Experiments

EXPERIMENT 10
Properties of gases

10.1. Safety

Strong acids will burn the skin. If you come into contact with the acid used here, flush the affected area of skin with copious amounts of water. Gloves must be used at the stipulated points in the procedure.

10.2. Gas Equations of State

Gases represent one of the three common phases of matter (the other two phases being liquids and solids). A gas is a collection of particles that completely fill any volume and are in random motion. Gases are characterized by an equation of state that relates the number n of moles of particles, the volume V occupied by the particles, the pressure p exerted by the particles, and the temperature T of the system. In the 17th and 18th centuries, scientists were investigating the relationships between gases and liquids in order to build an engine. One of the first relationships discovered was the fact that the volume of a gas is inversely proportional to the pressure at constant temperature, or

$$V = \frac{c_0}{p} \; , \tag{10.1}$$

where k_0 is the same for all gases. This relationship is known as Boyle's Law in honor of Robert Boyle, who first presented this law in 1662. In the late 18th century, Jacques Charles observed that the volume and temperature are proportional to one another, or

$$V = c_1 T \; . \tag{10.2}$$

Finally, in 1802, Louis Gay-Lussac showed that the pressure of a fixed amount of gas held at constant volume is directly proportional to the Kelvin temperature, or

$$p = c_2 T \; . \tag{10.3}$$

In 1811, Amedeo Avogadro stated that equal volumes of a gas contain the same number of particles if kept under constant temperature and pressure, or

$$V = c_3 n \; . \tag{10.4}$$

When Boyle's Law, Charles' Law and the Gay-Lussac Law are combined with Avogadro's principle, one obtains the simplest of the state equations for a gas. This equation of state is the perfect gas equation:

$$p\,V \;=\; n\,R\,T \; , \tag{10.5}$$

where $R = 8.2057 \times 10^{-2}$ L atm mol^{-1} K^{-1} is the gas constant. The perfect gas equation is only valid for non-interacting point particles. However, all gases possess a range of temperatures, pressures and volumes were eq. (10.5) is valid. **The laboratory instructor will assign which parts of the experiments below should be completed. You will share data with your classmates so that all parts have been completed.**

10.3. Experiment 10A. Boyle's Law

Before Laboratory Questions – Experiment A

These questions should be used to help you write your notebook and should be answered in some form before you go to the laboratory.

(1) What is the purpose of Experiment A?
(2) What is your hypothesis? Answer in if/then statements.
(3) What materials are required for this experiment? Are any chemicals needed? If so, what are they? Which materials must be obtained from the stockroom, which must be obtained from the instructor, and which are in your laboratory drawer?
(4) Create a table to record the temperature, volume and pressure for each measurement in this experiment.

After Laboratory Questions – Experiment A

These questions should be used to help you write your notebook and should be answered in some form after the laboratory.

(1) Determine the average temperature and the uncertainty.
(2) For each measurement is the ratio V/p constant? If so, what is the average ratio and the uncertainty?
(3) For each measurement is pV constant? If so, what is the average for this constant and the uncertainty?
(4) Using the results, what do you need to graph such that your data fall on a straight line? Create this graph and place it in you notebook. What is the slope (including uncertainty)? What is the intercept (including uncertainty)? What are the physical meanings of the slope and intercept?

(1) Your laboratory instructor will inform you during pre-laboratory if you must share equipment during this experiment. Although you will share equipment, the data set must be your own.
(2) Obtain from the Stockroom a Vernier LabQuest unit, a gas pressure sensor, a gas pressure sensor accessory kit, and a temperature sensor.
(3) Draw gas into the syringe to approximately 10 mL, this gives you a fixed volume of gas at atmospheric pressure.
(4) Connect the gas pressure sensor and the temperature sensor to the Vernier LabQuest. Calibrate the temperature sensor using a boiling water bath and an ice water bath as you did in Experiment 9. The gas pressure sensor does not need calibration.
(5) Use the temperature sensor and the gas pressure sensor to determine the ambient temperature and pressure. This gives you the initial pressure reading.
(6) Connect the syringe to the gas pressure sensor using a half turn to lock the syringe into the Luer connector (cf. Fig. 10.1).
(7) Move the plunger to three different larger volumes and record the pressure and the ambient temperature.
(8) Then return the plunger to your initial volume and record the pressure to confirm your original ambient pressure and temperature reading.

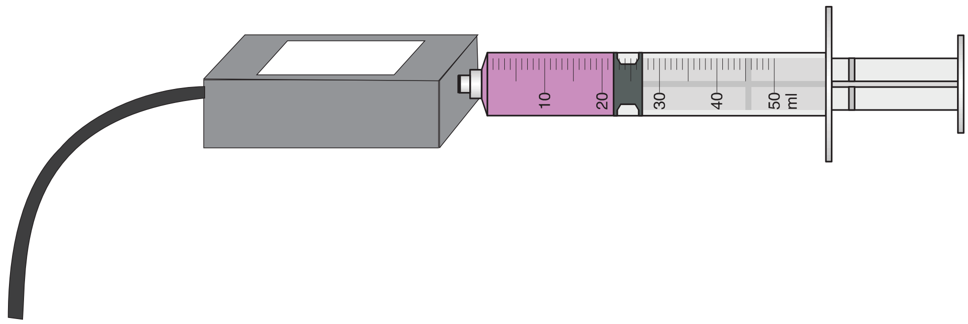

Fig. 10.1: Schematic of the Vernier gas pressure sensor with syringe connected.

(9) Move the plunger to three different smaller volumes and record the pressure and the ambient temperature.

10.4. Experiment 10B. Charles' Law

Before Laboratory Questions – Experiment B

These questions should be used to help you write your notebook and should be answered in some form before you go to the laboratory.

(1) What is the purpose of Experiment B?
(2) What is your hypothesis? Answer in if/then statements.
(3) What materials are required for this experiment? Are any chemicals needed? If so, what are they? Which materials must be obtained from the stockroom, which must be obtained from the instructor, and which are in your laboratory drawer?
(4) Create a place to record the volume of the Ehrlenmeyer flask. Create a table to record the following information: temperature, gas volume in syringe, and pressure.

After Laboratory Questions – Experiment B

These questions should be used to help you write your notebook and should be answered in some form after the laboratory.

(1) Determine the average pressure and the uncertainty.
(2) For each measurement, what is the total volume? Show your work.
(3) For each measurement is V/T constant? Show your work. If so, what is the average ratio and the uncertainty?
(4) For each measurement is VT constant? Show your work. If so, what is the average ratio and uncertainty?
(5) Using the results, what do you need to graph such that your data fall on a straight line? Create this graph and place it in you notebook. What is the slope (including uncertainty)? What is the intercept (including uncertainty)? What are the physical meanings of the slope and intercept?

(1) Fill a clean Ehrlenmeyer flask with water to the top of the flask. Insert the Vernier two hole stopper, allowing the water to overflow around the stopper. Then remove the stopper and measure the volume of water using a graduated cylinder. This gives you the total volume of the Ehrlenmeyer flask. The volume of the tubing from the rubber stopper to the gas pressure sensor as well as the volume of the valve in the stopper is approximately 4 mL. The volume of the syringe will change

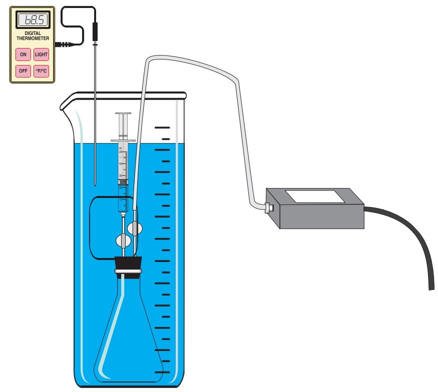

Fig. 10.2: Schematic of the apparatus for investigating Charles' Law. Both the temperature probe and the pressure sensor will connect back to the Vernier LabQuest unit.

as a function of temperature and will be monitored. This volume will need to be included in your calculations.

(2) Once the volume of the Ehrlenmeyer is known, clean and dry the flask again.

(3) Setup the apparatus as shown schematically in Fig. 10.2. Make sure that your water bath is around 15°C and the syringe plunger is at the 0 mL mark. Make sure that the lower part of the syringe is in the water, but that there is no water in the plunger area of the syringe. Also make sure that no water is leaking into the Ehrlenmeyer flask.

(4) Have the laboratory instructor check and approve your apparatus. Failure to get approval for continuing will result in a loss of 5 points to your laboratory safety grade.

(5) Once the apparatus has been checked for leaks, you can begin to heat the water using the hot plate. Monitor the pressure and volume as the temperature increases. Since the piston can move freely, the pressure should remain constant. If not, adjust the volume by moving the piston in order to maintain constant pressure at constant temperature. You must let the temperature stabilize before recording the volume. Thus, step the heater intensity up slowly. A good range set of temperatures is between 15°C to 65°C, stepping every 10°C.

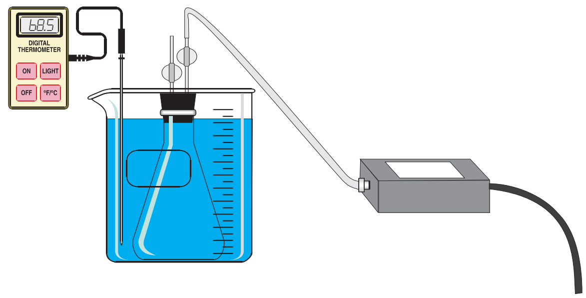

Fig. 10.3: Schematic of the apparatus for investigating the Gay-Lussac Law. Both the temperature probe and the pressure sensor will connect back to the Vernier LabQuest unit.

10.5. Experiment 10C. Gay-Lussac Law

Before Laboratory Questions – Experiment C

These questions should be used to help you write your notebook and should be answered in some form before you go to the laboratory.

(1) What is the purpose of Experiment B?
(2) What is your hypothesis? Answer in if/then statements.
(3) What materials are required for this experiment? Are any chemicals needed? If so, what are they? Which materials must be obtained from the stockroom, which must be obtained from the instructor, and which are in your laboratory drawer?
(4) Create a table to record the following information: temperature and pressure.

After Laboratory Questions – Experiment C

These questions should be used to help you write your notebook and should be answered in some form after the laboratory.

(1) Why is it not necessary to know the volume for each data point?
(2) For each measurement is p/T constant? Show your work. If so, what is the average ratio and the uncertainty?
(3) For each measurement is pT constant? Show your work. If so, what is the average ratio and uncertainty?
(4) Using the results, what do you need to graph such that your data fall on a straight line? Create this graph and place it in you notebook. What is the slope (including uncertainty)? What is the intercept (including uncertainty)? What are the physical meanings of the slope and intercept?

(1) Setup the apparatus schematically shown in Fig. 10.3.
(2) Have the laboratory instructor check and approve your apparatus. Failure to get approval for continuing will result in a loss of 5 points to your laboratory safety grade.
(3) Record the initial temperature and pressure of the system.
(4) Increase the heater intensity on the hot plate slightly and allow the temperature to stabilize. Record the pressure and the temperature.
(5) Repeat (3) until you have obtained 5 - 6 data points. Do not increase the temperature more than 30°C from the initial value.

10.6. Experiment 10D. Perfect gas equation

Before Laboratory Questions – Experiment D

These questions should be used to help you write your notebook and should be answered in some form before you go to the laboratory.

(1) What is the purpose of Experiment D?
(2) What is your hypothesis? Answer in if/then statements.
(3) What materials are required for this experiment? Are any chemicals needed? If so, what are they? Which materials must be obtained from the stockroom, which must be obtained from the instructor, and which are in your laboratory drawer?
(4) The following information needs to be recorded: mass of magnesium ribbon, volume of concentrated HCl, concentration of HCl, volume of hydrogen gas produced, barometric pressure, and temperature of the gas.

After Laboratory Questions – Experiment D

These questions should be used to help you write your notebook and should be answered in some form after the laboratory.

(1) What gases are present in the eudiometer at the end of the reaction?
(2) What is the vapor pressure of water for the measurement? (Hint: Search the web to find a table that gives the vapor pressure of water at various temperatures. Be sure to reference where you obtained your information.)
(3) Since the gas produced during the reaction is collected over water, the pressure p_g of the gas in the eudiometer is given by $p_g = p_{atm} - p_v$, where p_{atm} is the barometric pressure and p_v is the vapor pressure of water at the temperature of the measurement. What is p_g for your experiment?
(4) Using the data from the experiment, how many moles of gas are produced?
(5) Write the balanced chemical equation for this reaction. Using this equation, determine the theoretical number of moles of gas that should have been produced.
(6) What is your percent yield? Explain your results.

From Experiment 5, you learned that some metals reduce the hydronium ion to hydrogen gas. In this experiment, you will use the oxidation/reduction reaction of magnesium with aqueous hydrochloric acid to form hydrogen gas and magnesium(II). You will then use eq. (10.5) and your results to determine the percent yield of hydrogen gas for this experiment.

The procedure for this experiment is as follows:

(1) Weigh and record the mass of a piece of magnesium ribbon obtained from the instructor.
(2) Place approximately 7 mL of 12 M HCl (concentrated) in a eudiometer, which is obtained from the stockroom. Do this very gently and carefully so that you get as little HCl on the inside walls of the eudiometer as possible.
(3) Holding the eudiometer at a 45° angle, carefully pour water into the tube until it is filled to the brim of the tube (cf. Fig. 10.4a). Pour the water gently down the side of the tube and try to prevent the water and acid from mixing. When full, you should have no air pocket when you place your finger over the top of the tube.
(4) Bend the magnesium ribbon from (1) into a V and place it into the eudiometer tube so that both arms of the V point outward, toward the mount of the tube (cf. Fig. 10.4b). Hold the metal in place at the top lip of the tube.
(5) *Make sure that you are wearing gloves for this procedure.* Using your thumb to close the mouth of the eudiometer completely, invert the eudiometer into the large

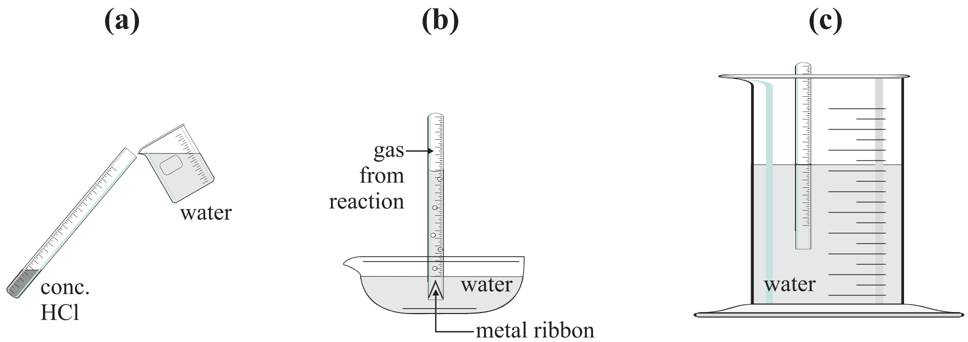

Fig. 10.4: Schematics of (a) filling the eudiometer, (b) the reaction in progress, and (c) the leveling of the eudiometer.

evaporating dish (supplied by the instructor) that is three quarters filled with water (cf. Fig. 10.4b). No air or bubbles should be present until a reaction occurs, since these bubbles will influence your results.

(6) After the acid has descended and all the metal has undergone reaction, liberating hydrogen, place your thumb (again wear gloves for this procedure) over the mouth of the eudiometer and immerse the tube in a large cylinder of water so the gas can come to room temperature (this should take only a few minutes).

(7) Raise the tube in the cylinder until the level of water in the eudiometer is the same as the level in the cylinder, thereby equalizing the pressures (cf. Fig. 10.4c). Use the graduations on the eudiometer to read the volume of gas to the appropriate level of precision. Read and record the temperature of the water in the cylinder. Obtain the barometric pressure from the instructor.

(8) Remove the eudiometer from the cylinder, empty the eudiometer in the sink and flush the sink with water. Rinse the eudiometer thoroughly to clean it.

10.7. Experiment 12E. Vapor pressure of a volatile liquid

Before Laboratory Questions – Experiment E

These questions should be used to help you write your notebook and should be answered in some form before you go to the laboratory.

(1) What is the purpose of Experiment E?
(2) What is your hypothesis? Answer in if/then statements.
(3) What materials are required for this experiment? Are any chemicals needed? If so, what are they? Which materials must be obtained from the stockroom, which must be obtained from the instructor, and which are in your laboratory drawer?
(4) Create a place to record the name of the alcohol, the ambient temperature and pressure, and the volume of alcohol added to the setup. Create a table to record the temperature and total pressure.

After Laboratory Questions – Experiment E

These questions should be used to help you write your notebook and should be answered in some form after the laboratory.

(1) For each measurement, what is the vapor pressure of the alcohol?
(2) Based on eq. **??**, what do you need to graph such that your data fall on a straight line? Create this graph and place it in you notebook. What is the slope (including uncertainty)? What is the intercept (including uncertainty)? What are the physical meanings of the slope and intercept?
(3) What is the error in this measurement when compared to a theoretical enthalpy of vaporization? (Be sure to reference the book or website where you obtained the enthalpy of vaporization for your alcohol.)

The vapor pressure of a volatile liquid depends on the temperature of the liquid and the enthalpy of vaporization ΔH_{vap} through the Clausius-Clayperon equation of

$$\ln \frac{p_{vap}}{p^\circ} = -\frac{\Delta H_{vap}}{R}\left(\frac{1}{T}\right) + C \ , \tag{10.6}$$

where C is a constant and p° is exactly 1 atm. When a liquid is added to a sealed container at an initial temperature T and pressure p_{air}, then the vapor pressure p_{vap} of the liquid is given by:

$$p_{vap} = p - p_{air} \ , \tag{10.7}$$

where p is the total pressure and p_{air} is the pressure of air. The procedure for determining the vapor pressure of a volatile liquid as a function of temperature is:

(1) Use a bunsen burner to heat approximately 200 mL of water in a 400 mL beaker to approximately 70°C.
(2) Prepare a room temperature water bath in a 600 mL beaker. The bath should be deep enough to completely cover the gas level in the 125 mL Ehrlenmeyer flask.
(3) Setup the LabQuest data logger with the gas pressure sensor and a calibrated temperature probe.
(4) Use the clear tubing to connect the white rubber stopper to the gas pressure sensor. Twist the white stopper snugly into the neck of the Ehrlenmeyer flask and seal with parafilm.
(5) Open the valve between the gas pressure sensor and the flask. Close the other valve.
(6) Use the calibrated temperature probe and the gas pressure sensor to determine ambient temperature and the initial pressure in the system.

(7) Place the temperature probe and the Ehrlenmeyer flask into a room temperature water bath. Hold the flask down into the water bath until the water bath comes to the bottom of the white stopper.
(8) Open the white stopper and then after 30 seconds close the white stopper. Record the temperature and the pressure. This establishes the initial pressure and temperature for these studies.
(9) Obtain a small amount of isopropanol, ethanol or methanol. Draw 3 mL of the alcohol into the 20 mL syringe. Thread the syringe onto the valve on the white stopper.
(10) The alcohol is added by opening the valve below the syringe. Push down the plunger of the syringe to inject the alcohol into the Ehrlenmeyer flask, then quickly pull the plunger back to the 3 mL mark. Close the valve below the syringe. Remove the syringe from the stopper.
(11) Once the alcohol is added, rotate the flask in the water bath to accelerate the evaporation of the ethanol. Do NOT remove the Ehrlenmeyer flask from the water bath, since this will change the temperature. After a few minutes, the pressure should stabilize. Record the temperature and pressure.
(12) Use a plastic spoon to added enough hot water to the beaker to increase the water temperature by $3 - 5°C$. Stir the bath with the temperature probe. When the temperature and pressure readings stabilize, record the values.
(13) Repeat the previous step up to five additional trials. Do not allow the temperature to increase above 45°C because the pressure increase may pop the stopper out of the flask. If you have to remove water from the flask, do so without disturbing the Ehrlenmeyer flask.
(14) When you have your five trial readings at different temperatures (not counting the initial reading before the addition of the alcohol), you can open the valve to release the pressure. Remove the stopper, dispose of the chemicals as directed, and clean the glassware.

10.8. Practice problems

The problems below are excellent practice problems for the laboratory quiz and the laboratory practical. Since these problems will not be graded, the answers are given in Appendix I.

(1) Suppose you are given two 1.0 L flasks and told that one contains a gas of molar mass 30 and the other a gas of molar mass 60. Both flasks are at the same temperature, and each flask has 1.2 g of gas present in the flask. However, the pressure in flask A is x atm, while that in flask B is $0.5x$ atm. Which flask contains gas of molar mass 30 and which contains the gas of molar mass 60?

(2) For each row in the following table, determine x in the units given.

p	V	n	T
2.00 atm	1.00 L	0.500 mol	x K
0.300 bar	250. mL	x mol	27°C
760 Torr	x gal	0.333 mol	350 K
x atm	0.585 L	0.250 mol	70°F

(3) The Goodyear blimps hold approximately 175,000 ft^3 of helium. If the gas is at 23°C and 1.0 atm, what mass of helium is in the blimp?

(4) How many molecules of air are in a deep breath assuming that an average person's lung capacity is 2.25 L at a body temperature of 37°C and a pressure of 735 Torr?

(5) Calculate the molar mass of a gas if 2.50 g occupies 0.875 L at 685 Torr and 35°C.

(6) Calculate the molar mass of a vapor that has a density of 7.135 g/L at 12°C and 743 Torr.

(7) Calcium hydride reacts with water to form hydrogen gas and aqueous calcium hydroxide. This reaction is sometime used to inflate life rafts, where a simple compact means of generating H_2 is desired. How many grams of calcium hydride are needed to generate 53.5 L of hydrogen gas if the pressure of hydrogen gas is 814 Torr at 21°C?

(8) Hydrogen gas is produced when zinc reacts with sulfuric acid. If 159 mL of wet hydrogen gas is collected over water at 24°C and a barometric pressure of 738 Torr, how many grams of zinc have been consumed?

(9) Acetylene gas C_2H_2 and solid calcium hydroxide can be prepared by the reaction of solid calcium carbide CaC_2 with water. Calculate the volume of acetylene gas that is collected over water at 23°C by reaction of 0.752 g of calcium carbide if the total pressure of the gas is 745 Torr.

(10) The following table gives the vapor pressure of hexafluorobenzene C_6F_6.

Temperature (K)	Vapor pressure (Torr)
280.0	32.42
300.0	92.47
320.0	225.1
330.0	334.4
340.0	482.9

By plotting these data in a suitable fashion, determine whether the Clausius-Clapeyron equation is obeyed. If it is obeyed, use your plot to determine ΔH_{vap} for C_6F_6.