Experiment

GASES: BOYLE'S AND CHARLES' LAWS

The CCLI Initiative

Computers in Chemistry Laboratory Instruction

LEARNING OBJECTIVES

The objectives of this experiment are to . . .

•   introduce the concepts and units of pressure, volume and temperature.

•   experimentally determine the relationship between pressure and volume, using the *MicroLAB* interface system to collect and analyze the data.

•   experimentally determine the relationship between temperature and volume, using the *MicroLAB* interface system to collect and analyze the data.

BACKGROUND

One of the major differences between gases and solids or liquids are that the volume of a sample of gas varies when pressure or temperature is changed to a much greater extent than do the volumes of solids and liquids. Solids and liquids are also affected by temperature and pressure, but the magnitude of the volume change is very small. When the densities of solids and liquids are measured, there is little need to control temperature or pressure. Within normal limits of measurement precision, these densities are the same under somewhat different laboratory conditions. As you will observe in this experiment, the density of a sample of gas is much more sensitive to changes in temperature and pressure. The dependence of the density on these two factors is determined by varying the pressure and the temperature separately.

Pressure is defined as the force per unit area. A gas exerts pressure on any surface it touches. Thus, air, which is a mixture of gases, exerts pressure on the surface of the earth. This pressure is called atmospheric pressure. It depends on the mass of air above the surface and thus will be affected by wind conditions and by the relative elevation of the surface of the earth where the measurement is made. The *standard atmosphere* (1 atm) is defined as 101.325 kPa. A *pascal* (Pa) is the SI unit of pressure, which is the force of one newton exerted on an area of one square meter.

Atmospheric pressure can support a column of liquid, as shown in Fig. 1. Assume that all three tubes in the figure were originally filled with liquid, then were inverted into the dishes of liquid, as shown. The pressure of the atmosphere on the surface of liquid in each dish, at C and D, is just balanced by the pressure due to the mass of the column of liquid above the surface of the dish, at A, B, and E. If the liquid exerted a greater pressure than the atmosphere, then the level of the liquid would fall until the remaining mass of liquid produced the same pressure as the atmosphere. The same atmospheric pressure is able to support a higher column of liquid2 than of liquid1. Since the pressure exerted by the liquid depends on its mass, liquid 2 must be less dense than liquid 1.

Measurement of the height of a column of liquid, supported by a gas, in a tube of uniform diameter, is a convenient way of measuring pressure. The very dense liquid metal, mercury, is usually used to measure pressure. A column of mercury 760.0 mm high exerts a pressure of 1 atm or 101.3 kPa. Laboratory measurements are thus often expressed as mm Hg, or mm of Hg. One mm of Hg is also defined as one torr. The density of Hg is 13.6 g/cm^3 and that of the water is 1.00 g/cm^3. A column of mercury is therefore 13.6 times heavier than a column of water of the same height and diameter, so that the column of mercury will exert a pressure 13.6 times as great as the same column filled with water. A given atmospheric pressure can support a column of water which is 13.6 times as high as the column of mercury. This is one reason mercury is used in barometers and manometers for measuring pressure; a water barometer would have to be 34 feet high!
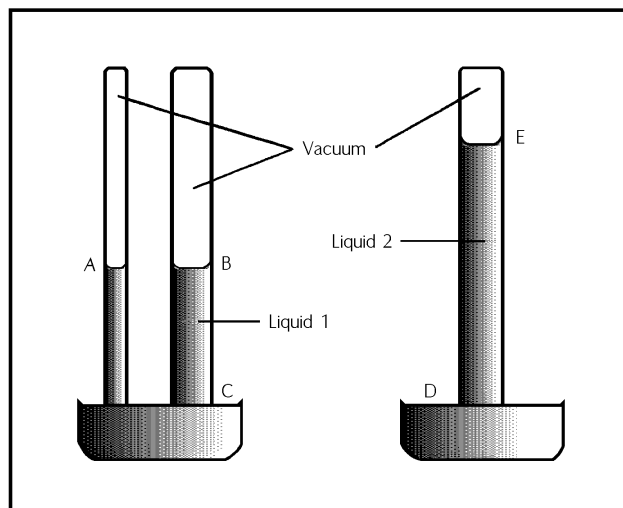

Figure 1. Column of liquid supported by atmospheric pressure.

Robert Boyle, a British chemist, was one of the first to study gases quantitatively. In one set of experiments, Boyle established a relationship between the pressure and volume of a gas at constant temperature. He found that at a constant temperature, the volume (V) occupied by a definite mass of gas is inversely proportional to the applied pressure (P). This is known as Boyle's Law. Mathematically, this relationship can be stated as follows:

$$V \; \alpha \; 1/P$$

The symbol "α" means "is proportional to." Boyle's Law may be restated as: for a given amount of gas at a constant temperature, the product of the pressure and the volume is a constant. If we replace the proportionality constant in the previous equation with a constant of proportionality, we will obtain another form of Boyle's Law.

$$V \; = \; k \, (1/P) \qquad\qquad or \qquad\qquad PV \; = \; k$$

We will see how this is derived experimentally in today's experiment.

SAFETY PRECAUTIONS

No chemicals are used in this experiment, so there is no concern for chemical hazards. Eye protection should be worn in case there is a rupture of the apparatus under pressure. In the Charles' Law investigation, care must be taken to avoid being scalded or burned.

BEFORE PERFORMING THIS EXPERIMENT . . .

...you will need two MicroLAB programs capable of

• Measuring pressure from an absolute pressure sensor and inputting the corresponding volume from the keyboard. Choose the ***press.vs.Vol.exp*** from the **Gas Laws** tab on the opening window.

• Measuring temperature from the temperature probe and inputting the corresponding volume from the keyboard. Choose the ***temp.vs.vol.exp*** from the **Gas Laws** tab on the opening window.

EXPERIMENTAL PROCEDURE

Boyle's Law

Equipment set-up
You will use a large, 60 ml syringe to measure the volumes for this experiment, and to generate the pressures as shown in Figure 2. Attached to the syringe by a short piece of Tygon tube will be a Y or T tube, which will also have short pieces of Tygon tube attached to the remaining openings of the tube. This will be attached to the pressure sensor as described below for measuring the pressure. The open end of the Y tube should either have a valve or have a screw clamp to facilitate isolation from atmospheric pressure.

Pressure sensor set-up
1. Read the *atmospheric pressure* from the barometer, convert from inches to torr if necessary and record the value in torr as P_{atm} in step 6 on the following page.

2. Adjust the plunger of the syringe to 30 ml attach the Lure lock end to the presser sensor connection on the back of the ***MicroLAB***, then tighten the screw clamp to completely close off the opening of the tubing. **Note:** The volume of the Y tube system is approximately 3 mL, this must be added to the total volume reading on the syringe on each of the following readings.

3. Before starting data collection, you should check that the pressure being measured by the ***MicroLAB*** is the same, within a percent or two, as the pressure you determined from the barometer. If it is not, consult with your instructor.
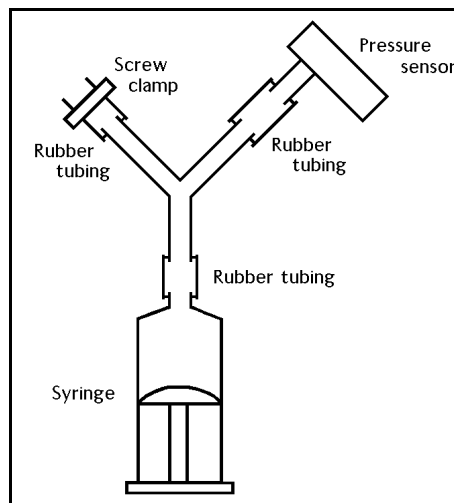

Figure 2. Equipment set-up

Collecting the data

       Small volume (choose a file name for this section of the experiment: _____)

1. Select **Perform an Experiment**, press **Enter**, select the experiment named *boyle.exp*, press **Enter**, select **Graph Right**, **Enter**, select **Interface**, **Enter**, type in your file name, **Enter**, and you should now be in the program.

2. With the syringe at 15 mL, tighten the screw clamp. (15 ml will be your *return volume* for all measurements in this section.)

3. While one student presses the syringe in to the 10 ml volume, the other student enters the *total volume*, then **Enter**. (Don't forget to *add* the volume of the Y tubing.)

4. Release the plunger, open the screw clamp, adjust the plunger to exactly 15.0 ml again (the return volume), then **Enter** to get the reading at 15.00 mL. Now retighten the screw clamp.

5. Again, while one student pulls the syringe out to the 20 ml volume, the other student enters the total volume, then **Enter**. (Don't forget to *add* the volume of the Y tubing.)

6. Continue the above procedure for all volumes of 25 through 60 ml at 5 ml increments of the syringe.

       Middle volume (File name: _____)

1. Again select **Perform an Experiment**, and continue as in step 1 above for small volume.

2. This time use 30 ml as your *return volume*, repeating the above steps for 20 ml through 60 ml at 5 ml increments of the syringe.

       Large volume (File name: _____)

1. Again select **Perform an Experiment**, and continue as in step 1 above for middle volume.

2. This time use 45 ml as your *return volume*, repeating the above steps for 30 ml through 60 ml at 5 ml increments of the syringe.

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Charles' Law

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Around 1800, a French scientist and balloonist named Jacques Charles began studying the effect of increasing temperature on gases. He observed that the rate of expansion of gases with increasing temperature was constant and was the same for all gases as long as the pressure was constant.

In 1848, Lord Kelvin, a British physicist, noted that when studying gases at different initial but constant pressures, extending the temperature-volume lines back to zero volume always produced a common intercept. This common intercept on the Celsius temperature axis is –273.15 °C.
Kelvin named this temperature absolute zero. The Kelvin absolute temperature scale, in which K = °C + 273.15, is named in his honor. The volume-temperature relationship for gases using the absolute temperature scale becomes obvious and is known as Charles' Law: at a constant pressure, the volume of a definite 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:

$$V \propto T \qquad \text{or} \qquad V = kT$$

We will explore this relationship next.

Equipment set-up

1. Calibrate the apparatus as follows:

    a. Connect the temperature probe leads to the CAT-5A input on the *MicroLAB*.

    b. Open the **MicroLAB** program *temp.vs.vol.exp* from the **Gas Laws** tab on the opening window and **recalibrate**, the temperature probe at a minimum of three temperatures covering the range from 0 to 50 °C. If you are not familiar with this process, check the **Measurement Manual** for instructions.

    c. The thermistor should now be calibrated to read in °C.

2. Assemble the apparatus as follows on top of a magnetic stirrer:
    a. A 1 ml pipet tube which has been cut off just above the top calibration mark is mounted vertically from a utility clamp. A rubber bulb is used to suck up about 0.5 ml of a nonvolatile, nonhygroscopic liquid such that there is about a two ml volume from the beginning calibration mark.
    b. The pipet is then suspended with the beginning calibration end down, into an 800 ml beaker with ice such that the temperature is about 2 to 3 °C.
    c. Reconnect the temperature probe leads to the **CAT-5A** input, if necessary and solidly mount the probe alongside the pipet in the beaker.
    d. Add the stirring bar and begin stirring at a moderate rate.

Collect the data

1. Select the *temp.vs.vol.exp* (Charles' Law) from the **Gas Laws** tab on the opening window.

3. Start the program so that the temperature can be read.

4. When the temperature reaches 5 °C, take your first *volume* measurement. (Read the bottom of the liquid plug in the tube.)

5. Turn the plate heater on **High** and monitor the temperature so that it is increasing at about 1 °C per minute. **Caution**: If you heat the water too rapidly, you will not get good results. As you heat the beaker, be sure the water level *does not rise above the top* of the beaker and overflow. To avoid this, remove water with the 60 ml syringe.

6. Continue step 5, taking measurements about every 5°C until the water has been heated to about 50 °C, or until the liquid plug in the pipet approaches the liquid level in the beaker.

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DATA ANALYSIS

PRESSURE VS VOLUME DATA WORK UP:

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Data Manipulations for Boyle's Law

1. For each different PV set of measurements, open the file in the spreadsheet, and using the **Add Formula** function, calculate the product of P times V and drag it to **column C**. Using the **Statistical** function by **right** clicking on **Column C**, determine the mean and standard deviation (the standard deviation represents the "standard error" on the mean value) of the data in column C and record these

in your lab book and in T1 in your lab report. Calculate a percent error value on the standard deviation for each of the data sets and add this to the table. Insert this table, T1, containing the data for each of the three PV data sets, within the body of the Results and Conclusions section of your written report. The P vs. V table on your experiment write up is an example of how this should be set up.

2.   Graph your dependent variable on Y, and your independent variable on X for each PV data set. Print these graphs with the spreadsheet data and the appropriate title as described above. (**G1.1-G1.3 set**)

3.   Compare your graphs against the attached series of graphs to determine what mathematical transformation could be used to make your data linear. (**HINT**: To decide on the transformation to use, think about what you physically "felt" in the qualitative pressure/volume experiments as you adjusted the syringe plunger. **CAUTION**: Going for the highest correlation coefficient is not always the best approach if the transform necessary to achieve it is not realistic or does not conform to the experimentally observed conditions. It is possible to find a transform that will give a perfect correlation, but may not correspond to the physics or chemistry of the experiment.)   Using the **Add Formula** function, calculate this transformation, drag it to **Column D** and the X-axis and using the **Analysis** function, add a **Linear Curve fit** to the data, then drag the curve fit to the Y-2 axis. Print each of these as **Graphs G2.1, G2.2 and G2.3** (**Remember** to do the transform on the independent variable and then graph the transform on the X axis.)

4.   Add the value of the "slope" from each linear graph (**G2.1 - G2.3**) to table **T1** for each of the three PV data sets?

5.   Calculate the percent difference between the slope and the P*V product for each data set in table **T1**, and add this value to table **T1**.

6.   Using PV = nRT, calculate "**n**" for each PV data point set of the three gas volume series, determine the mean, standard deviation and % error on the mean for each, and add that data to your table of data.

(**T1.1** Include an expanded table like this in your Results and Conclusions section.)

Experiment	P*V mean	Std. Dev.	%err. on P*V mean	Lin. Reg. Slope	% Diff. (P*V vs. slope)	"n" mean value	Std. Dev. on "n"	% err. on "n" mean
Small Vol.								
Med. Vol.								
Large Vol.								

VOLUME VS TEMPERATURE DATA WORK UP:

Data Manipulations for Charles' Law

The volume-temperature data are stored on your disc under the file names you gave it.

1.   For each experiment run, graph the dependent variable on the Y axis and the independent variable on the X axis.   If the points of the scatter graph appear linear, then do a regression line through the data. If the points are **clearly not** linear, then perform the proper transform to make the data linear. Print this graph with the appropriate title as described above. (**Graph 1.1 to 1.3**).

2.   Plot a linear regression graph of temperature on Y and volume on X. Print this graph with the appropriate title as described above. (**Graph 4.**)

3. Using the **Predict** function under **Analysis**, for **Graph 4**, predict the temperature value for zero (0) volume from the above graph. Enter the predicted value and the Y intercept value in Table 1.2 and calculate their percent difference.
4. Using the **Add Formula** function, calculate the corresponding Kelvin temperature and drag to **column C**.
5. Using the **Add Formula** function, divide the temperature in Kelvin by the volume (This is the reverse of the normal procedure, but for a purpose.), drag this to **column D**, then determine the mean, standard deviation and percent error on the standard deviation of the data in **Column D** and enter it in **Table T1.2**.
6. Plot a linear regression graph of Kelvin on Y and volume on X. Print this graph with the appropriate title as described above. **Graph 5**
7. Calculate the percentage difference between the mean and slope values in the above question and add this value to **T1.2**.

(**T1.2** Include an expanded table like this in your Results and Conclusions section.)

Y intercept value (A5, R10)	Predicted intercept (R10)	K/P Mean (A7)	Std. Dev. (A7)	% error on Std. Dev. (A7)	L.R. slope (R13)	% Diff. (K/P vs Slope (A8)

7

1a Original Data

$R^2 = 0.9498$

1b Y vs X^2

$R^2 = 1$

2a Original Data

$R^2 = 0.8619$

2b Y vs X^3

$R^2 = 1$

3a Original Data

$R^2 = 0.5120$

3b Y vs e^X

$R^2 = 1$

4a Original Data

$R^2 = 0.6539$

4b Y vs 1/X

$R^2 = 1$

5a Original Data

5b Y vs 1/X^2

6a Original Data

6b Y vs 1/log X

7a Original Data

7b Y vs X^0.5

8a Original Data

8b Y vs log X