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High jump of impinged droplets before Leidenfrost state

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Unlike the traditionally reported Leidenfrost droplet which only floats on a thin film of vapor, we observe a prominent jump of the impinged droplets in the transition from the contact boiling to the Leidenfrost state. The vapor generation between the droplet and the substrate is vigorous enough to propel the spreading droplet pancake to an anomalous height. The maximum repellent height can be treated as an index of the total transferred energy. Counterintuitively, a stronger vaporization and a higher jump can be generated in the conditions normally considered to be unfavorable to heat transfer, such as a lower substrate temperature, a lower droplet impact velocity, a higher droplet temperature, or a lower thermal conductivity of the deposition on the substrate. Since the total transferred energy is the accumulation of the instantaneous heat flux during the droplet contacting with the substrate, it can be deduced that a longer contact time period is secured in the case of a lower instantaneous heat flux. The inference is supported by our experimental observations. Moreover, the phase diagrams describe the characteristics of the high repellency under different substrate temperatures, droplet subcooling temperatures, and Weber numbers. It allows us to manipulate the droplet jump for the relative applications.

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I. INTRODUCTION

Droplet impact is a ubiquitous phenomenon in nature and many industrial processes, such as ink-jet printing, spray cooling, combustion, etc. Recently, particular attention has been paid to the droplet impingement on special targets, such as the moving surface [1,2], the wet surface [3], the moving liquid film [4], the inclined liquid film [5], the immiscible liquid film [6], the textured surface [7], etc. Among the investigations, the heated dry surface [8] or the heated liquid film [9] was applied. Once the substrate temperature is high enough to establish the Leidenfrost state [10], the generated stable thin vapor film prevents the further contact between the droplet and the heated substrate [11] or the heated liquid pool [12] and reduces the friction [13]. The minimum temperature to reach the state, defined as the Leidenfrost temperature, is not a constant, but depends on the surface pattern [14,15] or the droplet velocity [16,17]. For the static Leidenfrost droplets, the droplet size gives rise to the droplet shape variation [18], levitation [19], and droplet taking off [20]. For the impinged droplet, a transition Leidenfrost boiling regime might exist between the vigorous contact boiling and the gentle Leidenfrost state [21]. In the transition regime, the impinged droplet was partially levitated on the superheated transparent substrate with the interesting observation including the fingering pattern and the contact area oscillation [22,23]. Therefore, the regime

between the contact boiling and the Leidenfrost state deserves further investigation.

Besides, according to the measurements in the literature, the thickness of the generated vapor layer between the Leidenfrost droplet and the superheated substrate was in the magnitude of 0.1 mm [24]. However, in the current paper, we have observed a phenomenon that the droplet pancake can be repelled to a relatively enormous height from a superheated substrate during the spreading. It is noteworthy that it differs from the rebound normally observed after the spreading and recoil of the impinged Leidenfrost droplet [25,26]. In this paper, we describe the high-repellency phenomenon and explain why the unique high jump is generated.

II. EXPERIMENTS

The experimental setup is illustrated in Fig. 1. The stable deionized water droplet stream was initiated with the droplet train generator from FMP Technology GMBH, Germany and then impinged onto the top surface of a heated copper block. The key component of the droplet train generator is a nozzle with the piezoelectric element and heaters. As shown in the inset of Fig. 1, a microjet was produced after the nozzle. It could break into the equally spaced droplet stream once the upstream pressure was disturbed periodically by the excited piezoelectric vibrator. The frequency of the generated droplet train could be manipulated by adjusting the output of the function generator. A heater was mounted on the generator

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FIG. 1. The schematic of the experimental setup. The inset is the photograph of the droplet train generation, which was captured by the high-speed camera.

so as to control the liquid temperature at the outlet. The liquid temperature before the micronozzle was measured with two embedded thermocouples. The images were captured with a Phantom v711 high-speed camera. The droplet repellency was captured at a frame rate of 150 000 fps with a resolution of 256×128 pixels. Moreover, a frame rate of 680 000 fps at a resolution of 128×32 pixels was used for measurements of the contact time. A magnification lens was mounted on the camera, which gave a ratio of $3.97 \mu\text{m}/\text{pixel}$ according to the calibration. The shutter speed was $1 \mu\text{s}$ while a light-emitting diode lamp was arranged in a line with the droplet and the camera for supplying sufficient light. In the baseline test, the droplet frequency f , the diameter d_0 , the velocity U , and the subcooling temperature ΔT_{sub} , were kept at 28 000 Hz, $123 \mu\text{m}$, 14.1 m/s , and -70°C . Their deviations were $\pm 10 \text{ Hz}$, $\pm 4 \mu\text{m}$, and $\pm 0.6 \text{ m/s}$, $\pm 0.5^\circ\text{C}$, respectively. The subcooling temperature of the droplet was calculated as $\Delta T_{\text{sub}} = T_d - T_s$, where T_d and T_s are the droplet temperature and saturation temperature, respectively. The corresponding droplet Weber number $We = \rho U^2 d_0 / \sigma$ was 339, and the Reynolds number $Re = \rho U d_0 / \mu$ was 2172, where σ and μ are the surface tension and dynamic viscosity. In the current paper, the variation of the Weber number was achieved by adjusting the upstream pressure of the nozzle, which changed the droplet velocity and diameter from 8.5 to 18.7 m/s and from 0.104 to 0.138 mm , respectively. The droplet velocity was significantly varied, whereas the droplet diameter was only slightly influenced.

In preparation of the target surface, it was furnished by a sand paper (No. 1200) to show the unoxidized bare copper initially, then a droplet train was continuously impinged onto the heated substrate until a layer of stable oxidization was formed. In the vicinity of the stagnation zone, a surface temperature oscillation and a high-temperature gradient were generated due to the effects of the periodic droplet impingement and the point heat sink (a spherical heat conduction pattern was created in the substrate [27]). In the case, the “far-field” temperature in the substrate could be a suitable parameter to represent the heating degree of the substrate because the

temperature gradient was relatively small, and the temperature oscillation was damped in the far field. To this end, three calibrated thermocouples were inserted into a hole 2 mm below the target surface, which could be considered as far field compared to the droplet size. The average of the three temperatures was considered as the substrate temperature T_w in the following analyses. It was measured that the standard deviation of the three temperature readings was around 0.68°C in the series of tests. Moreover, the experiments were conducted in a surrounding with the temperature of $26 \pm 1^\circ\text{C}$, the pressure of 1 atm , and the relative humidity of $48 \pm 5\%$.

III. RESULTS AND DISCUSSIONS

A. Significant droplet jump

As illustrated in Figs. 2(a) and 2(b), the remarkable jump of the spreading droplet is observed when the high-frequency droplet stream impinges onto the superheated substrate. Although the multiple droplets are involved, the significant jump of the impinging droplet can be distinguished after a short period of contact [see the evolution of droplet No. 2 in Fig. 2(a)]. The droplet bottom contacts the substrate at the time $t = 0$. Due to the significant repellency, the bouncing liquid film interacts with the following spherical droplet. The series of experimental snapshots (captured at 150 000 fps) and the corresponding schematics reveal the five different phases of the interaction: droplet falling, film penetrating, film dragging, droplet spreading, and self-levitating. The spherical droplet falls with a high velocity then collides with and penetrates the bouncing liquid film. After that, it drags and deforms the thin film substantially. The droplet then impacts the substrate and spreads, whereas the previous liquid film breaks up. After a short period, the spreading pancake is finally levitated by its own vapor. The jump is accompanied with the continuing spreading. When the droplet film takes off slightly, some local contacts still remain between the film and the substrate. Because of the periodical nature of the steady-state droplet train, the next phase of droplet No. 2 in state (v) repeats the scenario of droplet No. 1 in state (i). The corresponding movie is available in the Supplemental Material [28].

Once the high jump of each droplet is established, the interaction between the continuous droplets is just liquid film penetration in the air as shown in Fig. 2(b). Thus, the impingement of each droplet on the superheated substrate could be considered as “single droplet impact” in the high-jump cases since the impact droplet is almost not influenced by the liquid film. For supporting this proposition, the bouncings of droplets with or without film penetration are compared. The result shows that the repellency is not affected by the film penetration [see Fig. 2(c)]. The nonpenetration configuration was achieved when the droplet interval was unstable. Once the intervals between droplets are sufficiently large, the liquid film penetration was avoided. Thus, the following analysis and discussion are focused on the impingement and the repellency of a single droplet.

B. Dependency of repellent height on substrate temperature

The high jump of an impinging droplet is only able to be observed in a specific band of substrate temperature. In

FIG. 2. (a) and (b) The high repellency of the impinging droplets on the heated substrate (see the evolution of droplet No. 2) and the consequent droplet interactions. The illustrative diagram and the captured images regarding the evolution of the droplet-film interaction in one cycle. Due to the periodical nature, the next phase of droplet No. 2 in (v) repeats the scenario of droplet No. 1 in (i). The corresponding movie is available in the Supplemental Material [28] ($f = 28\,000$ Hz, image 150 000 fps). (c) The high jump can be generated without the film penetration.

Fig. 3, we illustrate the bouncing height H and the spreading diameter D in the period from the droplet falling to the fully levitated. Both of the parameters are normalized with droplet diameter d_0 . The bouncing height of each liquid film was measured three times at the left edge, at the center of film, and at the right edge, respectively. The error bar of H reflects the degree of the deformation of the liquid film. The observational uncertainty of the spreading diameter is

conservatively estimated on the basis of the fuzziness of the edge in horizontal direction, which is ± 1 pixel for spherical droplets, ± 8 pixel for $d_0 < D < 3d_0$, and ± 16 pixels for $D > 3d_0$, respectively ($3.97 \mu\text{m}/\text{pixel}$). In the set of baseline tests, the droplet parameters were fixed, whereas the substrate temperatures were varied from 234°C to 246°C . The centroid and lower boundaries of the impinging droplets are marked in Fig. 3(a) with two parallel lines. The height of each droplet decreases linearly before the touchdown ($t < 0$). The bottom of the droplet touches the substrate at the time of $t = 0$, after which the droplet bounces and spreads until the maximum bouncing height H_m is reached. It is shown that a higher substrate temperature results in a lower repellent height, which is not intuitive. However, the spreading diameter is almost independent of the substrate temperature before the point at $t = 25 \mu\text{s}$. The corresponding movie can be seen in the Supplemental Material [29].

In accordance with the droplet spreading on an ambient temperature substrate, the variation of the spreading diameter follows the simplified Wagner's law [30] $D \sim \sqrt{3r_0 U t}$ in which r_0 is the droplet radius. The fitted curve in Fig. 3(b) is $D/d_0 = 1.15 \times 10^3 t^{0.5}$. In addition, for the impinging Leidenfrost droplets, it is proposed that the maximum spreading diameter D_m is a function of the Weber number as $D_m/d_0 = 0.571 \text{We}^{0.39}$ ($\text{We} > 10$) on the basis of the data fitting [24]. Therefore, it could be estimated that $D_m/d_0 = 5.5$ for $\text{We} = 339$. It is noteworthy that the data in Fig. 3 were measured based on the captured images at a frame rate of 150 000 fps (with a time interval of $6.67 \mu\text{s}$). Since the droplet bouncing was developing during a time period around $40 \mu\text{s}$ after the contact, only five or six frames could be recorded for each droplet in such a short period. In order to obtain sufficient data to characterize the behavior of a single droplet, we have conducted a series of measurements of more than ten droplets and then collapsed the data to one cycle by simply shifting the time axis. Each group of data in Fig. 3 was measured from the repeating impingement and jump of the droplets but

FIG. 3. The droplet repellency strongly depends on the substrate temperature, whereas the spreading is almost independent of the wall temperature. (a) A higher substrate temperature results in a lower rebound height. (b) The evolution of the spreading diameter follows the simplified Wagner's law $D \sim \sqrt{t}$. The corresponding movie is available in the Supplemental Material [29].

FIG. 4. (a) The identified three regimes: contact boiling (I), high repellency (II), and thin-film levitation (III). (b) Variation of H_m as a function of T_w in the baseline test.

converged to a single trend. The results indicate an excellent repeatability of the phenomenon.

So far, we understand that the high jump could be generated on the substrate with a temperature in the range between 234 °C and 246 °C. The repellent height is weakened once the substrate temperature is elevated. However, it is still unclear what will happen on the substrate with a higher or lower substrate temperature. The variation of H_m in a wider range of T_w is shown in Fig. 4. It can be seen that the high jump is only able to be established in the range of 229 °C < T_w < 250 °C. With a lower substrate temperature, the contact boiling is established, and the droplet interaction is enhanced. Each droplet impacts on the residual liquid film on the high-temperature substrate. However, in the cases of a higher substrate temperature, the repellent height reaches the minimum. Therefore, we could consider it as the traditional Leidenfrost levitation. To make the analysis below easy to follow, the boiling regime, high-repellency regime, and Leidenfrost regime are named as regimes I, II, and III.

Figure 4(b) illustrates the variation of the maximum repellent height H_m in a wider range of substrate temperatures. Since regime I is the contact boiling, there is no levitation at all ($H_m = 0$). However, the maximum repellent height increases abruptly at the boundary between regimes I and II. For instance, in the baseline experiment with $We = 326$ and $\Delta T_{\text{sub}} = -70$ °C, the transition temperature from regime I to regime II is around $T_w = 229$ °C. A slight increase in the substrate temperature results in a significant change in the hydrodynamic pattern. The high repellency is almost established instantly when the critical T_w is reached. The maximum repellent height is around at $H_m = 0.15$ mm, which is larger than the droplet diameter at $d_0 = 0.123$ mm. After the peak, H_m reduces almost linearly until a minimum repellent height, accordingly regime III is reached. It is noted that the maximum repellent height illustrated in Fig. 4 is the height

FIG. 5. The phase diagrams reveal the boundaries of the different regimes in the plot of T_w as a function of (a) ΔT_{sub} and (b) We . (c) T_w versus H_m as ΔT_{sub} is -54 °C, -70 °C, or -75 °C. (d) T_w versus H_m as We is 188, 326, or 562.

of the centroid of the levitated liquid film but not the vapor film thickness. Therefore, the thickness of the vapor film in regimes II and III should be lower than the H_m value in the figure.

C. Phase diagrams for the droplet jump

We have conducted the parametric studies by systematically varying the droplet subcooling temperature and the Weber number for further understanding the phenomenon. The experiments were carried out under eight different droplet subcooling temperatures ranging from -75 °C to -54 °C and nine different droplet Weber numbers ranging from 105 to 672. Figures 5(a) and 5(b) illustrate the phase diagrams which give the boundaries among the different regimes. The corresponding H_m values versus T_w in the typical cases are shown in Figs. 5(c) and 5(d). The three different regimes and the transitions are observed in all cases. However, the transition points from regime I to regime II are distinct. A higher droplet temperature or a smaller Weber number results in the shift of boundary between regimes I and II to the lower T_w direction. Moreover, a higher peak of H_m is generated as the droplet temperature is increased or the Weber number is reduced. Interestingly, the data measured at the different droplet subcooling temperatures and Weber numbers converge to the same curve in the decreasing phase of H_m after the peak. It is indicated that the parameters of ΔT_{sub} and the Weber number almost play no role in influencing H_m once the high repellency is established. The boundary between regimes II and III is almost independent of the two parameters. The high jump ends, and the repellent height reaches the minimum at the same substrate temperature at the point of $T_w \approx 250$ °C regardless of the droplet parameters. The phase diagrams can provide us the guideline for manipulating the repellent height or the start T_w of regime II.

FIG. 6. (a) The high repellency is only observed on the surface in Zone A rather than Zone B. Once the droplet impacts on the boundary, a partial rebound can be found. Please see the corresponding movie in the Supplemental Material [34]. (b) The measurement of the scanning electron microscope (SEM) and energy-dispersive x-ray spectroscopy (EDS) with the embedded atomic percentage.

D. Effect of surface deposition

Compared with the previous works with similar configurations and parameters [31–33], the levitation here is very remarkable. Even on the same substrate, the high repellency is only to be established in the specific area. As shown in Fig. 6(a), the high repellency vanishes when we shift the droplet train from Zone A to Zone B on the same copper substrate. A partial rebound is generated if the droplet stream is impinged on the boundary between them (see the movie in the Supplemental Material [34]).

As aforementioned in the Experiments section, it was furnished initially in preparation of the target surface to have the bare copper. Then the droplet train was impinged onto the heated substrate until the copper was fully oxidized. However, the oxidization in the droplet contact area (Zone A) and the rest area (Zone B) is nonidentical, although the surface roughnesses in both zones are in the same magnitude (around $0.31 \mu\text{m}$). The SEM images reveal that a darker deposition is generated in Zone A in Fig. 6(b). The results from the EDS suggest that atomic percentages of O and Cu are 48.1% and 51.9% on the surface in Zone B, indicating that the surface is mainly covered by copper oxide. However, a very different combination of elements is measured in Zone A where the impinging droplets boil; the atomic percentages of the three major elements of O, Cu, and Fe are 58.5%, 26.3%, and 11.7%, respectively. The left 3.5% atoms include P, Mn, Ni, and W. The deposition can be regenerated, and the high repellency can be reproduced once the substrate is refurbished and reoxidized with the droplet train impingement. The abundance of the Fe element, which might originally be carried by the de-ionized water, is crucial to the high repellency. It changes the properties of the target surface including wettability, thermal conductivity, etc. Among those factors, the large difference of the thermal conductivity between iron oxides and copper

oxide could be critical. Different from copper oxide with a thermal conductivity of $69\text{--}76 \text{ W m}^{-1} \text{ K}^{-1}$, the thermal conductivity of iron oxides at temperature 200°C is only in the range of $4\text{--}9 \text{ W m}^{-1} \text{ K}^{-1}$ [35]. A higher thermal resistance in Zone A can lead to a lower instantaneous heat transfer but a longer contact time. It bears analogy with the scenario that a higher substrate temperature with a larger potential for heat transfer induces lower repellency and less transferred energy.

E. Heat transfer analysis

As shown in Figs. 4 and 6, once the droplet parameters are fixed, the pancake droplet repellency is more remarkable on the substrate with the lower wall temperature of T_w or the lower thermal conductivity λ of the thin layer of deposition. Figure 5 illustrates that the droplet repellency is more prominent for the droplets with a higher droplet temperature T_d or a lower We as T_w is fixed ($T_w = 225^\circ\text{C}$, for example). The following heat transfer analysis demonstrates that the four factors could result in a reduction of the instantaneous heat flux.

Consider the heat transfer process from the copper substrate to the spreading droplet through the thin layer of deposition. According to Fourier's law of heat conduction, $\dot{q} = \lambda(T_{w,c} - T_{w,i})/\delta$ in which $\dot{q}$ is the heat flux through the thin layer, δ and λ are the thickness and the thermal conductivity of the thin layer, $T_{w,i}$ is the surface temperature at the liquid-solid interface, and $T_{w,c}$ is the copper temperature at the bottom of the thin layer. During the droplet impact, the droplet-to-substrate heat transfer could be calculated as $\dot{q} = h(T_{w,i} - T_d)$, where h is the convective heat transfer coefficient. Therefore, the heat flux can be expressed as

$$\dot{q} = \frac{T_{w,c} - T_d}{\delta/\lambda + 1/h}. \quad (1)$$

It can be seen that a smaller $\dot{q}$ could be achieved with a lower value of $T_{w,c}$, λ , or h , or a higher value of T_d . In the current paper, the variation of the Weber number is achieved by adjusting the droplet velocity. Therefore, the droplet with a higher Weber number, or a higher Reynolds number, is corresponding to a higher convective heat transfer coefficient. Thus, it can be generalized from the parametrical studies that the factors resulting in a lower instantaneous heat flux can generate a higher droplet jump.

F. Variation of contact time

It is understandable that the high jump is propelled by the vigorously generated vapor during the contact. The initial pressure of the vapor before the jump must be higher than the ambient pressure to propel the liquid film, then it is reducing in the expansion process until the pressure difference vanishes. If we assume that the vertical expansion and the horizontal expansion are in the same magnitude as the maximum jump and spreading are reached, the volume of the vapor could be estimated as $V_v = H_m \pi (D_m + 2H_m)^2/4$ where the repellent height is H_m and the spreading diameter is D_m . Thus, the mass of vapor generated from the boiling could be estimated as $m_v = \rho_v V_v$, where ρ_v is the density of the vapor under the saturation temperature and ambient pressure. On the other hand, the mass of the generated vapor is related to

FIG. 7. The proposed explanation for the transition of the repellent height. By assuming that the instantaneous heat transfer $\dot{q}A$ is proportional to the wall superheat, a longer t_c is anticipated in the case of a lower T_w (with a smaller $\dot{q}A$) to transfer sufficient energy $Q_d = \int_0^{t_c} \dot{q}A dt$ for the repellency.

the energy transfer, written as $m_v = Q_d/[h_{lv} + (T_s - T_d)c_p]$, where Q_d , h_{lv} , and c_p are the boiling heat transfer of a single droplet impact, the latent heat of phase change, and the heat capacity of the droplet. Thus, a simplified deduction gives Eq. (2),

$$Q_d = \frac{\pi}{4} \rho_v [h_{lv} + (T_s - T_d)c_p] (D_m + 2H_m)^2 H_m. \quad (2)$$

As shown in Fig. 3 for the droplet repellency under different substrate temperatures, D_m is roughly independent of T_w , whereas H_m is a function of T_w . Therefore, it can be inferred that a higher jump is corresponding to a stronger energy transfer. In the baseline test, the corresponding parameters are $D_m = 0.70$ and $H_m = 0.15$ mm according to Fig. 4. The vapor density, latent heat, and heat capacity are at $\rho_v = 0.60$ kg/m³, $h_{lv} = 2256$ kJ/kg, and $c_p = 4.2$ kJ kg⁻¹ K⁻¹, respectively. The transferred energy by a single droplet impact is estimated as $Q_d = 1.80 \times 10^{-4}$ J. Therefore, the mean cooling power of the droplet train impingement with a frequency of $f = 28\,000$ Hz is $Q = fQ_d = 5.03$ W. In Ref. [27], the mean cooling power of a droplet train impingement ($We = 371$, $f = 40\,000$) was measured to be 10.7 and 6.4 W before and after the Leidenfrost point. The current estimation shows good agreement in the magnitude of droplet impingement heat transfer with the previous measurements.

A lower T_w leads to a higher H_m in regime II as illustrated in Fig. 4; it is corresponding to a larger Q_d and a better heat transfer. The observed result seems counterintuitive since a higher T_w should normally power a stronger heat transfer. For a further understanding, a qualitative schematic is illustrated in Fig. 7. The liquid-to-substrate energy transfer can be expressed as $Q_d = \int_0^{t_c} \dot{q}A dt$, where t_c is the end time of the contact, and A is the instantaneous contact area. We have the assumptions for the analysis: (a) The instantaneous heat flux $\dot{q}$ only depends on the wall superheat and does not change during the contact of the droplets to the substrate surface, thus, $Q_d = \dot{q} \int_0^{t_c} A dt$. (b) Across the contact period, the significant vapor generation and the resulting liquid film detachment is

only happening suddenly at the point $t = t_c$ before which the nominal contact area could be considered as the spreading area with $A = \pi D^2/4$. The spreading diameter varies as $D \sim \sqrt{t}$ according to Wagner's law [30], thus it could be deduced that $A = c_1 t$ before the sudden detachment of the liquid film. Therefore, the energy transfer can be estimated as

$$Q_d = \int_0^{t_c} \dot{q}A dt = c_1 \dot{q} \int_0^{t_c} t dt = \frac{c_1}{2} \dot{q} t_c^2. \quad (3)$$

From Eqs. (2) and (3), the contact time can be expressed as

$$t_c = \sqrt{\frac{2Q_d}{c_1 \dot{q}}} = c_2 \sqrt{\frac{(D_m + 2H_m)^2 H_m}{\dot{q}}}, \quad (4)$$

where $c_2 = \sqrt{\pi \rho_v [h_{lv} + (T_s - T_d)c_p]/2c_1}$ is a constant if the droplet parameters are fixed. Therefore, it can be deduced from Eq. (4) that the contact time t_c must be smaller on a substrate with a higher T_w . The reason is that a higher T_w results in a smaller H_m as shown in Fig. 4, but it is corresponding to a higher $\dot{q}$ according to Eq. (1).

Comparing the contact time in the high-repellent regime $t_{c,H}$ with that in the Leidenfrost-levitation regime $t_{c,L}$, we can predict that $t_{c,L} < t_{c,H}$. In regime II, a lower initial heat flux renders a longer contact time, which, in turn, gives a stronger heat transfer and the droplet vaporization. When it steps into regime III, the instantaneous heat transfer is so significant that the sudden vaporization in a shorter period could generate sufficient vapor to prevent the further contact. Thus, the contact time is shorter, and the total transferred energy in the short period is only able to float the spreading droplet on a thin vapor layer.

The presumption is supported by the measurements of the contact time with a frame rate of 680 000 fps. The evolutions of the contacts on the substrate with two different temperatures are compared in Fig. 8(a). Since the resolution of the image is only 128×32 pixel at such a high frame rate, only a small region close to the substrate is recorded by the camera as illustrated in Fig. 8(b). Point A represents the state that the vapor pockets are observed, whereas point B is the state that the fully detachment of the liquid droplet film is distinguished. It can be observed that the impinged droplet departs earlier from the substrate with a higher substrate temperature. The contact time reduces from $t_c = 21.3 \pm 0.7$ to 14.0 ± 0.7 μ s as the substrate temperature increases from 234 °C to 246 °C, which translates to a reduction of time ratio t_c/τ from 0.38 to 0.25. Here, the contact time is normalized with the inertial-capillary timescale $\tau = \sqrt{\rho r_0^3/\sigma}$ in which ρ and σ are the droplet density and surface tension. Moreover, the contact time reduces with an increase in substrate temperature as shown in Fig. 8(c).

It has been reported that the time ratio was $t_c/\tau \approx 2.6$ for the impinged droplets with a wide range of the Weber number [36], but it depended on the surface structure [26,37]. The contact time could greatly be shortened on the pillar-structured surface with ambient temperature [38] because the droplet surface between pillars could conserve and release the kinetic energy of the droplet. The droplet pancake could bounce from the substrate during the spreading, and the contact time period could be as short as $t_c/\tau \approx 0.25$ in the case of the low Weber numbers ($We \approx 10$), however, it was prolonged

FIG. 8. From the captured images at 680 000 fps, it is proved that the contact time t_c is shorter on a substrate with a higher T_w . Point A represents the time that the vapor pockets are observed, whereas Point B is the end time of the contact.

at the higher Weber number. In the current paper, the similar fast detachment of the impinged droplet is observed, but the mechanism is quite different. The high jump is induced by the sudden vaporization during the contact not by the pillared substrate induced “spring effect.”

We can summarize that a higher instantaneous heat flux results in a smaller total transferred energy and, therefore,

a lower repellant height. It is induced by the reduction of the contact time. It brings us a new concept that the droplet impingement heat transfer can be strengthened by increasing the thermal resistance of the substrate in the transient heat transfer process under the Leidenfrost state.

IV. CONCLUSION

A significant droplet jump was observed after the droplets impinging on the copper substrate in the transition from the contact boiling to the Leidenfrost state. In the high repellent regime, the counterintuitive observations were made that a higher amount of energy could be transferred with a lower instantaneous heat flux, which was induced by a lower substrate temperature, a higher droplet temperature, a lower droplet velocity, or a lower thermal conductivity of the deposited layer on the substrate. A lower instantaneous heat transfer secured a longer period of contact, which resulted in a larger accumulated transferred energy. The phase diagrams revealed that the high repellency could be established on a substrate with a lower temperature if the droplet temperature was increased or the Weber number was reduced. However, those two parameters played no significant role in influencing the transition of the repellent height after establishment of the jump. The above findings allow us to manipulate the droplet impingement heat transfer and the associated high repellency for the potential applications.

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