# The Weather Glass

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The weather glass, also called a storm glass, used to be a widely accessible instrument for weather observation (figure 1). In 1619, it was known in the Netherlands as a thunder bottle, but it had probably been used even earlier in other regions. The instrument is said to have been imported to America by the Pilgrim Fathers in 1620. Other countries use specific names such as Goethe Barometer (after the German poet) [1].

An empty weather glass is filled with (coloured) water under normal barometric pressure, so that the water levels in the air-tight body and in the thin spout are equal. When the barometric pressure increases, the water level in the spout decreases, and when the pressure decreases, the level rises – under the precondition that the temperature stays constant (figure 2). In this way, variations in atmospheric pressure, but not in absolute pressure, can be measured.

If the temperature rises, the water level in the spout also rises (assuming the atmospheric pressure remains constant). Vice versa, if the temperature decreases, the level in the spout also decreases. The change in level due to temperature changes is normally much greater and can even become so great that water drips out of the spout. Temperature variations can be measured in this way, but not the absolute temperature.

Often both variables change at the same time, with the consequence that it is not possible to distinguish exactly between these two factors. This was the reason why, in the 19th century, the weatherglass was abandoned completely as a measuring instrument. It is still available and nice to have as a decorative, historical relic, but do not trust any advertising stating that the instrument can accurately forecast the weather.

The weather glass is, however, still useful as a device which you can build easily by yourself and which can teach some applications of fundamental laws of physics.



fig.1: Typical weather glass. The round-bodied vessel contains coloured water. Differences in the water level in the beak-shaped spout indicate changes in barometric pressure.



fig.2: High atmospheric pressure leads to a low water level in the spout, low pressure to a high level (at constant temperature).

# Construction of a Weather Glasses

Easily available materials can enable the construction of a device which works like a weather glass but functions even better (figure 3). However, the decorative aspect of a commercial weather glass is, of course, lost.

Use a big, transparent plastic bottle with a plastic screw cap. A cylinder with a circular cross-section would be optimal. Drill a hole through the screw cap (8 to 10 mm has proven to work well) and insert a transparent, flexible plastic tube with a diameter of 8 to 10 mm and a wall-thickness of 0.5 to 1 mm. If the tube fits tightly through the drilled hole, the construction is often water-tight. Otherwise, you must apply an appropriate sealing material. Fill the bottle to less than the half-way mark with water; the tube can be arranged on the side of the bottle (see figure 3; left section). A ruler enables a quantitative reading of the water level.



fig.3: construction of a weather glass with a plastic bottle and tube or with a syringe and tube.

Quantitative measurements can be made far more easily with this construction than with a commercial device. Furthermore, there is no risk of glass breakage. The left section in figure 3 shows an air volume of about $V_0 = 1035\,cm^3$ in the bottle; the inner cross-section of the bottle is $A_1 = 57\,cm^2$, the inner cross section of the tube $A = 0.5\,cm^2$.

A construction with a syringe (e.g. 60 ml) and a tube is even simpler (figure 3; right part). The device is simultaneously air and water-tight; you can easily calculate the air volume in the calibrated syringe and then can simply calculate the cross-section. In the example, the air volume in the syringe is $V_0 = 24\,cm^3$, the cross-section $A_1 = 6.2\,cm^2$ and the inner cross-section of the small tube $A = 0.07\,cm^2$. The whole construction can even be placed in a vacuum jar (figure 4). In this way, low and high atmospheric pressure can be simulated in the laboratory.



fig.4: A syringe with the tube in a vacuum jar. Additionally there is a digital barometer and thermometer inside.

Smaller vessels and tubes need more accurate handling and measurements. It is generally recommended that the vessels be touched as little as possible to avoid warming. If this cannot be avoided, try to wait at least several minutes because reaching a temperature equilibrium takes time.

Ready-made construction sets for weather glasses can also be bought [3].

# Ideal Gas Law [1]

The basic structure of a weather glass can be seen in figure 5. There is a large, airtight vessel filled halfway with water and connected by a tube. If the atmospheric pressure decreases, the water level inside the vessel decreases by a small amount. The level in the tube rises much more because the cross section of the tube is small compared with that of the vessel.

At the beginning, the state variables of the air in the upper part of the vessel are $p_0$, $V_0$ and $T_0$, and after variation $p_1$, $V_1$ and $T_1$ (temperatures $T$ in Kelvin). The ideal gas law is applicable here

$$(1) \qquad \frac{p_0 \cdot V_0}{T_0} = \frac{p_1 \cdot V_1}{T_1}$$

In the example shown in figure 5, the pressure $p_0$ inside the vessel is initially the sum of the atmospheric pressure $p_a$ and the hydrostatic pressure of the water column in the tube $p_h = g \cdot \rho \cdot h$  (g = gravitational acceleration; ρ = density of the water). $h$ is positive if the water level in the tube is higher than in the vessel, and otherwise negative. Therefore, $p_h$ could be positive or negative!

$$(2) \qquad p_0 = p_a + p_h$$

If the atmospheric pressure changes to $p_a^/ = p_a + \Delta p$   (Δp could be positive or negative), the level in the tube will change to $p_1$.

In figure 5, the atmospheric pressure decreases by Δp, the level in the tube rises by Δh, and the level in the vessel decreases by $\Delta h_1$ , in which case $\Delta h_1$ is negative.

The volume of the air in the vessel increases by $\Delta V$ , i.e. $V_1 = V_0 + \Delta V$ . The new pressure $p_1$ is then the sum of the atmospheric pressure  $p_a^/$  and the new hydrostatic pressure  $p_h^/$

$$(3) \qquad p_1 = p_a^/ + p_h^/ = p_a + \Delta p + p_h + g \cdot \rho \cdot \Delta h - g \cdot \rho \cdot \Delta h_1$$

$\Delta V$ and $\Delta h_1$ are connected with the cross-section $A_1$ in the vessel: $\Delta V = -A_1 \cdot \Delta h_1$. The same is valid for $\Delta V$, $\Delta h$ and $A$ in the tube: $\Delta V = -A \cdot \Delta h$. If you assume, additionally, that the temperature changes by $\Delta T$, i.e. $T_1 = T_0 + \Delta T$, the ideal gas law can be written as

$$(4) \qquad \frac{(p_a + p_h) \cdot V_0}{T_0} = \frac{(p_a + \Delta p + p_h + g \cdot \rho \cdot \Delta h - g \cdot \rho \cdot \Delta h_1) \cdot (V_0 + A \cdot \Delta h)}{T_0 + \Delta T}$$
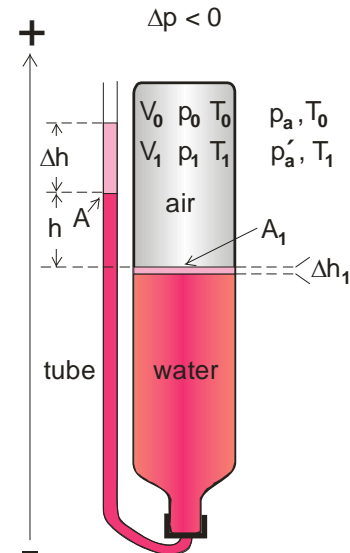


fig. 5: Structure of a weather glass (plastic bottle with plastic tube)

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[1] *This derivation is oriented on a German internet publication www.hjena.de/goethe-barometer/Goethe-Barometer.pdf*

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If this equation is solved for $\Delta p$, the following expression is obtained:

$$(5) \qquad \Delta p = \left[ \frac{1 + \dfrac{\Delta T}{T_0}}{1 + \dfrac{A}{V_0}\Delta h} - 1 \right] \cdot (p_a + p_h) - g \cdot \rho \cdot \Delta h \cdot \left( 1 - \frac{A}{A_1} \right)$$

Application of this formula to commercial weather glasses leads to approximate values. One reason for this is the difficulty in measuring the volume $V_0$ and the cross-sections $A$ in the spout and $A_1$ in the vessel. Another reason is that the cross-sections vary with the height. With a construction, as in figure 3, these parameters can be measured and optimized easily. Under such conditions, a weather glass can be used for the measurement of variations in atmospheric pressure with the addition of a thermometer. Alternatively, the weather glass can be used to measure variations in temperature if the pressure does not change.

Some approximations simplify formula (5). The ratio $A/A_1$ is normally smaller than 0.01, which means that the ratio can be disregarded in comparison with 1. A corresponding approximation is valid for the hydrostatic pressure $p_h$. A water column of 10 cm generates only 10 hPa. Compared with the standard pressure of 1000 hPa, this is negligible. Furthermore, the experiment can be started with $p_h = 0$, which means equal levels in the vessel and the tube. The ratio $A/V_0$ is usually also relatively small. Typical values are about 0.01 cm$^{-1}$ or smaller. If $\Delta h < 10\,cm$, an error lower than 1% can be assumed: $1/(1+A\Delta h/V_0) = 1-A\Delta h/V_0$.

The result is thus

$$(6) \qquad \Delta p = \left[ \frac{\Delta T}{T_0} - \frac{A}{V_0}\Delta h \right] \cdot p_a - g \cdot \rho \cdot \Delta h$$

As always, attention should be paid to the use of consistent units.

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## Playing with formula (6)

Formula (6) was derived with some approximations. $\Delta h_1$ does not appear; hence, the formula could be used for every shape of the body or vessel. Measurement of $V_0$ may face certain obstacles if the shape of the volume is irregular. Under these preconditions, formula (6) could also be used in the case of commercial weather glasses with spouts of approximately constant diameter (fig. 6).

Let us assume $\Delta T = 0$ and a standard pressure $p_a = 1000\,hPa$ at first. If the water levels in the vessel and tube/spout are equal, the pressure in the vessel and the atmospheric pressure are the same. If the atmospheric pressure decreases, the water level in the tube rises. The level in the vessel remains approximately constant because the cross-sections, for commercial weather glasses as well as home-made devices, differ by more than a factor of 100 ($A/A_1 < 0.01$).

*fig.6: Weather glass with an almost cylindrical spout (with permission from [1]).*

The ratio $A/V_0$ plays a significant role in formula (6). Commonly, $A/V_0 < 0.01\,cm^{-1}$ for commercial weather glasses. If we assume $A/V_0 = 0.01\,cm^{-1}$ and a difference of 1cm in the water levels between vessel and tube, results with formula (6) $\Delta p = -11\,hPa$ (exact formula (5) delivers $\Delta p = -10.9\,hPa$). The variation from standard pressure to high or low is hardly more than $\pm 20\,hPa$. These differences would only cause variations of about $\pm 2\,cm$ in the water levels. Therefore, commercial weather glasses are not very sensitive with regard to pressure variations.

If the ratio $A/V_0$ is much smaller than in the calculated example, formula (6) simplifies to $\Delta p = -g \cdot \rho \cdot \Delta h$. It is only in this case that a difference of 1cm in the water levels is equivalent to 1hPa. With the home-made weather glasses, almost such a ratio can be achieved, which is a big advantage.

A different estimate applies to the sensitivity of the weather glass with regard to height. The atmospheric pressure $p$ depends on the height $h$ according to

$$p(h) = p_a \cdot e^{-\frac{h}{7990}} \qquad h = \text{height in m}; p_a = 1000\,hPa$$

A height of 10 m corresponds to a pressure of $p = 998{,}75\,hPa$. If you walk up or down four floors of a building (about 10 m) with a very sensitive weather glass ($1\,cm \cong 1\,hPa$), the difference in the water levels should be about 1.25 cm, with constant temperature assumed! This is relatively sensitive. Most commercial weather glasses are not appropriate for this experiment since they show only level differences of about 0.1 cm. A trip in an elevator in a skyscraper would be much more impressive but remember to keep temperature constant, which is not always possible.

A third estimate shows the sensitivity for temperature variations. A constant atmospheric pressure, i.e. $\Delta p = 0\,hPa$, is now assumed. From formula (6), the result is:

$$\Delta h = \frac{\dfrac{\Delta T}{T_0}}{\dfrac{A}{V_0} + \dfrac{g \cdot \rho}{p_a}}$$

A temperature difference of $\Delta T = 1K\ (= 1°C)$ with an absolute temperature of $T_0 = 293\,K$ $(= 20°C)$ and a ratio $A/V_0 = 0.01\,cm^{-1}$ (commercial devices) produces a difference in height of $\Delta h = 0.33\,cm$. This means that these weather glasses are more sensitive to temperature variations than to pressure variations. Homemade weather glasses are even more sensitive because the ratio $A/V_0$ is much smaller. The temperature sensitivity can be observed very well if the air-filled body of a weather glass is covered with your hands. The water drips easily out of the spout. At the same time, it is possible to get a sense about how the temperature reaches an equilibrium.

If you know formula (6) and construct your own weather glass, you can observe the factors that influence the sensitivity of the device. You can especially try to make $V_0$ as large as possible and to select a tube with a small cross-section $A$, thus minimizing the ratio $A/V_0$.

More hints and detailed error analysis can be found in the weblink [2].

**Weblinks**

[1] http://www.tomlom.de/flasche/flasche1.htm   *(mainly German, some English)*
[2] http://www.hjena.de/goethe-barometer/Goethe-Barometer.pdf *(in German)*
[3] http://www.ecobobs.co.uk/weather-glass-835-0.html