BOYLE’S LAW

LEARNING OBJECTIVES

1. Verify Boyle’s law Experimentally
2. Practice taking precise measurements
3. Get exposed to using a spreadsheet for making graphs
4. Be able to distinguish between random and systematic error

INTRODUCTION

In this experiment we will investigate the relationship between pressure and volume of gas at constant temperature, first made by Robert Boyle in 1662 using a slightly different apparatus. The experiment demonstrates that the product of a gas sample’s pressure ($P$) and volume ($V$) is a constant at a fixed temperature. In our experiment, the gas sample is air enclosed in the total volume of the apparatus. The apparatus (see Figure 1 below) consists of a side-arm flask partially filled with water, a syringe connected to the flask with a short length of tubing, and a long glass tube (extending out the top of the picture in Figure 1 or see Figure 2) inserted into the flask through a one-holed stopper in the neck of the flask. As the plunger on the syringe is moved inward, the pressure on the gas is increased, and water in the flask is forced up the tube. We determine the pressure above the laboratory’s atmospheric pressure by measuring the height of the water column in the glass tube, using a meter stick held along side the apparatus. In effect, the apparatus functions as an open-ended manometer. We will observe that as the volume decreases, the pressure increases in such a way that the product $PV$ remains essentially constant.

Figure 1. Boyle’s Law Apparatus
Total volume: flask, tubing & syringe ($V_i$)
PROCEDURE

- Record the posted values of the barometric pressure and room temperature at the time of the experiment.

- To determine the total initial volume of your apparatus, $V_i$, take it to a deep sink, close the plunger all the way to the 0 mL mark and remove the stopper and fill the apparatus completely with tap water, taking care to expel any air bubbles that may collect in the tubing and syringe. This is best done as a team and very slowly. One person holds the syringe below the top of the flask and slowly sucks some water into the syringe without getting air bubbles into the syringe. Once a little bit of water is sucked in, their partner should refill to the top. This process should be repeated until the syringe is filled to the 50 mL mark, there are no air bubbles and the flask is filled to the brim. If air bubbles form, move the syringe plunger in and out several times with the apparatus filled with water. Top off the water level in the flask, if necessary. Now place the rubber stopper with the long glass tube into the neck of the flask without trapping air bubbles under the stopper. Try to avoid forcing water up the tube; the level should be as close to the top of the stopper as possible. You can take out a little water with your fingers to get the volume level just right. Once the apparatus has been filled with water, carefully pour the water into graduated cylinders to determine its volume. Record this volume on your data sheet as $V_i$.

- Empty the water from your apparatus as completely as possible. Then return it to your work place on the laboratory bench.

- Measure 100.0 mL of water in a graduated cylinder, and carefully transfer all of it to the flask. This volume will be designated $V_w$. Reassemble the apparatus and set the plunger of the syringe to the 50.0-mL line. Before proceeding, check the following:
  
  - The rubber stopper is firmly in place.
  - The tubing is firmly connected to both the flask and the syringe.
  - The bottom of the glass tube is below the surface of the water.
  - The meniscus level in the tube is above the water level in the flask, but it is not more than 3 cm above that surface.

- Test the apparatus by slowly moving the plunger completely in and then back out to the 50.0-mL mark. *Going slow is the key to the success of this experiment.* The water level in the tube should reach to about 80 cm with the plunger all the way in. If water comes out the top of the tube, either your initial level was too high or your tube is too short. In either case, you must refill with 100.0 mL of water before proceeding.
• If necessary, adjust the meter stick so that the 0.00 cm mark matches the water level in the flask. Make measurements of water heights in the tube, \( h \), at the syringe plunger positions, \( r \), indicated on the data sheet. The water heights are measured in centimeters (cm) from the surface of the liquid in the flask to the bottom of the meniscus in the glass tube. Be sure to adjust the plunger very slowly and that the plunger is held in place at the desired position \( r \) while making each reading. If the water level for a plunger position is obscured by the stopper, simply omit that reading and proceed to the next one indicated on the data sheet.

**CALCULATIONS**

1. The volume of the air enclosed in the apparatus changes as the position of the plunger changes. The original volume, \( V_i \), measured with the plunger set at \( r = 50.0 \) mL, is decreased as the plunger is moved in. The amount of this volume reduction is \( v_r = 50.0 - r \), where \( r \) represents the position of the plunger on the syringe. The volume of the apparatus is also reduced by the 100.0 mL of water, \( V_w \), added to it. But some of this water moves up into the glass tube as the syringe plunger is moved in, lowering the volume by some amount, \( v_t \). Using the formula for the volume of a cylinder, the volume of water in the tube is \( v_t = \frac{1}{4} \pi d^2 h \), where \( d \) is the inside diameter of the tube and \( h \) is the height of the column. For the tubing used in our apparatus, \( d = 0.45 \) cm, and therefore the volume in the tube is \( v_t = \frac{1}{4}(3.14)(0.45)^2 h = 0.16h \). Combining all these factors together, the formula for the volume of enclosed air in the apparatus in milliliters is

\[
V = V_i - v_r - (V_w - v_t) = V_i - (50.0 - r) - (V_w - 0.16h) \tag{1}
\]

If \( V_w = 100.0 \) mL, we can combine the numeric terms and simplify equation (1) as follows:

\[
V = V_i + r + 0.16h - 150.0 \tag{2}
\]

Use equation (2) to calculate the volumes in the third column of the data table.

*Sample calculation:* If you’re the total volume of your system was 607 mL, you added 100.0 mL of water to your flask, and the height of the water in the tall tube was 16.2 cm when the plunger is compressed to the 40.0 mL mark, then

\[
V_i = 607 \text{ mL}, \quad r = 40.0 \text{ mL}, \quad h = 16.2 \text{ mL} \quad \text{and the total volume of air in the apparatus is}
\]

\[
V = 607 + 40.0 + (0.16 \cdot 16.2) - 150.0 = 499.6 \text{ mL}
\]

2. The pressure exerted on the enclosed air is the sum of the barometric pressure in the laboratory plus the hydrostatic pressure of the column of water, measured by its height, \( h \). Both pressures should be converted to standard atmospheres (atm) to obtain the total pressure, \( P \), to be reported in the fourth column of the data table. For this purpose, use the following conversion factors: 1 atm = 760 mm Hg (exactly) = 1033 cm H\text{H}_2\text{O}. 
3. For each reading, calculate the $PV$ product and enter it in the fifth column of the data table. Calculate the average and standard deviation of your $PV$ products.

4. Use your average $PV$ product and the room temperature to calculate the moles of enclosed gas. For this calculation, use $R = 0.08206 \text{ L-atm-K}^{-1}\text{Amol}^{-1}$ and $T (K) = T (\degree C) + 273.15$.

5. Ideally, your series of $PV$ numbers should be constant, but this is probably not what you observed, due to small reading errors. A better way of looking at the data is to calculate the percent variation in $PV$ and compare it to the percent variation in $P$. (Variation in $V$ could also be used, but it will be virtually the same as variation in $P$) Calculate these as

\[
\text{percent change in } P = \left\{ \frac{(P_0 - P_{50})}{P_{50}} \right\} \cdot 100\% \quad (3)
\]

\[
\text{percent change in } PV = \left\{ \frac{(P_0V_0 - P_{50}V_{50})}{P_{50}V_{50}} \right\} \cdot 100\% \quad (4)
\]

where the subscripts refer to the values at $r = 0.0$ and $r = 50.0$. 
Name____________________________________________  Section________________

Partner(s)___________________________________________________________________

Barometric pressure ______ mm Hg = _______ atm

Room temperature ___________ °C = _________ K

Measured apparatus volume, $V_i$ _________ mL

<table>
<thead>
<tr>
<th>Syringe reading, $r$ (mL)</th>
<th>Water height, $h$ (cm)</th>
<th>Air volume, $V$ (mL)</th>
<th>Air pressure, $P$ (atm)</th>
<th>$PV$ (mL·atm)</th>
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Average $PV \pm$ standard deviation ______________________ mL·atm

Moles of enclosed gas _____________ mol

Percent change in $P$ _____________%

Percent change in $PV$ _____________%
THE LAB REPORT

Your lab report will consist of your data sheet (pg 6), a written abstract, the answer to the question below and a plot produced using Excel. The data sheet is worth 30 pts. Both the answer and the plot are each worth five points. The abstract is worth 20 points. The following is a grading rubric for the abstract.

Abstract

Content
2 pts All of the key pieces of data discussed.
2 pts The data is interpreted correctly.
2 pts The conclusions drawn from the data are correct.
2 pts It is evident that the student understands the main points of the laboratory experiment.
2 pts It is evident that the student was able to connect the learning goals of the experiment with data obtained in the experiment.

Quality of your writing
2 pts It is written in complete sentence(s).
2 pts The sentences are comprehensible to the reader.
2 pts It summarizes the experiment and the result and puts the results in context of the learning goals.
2 pts It is an appropriate length; 3-6 sentences.
2 pts It is written in the passive voice with no pronouns or phrases such as “In this lab we”.

Question and Excel Plot (10 pts total)

Technically, the use standard deviation is only meaningful, when the uncertainty is random. In this case it would be indicated by random fluctuation in PV during the course of the experiment.

Is the variation in PV random or systematic? Use a spreadsheet to make a plot of PV (on y axis) as a function of the syringe reading (x-axis). Include the graph in your report. Speculate on the source of this variation. See course website for help with using Excel for making the graph. (5 pts for the question and 5 pts for the plot)