

Experiment No. 51

Pressure measurement in gases (determination of a gas volume)

Keywords:

Pressure, pressure units, pressure measuring devices (manometers, vacuum gauges), pressure measurement in U-tube manometers, gas laws, isotherms of the ideal gas (Boyle-Mariotte law)

Literature:

Atkins "Physical Chemistry"
Barrow "Physical Chemistry", Part 1
Kohlrausch "Practical Physics", Volume 1
Gerthsen, Kneser, Vogel "Physics"

Basics:

Pressure is a thermodynamic state variable that is defined as the quotient of the amount of a force acting perpendicularly on a surface (uniformly distributed) and the size of this surface. The SI unit (SI = Systeme International d' Unites) of pressure is the Pascal (Pa). The following conversions apply:

$$1 \text{ Pa} = 1 \text{ N} \cdot \text{m}^{-2} = 1 \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2} = 10^{-5} \text{ bar} \cong 9,87 \cdot 10^{-6} \text{ atm} = 7,5 \cdot 10^{-3} \text{ torr}$$

or

$$1 \text{ atmosphere (atm)} = 760 \text{ torr} = 1013,25 \text{ mbar} = 101325 \text{ Pa} \\ \cong 760 \text{ mm Hg (at } 0^\circ\text{C, } g = 9,80665 \text{ m} \cdot \text{s}^{-2})$$

The pressure of a gas, e.g. on the wall of a vessel or manometer, is the impulse per unit area and time transferred by the gas molecules to the wall by elastic reflection over time. It is independent of the orientation of the wall surface and is the same everywhere in the absence of external forces. The devices used to measure pressure are called manometers for pressures $> 1 \text{ mbar}$ and vacuum gauges for pressures $< 1 \text{ mbar}$. The term vacuum covers the entire pressure range below 1013 mbar. The lowest pressures currently achievable are in the order of 10^{-13} mbar .

There are four vacuum ranges:

- Rough vacuum 10^3 to 10 mbar
- Fine vacuum 10 to 10^{-3} mbar
- High vacuum 10^{-3} to 10^{-7} mbar
- Ultra-high vacuum $< 10^{-7}$ mbar

For physical reasons, it is impossible to build a measuring device that covers the entire vacuum range. To cover the entire range, a number of pressure gauges are therefore

available which are based on different measuring principles. Each of these gauges covers a characteristic measuring range:

- mechanical manometers (spring tube, membrane, quartz spiral manometers)
- liquid manometers (mercury U-tube manometers, oil manometers)
- heat conduction vacuum gauges
- capacity vacuum gauges
- ionization vacuum gauges

Mercury U-tube manometers are mainly used to measure absolute pressures between ~10 and 1000 mbar. In a similar way, other liquids with lower densities than mercury (e.g. water, alcohol, toluene, petroleum) can be used in U-tube manometers for the pressure range between about 1 mbar and about 100 mbar. Such manometers, open on both sides, are often also used to measure small pressure differences at higher absolute pressures.

Compression vacuum gauges filled with mercury (also called "McLeod vacuum gauges") can be used to measure absolute pressures between 1 mbar and 10^{-5} mbar (see experiment 56). In addition to pressure and temperature, volume is another state function for describing the thermodynamic properties of a system. Since it depends on the expansion of the system, it is an extensive quantity and thus additive.

The isotherms of an ideal gas are given by Boyle-Mariotte's law.

$$(1) \quad p \cdot v = \text{const.}, \text{ where } T = \text{const. and } n = \text{const.}$$

This results in:

$$(2) \quad d(p \cdot v) = 0 \quad \text{or} \quad p dv + v dp = 0 \quad \text{or} \quad \frac{dv}{v} = -\frac{dp}{p}$$

A certain relative change in volume results in an equal relative change in pressure with the opposite sign. Using Eq. (1) it is thus possible to determine unknown volumes, such as the interior of a container with a complicated geometry or complex supply lines, by simply measuring pressures.

Task:

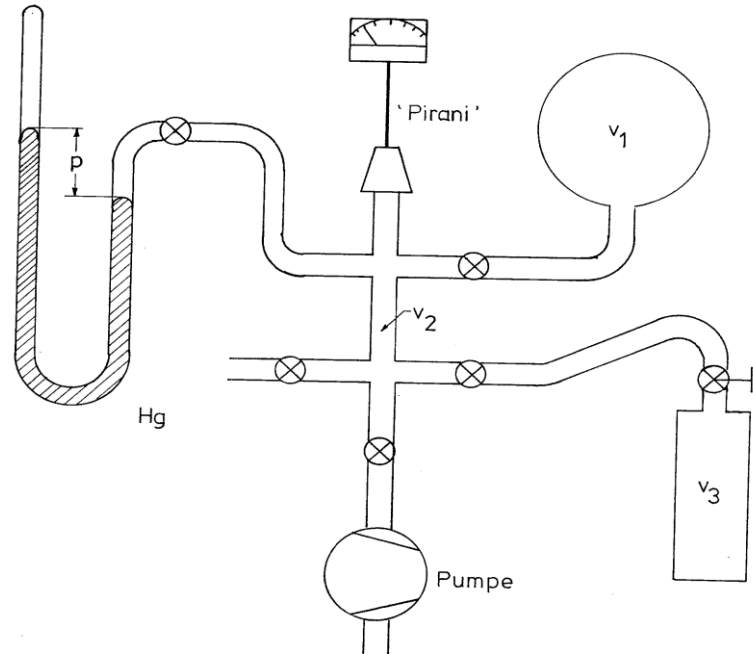
Measure the volume of a laboratory gas cylinder.

Experimental setup:

The experiment is carried out on a glass vacuum apparatus (with the volume v_2) that is connected via glass taps to a mercury U-tube manometer, to a large glass flask whose volume v_1 is known by weighing, and to the laboratory gas cylinder (with the unknown volume v_3) (Fig. 1).

Fig. 1:
Schematic structure of the
experimental setup

v_1 = known volume
 v_2 = volume of the apparatus
 v_3 = unknown volume



Procedure:

- 1) The entire apparatus is evacuated to a pressure of < 0.2 mbar.
- 2) The valve of the laboratory gas bottle is carefully closed and the rest of the apparatus is ventilated.
- 3) The air pressure (p_1) is read off the U-tube manometer and then the tap to the glass flask (v_1) is closed.
- 4) The rest of the apparatus is evacuated to a pressure of < 0.2 mbar and then the main tap to the pump is closed.
- 5) The connecting tap between the glass flask (v_1) and the apparatus is opened and the resulting pressure (p_2) is read off the U-tube manometer. The following now applies according to equation (1):

$$(3) \quad p_1 \cdot v_1 = p_2 \cdot (v_1 + v_2)$$

- 6) The valve to the gas bottle (v_3) is opened and the resulting pressure (p_3) is measured on the U-tube manometer. The following again applies according to equation (1):

$$(4) \quad p_1 \cdot v_1 = p_3 \cdot (v_1 + v_2 + v_3 - \Delta v)$$

The term Δv takes into account the volume change that occurs as a result of the displacement Δh of the mercury meniscus in the U-tube manometer.

It is: (5) $\Delta v = \pi r^2 \cdot \Delta h$, where $r = 4.5$ mm.

From equation (3) and equation (4) follows:

$$(6) \quad v_3 = p_1 \cdot v_1 \cdot \left(\frac{1}{p_3} - \frac{1}{p_2} \right) + \Delta v$$

7) The measurements are repeated with 5 other starting pressures ($p_1 > 500$ torr).

Evaluation:

1) The volume of the laboratory gas bottle (v_3) is determined according to equation (7) as the arithmetic mean of the 6 measurements.

2) Discuss the accuracy of the result!

- How large is the range of the measured values v_3 ?
- How large is the maximum error of a pressure measurement?
- How much do the maximum errors of the individual pressure measurements affect the maximum error of v_3 ?
- What relative error occurs if Δv is not taken into account?

Accessories:

Rotary vane pump, U-tube manometer, heat conduction vacuum meter with display device, round-bottomed flask made of glass, steel bottle with valve, vacuum apparatus made of glass.