1.23 Gas Calculations

Gas calculations at A-level are done in two different ways although both link the volumes of a gas to the amount in moles of the gas. The same amount in moles of any gas will have the same volume under the same conditions of temperature and pressure.

Molar Gas Volume (OCR +EDEXCEL only)

The simplest way of working out the volume of gas is using the molar gas volume of a gas. This works on the principle that 1 mole of any gas will have the same volume under the same conditions of temperature and pressure. Most often this is given as $24dm^3$ which is the volume of a gas at room pressure (100kPa) and room temperature 25^oC. Different temperatures and pressures will have different molar gas volumes.

$$\boxed{\text{Gas Volume } (dm^3) = \text{amount} \times 24}$$

This equation gives the volume of a gas at room pressure (100kPa) and room temperature 25^oC.

Ideal Gas Equation

The ideal gas equation is a slightly more difficult way of working out a gas volume. It can calculate the volume for any temperature and pressure though so is a more useful method.

$$\boxed{\mathbf{PV = nRT}}$$

Unit of Pressure (P):Pa
Unit of Volume (V): **m^3**
Unit of Temp (T): K
n= moles
$R = 8.31\ JK^{-1}mol^{-1}$

More detail is given on page 2 about how the ideal gas equation is derived and its limitations.

The biggest problems students have with this equation is choosing and converting to the correct units, so pay close attention to the units.

Converting temperature

$^oC \rightarrow$ K add 273

Example 1: What is the mass of Cl_2 gas that has a pressure of 100kPa, temperature 293K, volume $500cm^3$. ($R = 8.31\ JK^{-1}mol^{-1}$)

100 kPa = 100 000 Pa
$500\ cm^3 = 0.0005\ m^3$

moles = PV/RT

= 100 000 x 0.0005 / (8.31 x 293)

= 0.0205 mol

Mass = moles x Mr
= 0.0205 x (35.5 x2)
= 1.46 g

Example 2: 0.15g of a volatile liquid was injected into a sealed gas syringe. The gas syringe was placed in an oven at 70^oC at a pressure of 100kPa and a volume of $80cm^3$ was measured. What is the Mr of the volatile liquid ? ($R = 8.31\ JK^{-1}mol^{-1}$)

100 kPa = 100 000 Pa
$80\ cm^3 = 0.00008\ m^3$

moles = PV/RT

= 100 000 x 0.00008 / (8.31 x 343)

= 0.00281 mol

Mr = mass/moles
= 0.15 / 0.00281
= $53.4\ g\ mol^{-1}$

Derivation of the Ideal Gas Equation

The ideal gas equation is a combination of three important gas laws.

Boyle's Law - The volume of a fixed amount of gas at a given temperature is inversely proportional to its pressure.

$$V \propto \frac{1}{P}$$

$$\boxed{\boldsymbol{P_1V_1 = P_2V_2}}$$

at constant T & *n*

Charles's Law -If a fixed amount of a gas is held at constant pressure, the volume of the gas is directly proportional to the temperature of the gas.

V ó T

So for a system that changes T and V –

$$\boxed{\frac{V_1}{T_1} = \frac{V_2}{T_2}}$$

at constant P & *n*

Avogadro's Law -Equal volumes of gas at constant temperature and pressure have equal numbers of molecules.

Boyle's Law

V ó $\frac{1}{P}$

Charles's Law

V ó T

Avogadro's Law

$$\boxed{V \propto n}$$

Expressed Mathematically –

$$\boxed{\mathrm{V} \propto \frac{\mathrm{Tn}}{\mathrm{P}}}$$

$$\boxed{\mathrm{V} = \mathrm{R}\left(\frac{\mathrm{nT}}{\mathrm{P}}\right) \quad \Rightarrow \quad \mathrm{PV} = \mathrm{nRT}}$$

An ideal gas has the following properties:

1. An ideal gas is considered to be a "point mass". A point mass is a particle so small that its mass is very nearly zero. This means an ideal gas particle has almost no volume.

2. There are no attractive or repulsive forces involved during collisions. Also, the kinetic energy of the gas molecules remains constant since the intermolecular forces are lacking.

These assumptions do not actually hold true for many gases. They work best for the Noble gases. Heavier gases and ones with significant intermolecular forces will deviate from ideal gas behaviour

Changing the Conditions of a gas

Questions may involve the same amount of gas under different conditions.

Example 3

40 cm^3 of oxygen and 60 cm^3 of carbon dioxide, each at 298 K and 100 kPa, were placed into an evacuated flask of volume 0.50 dm^3. What is the pressure of the gas mixture in the flask at 298 K?

There are two approaches to solving this

1. Work out moles of gas using ideal gas equation then put back into ideal gas equation with new conditions
2. Or combine the equation n= PV/RT as on right

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Can do this as moles of gas do not change

As Temperature is the same can make the above equation $P_1V_1 = P_2V_2$

$P_2 = P_1V_1 / V_2$

$= 100000 \times 1\text{x } 10^{-4} / 5\text{x}10^{-4}$

$= 20\ 000\text{Pa}$

Questions using the Ideal Gas Equation

(In all questions use the Ideal Gas Equation and use the gas constant *R* = 8.31 $JK^{-1}mol^{-1}$)

1.1) Calculate the volume of 1.50 mol of carbon dioxide gas at 298K and 100 kPa.

1.2) A sample of ammonia gas occupied a volume of 0.0278m^3 at 28^oC and 103 kPa. Calculate the number of moles of ammonia in the sample.

1.3) A gas cylinder, of volume 5.00×10^{-3} m^3, contains 348 g of argon gas. Calculate the pressure of the argon gas in the cylinder at a temperature of 20^oC

1.4) A 0.153g gaseous sample of ammonia occupied a volume of 2.91×10^{-4} m^3 at a temperature ***T*** and a pressure of 100 kPa. Calculate the number of moles of ammonia present and deduce the value of the temperature ***T***.

1.5) A sample of ethanol vapour, C_2H_5OH (*M*r = 46.0), was maintained at a pressure of 100 kPa and at a temperature of 358K. Calculate the volume, in cm^3, that 2.78 g of ethanol vapour would occupy under these conditions.

1.6) When a sample of liquid, **A,** of mass 0.306 g was vaporised, the vapour was found to occupy a volume of 1.76×10^{-4} m^3 at a pressure of 110 kPa and a temperature of 200^0C. Calculate the number of moles of **A** in the sample and hence deduce the relative molecular mass of **A.**

1.7) Compound **B** is an oxide of sulphur. At 423 K, a gaseous sample of **B**, of mass 0.354 g, occupied a volume of 148 cm^3 at a pressure of 105 kPa. Calculate the number of moles of B in the sample, and hence calculate the relative molecular mass of **B**.

1.8) In an experiment, 0.612 mol of hydrogen gas was produced when a sample of magnesium reacted with dilute nitric acid. Calculate the volume that this gas would occupy at 298 K and 98.0 kPa. Include units in your final answer.

Calculations involving masses, solutions and gases

Commonly in questions converting between quantities of substances reacting we will use more than just mass data. We might have the volume and concentration of a solution, or the volume of a gas. We need to adapt our existing method or reacting masses to include other quantities. Any of the equations below can be used to convert quantities into moles.

1. For pure solids, liquids and gases

$$\text{amount} = \frac{\text{mass}}{\text{MolarMass}}$$

Unit of Mass: grams
Unit of amount : mol

2. For Gases

Gas Volume (dm^3)= amount x 24

This equation give the volume of a gas at room pressure (1atm) and room temperature 25°C.

Or use the ideal gas equation to work out gas volumes at other temperatures and pressures

$$PV = nRT$$

3. For solutions

$$\text{Concentration} = \frac{\text{amount}}{\text{volume}}$$

Unit of concentration: mol dm^{-3} or M
Unit of Volume: **dm^3**

General method

Step 1:
Use one of the above equations to convert any given quantity into amount in mol
Mass → amount
Volume of gas → amount
Conc and vol of solution → amount

→

Step 2:
Use balanced equation to convert amount in mol of initial substance into amount in mol of second substance

→

Step 3
Convert amount, in mol, of second substance into quantity question asked for using relevant equation
e.g. amount ,Mr → mass
Amount gas → vol gas
amount, vol solution → conc

Example 4 : Using Ideal Gas
What is the total volume of gas produced in dm^3 at 333K and 100kPa when 0.651 g of magnesium nitrate decomposes when heated?
$2Mg(NO_3)_{2\,(s)} \rightarrow 2MgO_{(s)} + 4NO_{2\,(g)} + O_{2\,(g)}$

Step 1: work out moles of magnesium nitrate
Moles = mass / Mr
= 0.651 / 148.3
= 0.00439 mol

Step 2: use balanced equation to give moles of gas produced
2 moles $Mg(NO_3)_2$: $4NO_{2\,(g)} + O_{2\,(g)}$ ie 5moles of gas
So 0.00439 $Mg(NO_3)_2$: 0.01098(0.00439 x $^5/_2$) moles gas

Step 3: work out volume of gas

Volume = nRT/P
= (0.01098 x 8.31 x 333)/ 100000
= 0.000304m^3
= 0.303dm^3

Example 5: Using molar gas volume
What volume in cm^3 of oxygen gas would be produced from the decomposition of 0.532 g of potassium chlorate(V)?
$2KClO_3 \rightarrow 2KCl + 3O_2$

Step 1: work out amount, in mol, of potassium chlorate(V)?
amount = mass / Mr
= 0.532 /122.6
= 0.00434 mol

Step 2: use balanced equation to give amount in mol of O_2
2 moles $KClO_3$: 3 moles O_2
So 0.00434 HNO_3 : 0.00651moles O_2

Step 3: work out volume of O_2

Gas Volume (dm^3)= amount x 24
= 0.00651 x 24
= 0.156 dm^3
= 156 cm^3

Questions combining masses, equations and ideal gas volumes

(In all questions use the Ideal Gas Equation and use the gas constant R = 8.31 $JK^{-1}mol^{-1}$)

2.1) Sodium hydrogencarbonate decomposes on heating as shown in the equation below.
$2NaHCO_3(s) \rightarrow Na_2CO_3(s) + CO_2(g) + H_2O(g)$
A sample of $NaHCO_3$ was heated until completely decomposed. The CO_2 formed in the reaction occupied a volume of 472 cm^3 at 1.00×10^5 Pa and 298 K.
Calculate the number of moles of CO_2 formed in this decomposition and the mass of $NaHCO_3$ that was decomposed .

2.2) When heated, ammonium carbamate, $H_2NCOONH_4$, decomposes as shown below.
$H_2NCOONH_4(s) \rightarrow 2NH_3(g) + CO_2(g)$
In a closed container, a 6.50 g sample of ammonium carbamate was heated. The solid decomposed completely into ammonia and carbon dioxide at 463 K and 99.7 kPa.
(i) Calculate the number of moles of ammonium carbamate used and the total number of moles of gas produced.
(ii) calculate the total volume of gas produced 463 K and 99.7 kPa. Include units in your answer.

2.3) A sample of ammonium nitrate decomposed on heating as shown in the equation below.
$NH_4NO_3 \rightarrow 2H_2O + N_2 + ½ O_2$
On cooling the resulting gases to 298 K, the volume of nitrogen and oxygen together was found to be 0.0550 m^3 at a pressure of 98.0 kPa.
(i)Calculate the total number of moles of nitrogen and oxygen formed.
(ii)Deduce the number of moles of ammonium nitrate decomposed and hence calculate the mass of ammonium nitrate in the sample.

2.4) An equation representing the thermal decomposition of lead(II) nitrate is shown below.
$2Pb(NO_3)_2(s) \rightarrow 2PbO(s) + 4NO_2(g) + O_2(g)$
A sample of lead(II) nitrate was heated until the decomposition was complete. At a temperature of 450K and a pressure of 100kPa, the total volume of the gaseous mixture produced was found to be 1.35×10^{-4} m^3.
(i)Calculate the total number of moles of gas produced in this decomposition.
(ii) Deduce the number of moles, and the mass, of NO_2 present in this gaseous mixture.
(iii) Calculate the original mass of the lead nitrate that was decomposed

2.5) Potassium nitrate, KNO_3, decomposes on strong heating, forming oxygen and solid KNO_2 as the only products.
A 1.00 g sample of KNO_3 was heated strongly until fully decomposed
(i) Calculate the number of moles of KNO_3 in the 1.00 g sample.
(ii) Calculate the number of molecules of O_2 produced (The Avogadro constant L = 6.022×10^{23}
(iii) Calculate the volume of oxygen gas produced in cm^3 at 298 K and 100 kPa

2.6) UDMH, $(CH_3)_2N_2H_2$, can be used as in combination with dinitrogen tetroxide, N_2O_4 as a fuel in thruster rockets. A thruster rocket contained a total mass of propellant (UDMH and, N_2O_4, together) of 240 kg mixed in a 1:2 molar ratio. The equation below shows the reaction

$$(CH_3)_2N_2H_2(l) + 2N_2O_4(l) \rightarrow 2CO_2(g) + 4H_2O(g) + 3N_2(g)$$

(i) Calculate the mass of UDMH in the propellant mixture.
(ii) Calculate the total number of moles of gas produced from the complete reaction of this mass of UDMH with dinitrogen tetroxide,
(iii) Calculate the total volume of product gases formed from the reaction of this mass of UDMH with dinitrogen tetroxide at a temperature of –9.0 °C and a pressure of 550 Pa.

Reacting Volumes of Gas

Equal volumes of any gases measured under the same conditions of temperature and pressure contain equal numbers of molecules (or atoms if the gas in monatomic)

1 mole of any gas at room pressure (1atm) and room temperature 25^{o}C will have the volume of 24dm^3

Volumes of gases reacting in a balanced equation can be calculated by simple ratio

Example 6 If one burnt 500 cm^3 of methane at 1atm and 300K what volume of Oxygen would be needed and what volume of CO_2 would be given off under the same conditions?

$CH_4(g)$ + **2** $O_2(g)$ → $CO_2(g)$ + 2 $H_2O(l)$

1 mole   **2** mole   1 mole

500cm^3 1dm^3 500cm^3

Simply multiply gas volume x2

Example 7 An important reaction which occurs in the catalytic converter of a car is
$2CO(g) + 2NO(g) \rightarrow 2CO_2(g) + N_2(g)$
In this reaction, when 500 cm^3 of CO reacts with 500 cm^3 of NO at 650 °C and at 1 atm.
Calculate the **total** volume of gases produced at the same temperature and pressure ?

$2CO(g) + 2NO(g) \rightarrow 2CO_2(g) + N_2(g)$

500cm^3 500cm^3 **500cm^3**   **250cm^3**

total volume of gases produced = 750cm^3

3.1) If one burnt 1 dm^3 of butane, what volume of Oxygen would be needed and what volume of CO_2 would be given off?

$2C_4H_{10}(g) + 13\ O_2(g) \rightarrow 8CO_2(g) + 10\ H_2O(l)$

3.2) What volume of air is needed for the complete combustion of 500 cm^3 of hydrogen? (Assume air contains 20% oxygen)

$2H_2(g) + O_2(g) \rightarrow 2\ H_2O(l)$

3.3) The overall equation for the reaction between sulfur and oxygen to form sulfur trioxide is shown below.
$2S(s) + 3O_2(g) \rightarrow 2SO_3(g)$
2 dm^3 of $O_2(g)$ reacted completely with excess sulfur. What volume, in dm^3, of sulfur trioxide would form?

3.4) The equation for the complete combustion of octane is
$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$

The volume of 1 mol of any gas (measured at room temperature and pressure) is 24 dm^3. Calculate the volume of oxygen (measured at room temperature and pressure) required for the complete combustion of 5 mol of octane.

3.5) 90 cm^3 of methane was reacted with 450 cm^3 of oxygen. How much of each gas is present after the combustion and what is the total volume of all gases at the end?
$CH_4(g) + 2\ O_2(g) \rightarrow CO_2(g) + 2\ H_2O(l)$

3.6) 20cm^3 of an unknown hydrocarbon needed 120 cm^3 of oxygen for complete combustion. 80cm^3 of CO_2 was produced. All volumes were measured at rtp. Find the formula of the hydrocarbon.

Answers

1.1 V = $0.0371m^3$
1.2 n = 1.14 mol
1.3 P= 4250kpa
1.4 T=389K
1.5 V=$1800cm^3$
1.6 *M*r = 62.1
1.7 *M*r =80.1
1.8 V=$0.0155m^3$

2.1 moles CO_2 =0.01906 mass $NaHCO_3$ 3.2g
2.2 (i)moles of ammonium carbamate = 0.083 moles gas=0.25
(ii) V= $9.65 X10^{-3} m^3$
2.3 (i) 2.177 moles total gas
(ii) Moles ammonium nitrate 1.45mol mass= 116g
2.4 (i) moles = 0.00361mol
(ii) Moles NO_2 = 0.002888 Mass NO_2 = 0.133g
(iii) Mass lead nitrate 0.478g
2.5 (i) $9.89 X10^{-3}$ mol
(ii) $2.98x 10^{21}$
(ii) 122 cm^3
2.6 (i) mass UDMH 59kg
(ii) Moles gas 8850 mol
(iii) Volume gas $35300m^3$

3.1 6.5 dm^3 O_2 4 dm^3 CO_2
3.2 1.25 dm^3
3.3 1.33 dm^3
3.4 1500 dm^3
3.5 $270cm^3$ O_2 $90cm^3$ CO_2 total $360cm^3$
3.6 C_4H_8