87 |
| Freezing point of water | 273.15 |  |
| Triple point of water |  | 0.01 |
| Room temperature | 293.15 |  |
| Boiling point of water |  | 100 |
| Melting point of tungsten | 3965 |  |

1. Fig. 6.1 shows the apparatus used to observe Brownian motion using pollen grains suspended in a liquid.



1. State **two** conclusions that may be deduced about the molecules of the liquid from the motion of the pollen grains observed with the microscope.

[2]

 (ii) Suggest how the motion of these pollen grains could be increased.

 **[1]**

2. Define the internal energy of a substance. [1]

3. A block of paraffin wax is melting at a constant temperature of 52 °C. Use the behaviour of paraffin molecules to describe and explain the changes to the internal energy of the molecules of the paraffin wax as it melts. [4]

# *Specific Heat Capacity*

The specifics

We know that when we heat a substance the temperature will increase. The equation that links heat (energy) and temperature is:



*c* is the specific heat capacity which is the energy required to raise the temperature of 1 kg of a substance by 1 degree. It can be thought of as the heat energy 1 kg of the substance can hold before the temperature will increase by 1 degree.

**Specific Heat Capacity is measured in Joules per kilogram per Kelvin, J/kg K or J kg-1 K-1**

# *Water Analogy*

We can think of the energy being transferred as volume of water. Consider two substances: one with a high heat capacity represented by 250 ml beakers and one with a low heat capacity represented by 100 ml beakers. When a beaker is full the temperature of the substance will increase by 1 degree.

We can see that 2 litres of water will fill 8 of the 250 ml beakers or 20 of the 100ml beakers meaning the same amount of energy can raise the temperature of the first substance by 8 degrees or the second by 20 degrees.

# *Changes of State*

When a substance changes state there is no change in temperature.

When a solid is heated energy is transferred to the particles making them vibrate more which means the temperature increases. The potential energy of the solid remains constant but the kinetic energy increases.

At melting point the particles do not vibrate any faster, meaning the kinetic energy and temperature are constant. The bonds that keep the particles in a rigid shape are broken and the potential energy increases.

In liquid form the particles are still in contact with each other but can slide past each other. As more energy is transferred the particles vibrate more. The kinetic energy increases but the potential energy is constant.

At boiling point the particles do not vibrate any faster, meaning the kinetic energy and temperature are constant. The bonds holding the particles together are all broken, this takes much more energy than when melting since all the bonds need to be broken.

When a gas is heated the particles move faster, meaning the kinetic energy and temperature increases. The potential energy stays constant.

# *Specific Latent Heat*

Different substances require different amounts of energy to change them from solid to liquid and from liquid to gas. The energy required is given by the equation:



*l* represents the specific latent heat which is the energy required to change 1 kg of a substance from solid to liquid or liquid to gas without a change in temperature.

**Specific Latent Heat is measured in Joules per kilogram, J/kg or J kg-1**

The specific latent heat of fusion is the energy required to change 1 kg of solid into liquid

The specific latent heat of vaporisation is the energy required to change 1 kg of liquid into gas.

As we have just discussed, changing from a liquid to a gas takes more energy than changing a solid into a gas, so the specific latent heat of vaporisation is higher than the specific latent heat of fusion.

***Specific Heat Capacity***

|  |  |
| --- | --- |
| Substance | Specific heat capacity (Jkg-1K-1) |
| Water | 4200 |
| Copper | 385 |
| Iron | 440 |
| Soapstone | 1000 |

1. Kettles typically can hold 1.70 litres of water. Calculate the energy required to heat 1.70 litres of water from 22.0°C to 100.0°C.

2. Ice has a very different heat capacity to water. A loss of 735 J is required to cool 50.0g of ice from -3.00°C to -10.0°C. Calculate the specific heat capacity of ice.

3. A unknown mass of copper experiences a temperature rise from 2.50°C to 21.0°C. The copper gained 2671J of thermal energy during this rise. Calculate the mass of the copper.

4. A 1.45kg iron rod at 293K is heated in a furnace during which it gains 240.0 kJ of thermal energy. Calculate the rod’s final temperature.

5. An electric kettle has a power rating of 2.1 kW. It is filled with 1.5 kg of water at a temperature of 20 °C.

* 1. How long after it is switched on will it start to boil?
	2. What is happening to the energy of the particles as they are heated?

6. 0.38 kg of a liquid at 12 °C is heated in a copper can weighing 0.9 kg by an electrical heater of power 20 W for 3 minutes. It reaches a temperature of 17 °C. Assuming no heat losses to the surroundings, calculate a value for the specific heat capacity of the liquid.

7. This question is about the operation of an electrically powered shower designed by an electrical firm.



The water enters the heater at a temperature of 14 °C. At the maximum flow rate of 0.070 kg s−1, the water leaves the shower head at a temperature of 30 °C.

(i) Calculate the rate at which energy is transferred to the water. Give a suitable unit for your answer.

rate of energy transfer = ............................. unit .............. **[3]**

(ii) Explain why water is used in hot water systems and car radiators.

 (*2 marks*)

8. A metal block of mass 200g is placed into a container with boiling water until thermal equilibrium is reached. It is then removed and placed quickly into another container with 100g of water at 20⁰C. The maximum temperature recorded is 34⁰C. Calculate the specific heat capacity of the metal block.

Specific heat capacity of metal block = ………………………………….J kg-1 K-1 [3]

9. An electric water heater has a flow rate of 25.0 kg per minute. The water enters the heater at 18.0°C and leaves at 30.0°C. Calculate the power rating of the heater.

………………………………..kW

10. A 0.8 kg block of copper at a temperature of 76 °C is placed in 2.0 kg of water at 15 °C. Assuming no loss of heat to the surroundings, calculate the final temperature of both the copper and the water.

 (*3 marks*)

11. An experiment was conducted to determine the specific heat capacity of a metal solid using the method of mixture technique. The initial temperature of the water and calorimeter was 20 °C. The mass of the calorimeter used was 400 g and the specific heat capacity of the calorimeter was 450 J kg-1 K-1. 600 g of the metal solid was placed into 0.2 kg of water with a specific heat capacity of 4200 J kg-1 K-1. The metal solid was originally placed in water at 90 °C. Calculate its specific heat capacity from this method, assuming no other heat losses and a final equilibrium temperature of 40 °C. (*3 marks*)

12. You are provided with a small bottle of cooking oil and standard physics laboratory equipment. With the help of a **labelled** diagram, describe an electrical experiment to determine the specific heat capacity c of the oil.
State **two** sources of uncertainty in your measurements and discuss how these could be reduced.

  In your answer, you should use appropriate technical terms spelled correctly.

**[6]**

13. This question is about the determination of the specific heat capacity of aluminium.

An electrical heater is used to raise the temperature of a 1.0 kg aluminium block in the circuit shown in Fig. 1.1.

The switch is closed, switching the heater on for ten minutes before the switch is opened, which turns the heater off.

The temperature of the block is recorded at one minute intervals for fifteen minutes.



Fig. 1.1

Readings are taken of potential difference across the heater and current through the heater every two minutes. The results are shown in the table.

|  |  |  |  |
| --- | --- | --- | --- |
| Time *t* / minutes | Potential difference *V* / V  | Current *I* /A  | Power *P* / W  |
| 0 |  | 2.30 | 19.8 |
| 2 | 8.67 | 2.35 | 20.4 |
| 4 | 8.74 |  | 20.3 |
| 6 | 8.75 | 2.42 | 21.0 |
| 8 | 8.69 | 2.39 | 20.8 |
| 10 | 8.70 | 2.41 |  |

1. Complete the missing values in the table. [3]
2. Calculate the mean power. Include the uncertainty in the value.

mean power = ............................. ± ............................. W [2]

Fig. 1.2 shows a graph of temperature against time.



Fig. 1.2

|  |  |
| --- | --- |
|   (b). | 1. Use data from the first ten minutes of the graph and your answer to (a)(ii) to show that the specific thermal capacity of aluminium is about 1000 J kg−1K−1.

[3]1. Use Fig. 1.2 to estimate the maximum rate of cooling when the switch is opened.

maximum rate of cooling = .......................K min−1[2] |

(c) The total percentage uncertainty in the investigation is found to be 5 %. The accepted value of the specific thermal capacity of aluminium is 897 J kg–1 K−1.

Calculate the percentage difference between your calculated value from (b)(i) and the accepted value and use this to comment on the accuracy of the investigation. Suggest reasons for the difference between the investigation value and the accepted value.

[4]

***Specific Latent Heat***

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Material | Specific heat capacity (J kg−1 K−1) |  | Change of state of water | Specific latent heat (J kg−1) |
| Aluminium |  900 |  | Fusion |   334 000 |
| Water (Liquid) | 4200 |  | Vaporisation | 2 260 000 |
| Copper |  400 |  |  |  |

1. How much thermal energy must be removed from 5 kg of water at 0 °C to turn it into ice? What happens to the energy of the particles as the water changes state?
2. Calculate the energy released when 5.70 litres of water at 0.00°C freezes.
3. How much copper can be melted using 620.0 MJ of thermal energy. Assume the copper is already at its melting point.
4. 12500 kg of molten rock solidifies by releasing 5.25 GJ of thermal energy. Calculate the latent heat of fusion of this rock.
5. An unknown mass Ice starts at -5.00°C and is heated until it forms vapour at 100.0°C. The total energy absorbed by the water during this process is 509 kJ. Calculate the mass of the ice.
6. 100.0g of ice at -5.00°C is added to 500.0ml of water at 19.0°C. The ice eventually melts leaving water in thermal equilibrium.
7. Write an equation for the total energy gained by the melted ice, using T as the final temperature of the resulting extra water.
8. Write an equation for the energy lost by the initial water, using T as the final temperature.
9. Solve for the final temperature of the mixture, assuming no exchange of energy with the surroundings.
10. An electrical heating element is used to heat an insulated container of water from room temperature to boiling point and then to vaporise a small amount of the water. The data from this procedure is shown below:

Room temperature = 20⁰C Starting mass of water = 120g

PD across heater = 11.8V

Current through heater = 4.8A

Total time of procedure = 15 minutes

a) Calculate the total energy transferred to the water during the procedure [2]

total energy transferred = ………………………..J

b) Calculate the minimum time from turning the heater on before the water started to boil [2]

minimum time of heating………………………….s

c) Calculate the minimum mass of water left after the heater was turned off [2]

minimum mass of water left in container = ………………………g

d) Explain why it was necessary to use the term “minimum” in the above questions.

…………………………………………………………………………………………

…………………………………………………………………………………………

…………………………………………………………………………………………[2]

1. A coffee machine passes steam at 100 °C into 0.18 kg of cold coffee to warm it. Assuming the specific heat capacity of coffee is the same as that of water, what mass of steam must be supplied if the temperature of the coffee is raised from 14 °C to 85 °C.

 [3]

9. 3 kg of molten lead (melting point 600 K) is allowed to cool down until it has solidified. The temperature of the lead falls from 605 K to 600 K in 10 s, remains constant at 600 K for 300 s, and then falls to 595 K in a further 8.4 s. Assume that the rate of loss of energy is constant, and the specific heat capacity of solid lead is 140 J kg–1 K–1.

 Calculate:

a the rate of loss of energy from the lead

[2]

b the specific latent heat of fusion of the lead

[2]

c the specific heat capacity of liquid lead.

[2]

# *Gas Properties*

Gas laws

Volume, *V*: This is the space occupied by the particles that make up the gas.

**Volume is measured in metres cubed, m3**

Temperature, *T*: This is a measure of the internal energy of the gas and this is equal to the average kinetic energy of its particles.

**Temperature is measured in Kelvin, K**

Pressure, *p*: When a gas particle collides with the walls of its container it causes a pressure. Pressure is given by the equation pressure = Force/Area or ‘force per unit area’.

**Pressure is measured in pascals, Pa**

1 pascal is equal to a pressure of 1 newton per square metre.

# *Understanding the Gas Laws*

We are about to look at the three different laws that all gases obey. To help us understand them let us apply each one to a simple model. Image one ball in a box; the pressure is a measure of how many collisions between the ball and the box happen in a certain time, the volume is the area of the box and the temperature is the average speed of the ball. To simply thing further let us assume it is only moving back and forth in the x direction.

# *Boyle’s Law*

The pressure of a fixed mass of gas is inversely proportional to its volume when kept at a constant temperature.

 for constant *T*

***Think about it…***

If temperature is constant this means that the ball is travelling at a fixed, constant speed. If we increase the size of the box it makes fewer collisions in the same time because it has to travel further before it collides with the side. If we make the box smaller the ball will collide with the box more often since it has less distance to travel.



# *Charles’ Law*

All gases expand at the same rate when heated. The volume of a fixed mass of gas is proportional to its temperature when kept at a constant pressure.

 for constant *p*

***Think about it…***

If pressure is constant that means that the same number of collisions with the box are taking place. So if the box was made bigger the ball would have to move faster to make sure there were the same amount of collisions per unit time.



# *The Pressure Law*

The pressure of a fixed mass of gas is proportional to its temperature when kept at a constant volume.

 for constant *V*

***Think about it…***

If the volume in constant it means the box has a fixed size. If we increase the speed at which the ball is moving it will hit the sides of the box more often. If we slow the ball down it will hit the sides less often.

***Gas Laws***

**Isobaric = constant pressure**

1. A gas is maintained at constant temperature while in a variable volume. The gas starts at atmospheric pressure. When compressed into a volume of $2.75 ×10^{-2}m^{3}$ the pressure of the gas rises to 786 kPa. Calculate the initial volume of the gas.

2. A gas that obeys Charles’ law occupies a volume of 320 litres when it is at a temperature of 280 K under constant pressure. Calculate the volume occupied at this same constant pressure if the temperature is changed to:

**a** 560 K

**b** 140 K

**c** 140 °C

3. A gas bubble of volume $5.68 ×10^{-6}m^{3}$ is trapped within a cylindrical tube at constant pressure. The temperature of the gas rises from 293 K to 347 K. Calculate the new volume of the gas bubble.

4. A gas at atmospheric pressure (101kPa) is trapped in a glass container whose volume cannot vary. The container and gas are gradually cooled from 295 K down to 187 K. Calculate the final pressure of the gas.

5. A gas is compressed into a steel container until its pressure is 1.75 MPa and temperature is 155°C. The gas is then allowed to cool to 25.0°C. Calculate the final pressure of the gas.

6. A sealed bicycle pump of length 30.0cm and diameter 3.00cm is filled with air at atmospheric pressure (101kPa). The plunger is pressed down 12.0cm and fixed in place, during which the gas inside the pump undergoes an isothermal change to its pressure. The same pump, still sealed and fixed in place, is left out in the sun where the temperature of the gas rises from 15.0°C to 28.0°C.

* 1. Calculate the pressure of the pump at the end of the isothermal compression.
	2. Calculate the pressure of the pump at the end of the heating period.

7. A semi-circular soap bubble is formed outside during the winter, just before night-time. At night, the temperature drops resulting in an isobaric change in bubble volume, with its radius dropping from 5.00cm to 4.9cm. The bubble then freezes at this size. At sunrise, the air within the bubble warms without melting the shell itself, resulting in a pressure increase from 101kPa to 104kPa.
Calculate the initial temperature the bubble formed at if the final temperature was -1.00°C.

8. A group of students are conducting an experiment in the laboratory to determine the value of absolute zero by heating a fixed mass of gas. The volume of the gas is kept constant.
Fig. 17.1 shows the arrangement used by the students.



**Fig. 17.1**

The gas is heated using a water bath. The temperature θ of the water is increased from 5 °C to 70 °C.
The temperature of the water bath is assumed to be the same as the temperature of the gas. The pressure p of the gas is measured using a pressure gauge.

The results from the students are shown in a table.

|  |  |  |  |
| --- | --- | --- | --- |
|   | θ **/ °C** | **p / kPa** |   |
|   | 5 ± 1 | 224 ± 3 |   |
|   | 13 ± 1 | 231 ± 3 |   |
|   | 22 ± 1 | 238 ± 3 |   |
|   | 35 ± 1 | 248 ± 3 |   |
|   | 44 ± 1 |   |   |
|   | 53 ± 1 | 262 ± 3 |   |
|   | 62 ± 1 | 269 ± 3 |   |
|   | 70 ± 1 | 276 ± 3 |   |

(a) Describe and explain how the students may have made accurate measurements of the temperature θ. [1]

(b) Fig. 17.2 shows the pressure gauge. Measurements of p can be made using the kPa scale or the psi (pounds per square inch) scale. The students used the psi scale to measure pressure and then converted the reading to pressure in kPa.



**Fig. 17.2**

**(i)** Suggest why it was sensible to use the psi scale to measure p. [1]

(ii) The students made a reading of p of 37.0 ± 0.5 psi when θ was 44 ± 1°C.
Convert this value of p from psi to kPa. Complete the table for the missing value of p. Include the absolute uncertainty in p.

1 pound of force = 4.448 N

1 inch = 0.0254 m

(c) Fig. 17.3 shows the graph of *p* against *θ*.



**Fig. 17.3**

i. Plot the missing data point and the error bars on Fig. 17.3. [1]

ii Explain what is meant by absolute zero. Describe how Fig. 17.3 can be used to determine the value of absolute zero.
Determine the value of absolute zero. You may assume that the gas behaves as an ideal gas. [6]

(d) Describe, without doing any calculations, how you could use Fig. 17.3 to determine the actual uncertainty in the value of absolute zero in **(c)(ii)**. [2]

(e) The experiment is repeated as the water bath quickly cools from 70 °C to 5 °C. Absolute zero was found to be −390°C.

Compare this value with your value from **(c)(ii)** and explain why the values may differ. Describe an experimental approach that could be taken to avoid systematic error in the determination of absolute zero. [4]

# *Messing with Gases*

Ideal gases

The three gas laws can be combined to give us the equation: 

We can rearrange this to give: *constant*

We can use this to derive a very useful equation to compare the pressure, volume and temperature of a gas that is changed from one state (*p*1, *V*1, *T*1) to another (*p*2, *V*2, *T*2). 

**Temperatures must be in Kelvin, K**

# *Avogadro and the Mole*

One mole of a material has a mass of *M* grams, where *M* is the molecular mass in atomic mass units, u. Oxygen has a molecular mass of 16, so 1 mole of Oxygen atoms has a mass of 16g, 2 moles has a mass of 32g and so on. An Oxygen molecule is made of two atoms so it has a molecular mass of 32g. This means 16g would be half a mole of Oxygen molecules.

  where *n* is the number of moles, *m* is the mass and *M* is the molecular mass.

Avogadro suggested that one mole of any substance contains the same number of particles, he found this to be 6.02 x 1023. This gives us a second way of calculating the number of moles

  where *N* is the number of particles and *NA* is the Avogadro constant.

 **NA is the Avogadro Constant, *NA* = 6.02 x 1023 mol-1**

# *Ideal Gases*

We know from the three gas laws that *constant*

Ideal gases all behave in the same way so we can assign a letter to the constant. The equation becomes:

 

If the volume and temperature of a gas are kept constant then the pressure depends on *R* and the number of particles in the container. We must take account of this by bringing the number of moles, *n*, into the equation:

  🡪 

**R is the Molar Gas Constant, *R* = 8.31 J K-1 mol-1**

This is called the *equation of state* for an ideal gas. The concept of ideal gases is used to approximate the behaviour of real gases. Real gases can become liquids at low temperatures and high pressures.

Using the Avogadro’s equation for *n* we can derive a new equation for an ideal gas:

  🡪  🡪 

# *Boltzmann Constant*

Boltzmann noticed that *R* and *NA* in the above equation are constants, so dividing one by the other will always give the same answer. The Boltzmann constant is represented by *k* and is given as



**k is the Boltzmann Constant, *k* = 1.38 x 10-23 J K-1**

 can become which can also be written as 

***Moles and the Kinetic Theory of Gases***

1.The molar mass of carbon dioxide is 44.0 × 10−3 kg. Calculate:

* 1. the number of moles in 1.00 kg of gas
	2. the number of molecules in 1.00 kg of gas.

2. The molar mass of nitrogen is 28.0 × 10–3 kg. There are 6.02 × 1022 molecules in a sample of the gas. Calculate:

 a. the number of moles in the gas

 b the mass of the gas

3. A gas cloud has a density of 1.45 kg/m3 and fills a volume of 7.20 m3. There are 326 moles in the cloud, what is the molar mass of the gas?

4. A gas cloud containing 295 moles of gas has a density of 0.85 kg/m3 and fills a volume of 4.60 m3. What is the mass of a single molecule of the gas?

5. In terms of the motion of the gas particles, explain why a greater pressure is exerted by a gas when it is compressed to a lower volume at a constant temperature.

***Ideal Gas Equation***

1. A tyre has a volume of 0.8 m3 and is under a pressure of 32 psi when held at a temperature of 32 °C. Calculate the pressure inside the tyre if its volume decreases to 0.64 m3 and the temperature rises by 10 °C.

2. The equation relating pressure, *p*, and the volume, *V*,of an ideal gas is

*pV* =*nRT*

 Identify the terms *n*, *R*, and *T*.

3. What is the volume of 3 moles of an ideal gas kept at a pressure of 1.0 x 10 5 Pa and a temperature of 313K?

4. What is the temperature of 0.15 moles of gas contained in a volume of 9.0 x 10 -4 m3 and at a pressure of 5.0 x 10 5 Pa?

5. What is the volume of one mole of an ideal gas at a temperature of 273K and a pressure of 1.01 x 10 5 Pa ?

6. A car tyre when inflated has a volume of 1.4 × 10−2 m3. The pressure of the air is measured at a temperature of 17 ºC and recorded as 210 kPa.

 The molar mass of air is 0.029 kg mol−1.

 **i** Calculate the amount of air, in mol, in the tyre.

 **ii** When the car is driven, the temperature of the tyre increases to 35 ºC.

Assuming that the volume of the tyre is unchanged, calculate the pressure in the tyre at its operating temperature.

7. 0.5 moles of an ideal gas is kept at a temperature of 27oC in a sealed container of volume 4.0 x 10-3m3. What is the pressure in the gas?

8. What is the temperature of 19.0 m3 of an ideal gas at a pressure of 0.8 x 105 Pa if the same gas occupies 12.0 m3 at 1.01 x 105 Pa and 27oC?

9. A bottle of volume 1.2 × 10−4 m3 contains air. A vacuum pump reduces the pressure of the air in the bottle to 180 Pa at a temperature of 20 ºC.

 Molar mass of air = 0.029 kg mol−1

 Calculate:

 **i** the number of air molecules remaining in the bottle

 **ii** the density of the air remaining in the bottle after evacuation.

10. A gas has a molar density of 48.5 $mol m^{-3}$ at a temperature of -53°C. Calculate the pressure of the gas.

11. A cylinder of volume 5.5 × 10−3 m3 contains nitrogen at a temperature of 18 °C and a pressure of 3.0M Nm−2.

 Calculate the volume the nitrogen would occupy at a temperature of 0 °C and a pressure of 1.0 × 105 Nm−2.

**Q1.**

The number of molecules in one cubic metre of air decreases as altitude increases. The table shows how the pressure and temperature of air compare at sea-level and at an altitude of 10 000 m.

|  |  |  |
| --- | --- | --- |
| **altitude** | **pressure/Pa** | **temperature/K** |
| sea-level | 1.0 × 105 | 300 |
| 10 000 m | 2.2 × 104 | 270 |

(a)     Calculate the number of moles of air in a cubic metre of air at

(i)      sea-level,

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(ii)     10 000 m.

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**(3)**

(b)     In air, 23% of the molecules are oxygen molecules. Calculate the number of extra oxygen molecules there are per cubic metre at sea-level compared with a cubic metre of air at an altitude of 10 000 m.

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**(2)**

**(Total 5 marks)**

**Q2.**

(a)     Use the kinetic theory of gases to explain why

(i)      the pressure exerted by an ideal gas increases when it is heated at constant volume.

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(ii)     the volume occupied by an ideal gas increases when it is heated at constant pressure.

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**(4)**

(b)     A quantity of 0.25 mol of air enters a diesel engine at a pressure of 1.05 × 105 Pa and a temperature of 27°C. Assume the gas to be ideal.

(i)      Calculate the volume occupied by the gas.

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(ii)     When the gas is compressed to one twentieth of its original volume the pressure rises to 7.0 × 106 Pa. Calculate the temperature of the gas immediately after the compression.

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**(4)**

**(Total 8 marks)**

**Q3.**

(a)     The pressure inside a bicycle tyre of volume 1.90 × 10–3 m3 is 3.20 × 105 Pa when the temperature is 285 K.

(i)      Calculate the number of moles of air in the tyre.

answer = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ mol

**(1)**

(ii)     After the bicycle has been ridden the temperature of the air in the tyre is 295 K.
Calculate the new pressure in the tyre assuming the volume is unchanged.
Give your answer to an appropriate number of significant figures.

answer = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ Pa

**(3)**

(b)     Describe **one** way in which the motion of the molecules of air inside the bicycle tyre is similar and **one** way in which it is different at the two temperatures.

similar \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

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different \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

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**(2)**

**(Total 6 marks)**

**Q4.**

**Figure 1** shows a *p–V* graph that you are to use to illustrate the process of a gas undergoing two changes.
In its initial state, the gas has a pressure of 50 kPa and a volume of 1.5 m3; this is plotted on the graph.
First, the gas undergoes an isothermal change from an initial volume of 1.5 m3 to 0.85 m3 followed by a compression at constant pressure to a volume of 0.35 m3.



**Figure 1**

(a)     Show that the final pressure of the gas is about 90 kPa.

**(2)**

(b)     Complete the graph in **Figure 1** to show both changes.

**(2)**

(c)     (i)      Use your graph to estimate the work done during the whole process.

**(3)**

(ii)     State and explain whether the work in part (c)(i) is done *on* or *by* the gas.

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**(1)**

**(Total 8 marks)**

# *Assumptions*

Molecular kinetic theory model

1. There are a very large number of molecules (*N*)
2. Molecules have negligible volume compared to the container
3. The molecules show random motion (ranges of speeds and directions)
4. Newton’s Laws of Motion can be applied to the molecules
5. Collisions are elastic and happen quickly compared to the time between collisions
6. There are no intermolecular forces acting other than when they collide

# *The Big Derivation*

The molecules move in all directions. Let us start with one molecule of mass *m* travelling with velocity *v*x. It collides with the walls of the container, each wall has a length of *L*.

Calculate the change in momentum: before it moves with velocity *v*x and after the collision it move with –*v*x . 🡪  **Equation 1**

The time can be given by using distance/speed: the speed is *v*x and the distance is twice the length of the box (the distance to collide and then collide again with the same wall)  **Equation 2**

Force can be calculated by:  Substitute in **Equation 1 and 2** 🡪 🡪



* **Equation 3**, gives the force of **one** molecule acting on the side of the container.

We can now calculate the **pressure** this one molecule causes in the x direction:

 Substituting **Equation 3** 🡪  🡪  🡪  **Equation 4**

(If we assume that the box is a cube, we can ***replace*** *L*3 with *V*, both units are m3)

All the molecules of the gas have difference speeds in the x direction. We can find the pressure in the x direction due to them all by first using the mean value of *v*x and then multiplying it by *N*, the total number of molecules:  🡪   **Equation 5**

**Equation 5** gives us the pressure in the x direction.

But since the average velocities in all directions are equal:

🡪

The mean speed in all directions is given by:

🡪

We can substitute this into the **Equation 5** for pressure above:

 🡪  🡪  🡪  **Equation 6**

# *Kinetic Energy of a Gas*

From the equation we have just derived we can find an equation for the mean kinetic energy of a gas:

Since  and  combine these to get  **Equation 7**

Kinetic energy is given by  so we need to make the above equation look the same.

 🡪  🡪  🡪 

 🡪  🡪  

Then substitute in Boltzmann’s constant  🡪  **Equation 8**

***Root Mean Square Speed***

1. Calculate **a**, the mean velocity, **b**, the mean speed, and **c**, the rms speed of a group of atoms with velocities: -150 ms−1, 100 ms−1, 200 ms−1, 250 ms−1. [4]

2. Using the equation ****, find the pressure of a gas if *V* = 4.8 m3, *N* = 2.0 × 1024, *m* = 7.0 × 10−27 kg, and *c*rms = 400 ms-1. [2]

3. Calculate the new pressure if *c*rms is decreased to 360 ms−1. [2]

4. Use *pV* = *nRT* and****,to show that . [4]

5. Complete the table below by calculating the missing values. The gas is helium which has a molar mass of 4 g. In one mole of a monatomic gas there are 6.02 × 1023 atoms.

 The universal gas constant is 8.31 J mol−1 K−1.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***P*** | ***V*** | ***n*** | ***N*** | ***m*** | (*c*rms)2 | ***T*** |
| 4 × 105 Pa |  | 1 × 10−2 |  |  |  | 300 K |
| 2.4 × 105 Pa | 3.2 m3 |  |  |  |  | 150 °C |

6. Show that the units of pV are equivalent to Joules. [2]

7. What temperature would one mole of helium gas need to have in order to have internal energy equal to the kinetic energy of a ball of mass 5 kg moving at 12 ms−1?

 (One mole of helium gas has a mass of 4 g.) [1]

***Boltzmann Constant***

1. A gas is made up of molecules of mass $5.32 ×10^{-26}kg$. Calculate the density of the gas when at 175 kPa and 293K.

**2.** The temperature of a room increases from 283K to 293K. The r.m.s. speed of the air molecules in the room increases by a factor of:

|  |  |
| --- | --- |
| **A** | 1.02 |
| **B** | 1.04 |
| **C** | 1.41 |
| **D** | 2.00 |

**3.** A fixed mass of gas occupies a volume *V*. The temperature of the gas increases so that the root mean square velocity of the gas molecules is doubled.

What will the new volume be if the pressure remains constant?

|  |  |  |  |
| --- | --- | --- | --- |
|   | **A** |   |   |
|   | **B** |   |   |
|   | **C** | 2*V* |   |
|   | **D** | 4*V* |   |

4. This question is about helium in the atmosphere of the Earth.

Experiment shows that most of the Earth's atmosphere is contained within a very thin shell around the surface of the Earth. Less than 0.0001% of this is helium.

It can be shown that the minimum velocity for an atom to escape the Earth’s atmosphere is:



1. The radius R of the Earth is 6.4 × 106 m. Calculate this escape speed vE.
2. Calculate the temperature T in kelvin required at the top of the Earth's atmosphere for the root mean square speed cr.m.s. of the helium atoms there to equal this escape speed.

Molar mass of helium = 0.004 kg mol−1
3. Fig. 1 shows the distribution of the speeds of the atoms of an ideal gas.



Use your knowledge of the kinetic theory of gases to describe the shape of this distribution and explain why some helium is able escape from the Earth. **[4]**

1. Over a very long period of time all of the helium should have escaped from the Earth. Suggest why there is still a small amount of helium, about 0.0001%, in the Earth's atmosphere.  **[2]**

5. A gas is made up of molecules of mass $5.32 ×10^{-26}kg$. Calculate the density of the gas when at 175 kPa and 293K.

6. The velocity required for molecules to escape from the Earth’s atmosphere is about 11 km s−1. Estimate the temperature to which hydrogen must be heated in order for the r.m.s. speed of its molecules to be equal to this escape velocity.

 Molar mass of hydrogen = 2.0 × 10−3 kg mol−1

7. A gas of density 1.46 $kgm^{-3}$ is at 115kPa and 285K. Calculate its molar mass.

8. A monatomic gas has a density of 1.08 $kgm^{-3}$ at a pressure of 70.4 kPa. Calculate the temperature of the gas if a single gas atom has a mass of $6.65 ×10^{-27}kg$.

**Q1.**

Helium is a monatomic gas for which all the internal energy of the molecules may be considered to be translational kinetic energy.

molar mass of helium       =    4.0 × 10–3 kg
the Boltzmann constant    =    1.38 × 10–23 J K–1the Avogadro constant      =    6.02 × 1023 mol–1

(a)     Calculate the kinetic energy of a tennis ball of mass 60 g travelling at 50 m s–1.

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**(1)**

(b)     Calculate the internal energy of 1.0 g of helium gas at a temperature of 48K.

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**(3)**

(c)     At what temperature would the internal energy of 1.0 g of helium gas be equal to the kinetic energy of the ball in part (a).

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**(1)**

**(Total 5 marks)**

**Q2.**

(a)     A number of assumptions are made when explaining the behaviour of a gas using the molecular kinetic theory model.

State **one** assumption about the size of molecules.

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**(1)**

The graph shows how the pressure changes with volume for a fixed mass of an ideal gas.

At **A** the temperature of the gas is 27 °C. The gas then undergoes two changes, one from **A** to **B** and then one from **B** to **C**.



(b)     Calculate the number of gas molecules trapped in the cylinder using information from the initial situation at **A**.

number of molecules = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**(2)**

(c)     Calculate, in K, the change in temperature of the gas during the compression that occurs between **A** and **B**.

change in temperature = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ K

**(2)**

(d)     Deduce whether the temperature of the gas changes during the compression from **B** to **C**.

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**(2)**

(e)     Compare the work done on the gas during the change from **A** to **B** with that from **B** to **C** on the graph.

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**(3)**

**(Total 10 marks)**

**Q3.**

(a)     Write down **four** assumptions about the properties and behaviour of gas molecules which are used in the kinetic theory to derive an expression for the pressure of an ideal gas.

Assumption 1 \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

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Assumption 2 \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

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Assumption 3 \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

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Assumption 4 \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

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**(4)**

(b)     (i)      A cylinder, fitted with a pressure gauge, contains an ideal gas and is stored in a cold room. When the cylinder is moved to a warmer room the pressure of the gas is seen to increase. Explain **in terms of the kinetic theory** why this increase in pressure is expected.

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(ii)     After a time, the pressure of the gas stops rising and remains steady at its new value. The air temperature in the warmer room is 27°C. Calculate the mean kinetic energy of a gas molecule in the cylinder.

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**(6)**

**(Total 10 marks)**

*Acknowledgements:*

The notes in this booklet come from TES user dwyernathaniel. The original notes can be found here:

<https://www.tes.com/teaching-resource/a-level-physics-notes-6337841>

Questions in multiple sections (including on the specifics, gas laws and kinetic theory) come from Bernard Rand’s resources (@BernardRand). His original resources can be found here:

<https://drive.google.com/drive/folders/1-2qNVLwGzJ_7AjQK9N0z4BQBIRmSHAwG>