Building a homemade barometer

Theory and test report on building a homemade barometer

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May 14, 2024 - August 21, 2024

Abstract

Barometers are devices, that measure air pressure. Usually, this is done in the field of meteorology to explore future weather predictions. Observing the atmospheric pressure evolution at some fixed point in space allows for a rough estimate of possible future weather, since a pressure drop usually is a precursor for bad, and a pressure rise an indication for good weather. This paper is concerned with development of theory coupled with a simple realization and test of a homemade barometer.

1 Introduction

Barometers are used to measure air pressure. Observing the atmospheric pressure at a fixed point in space over a given time interval allows for coarse predictions of the future weather. This is due to the observation that pressure drops are usually linked to bad weather, while pressure rises often indicate development of good weather.

High pressure air is heavier than low pressure air and thus has a tendency to sink due to buoyancy. Sinking air rises in temperature due to adiabatic and diabatic warming. Warm air can take up more water vapour and hence the relative humidity sinks. As a result, clouds tend to vanish and thus render precipitation unlikely. Low pressure air however tends to rise and thus to cool off with increasing height. Now, cold air is sooner saturated with water vapour than warm air. If air rises and cools off therefore, the air gets oversaturated with water vapour and hence clouds begin to form and precipitation becomes possible as well as likely.

As a rough estimate of the future weather helps with planning outdoor activities, it is nice to have a barometer at home to observe the pressure evolution. This paper hence aims to provide the necessary theory to build a homemade barometer using only equipment available in any hardware store. The general design of such a barometer will be provided here, whereas the details of an actual realization are left to the reader to figure out given the available tools and hardware.

2 Theoretical foundation

2.1 Background

The theoretical foundation of the proposed homemade barometer is comprised of two main equations and their theoretical background.

The first equation is the ideal gas law

$$PV = Nk_BT, \tag{1}$$

where P is the pressure of a gas, N the number of particles in the volume V, k_B the Boltzmann constant and T the temperature of the gas. There are number of assumptions processed in the derivation of this ideal gas law; but for the purpose at hand it suffices to state that air pressure in non-extreme environments on earth follows the ideal gas law very well.

The second main equation is the equation of hydrostatic pressure

$$P = \rho g h, \tag{2}$$

where P is the hydrostatic pressure of an incompressible fluid, ρ is the density of the fluid, g is the gravitational acceleration and h is the depth in the fluid, where the hydrostatic pressure P is measured.

2.2 Working principle

Consider an experimental setup as seen in fig. 1. The experimental setup consists of a U-shaped tube with the opening facing towards the sky. At the bottom of the U, a valve is placed which separates both the left part and right part of the U. The right part of the U is furthermore closable, whereas the left part remains open throughout the experiment and is therefore subject to the atmospheric pressure P_0, which is to be measured.

Initially, the red valve is closed and water is filled into the right and left part of the U. In the left end, the water is filled up to height $z_{l,0}$, whereas the water in the left tube is filled up to height $z_{r,0}$, fulfilling the condition $z_{r,0} \gg z_{l,0}$. After filling both ends of the U with water of density ρ, the right part of the U is closed, which means that at closed valve the pressure and volume of the residual air in the tube remains constant at P_0 and V_0. This situation is depicted in the left panel of fig. 1

and describes the experiment preparation required to carry out measurements.

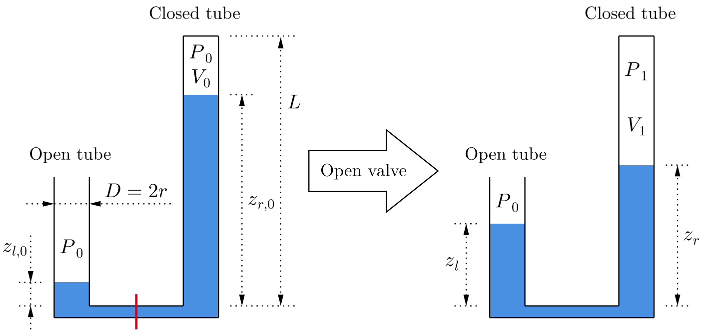


Figure 1: General working principle of the proposed homemade barometer.

Now, a measurement is carried out by first tediously preparing the experiment as described above. Then, the red valve is opened, which marks the starting point of the measurement process. Now, the water in the right part of the U is drawn to the left part of the U due to the higher hydrostatic pressure in the right part of the U. Water keeps flowing from the left part of the U to the right part until the sum of hydrostatic and atmospheric pressure in the right part of the U is exactly balanced by the sum of hydrostatic pressure and air pressure in the right (closed) part of the U. The water level in the left part of the U is now at z_l and z_r denotes the water level in the right part at equilibrium.

Mathematically speaking, the total pressure P_l at the bottom of the U in the left part is given by

$$P_l = P_0 + \rho g z_l, \tag{3}$$

where analogously the total pressure P_r at the bottom of the U in the right part is accounted for by

$$P_r = P_1 + \rho g z_r. \tag{4}$$

Now, at equilibrium, these two pressures must be equal to one another. Now, the pressure P_1 can further be expressed by means of the ideal gas law. Consider for this purpose the evolution of the residual air parcel located in the right part of the U. Initially, this air parcel exhibits pressure P_0 and a volume V_0. At equilibrium then, the pressure has dropped to P_1 due to an expanded volume $V_1 > V_0$. Considering the ideal gas law, the number of particles in the air parcel does not change from the initial condition to equilibrium, hence $N_0 = N_1 \doteq N$. Furthermore, the assumption $T_0 = T_1 \doteq T$ shall be made which means, that the temperature of the air parcel is assumed to stay constant throughout the measurement procedure. Writing out the ideal gas law for both initial and equilibrium conditions, one obtains

$$P_0 V_0 = N k_B T = P_1 V_1 \quad \Leftrightarrow \quad P_1 = P_0 \frac{V_0}{V_1}. \tag{5}$$

The volume V_1 can be expressed by means of the equation

$$\begin{aligned} V_1 &= V_0 + r^2 \pi (z_{r,0} - z_r) \\ &= r^2 \pi (L - z_{r,0}) + r^2 \pi (z_{r,0} - z_r) \\ &= r^2 \pi (L - z_r). \end{aligned} \tag{6}$$

The pressure P_1 can thus be expressed as

$$P_1 = P_0 \frac{L - z_{r,0}}{L - z_r}, \tag{7}$$

which renders the pressure P_r at the bottom of the right U-part at equilibrum as

$$P_r = P_0 \frac{L - z_{r,0}}{L - z_r} + \rho g z_r. \tag{8}$$

From the equilibrium condition $P_l \stackrel{!}{=} P_r$, the reasoning

$$\begin{gathered} \overbrace{P_0 + \rho g z_l}^{P_l} = \overbrace{P_0 \frac{L - z_{r,0}}{L - z_r} + \rho g z_r}^{P_r} \\ \Leftrightarrow \\ P_0 \left(1 - \frac{L - z_{r,0}}{L - z_r}\right) = \rho g (z_r - z_l) \end{gathered} \tag{9}$$

Thus, the final barometer expression $P_0(z_{r,0}, z_r, z_l, L)$ results as a function of initial water height $z_{r,0}$, equilibrium water heights z_r and z_l in both parts of the U and the total length L of the right U-part. This final equation is given by

$$P_0(z_{r,0}, z_r, z_l, L) = \rho g (z_r - z_l) \left(1 - \frac{L - z_{r,0}}{L - z_r}\right)^{-1}. \tag{10}$$

In fig. 2, a visualization of the barometer equation eq. (10) for the parameters $L = 1.99\,\mathrm{m}$, $z_{r,0} = 1.16\,\mathrm{m}$, $g = 9.81\,\mathrm{m\,s^{-2}}$ and $\rho = 1000\,\mathrm{kg\,m^{-3}}$ can be seen. As one

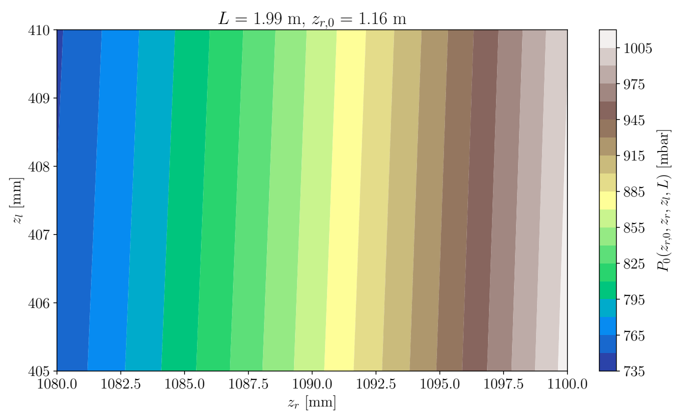


Figure 2: Visualization of the barometer equation eq. (10).

can see from this figure, the difference $\Delta z \doteq z_{r,0} - z_r$ in water level height between initial and equilibrium conditions in the right part of the U increases with dropping ambient pressure P_0. This is not surprising insofar as

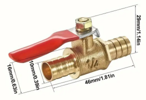
Description	Image	Link
Tube		tube-link
Valve		valve-link
Plug		plug-link

Table 1: Used materials for the homemade barometer reported in the paper at hand.

with less ambient pressure P_0, the pressure exerted on the left water level is lower and hence the water level in the left part of the U will rise stronger as with less pressure. As a result, the water level in the right part of the U will drop lower at lower pressure, which makes the difference Δz large.

The pressure regime in a practical experiment will range somewhere between 750 mbar and 1000 mbar. Hence, following fig. 1 and fig. 2, the barometer design will feature a tube length of $L \approx 2.0\,\mathrm{m}$, an initial right water level of $z_{r,0} \approx 1.1\,\mathrm{m}$ and an initial water height in the left part of the U of $z_{l,0} = 33\,\mathrm{mm}$. This setup should result in a difference Δz in the range of 60 mm to 90 mm between equilibrium and initial water level height in the right part of the barometric U.

3 Methods

3.1 Experimental apparatus

A homemade barometer was built according to the general sketch given in fig. 1. The barometric U was made from transparent plastic tubing of inner diameter $D = 10\,\mathrm{mm}$, which was attached to a wooden board of around 2 meters length using commercially available standard pipe clamps. At the bottom of the U, the valve was placed. Furthermore, a conic silicon plug of appropriate diameter was used to seal the right part of the barometric U airtight prior to measurements. The used materials are summarized in table 1 and were bought at the online shop `temu`[1]

3.2 Measurement procedure

Text.

3.3 Uncertainty evaluation

Text.

[1] See `https://www.temu.com/`.

4 Results

Text.

4.1 Uncertainty evaluation of results

Text.

5 Discussion

Text.

6 Conclusions

Text.

A Derivation of the ideal gas law

Text.

B Derivation of hydrostatic pressure

Text.

C Propagation of uncertainties

Consider $n \in \mathbb{N}$ random variables $x_1, \ldots, x_n$ and a function $f(x_1, \ldots, x_n)$ relating those variables. Let furthermore σ_{x_i} be the uncertainties (standard deviations) of the random variables x_i, which are assumed to be uncorrelated. In this case, the general propagation of uncertainties σ_{x_i} on the outcome $f(x_1, \ldots, x_n)$ is quantified by the uncertainty σ_f as

$$\sigma_f = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 \sigma_{x_i}^2} = \sqrt{\sum_{i=1}^{n} c_i^2 \sigma_i^2}, \tag{11}$$

where the short-hand notation $\sigma_i \doteq \sigma_{x_i}$ and $c_i \doteq \partial f / \partial x_i$ was introduced. Note, that the c_i factors are commonly called sensitivity coefficients.

References