



Surface tension measurement with a smartphone using a pendant drop

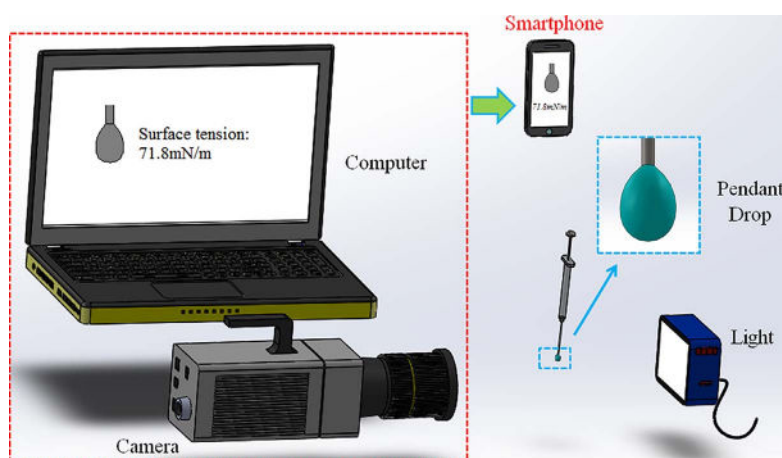
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GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a novel powerful mobile surface tension instrument based on a smartphone (mobile-phone or handy) is developed. Axisymmetric drop shape analysis method was implemented on a smart-phone (mobile-phone) for surface or interfacial tension measurements. The novelty of this work is that we have been able to implement all the needed calculations on a smartphone, and used the smartphone hardware for image acquisition and display purposes. As such we have been able to create an instrument that is significantly more economical compared to current systems; also it is compact, and can be mobile for field work. It is shown that the accuracy of our method can be 0.001% with ideal synthetic drop profiles (750 synthetic droplets representing a wide range of surface tension values were used). The performance of this instrument was also compared with a high-end commercial surface tension measurement instrument. We used various liquids (from high to low surface tension), and show that our instrument and the developed methodology can provide surface tension measurements as precise and accurate as current commercial instruments.

1. Introduction

Liquid surface tension is a fundamental physical property indicating

the tendency of a fluid surface acquiring the smallest possible surface area [1]. It is the key parameter governing the interaction between liquid and another bulk phase. As such, accurate measurement of liquid

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surface tension is of both fundamental and practical interest in a wide range of scientific and industrial areas, such as material science, polymer, semiconductor industry, coating, colloids, emulsions and printing industry [2–7]. The knowledge of surface tension can also be helpful in daily life. For example, the pure water has a large surface tension (~ 73 mN/m). When the water is contaminated by a chemical agent, the surface tension changes (usually decreases); then, the surface tension measurement can serve as a way for water quality testing [8].

Various techniques for surface tension measurement has been developed for a long time [1,9–12]. In general, these methods can be categorized into two groups, force tensiometer methods (e.g. Wilhelmy plate technique) and optical methods (e.g. axisymmetric drop shape analysis (ADSA)). The force tensiometer methods typically obtain the liquid surface tension by measuring the force acting between the liquid and a solid. In contrast, optical methods determine the surface tension from the image of an axisymmetric droplet by drop shape analysis (e.g. finding the drop outline by image processing and then calculating numerically the surface tension by fitting the drop outline to the solution of the Laplace equation). Compared with the force tensiometer methods, the optical methods have the advantages of a small sample liquid requirement, an improved accuracy, and convenience [1,9]. As such, the optical methods become the preferred method in many occasions.

Fig. 1 schematically shows a typical drop shape analysis system. A pendant droplet which is generated with a needle/capillary is positioned between a camera connected to a lens, and a light source [1,9]. Once the image of the pendant drop is taken by a capture device, it is imported into a computer for image processing, numerical calculation and data display. Such arrangement results in typically large instruments. Large bench bound instruments are also not suited to the increased demand for on-site (field) measurements in industry. Given the number of components involved in a standard setup, such instruments are also fairly costly.

In recent years, a number of studies have been reported the use of a smartphone for conducting advanced measurements, e.g. image processing, data treatment, clinical diagnosis, and environmental monitoring [13–16], profiting the advanced processing capabilities. These studies have shown that a smartphone can be utilized as a powerful instrument for advanced scientific measurements. In this study, we present an innovative surface tension measurement instrument based on smartphone platform. Many smart-phone models have large random-access memory (RAM), powerful central processor unit (CPU), high resolution screen and camera. Hence, any smart-phone platform is capable to execute all functions needed on a drop shape based surface tension tensiometer: image acquisition, image analysis, numerical calculation, data display and storage in a compact and durable form factor. All these lead to three major advantages over current commercial tensiometers. First, a drastic price reduction of the instrument is found since there is no need to set mechanical fixtures, elaborate chassis, lens, computer, etc. All mechanical parts and devices of the instrument is

available in a hand palm. Second, the complete instrument is very compact and portable, giving to researchers the possibility to measure and analyze the surface tension close to its users. Third, its mobility capabilities are very useful for working anywhere (in the field, lab, or a classroom) and its connectivity allows sharing the results in multiple formats. Furthermore, extra embedded functions of the smartphone, e.g. auto focus and touch screen zoom in/out, can be used to provide a better user experience compared with traditional systems.

The application of the drop shape analysis method in a smart-phone requires to solve several technical challenges. First, the large variability of the smartphone models on the market regarding shape, size and specification (e.g. CPU, RAM and camera) can cause potential difficulties during the instrument development in order to adjust its execution to the capabilities of each smartphone specification. For example, camera with different specifications can acquire images with varying quality, which can lead to inconsistent measurement results. Another difficulty is the calibration and adjustment process which can be challenging with the smart-phone system. Even though drop shape method is a convenient method, delicate calibration and adjustments are still needed. For example, in the typical surface tension measurement, camera must be levelled. However, it is difficult for one to take an image with a perfect levelled smartphone. Therefore, the smartphone version of the drop shape analysis is not simply installing the program found in a traditional computer based system onto smartphone, but significant development is needed, especially in the image acquisition and analysis. It is necessary to emphasize that the smartphone requires a minimum quality camera and other sensors like accelerometer to guarantee the accuracy on the measure.

We present a novel surface tension measurement based on smart-phone platform. We selected the Android operating system, as it is the most widespread operating system for mobile platforms. In the rest of this paper, we first introduce the surface tension measurement based on drop shape analysis method, then we explain the adaptation of drop shape analysis to the smartphone platform. At the end, the performance of this novel instrument is presented first with ideal synthetic drops, and then a comparison with a traditional commercial surface tension measurement instrument through experimentation with various liquids.

2. Methods

The shape of a liquid drop is governed by the competition between gravity and the surface tension of the liquid. The surface tension tries to maintain the drop shape as a sphere while the gravity tends to stretch a pendent drop. Therefore, theoretically, by knowing the shape of drop, the surface tension can be calculated. Fig. 2a shows the general procedures of drop shape methods. To proceed with surface tension measurement, an image of a pendant drop (generated using a needle connected with syringe) is obtained with the smart-phone camera. The outline of the drop (experimental profile, see Fig. 2b for yellow line) in an image was detected by using a variety of image analysis methods. The profile of a pendant drop can also be calculated (theoretical profile, see Fig. 2b for red line) by solving the differential equation, Laplace equation, [1] with knowing physical properties of the liquid drop, i.e. density difference between two fluids $\Delta\rho$, the gravity acceleration (g), surface tension (γ), length of drop profile (s), and the Laplace pressure difference (ΔP). For each measurement, the values of $\Delta\rho$ and g are needed as the initial input. Initial guesses for γ , s , and ΔP are also needed.

By comparing the theoretical and experimental profiles (yellow and green lines in Fig. 2b), the summation (F) of the Euclidean distance between experimental profile points and the theoretical profile can be calculated. The minimal value of F (varying all the three initial guess values) can be found by an optimization method of choice. The liquid surface tension of this liquid should be the guess values which give the minimal value of F .

In this study, the programming language used for smartphone

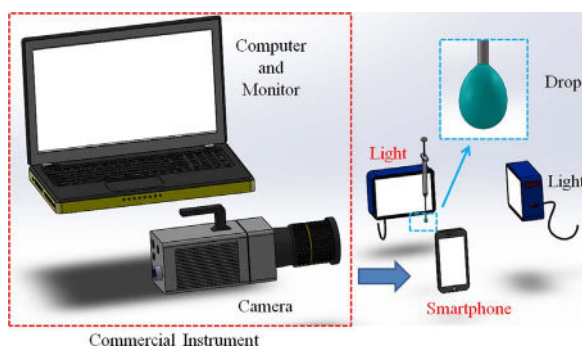


Fig. 1. Schematic for a typical surface tension measurement instrument based on drop shape method compared with the typical size of smartphone.

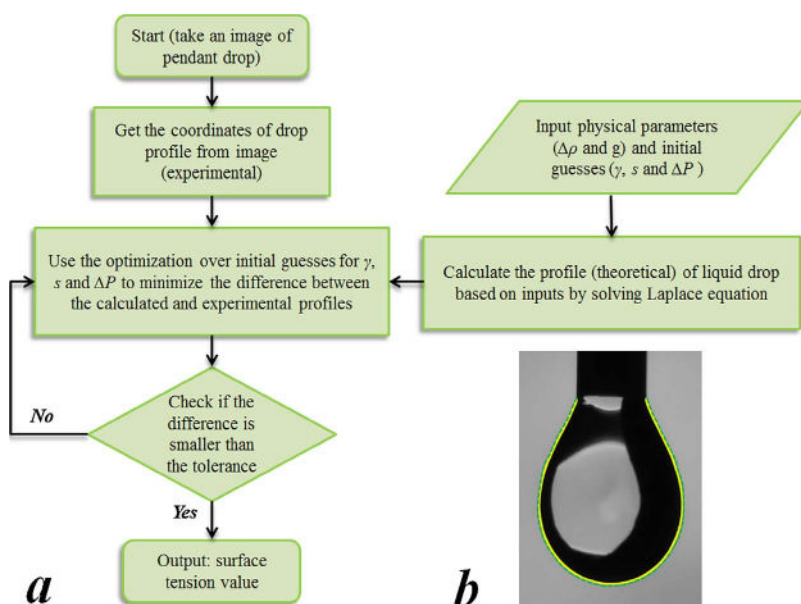


Fig. 2. (a) Flow chart describing the principle of using axisymmetric drop shape analysis method to find the surface tension of liquids. (b) Schematic of the experimental (yellow) and theoretical (green) drop profiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

implementation was C and Java. The outline of the drop in an experiment was detected by the Otsu's algorithm [17]. Shown in the Supplementary Information, with the image taken by smart-phone (digital zoomed image), Otsu's algorithm can provide a better quality of drop profile compared with other methods, e.g. Canny method. The Young-Laplace equation is solved by the Runge-Kutta method. In this instrument, the physical size of each image pixel is obtained by an automatic calibration system which measures the number of pixels in the capillary/needle seen in the image (the needle diameter is needed as an input).

Since in the drop shape methods, the gravity is always applied in the vertical direction and parallel to the axis of symmetry of the drop [7,18]. However, for one to use the smart-phone to take drop picture, it is very likely the phone is not perfectly levelled. Therefore, an off-set angle (α) can exist between the gravity (and axis of symmetry) and the vertical direction in the drop image. In the Supplementary Information, we have shown that this off-set angle can significantly affect the measurement results. To minimize the off-set angle error, a self-correction system was programmed in the smart-phone. This was done using the accelerometer of the smart-phone. If needed, the image orientation was corrected by the α value to minimize the error due to misalignment.

This instrument is tested by using two different smartphones, which are LG-G4 (released in 2015) and Nexus-5 (released in 2013). LG-G4 is equipped with Chipset Qualcomm MSM8992 Snapdragon 808 (quad core 1.44 GHz Cortex-A53 & dual core 1.82 GHz Cortex-A57) and 3GB of RAM LPDDR3 and Nexus 5 is equipped with Chipset Qualcomm MSM8974 Snapdragon 800 (quad core 2.3 GHz Krait 400) and 2GB of RAM LPDDR2. The LG-G4 and Nexus 5 systems represent the high and ordinary performance of the phones available in the market, respectively. For the experimental validation, the results from smartphones are compared with the results from a commercial surface tension measurement machine (Kruss DSA100E, using the drop shape method, image resolution: 1200 × 800).

For comparison, the image of a pendant drop was taken simultaneously by both Kruss DSA100E, and the smart-phone with perpendicular perspectives to each other (see Fig. 1). One additional well diffused backlight was placed opposite side of the pendant drop to the smartphone. Three liquids, dodecane (Aldrich: purity ≥ 99%), ethylene glycol (Aldrich: purity ≥ 99.8%), and distilled water were used, i.e. at 24 °C. Each of the liquid drop was generated with a flat needle of 1.83 mm diameter with a liquid injection speed of 0.1 ml/min. For each of the liquid, three pendant drops were generated and measured by

each device. For each drop, three measurements were taken. In both cases, the capillary have been used for calibration (to obtain the information of physical size of image pixel). It should be noted that the physical size of image pixel is not a fixed value, but dependent on the camera sensor of the smartphone, and the zoom applied by the user, as well as the distance between the drop and the camera. In this work, the physical size of each image pixel is between 5.40 μm to 6.66 μm (for LG G4) and 10.93 μm to 14.11 μm (for Nexus 5). The method developed will automatically calculate the value depending on the camera sensor and the parameters stated above.

3. Results

We firstly tested the performance of the computational core which calculates the surface tension value based on the experimental profile with ideal pendant drop profiles (synthetic profiles). The synthetic profiles were generated by a program called axisymmetric liquid-fluid interfaces (ALFI) [1]. ALFI can numerically integrate the Young-Laplace equation with the input of physical properties (e.g. surface tension) to obtain the ideal shape of the pendant drop. The coordinates of the points forming the theoretical (synthetic drop) profile from ALFI were imported into the smart-phone serving as the experimental profile. By comparing the results obtained from the smart-phone calculation (based on the synthetic profiles), and the value of the surface tension which was used to create the synthetic drops, the performance of the computation core of our instrument was evaluated.

In total, 750 pendant drops were generated by ALFI with the surface tension varying from 15 mN/m to 90 mN/m. The distance of each of the points along the drop profile (Δs) was set to be 5 μm (typical size of the pixel in a smart-phone). The difference between the surface tension obtained from our instrument (γ_m) and the one used to generate these drop profiles (ideal surface tension, γ_i) divided by γ_i was recorded as error ($e = \frac{\gamma_m - \gamma_i}{\gamma_i} \times 100\%$). The average, median, and maximum errors of these 750 tests are shown in Table 1. It can be seen that with an ideal image (synthetic drop profiles), the results from our instrument are highly accurate, since both the average error ($0.001 \pm 0.006\%$) and median error (0.000%) are close to zero. No case had an error larger than 0.141%. Based on the results of these 750 tests, it can be said that the instrument can accurately (with an accuracy of 0.001%) measure the surface tension on ideal drop profiles.

In practice, the drop profile extracted from an image is not accurate. The lack of drop profile accuracy can be due to image acquisition or

Table 1
Error of the surface tension measurement instrument working with the synthetic drop profiles.

Type of perturbation	Average e (%)	Median e (%)	Maximum e (%)
Ideal image	0.001 ± 0.006	0.000	0.141
0.5° rotation	0.357 ± 0.231	0.377	1.388
−5 μm shift	−0.003 ± 0.102	0.002	0.285
+5 μm shift	0.266 ± 0.105	0.258	0.646
−10 μm shift	0.822 ± 0.188	0.832	1.342
+10 μm shift	1.654 ± 0.346	1.709	2.450
−15 μm shift	0.111 ± 1.327	−0.412	4.841
+15 μm shift	0.273 ± 0.182	0.233	0.979
−20 μm shift	0.940 ± 0.310	0.855	2.213
+20 μm shift	2.057 ± 0.545	1.928	3.971
−50 μm shift	2.965 ± 0.899	3.043	5.692
+50 μm shift	4.663 ± 2.258	4.082	15.204
± 5 μm shift	−0.124 ± 0.139	−0.120	0.540
± 10 μm shift	−0.135 ± 0.200	−0.138	1.661
± 15 μm shift	−0.124 ± 0.265	−0.113	1.010
± 20 μm shift	−0.142 ± 0.342	−0.129	4.370
± 50 μm shift	−0.168 ± 0.826	−0.200	4.370

image analysis processes; we categorized them into two general types. The first profile error is the off-set angle explained in the previous section. Even though the self-correction system was used to minimize the off-set angle, a small angle can still exist. In the tests, it was found that the value of off-set angle read from the accelerometer fluctuates (usually within the range of 0.5°) even with the phone completely fixed; hence there can be a 0.5° error of the off-set angle. Another type of drop profile error can be introduced by the deviation of pixels location from the ideal position of the drop profile. For most smartphones a digital zoom system is applied. In contrast to optical zoom, the digital zoom is accomplished by cropping the image and then interpolating the pixels. Interpolation means that the pixels are being digitally recreated in order to reach higher magnifications, sacrificing ultimately the image quality.

To evaluate the performance of the smart-phone based instrument with the not accurate profiles, the original 750 pendant drop profiles were modified to artificially create the defective drop profiles. To understand the tolerance to the off-set angle error, the original profiles were rotated by 0.5°. The errors of the measurements with rotated drop profiles are shown in Table 1. It can be seen that with 0.5° rotation, both the average error (0.357 ± 0.231%) and the median error (0.377%) are still small; hence, our novel smartphone based method can provide accurate surface measurement values with small off-set angles. Similar procedures were applied to test the performance with edge shifted profiles. The profile of the 750 ideal pendant drops was shifted inside, outside, and randomly (denoted as −, + and ± respectively) by some certain distance to create new shift drop profiles. Since the typical pixel size of the image from smart-phones camera at the shortest focus distance and maximal zoom is usually around

8–10 μm. Therefore, the profile of the drop were shifted by 5 μm, 10 μm, 20 μm, 50 μm, respectively, which correspond to 0.5, 1, 2 and 5 pixel errors of profiles detection in the real image. The results of the shifting tests are shown in Table 1. It can be seen that the surface tension instrument works well with these shifted drop profiles. Especially for the random shift profile (the most likely scenario), the average value (−0.168 ± 0.826%) and median value (−0.200%) are close to zero, with the random shift of 50 μm (5 pixels shift). Based on the results shown in Table 1, it can be concluded that the smartphone system can not only work with the ideal pendant drop profile, but also shows a robust performance with the potential error from the drop profile detection.

Finally, the performance of this instrument was tested by comparing its measurement results with a traditional commercial surface tension measurement instrument using various liquids. The surface tension of three different liquids were measured use both our instrument (using both LG-G4 and Nexus-5) and the commercial instrument. For each of the liquid, three pendant drops were generated and measured by each device. Measurement results are shown in Fig. 3 (comparison between LG 4 phone and commercial instrument) and 5 (comparison between Nexus 5 phone and commercial instrument), respectively. It can be seen that the results obtained from our smartphone are almost identical with the results from commercial instrument; hence, we can conclude that our smartphone based surface tensiometer instrument can match the performance of one of the most sophisticated system for such work available today. It also shows that the method developed is independent of the phone model. Furthermore, our tests also show that measuring the surface tension using smartphone will not cause a significant increase of measurement time. Only 353 ms and 705 ms are needed, respectively, for the LG G4 and Nexus 5 to conduct one measurement (image analysis and surface tension calculation).

This instrument can not only conduct the surface tension measurement based on the image taken by itself, but also can work with other imported images. In Figs. 3 and 4, we show the measurement values of using the smartphone with the images from the commercial instrument machine (named as combined measurement). It can be seen that the results for such combined measurement are also identical with the other two separated measurements. This suggests that our instrument can also be used to perform the surface tension measurement based on the imported image from other equipment as other traditional instrument.

4. Conclusion

In this study, a powerful smartphone based surface tensiometer was developed and tested. Drop shape method was used for the surface tension measurements. Unlike traditional surface tension measurement instruments, the novel instrument has revealed new advantages such a low cost, compact form factor, and portability, providing a new generation of personal instruments. The accuracy of the new system can reach 0.001% error with ideal synthetic drop profiles. The performance

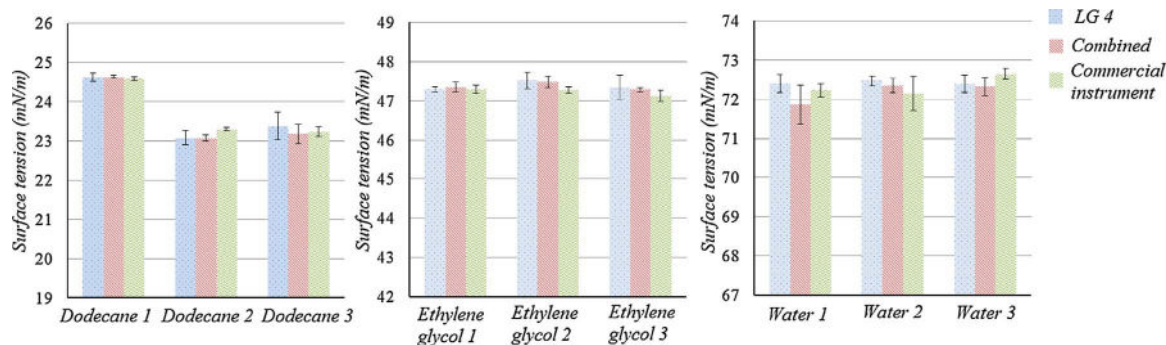


Fig. 3. Comparison between surface tension measurements results from LG4 and traditional commercial instrument. The data of combined measurement were obtained by using our program to measure the drop images obtained by the commercial instrument.

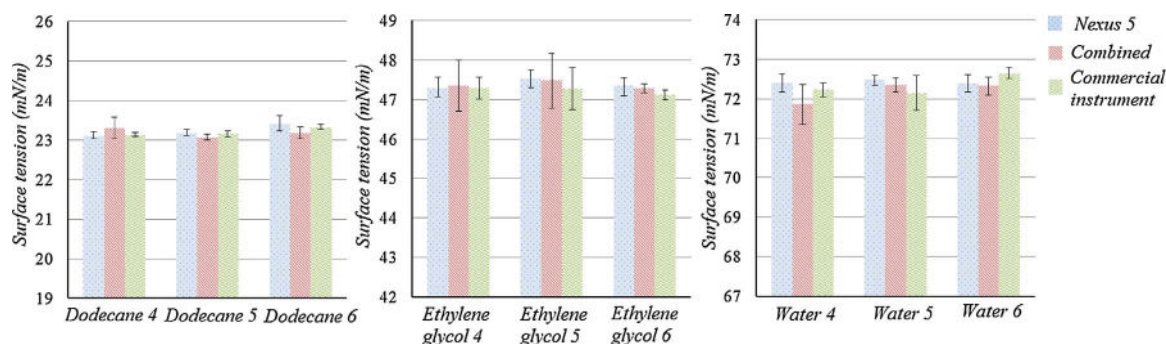


Fig. 4. Comparison between surface tension measurements results from Nexus 5 and traditional commercial instrument. The data of combined measurement were obtained by using our program to measure the drop images obtained by the commercial instrument.

of new instrument was tested with two different smartphones (high and low end). We showed the method developed is independent of the phone model. By comparing the measurement results from the smartphone and a high end commercial instrument, we conclude that the smartphone-based surface tensiometer instrument can match the performance of one of the most sophisticated system for such work available today.

Acknowledgment

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.colsurfa.2017.08.019>.

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