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ABSTRACT

While the droplet impact dynamics on stationary superhydrophobic surfaces has been extensively studied, the dynamic behaviors of impact droplets on moving superhydrophobic surfaces have received less attention. Here, we report the droplet impact dynamics on a moving superhydrophobic surface. We show that compared to the stationary surface, the moving superhydrophobic surface breaks the symmetry in both droplet spreading and retracting. Specifically, the shear force exerted by the moving surface acting on the impact droplet enlarges the maximum spreading in the moving direction, and thus, the droplet contact time is reduced. The contact time of impact droplets was examined thoroughly under the effects of the droplet impact (normal) and the wall moving (tangential) Weber numbers. We provide a scaling analysis to explain how the contact time depends on the normal and tangential Weber numbers. Our experimental investigation and theoretical analysis provide insight into the droplet impact dynamics on moving superhydrophobic surfaces.

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Droplet impact on solid surfaces is a ubiquitous phenomenon related to many natural and industrial processes such as aircrafts,^{1,2} wind turbines,³ spray cooling,⁴ chemical coating,⁵ and inkjet printing.⁶ Droplet impact dynamics is heavily dependent on the surface characteristics.^{7,8} In recent years, owing to their high nucleation barrier, low adhesion force, and self-cleaning features,^{9–11} superhydrophobic surfaces (SHPSs) have shown promising applications in anti-icing/frosting,^{12,13} anti-corrosion,¹⁴ and water desalination.¹⁵ These excellent capabilities of SHPSs are associated with the contact time (t_c) when a droplet impacts on such surfaces. The contact time (t_c) is described as the duration from a droplet contacting to rebounding off the SHPSs. Previous studies found that the dimensionless contact time t_c/t_0 (where $t_0 = \sqrt{\rho R_0^3/\sigma}$ is the capillary-inertia time and ρ , R_0 , and σ are the droplet density, radius, and surface tension, respectively) of a droplet is almost constant, i.e., $t_c/t_0 = 2.6 \pm 0.1$.^{16–18} To reduce this value for achieving the complete rebound, the inclined,^{19,20} curved^{21–23} SHPSs or SHPSs with macrotextures^{22,24,25} were considered, and the results amply showed that breaking of the spreading and bouncing symmetry during the impact process play vital roles in shortening the dimensionless contact time.^{19–27} However, these studies on reducing the droplet contact time were conducted exclusively on stationary SHPSs.

Due to the practical importance of moving surfaces such as aircraft wings, turbine blades, and inkjet printing, the droplet

impact on moving hydrophilic and hydrophobic surfaces has been investigated.^{28–32} The effects of these moving surfaces on the droplet spreading,^{28–30} splashing,^{31,32} and deposition pattern²⁹ were studied under different surface wettabilities.³⁰ The asymmetric spreading and retraction on the moving surfaces were also observed, in a similar fashion to those on the inclined, curved SHPSs or SHPSs with macrotextures. Since the SHPS has lower surface energy than the hydrophilic and hydrophobic surfaces, the droplets at impact on moving SHPSs will not only get reshaped but also rebound off. So far, we have not seen any research examining the effects of the moving SHPSs on the asymmetric spreading, retraction, and rebound of impact droplets. Exploration of such effects will deepen our understanding of the interactions between an impacting droplet and the moving SHPS, and the findings will be of importance to related applications.

In this Letter, we investigate the droplet impact dynamics on stationary and moving SHPSs. We find that compared to the stationary SHPS, the moving SHPS shows a significant reduction in the droplet contact time. Depending on the velocities of the moving surface and impact droplet, the dimensionless contact time can be reduced by 20% under our experimental conditions. We also provide scaling analyses to elucidate the variations of retracting velocity and contact time with the droplet impact velocity and surface moving velocity.

We prepared our SHPSs by spraying nano-SiO₂ coating^{21,33} (Glaco Mirror Coat Zero, Soft 99 Co.) on bare aluminum substrates. The aggregations of nano-SiO₂ particles (30–50 nm) in the coating form hierarchical structures and, thus, make the bare aluminum substrate surfaces become superhydrophobic. The static contact angle of our prepared surfaces is $150.7 \pm 2.8^\circ$, which was obtained on the basis of five measurements using the “First Ten Angstroms (FTA) 200” system. The detailed information about the fabrication and characteristics of our experimental surfaces is provided in [supplementary material S1](#). We built up an experimental setup mainly including a motorized linear stage for allowing the experimental surface to move horizontally (tangentially) in a velocity (U_t) range of 0–1.5 m/s, and the detailed description of the setup can be found in [supplementary material S2](#). The water droplet has a fixed volume of $8.5 \pm 0.2 \mu\text{l}$ (with its typical diameter of $D_0 \approx 2.53 \text{ mm}$), and the droplet (normal) impact velocity (U_n) is changed by altering the droplet’s initial falling height. We introduce the tangential and normal Weber numbers as $We_t = \rho U_t^2 D_0 / \sigma$ and $We_n = \rho U_n^2 D_0 / \sigma$, respectively, where U_t and U_n are the tangential moving velocity of the experimental surface and the normal impact velocity of the falling water droplet, respectively.

Figures 1(a) and 1(b) (Multimedia view) show the droplet impact behaviors, including spreading and retracting stages on both stationary and moving (at a speed of 1.5 m/s) smooth SHPSs, corresponding to $We_n = 52$ and $We_t = 78$, respectively. Both the side view and the top view (with 30° from the horizontal plane) are presented. During the spreading stage (0–4.0 ms), the droplet contact line on the stationary surface spreads symmetrically and, thus, appears as a circle.⁷ In our experiments, since the top view has an angle of 30° , the droplet contact line actually looks like an ellipse [Fig. 1(a)]. As a comparison, on the moving surface, the presence of tangential momentum imparts a wall shear force on the droplet upon impacting and, thus, drives the contact line to spread faster and more along the moving direction than

perpendicular to the moving direction, breaking the hydrodynamic spreading symmetry. Consequently, the contact line exhibits a 2D egg shape with its head pointing to the moving direction [Fig. 1(b)]. During the retracting stage (after 4.0 ms and before rebound), different from the stationary surface on which the droplet contact line retracts symmetrically and the contact time is $t_c = 13.2 \text{ ms}$ ($t_c/t_0 = 2.51$), the droplet contact line on the moving surface retracts faster perpendicular to the moving direction and the contact time is $t_c = 10.6 \text{ ms}$ ($t_c/t_0 = 2.01$), leading to about 20% reduction in the contact time. Additionally, at the rebounding moment, the reduced contact time shortens the jumping distance of the droplet. It should be pointed out in the literature that the asymmetric spreading and retraction behaviors of impacting droplets were also reported, not only on the moving hydrophilic^{28,30,32} and hydrophobic^{29,30,32} flat surfaces but also on the inclined,^{19,20,34} curved^{21–23,35} surfaces or surfaces with macrotextures.^{22,24,25} However, the reduction in the contact time resulting from the asymmetric behaviors occurs only on the SHPSs.^{19–25}

For ease of quantifying the dynamic behaviors of impact droplets on the stationary and moving SHPSs, Fig. 2 depicts schematic illustrations of the droplet impact processes to describe the experimental observations presented in Fig. 1, defining the spreading diameters and factors. On the stationary SHPS [Fig. 2(a)], the droplet spreading is symmetric, which can be denoted by the spreading factor as D/D_0 . The droplet impact point [blue cross in Fig. 2(a)] stands at its initial position [green hexagon in Fig. 2(a)] and, thus, coincides with the contact line center [red square in Fig. 2(a)] in the side view. However, on the moving SHPS [Fig. 2(b)], the asymmetric spreading leads to different spreading factors, D_x/D_0 and D_y/D_0 (with $D_x \geq D_y$) along the x and y directions, respectively. The droplet impact point [blue cross in Fig. 2(b)] also moves at the same velocity of the moving surface and will be different from the contact line center [red square in Fig. 2(b)] relative to the droplet initial impact position [green hexagon in

FIG. 1. Dynamic behaviors of impact droplets on superhydrophobic surfaces at $We_n = 52$. For all top view images, the top view angle is 30° from the horizontal plane. The droplet diameter is $D_0 \approx 2.53 \text{ mm}$, yielding a capillary-inertia time of $t_0 \approx 5.27 \text{ ms}$. (a) The surface is stationary, $We_t = 0$ ($U_t = 0.0 \text{ m/s}$). The contact time is $t_c = 13.2 \text{ ms}$ ($t_c/t_0 = 2.51$). (b) The surface is moving at a velocity of $U_t = 1.5 \text{ m/s}$ and $We_t = 78$. The contact time is $t_c = 10.6 \text{ ms}$ ($t_c/t_0 = 2.01$). Multimedia views: <https://doi.org/10.1063/5.0023896.1>; <https://doi.org/10.1063/5.0023896.2>

FIG. 2. Schematic illustrations of the droplet impact processes on (a) stationary and (b) moving superhydrophobic surfaces. For simplicity, the top view angle is 90° from the horizontal plane. The x and y directions are set to be parallel and perpendicular to the moving direction. The green hexagon, blue cross, and red square symbols represent the initial droplet impact position (keeping unchanged), the moving droplet impact point (on the surface), and the contact line center in the side view, respectively. They coincide with each other on the stationary SHPS but are different on the moving SHPS. For convenience, the initial droplet impact position is selected as the reference position when measuring all the distances, including X_{Up} , X_{Down} , X_{Shift} , and $X_{Center} = (X_{Down} + X_{Up})/2$.

Fig. 2(b)]. This initial position is the position where the droplet first touches the moving surface and remains unchanged. The spreading factors relative to the initial impact position and the moving impact point can be found in [supplementary material S3](#), which supports that choosing the initial impact position as the reference position makes it much easier to compare the droplet impact dynamics on the stationary and moving SHPSs. This is also caused by the significant slip between the moving SHPS and the droplet bottom. At the rebounding moment, the droplet departure point also shifts from the initial impact position, generating a shift distance of X_{Shift} .

Based on the descriptions in Fig. 2, Fig. 3 shows the quantitative evolution of the positions of the moving impact point and the contact line center, the upstream, downstream, and x -axis spreading factors at different tangential and normal Weber numbers. Of note, the quantitative results are obtained from the side-view based experimental images. At different tangential Weber numbers, We_t [Fig. 3(a)], both the upstream and downstream contact lines on the moving SHPS yield the same spreading velocities as those on the stationary one at the early spreading stage. The evolution of the upstream and downstream spreading factors on the moving surface acts different from those on

the stationary one at the late spreading and retracting stages. The moving surface yields a larger maximum downstream spreading factor than the stationary one, while the maximum upstream spreading factor shows the same in all cases, suggesting a greater influence of the tangential force on the motion of the downstream contact line. After the maximum spreading, although the upstream and downstream contact lines on the moving surface retract at different speeds, both of them retract much faster than on the stationary one, thereby causing the decrease in the contact time. Figure 3(b) further shows that upon increasing We_n , the maximum spreading factor becomes larger, whereas the contact time goes down.

Additionally, the position evolution of the moving impact point and contact line center [see Fig. 3(a)] shows that the contact line center has a much slower moving velocity than the moving impact point and it even remains at its initial position at the early spreading stage, indicating that the tangential velocity has little effect on the droplet early spreading because of the fast motion of the contact line at this stage. This is the reason why the initial impact position is chosen as the reference position rather than the moving impact point, as shown in Fig. 2. [Supplementary material S4](#) presents more experimental data on the

FIG. 3. Evolution of the positions of the moving impact point and the contact line center, the upstream, downstream, and x-axis spreading factors at different tangential (We_t) and normal (We_n) Weber numbers. In (a) and (c), the initial impact position is selected as the reference position when calculating all the dimensionless factors and $X_{\text{Center}} = (X_{\text{Down}} + X_{\text{Up}})/2$. (b) and (d) are obtained from (a) and (c) since $D_x = X_{\text{Down}} - X_{\text{Up}}$, respectively.

evolution of the upstream and downstream spreading factors and their center position relative to the moving impact point. With an increase in We_t , the moving surface imparts stronger momentum to the impact droplet and, thus, a greater shear force between the droplet and the surface, leading to the longer shift distance of the departure point (where a droplet rebounds) from the initial impact position.

Figures 3(c) and 3(d) show that the increasing normal Weber number (We_n) strengthens the spreading of upstream and downstream contact lines and increases the maximum spreading factor. The contact time is also slightly reduced. However, the time reaching the maximum spreading state remains almost the same at different We_n values. As We_n becomes larger, the departure point of the rebounding droplet on the moving SHPS goes farther from the initial impact position, suggesting higher momentum imposed by the moving surface on the droplet. More detailed experimental results of the y-axis spreading factors at different tangential and normal Weber numbers are provided in [supplementary material S4](#), which reveals that the droplet spreading and retracting perpendicular to the moving direction are hardly affected by the tangential moving surface.

The contact time is related to the maximum spreading diameter and retracting velocity. In the maximum spreading state, the impact droplet on a stationary SHPS can be treated as a pancake shape with a uniform film thickness of h_{max} .³⁶ Then, the retracting velocity U_r of the contact line can be estimated from balancing the surface energy with the kinetic energy, given by³⁷

$$U_r = \sqrt{2\sigma(1 - \cos \theta)/(\rho h_{\text{max}})}. \quad (1)$$

Based on our experimental observations and Ref. 30, the contact line on the moving SHPS is simply modeled as a combination of a half-circle upstream and a half-ellipse downstream. Then, the relationship of the film thicknesses at the maximum spreading on stationary and moving surfaces can be obtained on the basis of droplet volume conservation as

$$\begin{aligned} \pi D_{\text{max},S}^2 h_{\text{max},S}/4 &= \pi D_{y-\text{max},M} (X_{\text{Up}} + X_{\text{Down}}) h_{\text{max},M}/4 \\ &= \pi D_{x-\text{max},M} D_{y-\text{max},M} h_{\text{max},M}/4, \end{aligned} \quad (2)$$

where $h_{\text{max},S}$ and $h_{\text{max},M}$ are the film thicknesses on stationary and moving surfaces, respectively, $D_{\text{max},S}$ is the maximum spreading

diameter on the stationary surface, $D_{x-\max, M}$ and $D_{y-\max, M}$ are the x -axis and y -axis maximum spreading diameters on the moving surface, respectively [shown in Fig. 2(b)]. Accordingly, we have

$$h_{\max, M}/h_{\max, S} = D_{\max, S}^2 / (D_{x-\max, M} D_{y-\max, M}). \quad (3)$$

Hence, the retracting velocities on moving and stationary surfaces satisfy

$$\begin{aligned} U_{r, M}/U_{r, S} &= \sqrt{h_{\max, S}/h_{\max, M}} \\ &= \sqrt{(D_{x-\max, M}/D_{\max, S}) \cdot (D_{y-\max, M}/D_{\max, S})}. \end{aligned} \quad (4)$$

As the droplet will rebound off the surface when the short axis y retracts completely, the contact time is estimated as $t_c \sim D_{y-\max, M}/U_r$ by assuming constant retracting velocity. Consequently, the ratio of the contact time on the moving SHPS to that on the stationary one is scaled as

$$\begin{aligned} t_{c, M}/t_{c, S} &\sim D_{y-\max, M} U_{r, S} / D_{\max, S} U_{r, M} \\ &= \sqrt{D_{y-\max, M} / D_{x-\max, M}} < 1, \end{aligned} \quad (5)$$

which obviously reveals that the contact time reduction on the moving SHPS is directly related to the asymmetry of spreading and retracting denoted by $D_{y-\max, M}/D_{x-\max, M}$. A more asymmetric impact process results in a smaller aspect ratio value and, thus, a shorter contact time. Of note, similar asymmetric dynamic behaviors and reduced contact time are observed when a droplet impacted on an inclined,²⁴ curved SHPS^{19,21,23} or surface with macrot textures.^{24,25} The reduced contact time is promising for applications of SHPSs in anti-icing/frosting and self-cleaning.

Based on our experimental results, the y -axis maximum spreading diameter on the moving SHPS is nearly the same as that on the stationary SHPS, i.e., $D_{y-\max, M} \approx D_{\max, S}$ (see [supplementary material S4](#)). Thus, we have a scaling formula as below:

$$t_{c, M}/t_{c, S} \sim \sqrt{D_{y-\max, M} / D_{x-\max, M}} \approx \sqrt{D_{\max, S} / D_{x-\max, M}}. \quad (6)$$

Since both $D_{\max, S}$ and $D_{x-\max, M}$ can be extracted from Figs. 3(b) and 3(d), we make a comparison between the scaling contact time (shown by lines) and our experimentally obtained contact time (shown by symbols) for different We_t and We_n values and the comparison results are depicted in Fig. 4. The contact time is reduced with increasing We_t and We_n . Under our experimental conditions, the decrease in the contact time is 8%, 20%, and 18% corresponding to $We_n = 25$, 52, and 80, respectively. Clearly, our scaling formula can well capture the trend of our experimental results and it reasonably agrees with the experimental results, especially in the low We_t region ($We_t < 30$). The deviation from the experiments mainly results from the simplicity of the retracting stage assumed in the analysis. The droplet retracting velocity, in fact, varies with the film thickness during the retracting stage in the experiments (Fig. 3), while the scaling analysis assumes a constant retracting velocity to estimate the contact time using the value in the maximum spreading state. The downward trend in the contact time reveals that increasing the SHPS moving velocity will further shorten the contact time. In practical applications, the

FIG. 4. Contact times obtained from our experiments (symbols) and scaling analysis-based predictions (lines) at different tangential (We_t) and normal (We_n) Weber numbers. The left coordinate shows t_c/t_0 , where t_c is the contact time and $t_0 = \sqrt{\rho R_0^3 / \sigma}$ is the capillary-inertia time, with ρ , R_0 , and σ being the droplet density, radius, and surface tension, respectively. The predicted contact time on the moving superhydrophobic surfaces is calculated by using the scaling formula derived in this study. The dotted horizontal line is the reference case that the surface is stationary, $We_t = 0$ ($U_t = 0.0$ m/s), and the contact time is $t_c = 13.2$ ms.

tangential Weber number of moving surfaces (such aircraft wing and wind turbine blade) is usually one order of magnitude higher than that used in our experiments, demonstrating the good potential of using SHPSs.

In summary, we investigated the droplet impact dynamics on moving and stationary SHPSs. We found that the droplet impacting on the moving surface exhibits asymmetric spreading and retracting. Specifically, we observed that with the increasing moving surface velocity, the spreading of the impact droplet is enhanced in the moving direction, leading to a larger maximum spreading diameter, thinner film, and faster retracting velocity. Accordingly, the droplet contact time on the moving SHPSs is reduced (compared to that on the stationary SHPS), and such a contact time reduction is dependent on the droplet impact (normal) and the wall moving (tangential) Weber numbers. To explain our experimental findings, we derived a scaling analysis to show that the ratio of the droplet contact time on the moving surface to the stationary surface is proportional to the square root of the ratio of the maximum droplet spreading on the moving surface to that on the stationary surface. Through comparing with the experimental results, we showed that our scaling analysis can reasonably describe how the droplet contact time depends on the normal and tangential Weber numbers. We envisage that the present study can not only provide insight into the interaction mechanisms between the impact droplet and a moving superhydrophobic surface but also show good potential of using moving SHPSs for anti-icing/frosting and self-cleaning.

See the [supplementary material](#) for more details about the experimental surfaces and system and more data on the spreading factors.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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