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Temperature-regulated directional bounce of impacting droplets on gradient grooves

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ABSTRACT

Droplet impact dynamics on gradient textures at room temperature have been intensively studied in the past decade. The wetting gradient surfaces are reported to direct the droplet motion. In this work, we show an undirectional rebound behavior of impacting droplets on gradient grooved surfaces at high temperature. The impinging droplet rebounds towards the denser microstructure region at contact boiling state, but towards to the sparser region when at Leidenfrost film boiling state. Our analysis indicates that the non-directional rebounding direction is attributed to the unbalanced Young's forces or vapor pressure difference between the droplet and the substrate. In contact boiling regime, the droplet rebounds towards the denser region due to the unbalanced Young's force. However, in the Leidenfrost film boiling region, adequate vapor generated underneath the droplet impedes the direct contact and larger vapor pressure in the denser region causes the droplet to rebound oppositely. This study is envisioned to promote the understanding of droplet dynamics at high temperature and provide promising applications in various systems where regulating droplet motion is needed.

1. Introduction

Controlling directional motion of droplets on solid surfaces has attracted increasing attention in recent years, due to its broad importance for fundamental research and practical applications, such as fuel injection, spray cooling, and microfluidic manipulation [1,2]. In nature, water can be directionally transported on various biological surfaces [3,4]. For example, the 1D-oriented microstructures on butterfly wings realize the directional motion of impacting droplets, keeping a perfect shedding of the rain droplets [3]. A desert beetle can collect water from humid air using the microstructures with different wettability on its back [4]. Inspired by nature, a series of strategies have been proposed to deliver droplet directionally, including tailoring the surface structure [5–7], applying electric force [8–10], light stimulus [11] and nonequilibrium noise [12], regulating the surface wettability [13–16] and their combinations [17,18]. The aforementioned methods are generally adopted at room temperature. At high temperature, the chemical material used to change the surface wettability may be invalid in a long-term operation. Therefore, using asymmetric structures to promote droplet motion is more effective at high temperature, especially in the Leidenfrost regime [19–21], where the droplet levitates on a cushion of its own vapor layer. Under the effect of the vapor layer, liquids are reported to perform self-propelled motion when placed on the surfaces with a ratchet-like [22–27] or anisotropic morphology [28]. Various mechanisms including Laplace's pressure by the asymmetric structure, thermal creep effect driven by the asymmetric temperature profile [23], and viscous mechanism [26,27] have been proposed to interpret the above phenomena.

Apart from the surface morphology, the droplet self-motion could be driven by judicious control of the operating temperature of the solid substrate [28,29]. Grounds et al. [29] showed that transition boiling can provide additional control over droplets and ratchets with substructures enable their direction of motion to be controlled by varying the temperature of the surface. Recently, Li et al. [28] found a directional transport of impacting droplets on an asymmetry wetting surface which exists two concurrent thermal states including Leidenfrost and contact boiling state. This is due to the generated unbalanced Young's force that engenders a preferential motion of a droplet towards the contact boiling region with a higher heat transfer coefficient. However, few studies have been focused on the droplet rebounding direction on

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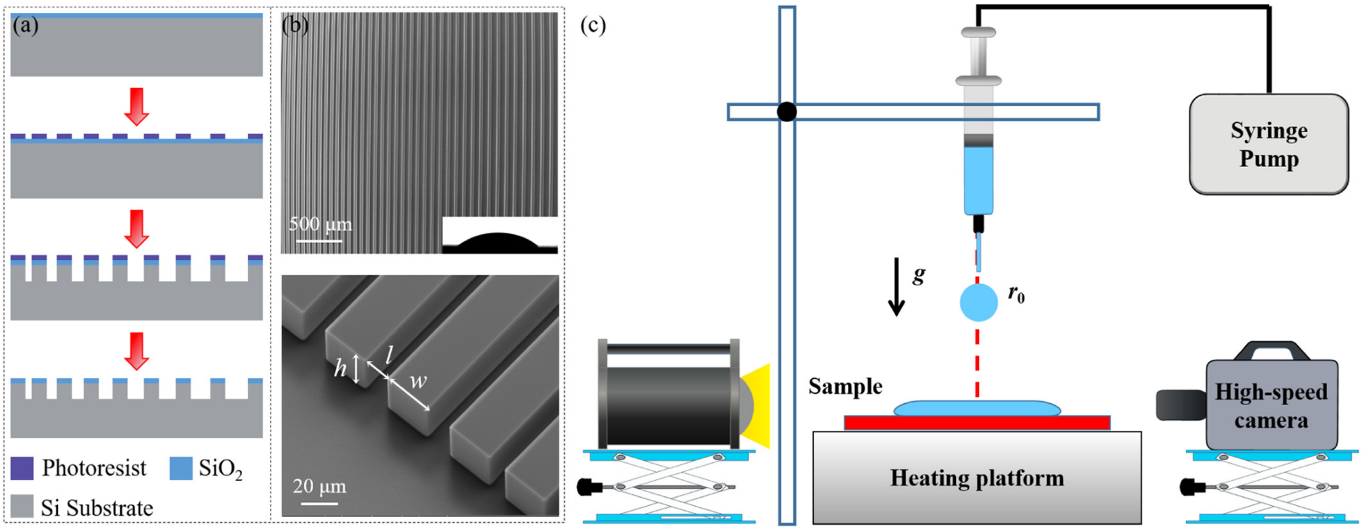

Fig. 1. (a) Illustration of the fabrication process of gradient grooved surfaces. (b) SEM images of the grooved substrates. The ridge width w (w = 30 μm) and the ridge height h (h = 20 μm) are constant, while the gradient spacing (l) changes gradually from 10 μm to 125 μm. (c) Schematic of the experimental apparatus showing the droplet impact on a heated substrate.

gradient textured surfaces at high temperature.

Here, we consider droplets impact on gradient grooved surfaces at different boiling state, to investigate the synergetic effect of surface structure and temperature on droplet motion. Directional rebound was observed on the grooved surface and the directionality can be controlled by regulating the surface temperature. The directional rebound is attributed to the unbalanced Young's force at contact boiling state, but the unbalanced vapor pressure provides control over the droplet at the Leidenfrost regime.

2. Experimental section

In our experiment, the gradient grooved surfaces were fabricated using the standard photolithography technique on a silicon wafer, as briefly illustrated in Fig. 1a. Namely, a SiO_2 layer with a thickness of 2 μm was first deposited on the silicon wafer with a thickness of 500 μm at high temperature. The photoresist was uniformly coated on the SiO_2 layer. Then the uncovered SiO_2 was etched by Reactive Ion Etching (RIE). Deep RIE was used to further etch the silicon substrate to form the microgrooves. The surface consists of uniformed micro arrays with ridge width w (w = 30 μm), ridge height h (h = 20 μm), but varying groove width l, as shown in Fig. 1b. The value of the spacing l gradually increases from 10 μm in the densest region to 125 μm in the sparsest region over a span of 8.4 mm, and the contact angle of the corresponding region resulting in a measured static contact angle gradually varied from 42.6° to 15.5°.

The experimental setup used in droplet impact experiments is schematically illustrated in Fig. 1c. The sample was placed on a heating platform which can be heated up to 600 °C in the ambient environment, at room temperature with 60% relative humidity. Here we define T_w as the temperature of the heated surface. Deionized water droplets of radius r_0 = 1.16 mm were released from a syringe pump equipped with a fine needle at a flow rate of 2 μL/s. The height between the droplets and the samples was adjusted to change the impact velocity v_0 from 0.3 to 1.4 m s^{-1}, corresponding to the Weber number (We) of $1.6 < We < 31.6$. The Weber number is defined as $We = (\rho v_0^2 r_0)/\gamma$, where r_0 is the drop radius, ρ is the liquid density, and γ is the liquid-vapor interface tension. The droplet impacting process on the surface was recorded by a high-speed camera (Photron SA5) from the side view at a frame rate of 5000 fps.

3. Results and discussion

Fig. 2a shows selected snapshots of droplets impacting on the flat surface (l = 0 μm) at We = 23.7, T_w = 270 °C (Supplementary Video 1, left side). The impacting droplet spreads on the substrate with an obvious upward liquid jet in the film center at 3.2 ms. The droplet boils violently on the surface and the exploding satellite droplets scatter until completely evaporated. In this case, the droplet in contact with the surface experiences a high-rate inflow of heat, and vapor bubbles grow from inside, causing disruption of the liquid surface and ejection of tiny droplets, indicating the contact boiling of impacting droplets [30–32]. As expected, the droplet retains a symmetrical shape on the flat surface, although exhibiting severe disturbance because of the intense heat exchange with the substrate. Distinct from that on flat surfaces, the droplet boiling is weaker on ridge surface, e.g., at hitting point with l = 70 μm at We = 23.7 and T_w = 270 °C (Supplementary Video 1, right side), as shown in Fig. 2b. Particularly, the droplets reach the maximum spreading at the same time about 3.2 ms where the leftmost front of the droplet is in contact with the denser ridge area with l = 20 μm, whereas its rightmost front is in contact with the sparer ridge area with l = 100 μm. The droplet boiling is much weaker than that on the flat surface during the retracting process, where there are only a few secondary droplets ejected although still at contact boiling and finally the drop bounced off the surface in an integrated shape. This is consistent with the previous experimental results [33]. On the grooved surface, the droplet penetrates into the grooves, leading to a relatively larger area of direct contact, thus more vapor forms instead of bursting bubbles and few secondary droplets eject. Moreover, the droplet bounced towards the denser region is observed.

When the substrate temperature is larger than a critical point (the Leidenfrost transition temperature), a stable vapor film develops between the droplet and the heated substrate. The vapor film acts as a lubricant layer, which inhibits the bubble bursting and reduces the energy dissipation during impacting, therefore enabling the rebound back of the droplet as a whole. This is similar to droplets impact on superhydrophobic surfaces [34–36]. Fig. 2c demonstrates that the impacting droplet spreads and retracts symmetrically and bounces off the flat surface vertically (Supplementary Video 2, left side). However, when the droplet impacts on the gradient grooved surface, e.g., at hitting point with l = 70 μm at We = 23.7 and T_w = 360 °C (Supplementary Video 2, right side), the droplets reached the maximum spreading at about 3.2 ms where it contacts the substrate with