

**“DO I DARE DISTURB THE
UNIVERSE?”**

(T. S. Eliot)

VERIFICATION OF GAS LAWS

Techniques

- graphing and graphical interpretation
- data interpretation

MSDS Available for

- air

Principles

- Charles' Law
- Boyle's Law
- ideal gases behaviour
- determination of experimental parameters
- validation of experimental results

Recommended Advanced Reading

- **Chapter on Gases and Gas Laws in all texts**

INTRODUCTION

The beginning

Welcome to the General Chemistry Laboratory! Today will be a busy day! You will be introduced to safety aspects in the lab. You will be assigned a partner and you will meet your demonstrator. You will find out where you will be located in the laboratory and you will do a locker examination to familiarize yourself with your equipment. Finally, you will do a short experiment. In today's session you will work with your partner to:

- learn about safety in the lab
- validate Charles' law and Boyle's law

This is a general overview of what you will be accomplishing in this experiment.

EXPERIMENT 1: *Validation of Gas Laws*

Introduction

“Breathing is a great example of how Boyle's law can be applied in our daily lives. If we breathe in, our lungs expand. When we breathe out, our lungs deflate.”

Gases

Gases are defined as having variable volume and variable shape. For this reason, they are affected by changes in pressure, volume and temperature. The variation of the **volume** of a gas with respect to the **pressure** is defined by **Boyle's Law**. The variation of the **volume** of a gas with respect to the **temperature** is defined by **Charles' Law**. Gases contract when they are cooled and expand when they are heated.

Ideal Gas

In theory, the particles of a gas are so small and so far apart, that essentially they do not have any volume and they do not have any attraction to one another. A gas that satisfies these conditions is said to be an **ideal gas**. An ideal gas can be defined by its temperature, pressure, volume and quantity using the equation $pV = nRT$. These conditions are satisfied in reality at low pressure and high temperature conditions. However, as pressures are increased or temperatures are lowered, deviations from ideality become more pronounced. This is to be expected because, in reality, particles in gases do have volume and do exert forces upon one another.

Charles' Law

Gases contract when they are cooled and expand when they are heated. What is interesting, though, is that all gases expand or contract by the same amount for a given temperature change. Jacques Alexandre Charles was one of the first scientists to make quantitative observations of gases at different temperatures. Later, John Dalton (in 1801) and then Joseph Louis Gay-Lussac (in 1802) continued this work to demonstrate clearly that

at a **fixed pressure**, the **volume** of a gas increases **linearly** with an increase in **temperature**. Further, Charles determined that the change in the volume of a gas with an increase of 1 °C corresponded to 1/273 of the volume of the gas at 0 °C and at a fixed pressure.

A similar effect is observed if the gas is cooled. A decrease in temperature of 1 °C causes the volume to decrease by 1/273 of the original volume at 0 °C. A look at Table 1 shows, however, that the increase in the volume is not directly proportional to the increase in the temperature in degrees Celsius.

TABLE 1
VOLUME-TEMPERATURE DATA
(AT CONSTANT MASS AND PRESSURE)

| Volume (mL) | Temperature (°C) | Temperature (K) | V / T (mL/°C) | V / T (mL/K) |
|-------------|------------------|-----------------|---------------|--------------|
| 1092 | 273 | 546 | 4 | 2 |
| 746 | 100 | 373 | 7.46 | 2 |
| 566 | 10 | 283 | 56.6 | 2 |
| 548 | 1 | 274 | 548 | 2 |
| 546 | 0 | 273 | undefined | 2 |
| 544 | -1 | 272 | -544 | 2 |
| 400 | -73 | 200 | -5.48 | 2 |
| 100 | -223 | 50 | 0.45 | 2 |
| 0 | -273 | 0 | 0 | undefined |

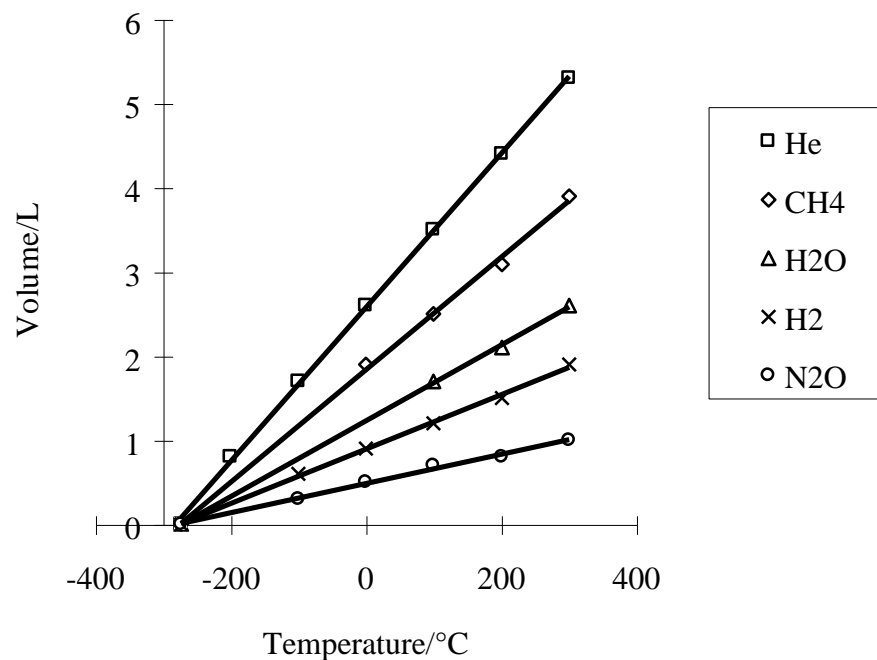
Charles' Law and Temperature

If a plot is made of the volume as a function of the temperature for a number of gases, as shown in Figure 1, the point of intersection with the x-axis, or the **x-intercept**, is found to have a value of $T = -273.15$ °C. What does this mean in terms of the physical properties of the gas? Since the volume is plotted on the y-axis and the temperature is plotted on the x-axis, it indicates that when the temperature is -273.15 °C, the volume of the gas is zero! Furthermore, this observation is true for all gases, independent of the quantity of the gas! Of course, in reality, we know that this is impossible! Why? Before the gas could reach -273.15 °C, the intermolecular forces would exceed the kinetic energy of the molecules and the gases would condense to form a liquid or a solid. As molecules occupy space (no matter how little that space may be!), the volume of a **real** gas will never be zero.

Graphical Determination of Absolute Zero

Nonetheless, the plot of the volume of a gas as a function of its temperature can be very useful.

Figure 1. Determination of the Value of Absolute Zero from a Plot of Volume as a Function of Temperature for Different Gases



Remembering that the equation for a straight line takes the form

$$y = mx + b \quad [1]$$

where **m** is the **slope** of the line and **b** is the **y-intercept**, we can express the relationship between the volume and the temperature of a gas, which we have seen from Figure 1 to be linear, in a similar manner.

$$V = mT + b \quad [2]$$

We can, however, solve for the intercept since we know from Figure 1 that at $T = -273.15$ °C, $V = 0$. Substituting these values into [2], we get

$$b = 273.15 m \quad [3]$$

Equation [2] can now be rewritten as

$$\begin{aligned} V &= mT + 273.15 m \\ &= m(T + 273.15) \end{aligned} \quad [4]$$

If we redefine the temperature in Equation [4] in another way,

$$T_K = T_C + 273.15 \quad [5]$$

it is easily recognizable as the relation between the temperature in the **Celsius** and **Kelvin** scales, where T_K is the temperature in Kelvin, and T_C is the temperature in degrees Celsius. Since absolute zero is defined as $T_K = 0$, from [5] we can determine that absolute zero can also be ascribed the value of $-273.15\text{ }^\circ\text{C}$. Thus, once again, we can rewrite [4] as

$$V = m T_K \quad [6]$$

This is **Charles' Law**, which states that the volume occupied by any sample of gas at a constant pressure is directly proportional to the temperature in Kelvin.

Boyle's Law

If a fixed amount of gas is trapped in a container and then the volume of the container is changed, the pressure exerted on or by the gas in the container will change. Historically, this relationship was first established by Robert Boyle in the seventeenth century and is known as Boyle's law. Boyle added one important condition to his law: the temperature of the trapped gas must remain constant.

Concept of the Experiment

In this experiment, you will investigate two of the gas laws: Charles' law and Boyle's law. The procedure for the verification of Charles' law using two different temperatures will be provided, as it is more complex. Boyle's law studies the relationship between the pressure and volume of a confined gas. You will verify this relationship by trapping a volume of air that **you will determine** in a 20 mL plastic syringe connected to a Gas Pressure Sensor (see Figure 2). As you move the plunger to change the volume of the syringe, the pressure exerted by the confined gas will change, and the pressure will be measured by the Gas Pressure Sensor. Remember, while we may treat gases as ideal, they are in fact **real**!

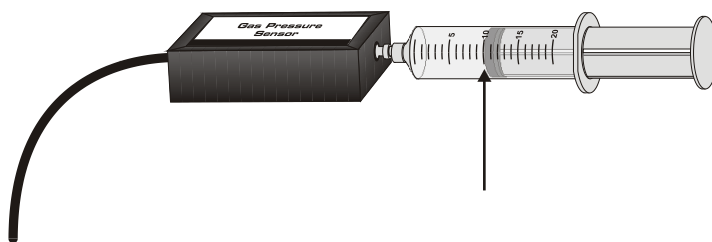


Figure 2. Syringe and pressure sensor connection

(TTD) Things to Do

- Complete the prelab exercises before coming to the laboratory.
- Using the procedure provided, verify Charles' law.
- Along with your partner, determine what variables you need to measure to verify Boyle's law. Decide which will be the dependent and which will be the independent variable. Explain how you decided.
- Select values for your independent variable. Are there any challenges/limitations/reasons that you may have to measure values in a certain way? Explain these.
- Once you have decided your variables and approximate values for your independent variable, write a step by step procedure indicating how you will actually perform the experiment in your lab notebook. Use the Assessment Criteria sheet to guide you. Show your procedure and Assessment to your TA. Once you have approval, proceed to the experimental stage.
- Using the equipment provided, collect the data that will allow you to verify Boyle's law.
- Depending on your data, revise your procedure or your choice of values if needed. Explain the reasons for the change.

Safety Precautions

1. **Wear approved eye protection at all times.**

PROCEDURE

Equipment and chemicals needed

Equipment

125 mL Erlenmeyer flask
1L or 600mL Beaker
Stopper with hole (big enough to fit thermometer)
Digital thermometer
Ice bath
Extension clamp
LabQuest 2
Vernier Gas Pressure Sensor
20 mL gas syringe
USB key (flash drive)

Verification of Charles' Law

1. Obtain a 125 mL Erlenmeyer flask and ensure that it is clean and **dry**. If it is not, rinse it with 2-3 mL of acetone (dispose of the waste in the organic waste container) and place the flask in the oven for 5 min.
2. Place a rubber stopper (with a hole in it) in the Erlenmeyer flask and mark the position of the bottom of the stopper with a marker or label.
3. Fill a large beaker (600 ml or 1 L) to two-thirds with tap water.
4. Place the beaker on a hot plate.
5. Clamp the Erlenmeyer with an extension clamp and place it in the beaker of water. The Erlenmeyer should be as fully submerged as possible; water should not spill over the edge of the beaker onto the hotplate (if needed, water can be added to the large beaker once the Erlenmeyer is in place). **Ensure** that water does not enter the Erlenmeyer flask!
6. Turn on the hotplate and heat the water to boiling. Once the water is boiling, allow the Erlenmeyer to remain in the boiling water for 6 - 7 minutes.
7. During this time, prepare a large ice bath (the temperature should be below 6 °C).
8. While you wait, work with your partner to write a step-by-step procedure for the second part of the experiment in your lab notebook. You should define your variables, identify the dependent and independent variables, determine starting and ending values, and plan how many measurements and at what intervals you will take them. Use the Assessment Criteria to help you plan the procedure.
9. Place a finger over the hole on the stopper and remove the Erlenmeyer from the hot water by disconnecting the extension clamp from the clamp holder. **Do not touch** the Erlenmeyer flask directly as it is **hot**.
10. Keeping your finger on the hole in the stopper, lower the Erlenmeyer flask into the ice bath (stopper facing downwards). Once the mouth is submerged, you can remove your finger. Water will enter the Erlenmeyer. If you see air bubbles escaping the Erlenmeyer flask, you must restart the experiment.
11. The Erlenmeyer flask should be submerged for 5 to 6 minutes until the temperature of the air inside the Erlenmeyer has time to equilibrate to the temperature of the water.
12. Record the temperature of the ice bath.

-
13. Keeping the stopper underwater, raise or lower the flask so that the level of the water in the flask matches the level of water in the bath (with the stopper pointing down).
 14. When the two levels are matched, place your finger over the hole again and remove the flask from the water bath.
 15. Transfer the water that is in the Erlenmeyer to a graduated cylinder and note its volume; call this volume V_{cw} . V_{cw} corresponds to T_2 (which is your measured temperature of the ice bath in Step 12). The volume, V_2 , occupied by the gas at temperature T_2 is the difference between the total volume, V_1 (described below) and V_{cw} .
 16. Fill the Erlenmeyer flask to the mark you had drawn indicating the bottom of the stopper. Transfer this volume of water to a graduated cylinder and note the volume; call this volume V_1 . V_1 corresponds to T_1 (the temperature of boiling water, which we will take to be 100 °C).
 17. Repeat the experiment at least once (twice, time allowing). **Make sure the Erlenmeyer is completely dry before each successive trial.**

Verification of Boyle's Law

1. Show the procedure in your notebooks to your TA (Step 8 above).
2. Your TA will complete the Assessment Criteria.
3. If your TA approves, perform the experiment using the procedure you and your partner have written in your notebooks. The instructions on proper use of the LabQuest 2 equipment are provided below.

Experiment: How to Use the Equipment

1. **Prepare the Gas Pressure Sensor and an air sample.**
 - a. Connect the Gas Pressure Sensor to your LabQuest 2. Turn on the LabQuest 2 and choose **New** from the **File** menu. (You are using a gas pressure sensor and a syringe. What are the two variables you will be using? What units do you think will be used to measure these variables?)
 - b. Move the plunger of a plastic 20 mL syringe to your chosen volume (you and your partner should have decided this volume beforehand). Decide which part of the tip

of the plunger you will line up on the volume mark, and line up your subsequent volumes the same way throughout the experiment.

- c. Attach the 20 mL syringe to the valve of the Gas Pressure Sensor. **IMPORTANT:** About a half-turn of the syringe will lock it into place on the sensor; do not over-tighten or you may strip the threading on the syringe and/or sensor.

2. **Set up the LabQuest 2 data-collection mode.**

- a. On the Meter screen, tap **Mode**. Change the mode to **Events with Entry**.
- b. Enter the **Name** (your variable) and **Units** (for your variable). Select **OK**.

NOTE: Any volume readings from the syringe need to be corrected. If you have positioned the plunger at the 10 mL mark, the total gas volume is not 10 mL because there is 0.8 mL of space inside the pressure sensor itself. **Make sure to add 0.8 to each of your volume readings.**

3. **Collect and plot measurements.**

- a. Start data collection.
- b. Hold the plunger at your initial volume mark.
- c. After the pressure reading stabilizes, tap **Keep** and **enter your volume + 0.8**, the gas volume in mL. Select **OK** to proceed.
- d. Move the plunger to change the volume of air in the syringe and hold the plunger in place. After the pressure reading stabilizes, tap **Keep** and enter the volume (plus 0.8, remember). Select **OK** to proceed.
- e. Continue in this manner until you have measured the pressure in the syringe at 6-8 different volumes. For your final volume measurement, move the plunger back to the original volume mark (there is a reason why you are measuring the same volume twice). Stop data collection.

4. **Decide which measurement at the original volume to keep (can be done out of lab on Logger Pro as well).**

- a. Examine the plotted points carefully and decide which of the two points at the same volume is better. Remember to explain why in your report.
- b. Tap the **table icon** (top of the screen). Choose the original data point for volume that you wish **to remove** from the graph by tapping on it.

-
- c. Open the table menu by tapping on the word **Table**. On the menu that appears, choose **Strike Through Data**. Lines passing through the data indicate its removal from the graph.
 - d. Tap on the **graph icon** to return to the graph screen.
5. **Analyze the graph of your variables to determine the mathematical relationship. To test various mathematical functions (can be done out of lab on Logger Pro as well):**
- a. Tap **Analyze** and choose **Curve Fit ► (your variable)** from the Analyze menu.
 - b. Open the menu below **Fit Equation** and choose a function to perform on your data.
 - c. Select **OK** to return to the graph screen, where the function you chose will be plotted along with your data.
 - d. **Repeat Steps a-c** if you wish to try another function.

DATA TABLE

| Independent variable (unit) | Dependent variable (unit) |
|--------------------------------|------------------------------|
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

DATA ANALYSIS

Charles' Law

1. Note down the volume/temperature pair V_1 and T_1 from Step 15.
2. Calculate V_2 , the volume of the gas at T_2 (the temperature of your ice bath) by subtracting V_{cw} from V_1 .
3. Verify Charles' law with your data.
4. Calculate an average value (if multiple trials were carried out).

-
5. Calculate a percent error as follows: $\% \text{ Error} = \frac{\frac{V_1}{T_1} - \frac{V_2}{T_2}}{\frac{V_1}{T_1}} \times 100\%$

Boyle's Law

1. Using your data, calculate a Boyle's law constant. Explain how you determined the constant.
2. Describe the mathematical relationship illustrated by Boyle's law, and use the constant you calculated in Step 1 to write an equation for Boyle's law.
3. You were directed to take your first and last measurements at the same mark on the syringe. Speculate about the importance of taking multiple readings of the dependent variable for the same value of the independent variable.
4. Boyle's law requires certain conditions be met for other gas variables. What are these variables? Did you take these variables into consideration? What did you do to ensure they remained constant? Does this affect your results? If so, how? If not, why not?
5. Use Logger Pro (software link available on Brightspace) to make all graphs.
6. Use the Worksheet for Experiment 1 (Brightspace, Experiment 1 Folder) to submit your report. It is a Word document and can be downloaded and edited. If the report is submitted in any other format, it will not be graded.

Assessment Criteria for Planning the Boyle's Law Investigation
(print and paste in your lab notebook before coming to lab)

| | | | |
|--|-----------------|------------------------------------|-----------|
| TA Name: | | Names of Students in Group: | a. |
| | | | b. |
| | | Date: | |
| | | | |
| Criteria: | Marks | Assessment | |
| | Possible | Self | TA |
| | | | |
| 1. Plan to vary only one independent variable at a time. | 1 | | |
| 2. Controls on other variables are clearly stated. | 1 | | |
| 3. Measurement errors are minimized by appropriate procedures or apparatus. | 1 | | |
| 4. The methods are clear enough to be followed by other students. | 1 | | |
| 5. Trials and replicas are stated. | 1 | | |
| 6. Limitations of the experimental design are described. | 1 | | |
| TOTAL: | 6 | | |

Rubric for Correction of Experiment 1

| | | | | | | |
|--|--|--|---|--|-------------------------------|---------------|
| Procedures (1+3) | Superior protocol that tests data, minimizes error and includes safety | Good protocol that tests data, minimizes error and includes safety | Acceptable protocol that tests data, minimizes error and includes safety | Poor protocol that tests data, minimizes error and includes safety | | |
| Graphs (2) | Clear, complete graphs | Complete graphs | Partial graphs | Poor/no graphs | | |
| Discussion (6+6) | <i>As outlined in Worksheet Guidelines:</i> Clear explanation of results based on observation and data; reasonable explanation for errors; comparison between trials; answers to all questions; ties to theory clearly shown; tables and graphs appropriately titled containing all required information and properly placed. | Explanation of results; some connection to observation/data; explanation of errors; some comparisons; answers to some questions; some ties to theory | Explanations are vague; connections to observation/data unclear; comparisons or ties to theories poorly explained | A few important points missing | Many important points missing | no discussion |
| Conclusion (1) | Results clearly stated. | | Results somewhat evident. | Results not evident/missing. | | |
| At least 1 peer-reviewed reference (1) | | | | | | |
| Calculations (2+2) | ONE complete set of calculations shown neatly | Some calculations shown neatly | | No calculations | | |
| Grade for Assessment Criteria (6) | | | | | | |
| Total (30) | | | | | | |