

Article

Spreading Dynamics of Droplet Impact on a Wedge-Patterned Biphilic Surface

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Featured Application: This work can be used in the droplet harvest process, for droplet impact on a solid surface with a wettability gradient like rain harvest and spray collection, as well as for regulation in a microchannel by spontaneous droplet spreading and migration.

Abstract: The influence of apex angle and tilting angle on droplet spreading dynamics after impinging on wedge-patterned biphilic surface has been experimentally investigated. Once the droplet contacts the wedge-patterned biphilic surface, it spreads radially on the surface, with a tendency toward a more hydrophilic area. After reaching the maximum spreading diameter, the droplet contracts back. From the experimental results, the normalized diameter β ($\beta = D/D_0$) was found to be related with the Weber number ($We = \rho DV^2/\gamma$) as $\beta_{\max} \sim We^{1/5}$ during the first spreading process. Below 67.4° , a larger apex angle can help a droplet to spread on the surface more quickly. The maximum spreading diameter has a tendency to increase with the Weber number, and then decrease after the Weber number, beyond 2.7. Approximately, the critical Weber number is about 5, when the droplet lifts off the surface. Considering the effect of apex angle, the maximum normalized spreading diameter has a rough expression as $\beta \sim \sqrt{\alpha\tau}$

Keywords: droplet impact; wedge-patterned; spreading diameter; surface tension

1. Introduction

Droplet impact is of great importance in many technological applications for pesticide spray coatings, drag reduction, water harvesting, heat exchangers, anti-icing and thermal management [1–6]. In practice, the spreading dynamics of droplet impact on a solid surface is a complex multi-phase flow problem, and yet it is not understood completely. After impacting on a solid surface, a droplet spreads radially outside. Then, the kinetic energy is transferred into surface energy and the dissipation energy is induced by viscosity. Finally, droplet retracts back under the action of surface tension, after reaching the maximum spreading diameter. Eventually, the droplet oscillates off the solid surface, or on it, depending on the initial impact states [7,8].

The wettability effect on droplet spreading dynamics has been investigated, using a static [9] or dynamic [10] contact angle. One can motivate droplets by using a surface with different wettabilities. There are several ways to build surface tension gradients: coatings, microstructures, temperature and wedged patterns [11]. The wettability of the solid surface described by the contact angle θ can be changed by coating different polymer particles with different hydrophilic properties. From the insights of the Wenzel [12] and the Cassie–Baxter model [13], one can change the practical contact area by changing the surface morphology as well. Accordingly, for now, a popular method of regulating the

surface morphology involves manufacturing microstructure arrays onto a solid surface. As the surface tension coefficient is a function that is dependent on temperature $\gamma(T)$, there is a famous phenomenon “Marangoni effect” that is based on this dependence. Changing the temperature is another practical way to control the surface tension. The gradient contact area can be accomplished by designing different wedged patterns (2-D) and cones (3-D), like a cactus spine, along the droplet-spreading direction. Then, the contact length, L , can be controlled. An early experiment for droplet transfer on a wettable gradient surface was performed by Chaudhury [14]. They made a surface with a wettable gradient along the radial direction by chemical coating, and studied the spreading characteristics that occur when a droplet impacts an edge of different wettability. Recently the statics and dynamics of liquid barrels in wedge geometries have been studied theoretically and experimentally [15,16].

Besides the wetting properties, the impact velocity shows great importance in droplet spreading after impact. Commonly, the Weber number ($We = \rho V^2 D / \gamma$) is applied, to characterize the initial state of impact velocity, as well as the surface tension. A low Weber number means that the surface tension is rather strong, compared with the inertia effect. Son et al. [17] performed experiments to measure the maximum spreading ratio under low Weber numbers (0.05 to 2) and low Reynolds numbers ($Re = \rho DV / \eta$, 10~100). In their study, the surface energy and the kinetic energy was comparable. Considering the effects of viscosity and surface tension, Lin et al. [18] performed a series of experiments at different Weber numbers, and promoted a universal scaling law of spreading time. The mesoscopic simulation on spreading diameter was accomplished in Wang and Chen’s work [19]. They simulated the spreading dynamics for when a droplet impacts on a homogeneous superhydrophobic surface. The ideal Cassie state was used, and three linear weight functions were applied in rebuilding the liquid–solid interaction. Considering the energy balance of the initial impact state, and that of the final spread, many models have been promoted [20,21].

Though the mechanisms of droplet impact have been researched abundantly, many detailed issues still remain unknown. The detailed hydrodynamic model of droplet spreading on a wedge-patterned surface with wettability difference has not been investigated before. The influence of the apex angle on droplet spreading and the critical Weber number when droplet lifts off the surface has not been studied well. In this research, the effects of both the apex angle and the Weber number on droplet spreading diameter after impact on a wedge-patterned surface have been studied experimentally. Experimental results have shown that the maximum dimensionless spreading diameter ($\beta_{\max} = D_{\max} / D_0$) is found to be related to the Weber number $\beta_{\max} \sim We^{1/5}$. Considering the effect of the apex angle, a semi-experimental relation of the spreading diameter versus time has been promoted, $\beta \sim \sqrt{\alpha \tau}$ where α represents the apex angle. The critical Weber number when droplet lifts off the surface is about 2.7.

2. Experimental Specifications

2.1. System Specifications

The experimental system consists of three parts: the injection part, including a syringe motivated by an electrical motor with a needle; the deposition part containing the test biphilic surface with several designed wedge patterns, mounted on a tilting stage (Sigma koki GOH40-51, Tokyo, Japan), which can change the inclined angle from -20° to 20° (precision $\pm 0.5^\circ$) manually; and the recording part, involving a strong backlight, and a high-speed camera (Camera: FASTCAM SA-X2, Lens: Nikon AF NIKKOR, Texas, TX USA) which is parallel with the test surface and connected with a computer. The injecting velocity of the electrical motor is 0.1 m/s, and the droplet volume is deposited on the test surface is $7.8 \mu\text{L}$ ($\pm 0.1 \mu\text{L}$). The recording rate is set 10,000 frames per second, and the spatial resolution is 0.12 mm per pixel. The whole schematic of experimental setup is shown in Figure 1.

Firstly, the contact length was calculated. The gravity deformed the droplet, which could be measured according to the capillary length ($L_c = \sqrt{\gamma / \rho g}$) or the Bond number ($Bo = \rho g D^2 / \gamma$).

When the droplet diameter is less than 2.7 mm or the Bond number is less than 1, the gravity could be neglected.

The test surface was first mounted onto the tilting stage. Then, the backlight and the electrical motor were turned, setting the ejection velocity. The droplet was deposited on the solid surface from a settled release height. The whole process from the droplet release to the final state on the test surface was imaged, using a high-speed camera.

The effects of the apex and tilting angles on the droplet spreading dynamics after impact were investigated from the change of the wedge-pattern and the tilting stage. Different Weber numbers were applied by using different release heights with the same droplet volume.

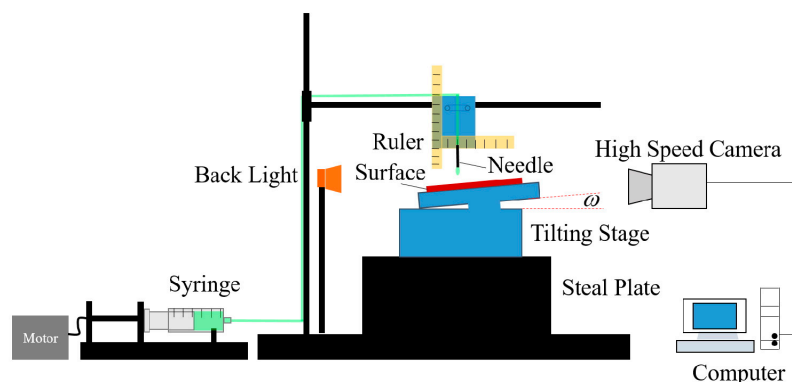


Figure 1. Schematic of the experimental system for droplet impact.

2.2. Characterization of the Solid Surface and Droplets

The biphilic surface was fabricated by coating a hydrophobic polymer particle (Never Wet©, Columbia, MA, USA) onto a hydrophilic silicone surface. The whole process of biphilic surface manufacture was shown in Figure 2. The silicone surface was firstly cleaned by acetone. Then, from the same height of 20 cm, the two layers were coated in the silicone surface. After that, a 30 μm -diameter laser beam was applied, to cut the wedged patterns according to the designs. The superhydrophobic layer was peeled off manually with a scalpel. The thickness of the coating layer was about 10 μm .

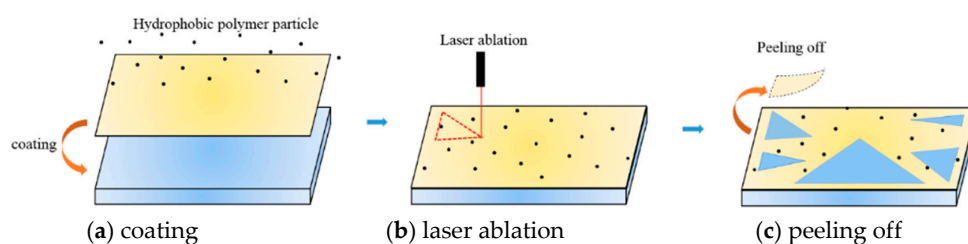


Figure 2. Schematic of the designed wedge-patterned biphilic surface manufactured.

The static contact angle was 68° and 142° , which was measured three times on a silicon surface, and a superhydrophobic coating, separately.

The advancing edge, the receding edge, and the apex angle are presented in Figure 3.

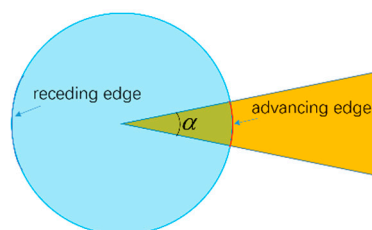


Figure 3. Schematic of the apex angle, advancing edge, and receding edge.

By changing the release height H , a different initial impact velocity v ($\sqrt{2g(H - D_0)}$), Weber number We , Reynolds number Re , capillary number Ca ($\eta V/\gamma$), and critical time scale $\bar{t}$ (D_0/v) can be derived, as shown in Table 1, where g is the gravitational acceleration, H is the release height, D_0 is the droplet initial diameter, v is the initial velocity of the droplet impacts on the solid surface, γ is the liquid surface tension. The Ohnesorge number Oh ($\sqrt{We}/Re = \sqrt{V\eta/\gamma}$) and the Bond number Bo are 2.1×10^{-3} and 0.84 for all the measurements in the present work. As $Bo < 1$, the impact and spreading dynamics are mainly surface tension-dominated.

Table 1. Different initial impact states.

	Case 1~4	Case 5~11	Case 12	Case 13	Case 14	Case 15
H (mm)	3.54	3.82	3.17	5.31	6.48	9.51
v (m/s)	0.14	0.16	0.11	0.23	0.28	0.37
We (-)	0.70	0.89	0.45	1.90	2.70	4.75
Re (-)	398	448	319	654	778	1032
Ca (-)	1.8×10^{-3}	2.0×10^{-3}	1.4×10^{-3}	2.9×10^{-3}	3.5×10^{-3}	4.6×10^{-3}
$\bar{t}$ (ms)	17.5	21.4	21.8	10.7	9.0	6.8

The working liquid in this study is distilled water. All experiments are performed at 1 atm and room temperature.

3. Results and Discussion

3.1. Effect of Apex Angle

Figure 4 shows the typical images of a droplet impinging on a wedge-patterned biphilic surface, with different apex angles. In Figure 4, the red arrow shows the transportation direction of the droplet. There are six instances selected for demonstration. At 0 ms, the droplet impacts on the solid surface. After the droplet contacts the solid surface, the bottom of the droplet formed a layer which quickly spreads on the solid surface as shown at $t = 20$ ms. Then, the droplet spread radially onto the solid surface with the tendency toward the more hydrophilic area. The hydrophilic area is also designed to be wider, so the droplet has a motivation subjected to the surface tension difference. Due to the relatively low release height, there is little oscillation in the normal direction. There are two main phenomena, in that the droplet spreads on the surface, as well as transporting it to the wider hydrophilic edge. The transportation properties along the wedge-patterned surface are studied somewhere else, using the force balance and energy conservation [22]. In this paper, attention is paid to the spreading characteristics. Comparing images at the same instance for different apex angles, the droplet is found to spread more quickly, and it reaches a larger attached diameter for a larger apex angle. The amplitude of droplet oscillation along the spreading direction is larger as well.

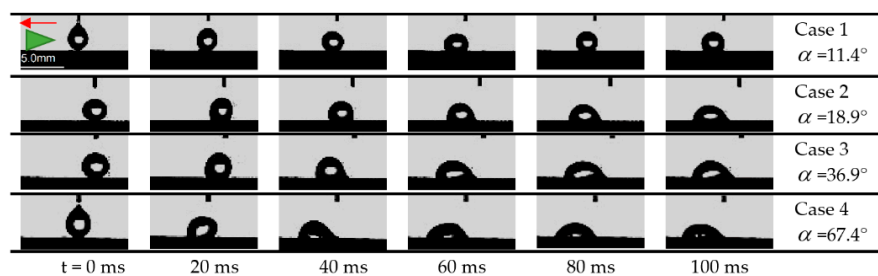


Figure 4. Images of a droplet impact for different apex angles.

The initial kinetic energy is dissipated, partly by the oscillation along the solid surface, and the viscosity dissipation inside the droplet. The increased surface energy and the reduced gravitational

potential energy are balanced by the kinetic energy reduction and the viscous dissipation along the solid surface and the droplet inside.

Here, a dimensionless time is defined as $\tau = t/\bar{t}$. The attached diameter versus time of the whole process is plotted in Figure 5. The y axis is the dimensionless spreading diameter, and x axis is the dimensionless time, defined as $\tau = tv_0/D_0$. Figure 5 shows that the advancing edge shows a close velocity, with the back edge at the initial state. The advancing edge that spreads on the hydrophilic area shows a faster velocity. The spreading diameter was deduced as the distance between the two edges. The equilibrium spreading diameter for 67.4° , is the largest, which is beyond $1.6 D_0$ at 4τ . The maximum spreading diameter for 36.9° and 18.9° , are very close to that of 67.4° which are also $1.6 D_0$. The droplet spreads only a little at 11.4° , only reaching at about $1.0 D_0$. For the advancing edge, the diameter oscillation is larger than that of the back edge. The surface tension helps the droplet to spread faster toward the more hydrophilic area, if the apex angle is larger.

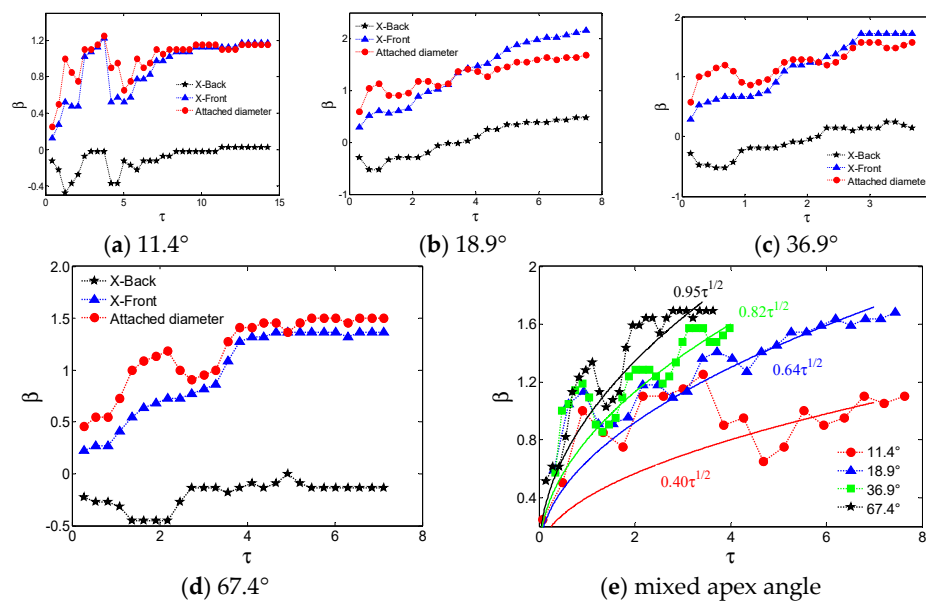


Figure 5. The recorded positions of droplet advancement, receding edge, and the attached diameter for different apex angles.

From the analysis of de Pierre [23] and Brochard-Wyart [24], the driving surface tension force could be measured as:

$$F = \gamma_{SG} - \gamma_{SL} - \gamma \cos \theta_d \quad (1)$$

where γ_{SG} , γ_{SL} , and γ represent the surface tension between the solid–gas interface, solid–liquid interface and liquid–gas interface, separately. θ_d is the dynamic contact angle when spreads and approximately equals to the static contact angle θ . Due to the superhydrophobic surface coating, the surface tensions related to the solid surface are different. The driving forces toward the coating part and the silicon hydrophilic surface varied.

In order to analyze the effect of the apex angle of wedged patterns on droplet spreading, the spreading model should be rebuilt. The initial diameter of the droplet was supposed to be D_0 , and the initial velocity before impact on the solid surface was v_0 .

After the impact on a solid surface, droplet spreads radially. When it reaches the maximum diameter, the droplet topology could be regarded as a cylinder whose bottom has a maximum spreading diameter $D_{\max}$, and its height is h .

According to the mass conservation, one can obtain:

$$\frac{\pi}{4} D_{\max}^2 h = \frac{\pi}{6} D_0^3 \quad (2)$$

$$h = \frac{2D_0^3}{3D_{\max}^2} \quad (3)$$

If the droplet flows into the cylinder with a velocity of v_0 through a circle area with a diameter d , then the spreading velocity v_R could be calculated, based on the mass conservation:

$$\frac{v_R}{v_0} = \frac{d^2}{4Dh} \quad (4)$$

Assuming the diameter $d \sim \pi D_0/4$, and combining Equations (3) and (4), gives:

$$\frac{dD}{dt} = 2v_R = \frac{3\pi^2 D_{\max}^2 v_0}{64DD_0} \quad (5)$$

By integrating Equation (5), the spreading diameter evolution can be given:

$$\frac{D}{D_{\max}} = \sqrt{\frac{3\pi^2 v_0 t}{32D_0}} \quad (6)$$

As the spreading diameter consists of the superhydrophobic part and the hydrophilic part within the wedged patterns, the spreading diameter has an expression that is roughly described according to the different apex angles:

$$A = \pi \left(\frac{D_{\max}}{2} \right)^2 \quad (7)$$

where A is the spreading area when reaching the maximum diameter $D_{\max}$. As the spreading area contains the hydrophilic part, as well as the superhydrophobic part, the exact expression should be:

$$A = \frac{1}{8} [(2\pi - \alpha)D_1^2 + \alpha D_2^2] \quad (8)$$

where α is the apex angle in rad on wedge patterned surface, and D_1 and D_2 are the spreading diameters on the superhydrophobic surface and on hydrophilic surface, separately.

For simplicity, a linear parameter is proposed here:

$$k = \frac{D_1}{D_2} < 1 \quad (9)$$

From Equations (6)–(8), this gives:

$$D_{\max} = D_2 \sqrt{\frac{1-k^2}{2\pi} \alpha + k} \quad (10)$$

k is constant for certain surfaces, and then Equation (10) can be changed into:

$$D_{\max} = C_1 \sqrt{\alpha + C_2 D_2} \quad (11)$$

where:

$$C_1 = \sqrt{\frac{1-k^2}{2\pi}} \quad (12)$$

$$C_2 = \sqrt{\frac{2\pi k}{1-k^2}} \quad (13)$$

Obviously:

$$C_1 C_2 = \sqrt{k} \quad (14)$$

Combining Equations (6) and (11), gives:

$$D = C_1 D_2 \sqrt{\frac{3\pi^2(\alpha + C_2)\tau}{32}} \approx C_1 D_2 \sqrt{(\alpha + C_2)\tau} \quad (15)$$

Thus, a relation between the spreading diameter and to time can be derived:

$$\beta \sim \sqrt{\alpha\tau} \quad (16)$$

3.2. Effect of the Tilting Angle

The inclined effect of the droplet impact on the solid surface has been investigated, by changing the tilting angle to estimate the ability for harvest droplet and transportation properties.

At a low Weber number, the droplet spreading is dominated by surface tension, and it cannot spread completely at the initial state. When the Weber number increases, the inertia effect becomes more important, and the droplet could spread during the first oscillation. The surface-tension effect on droplet spreading and migration becomes dominant, the more attached the area of the liquid–solid interface becomes. For a low Weber number, each oscillation has a similar period, until the droplet stops.

For droplet impact on a solid surface with a -15° tilting angle, where minus means that the driving force from the hydrophilic area is designed along the gravitational direction, the spreading diameter changes more obviously at the same instant. The period of each oscillation for each different tilting angle is quite similar. It is quite reasonable that the spreading is a combination of a normal spread, and a spring-like oscillation along the spreading direction. The oscillation is too complicated to research if the normal direction is considered. The main focus of this paper is on the final equilibrium spreading diameter.

The first oscillation along the spreading direction is quite similar for different tilting angles. The period of the first oscillation lasts for about 2τ , and the amplitude is about $1.2D_0$. When the droplet vibrates along the solid surface, the droplet has an obviously inclined posture as the droplet bottom spreads rather fast along the hydrophilic area, but the bulk and top parts of the droplet still stick to the initial site. When the tilting angle becomes larger, the inclined posture is more obvious. Considering the positions of -10° and -5° , the tilting angle has little influence on the final equilibrium diameter and the vibrating frequency of droplet spreading. It comes out differently for the positive tilting angles 5° , 10° , and 15° . When the droplet impacts the solid surface at a 15° angle, the final equilibrium spreading diameter is reduced by less than $1.5D_0$. The difference of the tilting angles has a minor effect on the spreading diameter, as well as the frequency of oscillation.

The spreading factors for the different tilting angle are presented in Figures 6 and 7. From Figure 6, $\Delta\beta_1$, $\Delta\beta_2$ and $\Delta\beta_3$ are roughly equal for each tilting angle. Thus, the conclusion can be made that the effects of gravitational force show no impact when the droplet spreads onto a solid surface at a low Weber number.

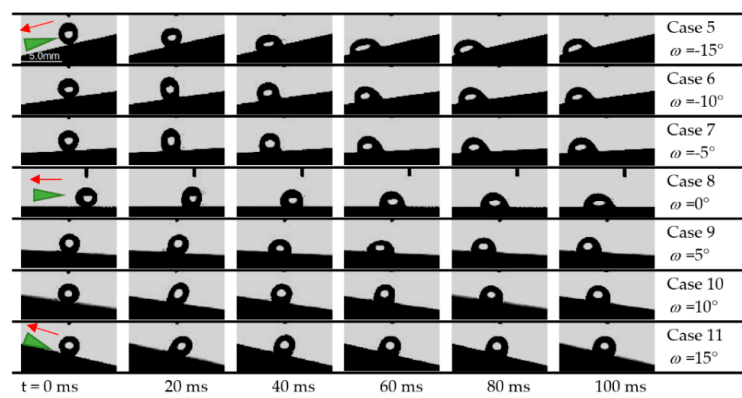


Figure 6. Images of a droplet's impact, for different tilting angles.

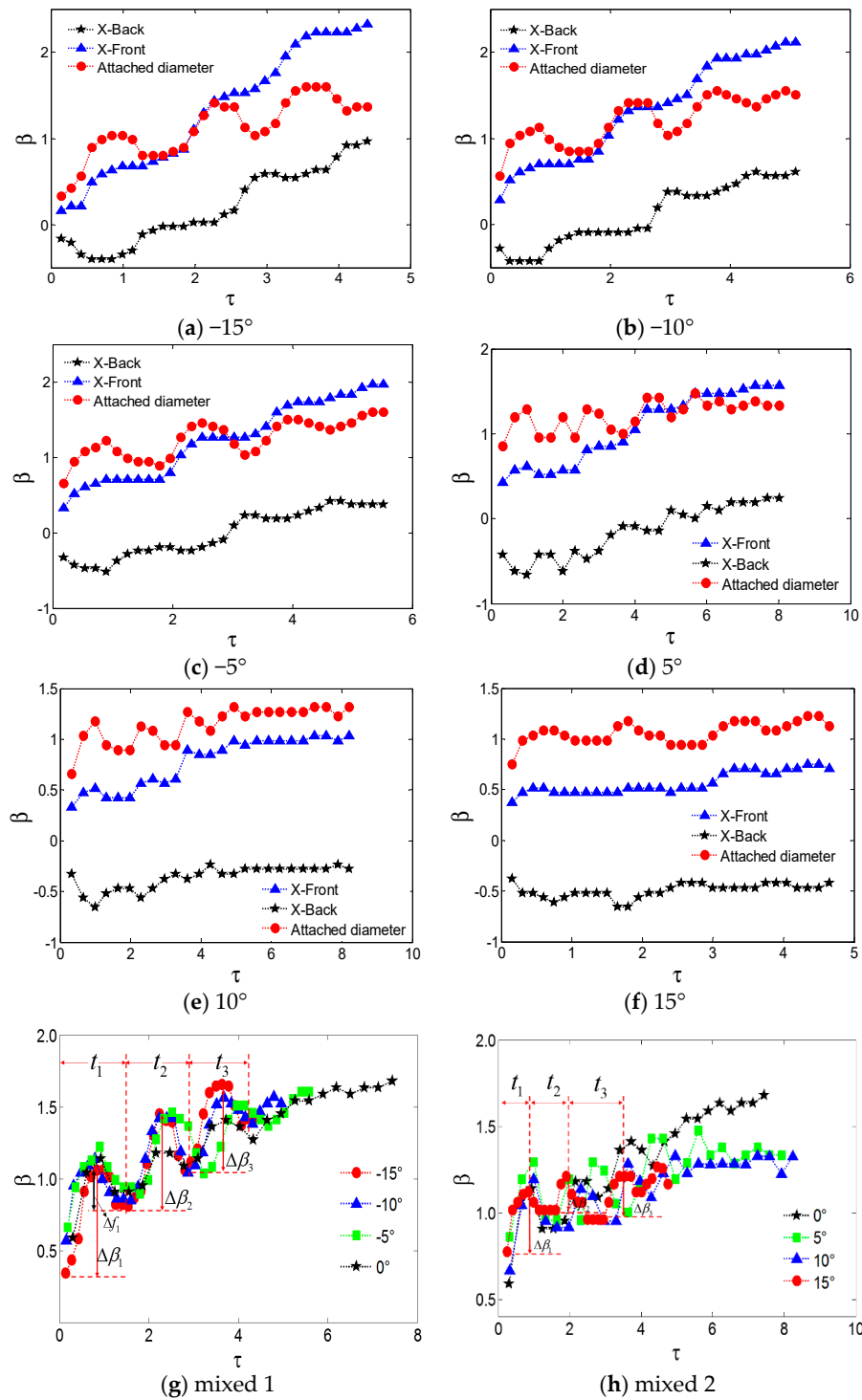


Figure 7. Recorded positions for different tilting angles.

3.3. Effects of Impact Velocity

The main harvesting ability of the wedge patterned biphilic surface is investigated through droplet impact experiments with different initial velocities. The release height is an easy way to adjust the initial impact velocity. The air viscosity and drag efficiency are neglected when calculating the critical time. The initial impact velocity of a droplet from a settled height can be roughly estimated by $V = \sqrt{2g(H - D_0)}$, which has little deviation when the Weber number is relatively low (<100). The release height is set as 3.2 mm, 5.3 mm, 6.5 mm, and 9.5 mm and the corresponding Weber number

and Reynolds numbers are listed in Table 1. As the initial velocity increases, the final spreading diameter increases accordingly. It is noticed that the final spreading diameter for $We = 2.7$ is the largest. For a proper Weber number of around 3, and an apex angle of 36.9° , the spreading diameter reaches the maximum.

For a 3.2 mm release height, the front edge spreads faster than the back one before 2τ . The time for when advancing edge spreads faster than the back edge occurred at 2τ , 3τ , and 3τ , for each height. Before that time, the spreading has the same velocity in all directions. For $We = 2.7$ the spreading diameter is much larger than the left.

One can see in Figure 8 that a low-Weber-number droplet spreads linearly with time. As the Weber number increases, the spreading diameter increases during the first oscillation. The maximum spreading diameter is reached within the first two oscillations. For $We = 4.8$, the maximum spreading diameter is reached within the first spreading.

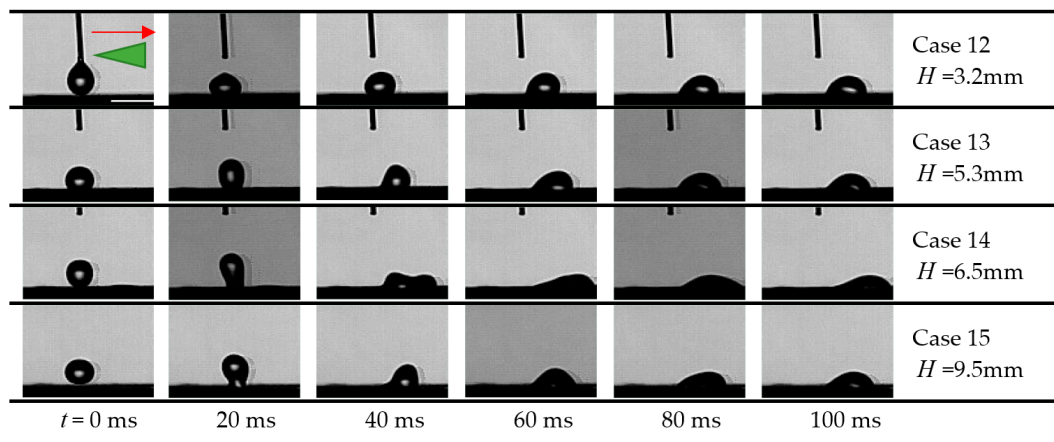


Figure 8. Images of a droplet impacting on the designed wedge-patterned biphilic surface for different release heights (the scale bar is 4 mm).

Comparing the dimensionless spreading diameters for each Weber number versus time, the periodic time of each oscillation changes little. During the same time scale, the driving surface tension shows dominance. For a low Weber number, the surface tension becomes dominant, with a spreading diameter that increased constantly. For a relatively high Weber number, the surface tension came into effect on migration at an earlier time than that of a low Weber number as the larger contact area.

The initial kinetic energy:

$$E_{k0} = \frac{\pi \rho D_0^3 v_0^2}{12} \quad (17)$$

The surface energy:

$$E_{d0} = \pi D_0^2 \gamma \quad (18)$$

The interfacial energy of the solid-gas interface is:

$$E_{s0} = \frac{\pi D_{\max}^2 \gamma}{4} \quad (19)$$

When the droplet reaches the maximum spreading diameter, the interfacial energy of the cylinder liquid is:

$$E_d = \gamma \left(\frac{\pi D_{\max}^2}{4} + \pi D_{\max} h \right) \quad (20)$$

The interfacial energy of solid surface is

$$E_s = \frac{\gamma \pi D_{\max}^2}{4} \quad (21)$$

The final kinetic energy is

$$E_k = 0 \quad (22)$$

The work of deforming the droplet by viscosity is [25]:

$$E_k = 0 \quad W = \int_0^{t_c} \int_{\Omega} \phi \, d\Omega \, dt \approx \phi \, \Omega \, t_c \quad (23)$$

where ϕ is the viscous dissipation function, Ω is the droplet volume, and t_c is the time taken to spread.

From the knowledge of [25], the viscous dissipation function has a rough expression:

$$\phi \sim \eta \left(\frac{v_0}{L} \right)^2 \quad (24)$$

where η is the liquid viscosity and L is the characteristic length in height.

As Pasandideh-Fard et al. [20] mentioned, the characteristic length should be approximately the boundary layer thickness:

$$L \sim \delta \quad (25)$$

The boundary layer then can be measured from White [26]:

$$\delta = \frac{2D_0}{\sqrt{Re}} \quad (26)$$

The liquid volume is:

$$\Omega = \frac{\pi D_{\max}^2 \delta}{4} \quad (27)$$

Combining Equations (23)–(27), gives:

$$W = \frac{4}{3\pi} \frac{We}{\sqrt{Re}} \gamma D_{\max}^2 \quad (28)$$

As the energy conservation, there should be:

$$E_{k0} + E_{d0} + E_{s0} = E_k + E_d + E_s + W \quad (29)$$

One can get:

$$3 \left(1 - \cos \theta_Y + \frac{16}{\pi^2} \frac{We}{\sqrt{Re}} \right) \beta_{\max}^3 - (12 + We) \beta_{\max} + 8 = 0 \quad (30)$$

Solve Equation (30), the maximum spreading factor can be derived:

$$\beta_{\max} = \frac{2}{3} \sqrt{\frac{12 + We}{1 - \cos \theta_Y + \frac{16}{\pi^2} \frac{We}{\sqrt{Re}}}} \cos \varepsilon \quad (31)$$

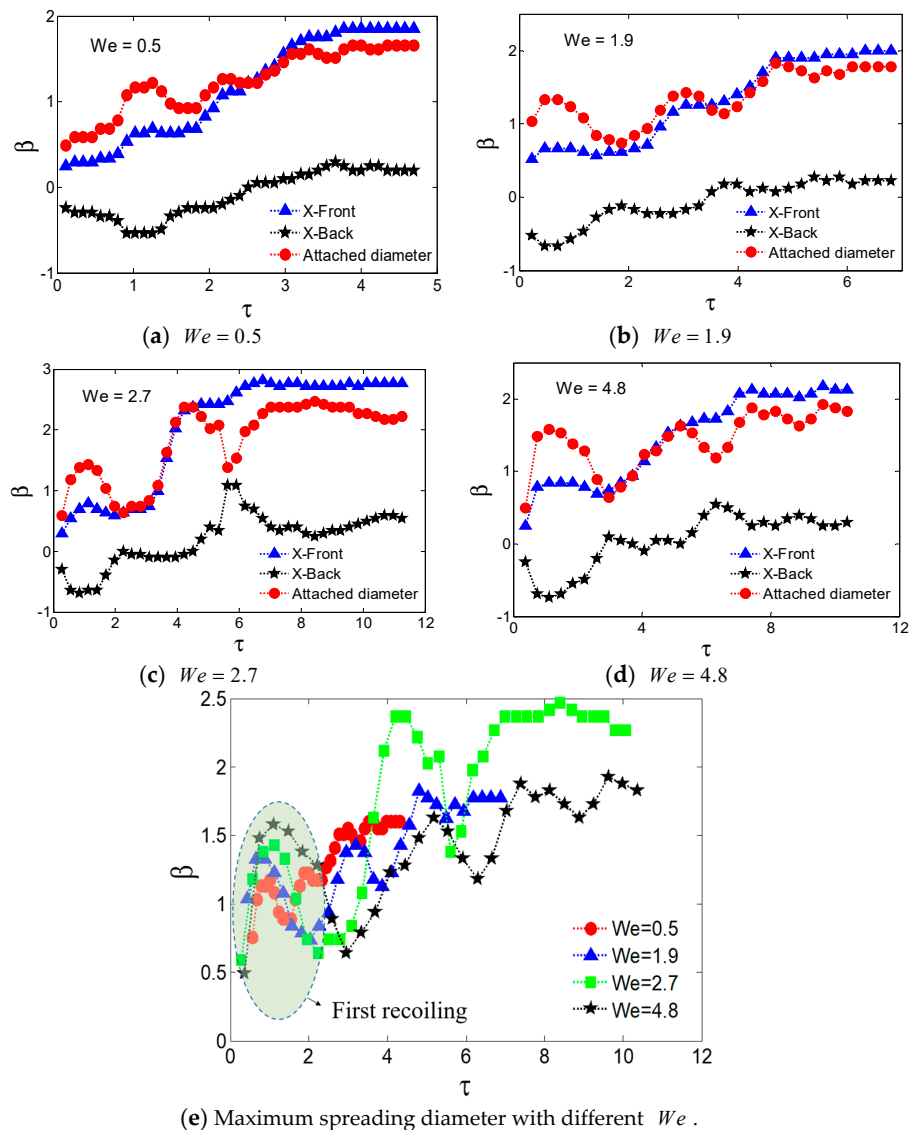
$$\varepsilon = \frac{1}{3} \arccos \left(-36 \sqrt{\frac{1 - \cos \theta_Y + \frac{16}{\pi^2} \frac{We}{\sqrt{Re}}}{(12 + We)^3}} \right) \quad (32)$$

For distilled water on the silicon surface $\theta_Y = 68^\circ$, the maximum spreading factor can be calculated from the model of Pasandideh-Fard et al. [20] and Zhao et al. [21]. The resolutions are shown in Table 2.

Table 2. Maximum spreading factor of the different Weber numbers for different models.

Contact Angle	We	0.5	1.9	2.7	4.8
	Exp. Data	1.18	1.33	1.43	1.58
$\theta_1 = 68^\circ$	Pasandideh-Fard [20]	2.51	2.52	2.54	2.59
	Zhao [21]	2.20	2.48	2.62	2.92
	Equation (31)	2.07	2.12	2.15	2.24
$\theta_2 = 142^\circ$	Pasandideh-Fard [20]	1.51	1.57	1.60	1.67
	Zhao [21]	0.90	1.33	1.46	1.73
	Equation (31)	0.88	1.04	1.15	1.33

The static contact angle has an effect on the maximum spreading diameter. For the static contact angle $\theta_1 = 68^\circ$ and $\theta_2 = 142^\circ$, the maximum spreading factor varies widely. As the apex angle is relatively small, the homogeneous surface model should be analyzed first. Taking the static contact angle $\theta = \theta_2 = 142^\circ$, the comparison between the different models are listed in Figure 9.

**Figure 9.** Recorded positions after impacting on the wedge-patterned biphilic surface.

In Figure 10a, there is not much difference between the different models. The model of Zhao et al. [21] agrees well with the experimental data for a homogeneous superhydrophobic surface.

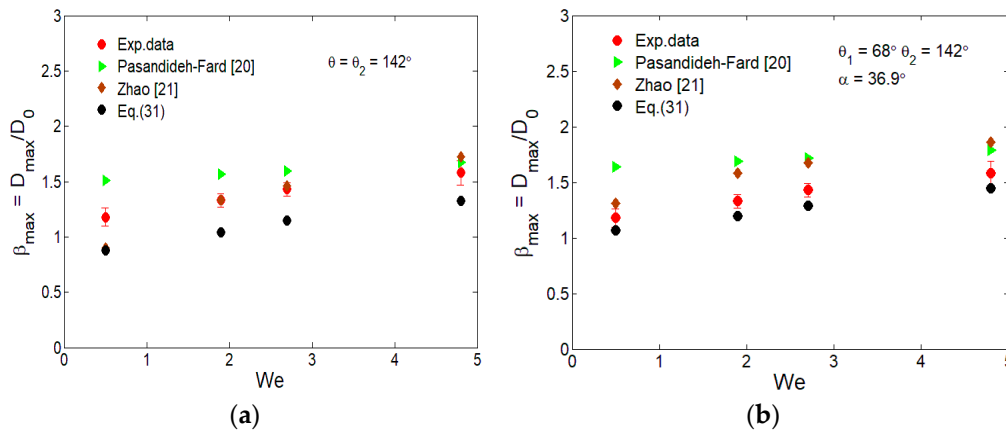


Figure 10. Maximum spreading factor for different Weber numbers (a) and different apex angles (b).

For a wedge-patterned biphilic surface with apex angle α , the equivalent diameter is promoted to be estimated according to the spreading area S :

$$S = \frac{\pi \bar{D}_{\max}^2}{4} \quad (33)$$

$$S_1 = \frac{\alpha D_{\max,1}^2}{8} \quad (34)$$

$$S_2 = \frac{(2\pi - \alpha) D_{\max,2}^2}{8} \quad (35)$$

$$S = S_1 + S_2 \quad (36)$$

where $D_{\max,1}$ and $D_{\max,2}$ represent the maximum spreading diameters on the hydrophilic surfaces and superhydrophobic surfaces, separately.

Combining Equations (33)–(36), one can get:

$$\bar{D}_{\max} = \sqrt{\frac{\alpha D_{\max,1}^2 + (2\pi - \alpha) D_{\max,2}^2}{2\pi}} \quad (37)$$

Taking the apex angle $\alpha = 36.9^\circ$, the equivalent maximum spreading diameters, calculated on different models are listed in Figure 10b.

Based on Equation (37), the equivalent maximum spreading diameters are calculated for apex angle $\alpha = 36.9^\circ$, as shown in Figure 10b. From Figure 10b, the maximum spreading diameters based on Equation (31) agree well with the experimental data, better than those two models of Pasandideh-Fard et al. [20] and Zhao et al. [21].

In order to derive a relation for the maximum spreading factor of the impact on wedge patterned surfaces, the first oscillation has been paid more attention. The maximum spreading factor during the first oscillation is shown in Figure 11 for different Weber numbers.

Taking account of the expression of Eggers et al. [27], an exponential function is promoted, then $\beta_{\max} \sim We^x$. Using the least squares procedure on the experimental results for maximum spreading diameters, one can find that $x \approx 1/5$.

The experimental data of the maximum spreading diameters under different Weber numbers and the fitting exponential curve are plotted in Figure 11.

Based on the limited experimental data during the first oscillation under different Weber numbers, the maximum diameter then has a relation with the Weber number:

$$\beta_{\max} \sim We^{1/5} \quad (38)$$

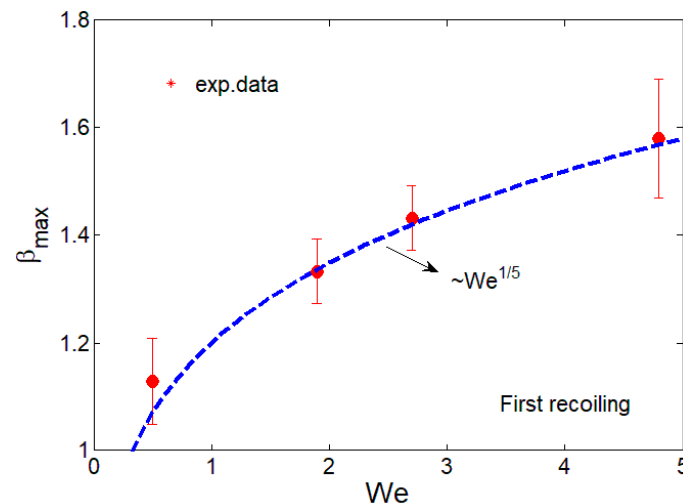


Figure 11. Maximum spreading factor with We .

4. Conclusions

In this work, the effects of apex angle and tilting angles on the spreading dynamics of droplet impact on solid surface has been investigated experimentally. Wedge-patterned biphilic surfaces were fabricated by chemical coating and laser ablation, to build the surface tension gradient. With the help of a high-speed camera, the whole process has been visualized, and then the droplet-spreading diameter versus time was analyzed, frame-by-frame. The experimental results showed that the effect of gravity has little effect on the droplet spreading when the droplet diameter is smaller than the capillary length. Based on the mass and energy conservation, the spreading process has been analyzed. The apex angle shows effective action on droplet spreading at the same Weber number. For a larger apex angle, it is faster to migrate toward the more hydrophilic area. During the first oscillation, the apex angle shows little effect at a low Weber number. For the spreading diameter, there is a relation with the apex angle, as $\beta \sim \sqrt{\alpha\tau}$ ($We = 0.7$, $Re = 400$). For the first oscillation, the maximum spreading diameter is $\beta_{\max} \sim We^{1/5}$. When the Weber number is beyond 2.7, the droplet will lift off from the wedge-patterned biphilic surface with a apex angle of 36.9° .

The conclusions above help to gain a better understanding of droplet spreading after impact on a wedge patterned surface, and they provide a basis for conceptual and theoretical analyses.

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