ME 331L Thermodynamics - Spring 2025

Lab 1: Gas Laws

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A. Abstract

In order to complete the measurements necessary to observe the ideal gas laws, a mass reservoir connected to a transparent expansion chamber underwent changes to the pressure, volume, and temperature along with a full thermal cycle. The results were then analyzed by graphing the data obtained and adding a curve fit to the data. Results show that our lines of best fit gathered from Experiment A's data did follow a linear model as predicted, but were much lower than the theoretical lines plotted using the ideal gas model and indicated some potential experimental error. Experiment B's results found that the thermal cycle had a very low efficiency, which was to be expected seeing as the cycle was not intended to act as an engine. Overall, the findings highlight the limitations of achieving ideal gas behavior in an experimental setting.

B. Introduction

The purpose of the gas laws lab is to observe how the ideal gas law behaves. Experimental apparatus were used to collect data to compare to the ideal gas law through testing the law under different conditions. This includes measuring pressure and temperature while holding volume constant (Amontom's law), measuring volume and temperature while pressure is held constant (Charles's law), measuring pressure and volume while holding temperature constant (Boyle's law), and running a basic thermal cycle.

C. Methods, Apparatus, Measurements

C.1. Materials and Setup

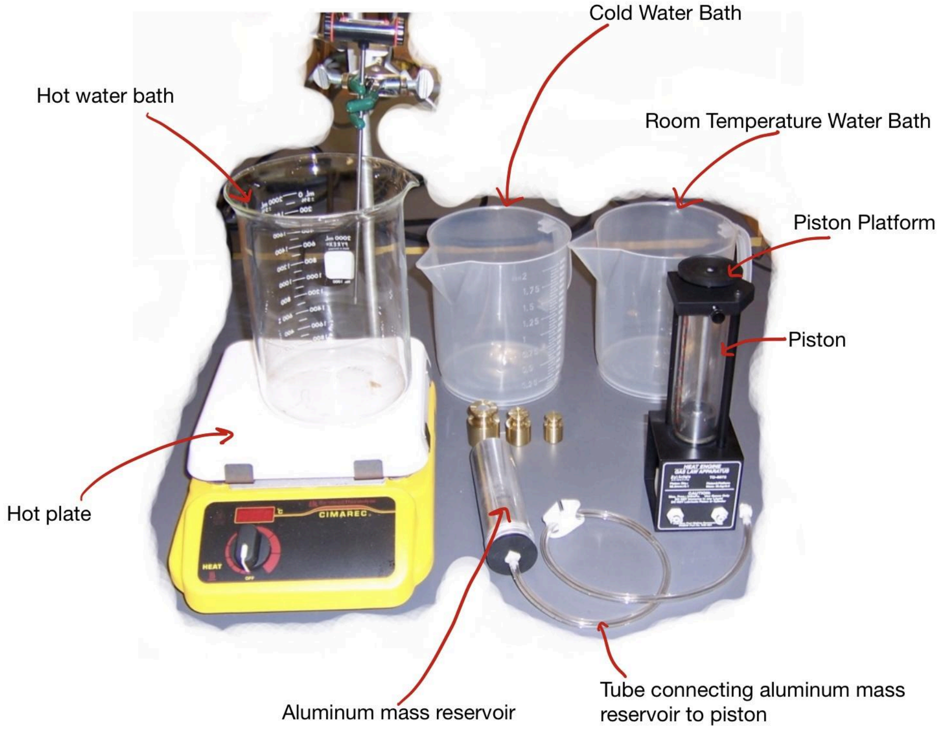


Figure 1: Labeled diagram of the experimental setup

Volume of Aluminum Cylinder	314.16 mm^3
Inner Diameter of Tubing	31.75 mm
Tubing Length	304.8 mm
Volume of Tubing	791.73 mm^3
Diameter of Expansion Chamber	32.5 mm
Mass of Piston and Platform Expansion Chamber	35 g
Room Temperature	21.2°C
Atmospheric Pressure	736.5 mm of mercury = 0.97 atm = 98.29 kPa

C.2. Procedures

First, Amonton's law was observed. The mass reservoir was placed in a hot water bath. After 5-10 seconds, the pressure was measured with a differential pressure manometer and recorded and the temperature of the hot water bath was measured with a digital thermometer and recorded. This process was repeated for a room temperature water bath and an ice water bath. The measurements for the hot, room temperature, and ice water bath were then repeated twice more. Second, Charles's law was observed. First, the piston apparatus was turned on its side and the aluminum mass reservoir was placed in the hot water bath. After 5-10 seconds, the temperature and height of the piston was recorded. This process was repeated in the room temperature and ice water baths. The measurements for the hot, room temperature, and ice water bath were then repeated twice more. Third, Boyle's law was observed. The cylinder position was recorded with no weight, 100g, 150g, and 200g sitting on the piston's platform. This step was repeated 3 total times.

Finally, a thermal cycle was run. To do this, the piston was first adjusted to the 40mm graduation mark and the aluminum mass reservoir was connected. The aluminum mass was placed in a cold bath, the position of the piston was recorded and a 200g weight was placed on the top plate of the piston. After 5 seconds, the position of the piston was recorded. The aluminum mass was then placed in the hot bath and the position of the piston was recorded. The 200g weight was then removed and the position of the piston was recorded. This process was repeated for 3 total cycles.

C.2. Error

Potential error sources include human error in reading the piston height and in gathering measurements for the setup specifications. Thermal inconsistencies can be explained by how each cylinder was not submerged for the same amount of time between trials and that thermal equilibrium between the air and each bath was likely not achieved in the short time that the cylinder was submerged. Also, there is error from small leaks of pressure in the piston.

D. Experiment A - Amonton's, Charles's, & Boyle's Law

In order to plot the data for experiment A, the mass of the air was found with,

$$m = \frac{P_{atm}V_{total}}{RT_{room}}$$

where V_{total} is the sum of the volume of the tubing, the volume of the aluminum cylinder, and the volume of the piston when it is at its starting position of 35 mm, P_{atm} is the atmospheric pressure, T_{room} is the room temperature, and R is the gas constant of air. The mass of the system was then used to plot the ideal gas model line on each plot.

To plot Amonton's Law, temperature in celsius was converted to kelvin and P_{atm} was added to the reading of the pressure gauge.

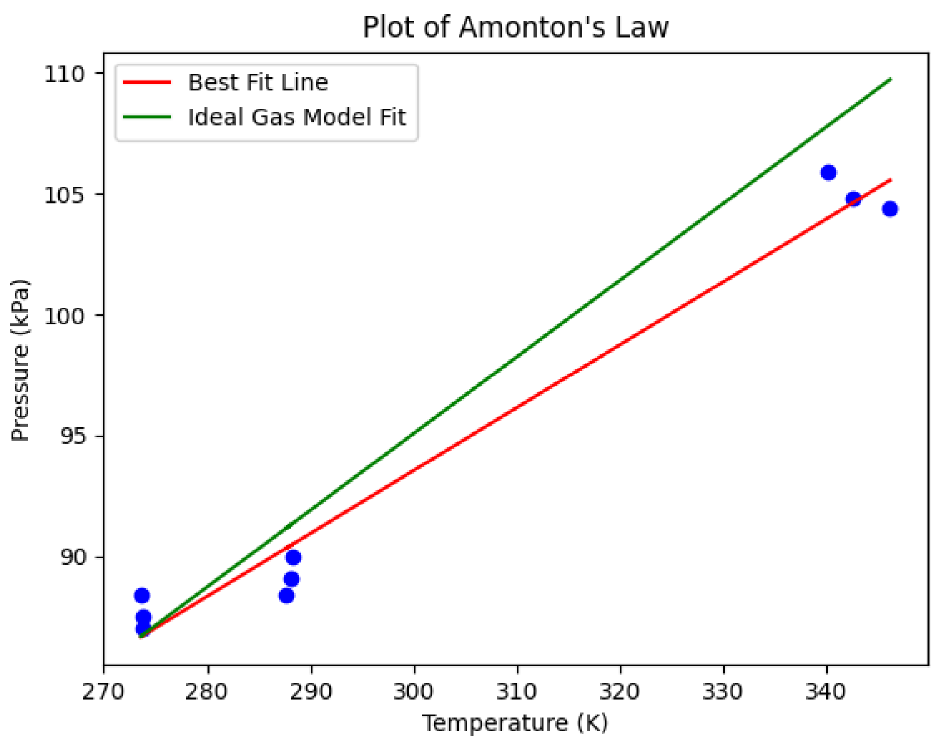


Figure 2: The data from our group's experiment A-1 plotted with a best fit line and the theoretical behavior according to Amonton's Law.

Based on the R^2 value of 0.974 for the best fit line to our group's data for Amonton's law (See Figure 2 above), a linear model was best for the experimental data and the error in the experiment didn't affect the linearity of our data. From visual inspection, it can be seen that the theoretical model has a larger slope than the best fit line from the experimental data, but overall the experimental data is a decent prediction for the theoretical values.

To plot Charles's Law (See Figure 3 below), volume was found by summing the volume from the piston (which varied) with the volume of the tubing and the volume of the aluminum cylinder. Then, temperature was converted from celsius to kelvin.

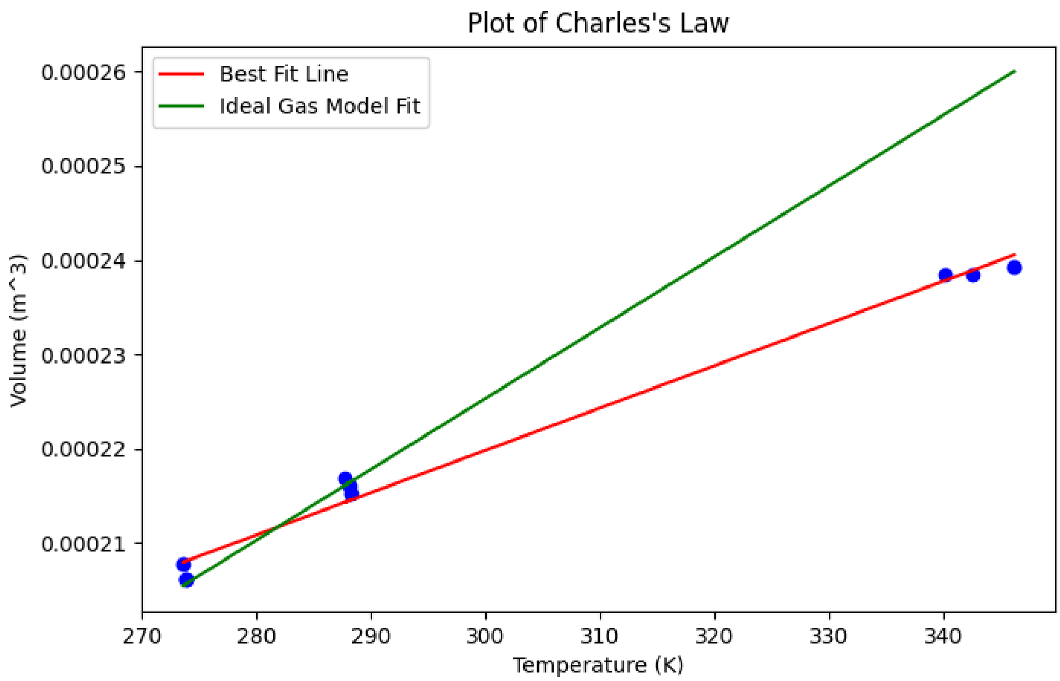


Figure 3: Our group's experiment A-2 data plotted with a best fit line and the theoretical behavior according to Charles's Law.

Based on the R^2 value of 0.995 for the best fit line to our group's data for Charles's Law, a linear fit was best for the experimental data. From visual inspection, it can be seen that again the theoretical model has a larger slope than the experimental data. Also, it can be seen that the data points for the hottest temperature don't fall near the ideal gas model fit like the lower two temperature points do. This could be due to error in the digital thermometer or error in reading the height in the piston.

To plot Boyle's Law (See Figure 4 below), volume was found by summing the volume from the piston (which varied) with the volume of the tubing and the volume of the aluminum cylinder. Then, the inverse of volume was taken to plot against. To find pressure, the mass placed on the piston was added to the mass of the piston. Force was calculated from the mass by multiplying the mass values by 9.81. The force was divided by the area of the piston, giving the different pressures from the weights.

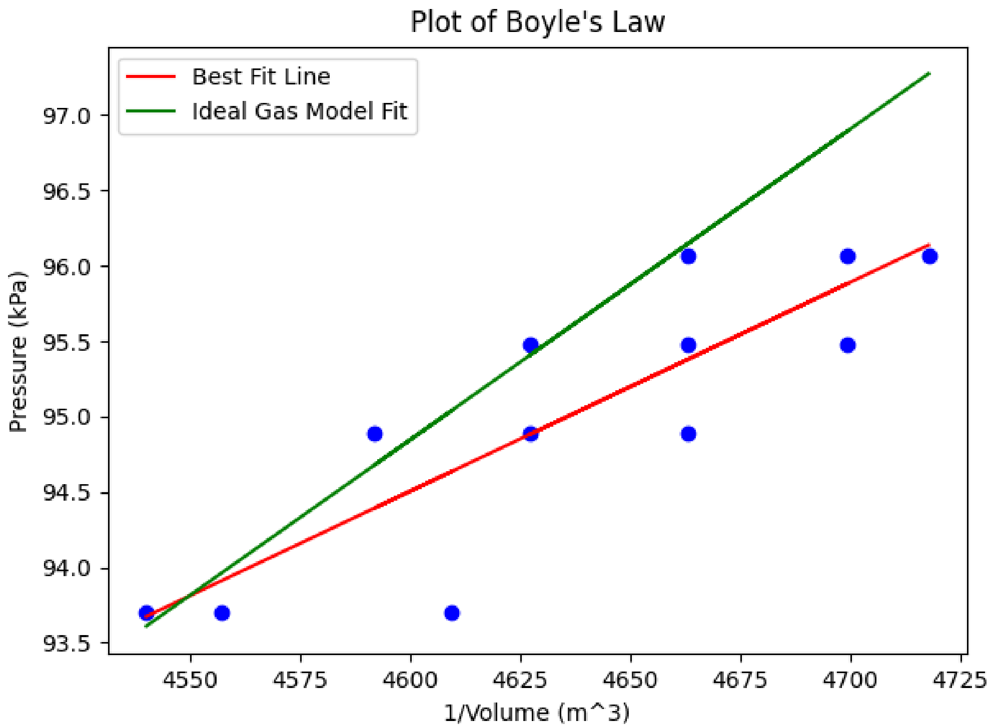


Figure 4: The data from our group's experiment A-3 plotted with a best fit line and the theoretical behavior according to Boyle's Law.

The R^2 value for the best fit line to the experimental data is 0.526. This indicates that there is error in the experiment. Sources of error could include human error when reading the piston height. The error from non-exact piston height readings is enhanced after manipulating the data to become an inverse volume reading. Also, as the volume is a sum of the volume of the tubing, the volume of the aluminum cylinder, and the volume from the piston. Error in any of these readings could also create errors in the final plot. Even though the R^2 value is low, upon visual inspection it can be seen that the data still follows the theoretical trendline.

E. Experiment B - Thermal Cycle

1.1 Volume Calculations

Fixed Volume. The fixed volume is composed of:

- **A tube** with length $L_{\text{tube}} = 304.8\,\text{mm}$ and diameter $d_{\text{tube}} = 3.175\,\text{mm}$. Its volume is calculated by

$$V_{\text{tube}} = \pi \left(\frac{d_{\text{tube}}}{2}\right)^2 L_{\text{tube}} = \pi \left(\frac{3.175}{2}\right)^2 (304.8) \approx 2413.194\,\text{mm}^3.$$

- **A cylinder** with *radius* $r_{\text{cyl}} = 20\,\text{mm}$ and height $H_{\text{cyl}} = 152.2\,\text{mm}$. Its volume is

$$V_{\text{cyl}} = \pi r_{\text{cyl}}^2 H_{\text{cyl}} = \pi (20)^2 (152.2) \approx 191511.488\,\text{mm}^3.$$

Thus, the total fixed volume is

$$V_{\text{fixed}} = V_{\text{tube}} + V_{\text{cyl}} \approx 2413.194 + 191511.488 \approx 193924.68\,\text{mm}^3.$$

Variable Volume (Expansion Chamber). The expansion chamber has a diameter of 32.5 mm, so its cross-sectional area is

$$A_{\text{chamber}} = \pi \left(\frac{32.5}{2}\right)^2 \approx 829.6\,\text{mm}^2.$$

We define a baseline reading of 40 mm at ambient conditions. For any measured piston height x (in mm), the extra (or reduced) volume is

$$V_{\text{variable}} = A_{\text{chamber}}\,(x - 40).$$

Thus, the total volume at a given piston reading x is

$$V_{\text{total}}(x) = V_{\text{fixed}} + V_{\text{variable}} = 191511.488 + 829.6\,(x - 40) \quad (\text{in mm}^3).$$

Using the average piston readings:

$$\begin{aligned}
x_a = 25\,\text{mm}: &\quad V_a &&\approx 191511.488 + 829.6\,(25 - 40) \approx 181481.030\,\text{mm}^3,\\
x_b = 17.67\,\text{mm}: &\quad V_b &&\approx 191511.488 + 829.6\,(17.67 - 40) \approx 175397.743\,\text{mm}^3,\\
x_c = 63.33\,\text{mm}: &\quad V_c &&\approx 191511.488 + 829.6\,(63.33 - 40) \approx 213281.198\,\text{mm}^3,\\
x_d = 68.67\,\text{mm}: &\quad V_d &&\approx 191511.488 + 829.6\,(68.67 - 40) \approx 217706.160\,\text{mm}^3.
\end{aligned}$$

2 Thermodynamic Process Calculations and Results

In our experimental cycle the working gas undergoes two types of processes:

2.1 Isothermal Processes

For an isothermal process the temperature remains constant so that the change in internal energy is zero,

$$\Delta U = 0.$$

By the first law of thermodynamics,

$$\Delta U = Q - W,$$

which immediately implies

$$Q = W.$$

For our calculations we assume that the work done is given by

$$W = p\,\Delta V,$$

where p is the (average) pressure and ΔV is the change in volume. Thus, for the isothermal processes we have

$$W_{\text{iso}} = p\,\Delta V \quad \text{and} \quad Q_{\text{iso}} = W_{\text{iso}}.$$

In our cycle, the processes $a \to b$ and $c \to d$ are treated as isothermal.

2.2 Isobaric Processes

For a constant-pressure (isobaric) process the work done is given by

$$W = p\,\Delta V,$$

1.2 Pressure Calculations

The pressure inside the chamber is determined by the force due to the weights and the ambient atmospheric pressure. The pressure from the applied weight is given by

$$p_{\text{weight}} = \frac{F}{A_{\text{piston}}},$$

where $F = m\,g$ (with $g = 9.81\,\text{m/s}^2$) and A_{piston} is the area of the piston. Since the piston and the expansion chamber share the same cross-sectional area,

$$A_{\text{piston}} = A_{\text{chamber}} = 829.6\,\text{mm}^2 = 829.6 \times 10^{-6}\,\text{m}^2 \approx 8.296 \times 10^{-4}\,\text{m}^2.$$

The ambient (room) pressure is measured as 736.5 mm Hg. Converting to Pascals:

$$p_{\text{atm}} = 736.5 \times 133.322 \approx 98192\,\text{Pa} \approx 98.192\,\text{kPa}.$$

For points **a** and **d** (no additional weight), only the piston mass contributes. With $m_{\text{p}} = 35\,\text{g} = 0.035\,\text{kg}$,

$$F_{a,d} = 0.035\,\text{kg} \times 9.81\,\text{m/s}^2 \approx 0.343\,\text{N},$$

$$p_{\text{weight}}^{a,d} = \frac{0.343}{8.296 \times 10^{-4}} \approx 413.9\,\text{Pa} \approx 0.414\,\text{kPa}.$$

Thus, the absolute pressure is

$$p_{a,d} = p_{\text{atm}} + 0.414 \approx 98.192 + 0.414 \approx 98.606\,\text{kPa}.$$

For points **b** and **c** an extra 200 g is added. Thus,

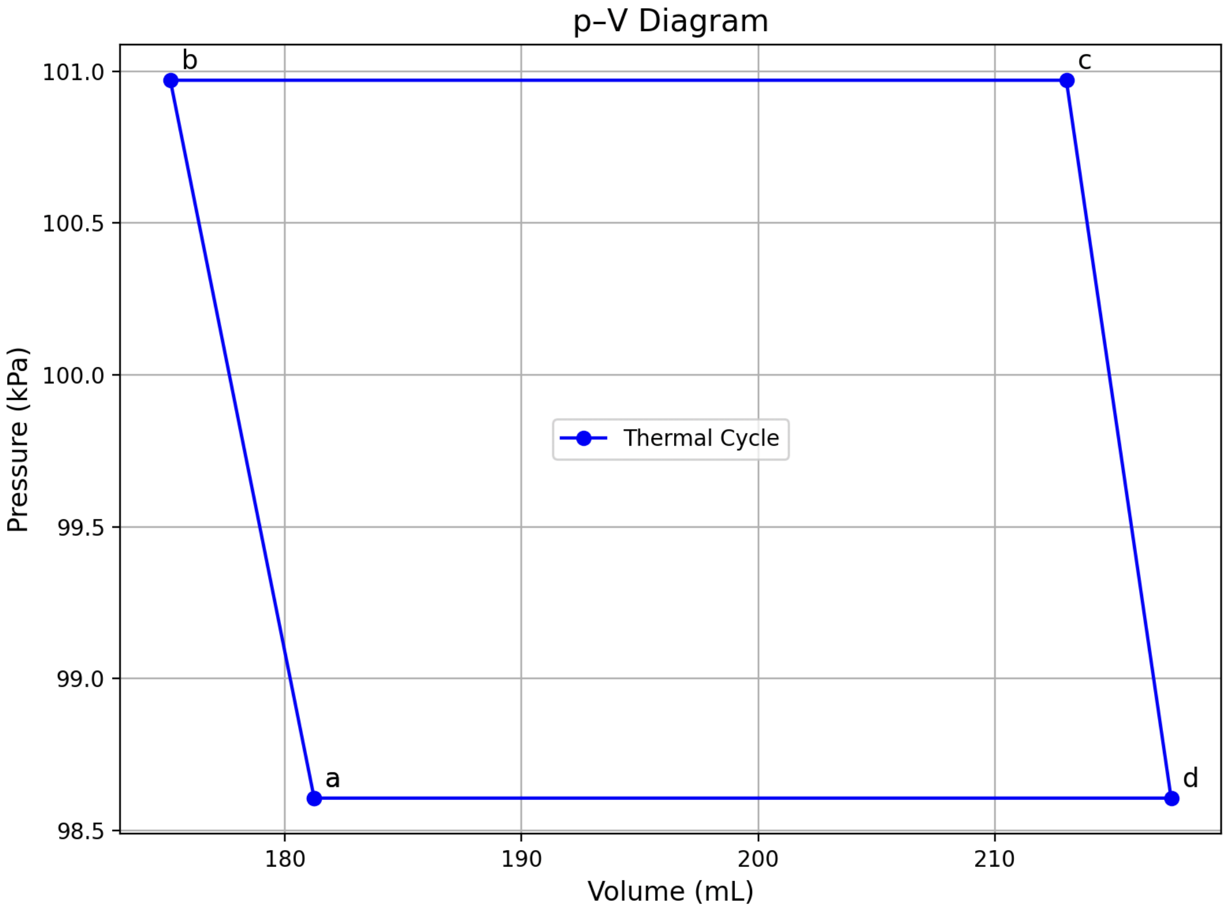
$$m_{\text{total}} = 0.035 + 0.200 = 0.235\,\text{kg},$$

$$F_{b,c} = 0.235\,\text{kg} \times 9.81\,\text{m/s}^2 \approx 2.305\,\text{N},$$

$$p_{\text{weight}}^{b,c} = \frac{2.305}{8.296 \times 10^{-4}} \approx 2778\,\text{Pa} \approx 2.778\,\text{kPa}.$$

Then,

$$p_{b,c} = p_{\text{atm}} + 2.778 \approx 98.192 + 2.778 \approx 100.970\,\text{kPa}.$$



(**Figure 5:** p-V Diagram of Thermal Cycle)

From the previous calculations, a pV diagram is able to be plotted (See Figure 5 above). Point A represents the unweighted submersion of the cylinder in cold water, point B is the weighted (200g) submersion of the cylinder in cold water, point C is the weighted submersion of the cylinder in hot water, and point D is the unweighted submersion of the cylinder in hot water.

F. Calculations

2 Thermodynamic Process Calculations and Results

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$$\Delta U = 0.$$

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$$W_{\text{iso}} = p\,\Delta V \quad \text{and} \quad Q_{\text{iso}} = W_{\text{iso}}.$$

In our cycle, the processes $a \to b$ and $c \to d$ are treated as isothermal.

2.2 Isobaric Processes

For a constant-pressure (isobaric) process the work done is given by

$$W = p\,\Delta V,$$

where the pressure p remains constant throughout the process. In addition, the change in the internal energy for an ideal gas is calculated as

$$\Delta U = m\, c_p\, \Delta T,$$

with:

- m the mass of air in the entire apparatus (cylinder, tube, and chamber),
- c_p the specific heat capacity at constant pressure, and
- ΔT the temperature change.

Then, applying the first law,

$$Q = \Delta U + W.$$

In our cycle the processes $b \to c$ (heating) and $d \to a$ (cooling) are isobaric.

2.3 Mass of Air in the Cycle

The mass of air is computed from the ideal gas law:

$$pV = nRT \quad \Longrightarrow \quad n = \frac{pV}{RT},$$

and hence,

$$m = nM = \frac{pV\,M}{RT}.$$

For our ambient conditions ($p = 98.192\,\mathrm{kPa}$, $T = 294.35\,\mathrm{K}$) and using $M = 28.97\,\mathrm{g/mol}$, this reduces to

$$m \approx 1162.386\, V,$$

with V in m^3 and m in grams.

2.4 Results

The following table summarizes the calculated work and heat (all in Joules) for each process in the cycle over three trials. For the isothermal processes (processes $a \to b$ and $c \to d$) we use the formula

$$W = p\,\Delta V,$$

with $Q = W$, and for the isobaric processes (processes $b \to c$ and $d \to a$) we use

$$W = p\,\Delta V \quad \text{and} \quad Q = \Delta U + W \quad \text{with} \quad \Delta U = m\,c_p\,\Delta T.$$

Table 1: Calculated Work and Heat for Each Process (in Joules)

Trial	W_{ab}	Q_{ab}	W_{bc}	Q_{bc}	W_{cd}	Q_{cd}	W_{da}	Q_{da}	W_{net}	Q_{net}
1.0	-0.579	-0.579	3.937	18.283	0.414	0.414	-3.681	-18.027	0.090	0.090
2.0	-0.579	-0.579	3.853	18.199	0.414	0.414	-3.599	-17.945	0.088	0.088
3.0	-0.662	-0.662	3.686	18.031	0.497	0.497	-3.436	-17.781	0.084	0.084

3.1 Efficiency Calculations

- **Trial 1:**
  - $W_{\text{net}} = 0.09\,\text{J}$,
  - $Q_{bc} = 18.283\,\text{J}$ and $Q_{cd} = 0.414\,\text{J}$ so that

  $$Q_{\text{in}} = 18.283 + 0.414 = 18.697\,\text{J}.$$

  Thus, the efficiency is

  $$\eta = \frac{0.09}{18.697} \approx 0.00482 \quad \text{or} \quad 0.482\%.$$

- **Trial 2:**
  - $W_{\text{net}} = 0.088\,\text{J}$,
  - $Q_{bc} = 18.199\,\text{J}$ and $Q_{cd} = 0.414\,\text{J}$ so that

  $$Q_{\text{in}} = 18.199 + 0.414 = 18.613\,\text{J}.$$

  Thus,

  $$\eta = \frac{0.088}{18.613} \approx 0.00473 \quad \text{or} \quad 0.473\%.$$

- **Trial 3:**
  - $W_{\text{net}} = 0.084\,\text{J}$,
  - $Q_{bc} = 18.031\,\text{J}$ and $Q_{cd} = 0.497\,\text{J}$ so that

  $$Q_{\text{in}} = 18.031 + 0.497 = 18.528\,\text{J}.$$

  Thus,

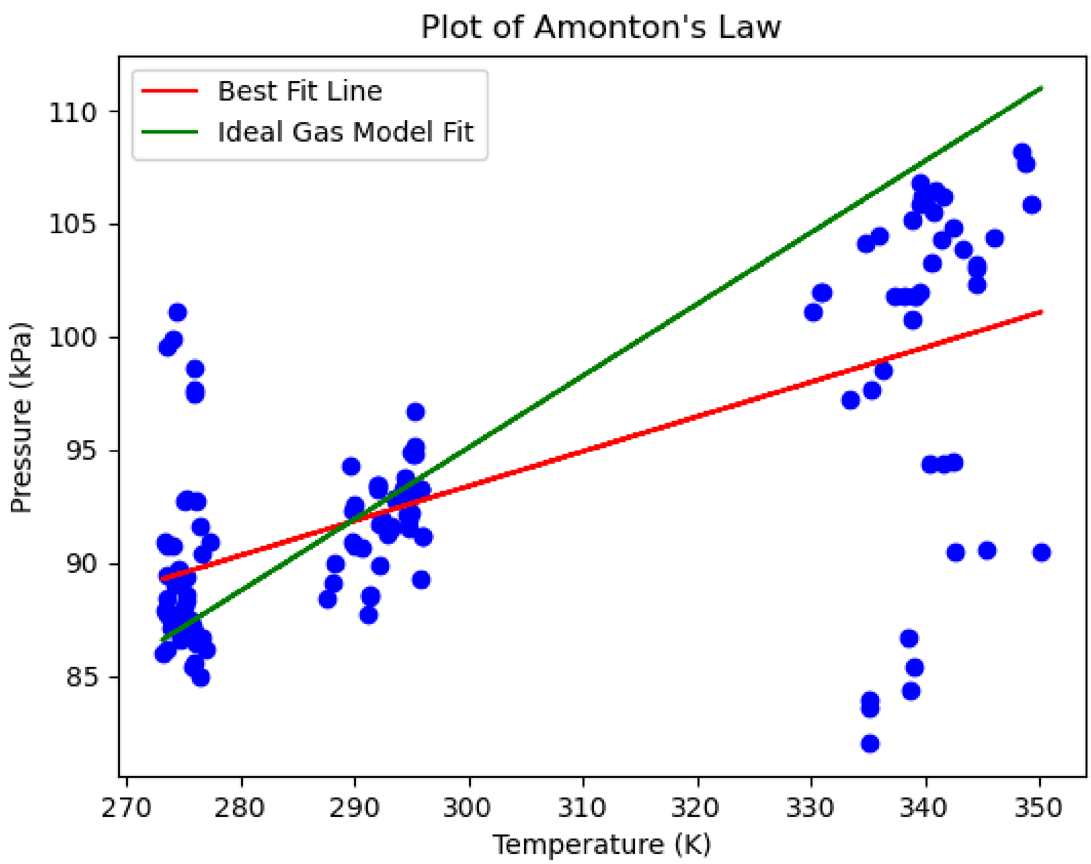
  $$\eta = \frac{0.084}{18.528} \approx 0.00454 \quad \text{or} \quad 0.454\%.$$

The final efficiency average is **0.47%.** The efficiency is expected to be very low. In our experiment the net work output is only a few tenths of a Joule while the heat input is on the order of 18 Joules, giving an efficiency of less than 1%. In our calculations, we found efficiencies of roughly 0.45–0.48%. This low efficiency is not surprising because the experiment is designed to demonstrate thermodynamic processes rather than to operate as an efficient engine.

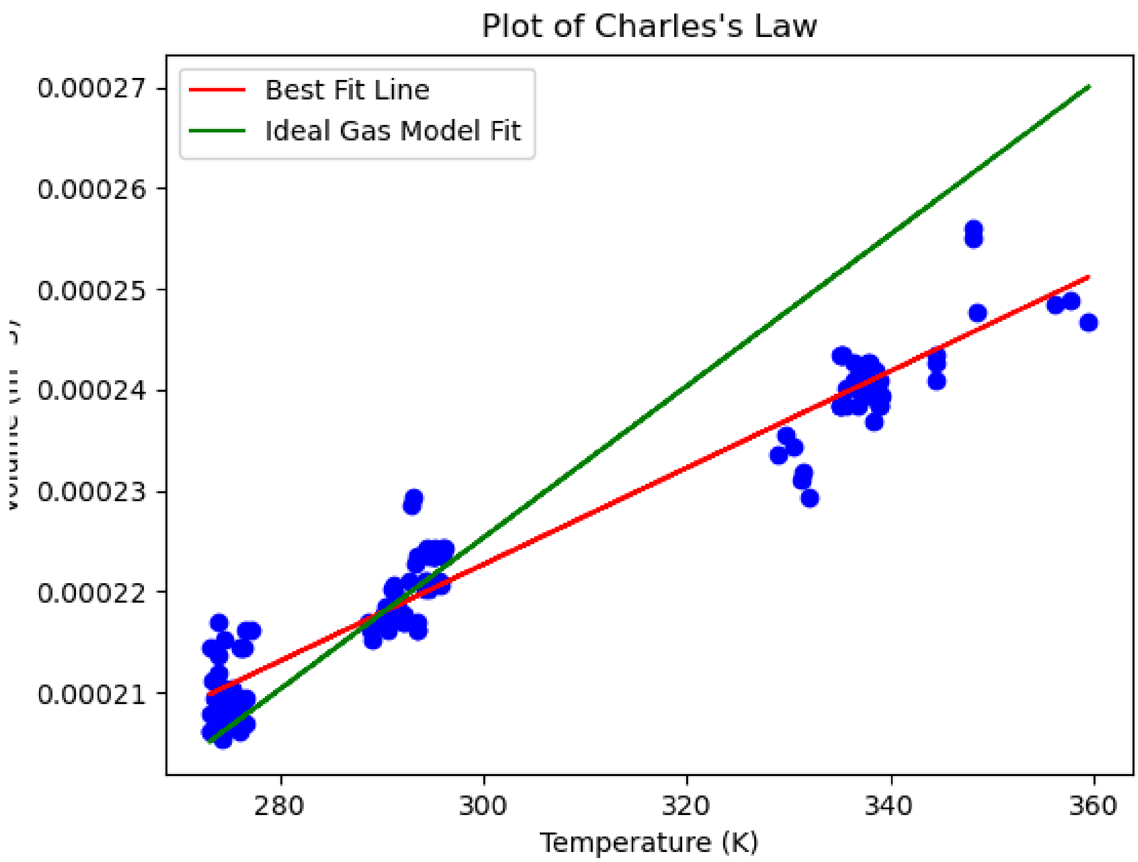
G. Conclusion: Experimental Inconsistencies and Findings

The final efficiency average of 0.47% indicates that there were some experimental inconsistencies. Thermal inconsistencies can be explained by how each cylinder was not submerged for the same amount of time between trials and the fact that thermal equilibrium between the air and each bath was likely not achieved in the short time that the cylinder was submerged. As a result, our calculated Q_{in} is much larger than the actual Q_{in} that the system experienced and explains why our calculated efficiency was extremely low. Similar to Experiment A, it can be assumed that pressure loss due to leaks in the setup and volume loss due to friction in the piston affected our findings by lowering our calculated W_{net}, thus once again lowering our calculated efficiency. Overall, it can be stated that experimental inconsistencies raised our calculations of Q_{in} and lowered those of W_{net}, consequently affecting our findings by significantly lowering the calculated efficiency. Outliers in experimental measurements can also be seen clearly in the graphs of class data plotting Amonton's, Charles's, Boyle's Laws (See Plots 1-3).

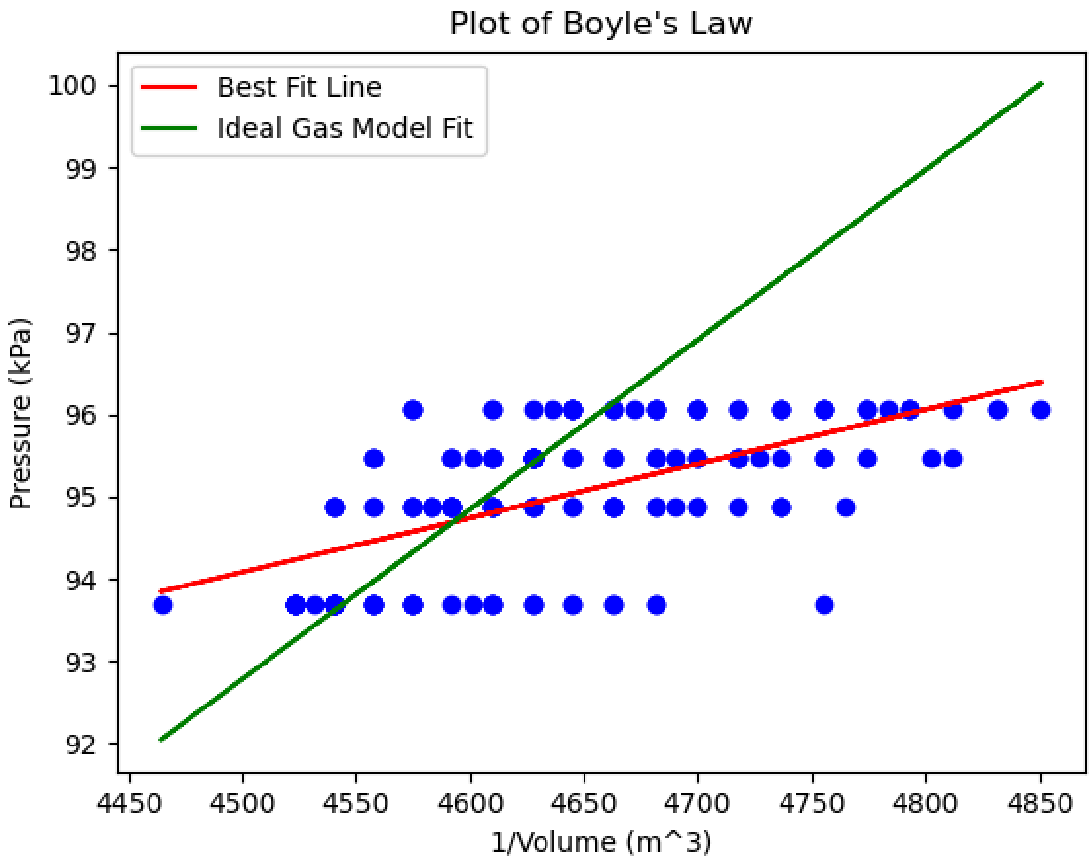
H. Appendix



(Plot 1 - Amonton's Law Class Data)



(Plot 2 - Charles's Law Class Data)



(Plot 3 - Boyle's Law Class Data)

A1 (Amonton's Law)	Pressure in Hot	Temp in Hot	Pressure in RT	Temp in RT	Pressure in Ice	Temp in Ice
Trial 1	11.07 kPa	73 C	-4.85 kPa	14.5 C	-4.9 kPa	0.4 C
Trial 2	11.5 kPa	69.4 C	-4.16 kPa	14.9 C	-6.22 kPa	0.7 C
Trial 3	12.61 kPa	67 C	-3.28 kPa	15.1 C	-5.75 kPa	0.7 C

(Chart 1 - Amonton's Law Group Data)

A2 (Charles's Law)	Height in Hot	Temp in Hot	Height in RT	Temp in RT	Height in Ice	Temp in Ice
Trial 1	57 mm	64.3 C	30 mm	15.5 C	19 mm	0 C
Trial 2	56 mm	63.6 C	29 mm	15.8 C	17 mm	0 C
Trial 3	56 mm	62.5 C	28 mm	16 C	17 mm	0.3 C

(Chart 2 - Charles's Law Group Data)

A3 (Boyle's Law)	Height at No Weight	Height at 100g	Height at 150g	Height at 200g
Trial 1	34 mm	31 mm	29 mm	27 mm
Trial 2	33 mm	29 mm	27 mm	25 mm
Trial 3	30 mm	27 mm	25 mm	24 mm

(Chart 3 - Boyle's Law Group Data)

B (Thermal Cycle)	Height at point a	Height at point b	Height at point c	Height at point d	Height at point a'
Trial 1	26 mm	19 mm	66 mm	71 mm	25 mm
Trial 2	25 mm	18 mm	64 mm	69 mm	24 mm
Trial 3	24 mm	16 mm	60 mm	66 mm	21 mm

(Chart 4 - Thermal Cycle Group Data)

(Code 1 - Python code used to graph Amonton's, Charles's, and Boyle's Laws for Group and Class Data)

```
import numpy as np

import matplotlib.pyplot as plt


def mmcubed_to_mcubed(V_mm):

    V_m = V_mm*10**-9

    return V_m


def C_to_K(T_C):

    T_K= 273.15 + T_C

    return T_K


def g_to_kg(m_g):

    m_kg=m_g*10**-3

    return m_kg


def find_mass(V_total, p_atm, R_air):

    T_r = C_to_K(21.2)

    m = (p_atm*V_total)/(R_air*T_r)

    return m


def find_volume(h, a):

    V_mm = h*a

    return V_mm
```

```
def mmsquared_to_msquared(a_mm):
    a_m = a_mm*10**-6
    return a_m


def find_pressure_kPa(m_kg, a):
    f = m_kg*9.81
    p_Pa = f/a
    p_kPa = p_Pa*10**-3
    return p_kPa



def amonton():
    T_c = np.array([73, 69.4, 67, 14.5, 14.9, 15.1, 0.4, 0.7, 0.7])
    p_gauge = np.array([11.07, 11.5, 12.61, -4.85, -4.16, -3.28, -4.9, -6.22, -5.75])
    p_atm = 93.29
    p_kPa = p_gauge + p_atm
    R_air = 0.287

    V_tubing = mmcubed_to_mcubed(791.73)
    V_cylinder = mmcubed_to_mcubed(191260.161)
    V_chamber = mmcubed_to_mcubed(29035.18835)
    V_total = V_tubing+V_cylinder+V_chamber
    m = find_mass(V_total, p_atm, R_air)
```

```
    T_k = C_to_K(T_c)


    slope, intercept = np.polyfit(T_k, p_kPa, 1)

    lsrl = np.polyval([slope, intercept], T_k)


    p_igm = (m*R_air*T_k)/V_total


    plt.scatter(T_k, p_kPa, color='b')

    plt.plot(T_k, lsrl, color='r', linestyle='-', label = 'Best Fit Line')

    plt.plot(T_k, p_igm, color='g', linestyle='-', label='Ideal Gas Model Fit')


    plt.ylabel("Pressure (kPa)")

    plt.xlabel("Temperature (K)")

    plt.title("Plot of Amonton's Law")

    plt.legend(loc='best')

    plt.show()



def charles():

    h_mm = np.array([57, 56, 56, 30, 29, 28, 19, 17, 17])

    T_c= np.array([73, 69.4, 67, 14.5, 14.9, 15.1, 0.4, 0.7, 0.7])

    p_atm = 93.29

    R_air = 0.287


    V_tubing = mmcubed_to_mcubed(791.73)
```

```
V_cylinder = mmcubed_to_mcubed(191260.161)
V_chamber = mmcubed_to_mcubed(29035.18835)
V_total = V_tubing+V_cylinder+V_chamber
m = find_mass(V_total, p_atm, R_air)


T_k = C_to_K(T_c)


a_chamber = 829.5768
V_mm = find_volume(h_mm, a_chamber)
V_m = mmcubed_to_mcubed(V_mm)
Vm_system = V_tubing + V_cylinder + V_m


slope, intercept = np.polyfit(T_k, Vm_system, 1)
lsrl = np.polyval([slope, intercept], T_k)


V_igm = (m*R_air*T_k)/p_atm


plt.scatter(T_k, Vm_system, color='b')
plt.plot(T_k, lsrl, color='r', linestyle='-', label = 'Best Fit Line')
plt.plot(T_k, V_igm, color='g', linestyle='-', label='Ideal Gas Model Fit')


plt.ylabel("Volume (m^3)")
plt.xlabel("Temperature (K)")
plt.title("Plot of Charles's Law")
plt.legend(loc='best')
```

```
    plt.show()


def boyle():
    m_g = np.array([35, 35, 35, 135, 135, 135, 185, 185, 185, 235, 235, 235])
    h_mm = np.array([34, 33, 30, 31, 29, 27, 29, 27, 25, 27, 25, 24])
    p_atm = 93.29
    R_air = 0.287

    V_tubing = mmcubed_to_mcubed(791.73)
    V_cylinder = mmcubed_to_mcubed(191260.161)
    V_chamber = mmcubed_to_mcubed(29035.18835)
    V_total = V_tubing+V_cylinder+V_chamber
    m = find_mass(V_total, p_atm, R_air)

    a_chambermm = 829.5768
    V_mm = find_volume(h_mm, a_chambermm)
    V_m = mmcubed_to_mcubed(V_mm)
    Vm_system = V_tubing + V_cylinder + V_m
    inverse_Vmsystem = 1/Vm_system

    m_kg = g_to_kg(m_g)
    a_chamberm = mmsquared_to_msquared(a_chambermm)
    p_kPa = find_pressure_kPa(m_kg, a_chamberm)
    p_total = p_kPa + p_atm
```

```
    slope, intercept = np.polyfit(inverse_Vmsystem, p_total, 1)

    lsrl = np.polyval([slope, intercept], inverse_Vmsystem)


    T_room = C_to_K(21.1)

    p_igm = (m*R_air*T_room)/Vm_system


    plt.scatter(inverse_Vmsystem, p_total, color='b')

    plt.plot(inverse_Vmsystem, lsrl, color='r', linestyle='-', label = 'Best Fit Line')

    plt.plot(inverse_Vmsystem, p_igm, color='g', linestyle='-', label='Ideal Gas Model Fit')


    plt.ylabel("Pressure (kPa)")

    plt.xlabel("1/Volume (m^3)")

    plt.title("Plot of Boyle's Law")

    plt.legend(loc='best')

    plt.show()



amonton()

charles()

boyle()
```

(Code 2 - Python code used to generate PV diagram)

```
import math
import matplotlib.pyplot as plt

tube_length = 304.8
tube_diameter = 3.175
tube_radius = tube_diameter / 2.0
cyl_radius = 20.0
cyl_height = 152.2

tube_volume = math.pi * (tube_radius ** 2) * tube_length
cyl_volume = math.pi * (cyl_radius ** 2) * cyl_height

fixed_volume = tube_volume + cyl_volume

print("Tube Vol (mm^3):", tube_volume)
print("Cylinder Vol (mm^3):", cyl_volume)
print("Fixed Vol (mm^3):", fixed_volume)


chamber_diameter = 32.5
chamber_radius = chamber_diameter / 2.0
baseline_height = 40.0
chamber_area = math.pi * (chamber_radius ** 2)


def total_volume(piston_reading):
  variable_volume = chamber_area * (piston_reading - baseline_height)
  return fixed_volume + variable_volume

piston_a = 25.0
piston_b = 17.67
piston_c = 63.33
piston_d = 68.67


vol_a = total_volume(piston_a)
vol_b = total_volume(piston_b)
vol_c = total_volume(piston_c)
vol_d = total_volume(piston_d)
```

```
vol_a_ml = vol_a / 1000.0
vol_b_ml = vol_b / 1000.0
vol_c_ml = vol_c / 1000.0
vol_d_ml = vol_d / 1000.0

print("\nTotal Volumes (mL):")
print("Point a: {:.3f} mL".format(vol_a_ml))
print("Point b: {:.3f} mL".format(vol_b_ml))
print("Point c: {:.3f} mL".format(vol_c_ml))
print("Point d: {:.3f} mL".format(vol_d_ml))

p_atm = 736.5 * 133.322
p_atm_kPa = p_atm / 1000.0
A_piston = chamber_area * 1e-6

def pressure_from_mass(mass_kg):
  F = mass_kg * 9.81
  return F / A_piston



p_weight_ad = pressure_from_mass(0.035)
p_weight_ad_kPa = p_weight_ad / 1000.0

p_weight_bc = pressure_from_mass(0.035 + 0.200)
p_weight_bc_kPa = p_weight_bc / 1000.0

p_a = p_atm_kPa + p_weight_ad_kPa
p_b = p_atm_kPa + p_weight_bc_kPa
p_c = p_atm_kPa + p_weight_bc_kPa
p_d = p_atm_kPa + p_weight_ad_kPa

print("\nPressures (kPa):")
print("Points a and d: {:.3f} kPa".format(p_a))
print("Points b and c: {:.3f} kPa".format(p_b))

pressures (in kPa) for the cycle.
volumes = [vol_a_ml, vol_b_ml, vol_c_ml, vol_d_ml, vol_a_ml]
pressures = [p_a, p_b, p_c, p_d, p_a]
point_labels = ['a', 'b', 'c', 'd', 'a']
```

```python
plt.figure(figsize=(8, 6))
plt.plot(volumes, pressures, marker='o', linestyle=':', color='blue', label='Thermal Cycle')
for i, (vol, pres) in enumerate(zip(volumes, pressures)):
    plt.annotate(point_labels[i], (vol, pres), textcoords="offset points", xytext=(5,5), fontsize=12)

plt.xlabel("Volume (mL)", fontsize=12)
plt.ylabel("Pressure (kPa)", fontsize=12)
plt.title("p–V Diagram", fontsize=14)
plt.grid(True)
plt.legend()
plt.tight_layout()
plt.show()
```