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Affordable methods for surface tension and contact angle measurements

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Abstract

In this paper, we present two different experiments aimed at supporting the understanding of surface phenomena at undergraduate level. In the first experiment, we measure the surface tension of several common liquids like water, oil, alcohol, etc by using a simplified custom-built Du Nouy ring apparatus. In the second experiment, the contact angle at the water-glass-air interface is estimated by means of two glass slides that form a sort of variable-size capillary. Materials and experimental apparatuses require a low budget, but the results agree very well with those reported in the literature, obtained with much more sophisticated and expensive equipment. This makes the experiments presented here suitable for educational paths aimed at understanding surface phenomena at undergraduate and even at high school level.

Keywords: surface tension, contact angle, educational experiments, liquids, Young-Duprè equation, Du Nouy ring apparatus

(Some figures may appear in colour only in the online journal)

1. Introduction

Although the comprehension of surface phenomena is relevant not only in Physics but also in disciplines such as Chemistry, Biology and Engineering, the traditional approaches for introducing surface tension often prove to be ineffective in supporting students'

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understanding [1–3]. For this reason, it is worth looking for new ways and new tools to present this topic [4, 5]. Fluid mechanics is one of the oldest branches of physics, with literature vast and complex. However, it has not sufficiently captured the interest of STEM educators like other subjects such as quantum mechanics [6, 7]. Research on teaching and learning fluid mechanics ranges from fundamentals to computational physics, from mathematical to interdisciplinary approaches [8, 9]. Few research papers deal with the field of surface phenomena and most of them are related to experiments for educational purposes. Particularly, some papers deal with the measurement of surface tension [10–12]. However, the experiments are usually designed to measure the surface tension only for one liquid (usually water) [11] or involve measurement procedures too complex for teaching laboratories [12]. Moreover, usually, the proposed methods make use of expensive equipment [13]. It is also difficult to find in the literature examples of experiments for the estimation of the contact angle between water and glass, for example.

Here, we propose and discuss two experiments that are part of a wider research aimed at promoting the development and testing of innovative and motivating strategies to improve the teaching-learning processes of surface phenomena at undergraduate level. These strategies require that students are involved in hands-on and minds-on experiments in the context of interactive lessons aimed at supporting students' active learning [14, 15]. Such an approach may be helpful in promoting students' interest and authentic reasoning [16] about physical phenomena.

The equipment required for the experiments is readily accessible and very cheap. A simplified custom-built version of the well-known Du Noüy ring [17] is used for investigating the surface tension of several common liquids. A system with a continuously variable-size capillary is used to estimate the contact angle at the water-glass-air interface.

2. Measurements of surface tension

2.1. The Du Noüy ring method

In the Du Noüy ring apparatus, a metallic (usually gold or platinum) ring is slowly lifted from the surface of a liquid. The ring is designed to have a very thin circular profile at one side (the one that is immersed in the liquid), like a knife blade. In this way, the liquid adheres to the ring forming a thin circular layer and determining a clear break of the liquid itself in correspondence with which it is possible to measure the surface tension. The force F required to detach the ring from the liquid surface can be related to the surface tension γ as follows:

$$F = F_{\text{ring}} + 2\,(2\,\pi\,R)\,\gamma, \tag{1}$$

where F_{ring} and R are the weight and the inner radius of the ring, respectively. Since the thickness of the ring is negligible with respect to its radius, inner and outer radius can be considered equal in size. The multiplying factor 2 in equation (1) is due to the internal and external forces applied on the circular profile of the ring. Equation (1) allows one to estimate γ once F, F_{ring} and R have been experimentally determined.

2.2. Experimental apparatus and results

The experimental apparatus that we designed to reproduce the Du Nouy experiment is shown in figure 1.

We use a digital scale with a resolution of 0.01 g to measure F and F_{ring}. It is worth noting that in this case, F_{ring} is equal to the weight of the ring with its support as shown in figure 1. In

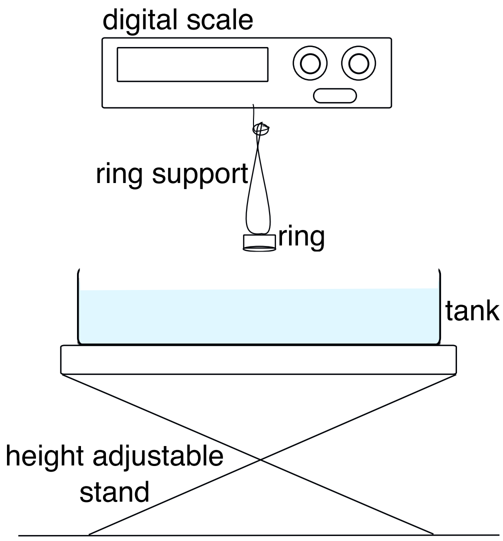

Figure 1. A sketch of the experimental apparatus for the surface tension measurements with the Du Noüy ring method.

Table 1. Reference and measured values of surface tension γ, expressed in Nm^{-1} at $\sim$20 °C.

Liquid	Reference value	Measured value
Demineralised water	0.073	0.069 ± 0.004
Glycerol	0.064	0.064 ± 0.012
Peanut oil	0.035	0.036 ± 0.003
Corn oil	0.034	0.033 ± 0.003
Sunflower oil	0.033	0.034 ± 0.003
Soap solution	0.025	0.026 ± 0.003
Ethyl alcohol	0.022	0.025 ± 0.003

this experiment, the force F acting on the ring is measured in traction by hanging the ring and its support on the scale by means of a suspension hook. The ring is made of aluminium, which is an inexpensive material easily machined with a common lathe. As for the Du Noüy's rings, it has a very thin profile (on the side that gets wet), comparable to the thickness of a sheet of paper and therefore about 2 tenths of a millimeter. The inner radius is $R = (1.410 \pm 0.005)$ cm. Figure 2 shows the ring at the moment of its detachment from the water surface. Water behaves as an elastic film.

It is worth noting that if the ring is rapidly detached, the liquid film may not properly break off from the thin profile of the ring obtaining unreliable measurements.

This low-cost Du Noüy ring apparatus allowed us to estimate the surface tension of many common liquids, as commercial demineralised water, 99% ethyl alcohol, pure glycerol, common commercial peanut, sunflower, corn oil and 30 ml dishwashing soap with 100 ml demineralised water mixture. The measured values with their uncertainty and the reference value [18, 19] for each liquid are reported in table 1. The uncertainties shown in table 1 were

Figure 2. A photo of the ring at the moment of its detachment from the water surface. It shows the deformation of the elastic film formed by the water at the liquid–air interface.

obtained as the sum of two contributions. A random uncertainty (for each liquid repeated measurements were made) and an instrumental uncertainty. In our measurements, the random uncertainty is always greater or equal to the instrumental one. For example, in the case of sunflower the random and instrumental uncertainties are about 0.0027 Nm^{-1} and 0.0022 Nm^{-1}, respectively.

3. Measurement of the water-glass contact angle

The apparatus used in this experiment is made of two microscope glass slides facing each other. On one side the slides are in contact, on the opposite side they are separated by a toothpick, which creates a separation between the slides of about 2 mm as shown in figure 3. The slides are held tight by tweezers, as shown in figure 4. In this way, we made a sort of continuously variable-size capillary.

When we immerse the lower base of the slides in a vessel filled with water, we observe that the liquid rises between the slides. The effect is gradually more evident where the slides are closest to each other as shown in figure 4. In figure 4 is also evident that the rising of water between the two glass slides varies with the position along the horizontal direction. We used the video analysis tool of the commercial software LoggerPro [20] to add red dots along the liquid profile, as shown in figure 5.

Let us derive, for this physical system, the relationship between the height reached by the liquid and the horizontal position x, by following a thermodynamics approach.

The distance between the two slides is a function of the coordinate x along the glass slide. The mass $\mathrm{d}m$ of water contained between the two slides in an infinitesimal interval $\mathrm{d}x$ and in a generic position x, is $\mathrm{d}m = \rho\, y(x)\mathrm{d}(x)\mathrm{d}x$ where $y(x)$ is the height reached by the liquid as a

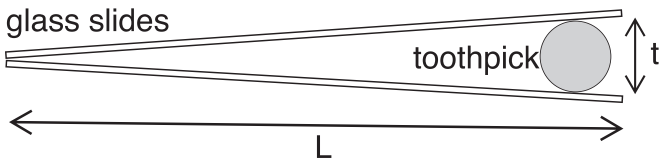

Figure 3. A sketch from the top view of the two glass slides.

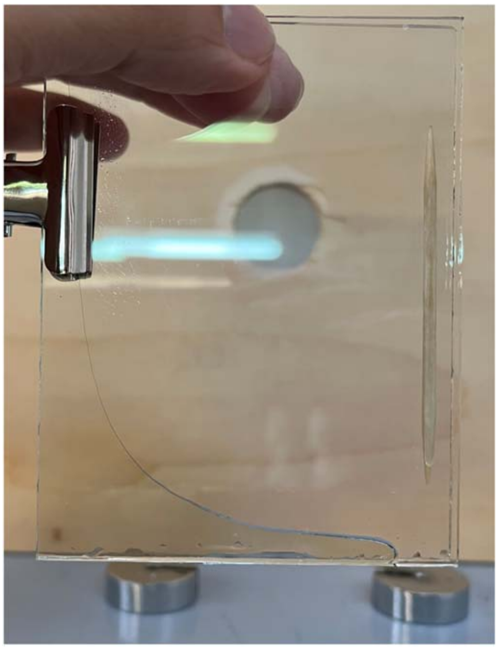

Figure 4. A photo of the experimental apparatus for the measurement of the interfacial tension and the contact angle.

function of x, $\mathrm{d}V = y(x)\mathrm{d}(x)\mathrm{d}x$ is the raised volume of water, ρ its density and $\mathrm{d}(x)$ the distance between the two slides. For a rise y of the water, the change of surface free energy due to the replacement of a solid–gas interface by a solid–liquid interface is equal to $\mathrm{d}E_S = 2\,(\gamma_{\mathrm{sl}} - \gamma_{\mathrm{sg}})y\mathrm{d}x$, where γ_{sg} and γ_{sl} are the solid–gas and the solid–liquid tension, respectively. It is worth noting that in the approach here considered the two quantities γ_{sl} and γ_{sg} are energy per unit area. At the same time, the change of gravitational energy is $\mathrm{d}E_g = \rho\; g\; \mathrm{d}(x)\;\; \mathrm{d}x\;\; \frac{y^2}{2}$, where g is gravitational acceleration. At equilibrium, the total free energy $\mathrm{d}E_T = \mathrm{d}E_S + \mathrm{d}E_g$ must be at a minimum value. Therefore, by requiring that $\frac{\mathrm{d}E_T}{\mathrm{d}y} = 0$ and solving the previous equation we obtain $y = \frac{-2\,(\gamma_{\mathrm{sl}} - \gamma_{\mathrm{sg}})}{\rho\;\; g\;\; \mathrm{d}(x)}$.

In our case, the system made of the two glass slides can be considered as a series of capillary of continuously variable size and we can write the distance between the two slides as a function of x (which varies between 0 and L) as $\mathrm{d}(x) = \frac{x\;\; t}{L}$, where t is the biggest distance (that is the thickness of the toothpick) between the two microscope slides and L the horizontal size of the two slides, as shown in figure 3.

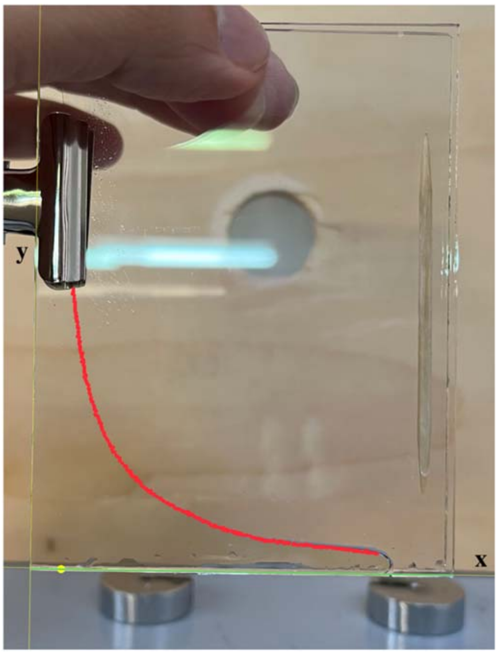

Figure 5. A photo of the two glass slides. The yellow lines indicate the axes of the reference frame. Red dots along the liquid profile highlight the curve to be fit.

Therefore, the height $y(x)$ reached by the liquid as a function of x is

$$y(x) = \frac{-2\ L\ (\gamma_{\mathrm{sl}} - \gamma_{\mathrm{sg}})}{g\ \ \rho\ \ t}\frac{1}{x} = \frac{a}{x}, \tag{2}$$

where $a = \frac{-2\,L\,(\gamma_{\mathrm{sl}} - \gamma_{\mathrm{sg}})}{g\ \rho\ t}$. In our case, $L = 7.5$ cm, $\rho = 1$ g cm^{-3}, $t = 0.25$ cm, $g = 980$ cm s^{-2}.

By plotting the red dots that we have graphically obtained through the video analysis, we have obtained a curve that can be fitted (see figure 6) by the function

$$y(x) = \frac{a}{x^b}. \tag{3}$$

By taking into account equation (2), we obtained $\gamma_{\mathrm{sl}} - \gamma_{\mathrm{sg}} = (-0.048\ \pm\ 0.004)\ \frac{N}{m}$. Here, the uncertainties were obtained through the propagation of uncertainties, known as the error on the parameter a (from the fitting) and the instrumental uncertainties related to the quantities L and t. We chose to let free the exponent of the variable x in equation (3) to verify that its value, obtained through the fitting, is compatible with 1.

By taking into account the Young-Dupré equation, $\gamma_{\mathrm{sl}} - \gamma_{\mathrm{sg}} = -\gamma_{\mathrm{lg}} \cos\theta$. So, the contact angle θ at the interface water-glass-air (see figure 7) is

$$\theta = a\cos\left(\frac{\gamma_{\mathrm{sl}} - \gamma_{\mathrm{sg}}}{\gamma_{\mathrm{lg}}}\right). \tag{4}$$

By substituting to γ_{lg} in equation (4) the value of γ previously obtained through the Du Noüy ring method, we obtained $\theta = 45° \pm 6°$. This value is correctly below 90° and agrees

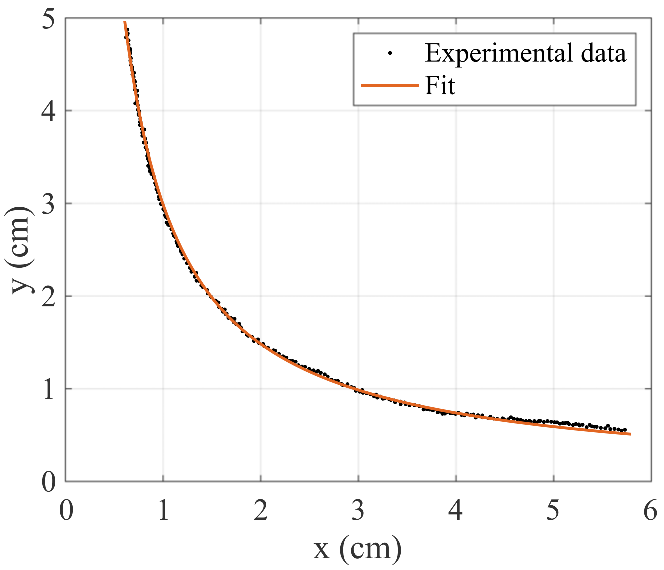

Figure 6. Fitting by using the equation $y = \frac{a}{x^b}$, where $a = (2.968 \pm 0.009)$ cm^{b+1} and $b = 1.007 \pm 0.007$. The coefficient of determination is $R^2 = 0.9995$.

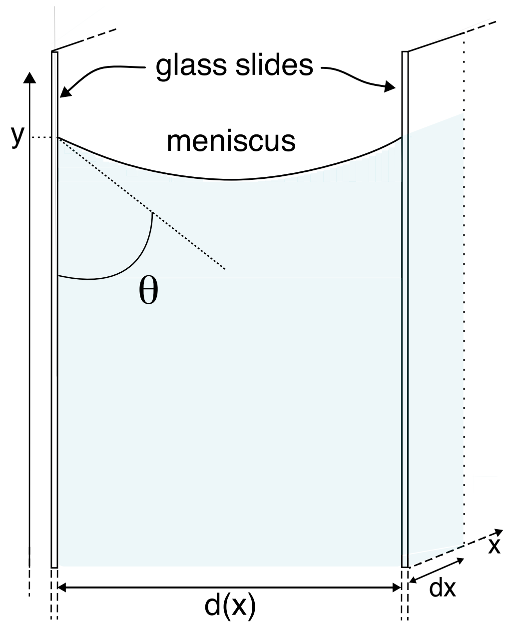

Figure 7. A sketch of a cross-sectional view of the two glass slides. The water-glass-air contact angle is highlighted.

with the values reported in the literature for water-glass interfaces [21–24]. A precise reference value of the contact angle is very complicated to identify since it depends on many factors such as the type of glass and its degree of smoothing. In the case of well-polished glass with a high degree of cleanliness, contact angle values are around 30° [21, 23, 24]. However, contact angle values in the range 47°–58° [22] and around 55° [25] are also known. The glass slides used in our measurements were carefully cleaned by using isopropanol. However, they are for commercial use and for this reason they certainly show some roughness that, as it is well-known, determines an increase in the contact angle [26].

4. Discussion

Surface tension measurements usually require very sophisticated and expensive equipment. It is worth noting that the customisation of the Du Noüy apparatus was particularly challenging. We found that by using cheap, pre-assembled commercial laboratory kits for this experiment, it is often not possible to obtain a reliable estimate of surface tension. In our trials, this was caused by the low sensitivity of the dynamometer supplied with the kit (insufficient to measure the forces acting on the ring) and the poor stability of the ring.

Instead, we, here, show that it is possible to make these measures with good accuracy and repeatability with affordable equipment. We think that this could represent a considerable advantage compared to what is already known in the literature to allow teachers to better actively involve students not only in collecting experimental data but also in the assembly of the experimental setup.

However, the use of affordable equipment requires greater attention to some aspects concerning the preparation for the measurements, as for instance, careful cleaning of the parts of the experimental apparatus that are directly involved in the surface tension measurements. For both the measurements it was essential to pay considerable attention to the cleaning of the instrumentation to obtain accurate results. We obtained the best results by using isopropyl alcohol both for cleaning the aluminium ring and the glass plates. In particular, it is fundamental to thoroughly clean both the ring and the glass slides before each measurement. We observed, for instance, that for not cleaned glass slides the value of the contact angle turns out to be much larger, even reaching about 70°.

For a reliable estimation of the surface tension value by the ring method it is very important that, for a given liquid, the cohesive force (the force between two liquid particles) be much smaller than the adhesion force (the force between a liquid particle and a solid one). If this condition is verified, the force measured just a moment before the liquid 'breaks' contains a cohesive contribution only and it is independent of the adhesive contribution.

For the measurements of the contact angle, a critical aspect regards the arrangement of the two glass slides with respect to the camera. It is essential to pay considerable attention to the arrangement of the two glass slides so that parallax error will not affect the photos.

Finally, it is worth noting that while the method here presented for measuring surface tension is capable of distinguishing water from oil or soap solution, it does not distinguish, for example, water from glycerol. This can represent a limit if the liquid whose surface tension is to be measured is not known. However, this limit can provide the starting point for an educational reflection on the meaning of uncertainties, on their interpretation and on the conclusions to be reached after a careful analysis of the measurements.

5. Conclusions

The two experimental apparatuses proposed here cost only a fraction of the professional ones commonly available. Despite that, the surface tension and the contact angle values obtained by using this experimental setup are well consistent with the results reported in the literature.

The experimental activities we propose here are part of a teaching/learning sequence (TLS) based on active-learning methodologies. It also includes computer simulations and lessons that engage students in inquiry-based activities. It has been pilot tested during the academic year 2021–22 with high school students attending introductory laboratory courses at the university in the framework of a national program to improve scientific knowledge and support enrolments in scientific undergraduate courses. It was also recently re-tested during the academic year 2022–23 on the basis of the results of the pilot test. All the activities were developed by following guided- and/or bounded-inquiry approaches [27] and allowed the students to familiarize with the methods of Physics, from both the experimental and the modelling points of view. During the pilot test we also noticed a significant interest and involvement of the students in the laboratory activities and the development of skills related to data collection and analysis. The development/improvement of reasoning lines focused on the construction of explicative models was also a result of the TLS trialling [28]. The TLS will be again trialed the next year with a wider sample of students, at both university and high school levels, to study differences and similarities in how students at various grade levels approach the use of laboratory and modeling in the study of physics, and the development of lines of reasoning suited to study scientific disciplines.

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors. The data are available at the web link https://sites.unipa.it/griaf/download/.

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