Getting Pumped Up on the Ideal Gas Law

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An important topic in the study of thermodynamics is the ideal gas law, $PV = nRT$, and experiments that test this law are common in student laboratories.[1] Usually in classroom experiments, the number of moles n in the sample is held fixed. Then, two of the other three variables P, V, and T, are varied, holding the third one constant. However, with very simple equipment it is possible to vary n, keeping V and T constant, thus allowing the student to investigate all the variables in the ideal gas law.

The apparatus is described in Ref. 2 and consists of a plastic soda bottle, a bicycle pump, automobile tire valve, and tire pressure gauge. One pumps up the bottle and measures how much the mass increases, Δm, as well as the increased pressure. We used a two-liter soda bottle, although a football makes a more interesting container.[3]

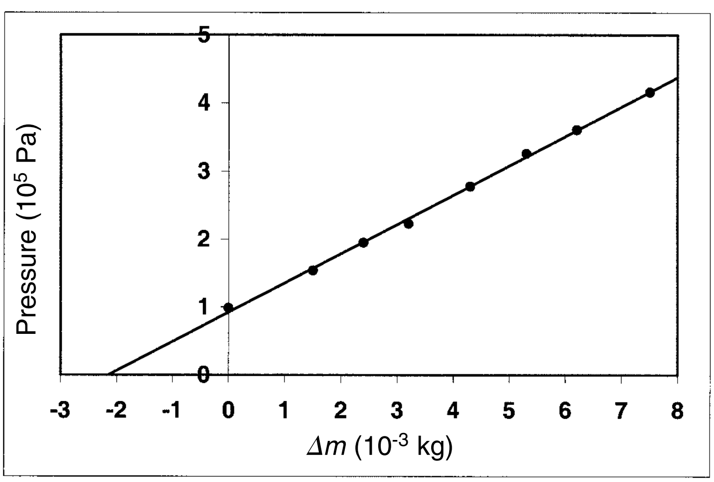

Fig. 1. A graph of P vs Δm for air in a 2-L bottle. The line drawn is the best-fit line using linear regression. The slope is 4.31 x 10^7 J/(m^3kg), and the horizontal intercept is –2.15 g.

Similar equipment can be used to determine the molar mass,[2,4] density of the gas for different pressures,[2] or the mass or volume of the container.[2,3]

In physics, we are also interested in verifying the gas law. One starts with the theory under investigation: $P = nRT/V$. Substituting $n = (m_0 + \Delta m)/M$ gives

$$P = \frac{RTm_0}{VM} + \left(\frac{RT}{VM}\right)\Delta m,$$

where m_0 is the mass of the air in the bottle just after the cap is put on without any extra air being pumped in. M is the molar mass of air. Thus, if a graph of P versus Δm produces a straight line, the dependence of P on n for the ideal gas law is verified. The slope of the line is equal to $RT/(VM)$. Since R, T, and V can be measured, one can determine the molar mass of air from the slope. The Δm intercept is equal to $-m_0$. Since V is known, the density of air (m_0/V) at laboratory pressure and temperature can also be determined.

In Fig. 1 we show a graph of P versus Δm for our data, with $V = 2.075$ L, $T = 296$ K, and the atmospheric pressure $P_0 = 741.5$ mm Hg $= 0.988 \times 10^5$ Pa. The data lie in a straight line, confirming $P \propto n$. From the slope we calculate the molar mass of air to be $M = 27.4$ g. In Ref. 2 a value of $M = 27.8$ g was obtained from data taken from a single point. The horizontal intercept gives $m_0 = 2.15$ g, resulting in 1.04 kg/m^3 for the density of air. This is to be compared with 1.17 kg/m^3 for the density of moist air at 296 K and 742 mm Hg pressure.[5]

It is advantageous to graph the absolute pressure, $P = P_0 + P_{gauge}$, inside the bottle instead of the gauge pressure so the student uses both types of pressures, and because it demonstrates to the student the large range of validity of the gas law. In Fig. 1, one can see that the linearity holds while the absolute pressure, and consequently n, is increased by a factor of 4. This is a large variation in comparison to other "gas law" experiments. For example, in experiments in which the temperature T is varied while keeping P or V constant, the relative change of the variables is smaller. Usually the students vary T from ice water, 273 K, to boiling water, 373 K, and the relative change is only 100/273 = 0.37 or 37%.

Adding n to P, V, and T completes the list of the experimental variables the students can analyze with the gas law. Since the experiment is simple and portable, it makes a good lecture demonstration and helps get the students "pumped up" on the ideal gas law.

References

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