Selective Experiments In Physics

- C.J. Overbeck — Northwestern University
- R.R. Palmer — Beloit College
- Marsh W. White — The Pennsylvania State University

CHARLES' LAW

OBJECT: To study the expansion of gases, to check Charles' law and to measure the temperature coefficient of pressure increase of dry air at constant volume.

METHOD: Charles' law for the expansion of gases is studied by the use of a simple form of constant-volume air thermometer. A fixed volume of dry air is subjected to certain measured temperatures and the corresponding pressures observed. From the resultant pressure-temperature curve the temperature coefficient of pressure increase at constant volume is determined. By extrapolating this curve the value of "absolute zero" is determined approximately.

THEORY: When the temperature of a confined gas is changed, the gas win change in volume if the pressure upon it is kept constant, or it will exert different pressures if the volume is kept constant. The present experiment is restricted to a study of the variation in pressure of dry air when its temperature is changed and its volume is kept constant.
Pioneer workers in this field were the Frenchmen Jacques Charles and L. J. Gay-Lussac. The law of the expansivity of gases was independently discovered by them and is variously known by each of their names. In this experiment the more common usage is followed by referring to it as *Charles' law*. These workers-and independently, John Dalton- found that *the pressure of a gas kept at constant volume changes linearly as the temperature of the gas is varied.* If the pressure is plotted against temperature, a curve similar to that shown in Fig. 1 is obtained. The equation of the straight line may be written

$$P_t = P_0\left(1 + \beta_v t\right) \tag{1}$$

where P_t represents the pressure at the temperature t and P_o is the pressure at some standard initial temperature, usually taken at 0°C. The quantity represented by β_v is called the temperature coefficient of pressure variation at constant volume. It is defined by the equation

$$\beta_v = \frac{P_f - P_0}{P_0 t} \tag{2}$$

or, in words, *the temperature coefficient of pressure variation of a gas at constant volume may be defined as the fractional change in pressure per unit temperature change, the initial pressure being measured at zero degrees centigrade*. The slope of the pressure-temperature curve divided by P_o (the pressure when t = 0°C) offers a convenient method for determining the coefficient of pressure variation.
It is a fact of extraordinary interest that the experimental value of β_v for most common gases turns out to be approximately 1/273 per degree centigrade. This means that for every degree centigrade change in temperature above or

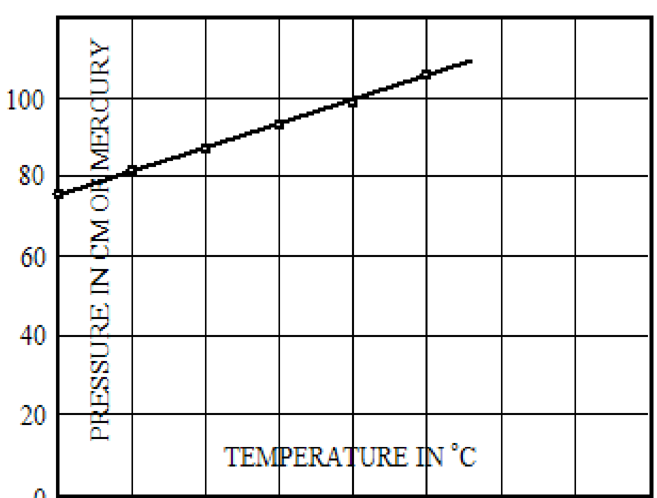

Fig. 1. Pressure against temperature, in degrees centigrade, for dry air at constant volume.

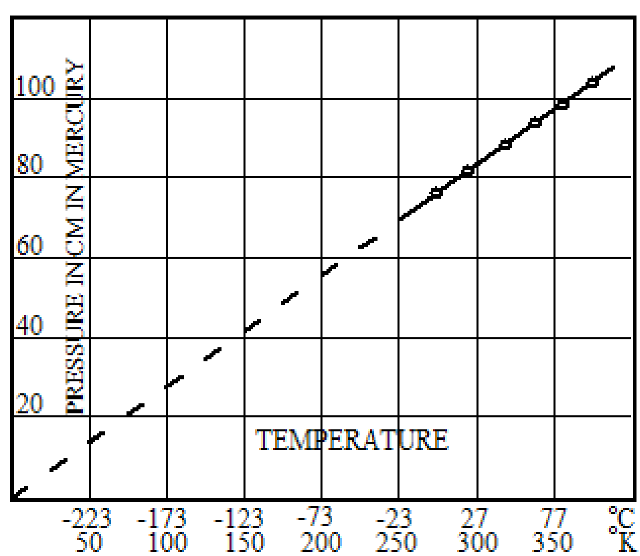

Fig. 2. Pressure against absolute temperature, in degrees Kelvin, for dry air at constant volume.

below zero degrees centigrade, the pressure changes by 1/273 of the pressure which the gas exerts at *zero degrees centigrade* (the volume being kept constant). Hence if the temperature were lowered by 273°C below 0°C, the change of pressure would be 273 x 1/273 of P_0 or the *change* of pressure would equal the initial pressure at 0°C and the final pressure would be *zero*! This irreducible minimum of temperature is called *absolute zero*, i.e., the temperature of an ideal gas at which molecular activity ceases and the pressure consequently is zero. Its value is roughly checked in this experiment by extrapolating (projecting beyond the measured values) the observed pressure-temperature curve until it intersects the axis of zero pressure, as in Fig.2. This should occur at a place where t = -273°C = 0°K (degrees Kelvin are the units of temperature on the absolute scale of temperatures).

A careful distinction should be drawn between a *linear relation* and a *direct proportion* in the present and many similar cases. The pressure here *varies linearly* with the temperature *in degrees centigrade*, as indicated by Eq. (1) and Fig. 1. It is also true that the pressure is *directly proportional* to the temperature *in degrees Kelvin* (absolute), but the pressure is *not* directly proportional to the temperature expressed on any other temperature scale. This may be more clearly seen by substituting the value 1/273 for, β_v in Eq. (1) and obtaining

$$P_t = P_0\left(1+\frac{t}{273}\right) = P_0\left(\frac{273+t}{273}\right) = \frac{P_0}{273}T = CT \quad (3)$$

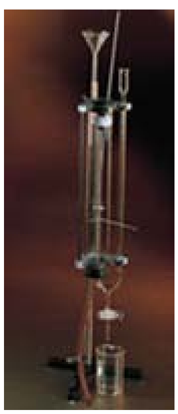

Fig. 3. Charles' Law Apparatus, or constant-volume air thermometer

where T = temperature in degrees Kelvin and C is a constant for any given case. From Eq. (3) and Fig. 2 it is apparent that the pressure is directly proportional to the temperature only if the latter is measured on the absolute scale.

APPARATUS: The Charles' law apparatus, or constant-volume air thermometer, is shown in Fig. 3. It consists essentially of a metal bulb to contain the gas under investigation, connected to an iron reservoir containing mercury in which a vertical glass tube is held by a tight stuffing box. The volume of the gas is kept constant by adjusting the mercury level until it is always brought to a fixed line etched on a short section of glass tubing through which the bulb is connected to the mercury reservoir.

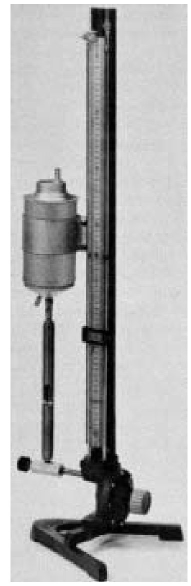

Fig. 4. Combination Boyle's Law and Charles' Law Apparatus

A copper jacket surrounds the gas bulb proper; it is provided with tubulures so that heating water may be added or removed as desired to control the temperature of the confined air. The water may be brought to and maintained at any particular temperature by an electric immersion heater, if desired. Adjustment of pressure between the gas and the mercury column of the open tube at the right is accomplished by turning a small-pitch screw by means of a large milled head. The end of the screw presses against a corrugated steel diaphragm which forms one side of the mercury reservoir and whose movement forces the mercury up into the manometers. *

*In one common modification of this type of Charles' law apparatus (Fig. 4) an additional vertical tube is inserted in the mercury reservoir for use when the apparatus is to be used in a study of Boyle's law. During the Charles' law experiment this portion of the apparatus may be ignored, as it will have no effect on the validity of the other readings.

To facilitate reading the pressure a horizontal line has been placed on the meter stick at the side of the open tube, the line being at the same height as the etched line on the tubing of the gas bulb. When, therefore, the mercury level on the closed tube is adjusted to this etched line, the actual pressure on the gas is merely the barometric pressure plus the difference between the height of the mercury at the top of the open tube and the height of the index line.

Since Charles' law does not hold for vapors it is essential that the air introduced into the gas bulb be perfectly try.

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 to enter the closed bulb and thus to vitiate the results.

As auxiliary apparatus there are required a l00°C thermometer, a steam generator and a Bunsen burner or an electric heater, two metal vessels for water and ice, a pinch clamp and suitable rubber tubing.

PROCEDURE:

Experimental: A series of readings will be taken of the pressure of the air in the closed bulb when kept at constant volume and adjusted to various measurable temperatures ranging from 0°C to 100°C. The temperatures will be read by a mercury thermometer and the pressures will be obtained from the barometric height and the open-tube manometer.

Fill the water jacket with a mixture of chipped ice and water. After equilibrium is attained, adjust the pressure until the mercury is brought to the line etched on the glass in the open portion of the metal tubing. Measure the actual pressure *P* on the gas as given by

$$P = B + (M - I) \qquad (4)$$

where *B* is the atmospheric or barometric pressure, M is the height of the mercury in the open tube and 1 is the height of the index line.

Heat the ice water to about 20°C by means of the electric heater (or run it off and introduce other water at room temperature), adjust the volume to the fixed value as before and again read the pressure and temperature. Repeat this process by approximately 20°C intervals until the water is near the boiling temperature. A final convenient value to observe is the one in which steam is passed to the upper tubulure from a steam generator. Arrange a rubber tube from the lower tubulure to a suitable vessel to catch the condensed water vapor.

WARNING! As the steam enters the jacket the mercury in the gas tube will descend and may go below the lower end of the meter stick and admit air to the bulb. This should be prevented by raising the pressure to keep the level of the mercury on the gas-bulb tube at the index line. Throughout the entire experiment one observer should continually watch the pressure and keep adjusting the screw to maintain the mercury levels at the desired values. When the hot water is removed from the vessel or when the steam is discontinued, the pressure will greatly decrease and the mercury might run up into the closed bulb if the adjusting screw were not manipulated to lower the level of the mercury in the closed tube.

The temperature of the steam is best obtained from a table of boiling points against pressure.

Interpretation of Data: Plot a curve to show the variation of the pressure with the temperature in degrees centigrade. Explain clearly the significance of the shape of this curve.

Determine the slope of the curve, choosing points near its ends, and divide the slope by P_o. This should give the value of β_v; determine the percentage difference between this value and the standard value, 0.003663 per degree centigrade.

Plot a curve from the observed data to show the variation of pressure with absolute temperature. Start the pressure scale with zero and the temperature scale with -273°C or 0°K. Include the values of the temperature in both degrees centigrade and degrees Kelvin on the temperature scale. Extrapolate by a dotted line the observed data to the axis of zero pressure. Compare this temperature intercept with the standard value for absolute zero. What is the ratio of the slope of the curve and the pressure at 0°C? Explain in the report the significance of the curve.

QUESTIONS: 1. The gas bulb of the Charles' law apparatus is made of cast iron. What happens to its volume when the temperature is changed from 0°C to 100°C? What effect does this have upon the "constant volume" assumption? Is the error serious? Why?

2. In the Charles' law apparatus as used, a portion of the air bulb is connected to the mercury reservoir by a glass capillary tube, the level of the mercury always being brought to a fixed point on this tube. Hence some of the air above this line but below the metal bulb is not subject to the same temperature as the air inside the bulb. Will this introduce a serious error into the results? Why?

3. The level of the mercury in the open arm of a Charles' law apparatus stands 5cm below the index when the volume bulb is surrounded by ice water, and 20cm above the index when the bulb is surrounded by steam at normal barometric pressure. Calculate the temperature coefficient of pressure increase at constant volume from these data.

4. The pressure of a gas is measured as 100cm of mercury at 50°C and 114.3cm of mercury at 100°C, volume constant. What value of absolute zero is obtained from these data?

5. An automobile tire gage registers a pressure of 35lb./sq. in. at the start of a trip. After 10 miles of driving the same tire gage registers 37lb./sq. in. on the same tire although no air has been added and the barometric pressure is unchanged. Explain what pressure the tire gage reads and account for the difference in readings by some physical law. Assume the tire gage reads perfectly.