(Pre-lab is in separate files; you must print it out and fill it)

Experiment 2: Kinetic Theory of Gases

1 Purpose

You are expected independently to list the objectives in your lab report. Each objective's success or failure needs to be addressed in your conclusion.

2 Introduction

The study of physics, as a whole, can be broken up into many specific sub-areas, such as classical mechanics, electromagnetism, and quantum mechanics. The branch of physics that studies the thermal energy (or "internal energy") of a system is called **thermodynamics – *thermo means heat and dynamics means motion***. Within thermodynamics, understanding the behavior of gases is particularly important, being enormously useful for daily life in applications such as engines, culinary and environmental science, and more.

A **gas** is one of the three fundamental states of matter, whose particles (atoms, molecules, or a combination of both) are not as strongly bonded as in a liquid state. Consequently, a gas fills the volume of whatever container it is put inside and exerts pressure on the container due to the collisions between the particles and the walls of the container.

2.1 The Ideal Gas Law

As one might imagine, there are countless number of gas molecules to consider when studying their behavior. Fortunately, if the density of the gas is low enough, all gases obey a relation called the **ideal gas law**:

$$PV = nRT \tag{1}$$

Here, P is the absolute pressure of the gas measured in pascals (Pa), V is the volume measured in m^3, T is the temperature of the gas measured in kelvins (K), R is a value called the **gas constant**, and n is the number of moles of the gas sample. The value of R is the same for all gases,

$$R = 8.31 \frac{J}{mol \cdot K}$$

A **mole** is a basic SI unit that denotes the number of particles (atoms or molecules) in a sample. The number of particles in 1 mole (abbreviated "mol") is given by N_A, **Avogadro's number**,

$$N_A = 6.02 \times 10^{23}\ mol^{-1}$$

The ideal gas law can be re-written into a form that directly reflects the number of particles in a sample, N. To do so, we use a quantity called the **Boltzmann constant, k_B**:

$$k_B = \frac{R}{N_A} = 1.38 \times 10^{-23} \frac{J}{K}$$

Since the number of moles in a sample is equal to the number of particles in the sample divided by the number of particles in a mole (Avogadro's number), $n = N/N_A$, we can use this relation with the definition of the Boltzmann constant to obtain a second version of the ideal gas law,

$$PV = Nk_BT \tag{2}$$

which is the form we will use in this experiment.

2.2 Translational Kinetic Energy

The translational kinetic energy (kinetic energy of motion through space) of an ideal gas particle at a given point in time is given by the familiar formula $K = \frac{1}{2}mv^2$. However, the *average* translational kinetic energy over time of an ideal gas particle, assuming that the average speed of all particles is the same, is given as $K_{avg} = \frac{1}{2}m{v_{rms}}^2$. Here, v_{rms} is the **root-mean-square-speed** of the particle, a quantity used to measure the speed of gas particles, defined as

$$\boldsymbol{v_{rms}} = \sqrt{\frac{\boldsymbol{3RT}}{\boldsymbol{M}}} \tag{3}$$

where M is the molar mass of the substance (the mass of the substance divided by the number of moles). We can substitute this expression for v_{rms} into our equation for K_{avg}, and, along with the useful relation that $M/m = N_A$, we get

$$\boldsymbol{K_{avg}} = \frac{3}{2}\boldsymbol{kT} \tag{4}$$

3 Experimental Simulator and Procedure

3.1 Experimental Simulator:

- PhET Interactive Simulations: Gas Properties Simulation

3.2 Procedure - Data goes into the data section of the Lab Report

Getting started

Go to phet.colorado.edu. On the home screen, go to the tab marked "Simulations" and select "Physics." You should then see a list of simulations. Choose the one titled "Gas Properties" and download the simulation. Take some time to familiarize yourself with the simulation's features before beginning the experiment. We will be using the "Ideal" screen as labeled at the bottom of the simulation.

Measuring the gas constant, *R*

1. Check the "width" box in the window to the right. This will display the width of the container beneath it in nanometers (1 nm = 10^{-9} m). Drag the handle on the left wall of the container to change its width to 15 cm. **The height and depth of the container are constant. They are 8.75 nm and 4.0 nm, respectively**.
2. Select the blue dot (indicating more massive particles) located under the pump. You can see the number of particles (N) you pump into the system by opening the window labeled "Particles" in the simulation. Use the pump or the arrow buttons to introduce 1000 of these "heavier" particles to the container.
3. Select the Pressure(V) option in the "Hold Constant" window. This will keep the pressure constant by automatically changing the volume (width) during your data collection. Record the pressure inside the container. The SI unit for pressure is the pascal (Pa). You can change the pressure units in the simulator from atm to Pa using the small dropdown under the gauge.
4. Record the temperature within the container, making sure that your units are in kelvin (K).
5. Once the width, pressure, and temperature are recorded, use the appropriate arrows in the "particles" window to decrease the number of particles in the container to 900. Record the changes to the width and temperature (pressure should still remain the same as before).
6. Repeat this for particle numbers of 800, 700, 600, and 500. Reset the simulation with the orange circular arrow, and collect a new set of data using N, T, and width values of your choice. Make

sure that nothing is selected in the "Hold Constant" window. You can alter the temperature inside the container by dragging and holding the appropriately labeled slider under the container to "heat" or "cool." Observe the effects that changing the temperature has on both the particles themselves and on the pressure in the container.

7. Repeat the previous steps, this time using the red "lighter" (less massive) particles.

4 Calculations and Analysis of the Data and Error for Lab Report

4.1 Computation of the gas constant, *R*

1. Calculate the volume of the container, V, in cubic meters, using your values for the width in conjunction with the values for the height and depth provided above.

2. For each of your seven values of N, use the ideal gas law and your recorded values for V, T, and P to calculate an experimental value for the Boltzmann constant, k_B.

3. Calculate your experimental values for the gas constant, R, using the values for k_B you just calculated and Avogadro's number, N_A. Use the value of N_A given above. Call these values for the gas constant R_{heavy}. As you do so, your Excel sheet will calculate the average, standard deviation, and standard error of your R_{heavy} values.

4. Repeat this process to calculate gas constants with the data you collected using the lighter particles. Call this value R_{light}.

4.2 Computation of Particle Translational Kinetic Energy

1. For each value of N, use the corresponding values of T and k_B to calculate the average translational kinetic energy of the first gas, $K_{avg,heavy}$.
2. Repeat the calculations using the corresponding T and k_B values to find $K_{avg,light}$.

Note: Because there are no accepted values for the average translational kinetic energies, we are unable to calculate percent difference to measure accuracy. You will conduct a more in-depth analysis of K_{avg} in Question 3.

5 Questions

1. Compare your results for the averages of R_{heavy} and R_{light}. Is this result expected?

2a. Shrink the container to its smallest size (width 5 nm) and fill it with 500 particles (either type). Now decrease the temperature to its lowest point, 0 K, and observe the particles inside the container. What does this say about temperature, namely what is the temperature of a substance (in this case, a gas) a measurement of?

2b. Now raise the temperature of the gas inside the container by applying heat. Once the temperature is high enough, something will happen to the system (you'll know what it is when it happens). Why does such an explosive result occur? (Hint: what else was changing as you raised the temperature?)

3a. Collect two more sets of data as you did previously (one using heavier particles and one using lighter particles), only this time keep N, V, and T the same (it is easier to set T last here). Following the same process as before, calculate $K_{avg,heavy}$ and $K_{avg,light}$. Now, calculate the PFE, the percent fractional error, between these two results. Based on this, what statement can you make regarding the average translational kinetic energy of **any** ideal gas particles at a given temperature T, regardless of mass?

3b. Given that the mass of one heavy particle is 28 atomic mass units (AMU), and the mass ofone light particle is 4 AMU, calculate the v_{rms} of the heavy and light particles in Question 3a.

6 Discussion

In this open response section of the lab report you have the opportunity to demonstrate that you have gained a comprehensive understanding of all aspects of the experiment. In your own analysis, what were the key elements of the experimental measurement? Are the results intuitive or do they appear in any way to be inconsistent with physical observations in daily life? Are there intrinsic aspects of either the experimental design or the way it was implemented that could introduce systematic errors or fail to account for relevant physical phenomena? A detailed discussion should include analysis of any experimental errors, instrumentation problems or mishaps that occurred, and how these may have impacted the results. Be thoughtful and think critically about these considerations. If an experiment was challenging, a discussion of exactly what made it challenging, and possibly, how it could be conducted differently, should be included. Or, if an experimental measurement went completely smoothly, this should also be discussed. Also, this section may include discussion of how the insights from one particular experiment are related or complementary to other experiments conducted in the course. Remember that your discussion should be a thoughtful scientific analysis, not a discussion of how you enjoyed or did not enjoy the lab.

7 Conclusions

The report should end with a clear conclusion statement. This is the “bottom-line” experimental result summarizing the main quantitative results of the experiment and the extent to which they are in agreement with theoretical predication and/or an established reference value. When the experiment results in a measurement of a constant (e.g., the acceleration due to gravity at the earth’s surface), compare it with its established handbook values for the Boston area. Use percent difference to quantify this comparison. To make this comparison meaningful, you should include the impact of the experimental error (random and systematic) on your results. This includes errors in plotting and reading linear graphs when determining their slope and intercept.

Source:
“Chapter 19: The Kinetic Theory of Gases.” *Fundamentals of Physics*,by David Halliday et al., Wiley, 2013, pp. 549-576