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Julien Vandermarlière

Jochen Kuhn and Patrik Vogt, Column Editors
University of Kaiserslautern, Kaiserslautern, Department of Physics/Physics Education Group, and University of Education Freiburg, Germany; kuhn@physik.uni-kl.de

On the inflation of a rubber balloon

Julien Vandermarlière, Collège Saint-Exupéry of Perpignan, France; julien.vandermarliere@ac-montpellier.fr

It is a well-known fact that it is difficult to start a balloon inflating. But after a pressure peak that occurs initially, it becomes far easier to do it! The purpose of this article is to establish the experimental pressure-radius chart for a rubber balloon and to compare it to the theoretical one. We will demonstrate that the barometer of a smartphone is a very suitable tool to reach this goal. We hope that this phenomenon will help students realize that sometimes very simple questions can lead to very interesting and counterintuitive science.

Theoretical background

Rubber balloons have been very good toys for children for decades. And for physicists too! Indeed, they do not deform according to Hook's law, but rather they expand in a strange way as we shall see below. They are made of long flexible chains of polymer that are coiled and joined together by randomly oriented chemicals bonds[1] (Fig. 1).

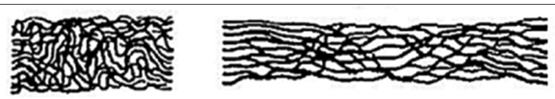

Fig. 1. Chains of polymer in a rubber material at different elongation.

When we inflate a balloon, those chains start to be straightened out. The average distance between bonds increases, and this initiates the restoring force, which tends to return the balloon to its initial shape. For a short time, it is very difficult to fight against it. But once the chains are stretched a little bit, they become more organized and the rubber becomes more stretchy. The pressure inside the balloon now evolves like the pressure inside a bubble soap: it decreases as the radius increases. But at large elongation the chains are completely stretched out and new phenomena like strain-induced crystallization result in some stiffening; the pressure goes up again!

A number of physicists have been interested in this behavior and introduced a variety of physical descriptions.[1-3] Verron and Marckmann[3] proposed Eq. (1) in the case of a Mooney-Rivlin type spherical balloon:

$$P = K\left[\frac{R_0}{R} - \left(\frac{R_0}{R}\right)^7\right]\left[1+0.1\left(\frac{R}{R_0}\right)^2\right], \qquad (1)$$

where R_0 is the initial radius and R the deformed radius. K is a coefficient dependent on the material parameters. The associated inflation curve looks like Fig. 2.

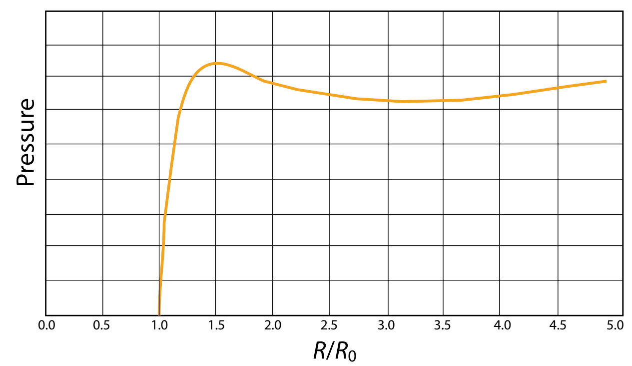

Fig. 2. Theoretical pressure-radius curve [see Eq. (1)].

The experiment

It has been reported in this column that smartphone barometers are good enough for real physics experiments,[4] so a Samsung S5 was inserted into a balloon. Hopefully, the rubber is a tactile enough material and is transparent enough to see the screen so that we can still control the smartphone!

The Barometer Graph[5] app was launched, and the evolution of the pressure vs. time was recorded while the balloon was being inflated. A single exhalation was used to inflate the balloon, made as regular as possible. A screenshot of the result is shown in Fig. 3.

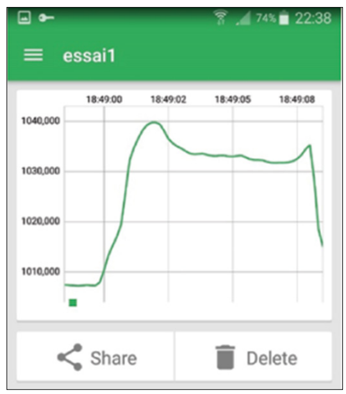

Fig. 3. Screenshot of the Barometer Graph app (pressure is in hPa, time in seconds is on the horizontal axis).

First, the pressure increases quickly and reaches a peak. Then it decreases, which is very counterintuitive! At the end of the inflation the pressure goes up again. Finally, the inflator's lips and balloon are separated and the balloon deflates. The main characteristics of the theory are seen.

In order to obtain better measurements, a second experiment was performed. This time the Physics Toolbox Sensor Suite app was used to measure the pressure.[6] The smartphone was controlled via Wi-Fi from a computer using the SideSync app[7] (Fig. 4). While the balloon was inflated, the circumference was measured as well. Then a spreadsheet was used to plot the pressure as a function of the radius ratio, $P = f(R/R_0)$ (Fig. 5).

Once again the experimental inflation curve (in blue) matches the theoretical curve. The pressure peak (1040.7 hPa) is only 3% greater than the atmospheric pressure and occurs when R/R_0 is about 1.44 (point A). This matches fairly well the theoretical prediction of Verron and Marckmann,[3] which is 1.48 [from Eq. (1)]. The difference is only

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Fig. 4. The smartphone in a balloon! The Physics Toolbox app is controlled from the computer via Wi-Fi with the SideSync app.

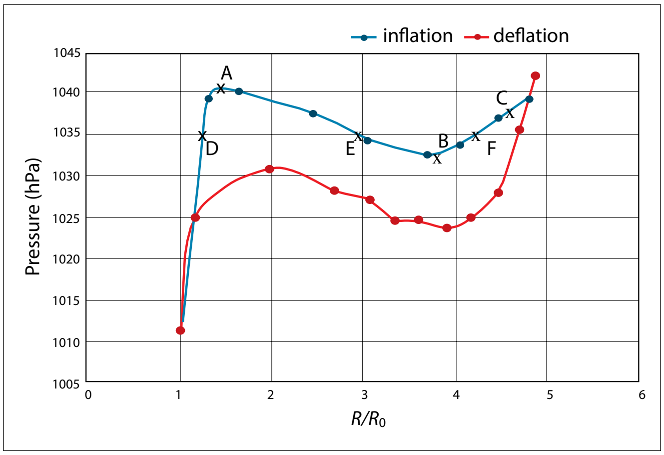

Fig. 5. Experimental chart.

2.8%. We also looked at the deflation of the balloon (in red). An interesting hysteresis phenomenon is clearly visible. It can be explained by the fact that when the balloon returns to its original shape, the polymer chains never get back to their initial orientations. This measurement process was repeated with several balloons and the experiment consistently produced similar results.

Comments

This work can help to explain what seems to be a paradox: the two balloons experiment.[8] If you connect two balloons with a hollow tube, one big and one smaller, and let the air rush between them, the small one can inflate the big one! This is because most of the time the balloons are on the [AB] interval of the chart in Fig. 5. But the opposite is also possible if the smallest balloon is at B and the biggest at C. It is possible to reach equilibrium as well. Take three balloons and inflate them to reach the D, E, and F points. Connect them together and… nothing will happen. Their internal pressures are exactly the same! This experiment can easily be done in the classroom, and students may learn lots of interesting things while doing it!

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8. See, for example, F. Weinhaus and W. Barker, "On the equilibrium states of interconnected bubbles or balloons," *Am. J. Phys.* **46**, 978 (1978).

Fermi Questions

Larry Weinstein, Column Editor
Old Dominion University, Norfolk, VA 23529; weinstein@odu.edu

Question 1: Miles of spaghetti

How many miles of spaghetti do Americans consume yearly? What linear speed does this represent (i.e., how fast would a single strand have to be slurped to cover that distance in a year)?

Question 2: Wrapping paper

How much wrapping paper do Americans use yearly?

Look for the answers online at *tpt.aapt.org*. Question suggestions are always welcome! For more Fermi questions and answers, see the now available *Guesstimation 2.0: Solving Today's Problems on the Back of a Napkin,* by Lawrence Weinstein (Princeton University Press, 2012).

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