The Gas Laws: Boyle’s Law and Charles Law

Objective

The simple laws governing the properties of gases can be readily demonstrated experimentally. In this experiment we will consider two of the gas laws:

Boyle’s Law \[ V \propto \frac{1}{P} \] or \[ P_1 V_1 = P_2 V_2 \]

Charles’ Law \[ V \propto T_{abs} \] or \[ \frac{V_1}{V_2} = \frac{T_1}{T_2} \]

By collecting appropriate data on the volumes of gas samples at varying pressures or temperatures, we will attempt to verify these laws.

Background

Boyle’s Law

Robert Boyle, a British chemist, was one of the first scientists to study gases quantitatively. In one set of experiments, Boyle established a relationship between the pressure and volume of a gas at constant temperature. In order to arrive at a physically significant law, Boyle simplified the problem by doing his experiments under controlled conditions. He kept the mass, \( m \), of the gas constant (i.e., no leaks in the container), and he kept the temperature constant. Under such circumstances, the relationship between pressure and volume is known as Boyle’s Law. At a constant temperature, the volume (\( V \)) occupied by a finite mass of gas is inversely proportional to the applied pressure (\( P \)). Mathematically, this relationship can be stated as:

\[ V \propto \frac{1}{P} \]

where the symbol \( \propto \) represents proportionality. By placing a proportionality constant in the previous equation, we will have Boyle’s Law in the form of an equation.

\[ V = k \left( \frac{1}{P} \right) \]

So a plot of \( V \) vs \( \left( \frac{1}{P} \right) \) should be linear with a slope of “k”. We can test this law by comparing the volumes occupied by the same sample of gas at various pressures.

The equipment for this experiment is Vernier Gas Pressure Sensor. This apparatus will be connected directly to the computer using a Vernier Go-LinK and measure pressures of various volumes of air.
Procedure

Working at room temperature, we will manipulate the plunger in a large plastic syringe to change the pressure of the air space within the syringe.

According to Boyle’s Law, volume of the air sample and the inverse of its pressure should be a linear relationship. We will use the Spreadsheet program to calculate the volumes and the corresponding inverses of the pressures. A subsequent plot of these should be linear.

Connecting the Pressure Sensor and Syringe

1. Position the piston of a plastic 20 mL syringe at the 20.0 mL mark. Attach the syringe to the valve of the Gas Pressure Sensor, as shown in Figure 1. A gentle half turn should connect the syringe to the sensor securely. Note: Read the volume at the front edge of the inside black ring on the piston of the syringe, as indicated by the arrow in Figure 1.

2. Connect the Go-Link to the USB connector of your computer and connect the Gas Pressure Sensor to the Go-Link.

3. Start the Logger Pro program on your computer. Open the file “30a Gases” from the Advanced Chemistry with Vernier folder. You should now see the screen shown here. This file allows you to collect pressure data from the Gas Pressure Sensor, using Events with Entry mode. For each pressure reading you take with a button, this mode lets you enter a volume value.

4. Double-click the top of the Pressure column to open the Column Options box. Change the units for today’s experiment to atmospheres (atm). Click Done. Now we’ll measure the pressure of the air in the syringe at various volumes and then print a copy of the graph and data.

Running the Experiment

1. With the syringe set at the 20.0 mL mark, click the Collect button on the Tool Bar.

2. Click the button. Instructions on the screen will prompt you to enter a volume. Enter 20.0 and click OK. We will record eight sets of volume/pressure data.

3. Reduce the volume in the syringe by 1.0 mL and hold the syringe in place. Have your lab partner click the button. Enter 19.0 mL in the dialogue box and click OK. Continue until you have collected eight data points. After the last data point is collected, click the Stop button.
Analysis of the Data

1. On the **Menu Bar**, click **Data** and select **New Calculated Column**

2. Assign the column the name **Inverse Pressure** and a short name of **1/P**. Units will be **atm**⁻¹. (Use the drop down menu for this window to assign superscripts) For the equation, type in **1/"Pressure"**. (note that this is case sensitive) Click **Done**.

3. On your graph, click on the y-axis title, **Pressure (atm)**, and select instead, **Inverse Pressure**. Click on the title once more and choose **more** to open the **y-axis options box**. Use the "scaling" drop-down menu to choose **autoscale**. Repeat this scaling change for the x-axis. Your graph should now look like the one shown here.

4. Choose **Analyze** from the **Menu Bar** and select **Linear Fit**. (or click the linear fit button on the **Tool Bar**) If your were careful with your measurements, we should have a linear plot with a correlation of at least 0.999.

5. Select **File/Print Graph** from the **Menu Bar**. Enter 2 copies so that each member of the partnership can include a copy with the lab report. Repeat this procedure to print 2 copies of your **Data Table**.

6. Before you clear the spreadsheet for the next experiment, transfer the values for the eight sets of volume/pressure data to your report sheet. You will note that according to Boyle's Law, the products of **P x V for each pair should remain constant**, (since volume decreases as pressure increases) so **manually** calculate **P x V** and enter these values on the report sheet (**rounded to 3 significant figures**). If these products do not seem to be constant, recheck your data.

7. Disconnect the **Go-Link** from the USB port of your computer  (and return the **Gas Pressure Sensor** and **Go-Link** to the dispensing table).

8. Select **File/New** from the **Menu Bar**. Click "no" when prompted to save the changes to the 30a Gases file. We will now be entering new data for the Charles Law experiment.
**Charles' Law**

Around 1800, French scientist and balloonist, Jacques Charles, began studying the effect of increasing temperature on gases. He observed that the rate of thermal expansion is constant and is the same for all gases as long as the pressure is constant. Charles examined the effects of temperature upon the pressure exerted by a confined gas with volume and mass remaining constant. Thus the graph of pressure versus temperature is a straight line.

In 1848, Lord Kelvin, a British physicist, noticed that by extending different temperature/volume lines (for gases at various but constant pressure) back to zero volume, he always found the same intercept. The intercept on the temperature axis is \(-273.15^\circ C\). Kelvin named this temperature absolute zero. The Kelvin absolute temperature scale, in which \(^oK = ^oC + 273.15\), is named in his honor. The volume/temperature relationship for gases using the absolute temperature scale is known as Charles Law. At a constant pressure, the volume of a finite amount (mass) of gas is directly proportional to the absolute temperature of the gas. Mathematically, Charles Law can be stated as follows (using the absolute temperature scale);

\[ V \propto T_{abs} \]

or

\[ V = kT_{abs} \]

or

\[ \frac{V_1}{T_1} = \frac{V_2}{T_2} \]

So a plot of the volume of a gas sample versus the temperature of the gas should be a straight line. If we extrapolate that line to where the volume of the gas has theoretically shrunk to zero, the corresponding hypothetical temperature should be \(-273^\circ C\) or \(0^\circ K\). (Fig.4)

We can test this law by comparing the volumes, \(V_1\) and \(V_2\), occupied by the same sample of gas at two different temperatures, \(T_{initial}\) and \(T_{final}\). We will use the quantity of air contained in a small glass tube at atmospheric pressure and about 100\(^\circ\)C. The volume of the tube can be calculated from measurements of its length and diameter. The experiment is designed so that as the hot air in the tube cools to the second temperature (room temperature), a drop of oil is sucked up into the tube. The inner meniscus of the oil drop marks the end of the air column, so we can obtain the new volume of the air sample at the second temperature from the new length of the column of air.

**Figure 4 Charles Law Plot**
Procedure

1. Measure the inside length, \( L_1 \), of the capillary tube. (1) The diameter of the tube will be given to you, or it can be measured. What is the radius of the tube? (2) Calculate the volume, \( V_1 \), of the capillary tube. (3)

2. Attach the capillary tube (open end down) to the thermometer with the small rubber band provided. Then lower the assembly into the prepared oil bath. (The capillary tube should be completely submerged in the hot oil) When the thermometer registers the same temperature as the bath thermometer, you can assume that the air in the tube is also at the bath temperature. Examine the open end of the tube through the side of the flask. If there is an air bubble at the end of the tube, shake it off so that the air column does not extend beyond the measured length of the tube. You now have a quantity of air with a volume, \( V_1 \), equal to that of the capillary tube at the temperature, \( T_1 \), of the oil bath. Record the oil bath temperature.(4)

3. Very carefully raise the assembly so that most of the tube is out of the bath, but make sure that the open end remains in the oil. Hold it in this position until the air column cools and contracts sufficiently to allow a drop of oil about 4 mm long to enter the tube. Now raise the thermometer and tube completely out of the bath and allow them to drain. (Avoid getting oil on the table and floor.) Remove the tube from the thermometer, dry off the oil from both, and let them lie on the lab bench until they have cooled to room temperature. Remember that the inner meniscus of the oil column marks the end of the air sample.

4. Measure the new length of the air column \( L_2 \) at room temperature. (5) Calculate the new volume, \( V_2 \). (6) Record the room temperature, \( T_2 \). (7) Discard the used capillary tube, and wipe the oil from the thermometer and lab bench surface.

5. Calculate the values of \( T_1/T_2 \) in Kelvin(8) and \( V_1/V_2 \) (9). Why can you not use °C for the temperature quotient?(10) Calculate the percentage by which the volume ratio differs from the Kelvin temperature ratio. (11) This is accomplished by taking the difference between the ratios divided by the temperature ratio then multiplying this quotient by 100.

Should \( T_1/T_2 = L_1/L_2 \)? (12) Why? Give an algebraic proof.(13)
Plotting the Charles Law data

1. Click on the title of the first column that represents the x-axis data to open the **Column Options Box**. Assign this first column the **Name** of **Volume**, the **short name** of **V** and **units** of mm³. Click **Done**.

2. Double click on the **first cell** the **Volume Column** and type in the **total volume** of your capillary tube. Repeat this for the **second cell** in the **Volume Column** and enter the second volume (that is, the volume after the tube has cooled).

3. Click on the title of the second column that represents the y-axis data to open the **Column Options Box**. Assign this first column the **Name** of **Temperature**, the **short name** of **T** and **units** of °C. Click **Done**.

4. Double click on the **first cell** in the **Temperature Column** and enter the oil bath temperature you recorded when you removed the capillary from the bath. (This should be recorded in Celsius). Double click on (or down arrow to) the **second cell** in the **Temperature Column** and enter the Celsius temperature you recorded after the tube had cooled. You should have a display like the one shown.

   *This time we must manually scale our plot so that we can see the extrapolation of the line all the way down to zero volume in order to obtain the theoretical temperature at this intercept.*

5. On your graph, click on th **y-axis title**, **Temperature** (°C), and choose **more** to open the **y-axis options box**. Use the "scaling" drop-down menu to choose **manual**. Enter 100 for the top and -350 for the bottom.

6. Now click on th **x-axis title**, **Volume** (mm³), and choose **more** to open the **x-axis options box**. Use the "scaling" drop-down menu to choose **manual**. Enter 0 for the left and 100 for the right.

7. Choose **Analyze** from the **Menu Bar** and select **Linear Fit**. (or click the linear fit button on the **Tool Bar**) Your plot should look like the one shown here.

8. At what temperature does your line intersect the **y-axis**? (14) What is the equivalent temperature on the Kelvin scale? (15) If you were careful in your measurements, this value should be near absolute zero, that is, -273°C.

9. Select **File/Print Graph** from the **Menu Bar**. Enter 2 copies so that each member of the partnership can include a copy with the lab report. Repeat this procedure to print 2 copies of your **Data Table**. Exit the program. There is no need to save the data.
REPORT SHEET
Gas Laws: Boyle's Law and Charles Law

**Boyle's Law Data**

Room temperature_______

<table>
<thead>
<tr>
<th></th>
<th>Volume (mL)</th>
<th>Pressure (atm)</th>
<th>Inverse Pressure (atm⁻¹)</th>
<th>P x V</th>
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Charles' Law Data

Oil Bath Data

1. \( L_1 = \) __________ mm
2. Diameter = __________ mm  Radius = __________ mm
3. \( V_1 = \) __________ mm\(^3\)  \((V_1 = \pi r^2 L_1)\)
4. \( T_1 = \) __________ °C = __________ K

Room Temp. Data

5. \( L_2 = \) __________ mm
6. \( V_2 = \) __________ mm\(^3\)  \((V_2 = \pi r^2 L_2)\)
7. \( T_2 = \) __________ °C = __________ K

8. \( \frac{T_1}{T_2} = \) __________  (note: you must use Kelvin temperatures)
9. \( \frac{V_1}{V_2} = \) __________

10. Why can you not use °C for the above ratio?

11. % difference between \( \frac{T_1}{T_2} \) and \( \frac{V_1}{V_2} = \) __________%

12. Should \( \frac{T_1}{T_2} = \frac{L_1}{L_2} \)? __________

13. Why? (Give an algebraic proof)

14. Temperature at which Volume = 0 (from your graph) __________ °C

15. Equivalent Kelvin temperature = __________ K
1. Ten (10.0) liters of hydrogen under 3.50 atm pressure is contained in a cylinder with a moveable piston. The piston is moved until the gas occupies only 3.00 liters. What is the new pressure of the cylinder?

2. A sample of gas at 25°C occupies 100.0 mL at atmospheric pressure, 740 mm Hg. If the pressure is increased to 800 mm Hg, what will be the new volume of the gas?

3. If 200 mL of oxygen at 100°C is heated to 200°C (the pressure remaining constant), what will be the new volume of the gas?

4. A 300 mL sample of hydrogen is measured at 27°C (room temperature). Assuming that the pressure does not change, at what temperature will the volume of this gas be 400 mL?

5. To what temperature must a gas sample at 20°C be heated in order to double its volume?