Equation of State for an Ideal Gas

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1. Results

Table 1 contains various quantities, both measured and given, that were relevant to the analysis. They are collected in a table to assist with lookup.

T is the temperature of the room measured using a digital thermometer. The temperature was initially measured as 71 °F, then converted to kelvins as show in Equation 1.

$$T = \left(\frac{5}{9}(71 - 32) + 273.15\right)\,\mathrm{K} = 294.82\,\mathrm{K} \tag{1}$$

P_0 is the atmospheric pressure measured using a digital barometer. The pressure was initially measured as 28.93 in Hg, then converted to pascals as shown in Equation 2.

$$P_0 = (28.93\,\mathrm{in\ Hg}) \cdot \frac{25.4\,\mathrm{mm\ Hg}}{1\,\mathrm{in\ Hg}} \cdot \frac{101\,325\,\mathrm{Pa}}{760\,\mathrm{mm\ Hg}} = 97\,968\,\mathrm{Pa} \tag{2}$$

m_p is the mass of the piston & platform, taken from the label on the gas law apparatus. D is the piston diameter, taken from the label on the gas law apparatus.

Some constants that were needed in the analysis were the universal gas constant R and the acceleration due to gravity g. Both values were taken from the lab manual. Note that the value of g used is for the science building, where the experiment was performed.

Table 1: Miscellaneous Quantities

Quantity	Value
T	294.82 K
P_0	97 968 Pa
m_p	35.0 g
D	32.5 mm
R	$8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$
g	$9.7955\,\mathrm{m\,s^{-2}}$

Table 2 contains the measurements of the mass put on the piston platform m and the resulting length of the column of air in the cylinder L. 7 samples were collected all together. The piston-holding thumbscrew was used to keep the piston in place at the top of the cylinder while connecting the cylinder to the 2-liter bottle. After the connection was made, the thumbscrew was released and the piston dropped down slightly. If the piston continued to slide down, without stopping, it would have indicated that air was escaping from the cylinder, tubing, or bottle. After finding the location of the leak and patching it, the piston would need to be reset to its highest position and the bottle reconnected. However, a small amount of air leakage was unavoidable. Thus, care was taken to quickly measure L after placing the slotted masses on the platform, only waiting a few seconds for the reading to stabilize before moving on to the next sample.

Table 2: Samples of Mass Added and Air Column Length

Sample	m (g)	L (mm)
1	0	94
2	20	87
3	40	80
4	60	72
5	80	65
6	100	57
7	120	48

2. Analysis

The cross-sectional area of the cylinder A is given by Equation 3. Substituting in the diameter D yields an area of $0.000\,830\,\mathrm{m}^2$, as shown in Equation 4.

$$A = \pi \left(\frac{D}{2} \right)^2 \tag{3}$$

$$A = \pi \left(\frac{32.5\,\mathrm{mm}}{2} \cdot \frac{1\,\mathrm{m}}{1000\,\mathrm{mm}} \right)^2 = 0.000\,830\,\mathrm{m}^2 \tag{4}$$

Table 3 contains various quantities involved in finding the pressure of the gas P and its reciprocal P^{-1} at each sample. M is the combined mass of the piston, platform, and the slotted masses put on the platform, calculated using Equation 5.

$$M = m + m_p \tag{5}$$

Sample Calculation (Sample 2 M)

$$M = (20\,\mathrm{g}) + (35.0\,\mathrm{g}) \tag{6}$$

$$M = 55\,\mathrm{g} \tag{7}$$

F_g is the force of gravity on the combined mass M, calculated using equation Equation 8.

$$F_g = Mg \tag{8}$$

Sample Calculation (Sample 2 F_g)

$$F_g = \left(55\,\mathrm{g} \cdot \frac{1\,\mathrm{kg}}{1000\,\mathrm{g}}\right)(9.7955\,\mathrm{m\,s^{-2}}) \tag{9}$$

$$F_g = 0.54\,\mathrm{N} \tag{10}$$

P is the total pressure exerted on the gas, calculated using equation Equation 11. P^{-1} is the reciprocal of the pressure P, calculated using equation Equation 12.

$$P = P_0 + \frac{F_g}{A} \tag{11}$$

$$P^{-1} = \frac{1}{P} \tag{12}$$

Sample Calculation (Sample 2 P & P^{-1})

$$P = (97\,968\,\mathrm{Pa}) + \frac{(0.54\,\mathrm{N})}{(0.000\,830\,\mathrm{m^2})} \tag{13}$$

$$P = 98\,618\,\mathrm{Pa} \tag{14}$$

$$P^{-1} = \frac{1}{(98\,618\,\mathrm{Pa})} \tag{15}$$

$$P^{-1} = 1.0140 \times 10^{-5}\,\mathrm{Pa^{-1}} \tag{16}$$

Table 3: Quantities Calculated to Find Pressure and its Reciprocal

Sample	M (g)	F_g (N)	P (Pa)	P^{-1} ($\mathrm{Pa^{-1}}$)
1	35	0.34	98 381	1.0165×10^{-5}
2	55	0.54	98 618	1.0140×10^{-5}
3	75	0.73	98 854	1.0116×10^{-5}
4	95	0.93	99 090	1.0092×10^{-5}
5	115	1.13	99 326	1.0068×10^{-5}
6	135	1.32	99 562	1.0044×10^{-5}
7	155	1.52	99 798	1.0020×10^{-5}

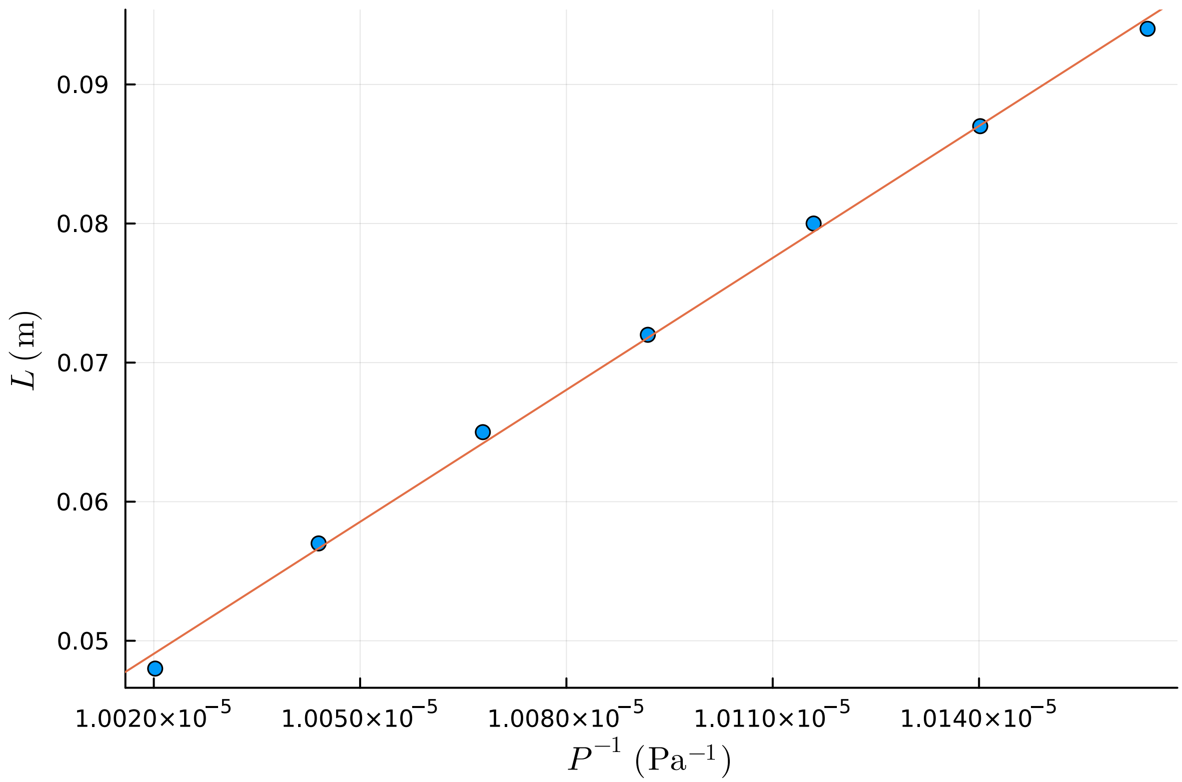

Figure 1: Response of the Enclosed Gas to Additional Force

$$L = (316\,223\,\mathrm{m\,Pa})P^{-1} + (-3.119\,\mathrm{m}) \tag{17}$$

Figure 1 plots L versus P^{-1}. As more mass m was put on the piston platform, the pressure P of the enclosed gas increased, thereby decreasing the reciprocal of the pressure P^{-1}. At the same time, the height of the column of air in the cylinder L decreased.

Boyle's law states that if a fixed amount of gas is kept at a constant temperature, then its volume and absolute pressure will be inversely proportional. In the experiment, the temperature T and the moles of gas enclosed n were both kept roughly constant. Thus, the results of this experiment can be used to support or contradict Boyle's law.

The ideal gas law, which implies Boyle's law, is given by Equation 18.

$$PV = nRT \tag{18}$$

In the experiment, the volume of the enclosed gas V consists of the volume of air in the cylinder LA plus the volume of air in the bottle and hose V_0. That combined volume V is given by Equation 19.

$$V = V_0 + LA \tag{19}$$

Combining Equation 18 and Equation 19 and rearranging yields Equation 22.

$$P(V_0 + LA) = nRT \tag{20}$$

$$PLA = nRT - PV_0 \tag{21}$$

$$L = \underbrace{\frac{nRT}{A}}_{\text{slope}} P^{-1} \quad \underbrace{-\frac{V_0}{A}}_{\text{y-intercept}} \tag{22}$$

Notice that L is linear with respect to P^{-1}. The slope of such a plot is given by Equation 23, and the y-intercept is given by Equation 24. Since the data in Figure 1 lie on a straight line as predicted, the experiment verifies Boyle's law.

$$\text{slope} = \frac{nRT}{A} \tag{23}$$

$$\text{y-intercept} = -\frac{V_0}{A} \tag{24}$$

The equation for the line of best fit for the data is given by Equation 17. The slope has a value of 316 223 m Pa, and the y-intercept has a value of −3.119 m.

Rearranging Equation 23 yields Equation 25, which can be used to find the moles of gas enclosed n. Substituting in values gives 0.107 mol, as shown in Equation 26.

$$n = \frac{\text{slope} \cdot A}{RT} \tag{25}$$

$$n = \frac{(316\,223\ \text{m Pa})(0.000\,830\ \text{m}^2)}{(8.314\ \text{J mol}^{-1}\ \text{K}^{-1})(294.82\ \text{K})} = 0.107\ \text{mol} \tag{26}$$

Rearranging Equation 24 yields Equation 27, which can be used to find the volume of the 2-liter bottle and tubing V_0. Substituting in values gives 2.59 L, as shown in Equation 28. This volume, slightly larger than 2 L, is consistent with the fact that a 2-liter bottle was used with a small connecting tube.

$$V_0 = -(\text{y-intercept})A \tag{27}$$

$$V_0 = -(-3.119\ \text{m})(0.000\,830\ \text{m}^2) \cdot \frac{1000\ \text{L}}{1\ \text{m}^3} = 2.59\ \text{L} \tag{28}$$

Table 4 provides a summary of all the calculated quantities that were not made for a single sample.

Table 4: Summary of Calculated Quantities

Quantity	Value
A	0.000 830 m^2
slope	316 223 m Pa
y-intercept	−3.119 m
n	0.107 mol
V_0	2.59 L