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**Main Manuscript for**

**Sessile Droplet Prompt Jumping Driven by Vapor Bubble Explosion on Hot Substrate**

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**Abstract**

In this paper, we present a surface topography strategy to modulate microdroplet jumping behaviors on superheated micropillared substrates by controlling the vapor bubble growth modes. Nucleate boiling initiates at the base of the sessile microdroplets dwelling on the substrates at a moderate superheat of 20-30 °C. With the small superheat, the growth rate of the vapor bubble is limited by the rate of heat transfer through the bubble interface, which can be described by a heat-transfer-controlled bubble growth model. In this condition, the droplet would vibrate periodically on the substrate and finally take off the surface in seconds. Specifically, the micropillar matrix would function as fin arrays to enhance the heat transfer, especially for a sessile microdroplet in the Wenzel state. By tuning the feature sizes of micropillars, one can adjust the vapor bubble growth at the microdroplet base from the heat-transfer-controlled mode to the inertia-controlled mode. As opposed to the relatively slow heat-transfer-controlled vapor bubble growth, the expanding velocity of the inertia-controlled vapor bubble growth can reach as fast as ~4 m/s. Such explosive growth of the vapor bubble would lead to the sessile microdroplet out-of-plane jumping in milliseconds. Violent energy from the rapid vapor bubble growth is utilized to achieve facile droplet detachment. Our observations in this study unveil the mechanism of droplet rapid detachment from a hot micro-structured surface and shed lights on designing engineered surfaces avoiding the potential damage of vapor explosion and condensate flooding.

**Significance Statement**

Nucleate boiling is a universal phase change process initiated at a low superheat temperature range. However, the vapor bubble generated in the nucleate-boiling region, which might result in vapor explosion, would be particularly detrimental in some contexts. In this work, we provide a simple but potential strategy to control the vapor bubble growth modes. Various remarkable droplet dynamic phenomena are observed during the interactions between droplets and superheated micro-structured substrates. Giant explosive vapor bubble growth processes are observed, and the kinetic energy of vapor explosion is thereby utilized for sessile droplet motivation to achieve rapid and facile droplet detachment. The controlling strategy for the vapor bubble growth mode on superheated substrates also offers opportunities for surface anti-corrosion.

**Main Text**

Liquid droplet rapid detachment and facile removal(1-3) from a surface has broad applications in various fields such as anti-frosting/icing(4), anti-fouling/corrosion(5), self-cleaning(6), evaporation desalination(7) and thermal management(8, 9). During the past two decades, many approaches to purging sessile droplets have been put forward by virtue of functional substrates with complex macro/micro/nanostructures(10-13) or resorting to costly external stimuli such as electrical(14), photothermal(15) or magnetic fields(16). As such, Leidenfrost effect(17-19) can lead to droplet hovering over a heated substrate but requires the surface temperature maintained at a high level, *e.g.*, 200 °C - 300 °C for water droplet. Nevertheless, our understanding of the interfacial phenomena including droplet wetting dynamics and phase changes at the solid-liquid interface remains elusive, impeding simple designs of engineered surfaces for droplet manipulations(3, 20-22). Nucleate boiling is a phase change phenomenon with vast thermal energy transferred for the growth of vapor bubbles. In this respect, nucleate pool boiling on micro/nanostructured surfaces has been extensively explored in previous studies(23, 24), however, the vapor bubble growth within a sessile droplet and its influence on droplet actuations have been seldom studied. In this work, we present a nimble strategy to manipulate droplet jumping behaviors by tuning surface topographical features on micro-pillared substrates at moderate superheat. Violent energy from the rapid nucleate boiling is utilized to achieve facile droplet detachment. For droplets staying in the Wenzel state, the micropillars penetrate the droplet base and hence function as fin array for heat transfer enhancement. By simply increasing the micropillar height, one can adjust the vapor bubble growth at the droplet base from the heat-transfer-controlled growth mode(25) to the inertia-controlled growth mode(25, 26), which can be applied to significantly promote vapor bubble expanding velocity and hence droplet rapid jumping.

We experimentally investigate the out-of-plane jumping behaviors of a sessile water droplet with diameter  on hot microstructured silicon substrates via high-speed cameras (Fig. 1). A water droplet is first deposited on the substrate and then the sessile droplet is carefully translated to a preheated hot plate, which is maintained at 130 °C, for the jumping observation (see experimental setup in Supplementary Fig. 1). The substrates are engineered with an array of micropillars coated with a thin layer of fluoropolymer (Figs. 1(A) and 1(D) insets and Supplementary Fig. 2). The substrate in Fig. 1(A) consists of a micropillar matrix with uniform micropillar diameter (), periodicity () and height (), hereafter named as . The droplet initially stays in the Wenzel state as designed and subsequently vibrate periodically while boiling on the hot substrate with obvious prolate-to-oblate ellipsoid transformation as shown in Fig. 1(A) (Supplementary Movie S1). It takes about for the vapor bubble to completely spread over the droplet base area as shown in the top-view snapshots in Fig. 1(B) (Supplementary Movie S1). The burst of the vapor bubble leads to the generation of capillary waves on the cap surface of the droplet, and it takes about one more second (1034 ) for the droplet to jump off the substrate. The relatively slow vapor bubble growth indicates a small overpressure inside the vapor bubble, leading to the relatively longer dwelling time before the sessile droplet completely jumps off the substrate.

Next, we consider promoting the droplet jumping behaviour, *i.e*., rapid detachment and facile removal from the substrate, by modulating the vapor bubble growth rate thereon. The underpinning mechanism is that increasing the substrate micropillar height can enhance the heat transfer between the droplet and the substrate and thus incur a faster vapor growth. Specifically, the rise of the micropillar height from causes substrate roughness changing from 1.087 to 1.349, leading to a 24.1% increase of the solid-liquid contact area and hence ~35.9% enhancement of heat transfer rate (Supplemental Fig. 3). For droplet resting on the hot substrate with tall micropillars ( at 130 °C), it takes only for the droplet to completely jump off the substrate as shown in Fig. 1(D)(Supplementary Movie S1), which is 500 times faster than the vibration jumping on the substrate of . Essentially, the increase of the micropillar height (from 20 to 80 ) incurs the explosive bubble growth at the droplet base, giving rise to the prompt jumping of the droplet in milliseconds, *i.e*., explosion jumping. The top view of a typical explosive bubble growth process is shown in Fig. 1(E). It takes only for the vapor bubble to fully cover the droplet contact base (Supplementary Movie S1), which is about 1500 times faster than the bubble growth on the substrate as shown in Fig. 1(B).

The vapor bubble burst at the droplet base leads to the generation of capillary waves on the droplet cap surface as shown in Fig. 2(A). When the bubble growth is slow, the overpressure between the vapor bubble pressure and the water base pressure is balanced by the surface Laplace pressure difference : . Similarly, a Laplace pressure difference balances the water base pressure and the surrounding air pressure : . The pressure difference between and causes the depinning of the droplet base contact line. That is, water entrapped on the micropillars around the contact zone, *i.e.*, liquid bridge, could be detached from the substrate micropillars. The release of the pinned liquid bridge at the droplet contact zone generates capillary waves on the droplet cap surface. This depinning process causes the shrink of droplet contact area and stretches the droplet into a prolate ellipsoid. Simultaneously, the momentum transfer during the capillary wave generation triggers the occurrence of droplet vibration. During the vibration jumping process, the droplet mass loss plays a negligible role (Supplementary Fig. 4) and the droplet vibrates like a bumping spring(27) with a relatively constant period of 24 (Fig. 1(A)), *i.e*., , where is the droplet mass and is the surface tension. The vibration behaviours on the substrate can be modelled as a mass-spring-damper system(3, 28) with continuous momentum input from the boiling-induced contact line depinning (Figs. 2(A) and 2(B), more details see Supplementary Fig. 5). As shown in Fig. 2(C), when the inertia force of the vibrating droplet is sufficient to overcome the adhesion force on the substrate, the droplet jumps off the micro-pillared surface(29). Assuming the adhesion force on each individual micropillar is the same, the overall adhesion force from the substrate is proportional to the total number of the micropillars underneath the droplet. Therefore, the total adhesion force can be scaled as . The inertial force of the droplet stems from the jumping velocity and can be scaled as , where is the liquid density. There should be a balance between the inertia and the adhesion force when the droplet is about to jump off the substrate surface with a take-off velocity :

[1]

Therefore, the take-off velocity is scaled as which is independent of the droplet diameter. Droplets with different volumes (different diameters) exhibit a relatively constant take-off velocity as shown in Fig. 2(D), which matches well with our scaling analysis.

Theoretically, there are two limiting vapor bubble growth modes(25): one is the inertia-controlled growth mode whose bubble growth rate is only limited by how fast it can push away the surrounding liquid and the other one is the heat-transfer-controlled growth mode whose relatively small bubble growth rate is mainly limited by the heat transport through the bubble interface. We attribute the observed relatively slow bubble growth on (Fig. 1(B)) to the heat-transfer-controlled mode and the explosive bubble growth on (Fig. 1(E)) to the inertia-controlled mode. The evolutions of inertia-controlled bubble expanding velocities on high-micropillared substrates and the evolution of a typical heat-transfer-controlled bubble expanding velocity on a short-micropillared substrate with the lateral diameter of bubbles are presented in Fig. 3, respectively (Supplementary Movie S2). For a vapor bubble with a relatively small diameter (< 0.7 mm), the inertia-controlled bubble growth exhibits a relatively constant expanding velocity of ~4 m/s whereas the heat-transfer-controlled bubble expanding velocity is orders of magnitude smaller, *i.e.*, only ~1.5 mm/s.

A typical Reynolds number of the fluid motion during the explosive vapor bubble expansion process can be scaled as , where is the vapor bubble expanding velocity, is the dynamic viscosity. The corresponding Mach number , where is the speed of sound in water . As a result, the viscous dissipation during the fluid motion can be neglected and the fluid is regarded as incompressible. Then the fluid motion during the explosive vapor bubble expansion can be modeled as a potential flow described by the unsteady Bernoulli equation:

[2]

where is the velocity potential, is the water motion velocity and is the gravitational acceleration. is a point on the vapor bubble surface and is a point on the droplet surface at the contact line. Considering the small size of the droplet and the fact that point and are almost at the same height, the gravitational term can thus be neglected. Moreover, it is observed that the droplet contact line is not moving during most periods of the vapor bubble expansion, until the vapor bubble surface approaches the droplet contact line. Thus, it is reasonable to treat the point as a stagnant point when the vapor bubble diameter is small. As a result, we can simplify Eq [2] with to obtain that:

[3]

Due to the incompressibility of the liquid, we have the mass conservation that . Thus, we can obtain the relation for the velocity potential . Then, the unsteady Bernoulli equation can be rewritten as:

[4]

Now the pressure term at point A can be calculated as: , which is the difference between the pressure inside the vapor bubble and the Laplace pressure caused by the vapor bubble surface curvature . Experimental observations indicate that the vapor pressure term is the main driven pressure for the bubble interface expansion, which should be much larger than the Laplace pressure term. Thus, pressure at point can be approximated(25) as the vapor pressure: . Also, pressure term near the stagnant point can be approximate as the ambient pressure. With the Clapeyron equation, the pressure term on the right hand side of Eq [4] can be expressed as:

[5]

where is the temperature of the superheated water; 73 K is the saturation temperature of water under the ambient pressure ; is water specific evaporation enthalpy; and is the water vapor density. Now we find the evolution equation for the vapor bubble radius as:

[6]

Accordingly, the inertial-controlled bubble interface velocity is independent of the bubble radius and time as evidenced in our experiments. The temperature measurement by an IR camera indicates that the maximum superheat of water is ~ 5 °C at the droplet contact zone before the droplet jumps off the substrate (Supplementary Fig. 6). As a result, it is reasonable to assume that the temperature at the droplet base is between 103 °C to 105 °C during the vapor bubble growth period. The expanding velocities of the vapor bubble interface at temperatures of 103 °C and 105 °C are 2.16 m/s and 3.55 m/s, respectively, which agree well with our experimental observations as shown in Fig. 3. Note that the deviation of the predicted vapor bubble expansion velocity and the experimental measurement when the bubble radius is large is due to the movement of the droplet contact line. When the bubble gets larger, *i.e.*, bubble diameter the droplet contact line starts to advance and point can no longer be regarded as a stagnant point.

On the other hand, the temporal evolution of the bubble radius during the heat-transfer-controlled growth can be approximated as(25):

[7]

where  is the liquid water conductivity and  is the liquid water specific heat. The typical expanding velocity of a bubble in the heat-transfer-controlled growth mode with a 105 °C superheat and at time is in the order of . As shown in Fig. 3, the experimental results of the bubble interface expanding velocities in both the inertia-controlled mode and the heat-transfer-controlled mode match well with the theoretical predictions.

The variations of droplet height , which is defined as the distance from the substrate surface to the droplet apex, and the droplet jumping snapshots on a variety of substrates are shown in Fig. 4. A typical Wenzel-to-Cassie transition(30) on substrate happens after the sessile droplet is translated on the hot plate as shown in Figs. 4(A)and 4(G)(Supplementary Movie S3). The relatively large micropillar diameter () and short micropillar periodicity () generate a high capillary pressure resistance(31)  at the micropillar tips (Fig. 4(F)), where is the intrinsic contact angle of water droplet on the fluoropolymer coating, inhibiting the replenishment of the dried cavities between the micropillars after evaporation and leading to the smooth Wenzel-to-Cassie transition (, where is the hydrostatic pressure at the droplet base).

Obvious vibrations of the boiling droplet appear on the substrate of with a smaller capillary pressure resistance 133 Pa as shown in Figs. 4(B) phase 4and 4(H). The relatively lower capillary pressure resistance makes it easier for the bulk liquid to replenish the droplet base cavities. Moreover, when a wetted cavity exists at the droplet base, the capillary pressure resistance of the neighbouring empty cavity would be reduced by half as illustrated in Fig. 4(F). The vibration motion of the droplet generates an additional wetting pressure , where  is vibration velocity(31). On the substrate of 20 mm/s and 75 Pa, which can overcome the reduced capillary pressure resistance, *i.e*., so that the droplet is apt to dwell in the Wenzel state. Capillary waves are triggered by the depinning of droplet contact line(32) (Fig. 2(A)) when the expanding vapor bubble approaches the droplet contact line. In general, the generation of capillary waves is accompanied by the shrink of droplet contact radius, leading to the gradual increase of the droplet height as shown in phase 3 of Fig. 4(B). The droplet in this phase is unstable with a prolonged height(33) (prolate ellipsoid) and starts to vibrate periodically with a relatively constant period and an increasing vibration amplitude as shown in phase 4 of Fig. 4(B) as well as in Fig. 4(C) (. The droplet continuously gathers energy from the successive depinning at the droplet base to achieve the jump-off eventually. Once the droplet body jumps off the substrate, there are no refilled wet cavities in the substrate and the complete capillary pressure is high enough to withstand the subsequent gentle falling of the jumping-off droplet (). After landing on the substrate again, the droplet would stay in the Cassie state and vibrate with decaying amplitude due to viscous dissipation as shown in phase 5 of Fig. 4(B) and Fig. 4(H). On substrate , however, the even smaller capillary pressure resistance of = 74 Pa is insufficient to endure the gentle impact of the falling droplet. The micropillars would puncture into the landing droplet again and the droplet recovers to the Wenzel state for subsequent vibration jumping. In this way, the droplet would trampoline(34) on the hot substrate due to the depinning-induced momentum exchange at the droplet base as shown in Fig. 4(C) phase 6 and Fig. 4(I)(Supplementary Movie S4).

Periodic vibration disappears for droplet boiling on the substrate of with a relatively large micropillar height () and there appears large capillary waves on the cap surface of the droplet as shown in Figs. 4(D)and 4(K)(Supplementary Movie S3). Since the capillary waves are generated by the depinning of droplet contact line, *i.e.*, the depinning of the liquid bridge as shown in Fig. 2(A), the initial amplitude of the capillary waves should be proportional to the length of the liquid bridge, which is mainly determined by the height of the micropillars(32). Thus, the capillary wave amplitude should be proportional to the micropillar height, *i.e*., . The total energy of capillary wave(35) on the droplet surface can be estimated as , where is the wavenumber and  is the radius of the droplet (Supplementary Fig. 8). The taller the micropillar height, the larger the capillary wave amplitude and the more energy contained in the capillary waves. Conceivably, the more the energy contained in the capillary waves, the less the energy stored in the droplet bulk. Therefore, the prolate-to-oblate ellipsoid deformation becomes less obvious, and the droplet can eventually achieve jumping due to the released capillary wave energy, *i.e*., capillary jumping.

On the substrate of with even taller micropillars () and hence even larger heat transfer area between the droplet and the substate, the explosive bubble growth adjacent to the droplet base intensely pushes the surrounding fluid and eventually gives rise to the prompt droplet jump-off as evidenced in Figs. 4(E) and 4(K). A sessile droplet of with a contact angle of 150° can achieve jumping velocity triggered by the explosive bubble, which is much faster than the maximum take-off velocity 40 mm/s (Fig. 2(D)) of vibrating droplets. The large jumping velocity indicates sufficiently strong inertial force to overcome adhesion on the substrate so that speedy droplet detachment from the substrate can be achieved within only several milliseconds.(29)

Our observations indicate that besides droplet properties the jumping modes of a boiling droplet are highly dependent on the substrate topography. The phase map of droplet jumping on substrates with different micropillar diameter , micropillar height and micropillar periodicity is shown in Fig. 5. The occurrence of droplet jumping is principally determined by the micropillar periodicity . No out-of-plane jumping is observed for droplet boiling on substrate with a short micropillar periodicity () due to the large thereon and the droplet prefers to stay in the Cassie state, *i.e.*, Cassie state maintaining(36) or the Wenzel to Cassie transition(30). The micropillar diameter would only slightly affects the threshold value for the occurrence of droplet jumping due to its secondary influence on . Obvious and versatile droplet jumping behaviours take place on substates with a large periodicity () due to the small and the easily replenished cavities underneath the droplet. In particular, the droplet jumping modes are mainly determined by the micropillar height , which dominantly affects the vapor bubble growth modes and therefore the generation of capillary waves. Droplet jumping mode gradually changes from the vibration jumping or the capillary jumping to the explosion jumping with the continuous increase of the substrate micropillar height. After jumping off the substrate, the falling droplet would impact on the surface again either hovering in the Cassie state when the substrate has a large (large and small ) or trampolining in the Wenzel state when the substrate has a small (small and large ).

In this study, we systematically investigated the versatile out-of-plane jumping behaviors, *i.e.*, Cassie state maintaining, Wenzel to Cassie transition, vibration jumping, capillary jumping, explosion jumping, Cassie state hovering and Wenzel state trampolining, of a boiling water droplet on microstructured substrates at a temperature much lower than the typical Leidenfrost point. For the first time, by tuning the feature sizes, *i.e*., micropillar height, of the engineered surfaces, the different vapor bubble growth modes can be modulated in a sessile microdroplet that have been less explored in previous studies. In essence, the enlarged contact area between the droplet and the substrate with relatively taller micropillars leads to enhanced heat transfer, providing the necessitated energy for the rapid commence of explosive vapor bubble growth. The phase map presents a comprehensive view of distinct vapor bubble growth modes and diverse droplet jumping behaviors contingent on the topology of the surface microstructures and hence provides an explicit guideline for designing engineered surfaces that prevent the potential damage of vapor explosion(37, 38) or alleviate condensate flooding(39).

**Materials and Methods**

**Substrate preparation**

Polished P-type silicon wafers of diameter and thickness were used as substrates in this work. Standard photolithography process was performed with a SUSS MicroTech Contact Aligner. Then the substrates were etched with Oxford PECVD to fabricate the well-defined micropillar arrays. The micro-pillared substrates were conformally coated with fluoropolymer (PFC 1601V, Cytonix Corporation) using a spin coater at 3000 rpm for 30 s and then baked at 100 °C for 1 hour. Substrate micropillar diameter, height and periodicity (pitch-to-pitch distance) are donated with , and , respectively. More detailed information about the substrates is given in Supplementary Fig. 2.

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**Figures and Tables**

**Graphical user interface

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**Figure 1.** Droplet vibration jumping and explosion jumping on hot micro-pillared surfaces. (A) High-speed images of droplet vibration jumping on substrate heated at 130 °C. Inset, scanning electron micrography (SEM) of micro-pillared substrate. Time-zero is set when droplet contact line depinning occurs and capillary waves emerge on the cap surface of the droplet. (B) Slow vapor bubble growth at the droplet base on substrate heated at 130 °C. (C) Diagram of a sessile droplet on a hot substrate decorated with 20--tall micropillars. (D) High-speed images of droplet explosion jumping on substrate heated at 130 °C. Inset, SEM of the micro-pillared surface. (E) Rapid vapor bubble growth at the droplet base on substrate heated at 130 °C. (F) Diagram of a boiling droplet on a hot substrate decorated with 80--tall micropillars. For droplet in the Wenzel state, the micropillars penetrate the droplet base functioning as fin array for heat transfer modulation. For more details, see Supplementary Movie S1.

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**Figure 2.** Droplet vibration on the hot substrate. (A)Diagram of contact line depinning at droplet base due to vapor bubble burst and capillary wave generation. The snapshot shows the capillary waves on the cap surface of a vibrating droplet. (B) Diagram of the droplet mass-spring-damper system. The vibrating droplet is modeled as two mass points connected with a spring and a damper. (C) Inertia-adhesion force balance of the vibrating droplet. When the inertia force is sufficient to overcome the adhesion on the substrate, the vibrating droplet is about to jump off the substrate surface. (D) Take-off velocities of vibrating droplets with different volumes of 2-16 on substrate heated at 130 °C. The take-off velocity is defined as the instantaneous velocity of the droplet mass center when the droplet is about to take off the substrate.

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**Figure 3.** Vapor bubble interface expanding velocity.Vapor bubble expanding velocities for water droplets dwelling on a variety of micro-pillared substrates with 20 , 60 and 80 tall micropillar arrays, respectively. The substrates were placed on a hot plate with surface temperature maintained at 130 °C. The vapor bubble expanding velocity in the inertia-controlled growth mode is theoretically predicted to be 3.55 m/s and the theoretical prediction of vapor bubble expanding velocity in the heat-transfer-controlled mode is 1.5 mm/s.

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**Figure 4.** Water droplet jumping height variation on different substrates at 130 °C.Jumping height variation on substrate (A) ; (B) ; (C) ; (D) ; (E) . (F) Diagram of capillary pressure resistance at the micropillar tips. (G) Side-view snapshots of droplet wetting state transition in (A). (H) Side-view snapshots of droplet vibration in (B). (I) Side-view snapshots of droplet trampolining in (C). (J) Side-view snapshots of droplet vibration and capillary jumping in (D). (K) Side-view snapshots of droplet explosion jumping in (E).

Chart, diagram

Description automatically generated

**Figure 5.** Phase map of versatile droplet jumping modes on micropillar-arrayed substrates with different topographies. (A) Substrate with micropillar diameter . (B) Substrate with micropillar diameter . (C) Substrate with micropillar diameter . The diverse out-of-plane jumping behaviors, *i.e.*, Cassie state maintaining, Wenzel to Cassie transition, vibration jumping, capillary jumping, explosion jumping, Cassie state hovering and Wenzel state trampolining, of a boiling water droplet have been identified. If the jumping-off droplet falls in the Wenzel state again, the droplet would trampoline on the hot substrate, *i.e*., Wenzel state trampolining. In the case of Cassie state, the falling droplet will hover over the hot substrate, *i.e*., Cassie state hovering. This phase map is valid for water droplets boiling on substrates heated at 120 °C - 170 °C.