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Air layer on superhydrophobic surface underwater

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ABSTRACT

Sustaining an air layer on superhydrophobic surface is known necessary for the applications of the “air layer effect” underwater on basis of previous literatures. However, the air layer becomes unstable when put underwater and even disappears when the hydraulic pressure increases. Thus much attention has been focused on the sustainability of an air layer on a superhydrophobic surface. This article studies the sustainability of the air layer on the surface of a lotus leaf by applying external pressure on the surface, which is a direct method to measure the sustainability of the air layer. It is displayed that the hydraulic pressure is a key factor to sustain an air layer on a superhydrophobic surface. Maintaining a certain amount of hydraulic pressure is necessary to sustain an air layer on a superhydrophobic surface, which may be important for the low drag or friction reduction of a superhydrophobic surface underwater. Therefore, we believe that the micro-designs of superhydrophobic surface which is capable of the “air layer effect” underwater should be connected with hydraulic pressure applied on it.

1. Introduction

The amazing water repellent property of the lotus leaves has attracted great interest of scientists for their potential applications, such as microchannels, self-cleaning windows, building exteriors and fabrics [1–5]. On the leaf surfaces, the presence of hydrophobic wax and the micro/nano hierarchy roughness of papillae allow air to be trapped under water drops on the leaves. Therefore, a water drop is not only with contact angle (CA) higher than 150° on leaf surfaces, but also easily roll off at a tilt angle (TA) less than 5°, which was termed as “lotus effect” [1–4]. Inspired by this, material scientists have synthesized a lot of artificial “lotus surfaces”, i.e., superhydrophobic surfaces by various methods, such as solution, sol–gel, chemical vapor deposition, electrospinning and so on [5–10]. However, some experiments and theories have indicated that such a low-retention state of a drop on the superhydrophobic surface is unsteady and considerably affected by ambient environment [11]. Lafuma and Quéré demonstrated that a wetting transition to high retention state could occur by pressing a drop between two ultrahydrophobic surfaces when the pressing force was high enough to overcome a critical pressure [12,13]. He et al. discussed a similar wetting transition on a superhydrophobic poly(dimethylsiloxane) surface, where a drop was wetted when impacting the surface from a certain height [14,15]. Narhe and Beysens noted an obvious retention increase with the growth of condensed water drops on superhydrophobic surfaces [16]. Cheng et al. observed that contact angle hysteresis increase and drop mobility was severely limited when condensation of drops occurred on a lotus leaf [11]. Wier and McCarthy studied the dynamic behaviors of condensed drops on superhydrophobic surfaces [17]. They showed that the condensation of drops on superhydrophobic surfaces may bring more wetting retention than smooth surface with little or no retention. Therefore, the issue about the wetting behaviors between superhydrophobic surface and water under various environments is complex and deserves analysis [18–22].

Recently, some encouraging applications of superhydrophobic surface have been extended to their contacts with the water flow or their movements underwater. For example, the experiments of microchannels with a low-retention superhydrophobic wall exhibited substantial (10–50%) drag reduction relative to the smooth microchannel wall for either laminar or turbulent flow [23]. The water strider’s legs can load as much as ∼15 times their total body weight because of water surface deformed by their superhydrophobic legs [24]. Thus a lot of principle researches were developed to explore the cause of these special behaviors of superhydrophobic surface with water. Su et al. found that a superhydrophobic ball can move more slowly underwater than a smooth glass ball. In contrast, a faster movement occurred on the skin of water surface. Dense air microbubbles covered on the surface of superhydrophobic ball was a main reason for its complex behaviors underwater [25]. Wang et al. observed the rapid bursting of some large air bubbles when they contacted a superhydrophobic lotus surface underwater. They believed that the lotus leaf provided enough space bridges to allow

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air bubbles escape from its surfaces and thus may be useful for industry separations [26]. Sakai et al. used a laser beam to evaluate the state of the superhydrophobic surfaces underwater and showed that different surface textures made different morphology of the air layer on their surfaces [27]. Specially, researchers have also illustrated that drag reduction of superhydrophobic surface (or wall) in the microchannels was due to the presence of a low-viscosity air layer trapped within the superhydrophobic surface, which resulted in the liquid exhibiting apparent slip over the wall [28–34]. Accordingly, sustaining air microbubbles or layers around the superhydrophobic surface seems important to realize their applications on water surface or underwater. However, recent research by Shirtcliffe et al. showed that the pressure of shear flow determined if the drag of water was reduced or induced on superhydrophobic surface in micropipes or microtubes, that is, a large shear pressure may cause the disappearance of the air layer and thus increased friction between water and superhydrophobic wall [35]. Bobji et al. found by a light reflection technique that the air bubbles on the underwater superhydrophobic surfaces with various textures (the arrays of pillar, ridges and holes) disappeared gradually as time goes by [36]. Therefore, we believe that to know sustainability (state) transition of air layers in water is essential for better applying these air-layered flow technologies of underwater superhydrophobic surfaces.

In this article, the sustainability (state) transition of air layer around the superhydrophobic surface underwater is firstly examined by applying a hydraulic pressure onto a lotus leaf which was used as a typical superhydrophobic surface. Distinct from the other methods, such as by pressing a drop between two equal superhydrophobic surfaces or suspending a large volume (depends on the variety of the surface tension), ours focused more on the variety of air layer on a superhydrophobic surface and may shed light on their sustainability underwater. In our experiments, the air layer even vanishes above the critical hydraulic pressure. Instead of resorting to light reflection technology on air–water interfaces, we have measured the wettabilities and retention of drops on the lotus surface to examine the state of air layer underwater after it is taken out of water. Finally, this article attempts to explore the complex relation between the microstructures of lotus surface and the critical pressure of the transition. Our findings might be helpful to the design of surface microstructures on the underwater applications, such as superhydrophobic microchannels or microtubes.

2. Experimental

2.1. Preparation and observation of the samples

The fresh lotus leaves used in the experiments were obtained from a pond in summer in Beijing, China. The microstructures of lotus leaves were observed by using an environmental scanning electron microscope (ESEM, Quanta 200, FEI), without coatings (e.g., Au, Pd or Ag, etc.), accompanying stage temperature of 5 °C, which ensured the freshness of the lotus leaves. An accelerating voltage of 5–15 kV was set for clear images.

The optic morphology of lotus surfaces was examined by stereomicroscope (LYNX, Vision Engineering Ltd, England). The digital images were captured by software Viewfinder V3.0.1.

2.2. Pressing water on lotus surfaces

A cut lotus leaf was placed into a vessel which was filled with water at the depth of ∼5 mm. After the air was pumped out, a piston rod was used to seal the water surface. Two O-rings were used to avoid overflow from the vessel when the piston acted. Fig. S1 schematically shows the setup to apply the external pressure on a lotus surface. After being applied various pressures for 30 min by the piston (the pressure varied from 0 to 100 kPa, the accuracy of the setup was controlled ∼0.1 kPa), the lotus leaves were taken out and then their wettabilities were directly measured.

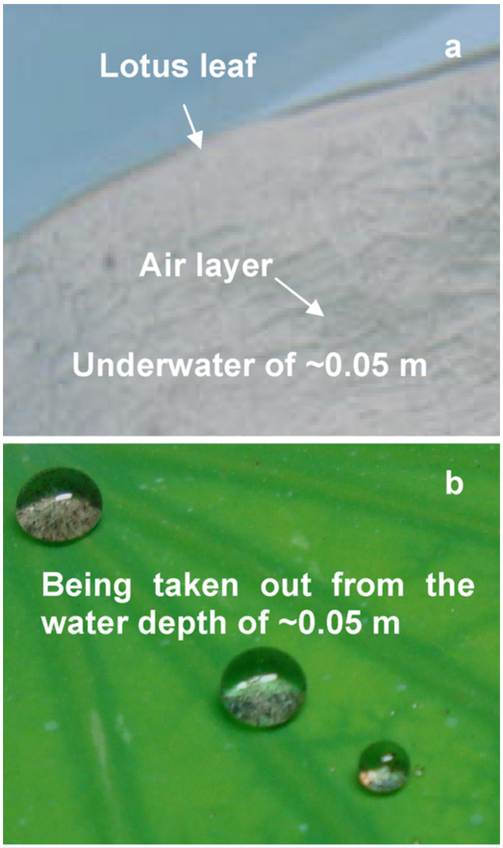

Fig. 1. The optic image of a lotus leaf (a) being placed underwater at the depth of ∼5 mm without additional pressure, (b) after being taken out from water depth of ∼5 mm with some drops on the surface.

2.3. Measurements of wetting behaviors

A 3-μL water contact angle (CA) on the lotus surfaces was measured (DataPhysics OCA 20, Germany) by sessile droplet method after it was taken off from water. Then the receded angles of drops were measured by withdrawing the volume of drops deposited on lotus surfaces to move the triple phase contact line (the withdrawn speed of drop volume was 1 μL/s).

3. Results and discussion

Fig. 1a shows an air layer attached to a lotus surface when it was placed underwater at the depth of ∼5 mm without additional pressure (see Fig. S1). It was clearly seen that water did not actually contact with the lotus surface. Fig. 1b shows the optic image of the surface of the same lotus leaf taken out from water. Note that the surface remained dry and some drops can easily roll off at a small tilt angle (TA) of below 5°. Fig. 2a shows the plot of applying hydraulic pressure, P versus the CA values of the drop on the lotus surface. Disregarding the compressibility of water and the depth of water in the vessel (∼5 mm), the pressure applied with the setup can be regarded as a pure transition of hydraulic pressure acting on the lotus surface. After being taken off from water, the lotus surface displayed the CA of ∼150° on condition that external pressure was below 13.5 kPa. While an obvious CA fall of ∼56° was seen at the pressure of 13.5 kPa. Moreover, the dispersion of