EXPERIMENT 30A5: MOLAR VOLUME OF A GAS

Learning Outcomes

Upon completion of this lab, the student will be able to:

1) Demonstrate a single replacement reaction.
2) Calculate the molar volume of a gas at STP using experimental data.
3) Calculate the molar mass of a metal using experimental data.

Introduction

Metals that are above hydrogen in the activity series will displace hydrogen from an acid and produce hydrogen gas. Magnesium is an example of a metal that is more active than hydrogen in the activity series. The reaction between magnesium metal and aqueous hydrochloric acid is an example of a single replacement reaction (a type of redox reaction). The chemical equation for this reaction is shown below:

$$Mg_{(s)} + 2HCl_{(aq)} \rightarrow MgCl_{2(aq)} + H_{2(g)}$$ **Equation 1**

When the reaction between the metal and the acid is conducted in a *eudiometer*, the volume of the hydrogen gas produced can be easily determined. In the experiment described below magnesium metal will be reacted with an excess of hydrochloric acid and the volume of hydrogen gas produced at the experimental conditions will be determined.

According to Avogadro's law, the volume of one mole of any gas at Standard Temperature and Pressure (STP = 273 K and 1 atm) is 22.4 L.

Two important Gas Laws are required in order to convert the experimentally determined volume of hydrogen gas to that at STP.

1. Dalton's law of partial pressures.
2. Combined gas law.

<u>Dalton's Law of Partial Pressures</u>

According to Dalton's law of partial pressures in a mixture of non-reacting gases, the total pressure exerted is equal to the sum of the partial pressures of the individual gases.

For instance, if there is a mixture of two gases whose individual partial pressures are P_1 and P_2, then the total pressure exerted by the two gases, P_T is given by:

$$P_T = P_1 + P_2$$ **Equation 2**

In order to see how this law applies to the current experiment, it is important to understand the experimental set up. As stated above, the reaction between magnesium metal and aqueous hydrochloric acid will be conducted in a eudiometer. See Figure 1 below.

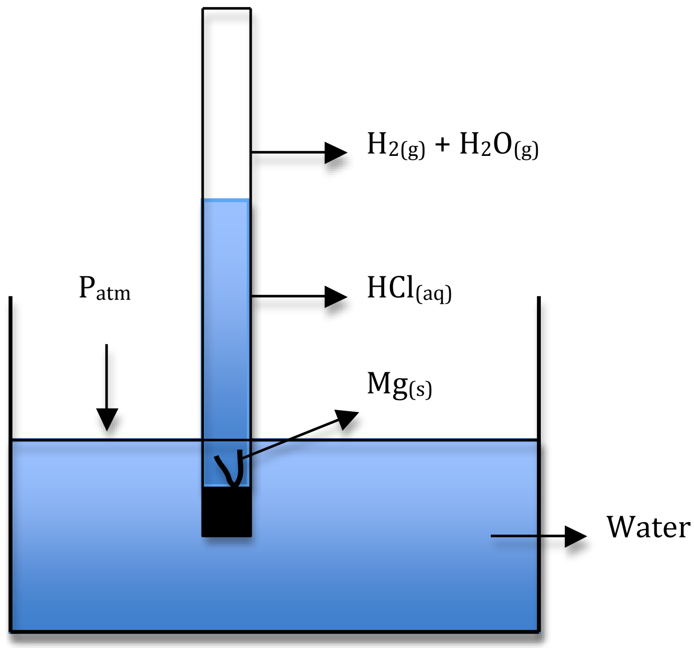

FIGURE 1: EXPERIMENTAL SET UP

The magnesium metal is attached to the stopper of the eudiometer. The aqueous hydrochloric acid is in the eudiometer. The inverted eudiometer is placed inside a water bath. When the metal comes in contact with the acid, the reaction produces hydrogen gas. The hydrogen gas fills the eudiometer. The reaction continues until all the magnesium metal (which is the limiting reagent in this experiment) is completely consumed.

As shown in Figure 1, the $H_{2(g)}$ that is formed is combined with water vapor. The water vapor is a result of the vapor pressure of water found in the aqueous medium. Therefore, the two gases: $H_{2(g)}$ and $H_2O_{(g)}$ are both found in the eduiometer.

Assuming the surface of liquid in te eudiometer is level with the water outside, the total pressure of the gases inside the eudiometer is the same as the atmospheric pressure. A barometer that is found in the laboratory is used to determine the atmospheric pressure.

Therefore, according to Dalton's law:

$$P_{atm} = P_{H_2} + P_{H_2O} \qquad \textbf{Equation 3}$$

In the above equation, P_{H_2} is the partial pressure of the hydrogen gas produced in the experiment and P_{H_2O} is the vapor pressure of water at the temperature at which the experimented is conducted.

The pressure, volume, and temperature of the $H_{2(g)}$ produced in the experiment are needed to calculate the molar volume of the gas at STP. Therefore Equation 3 is rearranged as follows:

$$P_{H_2} = P_{atm} - P_{H_2O} \qquad \textbf{Equation 4}$$

The vapor pressure of water varies with temperature. The vapor pressure of water at the temperature (T, in Kelvin) at which the experiment is conducted may be approximately determined using the following formula (the origin of the formula is beyond the scope of the current discussion).

$$P_{H_2O} = \exp\left(20.386 - \frac{5132}{T}\right) mmHg \qquad \textbf{Equation 5}$$

<u>Combined Gas Law</u>

As discussed in the previous section, the experiment allows for the determination of pressure, volume, and temperature of $H_{2(g)}$. Avogadro's law specifies that the volume of one mole of *any* gas at STP is 22.4 L.

Therefore two calculations are necessary to determine the *molar* volume of a gas at STP using the experimental results.

1. The volume of the gas at STP is calculated using the combined gas law.

2. The stoichiometry of the reaction (Equation 1) is used to determine the number of moles of the gas produced.

The mathematical form of the combined gas law is given below:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \qquad \textbf{Equation 6}$$

In Equation 6, assume that the values of pressure, volume, and temperature (in Kelvin), obtained from the experiment are respectively, P_1, V_1, and T_1. Then, V_2 would be the volume at STP, P_2 is 1 atm and T_2 is 273 K. These values should be substituted in Equation 6 to solve for V_2.

Finally, the moles of $H_{2(g)}$ produced in the experiment must be determined in order to obtain the volume of one mole of the gas. The experiment is designed such that the magnesium metal is the limiting reagent. Therefore, if the mass of the magnesium metal is known, the moles of $H_{2(g)}$ produced can easily be determined using the reaction stoichiometery (Equation 1).

Sample Data and Calculation

In a certain experiment, 0.0369 grams of magnesium was reacted with excess HCl. The reaction resulted in 38.2 mL of $H_{2(g)}$ at 22°C. The barometric pressure was recorded as 749.2 mm of Hg. Calculate the molar volume of the gas at STP.

Mass of magnesium metal = 0.0369 grams

Atomic mass of magnesium metal = 24 grams/mol

Moles of magnesium metal = 0.00154 moles

$Mg_{(s)} + 2HCl_{(aq)} \rightarrow MgCl_{2(aq)} + H_{2(g)}$

Moles of $H_{2(g)}$ = Moles of Mg × $\frac{\text{1 mole H}_2}{\text{1 mole Mg}}$ = 0.00154 moles

Temperature of $H_{2(g)}$ = 22°C = 295 K = $\mathbf{T_1}$

Calculate the P_{H2O} using equation 5: $P_{H_2O} = \exp\left(20.386 - \frac{5132}{T}\right) mmHg$

P_{H2O} = 19.89 mm of Hg

Barometric pressure = 749.2 mm of Hg

P_{H2} = 749.2 – 19.89 = 729.31 mm of Hg = $\mathbf{P_1}$

Volume of $H_{2(g)}$ = 38.2 mL = 0.0382 L = $\mathbf{V_1}$

At STP:

Pressure = 760 mm of Hg = $\mathbf{P_2}$

Temperature = 273 K = $\mathbf{T_2}$

Use Equation 6 to solve for V_2:

$$V_2 = \frac{P_1V_1}{T_1} \times \frac{T_2}{P_2} = \frac{729.31mmHg \times 0.0382L \times 273K}{295K \times 760mmHg} = 0.0339L$$

Moles of H_2 = 0.00154 moles

Therefore molar volume = $\frac{0.0339L}{0.00154moles} = 22.0\frac{L}{mol}$

Experimental Design

A small piece of magnesium metal will be tied to the stopper of a eudiometer. The eudiometer is filled with aqueous hydrochloric acid. The eudiometer will be inverted and suspended into a water bath. The volume and temperature of the gas should be recorded. Also, the atmospheric pressure should be recorded from the barometer in the laboratory.

Reagents and Supplies

Magnesium metal, 6 M hydrochloric acid

50-mL eudiometer, 600-mL beaker, thermometer, copper wire, sandpaper

(See posted Material Safety Data Sheets)

Procedure

1. Obtain a 50-mL eudiometer and a thermometer from the stockroom. Also obtain a buret stand and clamp from the laboratory.

2. Place a 100-mL graduated cylinder in an empty 600-mL beaker. Clamp the graduated cylinder in place and fill the graduated cylinder with water to the rim.

3. Cut a 2-cm strip of magnesium metal and scrape the metal with sandpaper to remove any dark oxides.

4. Measure the mass of the magnesium metal. [NOTE: The magnesium is the limiting reagent in this experiment]

5. Coil the magnesium strip. Using the copper wire, attach the magnesium metal to the inside of the stopper for the eudiometer, by forming a wire cage around the magnesium metal.

6. Add 10 mL of 6 M HCl into the eudiometer.

7. Fill the remainder of the eudiometer with deionized water slowly, attempting the disturb the HCl as little as possible. [NOTE: Normally, concentrated acid is added to water for dilution purpose. In this step, the reverse process is being recommended. Care must be taken to avoid spills or splashing.]

8. Seal the eudiometer with the stopper. Place the stoppered eudiometer above the 100-mL graduated cylinder containing water and turn it upside down. Immerse the stopper end of the eudiometer completely under water.

9. Clamp the eudiometer to the buret stand. The reaction between the magnesium metal and the HCl will start momentarily and hydrogen gas will collect in the eudiometer. The aqueous solution will be pushed out through the stopper into the 100-mL graduated cylinder, which will overflow into the 600-mL beaker that the graduated cylinder is placed in.

10. When the reaction is complete, move the eudiometer so that the level of the water in the eudiometer is equal with the water inside. If this is not possible, record the difference in height between the eudiometer and the graduated cylinder.

11. Measure and record the volume of the hydrogen gas.

12. Record the temperature of the water and assume this to be the temperature of the hydrogen gas.

13. Record the barometric pressure.

14. Empty the contents of the eudiometer into the 600-mL beaker and the contents of the 600-mL beaker into the waste container provided by the instructor. Rinse the eudiometer with deionized water.

15. Repeat steps 3-14.

Data Table

	Trial 1	**Trial 2**
Mass of magnesium (grams)		
Volume of $H_{2(g)}$, L		
Temperature of $H_{2(g)}$, K		
Barometric pressure, mm of Hg		
Height difference between eudiometer and graduated cylinder		

Calculations

MOLAR VOLUME OF A GAS AT STP

	Trial 1	Trial 2
Mass of magnesium, grams		
Atomic mass of magnesium (grams/mol)		
Moles of Magnesium		
Moles of $H_{2(g)}$ (use stoichiometry)		
Temperature of $H_{2(g)}$ (T_1 in Kelvin)		
Volume of $H_{2(g)}$ (V_1 in L)		
Barometric pressure (P_T in mm of Hg)		
$P_{H_2O(g)}$ (mm of Hg) (use Equation 5)		
$P_{H_2(g)}$ (same as P_1) (mm of Hg) (use Equation 4)		
Volume of $H_{2(g)}$ at STP (V_2 in L) (use Equation 6)		
Molar volume of $H_{2(g)}$ at STP (L/mol)		
Percent error		

ATOMIC MASS OF A METAL

Assume that the identity of the metal used in the experiment (i.e., magnesium) is unknown. Assume also that the stoichiometry of the reaction between the unknown metal M and HCl is as follows:

$$M_{(s)} + 2HCl_{(aq)} \rightarrow MCl_{2(aq)} + H_{2(g)}$$

Using the data collected, calculate the atomic mass of the metal M

	Trial 1	**Trial 2**
Temperature of $H_{2(g)}$ (T_1 in Kelvin)		
Volume of $H_{2(g)}$ (V in L)		
Barometric pressure (P_T in mm of Hg)		
$P_{H_2O(g)}$ (mm of Hg) (use Equation 5)		
$P_{H_2(g)}$ (mm of Hg) (use Equation 4)		
Moles of $H_{2(g)}$ produced (HINT: PV = nRT)		
Moles of metal (use stoichiometry)		
Mass of metal in grams (from the data table)		
Atomic mass of metal $\left(\frac{grams}{moles}\right)$		
Average value of Atomic mass $\left(\frac{grams}{moles}\right)$		