The effect of microstructure on self-propelled droplet jumping

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Abstract. The coalescence-induced droplet jumping on superhydrophobic surfaces has attracted considerable attention over the past several years. Most of the studies on droplet jumping mainly focus the droplet jumping on almost flat surfaces or ignore the effect of the microstructure. However, the microstructure often exists on superhydrophobic surfaces, and this effect remains little noticed and poorly understood. In this work, a simulation is carried out to investigate the effect of microstructure on droplet jumping. The microstructure with a similar scale to the jumping droplet on superhydrophobic will affect the jumping direction. The microstructure will improve the jumping velocity and change the jumping direction of the droplet. This work will provide effective guidelines for the design of functional SHSs with controlled and enhanced droplet jumping for a wide range of industrial applications.

1 introduction

On the superhydrophobic surface, the interaction between the liquid bridge and surface promotes droplet jumping when droplets coalesce. Jumping droplets can contain dirt, condensate droplets and unfrozen droplets on the surface so that the droplet jumping can be widely droplet jumping is widely used in micro-flow control [1-3], enhanced heat transfer [4-7], chip cooling [8-10], self-cleaning surfaces [11-15] and other areas. For the study of droplet jumping on a flat surface, Systematic research on droplet jumping has been conducted through experimental observations [16-19], theoretical analysis [20-23], and numerical simulations [24-27], the well-established understanding of droplet jumping. However, The microstructure often exists on superhydrophobic surfaces, and the current research on the effect of microstructures on droplet bounce is not very sufficient.
Because the dynamic force of droplet jumping comes from the surface reaction force, the surface structure has a very significant impact on droplet bouncing. Vahabi et al. studied the influence of triangular microstructures on droplet bouncing. It was found that the microstructures can greatly increase the ratio of surface energy released by coalescence to jumping energy. The improvement of energy conversion efficiency of droplet jumping can also cause self-propelled droplet jumping of working substances with low surface tension coefficient and high viscosity[28]. Chen et al. studied droplet jumping on the superhydrophobic surface with regular microstructures. Although they did not directly discuss the effect of microstructures on the jumping direction, it can be seen from the image of droplet position change in their paper that when the size of droplets is equal to that of microstructures, the direction of jumping droplets obviously deviates, which also appears in the study of Watson et al. [17, 29]. Wang et al. found that the interaction between bulge microstructures and liquid bridges enhance droplet jumping, which increases the energy conversion efficiency from 3.88% to 22.49%, while the sag microstructures reduce the energy conversion efficiency[30]. Attarzadeh et al. studied droplet jumping on superhydrophobic surfaces of micropillars with different sizes. Relative roughness was defined to characterize the effect of microstructural size on droplet jumping. When relative roughness was greater than 44, it could be considered that the surface was smooth, since the microstructures did not affect droplet jumping. When relative roughness was less than 44, the effect of microstructures on droplet bouncing was more significant[31]. The study of droplet jumping on an ideal surface suggests that only when the surface is superhydrophobic, droplet jumping can occur. However, according to Zhang et al.'s research on droplet jumping on fiber structure, although the fiber does not have high hydrophobicity, droplet jumping still occurs after coalesence[32]. Qu et al. observed droplet jumping on the superhydrophobic surface with micropillars, coalescence on the sidewalls of the micropillars leads to self-propelled jumping in a direction nearly orthogonal to the pillars and therefore parallel to the substrate[33].
At present, in the study of the effect of microstructures on droplet jumping, some directly point out that microstructures will affect the energy conversion efficiency and jumping direction of the jumping droplet, while others do not directly point out these effects, but these effects can also be observed indirectly from the experimental images displayed. In this work, two droplets jumping on a superhydrophobic surface with microstructures are simulated using the droplet jumping numerical model we built previously[26, 34, 35], and the effects of micro-structures on the jumping direction and energy conversion efficiency were explored.

2 Numerical model

2.1 Numerical model

The numerical simulations used the interFoam solver in OpenFOAM, which is based on the VOF [36]. The governing equations for the continuity and momentum equations are:

$$\nabla \cdot \mathbf{v} = 0 \quad (1)$$

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$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}\right)=-\nabla p+\nabla\left(\mu\left(\nabla\cdot\mathbf{v}+\nabla\cdot\mathbf{v}^{\mathrm{T}}\right)\right)+\rho g+\boldsymbol{F}_{\mathrm{SF}} \quad (2)$$

where $\mathbf{v}$ is the velocity vector, t is the time, p is the pressure, and $\boldsymbol{F}_{\mathrm{SF}}$ is the source term generated by the surface tension. ρ and μ represent the average density and dynamic viscosity of the fluid in the cell, which are functions of the liquid volume fraction in the cell, α.

$$\rho=\alpha\rho_{\mathrm{water}}+(1-\alpha)\rho_{\mathrm{air}} \quad (3)$$

$$\mu=\alpha\mu_{\mathrm{water}}+(1-\alpha)\mu_{\mathrm{air}} \quad (4)$$

The volumetric force term generated by the surface tension is calculated using the continuum surface force model (CSF):

$$\boldsymbol{F}_{\mathrm{SF}}=\gamma\kappa\nabla\alpha \quad (5)$$

where γ is the surface tension coefficient and κ is the mean curvature of the free surface:

$$\kappa=-\nabla\cdot\left(\frac{\nabla\alpha}{|\nabla\alpha|}\right) \quad (6)$$

2.2 Characteristic quantities and computational domain

R_{e} (the equivalent radius), to represent the total droplet volume,

$$\Delta E_{\mathrm{s}}=4\pi\gamma\left[\sum_{\mathrm{j}=1}^{n}\frac{(1-\cos\theta)R_{\mathrm{j}}^{2}}{2}-R_{\mathrm{e}}^{2}\right] \quad (7)$$

where R_{j} is the radius of the jth droplet in the droplet group.

When droplets coalesce on a superhydrophobic surface, the gas-liquid interface area shrinks which releases some surface energy,

$$\Delta E_{\mathrm{s}}=4\pi\gamma\left[\sum_{\mathrm{j}=1}^{n}\frac{(1-\cos\theta)R_{\mathrm{j}}^{2}}{2}-R_{\mathrm{e}}^{2}\right] \quad (8)$$

Part of the released surface energy is transformed into kinetic energy of the jumping droplet,

$$E_{\mathrm{k}}=\frac{2}{3}\pi\rho U_{\mathrm{d}}^{2}R_{\mathrm{e}}^{3} \quad (9)$$

where U_{d} s the velocity as the droplet departures from the surface. The ratio of the jumping kinetic energy to the released surface energy is defined as the energy conversion efficiency,

$$\eta=E_{\mathrm{k}}/\Delta E_{\mathrm{s}} \quad (10)$$

The mass-averaged velocity of the droplet is defined as the droplet jumping velocity [37]:

$$U(t)=\frac{\int_{\Theta}\alpha(u,w)\mathrm{d}\Theta}{\int_{\Theta}\alpha\mathrm{d}\Theta} \quad (11)$$

where Θ represents the computational domain and (u,w) are the velocity components in the horizontal and vertical directions.

The distribution of droplets is shown in Fig. 1 The centroid of the two droplets is parallel to the microstructures. The radius of the droplets is R, and the distance from the microstructures is D. The calculation domain is set up in the same way as our previous studies. The size of the calculation domain is 1×1×1 mm and the mesh resolution is 150×150×150. The contact angle between the superhydrophobic surface and microstructures is 160°

The time resolution δt is controlled by the maximum Co (Co=max(|U|)$\delta t/\delta x$, δx is the space step, max(|U|) is the largest velocity in the computation domain) number, and the maximum Co number is set to 0.5 in this paper. The superhydrophobic surface was set as a no-slip boundary with the other boundaries as pressure outlet boundaries [26, 27, 37]. As with previous experiments and simulations, the gas and liquid physical parameters were for air and water at 20°C [26, 38].

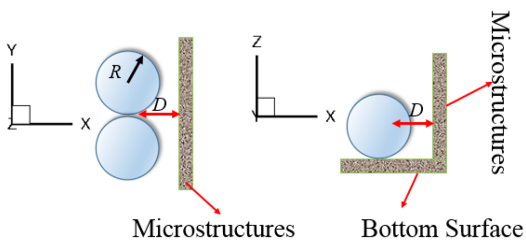


Fig. 1. The position relationship between droplets and microstructures. In this work, the effect of microstructural height on droplet jumping is not discussed, so the microstructures are applied to the calculation as a wall boundary.

RESULTS AND DISCUSSION

Fig. 2 shows the evolution of droplet morphology over time on a superhydrophobic surface with microstructures. As shown in the figure, similar to the conventional process of droplet coalescence, a liquid bridge (0.06 ms) is formed between the two droplets at the initial stage of coalescence, and then the liquid bridge develops impact microstructures and bottom surfaces and shrinks (0.12-0.36 ms). Under the reaction force of microstructures and bottom surfaces, the droplets separated from the bottom surfaces and microstructures simultaneously (0.48-0.84 ms).

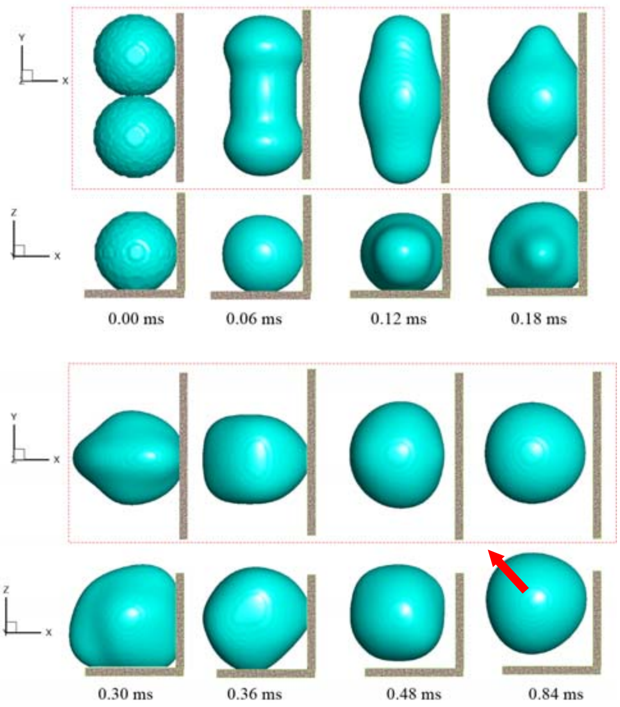


Fig. 2. The droplet morphology evolution with time. The radius of the two droplets is 100 μm and the distance between the droplets and the microstructures D=1.0R.

Fig. 3 shows the change of droplet centroid velocity and position with time. As shown in Figure 3 (a), when droplet coalesces and jumps on a superhydrophobic surface with microstructure, the interaction between microstructure and liquid bridge makes the droplet have a certain horizontal velocity after leaving the surface, and the horizontal velocity component is close to the vertical velocity component. On superhydrophobic surfaces without micro-structures, because of momentum conservation, the horizontal velocity component of droplets is 0. Microstructures can improve the energy conversion efficiency of jumping. The vertical velocity component of jumping droplets is larger than that of droplets without microstructures, increasing from 0.217 m/s to 0.2838 m/s, and the energy conversion efficiency of bouncing droplets increases from 5.38% to 16.57%. As shown in Figure 3 (b), the jumping direction of droplets on the superhydrophobic surface with microstructures is approximately 48 degrees, while on the superhydrophobic surface without microstructures, the jumping direction of droplets is perpendicular to the surface.

The interaction between liquid bridge and microstructures, the energy conversion efficiency of droplet jumping is improved, and the direction of jumping is changed, so the position relationship between liquid bridge and microstructures has a great influence on jumping. After the two droplets with radius R are fully coalescence, the large droplet radius R_e=1.259R. When the distance between droplets and microstructures is large, the bridge can not contact the microstructures or

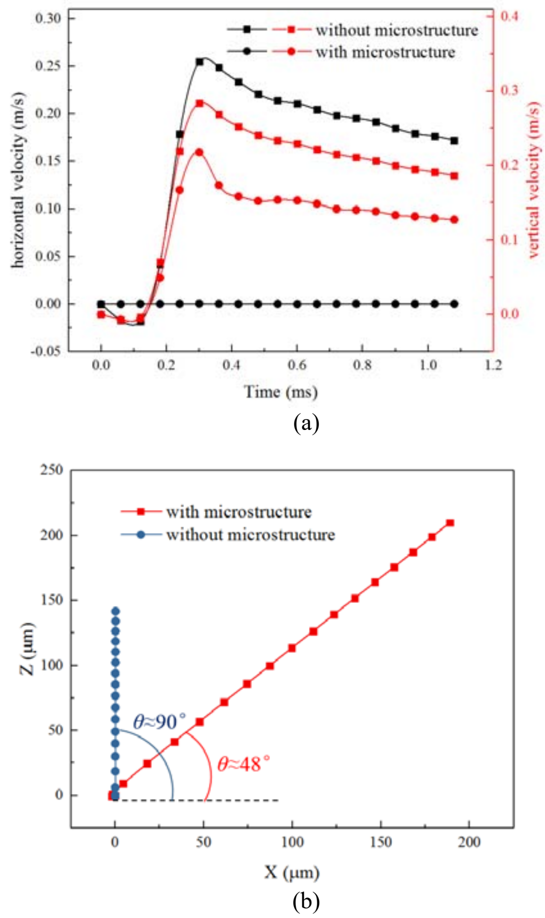
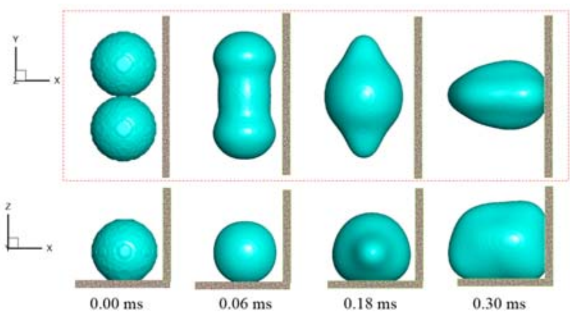


Fig. 3. (a) The evolution of centroid velocity of spontaneous jumping droplets in X and Z directions with time without microstructures and with microstructures; (b) the evolution of centroid position of jumping droplets on surfaces without microstructures and with microstructures

the interaction between the microstructures and the bridge is weak, which leads to the increase of energy conversion efficiency and the change of jumping direction. Figure 4 shows the evolution of droplet morphology with time when the distance D=1.25R. Compared with the case D=1.0R in Figure 1, in the early stage of the development of liquid bridge (0.06-0.18 ms), the liquid bridge will not contact the microstructure. In the later stage of the development of liquid bridge, the liquid bridge will be separated from the surface under the reaction force of the microstructure and the surface after a short contact between the liquid bridge and the microstructure (0.30 ms).



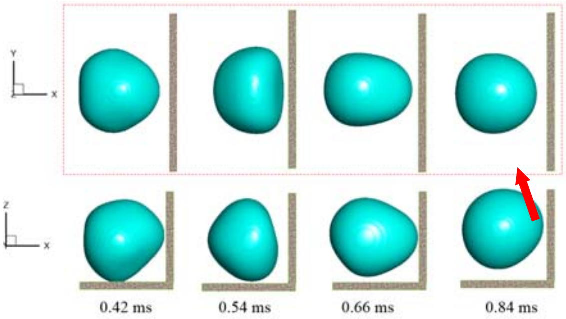


Fig. 4. The droplet morphology evolution with time. The radius of the two droplets is 100 μm and the distance between the droplets and the microstructures D=1.25R.

Fig. 6 shows the evolution of the horizontal and vertical velocity of jumping droplets with time at different D. As shown in Fig. 6(a), with the increase of the spacing D between droplets and microstructures, the influence of microstructures on the velocity of droplets decreases. When the spacing increases to 2.0R, the microstructures have little effect on the springing velocity. As shown in Fig. 6 (b), with the increase of spacing D, the effect of microstructures on the direction of jumping decreases gradually, and the direction of jumping droplets increases from 60° to 90°

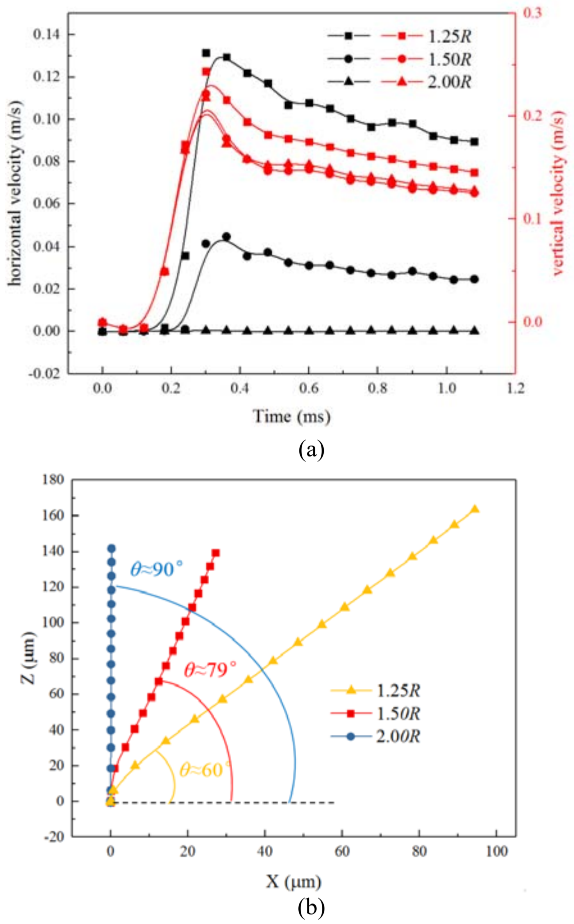


Fig. 6. (a) evolution of centroid velocity components in X and Z directions with time at different spacing D; (b) evolution of centroid position of springing droplets with different spacing D

Conclusions

In conclusion , In this paper, the effect of microstructures on droplet jumping is studied by simulation. Because of the interaction between the liquid bridge and microstructures, the energy conversion efficiency of droplet jumping increases, and the direction of droplet bouncing changes. With the increase of the spacing between droplets and microstructures, these effects gradually weaken.

Acknowledgments

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