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Determination Of Relative Molecule Mass Volatile Compounds

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ABSTRACT

Volatile compounds are organic substances with relatively low molecular weights (50–200 Da) that readily vaporize upon heating, leading to a decline in aroma and flavor quality. The relative molecular mass of these compounds can be determined by measuring the vapor density of the released gas. In 1807, Dalton proposed the atomic theory, which explained that matter consists of indivisible particles. Atoms within a single element are identical in nature, yet they differ from the atoms belonging to other elements. The relative molecular mass is defined as the comparison between the mean molecular mass and the mass of a carbon-12 atom. Ideal gas theory assumes that gas particles are numerous, move randomly, have negligible intermolecular forces, and undergo perfectly elastic collisions in accordance with Newton's laws of motion. The ideal gas law, formulated experimentally by Charles and Gay-Lussac in 1802, can be expressed as or, equivalently, , where R is the gas constant. In this study, the determination of the relative molecular mass of a volatile compound was carried out by measuring vapor density. Using chloroform ($CHCl_3$), the vapor density obtained was 3.692 g/L, corresponding to a relative molecular mass of 111.282 g/mol.

Keywords: Volatile compounds; Relative molecular mass; Vapor density

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1. Introduction

Volatile compounds are substances that readily evaporate into gases at relatively low temperatures, typically around 100°C. The evaporation of these compounds may result in the degradation of their quality. The molecular mass of a volatile compound can be identified by measuring the density of its vapor. Such measurement is

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essential in processes involving heat to anticipate the amount of volatile compounds that will evaporate, thereby preserving the aroma and flavor of the components [1].

A molecule is formed from the combination of several elements in specific proportions. Identical elements combine to produce elemental molecules, whereas different elements form compound molecules. The molecular mass of a substance, whether an element or a compound, is expressed as its relative molecular mass (Mr). This quantity is obtained by summing the relative atomic masses (Ar) of the atoms that make up the molecule [2].

Volatile compounds are characterized by their ability to evaporate easily. Volatile compounds typically have a lower relative molecular mass (Mr) compared to non-volatile compounds. This is because volatile compounds possess weaker intermolecular forces than their non-volatile counterparts.

The definition of relative molecular mass (Mr) has evolved significantly, from Dalton's early atomic theory in 1807 to the adoption of the carbon-12 isotope as the universal reference standard. While hydrogen and oxygen were once used as benchmarks, both were later considered unsuitable due to isotopic instability. Consequently, carbon-12 was chosen, where one atomic mass unit equals 1/12 of the mass of a carbon-12 atom (Shiferaw et al., 2011). This value provides a consistent basis for comparing molecular weights, including volatile compounds such as chloroform ($CHCl_3$).

In this experiment, the molecular mass of chloroform was determined using the vapor density method, a classical but still reliable technique for volatile liquids (Sevilla et al., 1993). The measured vapor density was 3.692 g/L, resulting in an experimental (Mr) value of 111.282 g/mol compared to the theoretical 119.4 g/mol, with a deviation of 6.79%. The discrepancy may be due to incomplete vaporization, trapped air inside the flask, or minor inaccuracies in weighing and temperature control (Fadil et al., 2025). While modern approaches such as mass spectrometry could provide more precision, the vapor density method remains valuable in laboratory practice and chemical education due to its simplicity, accessibility, and ability to demonstrate gas behavior in molecular mass determination (Sudaryono, 2022). In this context, the Victor Meyer method was chosen because it offers a balance between experimental feasibility and accuracy for volatile organic compounds, making it more suitable than other vapor density approaches (Atkins, 1996).

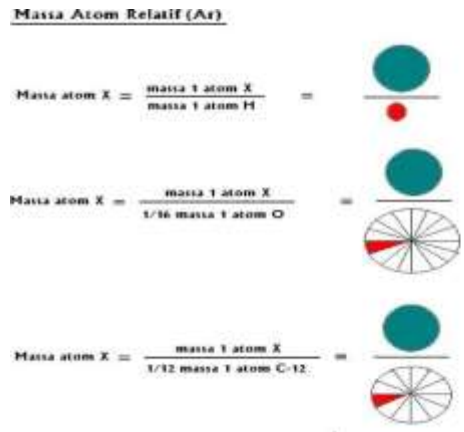

Figure 1. Calculation of Relative Atomic Mass

Advances in instrumentation allowed scientists to construct highly precise balances capable of weighing solids, liquids, and gases. Measuring gases is far more difficult compared to solids and liquids because gases are very light and must be confined within a closed container, as shown in Figure 2 [2].

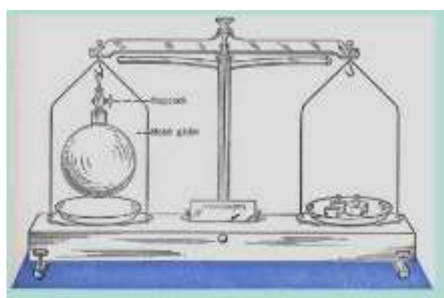

Figure 2. How to weigh past gas

With the advancement of accurate gas measurement techniques, scientists began conducting comprehensive studies on gases and their reactions. From these investigations emerged several gas laws, one of which is Avogadro's Law. This principle states that gases of equal volume, under the same temperature and pressure, enclose an equal number of molecules. As an example, two volumes of hydrogen contain double the molecules found in one volume of oxygen, aligning with the chemical reaction equation.

Avogadro suggested in his hypothesis that gases with identical volumes contain an equal number of particles if temperature and pressure are the same. One significant implication of this hypothesis, known as Avogadro's law, asserts that the volume of a gas varies directly with the mole quantity when both pressure and temperature are kept constant [4].

Volatile compounds are organic substances with molecular weights typically ranging between 50 and 200 Daltons. Due to their relatively low molecular weights, these compounds readily evaporate and diffuse in the gas phase as well as within biological systems. When these compounds volatilize, the quality of aroma and flavor components decreases. The molecular mass of volatile substances can be obtained through measurements of the density of their vapor.

A gas is always influenced by changes in environmental pressure and temperature. Various gas laws describe the dependence of a certain quantity of gas on pressure, temperature, and volume, which have been established through experimental observations. On the basis of these concepts, the molecular weight of a volatile substance may be determined by employing the ideal gas equation in combination with vapor density measurements [5].

An ideal gas consists of a very large number of particles uniformly distributed throughout the available space. These particles move randomly in all directions, with the distance between them being much greater than their own size. There are no intermolecular interactions, and all collisions, whether between particles or with the container walls, are perfectly elastic and occur within an extremely short time. Furthermore, Newton's laws of motion apply to these particles.

A simple relationship that connects the properties of gases is highly valuable for practical analysis, and this relationship is known as the equation of state. In 1802, J. Charles and J. Gay-Lussac experimentally established such a relationship, which is expressed as, and commonly referred to as, the ideal gas equation. Here, R denotes the gas constant, the value of which varies depending on the units applied. In terms of volume, this relationship can also be expressed as. When written to represent two different states, the equation of state takes the form:

$$\frac{p_1 v_1}{T_1} - \frac{p_2 v_2}{T_2}$$

At pressures lower than 10 kPa, the thermodynamic behavior of water vapor closely corresponds to that predicted by the ideal gas law [10]. The relative molecular mass of a compound is defined as the ratio of the average mass of one of its molecules to the mass of a carbon-12 atom. The expression for relative molecular mass is written as:

$$Mr\ x = \frac{average\ mass\ of\ 1\ molecule\ of\ compound\ x}{{}^{1}/_{12}\ mass\ of\ \ 1\ atom\ of\ {}^{12}C}\ [6]$$

The mole quantity of a gas, denoted as n, can be determined by dividing the gas's mass (M) by its molar mass, which is measured in grams per mole (g/mol). Thus, $n = \frac{m}{M}$. When expressed without dimension, the molecular weight is equal to the molar mass value. Accordingly, the ideal gas law can be expressed as follows:

$$PV = \frac{mRT}{M}\ [7].$$

A molecular formula is always an integer multiple of its empirical formula, representing the actual number of atoms bonded chemically to form a molecule. The molecular formula of a compound can be determined if its empirical formula and molar mass are known [6].

2. Materials and Method

Instruments and Materials

The instruments used in this experiment included an Erlenmeyer flask (150 mL), a beaker (600 mL), aluminum foil, rubber bands, a needle, an analytical balance, a desiccator, and a barometer. The materials employed in this practical work were volatile liquids, namely chloroform ($CHCl_3$) and carbon tetrachloride (CCl_4).

Experimental Procedure

A clean, dry 150 mL narrow-neck Erlenmeyer flask was weighed, sealed with aluminum foil secured with a rubber band, and filled with approximately 5 mL of the volatile liquid, and the flask was resealed. A small pinhole was made in the foil to release excess vapor, and the flask was placed in a water bath at ~100°C until the liquid fully evaporated, with the bath temperature measured. After vaporization, the flask was removed, dried externally, cooled in a desiccator, and reweighed. The flask volume was determined by filling it with water, recording the water mass, and calculating the volume using ϱ = m/V. Atmospheric pressure was obtained from a barometer. These measurements were then used to calculate the vapor density (ϱ) and molar mass (Mr) of the volatile compound.

3. Result

Experimental Data Results

- Mass of empty Erlenmeyer flask = 71.4504 g
- Mass of Erlenmeyer flask + aluminum foil + rubber band = 71.9934 g
- Mass of Erlenmeyer flask + aluminum foil + rubber band + condensed vapor = 72.6130 g
- Temperature of the water bath = 90°C
- Mass of Erlenmeyer flask + water = 167.7884 g
- Calculated volume of the Erlenmeyer flask = 100 mL
- Atmospheric pressure = 1 atm

Calculation

1. Volume of Erlenmeyer Flask

$$\begin{aligned} V &= \frac{m}{\rho} \\ &= \frac{167.7884\ g}{1\ g/cm^3} \\ &= 167.7884\ cm^3 \\ &= 0.1677884\ L \end{aligned}$$

2. Mass of Volatile Compound

$$\begin{aligned} m_2 - m_1 &= 72.6130\ g - 71.9934\ g \\ &= 0.6196\ g \end{aligned}$$

3. Density of Volatile Compound (ρ)

$$\begin{aligned} \rho &= \frac{m}{V} \\ &= \frac{0.6196\ g}{0.1677884\ L} \\ &= 3.692\ g/L \end{aligned}$$

4. Relative Molecular Mass (Mr)

$$\begin{aligned} Mr &= \frac{\rho RT}{\rho} \\ &= \frac{3.692\ gr/L.0.083.363,15K}{1} \\ &= 111.282\ g/mol \end{aligned}$$

5. Percentage Error

$$\% \text{ error} = \frac{Mr(theoretical) - Mr(experimental)}{Mr(theoretical)} \; x\; 100\%$$

$$= \frac{119.4g/mol - 111.282g/mol}{119.4g/mol}$$

$$= 6.79\%$$

4. Discussion

In this experiment, the molecular mass of chloroform ($CHCl_3$) was determined using the vapor density method. The results showed an experimental molecular mass of 111.28 g/mol, compared with the theoretical value of 119.4 g/mol, yielding a 6.79% error. According to IUPAC, relative molecular mass is defined as "the ratio of the mass of a molecule to 1/12 of the mass of a carbon-12 atom" [7], and our findings align closely with this definition.

In this study, the sample used was chloroform ($CHCl_3$). Its molecular mass was determined experimentally through the process of vaporization, condensation, and measurement of the mass difference before and after volatilization. Since chloroform is a volatile compound with a boiling point lower than that of water, its relative molecular mass can be determined by measuring the vapor density [3].

During the experiment, the empty Erlenmeyer flask was first weighed (71.4504 g), followed by weighing with aluminum foil and a rubber band (71.9934 g). Subsequently, 5 mL of chloroform was introduced, and the flask was sealed with foil and a rubber band. Small punctures were made in the foil to allow vapor escape. The flask was then immersed in a hot water bath until the chloroform had completely evaporated, with the water bath temperature recorded at 90°C. This measurement is crucial, as the pressure of the volatile gas is directly proportional to the surrounding temperature; an increase in temperature leads to an increase in vapor pressure. The calculation was based on the ideal gas law, expressed as [8]. Small deviations in experimental temperature may have affected the vapor pressure, leading to errors. Heat loss, incomplete vaporization, and vapor leakage are also potential sources of inaccuracy.

After condensation, the Erlenmeyer flask was reweighed, yielding a mass of 72.6130 g, while the flask filled with water weighed 167.7884 g. From the calculations, the mass of chloroform vapor was determined to be 0.6196 g, with a vapor density of

3.692 g/L. The experimental relative molecular mass was 111.282 g/mol, compared to the theoretical value of 119.4 g/mol, resulting in a percentage error of 6.79%. The 6.79% error may be attributed to trapped air inside the flask, incomplete condensation of vapor, vapor leakage during handling, or weighing inaccuracies. Similar challenges in vapor density experiments have been reported in previous studies [5].

Several methods exist to determine molecular mass, such as Regnault's, Victor Meyer's, and the limiting density method [5]. In this experiment, the vapor density method was selected due to its simplicity and suitability for volatile compounds such as chloroform.

5. Conclusions

Volatile organic compounds typically possess molecular weights in the range of 50–200 Daltons, enabling them to readily evaporate and diffuse in gaseous and biological systems. The determination of their molecular mass can be achieved through vapor density measurements. In this study, the relative molecular mass of chloroform ($CHCl_3$) was experimentally obtained as 111.28 g/mol, with a vapor density of 3.692 g/L. Compared to the theoretical value of 119.4 g/mol, the result showed a deviation of 6.79%, which may be attributed to experimental limitations such as incomplete condensation and measurement inaccuracies. These findings demonstrate that the vapor density method provides a reliable approximation for determining the molecular mass of volatile compounds, although precision is highly dependent on experimental conditions.

6. Patents

This study does not result in a patent. The work primarily focuses on the determination of the relative molecular mass of volatile compounds through experimental measurement of vapor density. While the findings provide valuable insights for laboratory practice, chemical education, and potential methodological improvements, they do not generate intellectual property rights in the form of a patent.

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