Using pycnometry and Archimedes’ principle to measure the gross and air cavity volume of fruit

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Abstract

A technique based on Archimedes’ Principle is described for measuring the volume of small objects (0.5–5 cm³) less dense than water. The volume of 10 small red chillies was measured by pycnometry and an immersion Archimedes technique which involved suspending the chillies in water in a container placed on an electronic balance. A pycnometer, which uses helium gas is able to determine the internal solid volume of the chillies and water immersion the outer volume. The difference between the two volumes gives the volume of internal air cavities in the chillies. The pycnometer and immersion techniques were compared by measuring the volume of wax candles with volumes between 0.3 and 2.5 cm³. A Bland-Altman analysis revealed that the Archimedes volumes were lower than pycnometry volumes by ±6.1 ± 2.3% which needs further investigation. A combination of pycnometry and water immersion may be a useful tool for botanical studies.

Introduction

Hughes (2005) described a quick, cheap and accurate method for measuring the volume of small objects (1.5–15 cm³). The technique involved suspending an object denser than water in a container of water placed on an electronic balance. The volume of the immersed object was the increase in the mass divided by the density of water. The technique can also be used to measure the density of an unknown liquid if an accurately known volume is immersed in liquid (Hughes 2006), and the technique is sensitive enough to measure the variation of the density of water with temperature, relevant to teaching students about climate change (Hughes and Pearce 2015). The Archimedes immersion technique has previously been used to measure the internal air cell volume of fruit, by measuring the volume before and after the removal of air by vacuum (Drazeta et al. 2004).

In the current paper, pycnometry is combined with the Archimedes immersion technique to measure air cell volume. Chillies were chosen to emphasise the value of the technique for measuring the volume of botanical samples less dense than water. When the Archimedes immersion method is used to measure the volume of objects with a density greater than water, objects can be suspended from a monofilament. However, this technique cannot be used for objects that float in water and so a pin was used to hold the chillies underwater.

Method

Ten small red chillies were bought from a local supermarket (figure 1). The residual stem was removed from each chilli. A chilli holder was constructed by fixing a sewing pin 0.6 mm in diameter, and 40 mm in length into the end of an empty plastic biro case using quick set Araldite. Two marks were made on the pin using an indelible marker, one 5 mm from the tip and the other 15 mm.

The holder was held in a laboratory stand placed on a laboratory scissor jack. Each chilli was inserted onto the end of the pin to a depth of 5 mm (figure 2). The scissor table was lowered to immerse each chilli to a depth of
10 mm in water in a container placed on an electronic balance (AND GX-2000) with a maxim capacity of 2.1 kg and precision of ±0.01 g (figure 3).

The error in positioning the chilli on the end of the pin was estimated at ±1 mm and positioning the 15 mm pin mark level with the water also ±1 mm. The presence of the meniscus makes it slightly more difficult to align the mark with the surface of the water. Therefore, the combined error in the length of the immersed pin is ±2 mm. This translates to an immersed pin volume of $2.8 \pm 0.6 \times 10^{-3}$ cm$^3$. This volume was subtracted off each immersion volume. The balance was tared before the immersion of each chilli. The volume was the increase in mass divided by density of water as 0.9983 cm$^{-3}$ at 20 °C the temperature of the laboratory.

Chilli volumes were measured using an Accupyc II 1340 pycnometer from Micromeritics. Each chilli sample was weighed and placed inside the 100 cm$^3$ sample chamber. After sealing the chamber of the pycnometer a series of cycles are performed to purge the contents inside the chamber with helium. Once the chamber is full of helium at a specific pressure (in this case is 19.5 PSI) the test starts. The device provides results for multiple cycles of pressurised helium in the sealed chamber. The mass of the chilli is typed into the pycnometer computer and at the end of the measurement the specific gravity is given. Volume is found by dividing mass by specific gravity. Five readings were averaged for each chilli (save one for which only four readings were available) and two readings for each wax candle.

There was a problem obtaining pycnometery volume with chilli volumes over 4 cm$^3$. This was probably due to helium being absorbed too fast by the chillies, which is a known problem when pycnometery is performed on organic materials. The pycnometer settings were adjusted to allow measurements to be made with a higher than normal helium absorption rate.

Another experiment was performed to measure the pycnometer and Archimedes volumes of wax candles. Wax is a good test material for this project since wax does not absorb helium or water and is less dense than water. Two pycnometer and Archimedes volumes were taken and averaged. A Bland-Altman plot (Bland and Altman 1986) was used to assess the agreement between the two methods of measuring volume.
A selection of wax birthday candles was cut into lengths between 0.5 and 5.0 cm in approximately 0.5 cm increments. The mass and Archimedes volumes were obtained using a balance with a capacity of 120 g and precision of \(\pm 0.1\) mg. The candles were pushed onto the end of the pin to an estimated depth of 1 mm and the pin with the candle on the end immersed to the 15 mm mark. However, the last two candles 4 and 4.5 cm in length were immersed to only the 5 mm line to stop the candles from hitting the bottom of the water container on immersion.

**Results**

The chilli masses, volumes and densities are shown in table 1. The mean Archimedes density was 0.77 \(\pm\) 0.061 g cm\(^{-3}\) and the mean pycnometer density 1.11 \(\pm\) 0.019 g cm\(^{-3}\). Figure 4 shows a scatter plot of pycnometer volume against Archimedes volume. Figure 5 shows a scatter plot of pycnometer volume and Archimedes volume verses chilli mass. Table 2 shows the mass, volumes and densities of the 10 wax candles. Figure 6(a) shows a scatter plot of Archimedes versus pycnometry candle volumes and figure 6(b) shows a Bland-Altman plot. The central horizontal dotted line

| Chilli # | Mass (g) | Pyc. Vol. (cm\(^{-3}\)) | Arc. Vol. (cm\(^{-3}\)) | Pyc. Den. (g cm\(^{-3}\)) | Arc. Den (g cm\(^{-3}\)) |
|---------|----------|--------------------------|--------------------------|--------------------------|--------------------------|
| 1       | 2.04     | 1.82                     | 2.69                     | 1.12                     | 0.76                     |
| 2       | 2.12     | 1.94                     | 2.88                     | 1.10                     | 0.74                     |
| 3       | 2.05     | 1.88                     | 2.66                     | 1.09                     | 0.77                     |
| 4       | 2.56     | 2.30                     | 2.93                     | 1.11                     | 0.87                     |
| 5       | 2.3      | 2.04                     | 3.21                     | 1.13                     | 0.72                     |
| 6       | 2.85     | 2.55                     | 4.02                     | 1.12                     | 0.71                     |
| 7       | 4.63     | 4.24                     | 5.62                     | 1.09                     | 0.82                     |
| 8       | 5.07     | 4.58                     | 6.48                     | 1.11                     | 0.78                     |
| 9       | 4.49     | 4.12                     | 6.32                     | 1.09                     | 0.71                     |
| 10      | 5.32     | 4.63                     | 6.38                     | 1.15                     | 0.83                     |
| Mean    |          |                          |                          | 1.11                     | 0.77                     |
| sd      |          |                          |                          | 0.019                    | 0.061                    |

Figure 3. Chilli on the end of a pin immersed in water in a container on a balance. The balance was tared before immersion and therefore the increase in mass is directly correlated with volume.
shows the mean difference between the two methods and the upper and lower dotted lines shows plus and minus two standard deviations, which are expected to encompass about 95% of the data points.

**Discussion**

The pycnometer and Archimedes volumes are significantly different. This is presumably because helium infuses through the skin of the chillies into the air spaces (figure 7). The Archimedes immersion technique gives the bulk

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**Figure 4.** Scatter plot of pycnometer verses Archimedes chilli volume.

**Figure 5.** Scatter plot of Archimedes and pycnometer volume verses mass. The difference in the pycnometer and Archimedes volume is the air cell volume of the chilli.
Figure 6. (a) Scatter plot of pycnometer and Archimedes candle volumes. The line of identity is shown. (b) Bland-Altman plot for candle volumes. The dotted lines show the mean difference plus and minus two standard deviations, which encompasses approximately 95% of normally distributed data points.

Table 2. Data obtained for the wax candles.

| Candle # | Mass (g) | Pyc. Vol. (cm$^3$) | Arc. Vol. (cm$^3$) | Pyc. Den. (g cm$^{-3}$) | Arc. Den. (g cm$^{-3}$) | % vol diff |
|----------|----------|--------------------|--------------------|-------------------------|-------------------------|------------|
| 1        | 0.2895   | 0.330              | 0.314              | 0.878                   | 0.921                   | 4.684      |
| 2        | 0.49     | 0.594              | 0.533              | 0.825                   | 0.919                   | 10.243     |
| 3        | 0.6163   | 0.715              | 0.670              | 0.862                   | 0.919                   | 6.212      |
| 4        | 0.8491   | 0.996              | 0.927              | 0.853                   | 0.916                   | 6.940      |
| 5        | 1.0696   | 1.289              | 1.178              | 0.830                   | 0.908                   | 8.586      |
| 6        | 1.39085  | 1.480              | 1.421              | 0.940                   | 0.979                   | 3.995      |
| 7        | 1.5006   | 1.700              | 1.633              | 0.883                   | 0.919                   | 3.915      |
| 8        | 1.7442   | 1.989              | 1.902              | 0.877                   | 0.917                   | 4.377      |
| 9        | 1.921    | 2.204              | 2.098              | 0.872                   | 0.916                   | 4.827      |
| 10       | 2.163    | 2.487              | 2.366              | 0.870                   | 0.914                   | 4.842      |
| Mean     |          |                    |                    | 0.869                   | 0.921                   | 5.862      |
| sd       |          |                    |                    | 0.032                   | 0.020                   | 2.131      |
chilli volume and pycnometry the solid volume. Therefore, the difference between the two is air cavity volume. The two types of volume correlate with mass.

The bulk density of chillies is less than water, as expected since chillies float on water. The solid density of the chillies is greater than water and the standard variation \( \sigma = 0.019 \text{ g cm}^{-3} \) is smaller than for the bulk density \( \langle \sigma = 0.061 \text{ g cm}^{-3} \rangle \).

There is a high correlation \( R^2 = 0.993 \) between candle pycnometer and Archimedes volumes (figure 6(a)), although the Bland-Altman plot (figure 6(b)) reveals that the Archimedes volume are smaller than the pycnometer volumes by 6.1 \( \pm \) 2.3\%. This discrepancy needs further investigation. There may be a layer of air between the water and wax which is affecting the Archimedes volume. Another issue in measuring the volume of the wax candles is that helium will fill the tiny cavities on the surface whereas water will not.

The combined pycnometer/Archimedes method described in this paper could be useful for botanical research where information is required on the ratio of the air cavity spaces to the total volume of a fruit or vegetable. The technique would also be useful for measuring the volume of objects of greater density than water where it is convenient to hold the object on the end of a needle.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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