Gas Laws

EXPERIMENTAL TASK

Determine the mathematical relationship between the volume of a gas sample and its absolute temperature, using experimental data; and to determine the mathematical relationship between the volume of a gas sample and its pressure, using previously tabulated data.

Objectives

After completing this experiment, the student will be able to:

1. Measure the volume of a gas sample at different temperatures.
2. Use the volume and temperature measurements to prepare a graph of the data.
3. Interpret the graph to determine the mathematical relationship between the volume of a gas sample and its absolute temperature.
4. Use previously tabulated data to construct a graph of the volume of a gas sample vs. its pressure, and interpret the graph to obtain the mathematical relationship between the two variables.

Additional Reading

- General, Organic and Biological Chemistry, by Timberlake, chapter 8.

Background

Gases, unlike liquids and solids, expand to fill their containers. This makes it very difficult to measure the amount of substance (moles) of a gaseous sample. The number of moles of a solid substance can be determined simply by measure the mass of the sample, and using the molar mass of the substance to convert mass to moles. With liquids, either the mass can be measured directly, or the volume of the liquid can be measured and converted to mass using the density of the substance. Gases, on the other hand, require 4 variables to completely describe the state of the substance: volume (V), temperature (T), pressure (P) and number of moles (n). These variables are related to each other and the Ideal Gas Constant, R, in the Ideal Gas Law (or Ideal Gas Equation):

$$PV = nRT$$

In addition, the mathematical relationship between any two variables may be described, as long as the other two variables are held constant. For instance, the pressure of a gas sample is directly proportional to its absolute temperature, when the number of moles and the volume of the gas are held constant:

$$P = kT \quad \text{or} \quad \frac{P_1}{T_1} = \frac{P_2}{T_2} \quad \text{(with n and V constant)}$$

Two of these relationships, or gas laws, will be examined in this experiment. The first is Boyle's Law, which relates volume and pressure:

$$PV = k \quad \text{or} \quad P_1V_1 = P_2V_2 \quad \text{(with n and T constant)}$$

These equations show that pressure is *inversely proportional* to volume, so that when the pressure of a gas sample is multiplied by a particular factor, the volume is divided by the same factor, and therefore the product of P x V will be constant (k) for that sample (as long as n and T are kept constant). You will investigate this law using a previously recorded data set, including P and V for a gas sample (with n and T constant), by finding the product of P and V for each data point, and comparing these products to see if, in fact, they are equal to each other.

The other gas law to be explored in this experiment is Charles' Law, which relates the volume of a gas sample to its temperature (with n and P constant):

$$V = kT \quad \text{or} \quad \frac{V_1}{T_1} = \frac{V_2}{T_2} \quad \text{(with n and P constant)}$$

These equations show that volume is *directly proportional* to temperature, so that when the temperature of a gas sample is multiplied by a particular factor, the volume is multiplied by the same factor.

Charles' Law shows how the temperature of a gas sample affects its volume, when the amount of gas (number of moles) and pressure are held constant.. In this experiment, you will determine this mathematical relationship between the temperature and volume of a gas sample. You will then extrapolate your experimental data to determine a value for absolute zero on the Celsius scale.

The final results of the experiment will be:

Boyle's Law: The completed table showing pressure, volume and P x V; and the graph of Pressure vs. Volume.

Charles' Law: The complete data, including both the temperature and the volume of the gas sample at two different temperatures; and the graph of Volume vs. Temperature, including the determination of absolute zero, in units of °C.

Pre-lab Questions

1. Why does a scuba diver need increased gas pressure in the air tank?

2. How does temperature affect the kinetic energy of a gas molecule?

3. If you start with a pressure (P_1) of 1.2 atm and a volume (V_1) of 2.5 L, and change the pressure to 3.6 atm (P_2), what would be the resultant volume (V_2)?

4. A gas sample with a volume of 525 mL and temperature of -25.0 °C is heated to 175.5 °C. What is the new volume of the gas if pressure and number of moles are held constant?

5. A sample of gas has a volume of 2.8 L at a temperature of 27 °C. What temperature is needed to expand the volume to 15 L? The pressure and number of moles are constant.

BEFORE STARTING THE EXPERIMENT

Safety

While no hazardous materials are used, always keep in mind the rules presented in both the "MCC Laboratory Safety Rules" and the Laboratory Handbook for General Chemistry. It is your responsibility to make sure that you follow all safety rules at all times, and to graciously help everybody else in the laboratory (including the instructor) to do the same.

Hot plates will be used to heat water to boiling--use "Hot Hands" to handle hot glassware.

EXPERIMENT PROCEDURE

Boyle's Law

Draw a table like the one below in your notebook, and copy the data from this one into the table in your notebook. Calculate the product, P x V, at the different conditions, and record the results it in the final column of the table in your notebook.

Trial	Pressure (P) (torr)	Volume (V) (mL)	P x V (Product) (torr-mL)
1	630.	32.0	
2	690.	29.2	
3	726	27.8	
4	790.	25.6	
5	843	24.0	
6	914	22.2	

You can also express your data graphically. Use the 'Blank Graph for Plotting Boyle's Law Data' at the end of this handout to plot the above data; note that Volume will be plotted on the x-axis and Pressure on the y-axis.

Charles' Law

You will experimentally determine the volume of a sample of gas at both a higher temperature and a lower temperature. You will graph your results, with volume (mL) on the y-axis and the temperature (°C) on the x-axis. After you have graphed these data, you will extrapolate (extend) your line between these two points to intersect the x-axis at a point where the volume would be zero. This value of temperature at the intersection point will represent the temperature when the volume of gas would be equal to zero, and therefore the value for absolute zero on the Celsius scale.

You will need the following equipment:

- Ring stand
- Two prong clamp

- Stirring hot plate
- Large beaker (600 or 800 mL)
- 250-mL Erlenmeyer flask (dry inside!)
- Rubber stopper assembly (a one-hole rubber stopper with a piece of glass tubing inserted into the hole, and a piece of latex tubing attached to the glass tubing)
- Stir bar
- Digital thermometer and probe

Attach the two prong clamp to the ring stand. Put the stirring hot plate on the base of the ring stand. Place the beaker on the hot plate, and put the dry 250-mL Erlenmeyer flask into the beaker. Insert the rubber stopper assembly into the mouth of the Erlenmeryer flask, making sure it is tight enough to be secure. Put the stir bar in the bottom of the beaker, under the flask. Attach the flask to the clamp, adjusting the height of the clamp on the ring stand so that the bar of the clamp is just above the top of the beaker, but making sure there is room for the stir bar to turn freely underneath the beaker.

Add enough water to the beaker to come up to the narrow neck of the flask, but make sure the beaker is not too full, or it the boiling water will splash out--ask your instructor if you are unsure about the water level. Turn on the 'Heat' control of the hot plate to the highest setting, and adjust the 'Stir' control to about 4 or 5, so that the water is stirred well without splashing. Once the water has reached a full boil, turn the heat control down to about 7 or 8, and continue to heat it gently for about 10 minutes to bring the temperature of the air in the flask to that of boiling water (the volume of gas occupied in the flask and tubing is the volume of the gas at the temperature of boiling water, V_{boil} --you will measure this volume later). At the end of 10 minutes, measure the temperature of the water (T_{boil}), which gives you the temperature of the gas inside the flask.

After you have determined and recorded the temperature of the boiling water, clamp the latex tubing, and immediately remove the flask from the boiling water. Quickly place your hot and still clamped flask into room temperature water (a deep pan or sink can be filled with water). Keep the flask fully immersed below the water line. Carefully remove the clamp, and let the cooler water flow into the flask. Keep the flask immersed in the water for at least 5 min. This will allow the gas on the inside of the flask to attain the temperature of the surrounding water. While the gas cools, it will decrease in volume, sucking water into the flask.

When you are confident that the temperature of the flask is the same temperature as the surrounding water, you need to do two things to obtain correct data. First, measure the temperature of the water. This temperature should be equal to the temperature of the gas inside the flask, will be recorded as T_{cool}. Second, keeping the still stoppered flask below the water level, raise the flask (with stoppered end pointed down), so that the water level inside the flask is exactly level with the water in the sink. Re-clamp the latex tubing so that no water can flow into, or out of, the flask

Caution: There are several sources of error in this section that you should be careful to avoid:

- The stopper must be firmly inserted into the flask prior to placing it in the sink of water. If the stopper is not firmly inserted, excess water could enter the flask.
- After the flask has reached the same temperature as the water, the water level inside the flask must be exactly level with the water on the outside. This equalizes the pressure inside and outside the flask, which will assure the pressure is the same for the two different temperatures, T_{boil} and T_{cool}.
- The temperature inside the flask must equal the temperature of the cool water on the outside of the flask. This is essential for accurately measuring the temperature of the gas inside the flask. You have plenty of time, so make certain you keep the flask in the cool water for at least five minutes before measuring the temperature.

After you have re-clamped the latex tubing, remove your cooled flask from the cool water. At this point you must measure the volume of the gas (V_{cool}) at the cooler temperature. This will be accomplished by measuring the amount of water that was "sucked" into the flask during cooling (V_{sucked}) and subtracting it from the total volume of the flask assembly (V_{boil}). Measure V_{sucked} by removing the stopper assembly from the flask (be sure not to spill any water!) and pouring the contents into a 100-mL graduated cylinder. Measure and record the volume of this water as V_{sucked}.

Next, measure V_{boil} : Fill the flask to the rim with water, and insert the stopper assembly into the flask while holding the latex tubing vertically above the flask--make sure the stopper is seated securely in the mouth of the flask. Excess water will flow into the latex tubing, with some of it spilling out--this is correct. Then, carefully, remove the stopper assembly allowing any water in the stopper to flow back into the flask. Measure V_{boil} by pouring the water into a 100-mL graduated cylinder; the volume of water in the flask will be more than 200 mL and possible more than 300 mL, and you only have a 100-mL graduated cylinder, you will need to fill the graduated cylinder so several times. Each time you pour water into the cylinder, make sure it does not go above the 100 mL mark, and record the volume measurement; V_{boil} is equal to the sum of these individual volume measurements.

To obtain the volume of gas at the cool temperature (V_{cool}), subtract the volume of water sucked into the flask (V_{sucked}) from the total volume of the flask (V_{boil}). You now have the two volumes and two temperatures necessary for plotting the Charles' Law graph.

You should repeat the experiment at least once. Be sure to start with a clean and dry flask for each trial, and plot a separate graph for each trial! You may use a different flask, but you will need to determine the volume of the new flask using the procedure described above.

Be sure to dry any spills and to clean up your area. Return any equipment used to its proper place in the lab or on the cart.

RESULTS

Boyle's Law

The completed data table, including the product of P x V for each data point, and the graph of Pressure vs. Volume, will be your results for this part of the experiment.

Charles' Law

Use the 'Blank Graph for Plotting Charles' Law Data' at the end of this handout to plot the two Volume and Temperature data points--[T_{cool}, V_{cool}] and [T_{boil}, V_{boil}]; note that Volume will be plotted on the y-axis and Temperature on the x-axis.

Once you have graphed the two data points, use a ruler to carefully draw a straight line that goes from the higher data point to the lower one, and continues all the way to where it intersects the x-axis. The value of Temperature at this point (where Volume = 0) is your experimental value of absolute zero, given in units of °C.

DISCUSSION

Boyle's Law

Are your results consistent with Boyle's Law? That is, is the product of P x V constant (within experimental error)? What shape is given by the graph when you plot Pressure vs. Volume? Is this consistent with an inversely proportional relationship between the variables?

Charles' Law

Are your results consistent with Charles' Law? How accurate is your experimental value of absolute zero?

Blank Graph for Plotting Charles' Law Data