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Investigation on contact angle measurement methods and wettability transition of porous surfaces

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ABSTRACT

Various solid surfaces (e.g., smooth titanium surface, smooth aluminum surface, polished copper surfaces, polished silver surfaces and porous copper surfaces) were prepared to quantify the reliability of half-angle algorithm and axisymmetric drop shape analysis (ADSA) algorithm for calculating contact angles. Besides, the effects of surface conditions on contact angle values were also investigated. The experimental results of 10 repeated tests for each surface show that both algorithms have good accuracy for an acute contact angle, while the ADSA algorithm is better than the half-angle algorithm for an obtuse contact angle. Furthermore, with the decrease of surface roughness, the contact angle increases but the standard deviation of contact angles by 10 repeated tests decreases. In addition, the porous layer on copper surface by electrochemical deposition shows a super hydrophilic property, but it could change to be super hydrophobic after exposed in ambient air for 24 h. Interestingly, the surface wettability reverses to be super hydrophilic again after it is immersed in water, and the inorganic contamination is the reason of formal change from the super hydrophilic status to the super hydrophobic status.

1. Introduction

Wettability of a solid surface is of paramount importance to boiling heat transfer [1]. A hydrophilic surface helps to enhance the boiling heat transfer coefficient and the critical heat flux (CHF) [2–7]. In order to obtain a well hydrophilic surface, various techniques have been developed, such as coating with nanoparticles [8–9], ultraviolet irradiation [10] and electron irradiation [11].

To characterize the surface wettability, two different types of contact angles are applied. One is static contact angle and the other is dynamic contact angle (e.g., advancing contact angle and receding contact angle). The static contact angle is more commonly used because it is relatively easy to be measured. Ways used to quantify the static contact angle mainly include sessile drop method and pendant drop method [12]. As for the sessile drop method, different techniques such as side-on method, top-down method and reflected-angle method have been proposed [13], in which the side-on method is more convenient to be used for contact angle measurement. Generally, three mathematical models could be used to calculate the contact angle, such as half-angle algorithm, axisymmetric drop shape analysis (ADSA) algorithm and drop snake algorithm [13]. Among them, the ADSA algorithm was reported to have the best accuracy of $\pm 0.3°$ [14].

As stated previously, surface wettability can be altered by different processes. Wang et al. [15] had reported a super hydrophilic copper layer formed by electrochemical deposition. Shirazy et al. [16] observed the transition of wettability from super hydrophilic to super hydrophobic on a copper foam surface and concluded that such transition of wettability is caused by the contamination of volatile organic compounds instead of surface oxidation which has been a more widely accepted reason.

In this study, various solid surfaces were prepared to investigate their wettability and the static contact angles were measured by the sessile drop method with the side-on way. The half-angle algorithm and ADSA algorithm were applied to calculate the contact angle and calibrate with each other. The effects of surface roughness on surface wettability and measurement repeatability were analyzed in detail. In addition, the copper porous surfaces processed by electrochemical deposition were used to confirm the wetting reversibility characteristics when they were exposed in open air and cleaned by water and acetone.

2. Half-angle algorithm and ADSA algorithm

2.1. Half-angle algorithm

The half-angle algorithm assumes that a sessile drop is part of an ideal sphere. As a result, the side view of the drop is an ideal circle. Thus, the contact angle is calculated with the height and the base diameter of the drop. Fig. 1 shows the schematic drawings of drop with an acute contact angle and an obtuse contact angle, in which, θ is the

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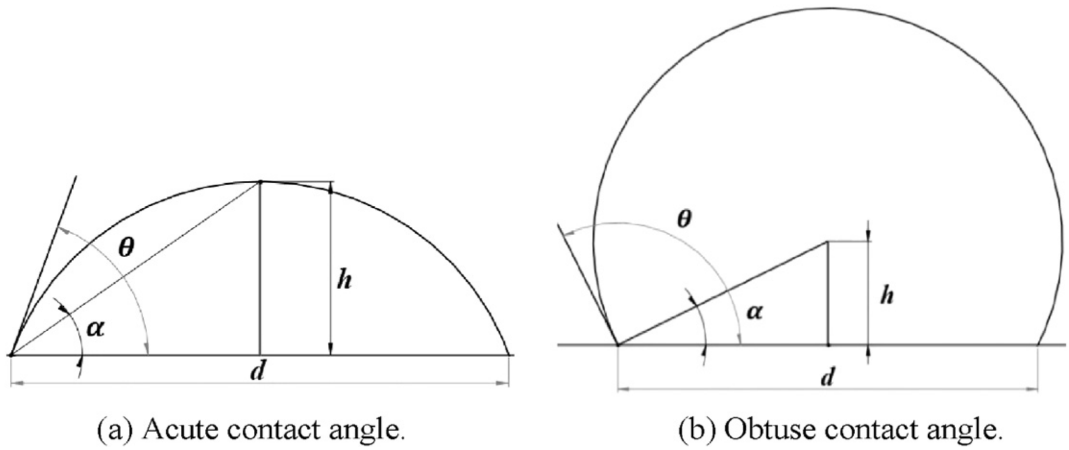

Fig. 1. Schematic drawing of the sessile drop analyzed by the half-angle method.

contact angle, α is the angle of osculation for the solid surface, h is the height of the drop and d is the base diameter of the drop.

With the ideal sphere assumption, the contact angle could be expressed as Eq. (1) for the acute and Eq. (2) for the obtuse:

$$\theta = 2\alpha = 2\tan^{-1}\left(\frac{h}{d/2}\right) \tag{1}$$

$$\theta = 90^\circ + \alpha = 90^\circ + \tan^{-1}\left(\frac{h}{d/2}\right). \tag{2}$$

To satisfy the ideal sphere assumption, volume of the drop could not be too large. Extrand and Moon [17] deduced the maximal volume of sessile drop relying on the contact angle as Eq. (3).

$$V_{max} = \frac{\pi}{48}\left(\frac{\gamma}{\rho g}\right)^{3/2}\left(\tan\frac{\theta}{2}\right) \times \left(3+\left(\tan\frac{\theta}{2}\right)^2\right)\left[\left(1+8\frac{(\sin\theta)^2}{1-\cos\theta}\right)^{1/2}-1\right]^3. \tag{3}$$

Based on Eq. 3, the maximal volume is calculated to be 10 μL for the drop with the contact angle between 10° and 140°.

2.2. ADSA algorithm

The ADSA algorithm is more sophisticated compared with the half-angle algorithm. Instead of the ideal sphere assumption applied by the half-angle algorithm, the drop is assumed to be axisymmetric and forces except gravity are neglected. Thus, the well-known Young–Laplace equation can be acquired as follows [18]:

$$\gamma\left(\frac{1}{R_1}+\frac{1}{R_2}\right) = \Delta\rho g H + \gamma\frac{2}{R_a} \tag{4}$$

where R_1 and R_2 are the principal radii of curvature at any point on the interface between liquid and gas, R_a is the radius curvature at the apex of the interface, γ is the surface tension, H represents the vertical distance to the reference plane and $\Delta\rho$ is the density difference between liquid and air.

Eq. 4 is solved numerically and different profiles can be acquired from the solutions based on different γ and R_a. Then, the contact angle of the drop is obtained through fitting the theoretical profile based on the Young–Laplace equation with the actual drop profile.

3. Experimental methods

3.1. Contact angle measurement facility and procedure

Fig. 2 shows the contact angle measurement facility. An optical table was used as the platform of all the instruments except the camera for well flatness and good vibration isolation. A 3D manipulator was used to fix the solid surface sample. A micro-syringe was mounted above the test sample for producing the sessile drop. The digital single-lens reflex camera with a micro-lens helped to record the drop image from the lateral side. A LED light source was arranged to illuminate the drop from the opposite direction of the camera for improving image quality by passing through a screen.

Based on the experimental facility mentioned above, the contact angle measurement was processed as following. The sample was cleaned by ethanol and deionized water in turn. After the sample dried, it was fixed on the 3D manipulator and adjusted to be horizontal. At the same time, the camera was also adjusted to be horizontal. Then, a sessile drop of deionized water with a volume of 4 μL (less than 10 μL to satisfy the spherical assumption) was deposited very carefully on it through the micro-syringe and its side view images were recorded by the camera after around 1 min when the drop was formed. The sample was dried with tissue paper, and every repeated test was performed after more than 5 min.

After acquiring the side view of the sessile drop, the half-angle algorithm and ADSA algorithm were applied to calculate the contact angle values.

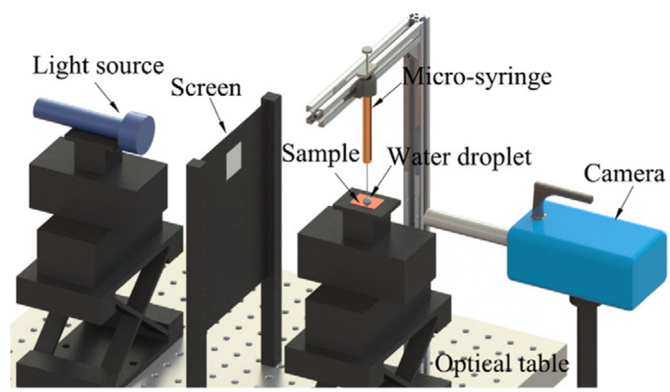

Fig. 2. The contact angle measurement facility.