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An equipment design to verify Boyle’s law

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Abstract. A portable and user-friendly tool was designed and built to measure pressure and temperature of the air with variable volumes. An Arduino board programmed to read pressure and temperature was installed in a closed container consisting of a syringe connected to a tightly sealed box. The volume of the air in the system can be altered by moving the piston. By considering the air as an ideal gas, the pressure and the volume readings allow a direct verification of Boyle’s law at various temperatures. The gas constant can be deduced and it is found to be $8.32 \pm 0.04 \text{ J mol}^{-1} \text{ K}^{-1}$.

1. Introduction

Boyle’s law states that the gas pressure is inversely proportional to the gas volume at constant temperature. This law follows the ideal gas law which summarizes a relationship between pressure, volume, temperature and the number of moles of the gas. The concept of Boyle’s law is usually taught in high school physics and chemistry classes and experimental verification of the law is an essential part of the lesson. Equipment has been designed and constructed to test Boyle’s law. A common idea of the design is that a gas is confined in a closed container where the gas pressure can be varied by changing the volume of the container. Pressure measurement can be done by several methods. A simple one includes a closed glass tube within which a column of mercury is trapped [1]. There are air columns above and below the mercury and the air pressure can be varied by changing the orientation of the glass tube. In this case, pressure of the air results from the weight of the mercury column above it. Another design involves a syringe containing air and vertically attached to a digital scale which reads how much force is applied on the piston [2]. Therefore, pressure can be deduced from the scale reading. A manometer can be used to read the pressure [3]. However, these methods involve the use of liquid substances such as mercury which is hazardous and water which may be spilled and cause a mess. Scale reading is an indirect pressure measurement. A direct and yet simple way to measure the gas is required.

The advent of Arduino board makes many measurements accessible in the physics classroom [4]. The board can be set to read pressure and temperature of air in a syringe. Moving the piston of the syringe changes the air volume and hence the air pressure in the syringe. This equipment design enables a straightforward verification of Boyle’s law at various temperatures and a practical test of ideal gas equation. Moreover, the gas constant can be obtained.
2. Apparatus design

Figure 1 shows the equipment design. A syringe is connected via a tube to a tightly sealed box which contains an Arduino board. The board run by 9-V DC supply is programmed to display pressure and temperature readings on the panel as shown in figure 2. There is a valve to let the air in and it can be securely closed so that the amount of air in the container is constant. With this setup, the volume of the air in the container is the volume of the syringe together with that of the tube and the space in the box. After closing the valve, the volume can be varied by pushing the piston, changing the air pressure and temperature.

3. Experiments and results

3.1. p-V diagrams

The air occupies a variable volume $V$ read by the scale on the syringe and a fixed volume $V_0$ in the tube and the box. By assuming ideal gas condition, the equation of state of the air inside reads

$$p(V + V_0) = nRT,$$  

where $p$ is the air pressure in the system, $n$ is the number of moles, $R$ is gas constant and $T$ is absolute temperature.

The experimental setup was prepared at room temperature of 25°C. The piston was pulled out until $V = 50$ cm$^3$ and the valve was closed. The corresponding pressure was recorded. The piston was then slowly pushed, reducing the volume of the air and keeping the temperature the same; the subsequent pressure readings were taken. By keeping the valve closed, the amount of air in the system was unchanged. The experiment was repeated outside with the temperature of 30°C and in a freezer with the temperature of 15°C. Figure 3 shows the isothermal graphs at these temperatures, which follow the usual hyperbolic curves.

Equation (1) can be rearranged into

$$V = \frac{nRT}{p} - V_0,$$  

Figure 1. Equipment design.  
Figure 2. Pressure and temperature display.
which represents a linear equation relating $V$ and $1/p$. Figure 4 illustrates this linearity at different temperatures with the same number of moles of the air. The graphs are fitted with linear trendlines with the corresponding equations shown. The intercepts on the vertical axis imply on average that $V_0 = 33.0 \pm 0.7$ cm$^3$ which is the volume of the tube and the space in the box. The linear relationship verifies Boyle’s law.

3.2. Determination of gas constant
The measurement of air pressure at different volumes allows calculation of the gas constant $R$. The number of moles $n$ is kept constant throughout the experiments, which can be calculated by

$$n = \frac{\rho(V + V_0)}{m_A}, \quad (3)$$

where $\rho$ is the density of air, $V + V_0$ is the volume and $m_A$ is the molar mass of the air (dry) which is 29.0 g·mol$^{-1}$. The air density at 25°C and atmospheric pressure is taken to be 1.18 kg·m$^{-3}$ [5]. At this temperature and pressure, the volume of air in the system reads $83.3 \pm 0.3$ cm$^3$ and hence, equation (3) gives $n = (3.39 \pm 0.01) \times 10^{-3}$ mol.

Equation (2) implies that the gas constant $R$ can be obtained from the slope of the graph of $V$ against $1/p$. By taking the slope at 25°C in figure 4 which is $8.40 \pm 0.03$ J, it can be calculated that $R = 8.32 \pm 0.04$ J·mol$^{-1}$·K$^{-1}$.

4. Discussion and conclusion
An Arduino board programmed as a pressure and temperature sensor is installed in a closed container connected to a syringe. The volume of the container can be adjusted by moving the piston. Reading pressure, volume and temperature, this device allows a practical test of the ideal gas equation for the air inside. However, it is easier to maintain a constant temperature of the air in the container by slowly pushing the piston, making the device suitable for the verification of Boyle’s law.

At a fixed temperature, the results show linear relationship between the volume and the reciprocal of pressure. The same trend is seen at different temperatures. By assuming that air behaves like an ideal gas, the gas constant can be obtained and it is calculated to be $8.32 \pm 0.04$ J·mol$^{-1}$·K$^{-1}$. 
References

[1] Hermens R A 1983 *J. Chem. Educ.* **60** 764
[2] Lewis D L 1997 *J. Chem. Educ.* **74** 209
[3] Ivanov D T 2007 *J. Phys. Educ.* **42** 193
[4] Kubínová Š and Šlégr J 2015 *J. Phys. Educ.* **50** 472
[5] Blevins R D 1984 *Applied Fluid Dynamics Handbook* (New York: Van Nostrand Reinhold Co.)