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What is Wrong with Water Barometers?

Dan Sullivan
University of Nebraska at Omaha, dsullivan@unomaha.edu

Robert W. Smith
University of Nebraska at Omaha, robertsmith@unomaha.edu

E. J. Kemnitz
University of Nebraska at Omaha, ekemnitz@unomaha.edu

Kevin Barton
University of Nebraska at Omaha, kbarton@unomaha.edu

Robert M. Graham
University of Nebraska at Omaha, rgraham@unomaha.edu

See next page for additional authors

Authors
Dan Sullivan, Robert W. Smith, E. J. Kemnitz, Kevin Barton, Robert M. Graham, Raymond A. Guenther, and Larry Webber

WHAT IS WRONG WITH WATER BAROMETERS?

Dan M. Sullivan, Robert W. Smith, and E.J. Kemnitz

Department of Chemistry

University of Nebraska at Omaha

Omaha, Nebraska 68182 USA

Kevin Barton, Robert M. Graham, Raymond A. Guenther, and Larry Webber

Department of Physics

University of Nebraska at Omaha

Omaha, Nebraska 68182 USA

Every student who studies atmospheric pressure in physics or chemistry learns the principles behind the construction of barometers. Cistern barometers, such as those found in most laboratories, consist of a long glass tube containing an inverted column of liquid having an open end in a cistern of the liquid. Students learn that the column of liquid is supported by air pressure and is equal in weight to a column of air of the same diameter.

While most cistern barometers are filled with mercury, many instructors describe cistern *water* barometers, but few such *permanent* barometers have actually been constructed and those reported in modern times require periodic adjustments. In fact, it is unlikely that any of the early water barometers actually functioned without continual adjustment. When we built a working water barometer, a line diagram of which is shown in Figure 1, we found and corrected systemic problems whose solutions lead us to believe that our present model is the first such barometer ever constructed that functions without constant adjustment.

Science teachers usually explain that cistern barometers contain mercury because water barometers are too tall to fit in a typical room. Since mercury has a density 13.6 times that of water, mercury barometers can be 13.6 times shorter than water barometers.

The Durham Science Center at the University of Nebraska at Omaha contains an atrium that separates the two halves of the building. After moving into this building in 1987, it occurred to us that this would be a suitable location for a water barometer. The instrument could be located inside, so we would avoid weather problems. A series of balconies would lend support for the barometer, and the 50-foot atrium of the building was tall enough to accommodate the column.

We built a base platform and fashioned a column of 1½-inch interior diameter transparent PVC tubes joined together with rubber “no-hub” type couplings. The column was nearly 11 meters long and was closed at the top with a valve so that a vacuum line could be attached. The column was attached by stand-off clamps to a two-by-four inch aluminum channel anchored to each level of the balconies. The lower end of the column was immersed in a five-gallon carboy. We used an aqueous solution of blue copper sulfate (specific gravity 1.018) as the fluid to improve visibility. After a vacuum pump was attached to the top end of the column, we evacuated the column and allowed air pressure to push the colored water up. At first, the water boiled at the top of the column, but eventually the boiling slowed and the height appeared to stabilize.

We placed a standard mercury barometer on the wall near the base of the water barometer and added signs on the column marking the typical pressures at various locations, such as Death Valley (near the top of the column), the top of Chimney Rock in western Nebraska, Pikes Peak, Mount Everest, the surface of Mars, and the surface of our Moon (a few centimeters above the surface of the liquid in the cistern). Tape with centimeter markings was placed on the top of the column to read variations in its height from the third-floor balcony. It was a beautiful installation.

Unfortunately, our euphoria was short-lived. To our dismay, the column of water fell several centimeters overnight, more the next day, and more the day after that. Bubbles of gas continually appeared in the solution near the top of the column, rose to the surface, and burst. Water solutions exert a vapor pressure. At 22 ºC, the vapor pressure of water is 19.83 mm of mercury, or about 27 cm of water, so the level of liquid in the column should have been that much lower, but bubbles continually rose to the surface, and the level of the column fell even farther.

Many hypotheses were advanced to account for the falling water level. One held that air was leaking through the plumbing fittings. Another suggested that the valve at the top was leaking. We sealed the joints with silicon-based glue and sealed the valve with a water lock, but the problem persisted. All these theories eventually gave way to an explanation we should have considered earlier, namely, that air is soluble in water, and that air was dissolving in the open carboy of water at the bottom and diffusing to the top of the column, where at low pressure, it bubbled out.

We tried many measures to stop the dissolving and outgassing of air. We first put a layer of mineral oil atop the solution in the carboy, and this slowed, but did not completely stop the transfer of air. Next, a plastic piston fitted with O-rings was inserted into the column, and some improvement was seen, but the piston did not move freely, and a large bubble of gas (probably from dissolved air outgassing from the column) accumulated on its lower side. The question was: How could we allow the fluid inside the column to be affected by changes in air pressure without coming into contact with air itself?

At last, we hit upon a solution which was not as aesthetically pleasing as the original design but was more practical: We filled a small automotive inner tube with copper sulfate solution and attached it with tubing to the bottom of the plastic column; see Figure 2.

The column was partially filled with liquid and pumped. The liquid rose as before and stopped at the same distance from the bottom. We again observed some outgassing, but less than before. With successive pumpings over a period of time, we observed less and less outgassing, and the level of liquid in the column now remains at nearly the same level except for changes in atmospheric pressure and temperature.

Our water barometer responds well to changes in atmospheric pressure. Of course, the air at the top of column is saturated with water vapor, and the vapor pressure of water varies with temperature, so the level of the column may fall 5-10 centimeters during a warm afternoon. In order to insure accuracy, temperature fluctuations must be considered.

Our experiences with water barometers led us to examine its literature.

In the Amateur Scientist column of the April, 1987 issue of *Scientific American,* Jearl Walker discussed the design of water barometers[1] and described an instrument built in 1641 by Gasparo Berti of Italy. He noted that the original design failed to function well and stated that the reason for this was the vapor pressure of water, which varied when the temperature changed.

Walker also reported that a Mr. Sam Epstein of Los Angeles had built a functioning water barometer and replaced the water with an ethylene glycol solution to reduce evaporation. By Walker's account, this barometer functioned correctly. However, the solubility of gases in aqueous solutions is often overlooked and we suspected that air is also soluble in ethylene glycol. To check this possibility, we added a column filled with dilute ethylene glycol alongside our water column, evacuated it, and observed that the column level fell as bubbles of gas again formed near the top.

We suspect that most previous water barometers suffered falling levels due to an outgassing of dissolved air, but that in most cases the builders believed that the drop in level was due to leaks in the column, just as we at first thought that our column was leaking. It is our further contention that the level in the water/ethylene glycol barometer built by Epstein probably also fell, and it would be natural to blame the drop on leakage.

This problem will afflict all cistern barometers that rely on a column of liquid in which air is soluble. In fact, Epstein later built a siphon barometer, with the pressure changes read by measuring the height of a column of ethylene glycol in the short end of J-tube connected to a longer closed column. Although we have not built and tested this device, we find no reason to believe that it would not suffer the same problem of air dissolving in and passing through the solution. Because air is insoluble in mercury, laboratory barometers do not suffer this problem, which together with mercury's high density makes it a felicitous choice for the barometer fluid.

As a general resource on the subject of barometers, we recommend to our readers the extensive and excellent historical study by W. E. Knowles Middleton[2].

The first true barometer is ascribed to Evangelista Torricelli. Although his predecessors probably experimented with mercury-filled columns, Torricelli was the first (in 1644) to actually describe construction of a mercury column suspended by the pressure of "fifty miles of air"[3]. During this period, minds such as those of Pascal, Boyle, Hooke, Torricelli and others were turned more to arguments about the absence or existence of a vacuum (science and philosophy being synonymous in their minds), and many early barometer-like devices were employed to this end.

Most early water barometers were filled by driving water up the tube from below to the top (steam power was sometimes used for this purpose) or by filling the tube, closing a stopcock at the top, and allowing the level to fall. A water barometer built by Robert Boyle could, in our opinion, have functioned nearly continuously as designed, because he used a vacuum pump to establish the column height and could have pumped a vacuum on the column daily[4].

To our knowledge, no other water barometer in *continuous* operation exists anywhere in the world, though some are reported to be on display in foreign museums but require daily pumping[5,6]. Russell Akridge of Kennesaw State College described an inexpensive, *temporary* water barometer for use in classroom demonstrations in 1993[7]. We first reported the construction of our water barometer at the September 1997 meeting of the American Chemical Society[8].

Our working water barometer stands today in the atrium of Durham Science Center on the campus of the University of Nebraska in Omaha as shown in Figure 3. It responds quickly to changes in barometric pressure, varying in level as much as twenty centimeters during a change in weather patterns. Movement of a high-pressure system into the area results in a dramatic rise in the level of fluid, and periods of low pressure are easily observed. We use the column as an example in classroom discussions of atmospheric pressure, and visitors can see an elegant example of the weight of the atmosphere in action.

Endnotes

1. J. Walker, “The amateur scientist,” *Sci. Am.* 256 (4), 122-127 (April 1987).

2. W.E. Knowles Middleton, *The History of the Barometer*, (Johns Hopkins Press, Baltimore, 1964).

3. E. Torricelli, *Opere, vol III,* G. Loria and G. Vassura, Eds. (Montanari, Faenza, 1919), p. 188.

4. W.E. Knowles Middleton, *ibid.*, p 365.

5. Hans de Grys, “Thirty feet and rising: Constructing and using a water barometer to explore chemical principles,” *J. Chem. Ed.* 80 (10), 1156-1157 (October 2003).

6. The Bert Bolle Barometer, Denmark (Australia) Visitor Centre. http://www.bertbolle.com (accessed May 2008).

7. Russell Akridge, “Water Barometer,” *Phys. Teach.* 31, 110-111 (February 1993).

8. D.M. Sullivan, E.J. Kemnitz, M.G. Reedy, K. Barton, R.M. Graham, R.W. Smith, S. Stenberg, and L. Webber, Presented at the 214th National Meeting of the American Chemical Society, Las Vegas, NV, September, 1997.

Figure Captions

Figure 1 A line diagram of the water barometer.

Figure 2 Professors Smith (left) and Sullivan (right) at the base of the water barometer. Notice the inner tube at the bottom of the water column.

Figure 3 A perspective from the third-floor balcony showing the entire water barometer in the atrium of the Durham Science Center on the campus of the University of Nebraska at Omaha.