2. MASS AND VOLUME RELATION SHIPS IN CHEMICAL REACTIONS

2.1 Relationship of Mass to the Stoichiometry of Chemical Reactions

We can establish the formula of magnesium oxide by burning a known mass of magnesium in air and weighing the magnesium oxide formed. The same can be done for a number of binary compounds. It is equally possible to approach the problem from the binary compound instead of from the constituent elements. This was done in Book 1 for the determination of the formulae of copper(II) oxide and copper(I) oxide. In either case, the mass of oxygen that combines with a known mass of copper was determined. Hence, the mole ratio of copper to oxygen was calculated.

WORKED EXAMPLE

In an experiment 1.12 g of iron was heated in a stream of hydrogen chloride gas to a constant mass. 2.54 g of product was formed. What is the formula of the product if it is known to be a binary compound of iron and chlorine?

SOLUTION

Mass of element	Fe		Cl
	1.12g		(2.54 – 1.12) g
			= 1.42g
Mole ratio	$\frac{1.12}{56}$	:	$\frac{1.42}{35.5}$
	= 0.02	:	0.04
	1	:	2

âˆ´ Formula of the iron chloride is $FeCl_2$

Analysis of mass relationships can also lead to the stoichiometry of chemical reactions.

Experiment 2.1: Determination of the stoichiometry of the displacement of copper ions from solution by zinc metal.

Weigh out about 5g of copper(II) tetraoxosulphate(VI) pentahydrate crystals and dissolve in a beaker of water. Accurately weigh out about 1g of zinc foil. Cut this to tiny bits, and add to the copper(II) tetraoxosulphate(VI) solution. Soon, a reddish-brown precipitate of copper is formed. Stir the mixture to dislodge the coating of copper on the zinc. The precipitate of copper falls to the bottom of the beaker and the blue colour of the solution fades. When all the zinc has reacted, filter off the copper through a paper. Wash the copper on the filter paper with hot distilled water. Dry and weigh it.

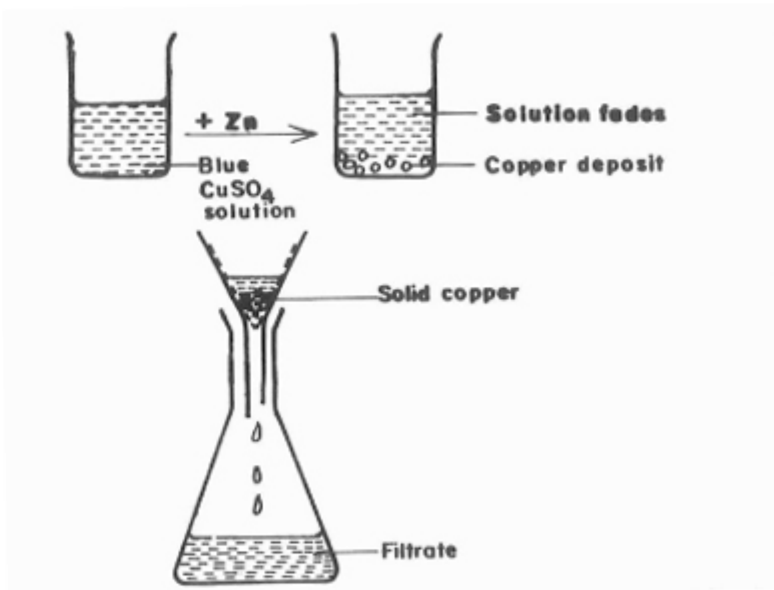

Figure 2.1 Precipitation of copper from copper ions with zinc

SPECIMEN RESULTS AND CALCULATIONS

Mass of zinc used in the displacement = 1.00 g.
Mass of copper displaced = 0.97 g.
Molar mass of zinc = 65 g.
Molar mass of coppper = 63.5 g.

$\therefore \frac{1.0}{65}$ mole of zinc displaces $\frac{0.97}{63.5}$ mole of copper

$\therefore$ 0.0154 mole of zinc displaces 0.0153 mole of copper.

$\therefore$ 1 mole of zinc displaces 1 mole of copper.
Hence we can write an equation for this reaction as:

$$Zn(s) + Cu^{2+}(aq) \rightarrow Cu(s) + Zn^{2+}(aq)$$

Experiment 2.2: Determination of the stoichiometry of the reaction between sodium chloride and silver trioxonitrate(V).

Weigh out accurately about 1 g of analar sodium chloride and dissolve in about 20cm^3 of water in a beaker. Add some 0.1 M silver trioxonitrate(V) to the sodium chloride solution. A white precipitate is formed as soon as the two solutions are mixed. When about 75 cm^3 of the silver trioxonitrate(V) solution has been added, allow the mixture to stand for some time. The heavy precipitate settles down.

Withdraw a sample of the supernatant liquid with a dropper pipette and add a drop of silver trioxonitrate(V) to it. If more precipitation occurs, add another $10cm^3$ silver trioxonitrate(V) solution to the bulk of the mixture. Continue doing this until a test sample does not precipitate silver chloride, indicating that precipitation is complete. Filter off the precipitated silver chloride through a weighed filter paper. Wash the solid on the filter paper with warm water. Dry and weigh to a constant mass.

SPECIMEN RESULTS AND CALCULATIONS

Mass of sodium chloride used = 1.0 g.
Mass of silver chloride precipitated = 2.45 g
Molar mass of sodium chloride = (23 + 35.5)g = 58.5 g.
Molar mass of silver chloride = (108 + 35.5)g = 143.5 g

$$\therefore \frac{1.0}{58.5} \text{ mole sodium chloride yields } \frac{2.45}{143.5} \text{ mole silver chloride.}$$

i.e. 0.017 mole NaCl yields 0.017 mole AgCl, or 1 mole NaCl yields 1 mole AgCl.
Hence the equation for the precipitation reaction is:
$NaCl(aq) + AgNO_3(aq) \rightarrow AgCl(s) + NaNO_3(aq)$
(1 mole) (1 mole)

The stoichiometry of any precipitation reaction can similarly be studied. An alternative method of doing this is described in Experiment 2.3.

Experiment 2.3

Prepare 100 cm^3 of a molar solution of sodium tetraoxosulphate(VI) by dissolving 14.2g of the anhydrous salt in water and making up the solution to 100 cm^3 with distilled water. Also prepare 100 cm^3 of a molar solution of barium chloride (24.4 g of $BaCl_2.2H_2O$ made up to 100 cm^3 of solution in water). Set up five test tubes labelled 1-5 in a test tube rack. Measure 1 cm^3 of the sodium tetraoxosulphate(VI) solution into test tube 1, then 2, 3, 4 and 5 cm^3 into test tubes 2, 3, 4 and 5 respectively.

Add 2, 4, 6, 8 and 10 cm^3 of the barium chloride solution into test tubes 1, 2, 3, 4 and 5 respectively. Note that a white precipitate of barium tetraoxosulphate(VI) forms in each test tube. Shake to mix well, wait for some time then filter off through weighed filter papers. Weigh the dried precipitates.

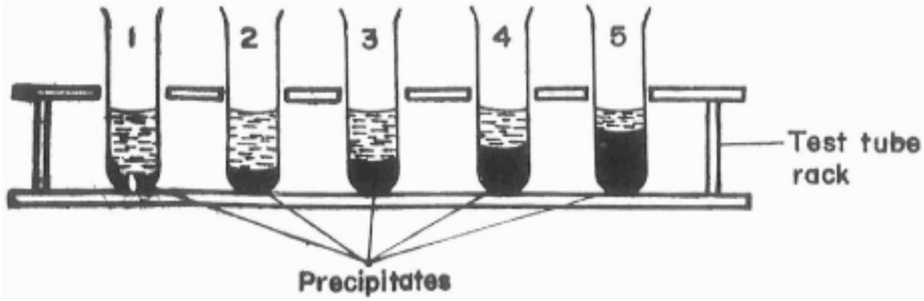

Figure 2.2 Precipitates of barium tetraoxosulphate (VI) in test tubes 1â€”5

Calculate the amount, in mole of barium tetraoxosulphate(VI) precipitated each test-tube. Also calculate the amount of sodium tetraoxosulphate(Vl), in mole added. Since barium chloride is in excess, we assume that all the sodium tetraoxosulphate(VI) is used up.

Plot a graph of number of moles of barium tetraoxosulphate(VI) against number of moles of sodium tetraoxosulphate(VI) (Figure 2.3). The slope of the straight line graph gives the ratio of number of mole of barium tetraoxosulphate(VI) to the number of mole of sodium tetraoxosulphate(VI).

SPECIMEN RESULTS

Test tubes	1	2	3	4	5
Volume of Na_2SO_4 (cm^3)	1	2	3	4	5
Number of mole of Na_2SO_4	0.001	0.002	0.003	0.004	0.005
Mass of $BaSO_4$ (g)	0.2	0.42	0.62	0.83	1.04
Number of mole of $BaSO_4$	0.001	0.002	0.003	0.004	0.005

The slope of the graph is equal to 1, therefore the mole ratio for the reaction is 1:1.

Na_2SO_4(aq) + $BaCl_2$(aq) â†’ 2NaCl(aq) + $BaSO_4$(s)

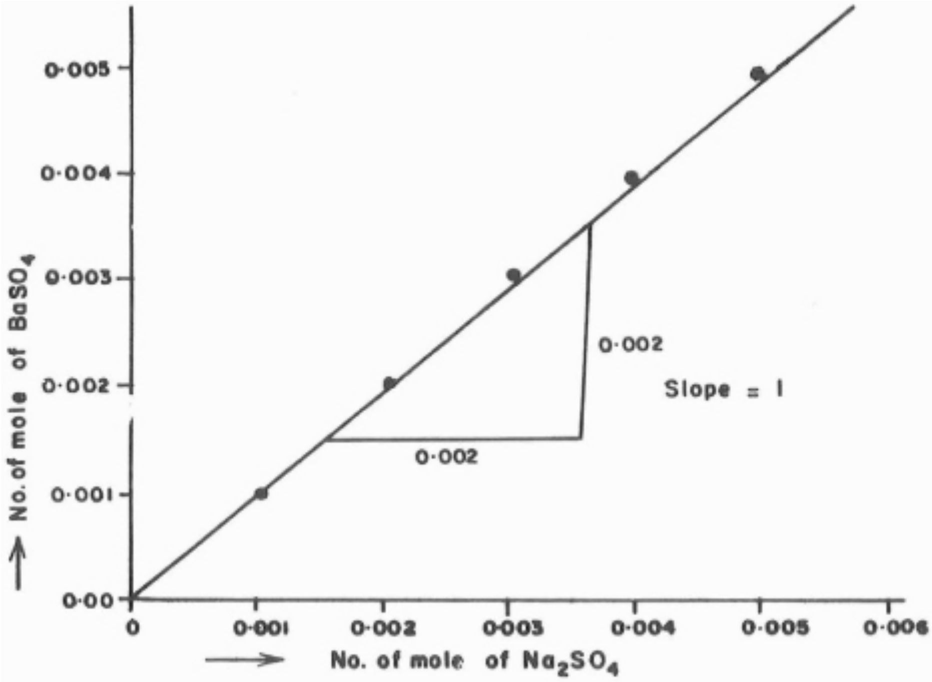

Figure 2.3 Graph of number of mole of BaSO. vs number of mole of Na_2SO_4

2.2 Relationship of Volume to the Stoichiometry of Chemical Reactions involving Gases

For gaseous reactions, volume rather than mass is measured. Using the information that at standard conditions of temperature and pressure, one mole of every gas occupies 22.4 dm^3 (the molar gas volume), the volume ratios of reacting gases or gaseous products can be converted to their molar ratios.

Experiment 2.4 : Determination of the stoichiometry of the displacement of hydrogen from dilute hydrogen chloride acid (hydrochlo ric acid) by zinc.

Weigh out accurately about 0.3 g of zinc foil into a micro test-tube, and set it up with other apparatus as shown in Figure 2.4. Lower the micro test-tube into the dilute hydrogen chloride acid (hydrochloric acid) and immediately fit the cork tightly.

A reaction occurs with effervescence, as hydrogen gas is liberated. Record the volume of hydrogen displaced, as indicated in the gas syringe.

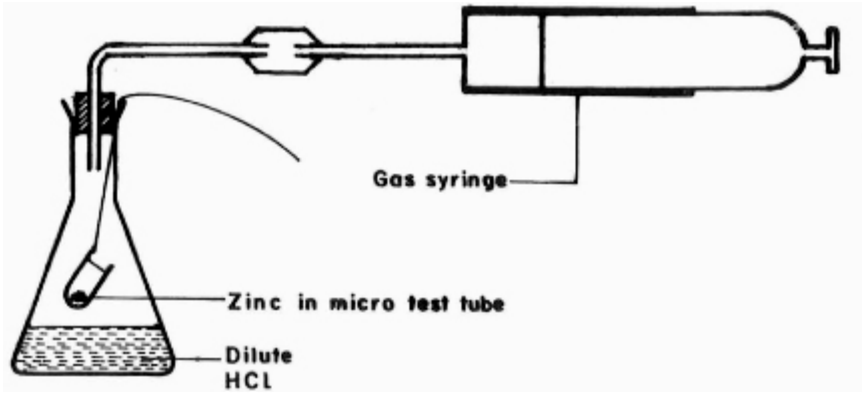

Figure 2.4 Determining the stoichiometry of reaction between dilute hydrogen chloride acid (hydrochloric acid) and zinc

Mass of zinc used = 0.3 g.

Volume of hydrogen displaced = 113 cm^3

Temperature of experiment = 25 Â°C

Atmospheric pressure during the experiment = 0.98 atmosphere

Using the universal gas equation we convert the volume of hydrogen at 25Â°C and 0.98 atmosphere to volume at s.t.p.

$$\frac{V \times 1}{273} = \frac{113 \times 0.98}{298}$$

$$\therefore V = \frac{273 \times 113 \times 0.98}{298}$$

$$= 101.5 \text{ cm}^3$$

$$22400 \text{ cm}^3 \text{ of hydrogen} = 1 \text{ mole}$$

$$\therefore 101.5 \text{ cm}^3 = \frac{101.5}{22400} \text{ mole}$$

$$= 0.00453 \text{ mole} = 0.0045 \text{ mole of hydrogen gas}$$

$$\text{But } 0.3 \text{ g of zinc} = \frac{0.3}{65} \text{ mole} = 0.0046 \text{ mole of zinc.}$$

â^´ I mole of zinc liberates one mole of hydrogen gas. From this we can write the equation of the reaction as

$Zn(s) + 2HCl(aq)$ â†’ $ZnCl_2(aq) + H_2(g)$

In the absence of a gas syringe, the volume of hydrogen displaced can be measured by letting it displace its own volume of water from an aspirator bottle. The displaced water is collected in a measuring cylinder and its volume read. The apparatus for this purpose is shown in Figure 2.5. Since the gas in the aspirator bottle contains water vapour, the pressure of hydrogen is got by subtracting the pressure of saturated water vapour at the temperature of the experiment from the atmospheric pressure.

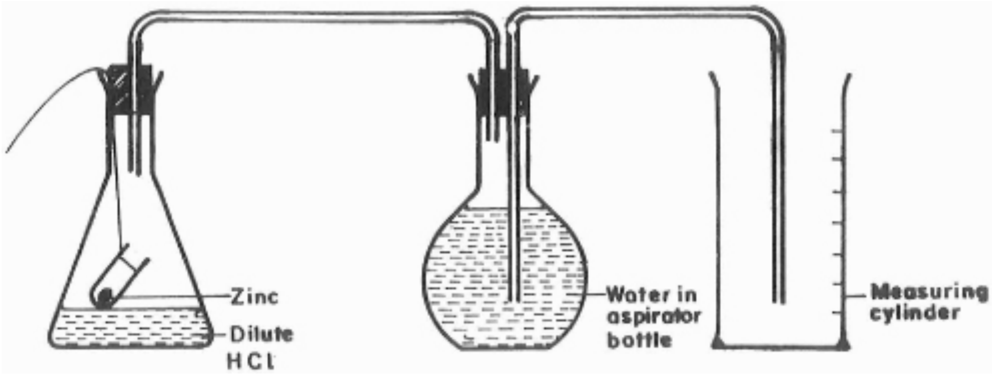

Figure 2.5 Measuring the volume of hydrogen liberated

Experiment 2.5: Determination of the stoichiometry of the oxidation of ammonia by chlorine.

This experiment requires the use of a special apparatus, shown in Figure 2.6.

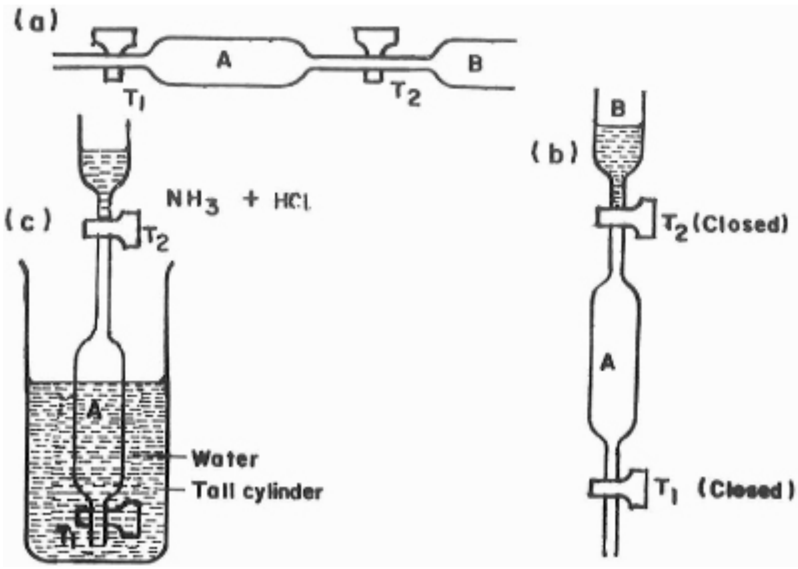

Figure 2.6 Determining the stoichiometry of the oxidation of ammonia by chlorine

A is a bulb graduated to read volume. With taps T_1 and T_2 open, fill the apparatus with dry chlorine gas by connecting the narrow end of the tube to the issuing gas. When the gas can be detected at the opposite end, the bulb is full of chlorine at atmospheric pressure. Then close taps T_1 and T_2 (Figure 2.6b). Now add concentrated ammonia solution into the wider end, while taps T_1 and T_2 remain closed (Figure 2.6a). Gently open tap T_2 and allow a drop of concentrated ammonia into bulb A. A flash of light is observed, followed by dense white fumes of hydrogen chloride. Add more ammonia slowly until the reaction is complete, making sure that ammonia remains in the wider tube throughout.

Neutralise the excess ammonia with concentrated hydrochloric acid mixed with a little methyl orange. Lower the apparatus, keeping it erect, into water contained in a tall cylinder (Figure 2.6c). Open tap T_1. Hydrogen chloride gas dissolves in water, causing the water level to rise inside bulb A. Adjust the level of water inside the bulb to the level in the tall cylinder, then read the volume of nitrogen in bulb A at atmospheric pressure.

SPECIMEN RESULTS AND CALCULATIONS

Volume of bulb A = volume of reacting chlorine gas at atmospheric pressure = 25 cm^3.
Volume of nitrogen gas at atmospheric pressure at the end of the experiment = 8.5 cm^3.
âˆ´ 25 cm^3 of chlorine produced 8.5 cm^3 of nitrogen from ammonia. Applying Avogadroâ€™s law, the volumes of the gases can be changed to mole.

âˆ´ 25 mole of chlorine produced 8.5 mole of nitrogen.

$\therefore$ 1 mole of nitrogen is produced by $\frac{25}{8.5}$ mole of chlorine
= 3 mole of chlorine.

Hence we can write the equation of the reaction as

$3CI_2(g) + 2NH_3(g)$ â†’ $N_2(g) + 6HCI(g)$
3 mole I mole

The mass and volume relationships in chemical reactions provide vital information to chemists. It enables them to determine the ratio of reactants to mix, and to predict the amount of products that will be formed.

It is not necessary to go through experimental determinations such as we have just gone through in order to determine ratios of reacting masses, if a balanced equation can be written for the reaction. The ratio of the coefficients before the formula of each reactant and product represents the mole ratio. The ratio of the reactant/product masses is derived by multiplying the molar mass of each reactant or product by its mole ratio. Thus, the reaction

$Fe_2O_3(s) + 2Al(s)$ â†’ $Al_2O_3(s) + 2Fe(s)$

indicates that one mole of iron(III) oxide is reduced by two mole of aluminium to two mole of iron. One mole of aluminium oxide is also formed.

1 mole of iron(III) oxide = [(2 Ã— 56) + (3 Ã— 16)] g = 160g.
2 mole of aluminium = (2 Ã— 27) = 54g.

1 mole of aluminium oxide = [(2 Ã— 27) + (3 Ã— 16)] g = 102g.

2 mole of iron = (2 Ã— 56)g = 112g

Equation: Fe_2O_3 + 2Al Ã— Al_2O_3 + 2Fe

Ratio of masses = 160 g Fe_2O_3 + 54 g Al â†’ 102 g Al_2O_3 + 112 g Fe

Steps used to deduce mass ratios of reactants and products:

1. From a balanced equation deduce the mole ratio of reactants and products.
2. Calculate the molar mass of each reactant and product.
3. Multiply the number of mole of each reactant and product by its molar mass.
4. Any fraction of these masses can react or be produced.

WORKED EXAMPLES

1. What mass of copper(II) sulphide is formed by passing excess hydrogen sulphide into a solution containing 1.6g of anhydrous copper(II) tetraoxosulphate(VI).

SOLUTION

Mole ratio: $CuSO_4(aq) + H_2S(g) \rightarrow CuS(s) + H_2SO_4(aq)$

Molar masses: $[(64 + 32 + (16 \times 4)]$ g : $(64 + 32)$g

i.e. 160 g : 96 g

$\therefore$ 160 g of $CuSO_4$ yields 96 g of CuS.

$\therefore$ 1.6 g of $CuSO_4$ will yield $\frac{96}{160} \times 1.6$ g of CuS

$= 0.96$g

2. In the Haber process, what volume of ammonia is formed if 6 dm^3 of nitrogen is used up? What volume of hydrogen is also used up?

SOLUTION

	$N_2(g)$	+	$3H_2(g)$	$\rightleftharpoons$	$2NH_3(g)$
Mole ratio:	1	:	3	:	2

i.e. 22.4 dm^3 of N_2 reacts with 3×22.4 dm^3 of H_2 to produce 2×22.4 dm^3 of ammonia.

$\therefore$ 6 dm^3 of N_2 will react with $\frac{3 \times 22.4 \times 6}{22.4}$ dm^3 of H_2

$= 18$ dm^3 of H_2;

and 6 dm^3 of N_2 produces $\frac{2 \times 22.4 \times 6}{22.4}$ dm^3 of NH_3

$= 12$ dm^3 of NH_3.

3. Ammonia reacts with excess oxygen to form nitrogen(U) oxide and water vapour according to the equation

$4NH_3(g) + 5O_2(g)$ â†’ $4NO(g) + 6H_2O(g)$

If 100 cm^3 of ammonia is mixed with 200 cm^3 of oxygen, calculate:

(i) the volume of nitrogen(II) oxide formed.

(ii) the volume of excess oxygen left.

SOLUTION

From the equation, 4 volumes of NH_3 produces 4 volumes of NO.

$\therefore$ 100 cm^3 of NH_3 produces 100 cm^3 of NO.

Also 4 volumes of NH_3 reacts with 5 volumes of O_2.

$$\therefore 100 \text{ cm}^3 \text{ of } NH_3 \text{ reacts with } \frac{5}{4} \times 100 \text{ cm}^3 \text{ of } O_2$$

$$= 125 \text{ cm}^3$$

$$\therefore \text{Excess oxygen} = (200 - 125) \text{ cm}^3$$

$$= 75 \text{ cm}^3.$$

Chapter Summary

An experimental determination of the mole ratio of reactants and products enables us to write a chemical equation for a reaction. Conversely, from a chemical equation we can calculate the mass (or volume) ratio of reactants and products of a chemical reaction.

1. To calculate the masses of reactants and products,
   - (a) Write a balanced equation for the reaction. The coefficients before their formulae give the mole ratio of the reactants and products.
   - (b) Calculate the molar masses of the reactants and products.
   - (c) Multiply the coefficient of each reactant or product with its molar mass to obtain mass ratio of reactants and products.
   - (d) Use simple proportion to calculate the mass of the required reactant or product.
2. To calculate the volumes of reactants and products (for gaseous reactions).
   - (a) Write a balanced equation for the reaction. The coefficients before their formulae give the mole ratio of the reactants and products. Multiply each coefficient by the molar volume to get their volume ratio.
   - (b) Use simple proportion to calculate the volume of the required reactant/product.

Note: One mole of a gas at s.t.p. occupies 22.4 dm^3 (the molar volume).

3. For the generalised equation

aA + bB - cC + dD

(a) Relative masses of reactants and products is given by: (a Ã— molar mass of A) + (b x molar mass of B) â†’ (c Ã— molar mass of C) + (d x molar mass of D)

(b) Relative volumes of reactants and products, if gaseous, is given by: (a âˆ´ molar volume of A) + (b âˆ´ molar volume of B) â†’ (c â†’ molar volume of C) + (d âˆ´ molar volume of D), at the temperature and pressure of the reaction.

Assessment

1. Butane burns in air according to the equation

$2C_4H_{10}(g) + 13O_2(g)$ â†’ $8CO_2(g) + 10H_2O(g)$

If oxygen is 21% of air by volume, what volume of air is required for the complete combustion of 100 cm^3 of butane? What volume of gaseous mixture is left at s.t.p?

2. $AgNO_3(aq) + NaCl(aq)$ â†’ $AgCl(s) + NaNO_3(aq)$

What is the mass of silver chloride formed when 34.0g of silver trioxonitrate(V) reacts with excess aqueous sodium chloride solution?

A. 43.2 g

B. 34.0 g

C. 28.7 g

D. 14.4 g

E. 7.2 g

3. (a) What mass of precipitate is formed if 11.2 dm^3 of carbon(IV) oxide, measured at s.t.p., is bubbled into excess lime water?

(b) What volume of oxygen, measured at s.t.p., is evolved if 24.5g of potassium trioxochlorate(V) is heated till no more gas comes off?

4. Calculate (a) the number of mole (b) the number of molecules present in each of the following:

(i) 160 g of oxygen; (ii) 124.5 g of copper(II) tetraoxosulphate(VI); (iii) 26.4 g of ammonium tetraoxosulphate(VI); (iv) 5.6 dm^3 of nitrogen, measured at s.t.p.; (v) 5.6 dm^3 of oxygen, measured at 25Â°C and 750 mm of mercury pressure. (Avogadro number = 6.02 Ã— 10^{23}).

5. 5.00g of a mixture of anhydrous sodium trioxocarbonate(IV) and sodium hydrogen trioxocarbonate(IV) were heated until there was no further change in mass. The mass of the resulting solid was 3.84 g.

Find the percentage by mass of sodium trioxocarbonate(IV) in the mixture. (WAEC,)

6. Use the equation

$CaCO_3$(s) + 2HCl(aq) â†’ $CaCl_2$(aq) + CO_2(g) + H_2O(l)

to calculate

(a) the mass of calcium chloride produced when 20.0 g of calcium trioxocarbonate(IV) reacts completely with dilute hydrogen chloride acid (hydrochloric acid);

(b) the volume of carbon(IV) oxide produced when 10.0 g of calcium trioxocarbonate(IV) reacts completely. (WAEC),

7. (a) An electric spark is passed through a mixture containing 100 cm^3 of hydrogen and 100 cm^3 of oxygen measured at s.t.p. until there is no more change.

   (i) Write an equation for the reaction.

   (ii) Name the gas left in the container.

   (iii) What is the volume of the residual gas at s.t.p.?

   (b) If oxygen in (a) above is replaced with an equal volume of air:

   (i) Name the residual gases

   (ii) Calculate the volume of the residual gas mixture at s.t.p.

   [Assume that air contains 21 % of oxygen and 79% nitrogen]

   (WAEC)

8. 9.60g of a gas X occupies the same volume as 0.30 g of hydrogen under the same conditions. What is the molar mass of the gas X?
   A. 8. B. 16. C. 32. D. 64. E. 128. (WAEC)

9. SO_2(g) + Â½O(g) â†’ SO_3(g)

   From the above equation calculate:

   (a) The volume of sulphur(IV) oxide which would react with oxygen to yield 8.00g of sulphur(VI) oxide.

   (b) The volume of oxygen which would react with 2.0 moles of sulphur(IV) oxide. (WAEC).