CHE 260: Analyzing the Behaviours of Gases Using the Ideal Gas Law

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Abstract

This experiment investigated the behaviour of air as an ideal gas in a two-tank system to demonstrate the path independence of thermodynamic state functions. Two processes in the two-tank system were compared: a rapid pressure equalization followed by thermal equilibration, and a quasi-equilibrium process where pressures were equalized slowly while maintaining near-thermal equilibrium throughout. The final equilibrium states of the left and right tanks differed by at most 3.0% and 11.5%, respectively, confirming that state properties such as pressure and temperature disregard the path of the function. In the second part of the experiment, by integrating the flow rate data, it was determined that (24.4 ± 0.1)g of air entered the tank, and the corresponding tank volume was (5.6 ± 0.1)L using the ideal gas law. During analysis, the compressibility of air was determined to have a negligible effect on mass and volume calculations under ideal gas conditions. Overall, the experiment exemplified that the ideal gas law is an effective model for air in pressure and temperature ranges experienced in the lab.

1. Introduction

Ideal gases have independently moving particles, no intermolecular forces, and negligible volume [1]. They obey the ideal gas law, which fundamentally relates pressure (P), volume (V), temperature (T), mass (m), and specific gas constant (R) to give the equation:

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

The objective of this experiment is to demonstrate the path independence of thermodynamic state properties, such as pressure and volume, and to derive the mass and volume ratios of the two tanks from a mass flow diagram.

The first part of the lab uses two different methods to show path independence: the rapid equalization of pressure through a Solenoid valve, compared to a quasi-equilibrium process with a micrometre, where an infinitesimal change in temperature allows the system to remain close to equilibrium at all times. Using measured values, we calculate the volume ratio between the tanks. The second part of the lab quantifies the initial mass of the left tank by integrating a mass flow rate graph and calculating the corresponding volume with *Equation (1)*.

These results, and their subsequent analysis, underscore both the theoretical significance of the ideal gas law and its practical applications in thermodynamics and heat transfer.

2. Experimental Method

2.1. Apparatus:

- Manometer: measures the ambient pressure of the room in psi.
- Two rigid pressurized tanks: store and transfer gas using different valves, as in *Figure 1*.

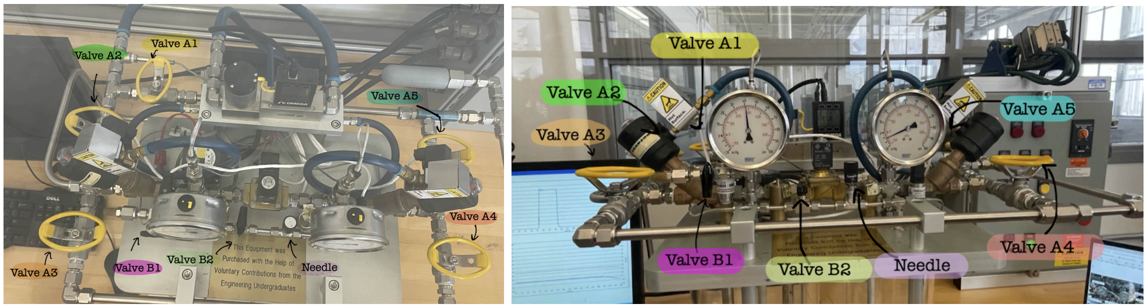

Figure 1—Top (left) and side (right) views of the apparatus setup of the pressure tanks. There are yellow valves (A1-5), black valves (B1, B2), a needle, and the connecting pipes.

- LabVIEW: controls the Solenoids (Left, Central, and Right) and flow rate, as well as records data (i.e., pressure, temperature, and mass flow).

- Pressure Gauge: displays the gauge pressure of each tank.

2.2. Procedure:

All safety warnings stated in the lab manual [2] were followed, and the instructions were taken from [3]. Before the experiment, a manometer was used to determine the ambient pressure of the lab. After data collection for each section, tanks were emptied by opening valve B1 and the Center Solenoid (see *Figure 1*) until both pressure gauges read 0 psig.

2.2.1. Pressurizing the Left and Right Tanks

To pressurize the left tank, valve A2 and the Left Solenoid were opened. The flow rate was gradually increased to 50 g/min until the left pressure gauge reached 40 psig. A2 and Left Solenoid were closed, and the flow rate was reset to 0 g/min. To pressurize the right tank to -6 psig, the same procedure was performed, except valves A1, A5, and the Right Solenoid were opened (until the pressure read -6 psig) and closed, instead of A2 and the Left Solenoid.

2.2.3. Path 1 Method 1: Rapid Equalization

The left tank was pressurized to 40 psig, and the right to -6 psig, following Section 2.2.1. For rapid equalization, the Center Solenoid was left open until an insignificant temperature difference was recorded. This process took around 45 seconds.

2.2.4. Path 1 Method 2: Slow Equalization:

The left tank was pressurized to 40 psig, and the right to -6 psig, following Section 2.2.1. For slow (quasi) equalization, the micrometre needle valve and B2 were left open until an insignificant pressure difference was noted on LabVIEW between the two tanks. This process took around 10 minutes.

2.2.5. Part 2 of the Experiment

The left tank was pressurized to 40 psig as described in 2.2.1. The Left Solenoid was left open until the pressure and temperature on the graphs in LabVIEW remained constant with time.

3. Results

3.1. Part 1 Results

The initial and final absolute pressures and temperatures for rapid and quasi-equilibrium processes are summarized in *Table 1*. The gauge pressure values against temperature are plotted on the Pressure-Temperature diagrams in *Figure 2*. Note that gauge pressure data was collected (psig), whereas absolute pressures (psia) were used in calculations, given by:

$$P_{absolute} = P_{gauge} + P_{atmosphere} \tag{2}$$

By the manometer, the atmospheric pressure was measured to be

$$P_{atmosphere} = (29.9 \pm 0.1)\ Hg \tag{3}$$

Process	**Tank**	**Initial pressure (Psig)**	**Initial pressure (Psia)**	**Initial temperature (°C)**	**Final pressure (Psig)**	**Final pressure (Psia)**	**Final temperature (°C)**
Rapid	Left	40.9	55.6	27.5	24.9	39.6	26.7
	Right	-4.1	10.6	25.0	24.5	39.2	29.8
Quasi-equilibrium	Left	40.4	55.1	27.4	24.7	39.4	27.3
	Right	-4.5	10.2	25.8	24.7	39.4	27.8

Table 1: Initial and final properties for rapid and quasi-equilibrium processes. Measured pressure and temperature uncertainties are ± 0.1 *for each point. Psia values were calculated using Equations (2) and (3).*

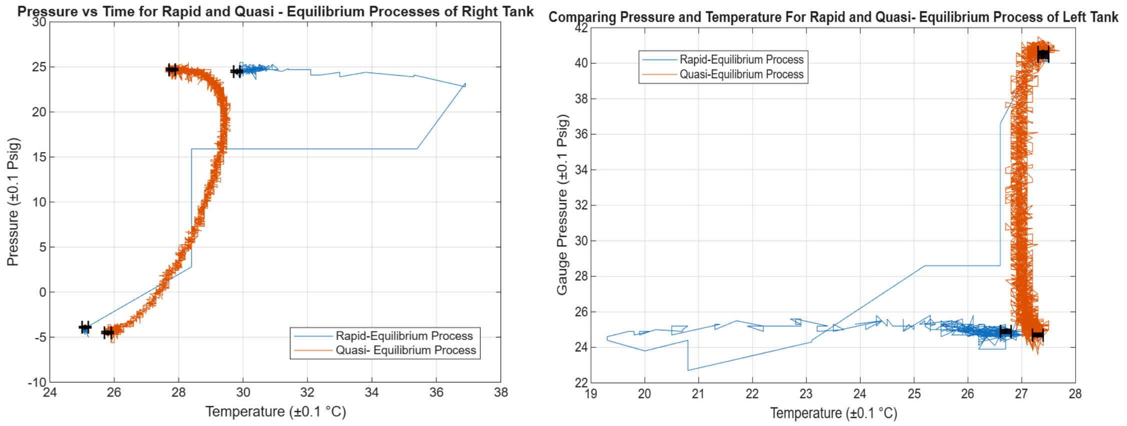

Figure 2: The left and right figures show Pressure-Temperature diagrams comparing the paths of a rapid (blue) and quasi-equilibrium (orange) process of the left and right tanks, respectively.

3.2. Part 2 Results

The mass flow rate into the left tank is shown in *Figure 3*, where, through integration in MATLAB, it is (24.3870 ± 0.1148) g.

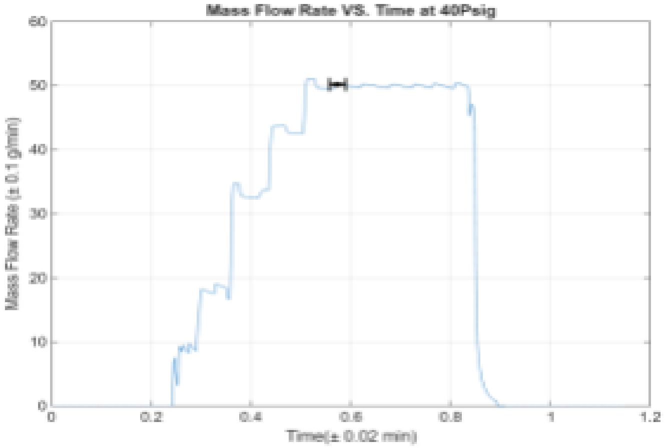

Figure 3: A Mass Flow Rate diagram of the left tank as it reaches 40 psig.

4. Discussion

The errors calculated in the discussion and analysis sections use the methods cited in [4].

4.1. Part 1: State Independence Analysis

In the first method, there was fast equalization between the two tanks. The Center Solenoid allowed gas to flow quickly from a high-pressure left tank to a low-pressure right tank. The process was brief and nearly adiabatic; heat transfer to the surroundings is negligible, as the gas did not stay at one location for long. However, after the Solenoid was closed and the pressure equilibrated, the tanks exchanged heat with the surroundings until they reached a common temperature.

Meanwhile, in the second method, the micrometre needle valve and B2 slowed the movement of gas from the left to the right tank. The infinitesimal changes in temperature allow constant thermal equilibrium for gradual heat exchange between the tanks throughout.

The percent difference [5] between the pressure-temperature ratios of a particular tank is:

$$\%\, difference = \frac{|a - b|}{\frac{1}{2}(a + b)} \times 100 \tag{4}$$

For $a = P_{quasi} / T_{quasi,}$ the pressure-temperature ratio for quasi-equilibrium, $b = P_{rapid} / T_{rapid,}$ the pressure-temperature ratio for rapid-equilibrium, *Equation (4)* turns to:

$$\% \, difference \ = \frac{\left| \frac{P_{quasi}}{T_{quasi}} - \frac{P_{rapid}}{T_{rapid}} \right|}{\frac{1}{2}\left(\frac{P_{quasi}}{T_{quasi}} + \frac{P_{rapid}}{T_{rapid}}\right)} \times 100 \tag{5}$$

The results from *Equation (5)* from the tanks are summarized in *Table 2*. The tanks reach similar final conditions, differing by at most 3.0% on the left tank and 11.5% on the right.

	$\frac{P}{T}$ $initial\ left$	$\frac{P}{T}$ $final\ left$	$\frac{P}{T}$ $initial\ right$	$\frac{P}{T}$ $final\ right$
% difference	$= 0.5\%$	$= 3.0\%$	$= 11.5\%$	$= 7.8\%$

Table 2: Percent Differences (%) between initial and final P/T ratios of left and right tanks

In both methods, the tanks reached approximately the same final states. From *Figure 2*, the initial and final temperature and pressure values are relatively the same, despite their trajectories deviating substantially. Since the tanks act as rigid containers, the change in internal energy depends on the final temperature, allowing the total net heat transfer to be zero for both methods. This proves that the state functions do not rely on path, making them path-independent.

4.2. Part 1: Volume ratio between the two tanks

The volume ratio between the two tanks can be calculated by relating the ideal gas law (*Equation (1)*), the assumption of conservation of mass within tanks, and the initial and final state properties from before and after the expansions to get:

$$m_{tot} = m_{L,i} + m_{R,i} = m_{L,f} + m_{R,f} = \frac{P_{L,i}V_{L}}{RT_{L,i}} + \frac{P_{R,i}V_{R}}{RT_{R,i}} = \frac{P_{f}(V_{L}+V_{R})}{RT_{f}} \tag{6}$$

The variables in *Equation (6)* are:

- m_{tot} = total mass, $m_{L,i}$ = initial left tank mass, $m_{R,i}$=initial right tank mass, in kg.
- $P_{L,i}$ and $P_{R,i}$ = the initial left tank and right tank pressures, respectively, in psi.

- V_L and V_R = the volumes of the left and right tanks, respectively, in m^3.
- R = specific gas constant of air (0.2870 kJ kg^{-1} K^{-1}, [6]).
- $T_{L,i}$ and $T_{R,i}$ = the initial temperatures of the left and right tanks, respectively, in K.
- T_f = average final temperatures of the left ($T_{L,f}$) and right tanks ($T_{R,f}$) ($T_f = \frac{T_{R,f}+T_{L,f}}{2}$) in K.
- P_f = average final pressure of the left ($P_{L,f}$) and right tank ($P_{R,f}$) ($P_f = \frac{P_{R,f}+P_{L,f}}{2}$) in psi.

Isolating *Equation (6)* for $\frac{V_L}{V_R}$ gives

$$\frac{V_L}{V_R} = \frac{P_f - \frac{P_{R,i}}{T_{R,i}}T_f}{\frac{P_{L,i}}{T_{L,i}}T_f - P_f}. \tag{7}$$

From *Equation (7)* and the measured values from *Table 1*, we achieve a ratio of left tank to right tank of 1.9 ± 0.1 for quasi-equilibrium and 1.8 ± 0.1 for rapid equilibrium. These values agree within 5.4% of each other (*Equation (4))*, showing that although the processes vary, they agree within less than 6% of each other for this volume ratio. Maintaining significant figures, the average between the two processes yields a left-to-right tank volume ratio of 1.9 ± 0.1.

4.3. Part 2: Calculating volume of the tank

The mass of air entering the left tank is found by integrating the mass flow rate graph, shown in *Figure 3*. Using MATLAB, the mass of air inside the tank (M_{in}) was determined to be (24.4 ± 0.12) g. The volume of the left tank (V_L) is calculated with *Equation (1)*, using M_{in}, the final temperature T_f, specific gas constant for air R, and the final absolute pressure P_{abs}:

$$V_L = \frac{M_{in} R T_f}{P_{abs}} \tag{8}$$

Using *Equation (8)* and measured values of T_f = 27ºC or 300.15K, R = 287 $\frac{J}{kg * K}$ [6], P_{abs} = 54.7 ± 0.1 from data, $V_L = (5.6 \pm 0.1)$ L.

4.4. Considering the impact of air compressibility on results

In reality, air compressibility becomes significant at extremely high pressures or very low temperatures [1], conditions beyond the scope of the lab. This allows us to neglect compressibility in our calculations. While no gas is perfectly ideal, the ideal gas law gives an accurate model at ambient conditions, where intermolecular forces are negligible.

Quantitatively, this assumption was validated using the compressibility factor Z [7] in *Equation (9)*, where m is mass, R is the specific gas constant, and T is temperature. For an ideal gas, Z = 1, and relating it to *Equation (1),* the result becomes:

$$Z = \frac{PV}{mRT} \tag{9}$$

Taking experimental values from Part 2 (see Section 4.3), Z ≈ 1.01. This value, being within 1% of ideal behaviour, supports our assumption that, under laboratory conditions, the ideal gas law holds.

4.5. Sources of Error

Possible sources of error include the accuracy of the apparatus and the assumptions behind calculations. The accuracy and resolution of the pressure gauge, temperature sensor, and mass flow meter affect the calculated volume ratio and tank volume, as volume is inversely proportional to pressure (*Equation (1)*). Furthermore, LABVIEW displays only integer values for mass flow, disregarding intermediate flow rates and thus increasing the uncertainty in the integrated mass calculation. A flow meter with higher resolution would reduce this. Additionally, valve leaks can violate the conservation of mass assumption, invalidating volume ratio calculations.

We hypothesize the right tank's pressure difference (*Table 2*) is due to its imperfect near-vacuum state. At low pressures, and thus lower densities, gas molecules spread apart due to vacuum theory [8], prompting residual contaminants (e.g. water vapour, oil) to account for larger portions of gas per unit volume composition; this can alter the specific gas constant R. To resolve this, we must thoroughly examine the tanks for contaminants beforehand. Secondly, the low gas density prevents effective heat conduction, likely causing the temperature sensor to measure the temperature of the tank wall instead of the gas molecules, causing an erroneous $T_{R,i}$ value. To resolve this, we require a sensor with enough immersion to reach the gas, insulate the sensor from the tank's walls, and actively mix the gas to allow a uniform gas temperature around the sensor.

5. Conclusion

By bringing a system to equilibrium through both a rapid equalization and a quasi-equilibrium process, we showed that thermodynamic state properties are independent of path, because the final equilibrium pressures and temperatures were similar, within 11.5%. The left-to-right tank volume ratio was approximately 1.9 ± 0.1, and the mass of air introduced into the left tank in part 2 was found to be (24.4 ± 0.12) g, resulting in a volume of (5.6 ± 0.1) L.

The primary sources of error included sensor calibration, resolution limitations from the mass flow meter, and challenges in setting up a vacuum in the right tank. The larger percent differences observed for the right tank (up to 11.5%) are attributed to its initial near-vacuum state, where residual contaminants alter the specific gas constant R, and low gas density causes the temperature sensor to measure the tank wall's temperature rather than the gas itself.

Despite these uncertainties, compressibility effects were neglected under the conditions of this lab. This is because ideal gas assumptions neglect long-range intermolecular forces and internal molecular pressures, which are minimal at moderate pressures and near-room temperature.

Overall, this experiment confirmed both the theoretical importance and practical applicability of the ideal gas law in modelling real systems under lab conditions.

6. References

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