2.3. MOLECULAR WEIGHT

- Introduction
- Definition of molecular weight of an element or compound
- Gram molecular weight
- Concept of Avogadro's hypothesis
- Application of Avogadro's hypothesis:

– determination of atomicity of an elementary gas like H_2, Cl_2, O_2, and N_2
– determination of the relationship between molecular Weight & Vapour density
– determination of the gram molecular volume of all gases is equal to22.4 litres at NTP
– determination of the gram molecular weight of any gas that contains the same no of molecules

- Avogadro's number
- Determination of molecular weight by Victor Meyer's method
- Solving related simple numerical problems **[4 Hrs.]**

Relative Molecular mass (weight)

Molecular mass is also defined similarly to atomic mass.

The molecular weight of a compound or an element is the number of times a molecule of the element or compound is heavier than 1/12th of a C-12 isotope.

Mathematically,

$$\text{Molecular mass} = \frac{\text{mass of 1 molecule of a compound or element}}{\text{mass of} \frac{1}{12\text{th}} \text{of C}-12 \text{ isotope}}$$

The molecular mass of a substance is calculated by summing up the mass of all the atoms present in the molecular formula.

Worked Examples

Example 1: Water (H_2O)
H = 1, O = 16
Mr(H_2O) = (2 × 1) + (1 × 16) = 2 + 16 = 18 amu

Example 2: Hydrated Copper Sulphate ($CuSO_4 \cdot 5H_2O$)
Cu = 63.5, S = 32, O = 16, H = 1
Mr = 63.5 + 32 + (4 × 16) + 5 × [(2 × 1) + 16]
= 63.5 + 32 + 64 + 5 × 18
= 63.5 + 32 + 64 + 90
= 249.5 amu

1. Calculate the molecular masses of;
   i. H_2 ii. N_2 iii. O_2 iv. KCl v. CO vi. SO_2 vii. NH_3 viii. NaCl ix. HCl x. NaOH xi. $CaCO_3$ xii. HNO_3 xiii. H_2SO_4 xiv. Na_2CO_3

Gram molecular mass (gram molecule)

The molecular mass of a substance expressed in grams is called its gram molecular mass or gram molecule.

Gram molecule/gram molecular mass = $\frac{mass\ in\ gram}{molecular\ mass}$

Examples

- Molecular mass of CO_2 = 44 amu
  Therefore, 44 g of CO_2 = 1 gram molecule of CO_2
- Molecular mass of H_2 = 2 amu
  Therefore, 4 g of H_2 = 2 gram molecules of H_2
- Molecular mass of (water) H_2O = 1 x 2 +16 = 18 amu
  18 g water = 1 gram molecule of water
  72 g water = 4 gram molecules of water

Practice Questions

1. How many gram atoms are present in 100 g of Calcium? 1
2. What is the mass of 2 gram atoms of potassium? 1
3. How many gram molecules of SO_2 are there in 32g of SO_2? 1
4. Calculate the mass of 0.5 gram molecules of water. 1

Definition of Avogadro's Hypothesis

"Equal volumes of all gases (or vapours) under similar conditions of temperature and pressure contain the same number of molecules."

e.g., if a litre of hydrogen, oxygen, nitrogen, or carbon dioxide is taken separately at **NTP,** then each of them contains the same number of molecules.

Mathematically, $V \propto n$

Where V = volume of gas; n = number of molecules

At constant temperature and pressure, doubling the volume doubles the number of molecules, & vice versa

Avogadro's Hypothesis

NTP = Normal Temperature and Pressure: 0°C temperature and 1 atm pressure.
This is the standard reference condition used in calculations throughout this course.

Important deductions from Avogadro's Hypothesis

1. determination of atomicity of an elementary gas like H_2, Cl_2, O_2, and N_2

Let us study the reaction between hydrogen gas and chlorine gas.

Reaction: Hydrogen + Chlorine → Hydrogen chloride

Experimentally, it is found that:

- **1 volume of hydrogen** reacts with **1 volume of chlorine**

- to produce **2 volumes of hydrogen chloride (HCl)**.

According to **Avogadro's law**, equal volumes of gases at the same temperature and pressure contain **equal numbers of molecules**.

Suppose **1 volume of any gas contains *n* molecules.**

Then, 1 volume of hydrogen = ***n* molecules**

- 1 volume of chlorine = ***n* molecules**
- 2 volumes of hydrogen chloride = **2n molecules**

This means:

- ***n* molecules of hydrogen** react with ***n* molecules of chlorine**
- to form **2n molecules of hydrogen chloride**.

Dividing the whole equation by ***n***:

1 molecule H_2 + 1 molecule Cl_2 → 2 molecules HCl

So, **1 molecule of HCl is formed from ½ molecule of H_2 and ½ molecule of Cl_2.**

Therefore,

1 molecule of HCl contains ½ molecule of hydrogen. ...(1)

How many hydrogen atoms are present in one HCl molecule?

Hydrogen chloride reacts with sodium hydroxide as follows:

HCl + NaOH → NaCl + H_2O

Only **one type of salt (NaCl)** is formed. This shows that HCl is a **monobasic acid**, which means **one HCl molecule contains only one replaceable hydrogen atom.**

Therefore,

1 molecule of HCl contains 1 hydrogen atom. ...(2)

Conclusion

From (1) and (2):

- ½ molecule of hydrogen contains **1 hydrogen atom**.
- Therefore, **1 molecule of hydrogen contains 2 hydrogen atoms.**

Hence, the hydrogen molecule exists as **H_2**.

Therefore, hydrogen is a diatomic molecule.

Molecular mass = 2× vapour density

The **vapour density (V.D.)** is the ratio of the mass of a given volume of a gas or vapour to the mass of the same volume of hydrogen, under the same conditions of temperature and pressure.
i.e.,

$$\boxed{\text{vapour density} = \frac{\text{mass of a certain volume of gas}}{\text{mass of the same volume of hydrogen at similar conditions of temperature and pressure}}}$$

Let the chosen volume of the gas contain 'n' molecules. By Avogadro's hypothesis, this number is the same for the gas and for hydrogen under identical conditions. Then,

$$\text{v.d.} = \frac{mass\ of\ n\ molecules\ of\ gas}{mass\ of\ n\ molecules\ of\ hydrogen}$$

$$\text{v.d.} = \frac{mass\ of\ 1\ molecule\ of\ gas}{mass\ of\ 1\ molecule\ of\ hydrogen} \quad \ldots\ldots\ldots\ldots\ldots\ 1$$

The Molecular mass of a compound/element is a number that shows how many times the molecule is heavier than one atom of hydrogen.

i.e., Molecular mass = $\frac{mass\ of\ one\ molecule\ of\ gas}{mass\ of\ 1\ atom\ of\ hydrogen}$ …………..2

Dividing equation 2 by 1, we get,

$$\frac{molecular\ mass}{vapour\ density} = \frac{\frac{mass\ of\ 1\ molecule\ of\ gas}{mass\ of\ 1\ atom\ of\ hydrogen}}{\frac{mass\ of\ 1\ molecule\ of\ gas}{mass\ of\ 1\ molecule\ of\ hydrogen}}$$

$$= \frac{mass\ of\ 1\ molecule\ of\ hydrogen}{mass\ of\ 1\ atom\ of\ hydrogen}$$

$$= \frac{mass\ of\ 2\ atoms\ of\ hydrogen}{mass\ of\ 1\ atom\ of\ hydrogen} = 2$$

∴ Molecular mass = 2 × vapour density

Gram molecular volume of all gases contains 22.4 L at NTP

(Molar volume of all gases equals 22.4 L at NTP)

We know that,
Molecular mass = 2 × vapour density

$$= 2 \times \frac{mass\ of\ the\ given\ volume\ of\ gas}{mass\ of\ \text{the}\ same\ volume\ of\ hydrogen\ at\ same\ temperature\ and\ pressure}$$

Let us consider 1 litre of gas at NTP,

$$\text{Molecular mass} = 2 \times \frac{mass\ of\ 1-litre\ gas\ at\ NTP}{mass\ of\ 1\ litre\ of\ hydrogen\ at\ NTP}$$

It has been found that the mass of 1 litre of hydrogen gas at NTP is 0.08986 grams. So,

$$\text{Molecular mass} = 2 \times \frac{mass\ of\ 1\ litre\ of\ gas\ at\ NTP}{0.08986}$$

Or, molecular mass in grams = $\frac{2}{0.08986}$ × mass of 1 L of gas at NTP

∴ molecular mass in grams = 22.4 L of gas at NTP

∴ Gram molecular mass = 22.4 L gas at NTP

This volume (22.4 L) is called the **gram molecular volume** or **molar volume** of a gas at NTP

3. Deduction of Avogadro's number

Avogadro's number (N_A) is the number of molecules present in one gram molecular mass (one mole) of any gas (or substance). Its value is approximately **6.023×10^{23}** molecules per mole.

Let us consider H_2 gas to deduce this number
We know,
The Molecular mass of H_2 = 2
1 gram molecular mass of H_2 = 2 gm
Let w gram = mass of one 1-atom
Then, 2w gram is the mass of the H_2 molecule.
2gram is the mass of 1/w H_2 molecule.
This implies
1 gram molecular mass of H_2 contains 1/w H_2 molecule.
This constant number of molecules is Avogadro's number, which is calculated as:
$\frac{1}{w} = \frac{1}{1.67 \text{ x } 10\text{^}23} = 6.023 \text{ x } 10^{23}$
i.e., 1 gram molecular mass of any gas contains Avogadro's number of molecules ($6.023 \text{ x } 10^{23}$).

Important Distinction

- Avogadro's number (6.023×10^{23}) applies to any substance — solid, liquid, or gas. One mole of iron, water, or glucose contains the same number of particles.
- The molar volume of 22.4 L applies only to gases at NTP. It **does not apply to solids or liquids**.

Determination of molecular weight by Victor Meyer's method

Victor Meyer's method is used to determine the **molecular mass (molecular weight)** of a **volatile liquid**, i.e., a liquid that easily changes into vapour.

Principle

When a known mass of a volatile liquid is heated, it completely changes into vapour.
The vapour displaces an **equal volume of air** from the apparatus.
According to **Avogadro's law**, equal volumes of gases at the same temperature and pressure contain an equal number of molecules.
Therefore, by measuring the **volume of displaced air**, we can find the volume of the vapour. Using the mass and volume of the vapour, its molecular mass can be calculated.

Apparatus

The apparatus consists of:

- Victor Meyer tube
- Small glass bulb (or bottle) containing the liquid
- Heating jacket (water bath or oil bath)
- Delivery tube
- Water trough
- Graduated measuring cylinder

Procedure

1. Heat the Victor Meyer tube until a constant temperature is reached.
2. Weigh a small amount of the volatile liquid in a glass bulb.
3. Drop the bulb into the hot Victor Meyer tube and quickly close it with a stopper.
4. The liquid vaporizes immediately.
5. The vapour pushes out an equal volume of air.
6. Collect the displaced air in an inverted graduated measuring cylinder over water.
7. Measure the volume of the collected air and note the room temperature and atmospheric pressure.
8. Correct the gas volume to **STP** and calculate the molecular mass.

Formula

The molecular mass is calculated using:

$$\boxed{\text{Molecular mass} = \frac{\text{Mass of volatile liquid} \times 22400}{\text{Volume of vapour at STP}}}$$

where:

- **Mass of liquid** = mass of the volatile liquid (g)
- **Volume of vapour at STP** = volume of displaced air corrected to STP (mL)
- **22400 mL** = volume occupied by 1 mole of a gas at STP.

Precautions

- Use only a **volatile liquid**.
- Heat the apparatus until the temperature becomes constant.
- Close the stopper immediately after dropping the bulb.
- Ensure there is no leakage of gas.
- Correct the collected gas volume to STP before calculation.

Concept	Key Statement
Avogadro's Hypothesis	Equal volumes of all gases at the same T & P contain the same number of molecules.
Vapour Density	V.D. = (mass of given volume of gas) / (mass of same volume of H_2) at same T & P
Deduction 1	Molecular Mass = 2 × Vapour Density
Deduction 2	Gram Molecular Volume of any gas = 22.4 L at NTP
Deduction 3	Avogadro's number $N_a = 6.023 \times 10^{23}$ molecules per mole

https://subarnam.com.np/

1. State Avogadro's hypothesis and deduce the relationship between the vapour density and molecular weight of a volatile substance. [1+3]
   State Avogadro's hypothesis. Show that the molecular weight of a substance is twice its vapour density. [1+4]
   State Avogadro's hypothesis. Derive a relation: molecular weight = 2 × Vap. Density. [1+4]
   State Avogadro's hypothesis. What is the relationship between Molecular weight and vapour density? Explain. [4]
   Show that the molecular weight is equal to twice the vapour density.
   Define Avogadro's hypothesis. Show that the molecular weight of the compound is twice of it's vapour density.
2. What is Avogadro's number? State Avogadro's hypothesis.

3. What do you mean by gram molecular weight?
4. How can you prove that hydrogen, chlorine and nitrogen are diatomic gases according to Avogadro's hypothesis? [4]
5. Prove that hydrogen and oxygen are diatomic molecules. [3]
6. State Avogadro's hypothesis. 1
7. In a Victor Meyer experiment, 0.12 g of a volatile liquid displaced 45.6 mL of air at 27°C and 752 mmHg pressure. Calculate the molecular weight and vapour density of the liquid. (Aqueous tension at 27°C is 22 mm of Hg) [3]
8. Define Avogadro hypothesis.
9. 0.15 g of volatile liquid, when treated with Victor Meyer's apparatus, displaced 40.5cm^3 air collected over water at 15°C and 746mm Hg Pressure. Calculate the molecular weight of liquid (Aqueous tension at 15°C = 13.17 mm Hg). [4]

…