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Research Paper

Cassie-to-Wenzel transition of droplet on the superhydrophobic surface caused by light induced evaporation

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HIGHLIGHTS

- Light induced droplet evaporation on the superhydrophobic surface is studied.
- Rapid transition of the droplet from the Cassie state to Wenzel state is observed.
- Condensed droplets in the microstructures present the Wenzel state.
- Coalescence between condensed droplets and original one cause the wetting transition.
- Dimensionless final migration distances under various conditions are similar.

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ABSTRACT

The droplet-based open microfluidics, which manipulates the liquid droplets in an open space to accomplish various functions, has attracted ever-increasing attentions all over the world. In recent, the incorporation of the optics into the droplet-based open microfluidics has resulted in new methods for optically manipulating the droplets. Among them, the photothermal effect has shown its distinct potentials in controlling the droplet by the light-caused phase change with unique merits of flexibility, precision, remarkable efficiency and non-contact state. In this work, we studied the droplet evaporation on the textured superhydrophobic surface actuated by the photothermal effect of a focused infrared laser with the wavelength of 1550 nm. The transition of the droplet from the Cassie state to the Wenzel state accompanying with the obvious extension of the triple-phase contact line was observed. It was confirmed that this Cassie-to-Wenzel transition was actuated by the continuous condensation in the microstructures of the superhydrophobic surface and coalescence between the condensed droplets and the original one. The effects of the laser power and the initial droplet volume on the Cassie-to-Wenzel transition and the extension of the triple-phase contact line were investigated. It was found that the final migration distance of the triple-phase contact line was gradually increased with the initial droplet volume. With the increase of the laser power, the extension process was accelerated as a result of the intensified light-caused evaporation. Noticeably, it was demonstrated that the dimensionless final migration distance under different conditions were similar.

1. Introduction

The droplet-based open microfluidics, which manipulates the liquid droplets in an open space to accomplish various functions, has attracted numerous attentions all over the world because it offers distinct advantages of mini volume of the reagents, quick response, elimination of the cross-contamination and easy integration. These advantages make it particularly applicable to the fields of biotechnology, pharmacy, medicine and nanomaterials [1–5]. In the droplet-based open microfluidic system, the manipulation of the droplet is considered to be significantly important for purposefully processing the reagents [6,7]. Nowadays, several technologies have been developed to manipulate the droplet, such as electrowetting [8,9], surface acoustic wave [10,11] and gradient surface tension [12,13]. However, these technologies usually

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suffer from the complex architectures of the substrates, the elaborate surface treatments and the miscellaneous systems. In fact, the practical applications of the droplet-based microfluidics usually demand the simple, efficient and reliable manipulation of the droplet [14,15]. Hence, seeking advanced droplet manipulation methods is of importance for the development of the droplet-based open microfluidics.

In recent, the incorporation of optics into the droplet-based microfluidics has opened a new avenue for manipulating the droplets by the interactions between the light and fluids, which presents the prominent features, including the precision, the adjustability of the light intensity and the beam pattern and the remote control [16–18]. Among the interactions between the light and fluids, the photothermal effect has shown the promising potential in the manipulation of the droplet by the light-driven phase change [19–21]. With the photothermal effect, the light energy could be effectively absorbed by the liquid and then converted into the heat. Because the light could be easily focused to a tiny spot, the photothermal effect is regarded as one of the ideal methods to form the localized heating source and thus flexibly manipulate the droplets. There are already some researches about the photothermal effect induced phase change accompanying with the dynamics of the liquid interface. Liu et al. [22] demonstrated an optofluidic micropump based on the photothermal nanoparticles. Zhang et al. [23] proposed a bubble generation technique using the patterned chromium pads to absorb a continuous-wave laser energy, which featured no constraint on the type of target solution and freely chosen location of bubble generation. Zhao et al. [24] presented the particle trapping and manipulation by the photothermal effect induced liquid interface motion. Using this approach, randomly distributed particles could be effectively collected and carried to desired locations. More recently, the photothermal effect induced droplet evaporation on the hydrophobic PDMS surface was also investigated by Jiao et al. [25]. It was shown that, due to the localized heating source of the focused infrared laser, numerous condensed droplets were formed near the triple-phase contact line and coalesced with the original one. Other than the continuous advancement of the liquid interface in the microchannel [26], the extension of the droplet interface on the hydrophobic PDMS surface was severely restrained by the open environment and the absence of the liquid supplementation.

Although the photothermal effect induced evaporation in the microchannels and on the hydrophobic substrate has been widely explored, to our best knowledge, the photothermal effect induced droplet evaporation on the superhydrophobic surface has not been visited yet. Generally, the droplet evaporation modes consist of the constant contact angle (CCA), the constant contact radius (CCR) and the mixed mode. With the large contact angle hysteresis, the droplet tends to evaporate with the CCR mode [27,28]. However, for the superhydrophobic surface, things become more complex. As known, the droplets on the superhydrophobic surface have two typical states: the Cassie state and the Wenzel state, depending on the level of the gas imprisoned in the microstructures of the superhydrophobic surface [29,30]. For the Cassie state, the gas imprisoned in the microstructures under the droplet resist the direct contact between the droplet and the solid substrate, resulting in small contact angle hysteresis. For the Wenzel state, the microstructures are filled with the liquid, resulting in efficient contact between the droplet and the substrate, thereby causing large contact angle hysteresis. In this case, the wetting configuration of the droplet on the superhydrophobic surface could be possibly switched by properly providing the stimulation [31–34]. Moreover, the vapor condensation on the superhydrophobic surface can induce the Wenzel droplet, which is significantly different from the deposited droplet [35,36]. Lo et al. [37] investigated the dynamics of the condensed droplets on the micro/nano-structure-roughened superhydrophobic surfaces. It was suggested that the microstructures easily yielded the highly-pinned Wenzel droplets, resulting in an increase in the droplet departure diameter. Rykaczewski et al. [38] revealed the impact of the surface micro topography on the condensed droplets coalescence. The multiple droplets merging occurred during the serial coalescence events, which culminated in the formation of the droplet that either departed or remained anchored to the surface. Wen et al. [39] investigated the dynamic evolution of the condensed droplets on the superhydrophobic surfaces at various growth stages. It was demonstrated that the initial droplet formation had a deterministic effect on the wetting state. The wetting transition from the mobile Cassie state to the pinned Wenzel state occurred spontaneously with the increase of the surface subcooling. Notably, in the case of the localized heating source created by the focused light, the evaporated vapor easily becomes supersatuated and condensed in the microstructures of the superhydrophobic surface. These condensed droplets tend to be in the Wenzel state rather than the Cassie state [40,41]. When the original droplet in the Cassie state coalesces with these condensed droplets in the Wenzel state, the heated droplet interface could be readily extended due to the lock of the triple-phase contact line of the condensed droplets. Thus, the photothermal effect induced droplet evaporation on the superhydrophobic surface accompanying with the evaporation-condensation-coalescence is likely to cause the obvious extension of the original droplet interface, presenting the transition from the initial Cassie state to the Wenzel state (schematically shown in Fig. 1). To date, however, there are few works on the photothermal effect or the localized heating source induced droplet evaporation on the microstructured superhydrophobic surface. In this work, the evaporation of the droplet on the microstructured superhydrophobic surface induced by the photothermal effect of a focused infrared (IR) laser with the wavelength of 1550 nm was investigated. Particular attention was paid to the phase change behaviors and the extension of the triple-phase contact line on the superhydrophobic surface. In addition, the effects of the laser power and the initial droplet volume were studied.

2. Experimental

2.1. Fabrication of the superhydrophobic surface

The fabrication of the superhydrophobic surface employed in this study is presented as follows. Firstly, a glass slide with the thickness of 1.15 mm was immersed into the Piranha solution for 30 min to remove the residual organics, and then washed with deionized (DI) water and finally dried with nitrogen gas. Secondly, 20-mg superhydrophobic coating (Solmont Technology Inc, FC3150) was uniformly sprayed onto the glass slide under the working pressure of 0.15 MPa. Superhydrophobic coating was composed of the fluorocarbon resin (Suzhou Chuangyuan Chemical, JF-3X), clay (12–20 mm), and AEROSILÒ Hydrophobic fumed silica R106 (Degusaa), hydroxyl group-containing fluorinated hydrocarboncarbon (Solmont Technology Inc, F620) and butyl acetate (Sigma-Aldrich). Fumed silica was first dispersed in butyl acetate sonicated for 5 min at 1000 rpm followed by adding clay and stirring for 2 h. After adding fluorocarbon resin and hydroxyl group-containing fluorinated hydrocarboncarbon, the mixture was stirred for additional 2 h at room temperature before the spraying. The superhydrophobic layer was then solidified at 80 °C for 30 min to accomplish the fabrication of the superhydrophobic substrate. Fig. 2a and b show the LSCM 3D topography (Nanofocus, MarSurf CM expert) and the SEM image (Hitachi, SU8020) of the fabricated superhydrophobic surface. It was found that there were numerous submicron microstructures on the superhydrophobic surface, which easily trapped the gas to impede the droplet wetting. The contact angle hysteresis and the static contact angle on the superhydrophobic surface were measured by a Drop Shape Analyzer (XYCXIE, XG-CAMB1) with the droplet volume of 4 μL. It was shown that the contact angle hysteresis was 4° while the static contact angle was 150°.

The 3D topography of the superhydrophobic surface was measured by a LSCM (Nanofocus, MarSurf CM expert). It was found that the sizes of the microstructures on the superhydrophobic surface were not uniform. The gap sizes of the microstructures on the superhydrophobic