

Droplet bouncing on the surface with micro-structure

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IN THIS PAPER, WE PRESENT STATIC AND DYNAMIC INTERACTIONS of water droplets with a micro-structured surface that exhibits hydrophobic properties. Droplets with two different diameters ($D_0 = 0.6 \pm 0.1$ mm and $D_0 = 2.6 \pm 0.1$ mm) were studied for impact velocities in the range of $0.1 \div 2.5$ m/s. This allowed to investigate the influence of gravity on the collision behavior during an impact. The main result of the present research is the determination of the critical conditions for consecutive transitions leading to various scenarios of droplet rebound for each of the investigated surface geometry.

Key words: bouncing, superhydrophobic surfaces, droplet impingement, pinning.

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1. Introduction

LIQUID DROPLET IMPINGING ON SURFACE IS FREQUENTLY ENCOUNTERED in many industrial processes, e.g., ink-jet printing, spraying, and fuel injection. Some applications require enhanced wettability, while others demand non-wetting properties. Recently, bio-inspired surfaces structured at the micron scale have been given a lot of attention, and it has been shown that the roughening of

hydrophobic surface leads to an increase of droplet apparent contact angle [1, 2]. Interestingly, the increase in apparent contact angle may be also realized by stretching Teflon [3]. Different manufacturing methods have been developed to mimic bio-surfaces: phase separation of a multi-component mixture [4], crystal growth [5], differential etching [6], diffusion-limited growth processes [7], lithographic techniques [8] and others [9–11]. Various scenarios of droplet rebound have been observed on such surfaces. Depending on the surface properties and the Weber number $We = \rho D_0 V_0^2 / \sigma$, i.e., the ratio describing the importance of inertia relative to surface tension forces, the droplet may fully [12] or partially [13] recoil from the surface (ρ , D_0 , V_0 and σ stand for the fluid density, initial diameter, impact velocity and surface tension respectively). Different models describing the transition between these impingement scenarios exist in the literature [14, 15], providing different and sometimes conflicting predictions. One may also find interesting a droplet impact on hydrophobic grid resulting in hydrodynamic focusing [16].

One has to notice that for large Bond numbers $Bo = \rho g D_0^2 / \sigma = \kappa^2 D_0^2$, the bouncing is significantly influenced by gravity forces that tend to increase the maximum spreading diameter and change the overall behavior during the impact (g stands for the gravitational acceleration, and $\kappa^{-1} = \sqrt{\sigma / \rho g}$ denotes capillary length). CHEVY *et al.* [17] have considered droplets with radius $\kappa D_0 \ll 1$ (i.e., for a very low Bond number) and low Weber numbers $We \ll 1$, obtaining only weak deformation of a droplet. In this regime, droplet behaves as nonlinear spring whose stiffness K_d decreases with deformation: $K_d = 4\pi\sigma / |(\log(e^{5/6}\epsilon_G/D_0))|$, where ϵ_G stands for the sag of the center of mass. Influence of gravity in bouncing regime has been taken into account in the theoretical study by MOLACEK *et al.* [18], however this done only in the regime of small deformations of the droplets. The regime of large deformations remains until now insufficiently investigated.

The mentioned studies have been performed in ambient temperature environment. It is worth mentioning that other works exist considering heat exchange properties of micro- and nanoengineered surfaces. Taking into account heat exchange of a droplet impinging such surface is important for many industrial applications, e.g., anti-icing application [19] and cooling systems [20, 21]. The present paper attempts to describe the influence of surface properties on the behavior of the bouncing droplet, in both regimes, namely in large and small deformations. For this purpose we investigated droplets, with the diameter in two ranges: $D_0 \approx \kappa^{-1} = 2.6 \pm 0.1$ mm ($Bo \approx 1$) in which gravity effects may be important and $D_0 = 0.6 \pm 0.1$ mm ($Bo \ll 1$) in which surface forces dominate. The droplet was impinging on different hydrophobic surfaces, each surface with a distinct micro-structure. We have investigated the maximum droplet spread factor d_{max}/D_0 and retraction rate for various surface geometries and droplet

diameters to determine the influence of gravitational acceleration. The main result is determining the critical conditions for consecutive transitions leading to various scenarios of rebound. We have also compared these results with the models already existing in the literature. The obtained improved transition criterion may prove valuable for future research in the field of surface engineering.

2. The investigated surfaces

The investigated surfaces were manufactured out of silicon wafers that were processed via standard photolithography to obtain the arrays of square pillars (see Fig. 1a). Each pillar height h was 10 μm while its width a was 8 μm . These parameters were kept constant throughout the entire work. By contrast, the spacing b between pillars ranged from 7 to 122 μm . The microstructured silicon substrates were hydrophobized in wet chemical process in which the substrates were dipped for 30 minutes at RT in 1% solution of 1H,1H,2H,2H-perfluorodecyltrichlorosilane (FDTs, $\text{CF}_3(\text{CF}_2)_7(\text{CH}_2)_2\text{SiCl}_3$, 96%, ABCR GmbH & Co. KG) in toluene. Dip coating was preceded by surface cleaning and activation in a radio-frequency air plasma (Harrick PDC-32G plasma cleaner, 10 min at 18 W). This procedure was described in details by PSARSKI *et al.* [22].

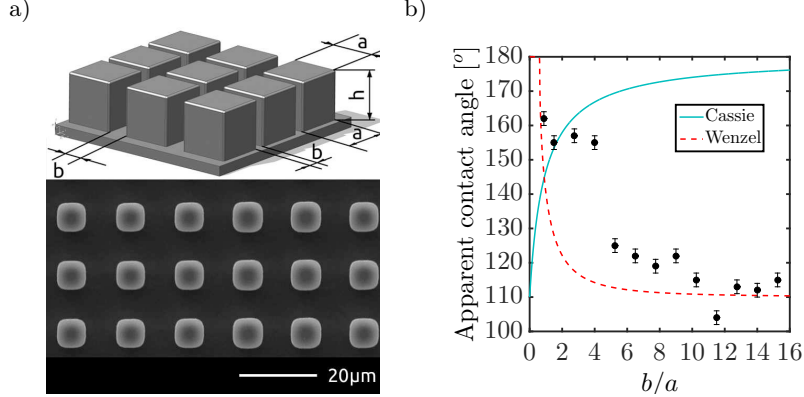


FIG. 1. a) The surface structure (top) and the SEM image of hydrophobic sample (bottom) with array of pillars characterized by $b/a = 0.875$ (a , b , h denote the pillar width, spacing, and height respectively). b) Static contact angle of 5 μL water droplet as a function of b/a ratio (spacing/pillar width). The solid and the dashed lines denote theoretical prediction for Cassie and Wenzel models respectively. Solid circles represent measured values of the WCA.

3. Contact angle measurement

Wetting properties of the surfaces were examined using DSA-100 droplet shape analysis system (KRUS GmbH). The static contact angle was measured

by depositing a sessile water droplet (5 μL of DI water), taking images by means of CCD camera and by applying the Laplace-Young fitting algorithm. The average WCA (water contact angle) was estimated from the measurements at five different locations in each sample. The results were compared with theoretical predictions given by CASSIE [1] and WENZEL [23] models and they are presented in Fig. 1b. Samples with $b/a = 0.875$ and $b/a = 1.5$ were characterized by high contact angle, which remains in agreement with the Cassie model. High contact angles were also observed for $b/a = 2.75$ and $b/a = 4$, for which a transition to the Wenzel state is expected to occur. For higher spacing-to-width ratios ($b/a > 4$) the transition to the Wenzel state was systematically observed. These samples were excluded from further analysis in this paper.

4. Droplet generation

Various droplet generation methods are commonly used in the industry: (i) vapor condensation and deposition, (ii) atomization, and (iii) spray or plasma spray of solid particles/wires. However, these methods do not provide a single drop on demand. Therefore a pneumatic generator was designed and manufactured (CHENG *et al.* [24]), which while being robust and inexpensive is also able to produce repeatable droplets irrespectively of the actual amount of water in the nozzle. The layout of the setup is shown in Fig. 2. The droplet is formed by applying pressure impulse to the top surface of the liquid enclosed in the nozzle, forcing a portion of water out of the nozzle.

The body of the generator consists of a copper T-junction with 6 mm outer diameter and 4 mm inner diameter. Custom-made nozzle with $\phi = 0.2$ mm orifice was installed at the bottom end of the vertical pipe, and the top end remained opened to the atmosphere. The diameter of the orifice was sufficiently

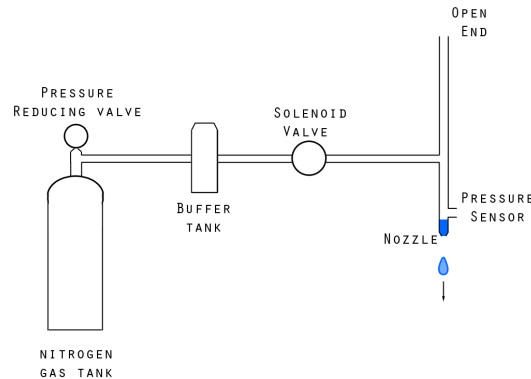


FIG. 2. Scheme of a single-droplet generator.

small so that water was unable to flow due to gravity alone. The horizontal pipe was connected to the solenoid valve characterized by extremely short opening time ($\Delta t \approx 5$ ms). This valve in turn was connected to the nitrogen gas tank through the buffer tank and the pressure reducing valve. This system allowed to vary peak pressure above the meniscus of the liquid (Fig. 3a). The solenoid valve was activated by applying a 24 V DC pulse. The pulse was controlled by means of AVR micro-controller programmed to send a rectangular impulse for a prescribed time-interval. The typical process of droplet ejection is presented in Fig. 3b. The generated droplets were in the range of 0.6 ± 0.1 mm. By contrast, large droplets ($D_0 = 2.6 \pm 0.1$ mm) were generated by a standard syringe with a $\phi = 0.5$ mm needle.

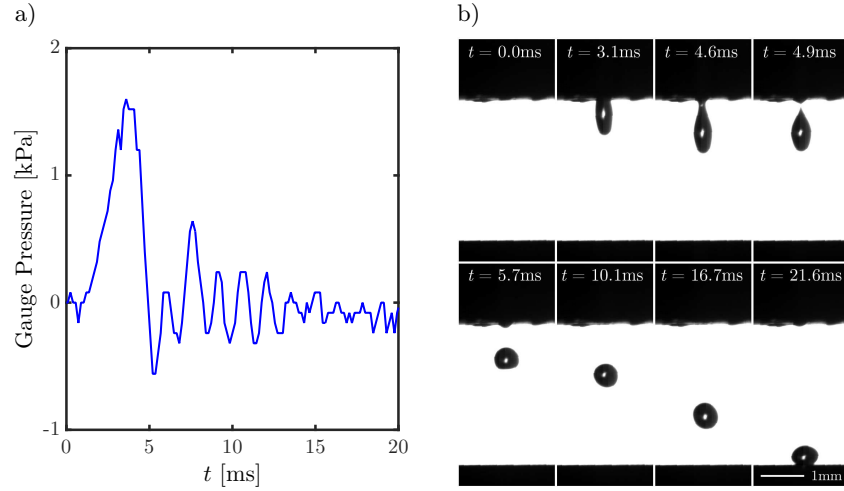


FIG. 3. a) The pressure measured above the meniscus of the liquid. b) The process of small droplet generation.

5. Experimental setup

The image magnification necessary to capture droplet impingement was achieved by the lens system shown in Fig. 4. The setup included a high-speed camera Photron FASTCAM SA5. Recordings were performed at a rate of 30 000 frames per second. The camera was triggered by the same signal as the solenoid valve. In order to alter the image magnification for droplets with different diameter, it was possible to change the distance between the camera, the lens system and the investigated sample placed on a support plate. The LED lamp Cree XM-L T6 1000 lumens was used as a source of light. In case of droplets generated by the syringe ($D_0 = 2.6 \pm 0.1$ mm), the camera was triggered using a light barrier placed below the orifice of the needle.

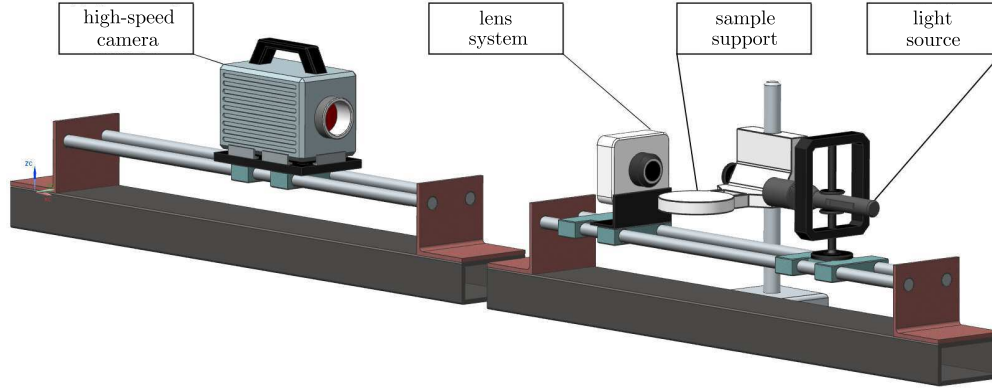


FIG. 4. Experimental setup.

6. Data analysis method

For the purpose of systematic investigation a MATLAB[®] program was developed to perform the automatic image analysis. In particular, the droplet diameter before the impact was estimated as $D_0 = \sqrt[3]{D_x^2 \cdot D_y}$ assuming spheroidal shape of the droplet.

6.1. Image preprocessing

Each recording was subjected to the same procedure of pre-processing. Each frame was converted to a grayscale with pixel intensity scale from 0 (black pixel) to 1 (white pixel). To avoid noise present in the image, the image without a droplet was subtracted from each frame. In this way, the perturbation of pixel intensity could be attributed to a droplet motion. Another important aspect of pre-processing was the necessity to exclude reflection of the droplet appearing at the substrate surface. This was achieved by cutting the image below a certain level of vertical coordinate (corresponding to the droplet contact line). The obtained perturbation image was converted into binary image with an adjusted threshold. White spots at the center of the droplet image were eliminated by filling-in the boundary of the largest detected object.

7. Droplet impingement scenarios

As droplet impinges on the hydrophobic surface (depending on the impact velocity), it can either: (i) remain on the surface after the impact until the oscillation are damped by viscous forces (as observed in the Cassie and Wenzel states, depending on the droplet diameter D_0 and the microstructure of the surface),

(ii) completely bounce off the surface (Fig. 6a) or (iii) partially recoil (part of the liquid remains stuck to the surface – Fig. 6b). Additionally, during the retraction phase of motion, the droplet may shoot out a violent jet, as observed and reported by Bartolo et al. [25] and Tsai et al. [26] (Fig. 6c). This phenomenon is attributed to the collapse of air cavity formed during the retraction phase. All four scenarios are experimentally investigated in the present research for small ($D_0 = 0.6 \pm 0.1$ mm) and large ($D_0 = 2.6 \pm 0.1$ mm) droplets in order to assess the influence of Weber and Bond numbers, i.e., for competing surface tension and gravity forces.

7.1. Small droplets ($D_0 = 0.6 \pm 0.1$ mm)

For small droplets with $D_0 = 0.6$ mm ($\text{Bo} \approx 0.05$), generated by means of the pneumatic system (see Section 4) all the described scenarios were observed, i.e., no rebound (droplet stuck to the surfaces oscillating with decreasing amplitude), bouncing, partial rebound and jetting. However, full rebound was observed only in the samples with microstructure $b/a = 2.75$ and $b/a = 4$. Additionally, it should be noted that the recoil of the droplet was not followed by the segmentation (Fig. 5) as it was the case for the droplet with $D_0 = 2.6$ mm (see Fig. 6a, $t = 8.73$ ms).

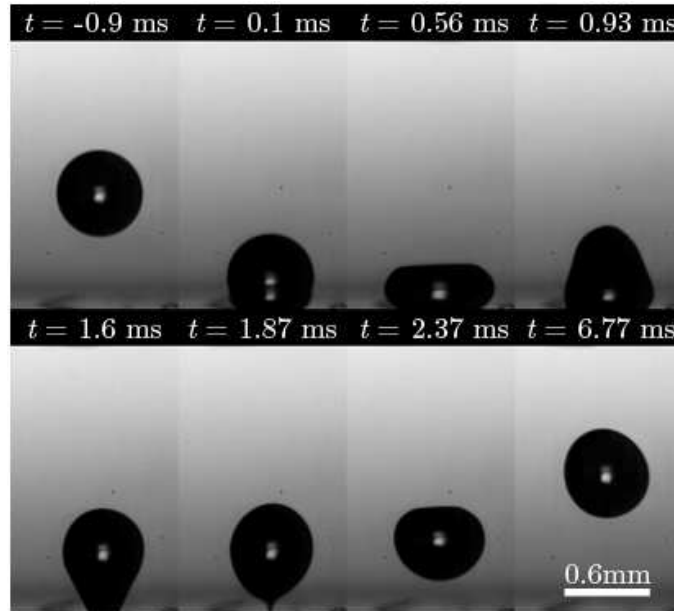


FIG. 5. Full rebound ($D_0 = 0.6$ mm, $We = 2.6$).

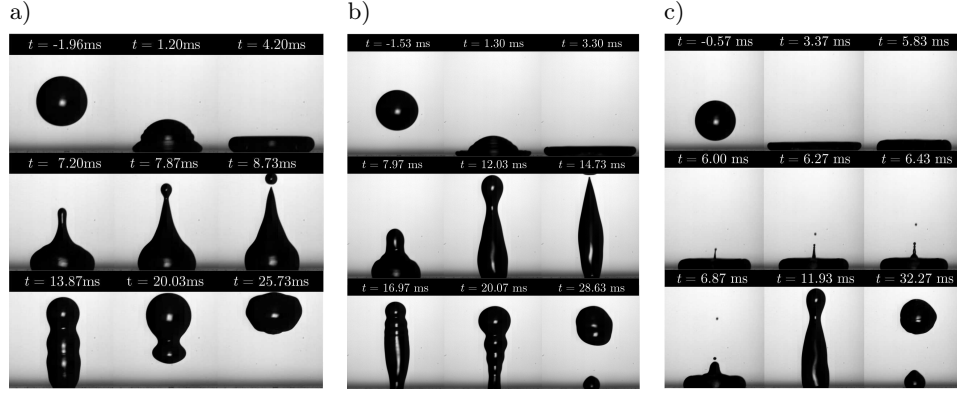


FIG. 6. a) Bouncing – complete recoil of the droplet ($D_0 = 2.6\text{ mm}$, $We = 18$), b) Partial recoil – part of the liquid remains stuck to the surface ($D_0 = 2.6\text{ mm}$, $We = 40$). c) Jetting followed by partial recoil – part of the liquid remains stuck to the surface ($D_0 = 2.6\text{ mm}$, $We = 46$).

7.2. Large droplets ($D_0 = 2.6 \pm 0.1\text{ mm}$)

For large droplets with $D_0 \approx \kappa^{-1} = 2.6\text{ mm}$ ($\mathbb{Bo} \approx 1$), thus with a significant influence of gravity, only three phenomena were identified, i.e., bouncing, partial rebound and jetting. Bouncing was observed for surfaces with $b/a = 0.875$ and $b/a = 1.5$ only. This scenario prevailed for $We < 36$ and $We < 18$, for $b/a = 0.875$ and $b/a = 1.5$ respectively. Higher We numbers resulted in the partial rebound (part of the liquid remained stuck to the surface). Jetting was identified for $41 < We < 46$ and $42 < We < 48$, for $b/a = 0.875$ and $b/a = 1.5$ respectively.

The observations for lower impact velocities, i.e., for lower We numbers, were significantly affected by the oscillations of a droplet induced by detachment of the droplet from the needle (as lower velocities were achieved through shortening the distance between the generator and the surface). Such oscillations change the spreading and recoiling behaviors, ultimately suppressing the rebound. The rebound suppression is due to the loss of axial symmetry as shown by YUN *et al.* [27]. The cases with undamped droplet oscillation were, therefore, excluded from the present analysis.

8. Droplet motion characteristics

In order to describe quantitatively the motion of the droplet center of mass (assuming centroid of extracted shape coincides with mass center), its estimated position was recorded as a function of time t (Figs. 7a and 7b). The same procedure was applied to the horizontal diameter $d(t)$ of a droplet (Fig. 7c).

As droplet impinges on the surface it spreads until the maximum deformation is reached (the maximum horizontal dimension is denoted as $d_{max} = \max d(t)$).

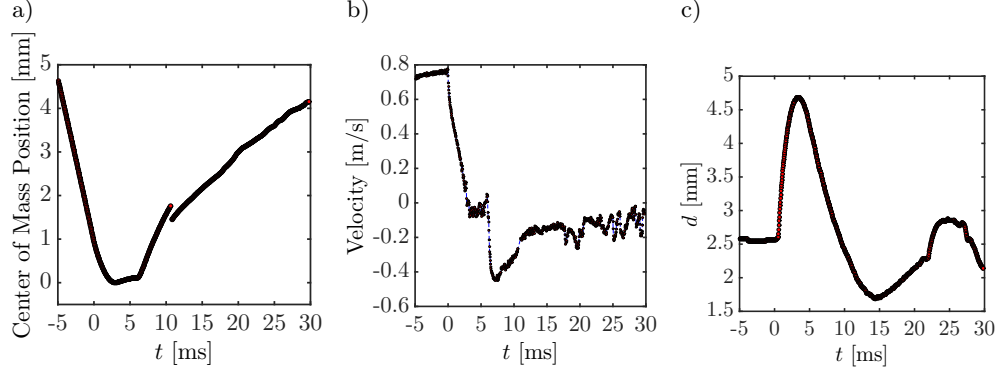


FIG. 7. a) Center of mass position as a function of time for $We = 20$ (0 ms corresponds to the time of impact). The discontinuity at $t = 10$ ms corresponds to the break up of the droplet into two parts, which results in the shift of the estimated position of mass center. b) Velocity of the mass center as a function of time for $We = 20$. c) Horizontal dimension of a droplet as a function of time for $We = 20$. a), b) and c) present results for droplet with diameter $D_0 = 2.6$ mm.

During the spreading phase, part of the kinetic energy, related to the droplet impact velocity, is converted into potential energy of the surface deformation. The remaining part is transferred into vortical motion of the liquid inside the droplet [28]. The maximum spread factor, defined as d_{max}/D_0 , was determined as a function of Weber number. For both investigated surfaces and for the impact number $\mathbb{P} = WeRe^{-4/5} \ll 1$ (in the present experiments $\mathbb{P} = 0.04 \div 0.12$), d_{max} scales as $D_0 We^{1/4}$, and thus as $V_0^{1/2}$ (see Figs. 8a and 8b), which agrees with the results of CLANET *et al.* [28]. This confirms the correctness and the accuracy of the applied data analysis procedure. However, such behavior of the spread factor

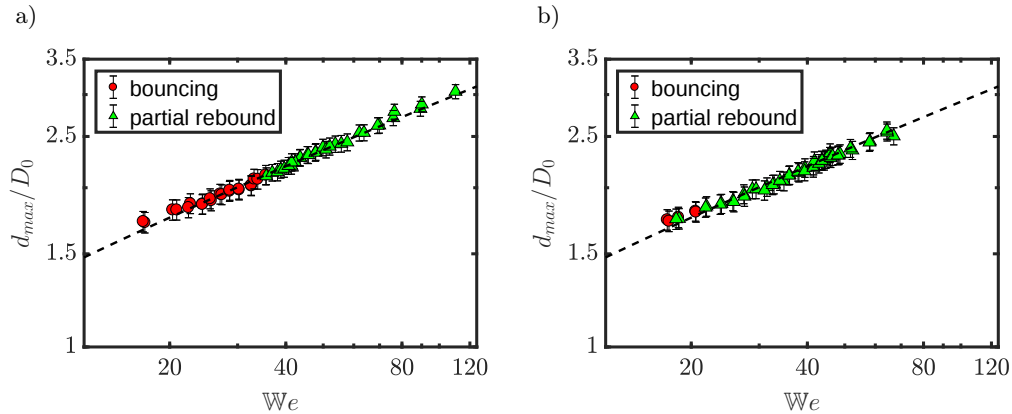


FIG. 8. a) Maximum spread factor for $b/a = 0.875$ and (b) $b/a = 1.5$; $D_0 = 2.6$ mm ($\mathbb{Bo} \approx 1$), dashed line is the best fit with a slope 1/4 (both scales are logarithmic).

is not universal. For the droplet $D_0 = 0.6$ mm, the evolution of the spread factor d_{max}/D_0 scales more as $\sqrt{\mathbb{W}e}$ (see Fig. 9). This means that the kinetic energy of the drop is completely converted into surface energy of the pancake-like droplet after impact ($\rho D_0^3 V_0^2 \sim \sigma d_{max}^2$ yields $d_{max} \sim D_0 \mathbb{W}e^{1/2}$).

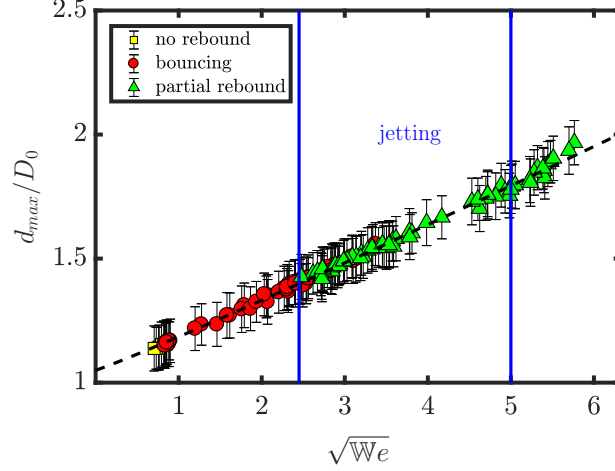


FIG. 9. Spread factor d_{max}/D_0 as a function of $\mathbb{W}e$ for $b/a = 0.875$ and the droplet $D_0 = 0.6$ mm ($\mathbb{B}o = 0.05$); the dashed line is the best fit ($d_{max}/D_0 = 0.135 \cdot \mathbb{W}e^{0.53} + 1.05$). Blue vertical lines denote range of $\mathbb{W}e$ for which jetting phenomenon was observed.

The subsequent stage of the droplet motion is the so-called retraction phase in which the surface energy transforms back into kinetic energy. Our systematic experiments (Fig. 10) suggest that the droplet retraction rate, defined as $\dot{\epsilon} = V_{ret}/d_{max}$ with $V_{ret} = \max[-\dot{d}(t)]$, does depend on the impact velocity. This

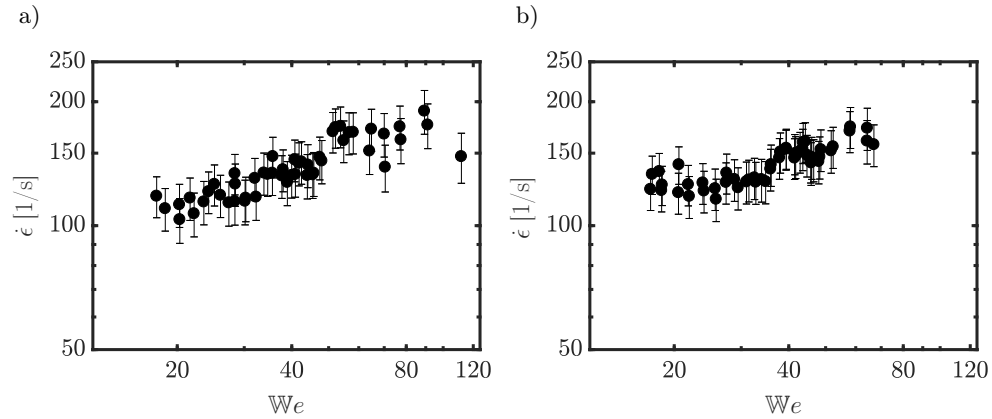


FIG. 10. Maximum retraction rate for a) $b/a = 0.875$ and b) $b/a = 1.5$ (measurements with $D_0 \approx \kappa^{-1} = 2.6$ mm).

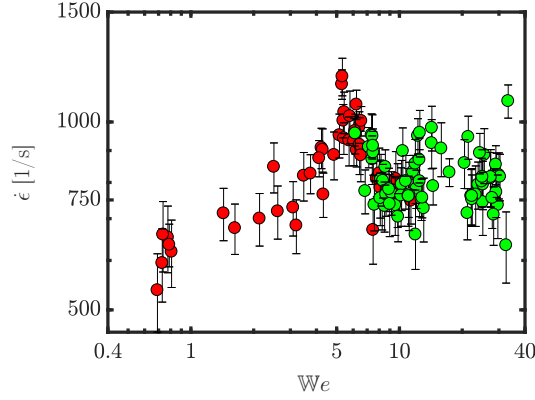


FIG. 11. Maximum retraction rate for $b/a = 0.875$ (measurements with $D_0 = 0.6$ mm; both scales are logarithmic). Red and green circles correspond to bouncing and partial rebound regimes, respectively.

result is in contradiction to the model proposed by BARTOLO *et al.* [29] who postulated that the droplet retraction rate should be regarded as a material constant that does not depend on the impact velocity. The same conclusion can be made for a droplet with diameter $D_0 = 0.6$ mm, where the variation is even greater (see Fig. 11).

9. Transition criterion

Transition between the regimes of partial rebound and full bouncing (see, e.g., Fig. 8a) was described in the past by different authors proposing different physical explanations and criteria. According to PATANKAR *et al.* [30] the droplet may or may not infiltrate the microstructured surface depending on the balance of texture-dependent capillary pressure (antiwetting pressure) and the pressure exerted by the droplet onto the surface upon impact (wetting pressure). The capillary pressure of the surface corresponding to the array of square pillars can be estimated as [30]

$$(9.1) \quad P_c = \frac{\sigma}{a} \left[\frac{-4 \cos \theta_a}{(1 + b/a)^2 - 1} \right],$$

where θ_a denotes the advancing contact angle on a smooth surface. In our measurements the capillary pressure P_c varied in the range of $P_c = 45 \text{ Pa} \div 5.85 \text{ kPa}$.

A different approach has been proposed by VARANASI *et al.* [31] and DENG *et al.* [15] who argued that one of the relevant wetting pressures at the contact stage of the impact is the effective water-hammer pressure appearing due to the compression of liquid behind the shock wave envelope, described as [32]

$$(9.2) \quad P_{wh} \approx 0.2\rho CV_0,$$

where C denotes the speed of sound in the liquid. In our measurements, the range of the investigated droplet impact velocities implies $P_{wh} = 42 \text{ kPa} \div 106 \text{ kPa}$. During the subsequent spreading phase of motion, the pressure drops to the value related to the Bernoulli-type dynamic pressure:

$$(9.3) \quad P_d = 0.5\rho V_0^2.$$

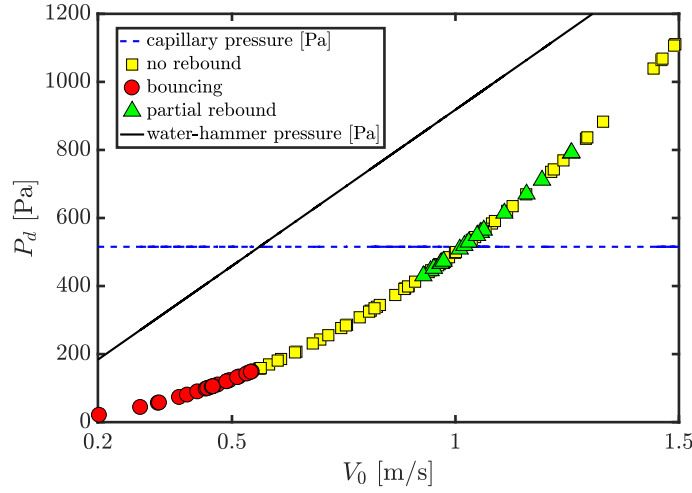


FIG. 12. Comparison of the droplet dynamic pressure (markers) with capillary pressure of the surface (blue dashed line) and water-hammer pressure (black solid line; calculated according to Eq. (9.6)) for the surface with $b/a = 4$ ($D_0 = 0.6 \text{ mm}$; partial rebound corresponds to jetting as part of the liquid is detached from the original portion of the liquid).

As a result of this argument the following sequence of transitions is proposed by DENG *et al.* [15]:

$$(9.4) \quad \begin{aligned} P_c < P_d < P_{wh} & - \text{complete infiltration and pinning,} \\ P_d < P_c < P_{wh} & - \text{partial pinning,} \\ P_d < P_{wh} < P_c & - \text{complete recoil.} \end{aligned}$$

This model suggests that in the case of $b/a = 0.875$ the transition from complete recoil to the partial rebound should occur for $P_{wh} = P_c = 5.85 \text{ kPa}$. In the range of investigated velocities, for $D_0 = 2.6 \text{ mm}$, P_{wh} is always significantly larger than P_c , therefore complete recoil should not be expected. This is in contradiction to our experiments, in which both the partial rebound and the full bouncing were observed (see Figs. 8a and 12).

Another model describing the droplet pinning was provided by JUNG *et al.* [14]. By equating the Laplace pressure of the droplet to the dynamic

pressure of the droplet impact velocity V_0 the following condition for complete rebound was obtained (the formula was adjusted to the array of pillars used in the present research):

$$(9.5) \quad V_c < \sqrt{\frac{16\sigma h}{\rho b^2}}.$$

According to this model the transition should occur for $V_c = 108$ m/s.

In our measurements, the transition from complete recoil to partial pinning ($b/a = 0.875$; $D_0 = 2.6$ mm) occurred for the impact velocity $V_0 = 1.02$ m/s ($P_d = 518$ Pa), which agrees neither with the model of VARANASI *et al.* [31] nor DENG *et al.* [15] nor JUNG *et al.* [14].

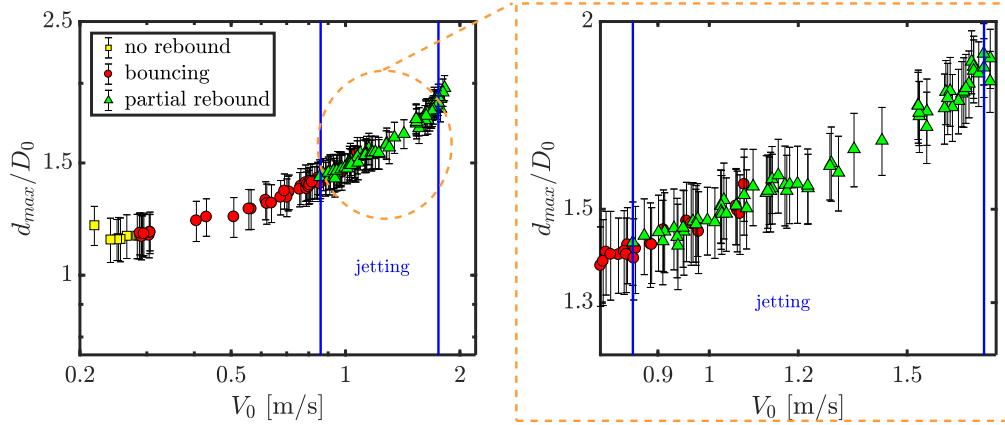


FIG. 13. Spread factor as a function of droplet impact velocity ($D_0 = 0.6$ mm) for $b/a = 0.875$.

Another, more general approach was proposed by Kwon *et al.* [33], who analyzed gentle deposition of a sessile droplet. The transition from the Cassie–Baxter to the Wenzel regime was associated with the rapid deceleration of center of gravity, generating deceleration-based water-hammer pressure:

$$(9.6) \quad P_{wh} = k\rho CV_0,$$

where k is a constant depending on the shape and the velocity of the droplet.

For the surfaces with $b/a = 2.75$ and $b/a = 4$ a transition occurs for the velocities lower than the velocity for which a jetting was observed. Additionally, it is worth noticing that the dynamic pressure related to the critical impact velocity is lower than the capillary pressure related to the surface (Fig. 12).

We have determined the k constant as $k = 9 \cdot 10^{-4}$ and $k = 6.2 \cdot 10^{-4}$, for $b/a = 2.75$ and $b/a = 4$ respectively. Assuming linear dependency of $k = k(V_0)$

it was estimated that the critical velocities for the samples with lower spacing-to-width ratio were given as $V_c = 1.45$ m/s and $V_c = 1.04$ m/s, for $b/a = 0.875$ and $b/a = 1.5$ respectively. This fact can explain pinning of the droplet for the velocities larger than the velocity range for which jetting was observed.

As the pillar spacing-to-width ratio b/a increases, the impact velocity for which a droplet sticks to the surface decreases (Fig. 14). As it was mentioned before, jetting makes the transition criterion unclear. This fact was included in Fig. 13 by taking into account the velocity regime in which bouncing and partial rebound could exist together with jetting phenomenon.

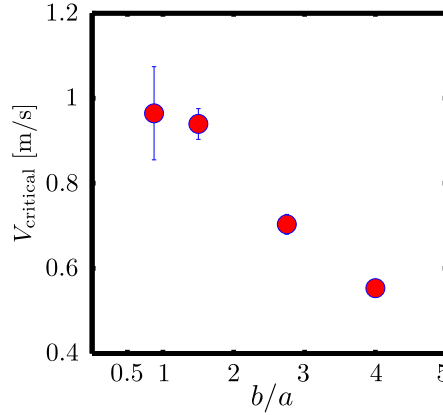


FIG. 14. Critical impact velocity for a droplet with $D_0 = 0.6$ mm (transition from full rebound to droplet pinning).

10. Conclusions

Our work suggests that the droplet may stick to the textured surface in two different ways. The first mechanism, observed in cases $b/a = 0.875$ and $b/a = 1.5$, is governed by high-speed jetting phenomenon, which occurs during the retraction phase. This process takes extremely short time (jet velocity may reach up to 40 times the value of the impact velocity). There are two consequences of jetting. Droplet ejecting a portion of liquid with extremely high velocity may significantly reduce momentum of initial droplet volume. This momentum reduction might be a source of bouncing absence. Secondly, as jetting is a violent process of jet ejection, droplet is being strongly pushed towards the surface. Related pressure increase can overcome capillary pressure and as a consequence droplet may stick to the surface. We estimated that the pressure increase due to the appearance of liquid ejection is sufficient to overcome capillary pressure related to the surface. Therefore it may be suspected that the droplet infiltrates the micro-structure. It

is worth noticing that because of the existence of jetting, there is no clear impact velocity onset for the transition. The velocity of ejected stream is highly dependent on the droplet impact velocity (see BARTOLO *et al.* [25]). Apparently, there is also a significant influence of surface wettability. The droplet impact velocity range for which a jetting was observed decreases as the spacing-to-width ratio b/a increases. The existence of jetting, according to our knowledge, has never been taken into account for transition criterion. We noticed large discrepancies between the existing models in the literature and our experimental results. The second mechanism seems to be more subtle. For surfaces $b/a = 2.5$ and $b/a = 4$ the droplet sticks to the surface, even though the dynamic pressure related to the droplet impact velocity is lower than the capillary pressure of the surface. This means that there has to be another source of the pressure increase. One may suspect that this happens in the analogy to the water-hammer pressure increase occurring as the valve is rapidly closed in the pipe system. KWON *et al.* [33] suggested that such a pressure increase may lead to transition to the Wenzel state even during the gentle deposition of the droplet. Kwon *et al.* introduced scaling constant that depends on the velocity of the droplet mass center. This constant should be independent of the surface properties. Following this model we have determined the k constant for $b/a = 2.5$ and $b/a = 4$. Another important aspect of this work was to determine the influence of gravity on the droplet bouncing. For a droplet with $D_0 = 0.6$ mm bouncing was observed for samples with $b/a \in \langle 0.875, 4 \rangle$. Full rebound with a droplet $D_0 = 2.6$ mm was observed only for $b/a = 0.875$ and $b/a = 1.5$ (in the investigated velocity regime). This suggests that indeed the shape of the droplet influences the pressure that increases due to water-hammer effect.

Acknowledgements

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