CENCO Physics

Selective Experiments In Physics

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BOYLE'S LAW

OBJECT: To study Boyle's law, at moderate pressures above and below atmospheric, by both analytical and graphical methods.

METHOD: A fixed mass of air confined in a glass tube is kept at room temperature and subjected to various pressures, ranging from half to double atmospheric pressure. A series of corresponding pressures and volumes are observed and Boyle's law is checked by noting the constancy of their products. The data are plotted in several graphical forms the interpretation of which also indicates the validity of Boyle's law.

THEORY: The relation existing between the pressure exerted by a confined gas and its volume is given by what is usually known as Boyle's law, namely: *The temperature remaining constant, the volume V occupied by a given mass of gas is inversely proportional to the pressure P to which it is subjected*. In symbols

$$V \propto \frac{1}{P}$$

or

$$V = k \times \frac{1}{P}$$

whence

$$PV = k \tag{1}$$

where k is (numerically) a constant under given conditions.

It is apparent that Eq. (1) is an equation of the second degree, since the left side is the product of two variable quantities. When the pressure is plotted as a function of the volume, an equilateral hyperbola, as shown in Fig. 1, is obtained.

The actual pressure P may be thought of as consisting of the *atmospheric or barometric pressure B plus an added pressure p*, the algebraic sign of the added pressure depending upon whether the actual pressure is above or below atmospheric pressure. Eq. (1) may therefore be written

$$(B + p)V = k \tag{2}$$

or

$$B + p = k \times \frac{1}{V} \tag{2a}$$

By placing $1/V = x$, Eq. (2) becomes

$$B + p = kx \tag{3}$$

or

$$p = kx - B \tag{4}$$

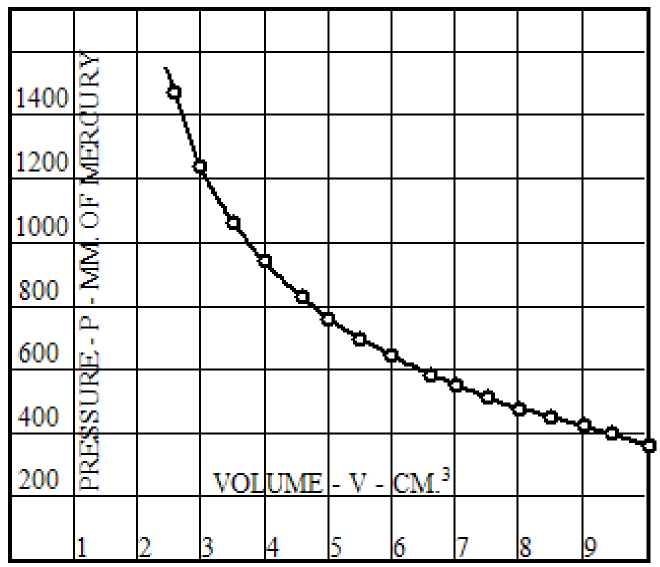

Fig. 1. Curve showing the variation of the volume of a gas at constant temperature as a function of the pressure.

Since B is numerically constant (for any given case), it will be seen that Eq. (4), being of the first degree, is the equation of a straight line. If, then, not the actual pressure but merely the *added* pressure p may be plotted as ordinates and the reciprocal of volume, $1/V$ or x, be plotted as abscissas, the resultant curve should be a straight line (Fig. 2). If the curve is produced downward until it intersects the pressure axis, i.e., when x or $1/V$ equals zero, the intercept on the p-axis gives immediately the negative of the barometric pressure at the time of the experiment. This is obvious from Eq. (4), for if x is placed equal to 0, then

$$p = -B \tag{4a}$$

While the present experiment is designed ostensibly to furnish a check upon the approximate validity of Boyle's law, it also furnishes a splendid example of a study of both graphical and analytical representation and interpretation of experimental data. In addition it offers an excellent illustration of the processes used in logical scientific reasoning. When this experiment is performed with this point of view in mind and the differences in the apparatus, procedure and precision are considered, it will be seen that the present experiment is far from a mere repetition of one of the commonest experiments of elementary-school physics.

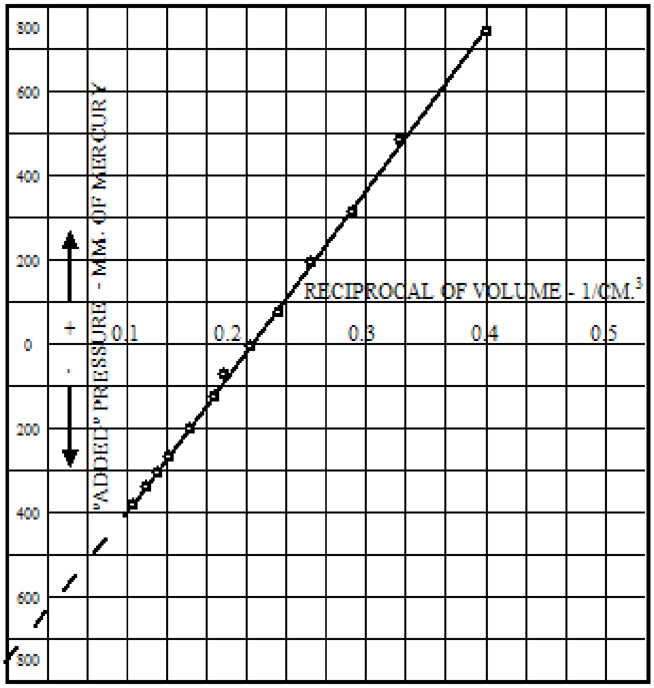

Fig. 2. Curve showing the variations of the reciprocal of the volume of a fixed mass of gas at constant temperature, as a function of the pressure above and below the atmospheric pressure.

APPARATUS:

The Barometer: The pressure of the atmosphere may be most accurately determined by the mercurial barometer illustrated in Figs. 3 and 4. The glass tube G, closed at its upper end, projects into the mercury cistern w. The metric scale S and the British scale S' have their zeros at the lower end of the ivory tip I. Consequently, it is necessary that the upper level of the mercury in the cistern always be brought to this point before a reading is taken. This is done by adjusting a screw at the bottom of the barometer. A vernier reading device V makes possible accurate settings and readings at the top of the mercury column.

The following procedure is used in making a measurement of atmospheric pressure by means of a mercurial barometer:

1. Adjust the mercury level to the tip of the ivory point by turning the well upward with great care until the tip of the ivory point just touches the mercury surface. When the mercury is clean this contact may be judged by noting apparent contact between the tip of the point and its image in the mercury. When the mercury has become contaminated, the mercury level is adjusted upward until the point has made the slightest depression discernible in the mercury surface. Another way of making the setting is to hold apiece of white paper behind the well as a background, keeping the eye at the level of the ivory point and adjusting the mercury surface until the light between the point and the mercury is just cut off.

2. Move the vernier up until the top of the mercury column appears below its lower edge. Tap the barometer lightly to permit the mercury to form a free meniscus. Then move the vernier downward until the sighting edges A and A' are in line with the uppermost point of the meniscus.

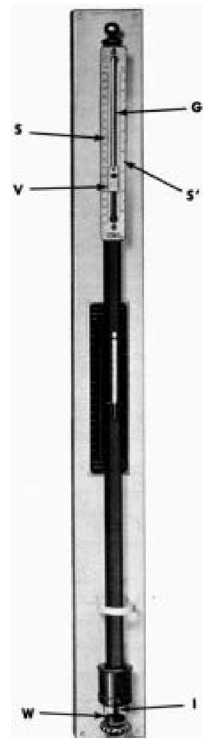

Fig. 3. Mercury Barometer

3. Read the scale in millimeters and determine tenths with the aid of the vernier.

The Boyle's Law Apparatus: The Boyle's law apparatus, Fig. 5, consists of two vertical glass tubes, one open at the top and the other closed by a stopcock, held at the lower end by stuffing boxes in an iron reservoir. The reservoir is mounted on a tripod base and is provided with a screw-operated diaphragm for varying the height of the mercury in the tubes and so changing the pressure and volume of the gas confined in the closed tube. *

*In one common modification of this form of Boyle's law apparatus (Fig. 6) an additional metal-bulb reservoir is provided for use in another experiment (Charles' law). When the apparatus is being used to study Boyle's law, this bulb is sealed off by tightly closing the needle valve provided for that purpose. Thereafter this portion of the apparatus may be ignored. To see that there is no leak into this bulb during the progress of the Boyle's law experiment, it is wise to have the level of the mercury in the metal-bulb side of the tube just at the index mark on the glass window and to observe from time to time that this level does not change.

The large, milled-head screw has a small pitch and it presses against the corrugated steel diaphragm to form one side of the mercury reservoir. Readings of the mercury levels to measure the corresponding pressures and volumes are taken from a metric scale mounted vertically between the tubes. A sliding glass cursor provided with a horizontally etched hairline makes it conveniently possible to read the mercury levels with satisfactory precision. The air admitted to the closed tube should be carefully freed from moisture by a method described later.

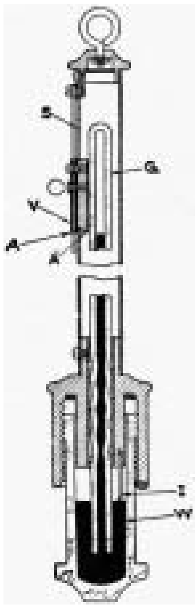

Fig. 4. Detail of Mercury Barometer

PROCEDURE:

Experimental: Place the apparatus in good light where the scale may easily be read. Before beginning the experiment, the instructor or student should be sure that the air in the closed tube is perfectly free from moisture. Introduction of dry air into the tube is effected by connecting a Dessigel S drying tube to the stopcock tube and running the mercury up and down in the tube, pumping dry air in and out and thereby removing water vapor. The stopcock tube is finally tightly closed at a place where the volume of the entrapped air is about one half the total volume of the closed tube when the levels of the mercury in both tubes are the same.

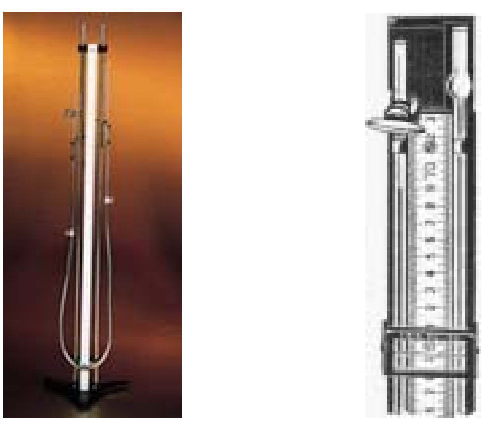

Fig. 5. Boyle's Law Apparatus. The insert shows a "close-up" of the upper end of the tubes.

Test for leaks by turning the milled head until the mercury is near the top of the open tube and observing it for a few minutes to see that the level remains constant. Check this also by having the mercury in the open tube near the bottom of the tube. To be sure that no air bubbles are present, turn the adjusting wheel back and forth several times to move the mercury in the open tube from the top to the bottom, meanwhile watching both tubes for bubbles. While this is being done the barometer may be read, as described above.

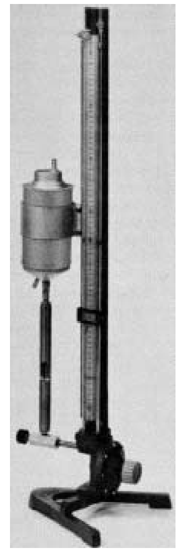

Fig. 6. Combination Boyle's Law and Charles' Law Apparatus.

Never allow the level of the mercury in the tubes to come below the lower end of the meter stick, as to do so will often allow air from the reservoir to enter the closed tube and thus to vitiate the results. During the experiment never adjust or open the stopcock on the closed tube, as to do so will change the mass of air, admit moist air and make necessary a complete drying of a new mass of air.

As the volume of the closed tube is not calibrated directly in cubic centimeters, the volume of the gas will be measured here in terms of the *length* of the tube above the mercury, since for a uniform bore the volume is proportional to the length. Since it is impossible to seal the glass stopcock to the end of the tube and still have a uniform bore right up to the barrel of the stopcock, an etched line on the tube is placed at such a point that the volume in the capillary between that line and the stopcock barrel represents exactly the volume of 1cm of uniform capillary bore. Hence the corrected scale reading for the top of the enclosed air column is obtained by adding 1cm to the reading of the scale just opposite the etched line on the tube below the stopcock. This corrected value will be designated R_t.

When the apparatus is properly adjusted, take a series of ten or twelve readings of corresponding pressures and volumes, choosing the values so that the open-tube readings vary by 70mm intervals over the entire scale. Take one reading then the mercury levels are the same on the open and closed tubes.

Tabulation of Data: Tabulate the following: (a) R_o, the reading of the open-tube mercury level; (b) R_c, the reading of the closed-tube mercury level; (c) p, the added pressure, i.e., $R_o - R_c$; (d) P, the pressure, or $B + p$; (e) V, the volume or R_t -

R_c; (f) $1/V$; (g) PV; (h) percentage variation of PV from the average value of all PV's.
Note that when the closed-tube readings exceed those on the open tube the confined gas is below atmospheric pressure and the values of p must be subtracted from B.

Interpretation of Data: Calculate the various *PV* products and take their average. Determine the percentage variation between the individual values of *PV* and their mean. What is the physical significance of the constancy of the various values of *PV*?

Curves: Plot the following curves: (1) P vs. V (begin both axes at zero); (2) "added" pressure p vs. reciprocal of volume $1/V$. Choose the axis of p near the center of the page and be sure that $-p$ extends as far as 770mm below the axis. In laying off the scale for $1/V$, begin with $1/V = 0$ at the origin. Carefully interpret in the report the significance of these curves. From curve (2) determine the barometric pressure by extrapolating the observed portion of the curve (use a dotted line for extrapolated portion) back to the intercept where $1/V = 0$. Compare this pressure-intercept value of B with that observed by the barometer.

QUESTIONS: 1. Show by dimensional reasoning that the constant k in the equation $PV = k$ is not a mere proportionality constant, i.e., one having no unit, but that it has the dimensions of work. On what does the value of k depend?

2. How would a P vs. V curve for data taken (a) at a higher temperature, (b) at a lower temperature, compare with the curve as actually obtained?

3. A certain automobile tire is labeled, “Inflate to 35lb. or 2.5kg." What does this mean? Is the statement clear? Is 35lb. equal to 2.5kg?

4. The moving coil of an ammeter weighs 1/2 gram and is supported in a jewel bearing by a needlepoint pivot which is rounded off to have a radius at the tip of 75/100,000 inch. Calculate the pressure, in pounds per square inch, which the pivot exerts on the bearing.

5. The mercury stands at a height of 74cm in a barometric tube. The top of the tube is 6cm above the top of the mercury column and the cross-sectional area of the tube is $0.6 cm^2$. A quantity of air is introduced above the mercury which then falls to 64cm. What was the volume of the air before it was introduced into the tube?

6. The closed end of uniform U-tube containing mercury has an air space 20cm long. The mercury in the open arm stands 5cm lower than in the closed arm. If more mercury is poured into the open arm until its level in this arm is 10cm higher than in the closed arm, how long will the air space be? The barometric height is 75cm of mercury.

7. A barometer having a little air in the top of the tube has the mercury 70cm above that in the cistern. If the level of the mercury in the cistern is raised so that the volume of the air space at the top is half as great as before, the mercury column stands 67cm above the level of that in the reservoir. What is the barometric pressure at the time?