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Original Article

Effect of Gravity on the Measurement of Contact Angle of Drop on a Solid Surface

Caixia WANG, Shenghua XU, Zhiwei SUN and Wenrui HU

[1] National Microgravity Laboratory; Institute of Mechanics,
Chinese Academy of Sciences, Beijing,100080, China, sunzw@imech.ac.cn

Abstract

In this study, a series of experiments were conducted, respectively, in the drop tower—which provides 3.5 seconds of microgravity and on the ground base (g=1) to test the effect of gravity on the contact angle of drops setting on the solid surface. The results show that the volume of the droplet has little influence on the measured contact angle in the microgravity condition. For small sized droplets, the measured contact angle on the ground is almost the same as in microgravity condition, while for large sized droplets, the measured contact angle on the ground is about 4° larger than the value of the microgravity.

1. Introduction

The equilibrium contact angle θ_e of a liquid placed on a flat solid surface is given by Young's equation[1,2]:

$$\cos\theta_e = \frac{\gamma_{sg} - \gamma_{sl}}{\gamma_{gl}} \qquad (1)$$

where γ_{sg}, γ_{sl}, and γ_{gl} are the solid-gas, the solid-liquid, and the gas-liquid interfacial tensions (of the interfacial free energies per unit area), respectively. As can be seen from Eq.(1), the equilibrium contact angle θ_e is determined by the three surface tensions of the solid-liquid-vapor system. Thus the Young's equation implies that the equilibrium contact angle θ_e is unique value for a given solid-liquid-vapor system corresponding to thermodynamic equilibrium. This contact angle, which can be called the macroscopic contact angle, is used as the boundary condition for the free surface of the liquid and thus needed for the determination of the surface shape. However, in most cases, the experimentally observed macroscopic, static contact angle θ_s, may not be the equilibrium contact angle θ_e; instead, the contact angle normally has a wide range of values. The largest and smallest of these angles are termed the advancing contact angle and receding contact angle, respectively.

With increasing the volume of the drop by a syringe a reproducible advancing contact angle is attainable. The advancing contact angle of a sessile drop on a solid surface is important in many natural and industrial processes such as coating of solids by liquid films, tertiary oil recovery and mineral processing. There have been many studies on advancing contact angle in the ground condition[3-5].

However, a few detailed observations of the effect of gravity on the macroscopic contact angle have been reported in the literature. Hideki and Tomiko[6] studied theoretically the effect of gravity on the rough solid-liquid interface and have shown the apparent contact angle of a drop on the rough solid surface is raised by gravity under the conditions of gas adsorption. Ward *et al.*[7] and Sasges and Ward [8] conducted experiments on a space shuttle flight and on the ground to study a closed, two-phase capillary system. They showed that the static contact angle at the upper three-phase line is smaller than that at the lower three-phase line and explained this result as being due to the gravity. A.Ababneh *et al.*[9] conducted a series of experiments concerning about the advancing contact angle and the results show that for water sessile drops on Teflon-coated silicon wafers, the advancing contact angle in the reduced gravity environment is less than that of the advancing contact angle in 1g by about 5°for the same three-phase contact line advancing rates. Therefore, the experimental results and the theory concerning about the influence of gravity on the contact angle are still unclear. And a systematical study is needed for understanding whether the gravity will influence the static contact angle or not, or how the gravity influences the contact angle.

As the drop shape is determined by the gravitational force and the surface tension force on the fluid, the drop shape will be inevitably affected by gravity, which may also affect the measured contact angle. Apparently, the effect of gravity on the measurement of contact angle of drop depends on the relative importance of the gravitational force and the surface tension force, as well as the size of the drop volume.

In this study, we performed a series of direct experiments on the contact angle for different sized droplets in drop tower, which provides 3.5 seconds of microgravity condition. The contact angles on the ground base (g=1) are also measured to compare with the results on microgravity condition.

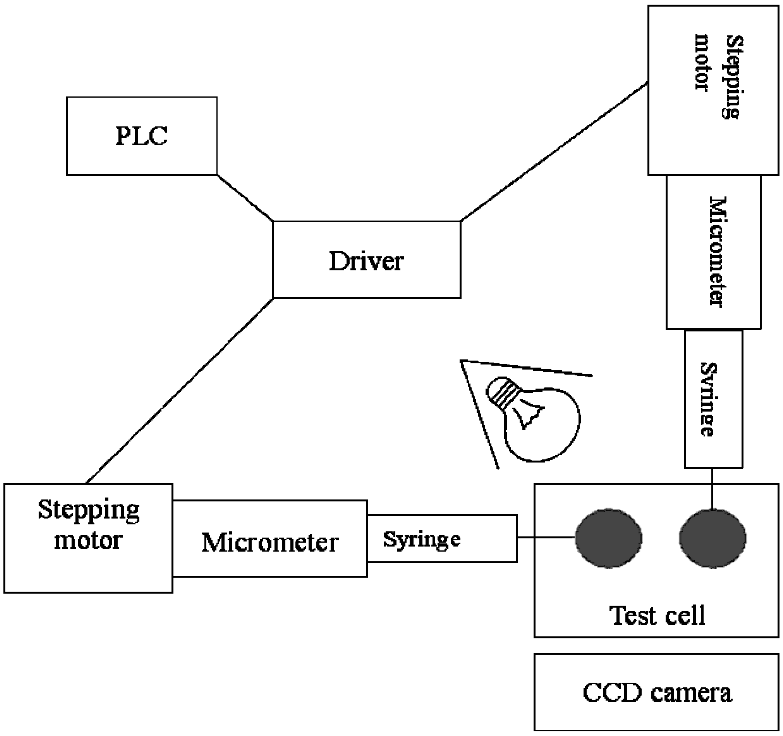


Fig. 1 Sketch-map of the instrument in drop tower

2. Experiments

The experiments of this study are quite straightforward. The droplet was placed on a plane surface and the gas-liquid-solid contact line was formed. The shapes of the droplet under microgravity condition and normal gravity conditions are recorded by CCD and the contact angles are measured from the images. All the experiments were conducted at room temperature (approximately 25℃).

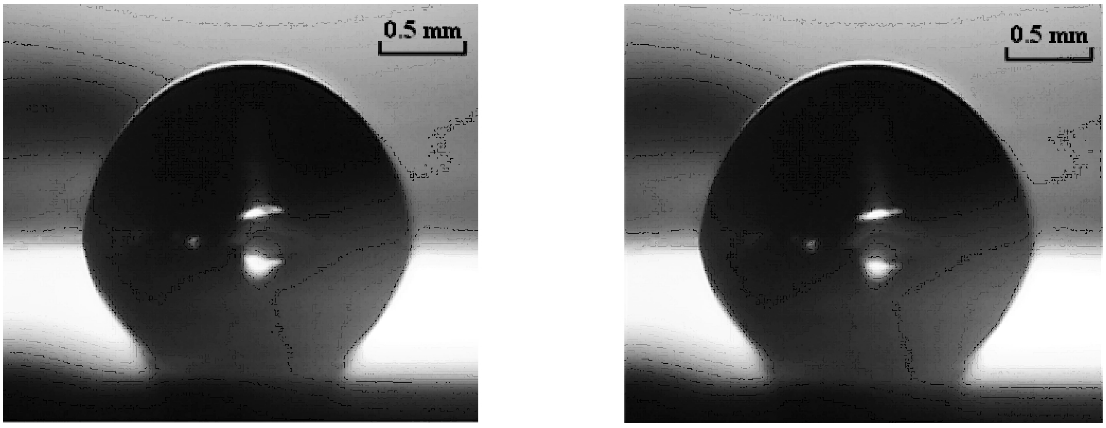
A. Materials (Solid surface and liquids)

The solvent of the droplet is purified water, which was obtained from Milli-Q ultra-purifying water system (Millipore S.A. 67120, MOLSHEIM Inc., France). The substrate surface used is commercial PMMA, in sheet form, 2mm thick. Before each experiment, the PMMA was put in a sonicator for about 10 min, and washed with purified water for many times. The measurement of the contact angle is expected to have little error because the water is purified and surface is cleaned.

B. Experimental setup

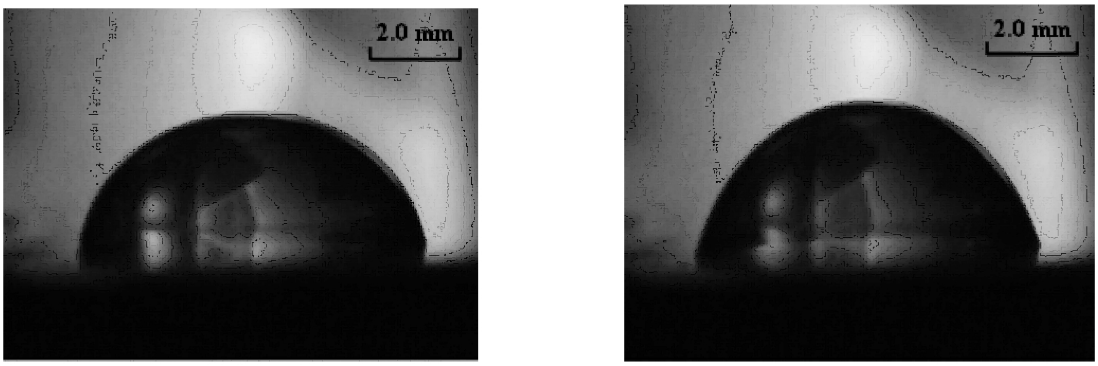
To measure the contact angle under normal gravity condition is quite easy. But for the experiment under microgravity, the experimental setup will be more complicated. The sketch map of the instrument is shown in **Figure 1**. As the time for elevating the drop capsule to the needed height before experiment is so long that the droplet will evaporate, the droplet cannot be put on the PMMA surface before closing the drop capsule. Therefore, we inject the droplet just before the capsule is freed for fall to avoid evaporation. In the experiment, when the capsule reaches the needed height, a signal will be given to PLC (Mistubishi FX1S-10MT) which is connected to stepping motor driver (RORZE RD-023MS), and the stepping motor (RORZE RM-2424S) is driven to rotate by the motor driver for a given angle that is pre-inputted in the PLC. The stepping motor take the thimble of a micrometer to rotate and the rod will move forward to push the plunger of the syringe in order to generate needed volume of the droplet on the surface, as is shown by Figure 1. To decrease the times needed for the drop tower experiments, two droplets was put on the surface in each experiment. And the images of the shape of the droplets are recorded by CCD camera (WAT-660D, Watec Co., Ltd.) at 25 frames per. second.

By this means, the contact angle under the microgravity condition in the drop capsule can be measured from the images. For the capsule system used in this experiment, the gravity is about $10^{-5}g_0$.



(a) (b)

Fig.2 The comparison of images of the droplet under 1g condition and microgravity condition. The volumes of the droplets are 2μl. (a) 1g condition; (b) microgravity condition



(a) (b)

Fig.3 The comparison of images of the droplet under 1g condition and microgravity condition. The volumes of the droplets are 80μl. (a) 1g condition; (b) microgravity condition

C. Contact angle measurement

Evaluation of the contact angle from the images was accomplished by the SCA-software, the add-ons of Optical Contact Angle Measuring Device (OCA20). This computer software is based on goniometry and contact angle can be assessed directly by measuring the angle formed between the solid and the tangent to the drop surface. The assignment of the tangent line which will define the contact angle is a factor which can limit the reproducibility of contact angle measurements. Conventional goniometry relies on the consistency of the operator in the assignment of the tangent line. This can lead to significant error, especially subjective error between multiple users. SCA-software removes this problem by using computer analysis of the drop shape to generate consistent contact angle data.

3. Results and Discussion

Figure 2 (a) and **(b)** give the images of the droplet on the normal gravity condition compared with that on the microgravity condition, respectively. The volumes of the droplets are both 2μl. **Figure3** is similar to figure2 but for the droplets of 80μl. From these figures we can see that the images for the droplets on the normal gravity and microgravity condition are quite different.

The contact angles measured for the droplets with different volumes on microgravity and normal gravity conditions are compared in **Figure 4**. It is shown in this figure that the contact angles for droplets with different volumes under microgravity condition are almost the same, while a difference about 4° in the contact angle can be observed for the droplets under normal gravity condition. However, for small volumes such as 2μl and 8μl, the gravity has little influence on the contact angle so that the measured value is compatible. For volumes larger than 30μl, the contact angle measured in normal gravity is larger than that measured under microgravity condition, but the measured value does not change with volume. For the volumes between 8μl and 30μl, there may be a continuous relationship of the measured contact angle with droplet volume under normal gravity, which is not confirmed in this study because the lack of experimental results (only the data of 10μl available) under normal gravity and microgravity for volumes in this interval.

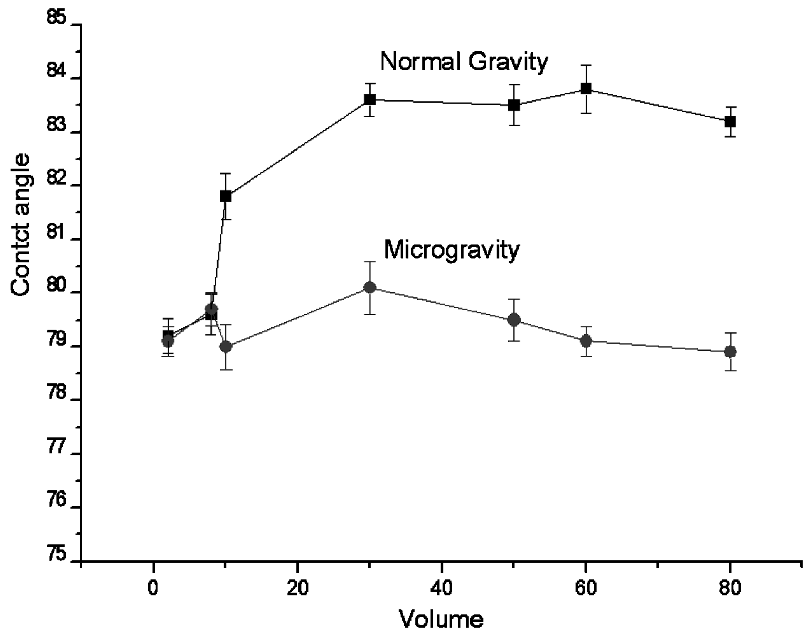


Fig.4 The measured contact angle of droplet for different volumes under microgravity and normal gravity condition; the error bars show the standard deviation from multiple runs

4. Conclusion

The effect of gravity on the measured contact angle for droplets with different volumes has been determined experimentally by comparing the ground experiments with reduced gravity experiments in drop tower. It shows that the volume of the droplet has little influence on the contact angle in the microgravity condition. In the normal gravity condition, the measured contact angle seems consistent with the microgravity when the volume of the droplet is less than 8μl. However, for large droplet the measured contact angle is about 4° larger than the value of the microgravity. The results help understanding the influence of gravity and volume size on the measured contact angle which can not be explained by the theory that is deduced from ideal conditions. These results also give the changing tendency of the measured contact angle for different volume size under microgravity condition and normal gravity condition. However, more experimental data will be helpful for better understanding the relationship of the measured contact angle of 1g and μg condition with the volume, especially for middle sized droplets.

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