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Full Length Article

Directional transport of droplets on wettability patterns at high temperature

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ABSTRACT

Directional transport of liquid has attracted increasing interest owing to its potential of application in lab-on-a-chip, microfluidic devices and thermal management technologies. Although numerous strategies have been developed to achieve directional transport of liquid at low temperature, controlling the directional transport of liquid at high temperature remains to be a challenging issue. In this work, we reported a novel strategy in which different parts of droplet contacted with surface with different wettability patterns, resulting in a discrepant evaporative vapor film to achieve the directional transport of liquid. The experimental results showed that the state of the liquid on wettability patterned surface gradually changed from contact boiling to Leidenfrost state with the increase of substrate temperature T_s, and liquid on superhydrophilic surface was in composite state of contact boiling and Leidenfrost when T_s was higher than 200 °C. Inspired by the different evaporation states of droplet on the wettability boundary, controlling preferential motion of droplets was observed at high temperature. By designing a surface with wettability pattern on which superhydrophobic region and superhydrophilic region are alternately arranged, a controlled directional transport of droplet can be achieved at high temperature.

1. Introduction

Directional transport and unidirectional spreading of liquid have attracted increasing interest for their potential of applications in lab-on-a-chip, microfluidic devices, fog harvesting, heat transfer, filtration, etc [1–5]. In nature, water can be directionally transported on various biological surfaces, such as the Nepenthes alata, spider silk, bird beaks, because of their special structural topography or wettability [6–11]. Inspired by the biologically functional surfaces, numerous strategies have been developed to realize the directional transport of liquid by considering factors such as capillary force gradients, pressure, chemical concentration, surface energy, temperature, vibration, light, geometrical shape, and the combination of them [12–19]. For example, Megaridis et al. [14] reported an open and non-planar microfluidic platform composed of a superhydrophobic substrate and a wedge-shaped superhydrophilic track, which realized pumpless fluid transport driven by surface tension. Jiang et al. [6,7,20,21] fabricated a peristome-mimetic surfaces to achieve unidirectional transport of liquid by mimicking the microstructure of the Nepenthes alata. The previous methods are beneficial for us to understand the physicochemical mechanisms of directional transport of liquid and design novel microfluidic devices. However, the stability and effectiveness of aforementioned methods at high temperatures remain to be investigated. Moreover, very few literatures have been published concerning the directional transport of liquid on surface with heated wettability pattern. It is noteworthy that Wang et al. [22] effectively controlled the directional transport of droplet on a specially patterned surface at high temperature using liquid transportation platform with two different thermal states. So far, although the design and fabrication of the transportation platform with two differently thermal states cannot meet the requirement for practical application, the novel method should serve as an inspiration for preferential droplet motion at high temperature.

In terms of fluid control, surfaces with different wettabilities, such as superhydrophobicity, superhydrophilicity, superoleophobicity and superoleophilicity are widely investigated [23–25]. Numerous evaporation dynamic models and experiments have

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been developed to explore the evaporation behaviors of droplets on surface with different wettability pattern [26–30]. Vakarelski et al. [31–35] reported that superhydrophobic surface and hydrophilic surface had significantly difference in heat transfer coefficient, Leidenfrost temperature and evaporative vapor film. Here, we proposed a novel strategy in which different parts of droplet contacted with surface with different wettability patterns, resulting in a discrepant evaporative vapor film to achieve the directional transport of liquid. First, we developed a facile twice-electrochemical-etching approach to fabricate wettability pattern containing superhydrophobic region and superhydrophilic region. With the increase of substrate temperature, the directional transport of droplet on heated wettability pattern can be achieved. By designing a wettability pattern with superhydrophobic region and superhydrophilic region being alternatively arranged, the controlled directional transport of droplet can be achieved at high temperature.

2. Experimental

2.1. Fabrication of the wettability patterns

The wettability pattern composed of the superhydrophobic (S-phobic) region and superhydrophilic (S-philic) region was fabricated on Al substrate by a simple twice-electrochemical-etching approach, as shown in Fig. 1. First, the Al plate was polished and electrochemically etched in the 0.1 mol/L aqueous NaCl solution at the 0.5 A/cm^2 current density for 5 min. Then, the etched Al plate was modified by Fluoroalkylsilane [FAS, $C_8F_{13}H_4Si(OCH_2CH_3)_3$] to achieve the S-phobic surface. After that, the area of S-phobic surface was covered by a mask with desired shape. Then, the sample was subjected to electrochemically etched again at the aforementioned electrolyte and current density for 3 min to etch the non-covered area. Subsequently, the sample was immersed in the boiling water for 10 min to achieve lasting hydrophilicity. Finally, the whole mask was torn out. After electrochemical etching and boiling water immersion, the non-covered area showed superhydrophilic while the covered area still kept superhydrophobic.

2.2. Characterization of the wettability patterns

Droplet (dyed in red for better visualization) was in spherical shape on S-phobic surface, while spreading out quickly on S-philic surface, as shown in Fig. 2(a). The contact angle measurement indicated that the water contact angle of the super-hydrophobic region was $157 \pm 2^\circ$ [Fig. 2(b)], while that of the super-hydrophilic area was less than 10° [Fig. 2(c)]. Fig. 2(d) shows the SEM image of the S-phobic Al surface. It can be seen that the aluminum surface was completely etched, with distribution of rectangular pits and structures in size of less than 5 μm. Fig. 2(e) shows the SEM image of the S-philic Al surface after secondary electrochemical etching and boiling water immersion. The results show that the S-philic surface as a whole is a new and finer structure containing irregular rectangular pits and micro/nanostructures. Through the insert graph of Fig. 2(e), it can be found that homogeneous nanometer-scale needle-like structures were formed on the substrate after boiling water immersion. Substrate detection by XRD showed that diffraction peaks of the S-phobic Al surface were derived from pure Al structure [Fig. 2(f)]. In addition to pure aluminum structure shown in the XRD diffraction peaks on the substrate after secondary electrochemical etching and boiling water immersion, AlOOH diffraction peaks were also observed, which means that the nanometer-scale needle-like structures on the S-philic surface are boehmite (γ –AlOOH) [Fig. 2(g)]. The element mapping images at the boundary of the S-phobic region and S-philic region are shown in Fig. 2(h). It can be seen from the figure that there is a significant difference in O and F element distribution between the S-phobic region and S-philic region. F element in the S-philic region after secondary electrochemical etching was significantly reduced, demonstrating that low surface energy materials on the uncovered substrate were almost completely removed. A large number of O elements in boehmite derived from boiling water immersion were uniformly distributed in S-philic region, while the O element distribution in S-phobic region was very small.

3. Results and discussion

3.1. Evaporation of droplets on heated wettability pattern

Fig. 3 shows the dynamic processes of droplets dripping on the heated wettability pattern. When the substrate temperature T_s was 80 °C (below water boiling point), droplet dropped on the S-phobic surface, and then quickly spread out with slight bouncing, and finally break away from the substrate [Fig. 3(a), and Movie S1]. In contrast, when the droplet dropped on the S-philic surface, it quickly spread into a water film till being completely evaporated [Fig. 3(b)]. When the droplet dropped on ordinary surface, the droplet spread out first and then contracted back, but the droplet would not escape from the substrate [Fig. 3(c)]. When the substrate temperature T_s was 150 °C, the droplet impacted on the S-phobic surface can still bounce and disengage from the substrate. However, the droplets on the S-philic surface and ordinary surface (T_s = 150 °C) could not completely spread on the substrate but gradually changed into spherical shape, and the contact angle was also increased. Wherein, the droplet on the S-philic surface was in a contact boiling state, and small droplet splashes were observed. When the substrate temperature T_s was 250 °C, the droplets on the S-phobic surface and ordinary surface both bounced normally. The droplet on the S-philic surface was intensely boiled, generating steam that suspended the liquid, and then the droplets hit the substrate and started to bounce under the effect of the steam layer.

As can be known from the above experimental phenomena, with the increase of temperature, the droplet on the S-phobic surface can keep integrity with bouncing process occurred. As droplet boiling and evaporation behaviours were intensified on the S-philic surface, droplet on the substrate could not be fully spread out with occurrence of droplet breakage. Droplet bouncing process can also occur under high temperature. Ordinary surface also gradually changed from hydrophilic state into hydrophobic state, with the occurrence of the bouncing process.

The wettability reversal of droplet on high temperature surface is called Leidenfrost phenomenon, which is due to the large amount of steam produced by evaporation of droplets on the substrate. To investigate the temperature of Leidenfrost transition on surface with different wettabilities, the time required for complete evaporation of droplet (volume, 5 μL) on surface with different wettabilities at different temperatures was analyzed. The results are shown in Fig. 3(d).

With the increase of T_s, the evaporation time of droplet on surface with different wettabilities decreased first and then increased. When T_s was lower than 200 °C, the droplet on the S-phobic surface evaporated slowly, while the droplet evaporation rate on the S-philic surface was the fastest. This is because the droplet was in contact boiling state on the substrate within the T_s range from 100 to 200 °C.

When T_s was higher than 200 °C, the evaporation state of the droplet gradually changed from contact boiling to the Leidenfrost state, resulting in decreased contact area between the droplet and the substrate, and thereby causing a decreased evaporation rate of droplet. On the whole, the evaporation rate of droplet on ordi-