Directional transport of droplets impacting on superhydrophobic opening triangular groove surfaces

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Abstract—Directional droplet transport is of great importance to various processes including heat transfer, water harvesting and microfluidics. Here, a facile superhydrophobic opening triangular groove surface was proposed, and the directional transport behavior of droplets impacting on the surface was observed. The results show that the essence of the directional transport on the opening triangular groove surface can be attributed to the interaction between the impinging droplet and the groove sidewall, and the directional transport distance is regulated by the contact area during the interaction. Further, by controlling the depth of triangular groove, the triangular opening angle, the impacting point position and the Weber number, the contact area between the droplet and the groove sidewall during the interaction can be changed, leading to the variation of directional transport distance. This study provides a new method for directional droplet transport on superhydrophobic surfaces and offers more options for the manipulation of droplet behavior.

1. Introduction

Directional transport of droplets impacting on solid surfaces has been extensively investigated and is crucial to many applications, such as water harvesting [1, 2], droplet-based electricity generators [3-5], and spray cooling [6, 7]. Many solid surfaces have been adopted to achieve directional transport of impinging droplets, such as superhydrophobic surfaces with hybrid wettability and patterned superhydrophobic surfaces. Chu et al. [8] reported that when the droplet impacted on the boundary between the superhydrophobic part and hydrophilic part, the directional transport distance of the droplet can be controlled by changing the proportion of the impinging droplet in the hydrophilic part. Zhao et al. [9] investigated the droplet impacting on a heterogenous superhydrophobic surface with hydrophilic strips, and quantitatively manipulated the directional transport distance of the droplet and suppressed the Plateau–Rayleigh instability successfully [10]. However, these surfaces exist many defects such as droplet loss, mixing, and contamination due to the hydrophilic regions. In another research line, on homogeneous superhydrophobic surfaces, an impinging droplet usually manifests a typical elastic rebound because of the negligible viscous dissipation caused by the hydrophobic roughness trapped underlying the impinging droplet. In addition, due to the short contact time [11, 12], the bouncing direction of the impinging droplet is hard to be accurately controlled, so special structures are necessary for directional transport of impinging droplets on homogeneous superhydrophobic surfaces. Wang et al. [13] fabricated a flexible needle-like surface with controllable
inclination angle by changing the magnetic field strength, and the horizontal offset distance of the droplet impacting on the surface was different under different inclination angles. Liu et al. [14, 15] proposed an array of equidistant circular grooves, and realized the directional transport of impinging droplets towards the center of the curvature. Nevertheless, the structures mentioned above are difficult to process and costly.

In this study, a facile homogeneous superhydrophobic opening triangular groove surface (SOTGS) is reported. The interaction between the impinging droplet and the groove sidewall causes directional transport of the droplet in the direction away from the top of the triangular groove. The effects of the groove depth $H$, the triangular opening angle $\alpha$, the distance between the impacting point and the top of groove (e. g., the impacting point position $L$), and the Weber number $We$ on the directional transport distance $\Delta L$ were explored. The findings may yield more insights into directional droplet transport on superhydrophobic surfaces.

2. Methods and Materials

2.1. Preparation and characterization of the SOTGS

The substrates, consisting of a superhydrophobic sheet with an opening triangular groove in the upper part and a flat superhydrophobic sheet in the lower part, were made of 6061 aluminum alloys. In the experiment, the grooves with depth $H = 1.0 - 3.0$ mm and opening angle $\alpha = 3 - 7^\circ$ were fabricated by wire electrical discharge machining (WEDM). The schematic of the surface topography is depicted in Fig.1 (a). The aluminum substrates were firstly polished by #500, #800 and #1000 abrasive papers, after that, ultrasonically cleaned in acetone, ethanol and deionized water. Next, the acid etching process was conducted to attain step-like microstructures [Fig.1 (b)] by putting cleaned substrates into 3.0 M HCl. After etching for ~ 7.5 min, substrates were immediately rinsed with deionized water. Then, boiling treatment process was proceeded to achieve needle-like boehmite and alumina nanostructures [Fig.1 (d)] by putting etched substrates into boiling water for ~ 15.0 min. Finally, to render the surfaces superhydrophobic, low surface energy modification was implemented by immersing the aluminum substrates into 0.5 mM n-hexane solution of trichloro(1H,1H,2H,2H-perfluorooctyl)silane for ~1 h, followed by heat treatment at 150 °C in air for ~1 h. The surface exhibits a superhydrophobic property with an apparent contact angle of over 170°, as shown in Fig.1 (c).

It is worth mentioning that the top of the groove after WEDM is not a strict tip, but the same molybdenum wire with a diameter of 0.18 mm was used to manufacture the groove with different $\alpha$, which can ensure that the top radii of different grooves keep the same ($R\sim150$ μm), as demonstrated in the inset in Fig.1 (a).

![Fig.1 (a) Schematic diagram showing a droplet impacting on the SOTGS with the opening angle $\alpha$, the groove depth $H$, and the impacting point position $L$. Inset: the enlarged image of point O. (b) SEM of the SOTGS after acid etching. (c) the apparent contact angle of a droplet on the flat part of SOTGS. (d) SEM of the SOTGS after boiling treatment.](image)
2.2. Droplet impact experiments
Deionized water droplets with diameter $D_0 = 2.6$ mm were released from a syringe pump equipped with a fine needle. The distance between the needle and the surface was adjusted to change the impacting velocity $v_0$ from 0.38 ms$^{-1}$ to 0.73 ms$^{-1}$, corresponding to $5.16 \leq \text{We} \leq 19.10$, where $\text{We} = \rho v_0^2 D_0 / \gamma$ is defined as the Weber number, with $\rho = 998$ kg/m$^3$ is the liquid density and $\gamma \approx 73$ mN/m is the interface tension of water. The droplet impacting dynamics were recorded synchronously from both the side and top views by two high-speed cameras (Photron SA4) at a frame rate of 3000 fps. The dynamic behaviors of impinging droplets were analysed using ImageJ software.

3. Results and Discussion

3.1. Dynamic behaviors of droplets impacting on the SOTGS
Fig.2 (a) shows the side and top views of a water droplet impacting on the flat superhydrophobic surface at $\text{We} = 15.61$. The impinging droplet holds a circular symmetry in all directions during the whole spreading and retracting processes.

However, on the SOTGS, as shown in Fig.2 (b), the droplet exhibits different behaviors, as exemplified by an impact on the SOTGS with $\alpha = 5^\circ$, $H = 2.0$ mm, and $L = 6.75$ mm at $\text{We} = 15.61$. In the first stage (0 - 3.3 ms), the droplet attains the maximum spreading in the perpendicular direction at ~ 3.3 ms, and spreads along the groove in the horizontal direction. Subsequently, in the second stage (3.3 - 10.0 ms), the droplet retracts in the perpendicular direction, while continues to spread in the horizontal direction and achieves the maximum spreading at ~ 10 ms. Note that, there are different spreading lengths on the left side and right side of the droplet in the horizontal direction at this time. Then, in the third stage (10.0 - 26.7 ms), the droplet retracts in the horizontal direction and bounces off the surface at ~ 26.7 ms. Lastly, in the fourth stage (26.7 - 60.0 ms), the droplet lands with a lateral offset distance $\Delta L = 3.6$ mm.

![Fig.2 Sequence images of droplets impacting on (a) the flat superhydrophobic surface and (b) the SOTGS with $\alpha = 5^\circ$, $H = 2.0$ mm and $L = 6.75$ mm at $\text{We} = 15.61$. $\Delta L$ is the lateral offset distance.](image-url)
From above analysis, the dynamic behaviors of the droplet impacting on the SOTGS are significantly different from that on the flat superhydrophobic surface in the horizontal direction. The possible reason is that the special triangular groove structure results in the interaction between the droplet and the groove sidewall in the horizontal direction, which further causes the lateral offset of the droplet.

3.2. Effect of H on the lateral offset distance
To explore the effect of the groove depth $H$ on the lateral offset distance $\Delta L$ of the droplet, the opening angle $\alpha$ was fixed at $5^\circ$, $H$ was selected as 1.0 mm, 2.0 mm and 3.0 mm. Fig.3 (a) shows that there is no significant difference in $\Delta L$ of the droplets for $H = 1.0$ mm and $H = 2.0$ mm at $L = 4.50$ mm. The possible reason is that the impinging droplet is difficult to penetrate into the groove at the small $L$ corresponding to a small gap. For $H = 3.0$ mm, the droplet has already broken up at a small We, e.g., We = 8.64 [Fig.3 (a), inset], and $\Delta L$ decreases.

When $L$ increases to 7.50 mm, it can be clearly seen that $\Delta L$ of the droplet on the SOTGS with $H = 2.0$ mm is significantly larger than that with $H = 1.0$ mm, as shown in Fig.3 (b). The possible reason is that the larger gap at the impacting point facilitates the penetration of droplets into the groove, and a larger groove depth can provide larger contact area during the interaction between the droplet and the groove sidewall, resulting in a larger lateral offset distance.

![Fig.3 Variation of the lateral offset distance $\Delta L$ as a function of We under different $H$ at: (a) $L = 4.50$ mm. (b) $L = 7.50$ mm.](image)

3.3. Effect of $\alpha$ on the lateral offset distance
According to above analysis, when the groove depth is $H = 1.0$ mm, the contact area between the droplet and the groove sidewall is small, leading to a small lateral offset distance. When $H = 3.0$ mm, the droplet has broken up at small $L$ [Fig.3 (a), inset], so $H = 2.0$ mm was selected here. To investigate the effect of the opening angle $\alpha$ on the lateral offset distance $\Delta L$ of the droplet, $\alpha$ was selected as 3°, 5° and 7°.

When the impacting point is close to the top of the groove ($L = 4.50$ mm), the droplet can hardly penetrate into the groove at We = 5.16, 8.64 and 12.12. Therefore, the interaction between the droplet and the groove sidewall is similar under different $\alpha$, leading to inconspicuous difference in $\Delta L$. However, when We increases to 15.61 and 19.10, $\Delta L$ increases sharply for the groove with $\alpha = 7^\circ$, while changes slightly for $\alpha = 3^\circ$ and $\alpha = 5^\circ$, as shown in Fig.4 (a). The possible reason is that the droplet is more easily to penetrate into the groove with $\alpha = 7^\circ$ at larger We, and the interaction with the groove sidewall is significantly enhanced, leading to a larger $\Delta L$.

As shown in Fig.4 (b), when $L = 5.25$ mm, the lateral offset distance of the groove with $\alpha = 7^\circ$ is prominently larger than that of the grooves with $\alpha = 3^\circ$ and $\alpha = 5^\circ$. $\Delta L$ of $\alpha = 5^\circ$ is generally larger than that of $\alpha = 3^\circ$. The possible reason is that when $L$ increases to 5.25 mm, the larger $\alpha$, the greater the gap at the impacting point, and the easier it is for the droplet to penetrate into the groove, leading to a larger $\Delta L$. Note that, at $\alpha = 7^\circ$, the droplet has broken up at We = 19.10 [Fig.4 (b), inset].
3.4. Effect of $L$ on the lateral offset distance

Based on the above discussion, $L$ has a slight influence on the lateral offset distance when $\alpha = 3^\circ$ [Fig.4 (a) and (b)], and the droplet breaks easily on the groove with $\alpha = 7^\circ$ even though $L$ is small [Fig.4 (b), inset]. Therefore, the groove with $\alpha = 5^\circ$ and $H = 2$ mm was chosen to explore the effect of the impacting point position $L$ on the lateral offset distance $\Delta L$ of the droplet.

Fig.5 (a) shows the variation of the lateral offset distance $\Delta L$ as a function of the impacting point position $L$ under various We. The lateral offset distance changes with similar tendency at $We = 8.64$, 12.12 and 15.61. The distinction is that the $L$ values corresponding to the transition points of $\Delta L$ (hollow dots) are different for different $We$. The $L$ values of the transition points for the increasing stage (hollow square dots) of small $We$ ($We = 8.69$ and 12.12) are greater than that of large $We$ ($We = 15.61$), which also applies to the decreasing stage (hollow circle dots). The possible reason is that the droplet is more easily to penetrate into the groove and interact with the groove sidewall for large $We$, leading to a smaller $L$ at the transition point of increasing stage (the green hollow square dot) for large $We$. Furthermore, the droplet is more easily to spread excessively in the horizontal direction for large $We$ ($We = 15.61$), which is similar to the Kelvin–Helmholtz instability [16], resulting in energy dissipation (that is, the decrease of $\Delta L$) and a smaller $L$ at the transition point of decreasing stage (the green hollow circle dot) for large $We$.

In current researches of directional droplet transport, the lateral offset distance $\Delta L$ generally increases with $We$ [14, 15]. In this work, $\Delta L$ does not monotonically increase with $We$, and is also related to $L$. As shown in Fig.5 (b), when $L = 5.25$ mm and 6.75 mm, $\Delta L$ increases with $We$ and the maximum $\Delta L$ appears at $We = 19.10$. However, $\Delta L$ shows a downward trend with increasing $We$ at other $L$. When $L = 7.50$ mm, the droplet breaks at $We = 19.10$ [Fig.5 (b), inset].
4. Conclusion
In this work, a superhydrophobic surface composed of an opening triangular groove was designed and realized the directional transport of impinging droplets. The effects of the groove depth $H$, the opening angle $\alpha$, the impacting point position $L$, and the Weber number $W_e$ on the lateral offset distance $\Delta L$ were experimentally studied. The results are as follows:

1. When $L$ is smaller, the droplet is difficult to penetrate into the groove, so $H$ can hardly cause differences in $\Delta L$. At larger $L$, increasing $H$ can provide larger contact area during the interaction between the droplet and the groove sidewall, leading to a larger $\Delta L$. However, the droplet breaks easily at a too large $H$.

2. When $L$ and $W_e$ are small, $\alpha$ has a slight effect on $\Delta L$ because the droplet is difficult to interact with the groove sidewall. Properly increasing $W_e$ or $L$ can promote the interaction between the droplet and the groove sidewall to differentiate the effect of $\alpha$ on $\Delta L$, that is, a larger $\alpha$ leads to a larger $\Delta L$.

3. For the groove with $H = 2.0$ mm and $\alpha = 5^\circ$, $\Delta L$ changes with $L$ under different $W_e$ show similar tendency, and the distinction is that the $L$ values of the transition points are different for different $W_e$. Besides, $\Delta L$ is not only related to $W_e$, but also affected by $L$, so it does not monotonically increase with $W_e$.

This work deepens the understanding of impinging droplets behavior on patterned superhydrophobic surfaces and facilitates the application of superhydrophobic surfaces in the field of the manipulation of impinging droplets.

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