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Home-made barometers under pressure

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As part of their continuing badge work, 71st Reading Cub Scout pack made some simple instruments and used them to record the local weather for a fortnight. I was asked to lead the activity and we made raingauges, wind vanes and barometers – or at least we thought they were barometers.

Inverting a partly filled bottle of water in a shallow dish of water and monitoring the water level, or air column height, *H*, inside the bottle (see Fig. 1) is a simple experiment* that is commonly used to teach children about the presence and influence of atmospheric pressure. Here, the usefulness of this apparatus is challenged.

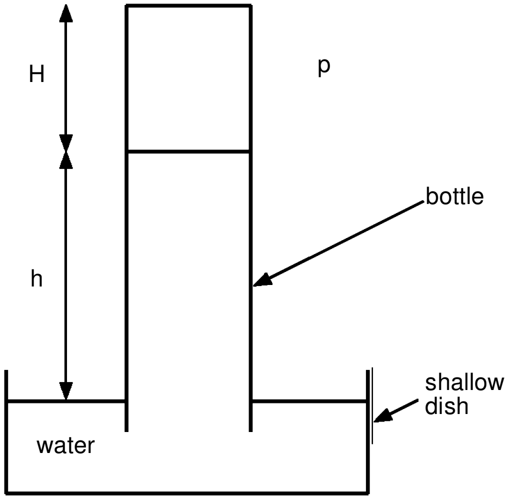

Fig. 1 Inverting a partly filled bottle of water in a shallow dish traps air in the bottle. Changes in the height, H, *of the trapped air correspond to changes in the atmospheric pressure,* p.

There are two types of home-made barometer often proposed as pressure-measuring devices, both measuring a changing volume of a fixed mass of trapped air. In the first method, the air is trapped by inverting a bottle in water (as in Fig. 1). In the other, the air is trapped in an empty food can that is sealed with a rubber balloon over the open top. Here, changes in air volume are measured with a drinking straw laid across the balloon to amplify volumetric changes in the air volume.† The practical difficulties of producing 20 equally tensioned balloon-sealed instruments made the simpler water-sealed instrument more convenient.

In preliminary tests of the instrument, there were no discernible changes in the air column height. After two weeks of recording, the cubs reported back that Reading had, barometrically speaking, seen an uninteresting fortnight; in fact, despite a 10 mbar pressure change that fortnight, the majority of cubs recorded 'no

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* For example, http://www.metoffice.com/education/curriculum/leaflets/es15.html

† For example, http://www.sciencenetlinks.com/lessons.cfm?DocID=156

change' in the air column height throughout the period. What went wrong? Why did the instrument not work?

Understanding the theory of the instrument

If the air trapped inside the inverted bottle (shown in Fig. 1) is approximated as an ideal gas, then the product of its volume (or height, H, in a container of uniform cross-section) and pressure is proportional to its temperature, T (in kelvins). Consequently, an expression for the pressure of the trapped air is given by atmospheric pressure, p, minus the hydrostatic head of water, height h, and can be written in terms of the air height, H, and the temperature, T:

$$(p-h\rho g)H = cT. \quad (1)$$

where ρ is the water density, g is the gravitational acceleration and c is a constant. For realistic variables ($p = 1000$ mbar, $h=0.1$ m, $\rho = 10^3$ kg m^{-3} and $g = 10$ m s^{-2}) the pressure of the trapped air is approximately the same as the atmospheric pressure, that is $p >> h\rho g$, and Eq. (1) becomes

$$pH = cT. \quad (2)$$

This means that the water in the bottle, of height $h = 0.1$ m, only acts to contain the trapped air. Moreover, for small pressure and temperature changes, Δp and ΔT, the fractional change in the air column height, $\Delta H/H$, is given by

$$\Delta H/H = \Delta T/T - \Delta p/p. \quad (3)$$

This states that either a pressure change of 10 mbar or a temperature change of 3 K will lead to a change in $\Delta H/H$ of 10^{-2}. In other words, for temperature and pressure changes in a typical week, this system is equally insensitive to changes in temperature and pressure.

Laboratory testing of the instrument

The hypothesis that the dominant physics of the instrument (shown in Fig. 1) can be modelled by an ideal gas trapped at atmospheric pressure, according to Eq. (2), is tested in a pressure chamber, as shown in Fig. 2. The instrument consists of an inverted test tube with 5 mm graduations, inverted in a beaker of water (Fig. 3(a)). The pressure in the chamber is calculated using a mercury manometer (Fig. 3(b)).

The air column height, H, is plotted against the chamber pressure for a range of pressures, 1000–470 mbar, and is shown in Fig. 4. These results are compared with the theoretical prediction of the air column height for an ideal gas. Assuming the environment to be isothermal and picking a constant pH that is the average of the experimentally determined values, it

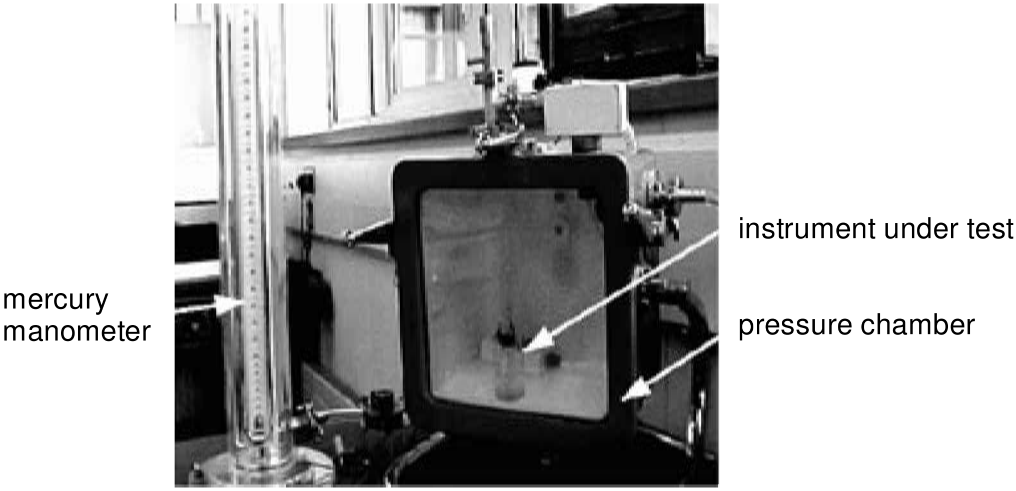

Fig. 2 The hypothesis that the instrument in Fig. 1 can be effectively modelled with ideal gas physics, described by Eq. (2), is tested in a pressure chamber

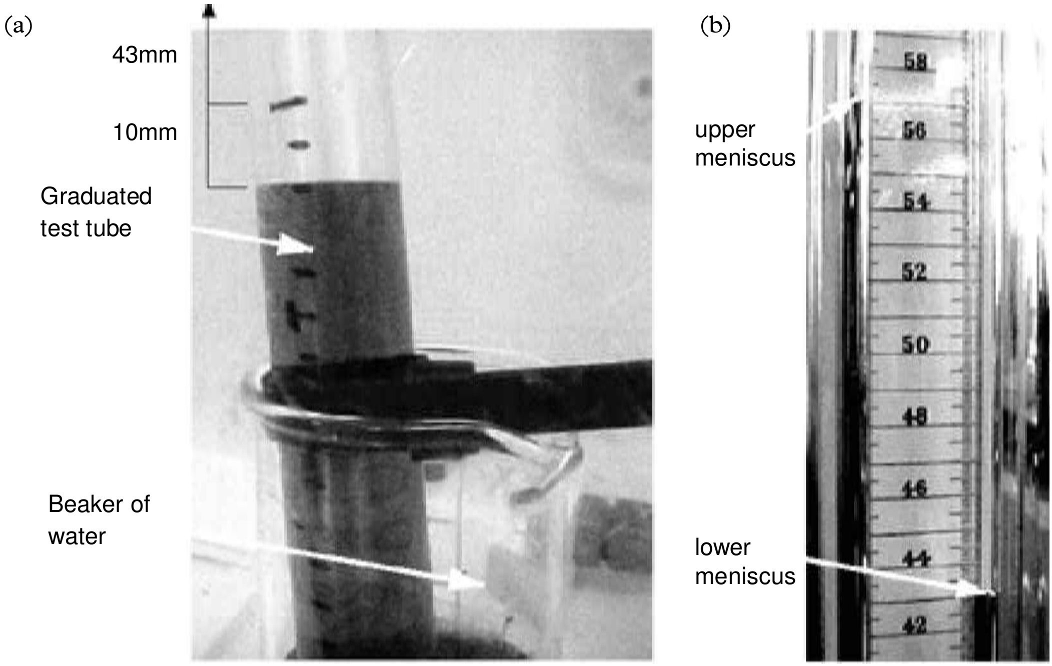

Fig. 3 The barometer consists of a test tube with 5 mm graduations inverted in a beaker of water, as shown in (a). The graduations start at 43 mm from the end of the tube such that, at atmospheric pressure, H=43 *mm. In (a) a decrease in pressure has resulted in a 10 mm drop in test-tube fluid height. This pressure drop is calculated from the mercury manometer, as shown in (b), using the apparatus set-up shown in Fig. 2. Here (b) shows a difference in mercury meniscus heights of 140 mm. This corresponds to a pressure drop of 190 mbar. Hence the 10 mm drop in test-tube fluid height is the result of a 190 mbar pressure drop.*

is found that there is only a 1% error in the ideal gas assumption.

Conclusions

The physics of the instrument shown in Fig. 1 is that of an ideal gas which, for typical atmospheric conditions, is as insensitive to temperature changes as it is to pressure changes. Indeed, Galileo Galilei (1564–1642) used the same mechanism to record temperature in an apparatus he called a 'thermoscope'.* As the system's behaviour can be described using ideal gas physics, pressure changes result in fractional changes in the trapped air volume, according to Eq. (3). This means that in order to monitor the variability in the daily pressure field with an instrument sensitivity of 1 mm mbar^{-1}, say, a uniform cross-section bottle with a 1 m trapped air column would be required. This is not realistically within the scope of the cited traditional designs.

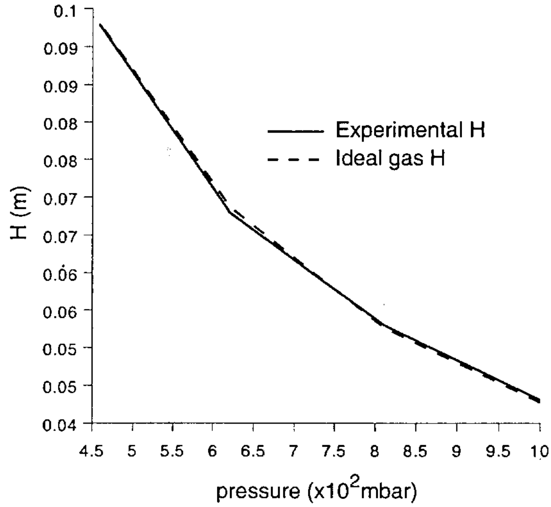

Fig. 4 Plotting the height, H, *of the trapped air column against the pressure,* p, *shows that the ideal gas assumption accurately models the behaviour of the instrument*

This apparatus could, however, be usefully

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* http://galileo.imss.firenze.it/museo/4/eiv07.html

employed as a thermometer to measure indoor/outdoor or diurnal temperature differences. Assuming $\Delta p/p = 0$, the temperature difference is calculated from Eq. (3) as:

$$\Delta T = (\Delta H/H) \times 280\,\mathrm{K}. \qquad (4)$$

In a 1-litre cola bottle (with an air column height of approximately 30 cm) this would be equivalent to a 1 cm change in gas height for every 10 K temperature change. Furthermore, not knowing the initial temperature would result in an error of less than 10% (the error obtained by guessing the initial temperature to be 280 K). The apparatus would be less useful, however, for measuring building heights when the surface pressure is unknown. Here, one would be better advised to follow Galileo's example by dropping the apparatus out of the window and timing its descent. In conclusion, this oft-quoted home-made instrument is simply inadequate for measuring atmospheric pressure variability.

Acknowledgements

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Obituary: P. J. Meade

Mr P. J. Meade, who died on 7 January 2002, just short of his 89th birthday, was one of the most effective and influential figures in the Meteorological Office during the post-war era. His appointment as Director of Services and Deputy to the Director-General from 1966 to 1973 was the culmination of 37 years of distinguished service in peace and war, and in many parts of the world.

Patrick Meade joined the Office in 1936 after graduating from Imperial College with first-class honours in mathematics and receiving the Lubbock Memorial Prize of London University. He was attracted by a phrase in the Office's advertisement for graduates in physics or mathematics, which stipulated that "candidates must be willing to serve in British territories overseas". He began his meteorological career at the Empire Flying Boat Base, Hythe, helping to provide forecasts for a flying boat attempting to fly across the North Atlantic, piggyback on another flying boat until it reached 2000 ft (610 m) before casting off! Having joined the Reserve of Air Force Officers (Meteorological Branch) in 1937, he served in northern France from September 1939 until evacuated from St. Nazaire in June 1940. He was then posted as Senior Meteorological Officer to GHQ Home Forces where, until July 1942, he advised on what weather situations would be favourable, especially for the release of smoke or poison gas, during a German invasion which, thankfully, did not materialise.

In October 1942 he set sail for north-west Africa as part of the Torch invasion force. As Chief Meteorological Officer, Eastern Air Command, he soon secured the co-operation of the French Meteorological Services of Tunisia, Algeria and Morocco in obtaining their routine observations so that he was able to establish, with the Americans, a forecasting service for the US and British armies as they advanced in north Africa and eventually through Sicily and Italy. Meade's outstanding work during these campaigns was recognised by the award of the OBE in 1944.

He left Italy early in November 1945 and in December arrived in Kandy (Ceylon), as Chief Meteorological Officer, Air Command South East Asia, with the task of rationalising the meteorological stations spread across south-east Asia from India to Japan, and of assessing the capability of the national services in the countries recently under Japanese occupation and the resources required to make them fully functional again.

After leaving the RAF in 1947 with the rank of Group Captain, he returned to the Office as