Honors Chemistry Lab #19: Experimental Determination of the Gas Constant

Question: How can you experimentally determine the ideal gas law constant using a eudiometer and the enthalpy of reaction and apply this methodology to quantify gas emissions from the STEM garden composting project?

Background : A gas is the state of matter that is characterized by having neither a fixed shape nor a fixed volume. Gases exert pressure, are compressible, have low densities and diffuse rapidly when mixed with other gases. On a microscopic level, the molecules (or atoms) in a gas are separated by large distances and are in constant, random motion.

Four measurable properties can be used to describe a gas quantitatively: pressure (*P*), volume (*V*), temperature (*T*) and mole quantity (*n*). The relationships among these properties are summarized by the Gas Laws, as shown in the table below.

Charles's Law:	$V \propto T$ [*P* and *n* are held constant] As gas temperature increases, gas volume increases.	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$
Boyle's Law:	$V \propto 1/P$ [*T* and *n* are held constant] As gas pressure increases, gas volume decreases.	$P_1V_1 = P_2V_2$
Avogadro's Law:	$V \propto n$ [*P* and *T* are held constant] As the number of moles of gas increase, gas volume increases.	$\frac{V_1}{n_1} = \frac{V_2}{n_2}$
Combined Law:	$V \propto T/P$ [*n* is held constant] Obtained by combining Boyle's Law and Charles's Law.	$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$

A closer look at the Combined Law reveals that the volume of a gas depends on both the pressure and temperature. Thus, if the volumes of two gases are to be compared, they must be under the same *P* and *T*. A commonly used set of *P* and *T* reference conditions is known as Standard Temperature and Pressure, or STP. Standard temperature is defined as exactly 0 °C (273 K) and standard pressure is defined as exactly1 atm (760 mm Hg).

The Ideal Gas Law is obtained by combining Boyle's Law, Charles's Law and Avogadro's Law together:

$$PV = nRT$$

Here, *P* represents as the gas pressure (in atmospheres); *V* is the gas volume (in Liters); *n* is the number of moles of gas in the sample; *T* is the gas temperature (in Kelvins). *R* is a proportionality constant called the Gas Constant, and has a theoretical value of 0.08206 L•atm/K•mol. Note that the units of *R* will allow the units of *P*, *V*, *n* and *T* in the Ideal Gas Law to cancel correctly.

In this lab, students will measure various properties of a sample of hydrogen gas in order to experimentally determine the value of the Gas Constant, *R*. The single displacement reaction between magnesium metal and hydrochloric acid will be used to generate the hydrogen gas:

$$Mg\ (s)\ +\ 2\ HCl\ (aq)\ \rightarrow\ MgCl_2\ (aq)\ +\ H_2\ (g)$$

The hydrogen gas will be collected in a eudiometer, a tube closed at one end and marked in milliliter volume units. The gas will be collected in the closed end of the tube over a water bath via the technique of water displacement (see figures on page 4).

Students will then obtain the following values for the collected sample of hydrogen gas: (1) Volume, (2) Temperature, (3) Moles, and (4) Pressure. The hydrogen volume will be directly measured from the eudiometer scale. The hydrogen temperature will also be directly measured using a thermometer. However, the mole quantity and pressure of the hydrogen gas must be determined indirectly. The mole quantity of the collected hydrogen can be easily calculated from the measured mass of the magnesium reactant using stoichiometry. But the hydrogen pressure is a little more difficult to obtain. Since hydrogen is collected over a water bath, a small amount of water vapor is mixed with the hydrogen in the eudiometer. The combined pressure of the H_2 and H_2O gases will be equal (after adjustments) to the external atmospheric pressure:

$$P_{atm} = P_{hydrogen} + P_{water\ vapor}$$

P_{atm} (atmospheric pressure) will be measured using a barometer. $P_{water\ vapor}$ (the partial pressure of water vapor) depends on the temperature of the water bath, and can be obtained from the table supplied below. By substituting these values in the above equation, the pressure of hydrogen ($P_{hydrogen}$) will be determined.

Temperature (°C)	$P_{\text{water vapor}}$ (mm Hg)
16	13.5
17	14.5
18	15.5
19	16.5
20	17.5
21	18.7
22	19.3
23	21.1
24	22.4
25	23.8
26	25.2
27	26.7
28	28.3
29	30.0

Finally, to determine the value of the Gas Constant (*R*), the quantities *V*, *T*, *n* and *P* obtained for the hydrogen gas must simply be substituted into the Ideal Gas Equation. Students can then evaluate their accuracy in this experiment by comparing their experimental result to the true theoretical value of *R*, and by calculating their percent error.

Safety: Concentrated HCl is dangerous. Handle it with extreme care as demonstrated by your instructor. If any spills occur, inform your instructor immediately. Wash under running water (sink or shower) and use the neutralizing sodium bicarbonate solution supplied at the sinks if necessary. Also note that hydrogen gas is flammable, so be sure to have no open flames nearby when you perform this experiment.

Materials and Equipment: 4.0-cm ribbon of magnesium, length of copper wire (reusable), 6M HCl (*aq*), 50-mL eudiometer*, eudiometer stopper with hole(s)*, burette stand, large beaker, thermometer, small funnel, small graduated cylinder, barometer, large tub of water, analytical balance, and sandpaper.

Magnesium Ribbon

1. Obtain a 4.0-cm ribbon of magnesium (Mg), a piece of sandpaper, and a length of copper wire.

2. Carefully sand the outside of the Mg ribbon to remove any oxide coating. Place the Mg ribbon on a paper towel while sanding. Weigh the cleaned Mg ribbon and record this mass on your report form. Note that this mass should be less than 0.040 grams. If it is heavier, your Mg ribbon will have to be "trimmed" or you will displace all of the solution in the eudiometer and have to start over.

3. Wrap the Mg around the end of the copper wire. Do this in a tight ball with only a small gap between layers. Then wrap the copper wire to form a cage around the Mg ball. The cage must be tight enough to keep the Mg inside, but loose enough to allow water to easily flow around the wire. Roughly 3-cm of copper wire should be left over as a "handle" (see Figure 1).

Eudiometer Set Up and Reaction

4. Obtain a eudiometer tube and stopper size 00 (with holes). Use the burette clamp to hold it in place, open end up.

5. I will add ~10-mL of 6M HCl (*aq*) to the eudiometer tubes and you will need to obtain the tubes from the front of the classroom. Then add colored tap water to the eudiometer carefully until it is filled to the ~50 mL mark. (see Figure 1).

6. Hang the Mg ball inside the open end of the eudiometer, ~2-cm down from the top. Then insert the stopper into this end, and, while holding it in place, quickly invert the entire tube into your largest beaker ¾ filled with water. Clamp the tube in the water in the upside down position (see Figure 2).

7. The reaction will occur as soon as the acid diffuses down the tube and reaches the Mg ribbon. As hydrogen gas is generated it will fill the eudiometer by forcing the water out of the tube and into the beaker via water displacement (see Figure 2). Allow the reaction to proceed until no Mg is left and no further gas is formed. Gently tap the eudiometer to dislodge any trapped gas. This should take 3-5 minutes.

Measurements

9. Record the following measurements:

   - The volume of hydrogen gas collected (read directly from the eudiometer scale), in mL
   - The temperature of the hydrogen gas collected, in °C. This can be measured by first removing the stopper then placing the thermometer directly in the eudiometer (keep the tube inverted so the gas does not readily escape). It is also acceptable to assume that the temperature of the hydrogen gas is the same as the temperature of the water bath, especially if you wait a while before making your measurements.
   - The atmospheric pressure (use the lab barometer), in inHg
   - The temperature of the water in the plastic tub (use the thermometer), in °C
   - The vapor pressure of water at the above temperature (obtain from Table on page 2), in mmHg
   - The pH of the solution in the large beaker that was filled ¾ full using a pH sensor.

10. When finished, repeat this entire procedure a second time with a fresh piece of magnesium ribbon. Find the average of the two values and calculate the percentage error for R.
11. Calculate the concentration of the hydronium ions in the large beaker solution using the pH you measured from the last bullet of #9.
12. Explain how your results would change if you repeated this experiment with sulfuric acid.

Write your claim and summary based on the evidence collected. Brainstorm ideas for collecting gas emissions from the STEM garden compost piles.