Applications of the First Law of Thermodynamics: Investigating Energy Transfer and Heat Loss in a Closed Gas Chamber System

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PRA101 (12-3 pm): First Law Lab

1 Abstract

This lab investigates the First Law of Thermodynamics through a series of trials aimed at understanding the energy dynamics in a gas chamber apparatus. The first part of the experiment determines the mass of air using pressure and temperature stabilization, yielding mass values for each trial, with trial a at 25.47 g, b at 42.99 g, c at 24.91 g, and d at 41.93 g. In the second part of the experiment, heat loss was measured by assessing equilibrium conditions, where average heat loss rate ranged from 70.1 W to 212.4 W across trials. Additionally, specific heat capacity was calculated with a wide range. For the last part, propeller work was found to minimally impact temperature change, with rates between 0.0029-0.0032 K/s, emphasizing the heater's dominant role. These results validate the First Law's application in predicting energy changes within closed systems.

2 Introduction

The First Law of Thermodynamics states that energy cannot be created or destroyed but only transferred or converted between forms. This is fundamental in understanding closed-system energy dynamics. This law, often expressed as

$$\Delta U = Q + \mathrm{W} \qquad [1]$$

which relates changes in a system's internal energy (ΔU), to the heat added Q and work done (W) on the system. This lab investigates the First Law through two experimental parts, each aimed at analyzing different aspects of energy transfer and loss within a closed gas chamber apparatus.

The first part of the experiment focuses on determining the mass of air in a tank by stabilizing pressure and temperature, using ideal gas assumptions. The second part of the experiment evaluates heat loss by measuring the energy input needed to maintain thermal equilibrium. Additionally, the experiment examines the effect of mechanical work done by a propeller in the chamber, estimating its impact on the temperature. The power exerted by the propeller, calculated with fan similarity equations, contributes minimally to the temperature change due to the dominance of the heater's energy input. Overall, this lab aims to apply the First Law of Thermodynamics to quantify both the mass of air in a closed system and the heat loss in maintaining thermal equilibrium, providing practical insights into energy conservation and transfer within confined gas systems.

3 Experimental Methodologies

3.1 *Equipment Utilized*

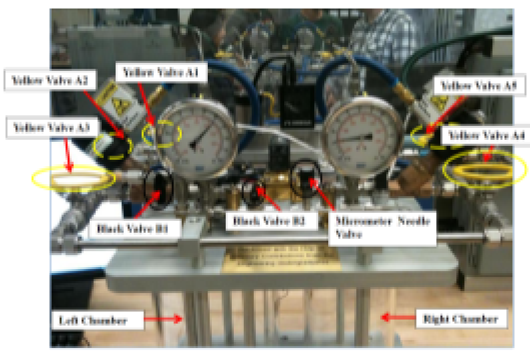


Figure 1: Gas Chamber Apparatus with labelled valves, and chambers

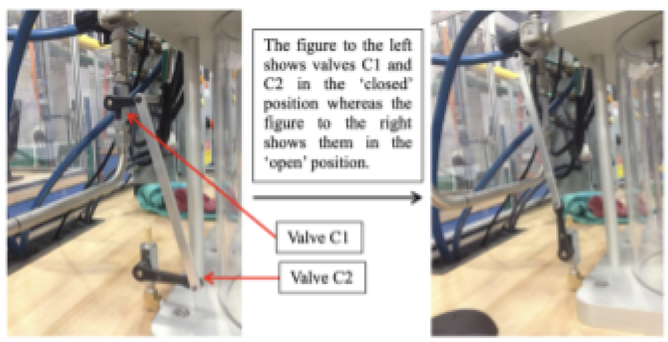


Figure 2: Valves C1 and C2 used labelled (utilized for cooling of chamber)

This lab utilized the 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), and valves. The valves can be opened and closed to set particular pressures (measured by the pressure gauge with measured pressure and temperature). The apparatus also consists of heaters that can be used to obtain a certain internal temperature in the chamber. Valves C1 and C2 as seen in Figure 2 are opened to allow for the chamber to cool. The Labview software is utilized in both experiments to control the mass flow rate, solenoids, the heaters, and save and collect data.

3.2 *Lab Methodologies*

In this experiment, four trials were conducted. Each trial set the initial condition of the chamber to a specific pressure, used heaters to heat the chamber to a specific temperature, and then cooled the chamber. (Table 1)

Part 1: Determining Mass in the Left Tank

1) The ambient pressure and the ambient temperature were measured.
2) Labview was set to “start collecting data”. To set initial conditions, Valve A2, and the left solenoid valve was opened. The flow rate was steadily increased to 50g/min. The left tank was pressurized to the trial temperature (as in table 1).
3) The left solenoid was closed, flow rate was decreased to 0g/ min. Data was collected on Labview until the Temperature and Pressure stabilized, and then was saved.

Part 2: Determining heat loss & specific heat capacity

4) Labview was set to “start collecting data”. The target temperature was set on Labview (according to trial temp in Table 1). The heaters were turned on.
5) After 5 minutes, the heaters were turned off, and data recording was completed and saved.
6) To cool the chamber, Labview was used to start collected data (without saving). Valve A2, C1, and C2 (as seen in Figures 1 and 2) were opened. Left solenoid was opened, and the flow rate was steadily increased to 50g/min.
7) The temperature was allowed to cool below Cool Temperature in accordance to Table 1. Flow rate was set to 0g/min, the temperature was allowed to stabilize for about 5 minutes. All valves were closed and the temperature was allowed to stabilize for 1 minute.

Steps 1-7 were completed 4 times according to each trial set up in table 1. Note in trial c, no cooling occurs therefore, steps 6-7 can be neglected.

Table 1. Trial Pressure, Temperature, and Post-Trial Temperature for each experiment trial.

Trial	Trial Pressure (PSI)	Trial Temp (℃)	Cool Temp (℃)
a	40	40	30
b	70	40	40
c	40	60	40
d	70	60	30

4 Results and Discussions

4.1 *Part 1: Determining the mass of the Tank*

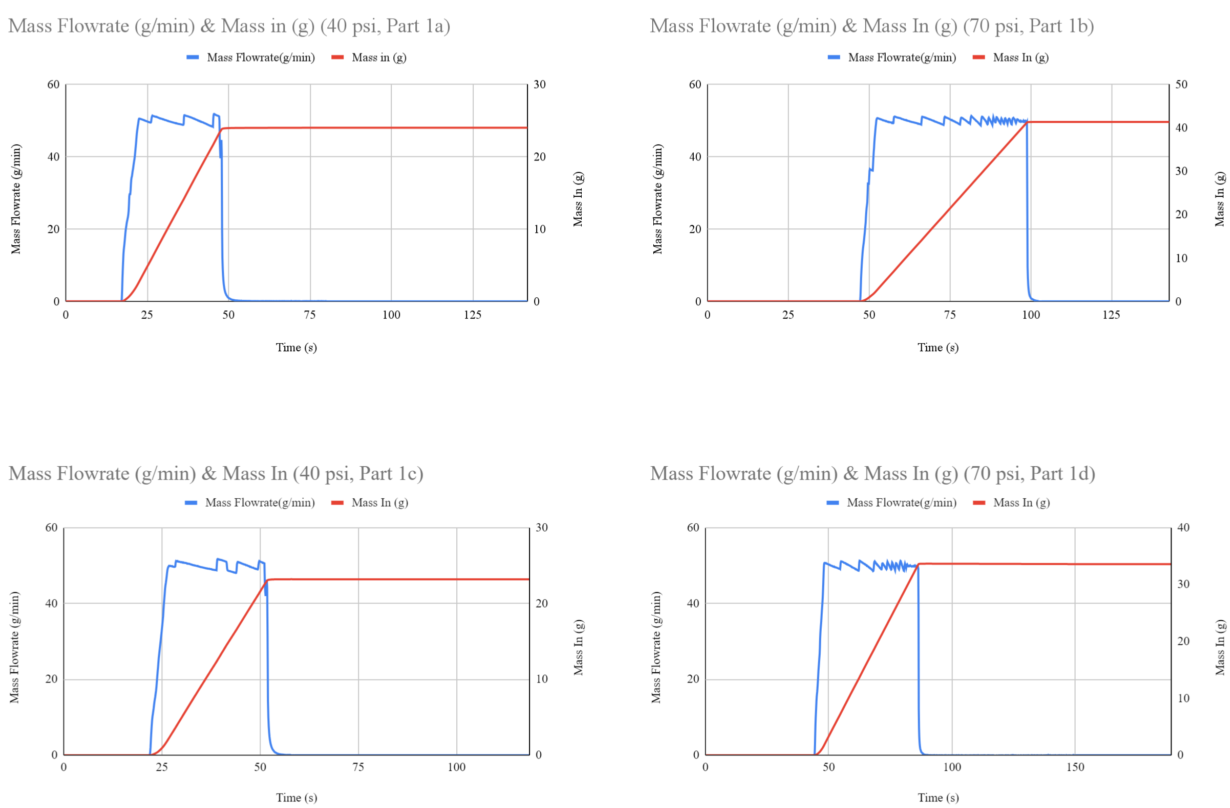


Figure 3: Mass Flowrate (g/min) & Total Mass In (g) Tank for Trials a, b, c and d

To determine the mass of the air in the left tank the following equation can be utilized:

$$m_{tank} = m_{added}\left(1 + \frac{1}{\frac{P_2 T_1}{P_1 T_2} - 1}\right) \quad [2]$$

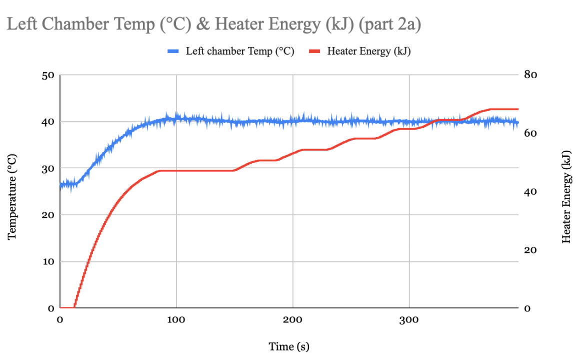
P_1 and P_2 are the initial and final absolute pressures, and T_1 and T_2 are the initial and final temperatures of the left chamber. The mass flow rate graph (Figure 3) of each trial was integrated over the duration of the experiment to find the total mass flow into the left tank. Table 2 shows the calculated value, using equation [2] for the mass in the tank during each trial.

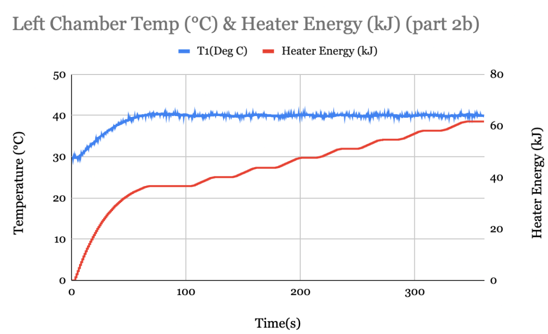
Table 2. Initial and Final Pressure, Temperature, and change in mass for lab part 1.

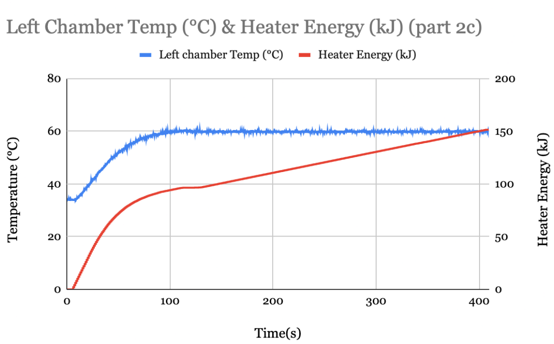
Trial	P_1 [Pa]	P_2 [Pa]	T_1 [K]	T_2 [K]	m_{added} [g]	m_{tank} [g]
Trial a	17236.9	275790.4	299.85	301.75	23.9632	25.4704
Trial b	19305.3	42633.2	302.75	303.25	41.271283	42.99388
Trial c	19305	275790	308.65	304.45	23.19027	24.91208
Trial d	96527	428633	308.85	307.55	33.5824	41.93398

The air in the tank is assumed to be an ideal gas. Variations in pressure, temperature, and interactions between real gas molecules might lead to deviations from experimental mass values.

4.2 *Part 2: Calculating Heat Loss and Specific Heat Capacity*







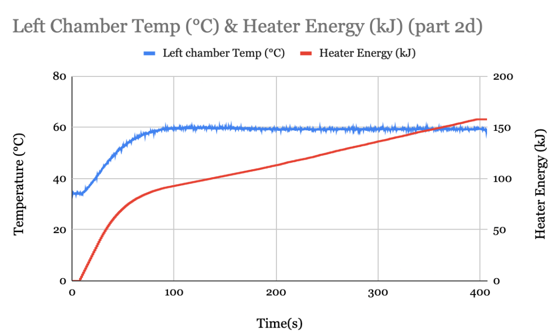


Figure 4: Left chamber temperature (℃) and Heater Energy (kJ) graphed against time for each trial.

4.2.1 Calculating heat loss of the Left Chamber

The heat loss of the chamber can be calculated using the input power required to keep the temperature of the tank constant, after thermal equilibrium is reached. Once the temperature stabilizes, thermal equilibrium is reached indicating $\dot{Q}_{in} = \dot{Q}_{out}$. The total heat added to the chamber can be given by the following, which is how the Labview software calculates added heat:

$$Q_{added} = 2 \cdot P_{heater} \cdot \sum t_{on} \quad [3]$$

To find the heat loss rate, the total heat added to the chamber can be divided by the time that the chamber was in equilibrium, which will provide the average heat loss over the time interval.

Table 3. Corresponding experimental data utilized to calculate total and average heat loss per trial.

	t_{eq} [s]	t_f [s]	Q_{eq} [kJ]	Q_f [kJ]	$\dot{Q}_{average}$ [W]	Q_{total} [kJ]
Trial a	80	394	46.2	68.2	70.1	22.0
Trial b	59	361	35.2	61.7	87.7	26.5
Trial c	98	410	93.7	151.4	184.9	57.7
Trial d	100	407	92.7	157.9	212.4	65.2

4.2.2 Calculating heat loss through the top and bottom plates

To determine the heat loss through the top and bottom plates, the heat loss through the acrylic walls must first be calculated, which can be done with the following equation:

$$\dot{Q} = 2k\pi l \cdot \frac{\Delta T}{ln(\frac{r_2}{r_1})} \quad [4]$$

where k is the conductive heat transfer coefficient, for acrylic it is 0.185 ± 0.15 W/mK, l is the length of the cylinder 0.28575 ± 0.00003m, ΔT is the temperature drop across the walls (which it will be assumed to be T_{inside} - $T_{external}$), and r1 and r2 are the inner and outer radii of the cylinder (0.092 ± 0.002 m and 0.1016 ± 0.0006 m respectively). Utilizing the total heat loss calculated in section 4.2.1, by subtracting the heat loss rate calculated using equation [4] multiplied by the duration in equilibrium, the heat loss through the top and bottom plates can be determined. The external ambient temperature was 24.4 ℃.

Table 4. Heat loss through the top and bottom plate alongside corresponding data utilized to calculate the values for each trial.

	$Q_{total\ lost}$ [kJ]	T_{inside} [℃]	ΔT [℃]	Q_{walls} [kJ]	Q_{plates} [kJ]
Trial a	22.0	40	15.6	16.4	5.6
Trial b	26.5	40	15.6	15.8	10.7
Trial c	57.7	60	35.6	37.2	22.1
Trial d	65.2	60	35.6	36.8	28.4

A potential source of error in calculating heat loss in this method may arise from only considering conduction through the chamber walls as the only mechanism of heat loss. In reality, heat transfer can occur not only through conduction but also via convection and radiation. Convection can contribute significantly, especially if there are differences in air movement around the tank, while radiation can lead to heat loss depending on the temperature difference between the tank surface and its surroundings. Neglecting these additional mechanisms may result in underestimating the total heat loss, affecting the accuracy of calculations based solely on conductive heat transfer.

A significant source of error in this calculation arises from uncertainty in the lab-provided values. For instance, there is a 15% uncertainty in wall thickness and a 10% uncertainty in the heat transfer coefficient of the acrylic walls. Additionally, we assume constant thermal conductivity, even though it varies with temperature. These uncertainties and assumptions propagate through the calculations, impacting accuracy.

4.2.2 Calculating specific heat capacity (c_v)

To calculate the specific heat capacity, the following equation can be used:

$$Q = mc_v \Delta T, \text{ where } c_v = \frac{Q}{m\Delta T} \quad [5]$$

where, c_v is the constant volume specific heat, Q is the total heat added during the heating process, m is mass and $\Delta T$is the change in temperature during the heating process.

Table 5. Specific constant volume heat capacity calculated for each trial, alongside relevant experimental data used.

	Q_{eq} [kJ]	Mass [kg]	ΔT [℃]	c_v [kJ/kg K]
Trial a	46.2	0.02547	14.3	126.8
Trial b	35.2	0.04299	10.3	79.5
Trial c	93.7	0.02491	25.9	145.2
Trial d	92.7	0.04193	26.0	85.0

It can be seen that the calculated specific heat capacity for air is different than the expected theoretical which is 0.717 kJ/ Kg K by a large margin. This can be attributed to propagated error and the assumption made in calculations that the experiment is done in ideal conditions, which is not the case in reality.

4.3 *Part 3: Determining Work Done by the Propellor*

In Part 3, we assess the work done by the propeller in the left tank to analyze its impact on system temperature and overall energy dynamics. Using fan blade similarity equations and an adiabatic assumption (where Q = 0), we reference the First Law of Thermodynamics, Equation (1), to examine the contributions of propeller work relative to the heat added by the heaters.

4.3.1 Equations and Methodology

The work done by the propeller was computed using the fan similarity equation:

$$\frac{P_2}{P_1} = \frac{\rho_2}{\rho_1}\left(\frac{n_2}{n_1}\right)^3\left(\frac{D_2}{D_1}\right)^5 \quad [6]$$

Where P_1 = 0.746 W (reference power), ρ_1 = 1.225 kg/m³ (standard air density), n_1 = 4200 rpm and n_2 = 2000 rpm (fan speeds), and $D_1 = D_2$ = 0.0635 m (constant fan diameter).

The operating air density, ρ_2, was calculated using the ideal gas law:

$$\rho = \frac{P}{RT} \quad [7]$$

Where R = 287 J/kg K (specific gas constant for air). The work done by the propeller over a 300-second interval was then computed with:

$$W = P \times t \qquad [8]$$

Assuming an adiabatic process (no heat transfer), the rate of temperature increase from the propeller work was estimated by rearranging Equation (11):

$$\frac{dT}{dt} = \frac{P}{mc_v} \qquad [9]$$

Where m is the mass of air (Table 2) and c_v is the specific heat capacity (Table 5).

4.3.2 Results and Analysis

Table 6. Summary of Part 3 with relevant information for calculations listed

Trial	P_{abs} (Pa)	T (K)	ρ_2 (kg/m³)	P_2 (W)	W (J)	m (g)	dT/dt (K/s)
Trial a	275790.4	301.75	3.18	0.27	81	25.47	0.0032
Trial b	426633.2	303.25	4.92	0.413	124	42.99	0.0029
Trial c	275790	304.45	3.13	0.263	78.9	24.91	0.0032
Trial d	428633	307.55	4.95	0.418	125.4	41.93	0.003

The table above presents the results for each trial, showing absolute pressure, calculated air density, propeller power, total work done, mass of air, and the rate of temperature change.

These results demonstrate a minimal rate of temperature change due to propeller work, approximately 0.0029-0.0032 K/s. Given the heater's greater energy input, this indicates that the propeller's work is negligible relative to the overall temperature change induced by the heater.

4.3.3 Error Analysis

Several assumptions may contribute to uncertainties in this analysis:

- Adiabatic Process: The assumption of no heat loss may not fully represent actual conditions, potentially overestimating propeller work.
- Ideal Gas Law Application: Ideal gas assumptions for air density calculations may introduce slight errors at high pressures.

- Measurement Uncertainty: Variances in fan speed, air mass, and temperature readings may propagate through the calculations, affecting precision.

Despite these potential sources of error, the small temperature increase due to the propeller's work supports the conclusion that it has minimal effect on the system.

5 Conclusion

This lab successfully applied the First Law of Thermodynamics to analyze energy transfer and heat loss within a closed gas chamber. By evaluating both the mass of air in a tank and the thermal energy dynamics, we confirmed the First Law's principles in practical scenarios. The first part of the experiment determined air mass based on stabilized pressure and temperature, yielding values consistent with ideal gas predictions. The second part highlighted the importance of heater energy in maintaining equilibrium, with heat loss rates varying significantly across trials. Calculations indicated that conductive heat transfer dominated but acknowledged that convection and radiation could affect accuracy. Additionally, our findings showed that work done by the propeller produced a negligible temperature change, further emphasizing the heater's primary role in energy input. Overall, the experiment validated theoretical expectations, though some errors were introduced due to assumptions about ideal gas behavior and heat transfer mechanisms. Future studies could improve accuracy by incorporating convective and radiative effects, as well as refining measurement methods for air mass and thermal energy.

6 References

[1] CHE260 Lab 2 - 1st Law of Thermodynamics

[2] Sanjeev Chandhra. *Energy, Entropy, and Engines: An Introduction to Thermodynamics.* 400 pages. Wiley, 2016. ISBN: 978-1-119-01317-4.