

## **Experimental Verification of the Ideal Gas Law**

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PRA101 (12-3 pm): Ideal Gas Law Lab

### **1 Abstract**

This lab analyzes the characteristics of ideal gasses and the mathematical relationships between their variables: temperature, pressure, volume, and mass; understanding these relationships is crucial for predicting gas behavior in various scientific and industrial applications, optimizing processes, and enhancing our fundamental knowledge of thermodynamics. The first portion of the lab verified that state properties (temperature and pressure) are independent of the path they take from initial to final conditions by utilizing two different methods to reach equilibrium. The volume ratios of the tanks were calculated with each method, and were determined to be the same. The second portion of the lab utilizes the ideal gas law, determines a methodology to calculate initial mass in the left chamber, and explores potential sources of error.

### **2 Introduction**

The ideal gas law is crucial and helps provide understanding the behavior of gasses under various conditions aiding in the study of thermodynamics. A precise understanding of gas properties and behavior is essential for applications in chemical engineering, aerospace engineering, and more. The ideal gas law [1] shows the relation between the following variables: P - Pressure (pa), V - Volume (L), T - Temperature (K), N - Number of moles, and  $R_u = 8.314 \text{ J/mol K}$ .

$$PV = NR_u T \quad [1]$$

It is important to note that the equation is a simplified model assuming ideal gas behavior which normally occurs under conditions of high temperature as well as low pressure (enough energy and space to move freely), where there are negligible intermolecular forces, and negligible partial

volume. This relationship is utilized to study the path independence of state variables (in part 1) and verifies the ideal gas law by calculating initial mass (in part 2).

### 3 Experimental Methodologies

#### 3.1 Equipment Utilized

The lab consists of two parts that utilize a gas chamber apparatus. Safety glasses were worn to protect the eyes using the high pressure apparatus. As can be seen in figure 1, this apparatus is made of 2 chambers (left and right), valves, and a flow controller device. The valves

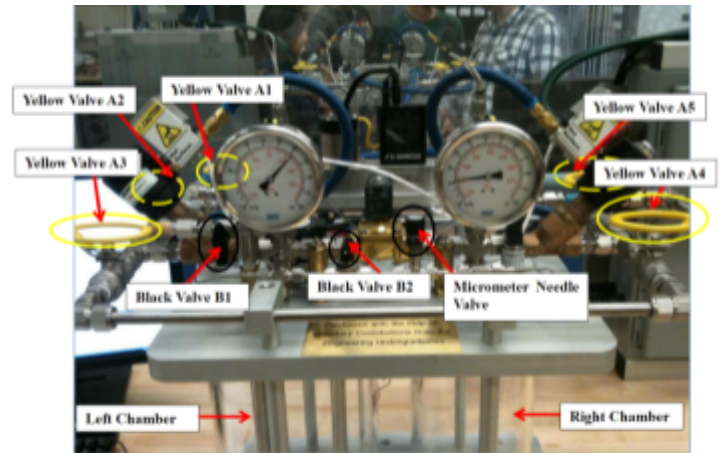


Figure 1: Gas Chamber Apparatus with labelled valves, and chambers

can be opened and closed to set particular pressures (measured by the pressure gauge with measured pressure and temperature). The Labview software is utilized in both experiments to control the mass flow rate, solenoids, and save and collect data.

#### 3.2 Lab Methodologies: Part 1

In part 1 of the experiment, 2 chambers were set in initialized conditions and brought to equilibrium in 2 different methods.

1. The ambient pressure and the ambient temperature were measured.
2. To set initial conditions, the flow rate was steadily increased to 50g/min. The left tank was pressurized to 40 psig by opening valve 2, and the right tank was evacuated to -6 psig by opening valves A1 and A5.

3. The central solenoid valve was opened to allow airflow between the tanks. Temperature and pressure data were recorded using LabVIEW until the temperature difference between the tanks became insignificant.
4. Step two was repeated to bring the chambers back to initial conditions, and method 2 was deployed where the small ball valve and micrometer valve were opened until an insignificant pressure difference was detected.

### **3.3    *Lab Methodologies: Part 2***

1. The ambient pressure and temperature were recorded, and data collection was initiated in the program.
2. The left tank was pressurized to 40 psig by activating the left solenoid (opening valve 2), and gradually setting the flow rate to 50 g/min. Once the pressure reached 40 psig, the solenoid valve was closed, and the data was recorded on LabVIEW until the temperature and pressure of the system were stabilized.

## **4       Results and Discussions**

### **4.1    *Lab Part 1***

#### **4.1.1   Results: Lab Part 1**

Through conducting the experiment, it can be seen that through both methods the chambers reach equilibrium with a varied amount of time. Prior to each method, the left and right chambers were brought to an initial state that was similar (left chamber 40 PSI, right chamber -6 PSI). The exact states prior to each method can be seen in table 1, and table 2 respectively. In method 1, where the center solenoid was used to allow the chambers to reach an equilibrium the chambers took approximately  $160 (\pm 0.01)$  s. In this method, equilibrium was deemed when the temperature difference between the two chambers were insignificant (within a 10% range). The right chamber's

temperature was 7.1% higher than the right chamber which was deemed as an insignificant enough difference to declare equilibrium. The exact values can be seen in table 1.

**Table 1.** Initial and Final Temp/Pressure Values (Method 1)

	Initial Pressure (PSI)	Initial Temp (°C)	Final Pressure (PSI)	Final Temp (°C)
Tank 1	$40.2 \pm 0.5$	$25.1 \pm 0.05$	$23.9 \pm 0.5$	$25.1 \pm 0.05$
Tank 2	$-5.7 \pm 0.5$	$24.5 \pm 0.05$	$24.2 \pm 0.5$	$27 \pm 0.05$
Average:		$24.8 \pm 0.05$	$24.05 \pm 0.5$	$26.05 \pm 0.05$

In method 2, where the microneedle valve was used to allow the chambers to reach an equilibrium the chambers took approximately 670 ( $\pm 0.01$ ) s. In this method equilibrium was determined when the chambers were at a pressure difference deemed insignificant (within a 10% range). The right chamber's pressure was 2.2% higher than the left chamber which was deemed as an insignificant enough difference to declare equilibrium. The exact values can be seen in Table 2. Figure 2 and Figure 3 portray a graphical representation of the temperatures and pressures in each chamber throughout the experiment.

**Table 2.** Initial and Final Temp/Pressure Values (Method 2)

	Initial Pressure (PSI)	Initial Temp (°C)	Final Pressure (PSI)	Final Temp (°C)
Tank 1	$39.4 \pm 0.5$	$25.5 \pm 0.5$	$22.8 \pm 0.5$	$25.5 \pm 0.05$
Tank 2	$-5.5 \pm 0.5$	$23.1 \pm 0.5$	$23.3 \pm 0.5$	$26.2 \pm 0.05$
Average:		$24.3 \pm 0.5$	$23.05 \pm 0.5$	$25.85 \pm 0.05$

Equilibrium of left and right tanks with Method 1

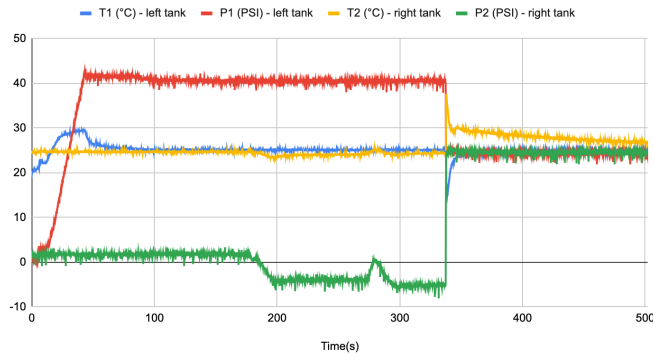


Figure 2: Temperature, Pressure, vs Time for left and right chambers with Method 1

Equilibrium of left and right tanks with Method 2

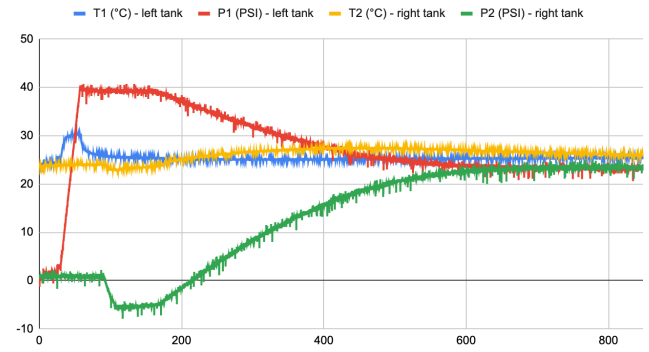


Figure 3: Temperature, Pressure, vs Time for left and right chambers with Method 2

#### 4.1.2 Discussion: Determining Volume Ratio (Lab Part 1)

By utilizing the data collected, the volume ratio between the left and right chambers can be determined by manipulating and using the ideal gas law equation [equation 1] and conservation of mass. Since the same air is expanded between the two chambers, the mass of air (number of moles,  $n$ ) remains constant before and after the expansion process. The volume ratio can be derived by comparing the pressures and temperatures before and after expansion. In the following calculations, the left chamber is represented with the subscript 1, and the right chamber with subscript 2.

Equilibrium is represented with the subscript eq.

$$P_1 V_1 = m_1 R T_1 \quad [2]$$

$$P_2 V_2 = m_2 R T_2 \quad [3]$$

$$P_{eq} V_{total} = m_{total} R T_{eq} \text{ (where } V_{total} = V_1 + V_2 \text{ and } m_{total} = m_1 + m_2) \quad [4]$$

Putting equation 2, 3, and 4 together, the following relationship can be derived.

$$\frac{P_1 V_1}{T_1} + \frac{P_2 V_2}{T_2} = \frac{P_{eq} (V_1 + V_2)}{T_{eq}} \quad [5]$$

Using equation 5, the relationship can be rearranged by determining the volume ratio as follows:

$$\frac{V_1}{V_2} = \frac{T_1(P_{eq}T_2 - P_2T_{eq})}{T_2(P_1T_{eq} - P_{eq}T_1)} \quad [7]$$

Using equation 7 and values from tables 1 and 2, the volume ratio through method 1 was determined to be  $1.70 \pm 0.5$  and the volume ratio for method 2 was determined to be  $1.73 \pm 0.5$  portraying both ratios are within a similar range.

#### 4.1.3 Discussion: Heat Transfer and Path Independence

In method 1 (rapid equalization - center solenoid valve) the chambers reach equilibrium quickly. Since the process happens over a short period, there is little time for significant heat transfer between the chambers and the surroundings. The temperature difference between the chambers at the end is small, suggesting that any heat transfer is negligible. The system can be considered adiabatic for this case, meaning the net heat transfer is close to zero. In method 2 (slow equalization - micrometer needle valve), the chambers take a longer time to reach equilibrium (670 seconds). Over this extended period, heat transfer between the chambers and their surroundings becomes more significant. The slower process allows for some heat exchange with the environment, particularly since the pressure and temperature differences are reduced more gradually. However, since the system is mostly insulated, we still consider the net heat transfer to be negligible for simplicity. In both cases, the total heat transfer within the system is minimal, with the final state properties indicating near-adiabatic behavior, particularly in the first case.

Furthermore, the experiment demonstrates the path independence of state properties by showing that the final equilibrium state (in terms of pressure and temperature) is the same, regardless of how the system reached equilibrium (rapidly or slowly). In Method 1 (rapid equalization), the chambers quickly reached a state where the temperature difference between them became insignificant, taking approximately 160 seconds. In Method 2 (slow equalization), even though the process took much

longer (670 seconds), the chambers also reached a final state of equilibrium, where the pressure difference was insignificant. Despite the different rates of expansion, the final thermodynamic state (pressures and temperatures) in both methods is nearly the same which can be seen by comparing the graphs in Figure 2, and Figure 3. Despite showing different rates, the temperatures and pressures of both chambers plateau at approximately the same level. This illustrates the key principle of path independence, which states that the final state properties (such as pressure and temperature) of a system depend only on the initial and final states, not on the process by which the system transitioned between these states.

## **4.2     *Lab Part 2***

### **4.2.1   Results: Lab Part 2**

The atmospheric pressure was measured at  $29.9 \pm 0.05$  inHg or  $101\,253 \pm 200$  Pa. The initial temperature and gauge pressure for the left tank were measured at  $23.3 \pm 0.05$  C [ $296.3 \pm 0.05$  K] and  $0.5 \pm 0.05$  PSI [ $3400 \pm 400$  Pa]. The mass flow rate graph was integrated over the duration of the experiment to find the total mass flow into the left tank, which measured  $23.8 \pm 0.5$  g. After stabilizing to a virtual equilibrium, the left tank's final temperature and gauge pressure were measured at  $26.0 \pm 0.05$  C ( $299.0 \pm 0.05$  K) and  $40.5 \pm 0.05$  PSI ( $280\,000 \pm 400$  Pa). Figure 4 shows Mass Flowrate (g/min) and Mass In (g) against time. Figure 5 shows the temperature (K) and pressure (PSI) of the tank against time.

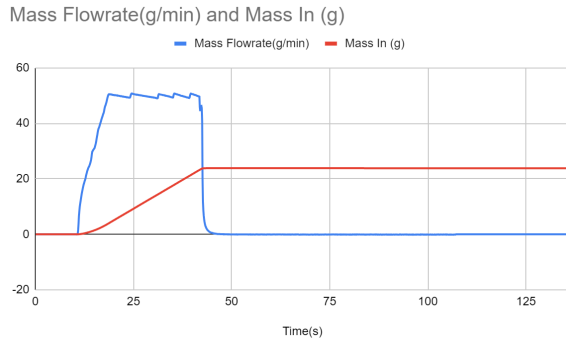


Figure 4: Mass flow rate and Total Mass in vs. Time

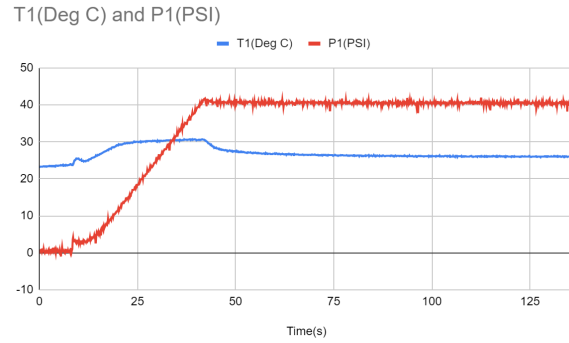


Figure 5: Temperature and Pressure of Left Tank vs. Time

**Table 3.** Initial and Final Pressure, Temperature, and change in mass for lab part 2.

	$P_{\text{atm}}$ (Pa)	$P_{\text{gauge}}$ (Pa)	$P_{\text{abs}}$ (Pa)	$T$ (K)	$\Delta m$ (g)
Initial	$101\,300 \pm 200$ Pa	$3400 \pm 400$	$104\,700 \pm 600$	$296.3 \pm 0.05$	$23.8 \pm 0.05$
Final		$280000 \pm 400$	$381300 \pm 600$	$299 \pm 0.05$	

#### 4.2.2 Discussion: Lab Part 2

The experimental setup enforces a constant volume equal to that of the left tank. By rearranging and manipulating the ideal gas law equation [1]:

$$PV = mRT, R = \frac{R_u}{M_{\text{air}}} \quad [8]$$

$$V = \frac{mRT}{P} \quad [9]$$

It can be assumed that  $V_i = V_f = V$ .

$$V_i = V_f \quad [10]$$

$$m_i RT_i / P_{\text{abs}_i} = (m_i + \Delta m) RT_f / P_{\text{abs}_f} \quad [11]$$

Isolating for  $m_i$ :

$$m_i = \Delta m (T_f / P_{\text{abs}_f}) \times [(T_i / P_{\text{abs}_i}) - (T_f / P_{\text{abs}_f})]^{-1} \quad [12]$$

$$\mathbf{m_i = 9.13 \pm 0.08 \text{ g}}$$



Solving for V using initial conditions:

$$V = m_i R T_i / P_{\text{abs}_i} \quad [13]$$

$$V = (7.4 \pm 0.1) \times 10^{-3} \text{ m}^3 = 7.4 \pm 0.1 \text{ L}$$

The initial mass and volume of the air in the left tank were  $9.13 \pm 0.08 \text{ g}$  and  $7.4 \pm 0.1 \text{ L}$  respectively.

Furthermore, some potential sources of error in this experiment are uncalibrated or faulty sensors, leaking of gas or improper sealing of the tank, and imperfect insulation. Pressure and temperature readings could show a systematic error if not calibrated properly. If the gauge pressure from the LabVIEW sensors reads a significant nonzero value after the tank has been emptied, the readings of initial and final pressures will have an inaccurate ratio to the real initial and final pressures, which can cause inaccuracies in the calculation of mass and volume.

Lack of proper sealing in the valves can lead to less mass in the tank compared to the theoretical change of mass calculated from the mass flow rate chart. This would result in an initial mass and volume value greater than the real initial mass and volume. Lack of proper sealing could occur due to wear or improper tightening of the valves. Imperfect insulation can also result in underestimating the volume calculation. Volume is directly proportional to the temperature of the gas. If heat escapes due to poor insulation, the volume will be underestimated.

In addition, the compressibility factor of a gas relates to how much the behaviour of a real gas deviates from an ideal gas. The compressibility factor ( $Z$ ) is defined as:

$$Z = PV/nRT \quad [15]$$

The compressibility factor of an ideal gas is  $Z = 1$ . For more compressible gases,  $Z > 1$ . For less compressible gases,  $Z < 1$ . With real gases, the compressibility factor tends to increase with pressure, resulting in  $Z > 1$  at higher pressures and  $Z < 1$  at lower pressures. The compressibility

factor is directly proportional to volume. When a real gas reaches higher pressures, the molar volume ( $V_m$ ) is greater than the molar volume of an ideal gas, and at lower pressures,  $V_m$  is lower than the molar volume of an ideal gas. Air in the temperature (290-300 K) and pressure (100-400 kPa) ranges present in this experiment has a compressibility factor of  $Z = 0.9999 \approx 1$ , therefore air can be treated as an ideal gas in these conditions and should not significantly affect the experimental results. [Perry]

## 5 Conclusion

Through this lab, the ideal gas law [1] was examined through various methods. In part 1 of the lab, two different methodologies to establish equilibrium were utilized. The results from this methodology demonstrated that state variables such as temperature and pressure are path-independent as the chambers reached a similar equilibrium regardless of the method used which can also be seen by the volume ratios. The volume ratio with the first method was  $1.70 \pm 0.5$  whereas for the second method it was  $1.73 \pm 0.5$ , both of which are close to each other within the margin of error. In part 2 of the lab, the initial mass and volume were computed using the ideal gas law. Given the initial mass from the mass flow rate graph, along with temperature and pressure for both paths, the results were  $m_i = 9.13 \pm 0.08\text{g}$  and  $V = 7.4 \pm 0.1\text{ L}$ . Although some potential sources of error, such as sensor calibration and gas leakage, were identified, their impact on the results was minimal. Overall, this experiment provides a practical confirmation of the Ideal Gas Law and highlights the robustness of its assumptions in near-ideal conditions.

## 6 References

- [1] John H. Perry. *Perry's Chemical Handbook*. McGraw-Hill. 1984. p. 3-162. ISBN: 0-07-049479-7.
- [2] Sanjeev Chandhra. *Energy, Entropy, and Engines: An Introduction to Thermodynamics*. 400 pages. Wiley, 2016. ISBN: 978-1-119-01317-4.