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Droplet impact on superheated micro-structured surfaces

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When a droplet impacts upon a surface heated above the liquid's boiling point, the droplet either comes into contact with the surface and boils immediately (contact boiling), or is supported by a developing vapor layer and bounces back (film boiling, or Leidenfrost state). We study the transition between these characteristic behaviors and how it is affected by parameters such as impact velocity, surface temperature, and controlled roughness (*i.e.*, micro-structures fabricated on silicon surfaces). In the film boiling regime, we show that the residence time of droplets impacting upon the surface strongly depends on the drop size. We also show that the maximum spreading factor Γ of droplets in this regime displays a universal scaling behavior $\Gamma \sim We^{3/10}$, which can be explained by taking into account the drag force of the vapor flow under the drop. This argument also leads to predictions for the scaling of film thickness and velocity of the vapor shooting out of the gap between the drop and the surface. In the contact boiling regime, we show that the structured surfaces induce the formation of vertical liquid jets during the spreading stage of impacting droplets.

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Introduction

Central to many technological processes such as spray cooling and fuel injection in combustion engines is the phenomenon of individual droplets impacting on superheated surfaces.^{1,2} The goal of these processes is to enhance the heat transfer rate between the liquid and the solid surface.² Effective heat transfer requires that the liquid comes into contact with the solid surface upon impact (the contact boiling regime). However, contact is only possible as long as the hot surface temperature is lower than a critical value, the Leidenfrost temperature.^{3,4} Beyond this temperature, the liquid remains separated from the hot solid surface by a developing vapor layer. In this so-called film boiling regime, the vapor layer, due to its poor thermal conductivity, drastically reduces the heat transfer between the liquid and the solid and potentially risks surface overheating and equipment burnout. As a result, studies of heat transfer enhancement cannot be separated from those of the Leidenfrost temperature, especially in the context of droplet impact on superheated surfaces.

An alternative way of improving the heat transfer performance is by enhancing the surface area, which is typically achieved by roughening the surface, or by fabricating microstructures on top of it.⁵⁻⁸ It was shown that surfaces with microstructures of different sizes and shapes enhanced the heat flux during spray cooling,⁹ although it is not clear whether the geometrical shape or the structure size has the dominant effect on the heat transfer.^{5,7,9} This lack of understanding,⁷ together with the lack of systematic studies of the Leidenfrost temperature for these surfaces, has made it difficult to utilize surface enhancement efficiently.

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Besides surface temperature, surface roughness, drop size, and velocity are also crucial contributing factors to the heat transfer efficiency^{1,7} as they directly affect quantities such as the dynamic Leidenfrost temperature,¹⁰ the residence time,^{11,12} and the maximum spreading.¹⁰ Although studies on these quantities have been reported in some detail, they have not addressed the effect of roughness (in particular controlled roughness) on the outcomes of droplet impact on heated surfaces.

The goal of the present study is to investigate the effects of surface roughness, temperature, and impact conditions on the thermo-hydrodynamics of droplet impact on heated surfaces. With an emphasis on the effect of roughness, we use microstructured surfaces with different sizes of structures. For each type of surface, we determine the dynamic Leidenfrost temperature. In the film boiling regime, we systematically vary the control parameters and determine their effects on the evolution of the contact area between the drop and the surface,

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the residence time, and the maximum spreading diameter of droplets. We also develop a scaling argument to account for the spreading factor in this regime and make predictions for both the vapor layer thickness and the vapor velocity under the drop. This scaling argument adds to the few known theoretical attempts to quantify the hydrodynamics and shape of the vapor layer under Leidenfrost droplets.^{4,13-16} In the contact boiling regime, we provide a qualitative description of the pronounced upward-directed jets formed during spreading of droplets as a result of the vigorous boiling processes.

Experimental details

Fabrication of micro-structured surfaces

The microstructure arrays are fabricated *via* deep reactive ion etching (DRIE) on double side polished silicon wafers (p-type, boron doped 5–10 ohm cm resistivity, 100 mm diameter, 525 μ m thickness, {100} crystal orientation; Okmetic Finland). Olin 907-17 photoresist is spun on the wafer at 4000 rpm for 30 s to obtain a layer thickness of ≈1.7 μ m. After a soft-bake step at 95 °C for 90 s, the photoresist layer is exposed for 3.5 s to mid UV light in an EVG 620 mask aligner through a photomask with the microstructure geometry, followed by development in OPD-

Table 1 Size of the micro-structures: height (H), interspacing (I), width (W)			
Surface	$H(\mu m)$	I (µm)	W (µm)
R_{20}^2	1.8	19.6	9.1
R_{20}^4	3.7	19.5	8.8
R_{20}^{8}	8.1	19.4	8.9
R_4^2	2.0	4.0	8.8
R_4^4	3.9	3.8	8.8
R_4^8	7.9	4.0	8.9

4262 and hard-baking in air at 120 °C for 30 min. The actual pattern is eventually formed by reactive ion etching in a DRIE system (Adixen AMS100-SE ICP), with a RF generator at 13.56 MHz and a 1.5 kW ICP plasma source. The total chamber pressure is kept at 75 m Torr. The temperature of the electrode with the silicon substrate is kept at 10 °C, using liquid nitrogen as a coolant. The etching time is varied from 53 s to 7 min to obtain pillar heights of approximately 2 μ m, 4 μ m, and 8 μ m (see Table 1). SF₆ and C₆F₈ flows are kept constant during the etching process at 250 sccm (standard cubic centimeter per minute) and 200 sccm respectively. After the silicon etching, the remaining photoresist is removed by O2 plasma etching (Etser Tepla-300 system), followed by a nitric acid and a subsequent 1% HF treatment, to remove the SiO₂ grown during O₂ plasma etching. The resulting micro-structures are shown in Fig. 1. Further details on the sample preparation were reported previously.17,18

Experimental method

In Fig. 2, we show the experimental setup used to study the impact of droplets on superheated structured surfaces. The liquid used in all of our experiments is Milli-Q water having density $\rho_1 = 998$ kg m⁻³, surface tension $\sigma = 72 \times 10^{-3}$ N m⁻¹, and viscosity $\nu = 10^{-6}$ m² s⁻¹ (these properties are measured at room temperature). We generate single droplets of diameter D_0 by pushing water out of a fine needle at a small rate (≈ 0.05 ml min⁻¹). The droplet detaches from the needle due to its own weight and falls on a heated solid surface with impact velocity V_0 . In our experiments $D_0 \approx 2.2$ mm and V_0 is varied between 0.4 m s⁻¹ and 4 m s⁻¹ by adjusting the drop release height.

We use the above-described silicon micro-structured surfaces as target substrates. The structures are arranged in a square lattice characterized through a micro-pillar interspacing



Fig. 1 Scanning electron microscope (SEM) images of the structured silicon surfaces used in the present study. (a) Structure surfaces having a pillar interspacing of 20 μ m and the pillar height being varied from 2 μ m to 8 μ m. (b) Structure surfaces having a pillar interspacing of 4 μ m and the pillar height being varied from 2 μ m to 8 μ m. (b) Structure surfaces having a pillar interspacing of 4 μ m and the pillar height being varied from 2 μ m to 8 μ m. The geometrical configuration of each structured surface is indicated by R_{I}^{H} , where H is the pillar height and I is the pillar interspacing. The pillar width W of all surfaces is roughly the same. The actual dimensions of the different structures are listed in Table 1.



Fig. 2 Schematics (not drawn to scale) of the experimental setup used to study the droplet impact on heated structured surfaces. Water droplets of diameter D_0 impact on a heated structured surface with velocity V_0 ; its spreading diameter during impact is denoted as *D*. The structured surfaces are heated by a plate P with cartridge heaters embedded inside. The impact dynamics and the boiling of the liquid are recorded from the side by a high-speed camera C_1 (Photron SA1.1). The heated plate P has a hole 2 cm in diameter allowing bottom-view recording when a transparent substrate (e.g., a sapphire plate) is used. In this case, we use another high-speed camera C_2 (Photron SA2) to record the impact from the bottom *via* a mirror M.

I, pillar width *W*, and height *H*. In order to examine the effect of surface roughness on the impact outcomes, we use two sets of structured surfaces: one has *I* fixed at 20 μ m and the other one at 4 μ m. The pillar height is varied between 2 μ m and 8 μ m in each set. The pillar width is kept fixed at $W \approx 9 \mu$ m for all

surfaces. The actual dimensions of the structures are listed in Table 1.

For purposes of comparison, we also carried out some experiments using a smooth sapphire plate, which, being transparent, enables us to record bottom-views as well as sideviews.

We heat the surface by placing it on a brass plate that can be heated up to 600 °C by six cartridge heaters embedded inside (Omega, Inc.); the temperature of the brass plate can be measured accurately to 1 K by a type K thermocouple. We verified that the temperature difference between the heated plate (measured by the thermocouple) and the structured surface (measured by a surface sensor N-141-K made by Tempcontrol I.E.P. B.V.) is less than 5 K, and therefore can be neglected for the present purposes.

We use two high-speed cameras (Photron Fastcam SA1.1 & SA2) to record the spreading and boiling processes of impacting droplets from the side and, for the sapphire plate, from the bottom. From the side-view recording of each impact experiment, we measure D_0 and V_0 , from which we calculate the Weber number We = $\rho_1 D_0 V_0^2 / \sigma$. The Weber number is a measure of the drop's kinetic energy compared to its surface energy and is used as one of the control parameters. In our experiments We is varied between 1 and 1000.

The dynamic Leidenfrost temperature

Typically, the behaviors of droplets during impact on superheated surfaces can be specified as contact boiling or film boiling.^{1,10,19} The differences between these two regimes are conveniently illustrated by using simultaneous side- and bottom-view snapshots of droplet impact on a smooth



Fig. 3 Representative series of snapshots during impact taken from the side and the bottom-views showing spreading and boiling processes of droplet impact on a smooth sapphire surface in (a) contact boiling regime, and (b) film boiling regime. In both cases, the impacting drop has diameter 2 mm, velocity 0.26 m s⁻¹, and Weber number 1.9.

superheated plate, shown in Fig. 3. The bottom-view images in this figure are from interferometric recordings.¹⁰ In the contact boiling regime (Fig. 3a), the spreading is accompanied by boiling at the wetted area. Note that the liquid does not wet the solid surface immediately but first deforms to create a cavity due to the pressure build-up of vapor underneath (as revealed by the interferometric snapshot at 0.5 ms). The liquid then makes direct contact with the solid surface and starts boiling. Depending on the temperature of the solid surface, the liquid may display boiling characteristics from mild bubble formation to vigorous bubble expansion and droplet ejection. Increasing the surface temperature induces more and more vapor to be generated between the liquid and the solid surfaces, which hinders the heat transfer rate. If the surface temperature is further increased beyond a critical point, *i.e.*, the Leidenfrost temperature, a vapor layer develops and prevents the liquid from making any contact with the solid surface, and the impact is said to be in the film boiling regime. The superheated surfaces that cause impacting droplets in the film boiling regime are herein referred to as Leidenfrost surfaces. In Fig. 3b, we show a series of snapshots illustrating the behavior of droplets in this regime. Note that it is evident from the bottomview that the drop is separated from the solid surface during the entire impact time. Since vapor conducts heat poorly, an impacting drop in the film boiling regime interacts with the heated surface through a thermal-insulating layer and therefore does not exhibit the characteristic boiling behavior such as that in the contact boiling regime. The drop spreads and retracts as if it had fallen on an unheated superhydrophobic surface.

The transition temperature between the contact boiling and the film boiling regimes is called the dynamic Leidenfrost temperature^{1,10} to distinguish it from its quasi-static counterpart, *i.e.*, the surface temperature at which the evaporation time of a deposited droplet is the longest.⁴ For smooth surfaces, it was shown that the dynamic Leidenfrost temperature $T_{\rm L}$ increases with the Weber number¹⁰ (see Fig. 4a). Here, we follow the work by Tran *et al.*¹⁰ and determine the dynamic Leidenfrost temperature for each structured surface by repeating the drop impact experiment numerous times while varying the Weber number ($1 \le We \le 1000$) and the surface temperature ($200 \degree C \le T \le 550 \degree C$). In Fig. 4b, we show a typical phase diagram of boiling behaviors on a structured surface with interspacing $I = 20 \ \mu m$ and pillar height $H = 2 \ \mu m$. In the phase diagram, the data points representing impacts in the contact boiling and film boiling regimes are marked by solid red diamonds and solid blue circles, respectively. Similar to the phase diagram obtained on smooth surfaces (Fig. 4a), there is a clear transition between the two regimes that marks the dynamic Leidenfrost temperature of this structured surface. The vertical bars indicate a transitional region that has characteristic behaviors of both boiling regimes.

Let us discuss the dependence of the dynamic Leidenfrost temperature $T_{\rm L}$ on the Weber number We. In Fig. 5a and b, we show $T_{\rm L}$ for two sets of structured surfaces respectively. In the first set, the pillar spacing is fixed at 20 µm while the height is varied from 2 µm to 8 µm. The second set has the interspacing fixed at 4 µm and the same height variation. The dynamic Leidenfrost temperature for impact on smooth surfaces is also shown as a reference. It is evident that $T_{\rm L}$ increases with the Weber number for all structures. This result is consistent with the few known experimental studies of dynamic Leidenfrost temperatures10,20 and can be understood by comparing the vapor pressure (which increases with surface temperature) and the inertial pressure of the drop (which is proportional to We). To maintain a droplet impact in the film boiling regime, an increased We requires a higher vapor pressure (hence higher surface temperature), in accord with our experimental results.

On the other hand, increasing the pillar height effectively lowers $T_{\rm L}$ if the pillar interspacing *I* and width *W* are kept fixed. For instance, compared to the smooth surface, the surface R_{20}^2 $(I = 20 \,\mu\text{m}, H = 2 \,\mu\text{m})$ reduces $T_{\rm L}$ by roughly 50 K for $6 \leq \text{We} \leq$ 270, while the surface R_{20}^8 ($I = 20 \,\mu\text{m}, H = 8 \,\mu\text{m}$) causes a larger reduction in $T_{\rm L}$, which is about 100 K for $10 \leq \text{We} \leq 890$.



Fig. 4 (a) Phase diagram for water droplet impact on a heated smooth surface showing that the contact boiling regime (red solid diamonds) is separated from the film boiling regime (blue solid circles) by a transition that marks the dynamic Leidenfrost temperature (violet dashed line). (b) Phase diagram for the water droplet impacting on a structured surface (R_{20}^2) having pillar interspacing $I = 20 \ \mu\text{m}$, height $H = 2 \ \mu\text{m}$, and width $W = 9 \ \mu\text{m}$. The solid black line represents the dynamic Leidenfrost temperature for this surface.



Fig. 5 (a) Dynamic Leidenfrost temperature for structured surfaces with pillar interspacing $I = 20 \ \mu m$: R_{20}^2 (solid upward triangles), R_{20}^4 (solid squares), R_{20}^8 (solid diamonds). The dynamic Leidenfrost temperature for smooth surfaces (solid line) is shown as a reference. (b) Dynamic Leidenfrost temperature for structured surfaces with pillar interspacing $I = 4 \ \mu m$: R_4^2 (solid downward triangles), R_4^4 (solid squares), and R_4^8 (solid diamonds). (c) The quantity $(T_L - T_b)\alpha_e$ for structured surfaces with pillar interspacing $I = 20 \ \mu m$. (d) The quantity $(T_L - T_b)\alpha_e$ for structured surfaces with pillar interspacing $I = 4 \ \mu m$.

As a possible explanation for the dependence of $T_{\rm L}$ on the pillar height H, we first note that varying H modifies the solid's total surface area: for the geometrical configuration of our structured surfaces (see Fig. 1), the total area per unit projected area (herein referred to as the enhancement coefficient) is $\alpha_e =$ $1 + \pi WH/(W + I)^2$. If convective heat transfer is neglected, then the rate of heat transfer to the liquid is proportional to the surface enhancement coefficient α_e and the superheat $\Delta T = T - T$ $T_{\rm b}$ between the solid and the liquid surface, which is assumed at the saturation temperature $T_{\rm b}$. Now consider two structured surfaces having different pillar heights (the corresponding enhancement coefficients are $\alpha_{e,1}$ and $\alpha_{e,2}$); the temperature of each surface (for the same Weber number) is set at its dynamic Leidenfrost temperature, *i.e.*, $T_{L,1}$ and $T_{L,2}$. Given the same impact conditions (*i.e.*, the same Weber number), we may further assume that the heat required to generate enough vapor to sustain an impacting droplet is insensitive to the pillar height. As a result, we can write $(T_{L,1} - T_b)\alpha_{e,1} = (T_{L,2} - T_b)\alpha_{e,2}$. In other words, for the same Weber number, the quantity

 $(T_{\rm L} - T_{\rm b})\alpha_{\rm e}$ is the same for surfaces having different pillar heights. To test our arguments, in Fig. 5c, we plot $(T_{\rm L} - T_{\rm b})\alpha_{\rm e}$ *versus* We for surfaces having the same interspacing $I = 20 \ \mu m$, but different heights (from 2 μ m to 8 μ m). All of the individual datasets collapse onto a master curve.

For surfaces having pillar interspacing $I = 4 \ \mu$ m, reductions in $T_{\rm L}$ are also observed for surfaces with pillar heights from 2 μ m to 8 μ m, although with larger data scattering (Fig. 5b). If we compare the quantity $(T_{\rm L} - T_{\rm b})\alpha_{\rm e}$, there is an agreement between surfaces with pillar height $H = 2 \ \mu$ m and $H = 4 \ \mu$ m (Fig. 5d). However, the data for pillar height $H = 8 \ \mu$ m (R_4^8) show a considerable deviation from the cloud of data points obtained from surfaces with lower pillar heights (*i.e.*, $H = 2 \ \mu$ m and $H = 4 \ \mu$ m). We attribute this discrepancy to the overestimation of the area through which heat is transferred, that is, in the case that His larger than I (as for surface R_4^8), the liquid may not fully penetrate the gap between pillars. Thus, the solid's total surface area is larger than the area through which the heat is transferred to the liquid. In order to determine the necessary condition for the liquid to penetrate the space between pillars, the inertial pressure of the liquid (which scales with $\rho_1 V_0^2$) has to overcome the opposing capillary pressure (which scales with σ/I).²¹ Then, by invoking the Weber number definition, this condition can be written as: We $\equiv \rho_1 V_0^2 D_0 / \sigma > D_0 / I$. If we take into consideration the typical drop diameter in our experiments $D_0 \approx 2.2$ mm and I = 4 µm for the surface R_4^8 , then the minimum Weber number for the liquid to fully wet the solid surface is We ≈ 550 , which is beyond the explored range of the Weber number for this surface. As a result, the overestimation of the quantity $(T_L - T_b)\alpha_e$ of the surface R_4^8 compared to that of surfaces having smaller pillar heights does not contradict our argument presented above.

We note that there is a discrepancy between the quantity $(T_{\rm L})$ $(T_{\rm h})\alpha_{\rm e}$ for smooth surfaces and that for structured surfaces, as shown in Fig. 5c and d. This discrepancy signifies that the reduction of $T_{\rm L}$ is not only resulted from the enhancement of the surface area, but also due to another mechanism that is not captured by our simple argument. This is most effectively demonstrated by comparing $T_{\rm L}$ for smooth surfaces and that for the surface R_{20}^2 : while the surface enhancement coefficient for R_{20}^2 is only 1.06 (*i.e.*, an increase of 6% in surface area compared to that of smooth surfaces), a significant reduction in $T_{\rm L}$ (≈ 50 K) occurs. This observation suggests that a different physical process may be playing a role. One possibility is that the liquid may not penetrate the gap between pillars. In this case, the liquid would be separated from the top of the pillars by a very thin vapor layer through which heat conduction would be very large, while heat exchange over the rest of the surface would be relatively insignificant. The outward flow of the vapor generated under the drop is inhibited by the pillars, so that the vapor pressure sufficient to support the drop builds up at a lower surface temperature.

Even though the dominant physical mechanism is still unclear, the experimental evidence permits us to conclude that the dynamic Leidenfrost temperature on structured surfaces is reduced with increasing pillar height for a given pillar interspacing and width. While results obtained on surfaces with uncontrolled roughness (*e.g.*, particle-blasted surfaces, rough sanded surfaces, *etc.*) have not always shown consistent dependencies on the characteristics of surface features,²⁰ our data show that structured surfaces offer a higher degree of control over the behavior of impacting droplets. This result suggests that $T_{\rm L}$ can be controlled accurately by manipulating the structure's geometry.

Film boiling regime: residence time

When the impact velocity is not too high, a drop impacting upon a superheated surface above the Leidenfrost temperature is observed to spread and then to bounce off the surface without splashing. For a certain time during this process, the distance *h* between the bottom surface of the drop and the heated surface is below the optical resolution of our system. As an example, in Fig. 3b, this condition is fulfilled in all snapshots starting from the first shown snapshot to the last one. In analogy with the literature on drop impact on unheated superhydrophobic surfaces, we refer to this time as the residence time τ_r . To estimate τ_r , it was observed,²² and as expected, that the spreading of droplets is generally opposed by both surface tension and viscosity. In the limit of low viscosity, the capillary effect becomes dominant. Thus τ_r can be approximated as the period of a freely oscillating drop, as calculated by Rayleigh:²³

$$\tau_0 = (\pi/4) \sqrt{\rho_1 D_0^{\ 3} / \sigma}.$$
 (1)

This estimate can directly be obtained (although without the pre-factor $\pi/4$) by balancing inertia with capillarity. Eqn (1) was experimentally verified for impact on unheated super-hydrophobic surfaces.²²

Due to the apparent similarity between impact on Leidenfrost surfaces and impact on unheated superhydrophobic surfaces, it was suggested that the residence time of impact on Leidenfrost surfaces may also be approximated by Rayleigh's expression for the period of a freely oscillating drop.²³ Indeed, it



Fig. 6 (a) Residence time measured for impact in the film boiling regime on different structured surfaces. (b) Residence time normalized by the period τ_0 of an oscillating drop as described in the text. The data show that τ_r/τ_0 is independent of the impact velocity. Inset: residence time as a function of the drop diameter D_0 in the log–log plot. The solid line represents the expression for the period of freely oscillating droplets by Rayleigh ($\tau_0 = (\pi/4)\sqrt{p_lD_0^3/\sigma}$).

was shown in several studies^{11,12,24,25} that the measured residence time can be approximately described by the expression $\tau_r = C \sqrt{\rho_l D_0^3 / \sigma}$, where *C* is a constant. These studies were, however, limited to the case of superheated smooth surfaces or surfaces having uncontrolled roughness. In Fig. 6a, we present a plot of the residence time measured for impact on smooth and different structured surfaces in the film boiling regime under various impact conditions. The drop size was varied from 1.7 mm to 2.6 mm and the impact velocity from 0.5 m s⁻¹ to 2 m s⁻¹. The impact velocity was limited to 2 m s⁻¹ to prevent disintegration of small droplets during spreading (in which case Rayleigh's approximation of the residence time is not



Fig. 7 (a) Diameter *D* of the deforming drop normalized by the initial drop diameter D_0 versus time *t* measured for droplets impacting upon different surfaces with the diameter $D_0 = 2.4$ mm, velocity $V_0 = 1.0$ m s⁻¹, and Weber number We = 33. The structured surfaces (R_{20}^2 (solid upward triangles), R_{20}^4 (solid squares), R_{20}^8 (solid downward triangles)) have the same temperature T = 400 °C to bring droplet impact to the film boiling regime. The data for impact on an unheated superhydrophobic surface (solid circles) are collected under the same impact conditions.

applicable). The variations in drop size and impact velocity cause τ_r to vary from 7 ms to 12 ms. However, when normalized by τ_0 , the data of residence time for impact on all different surfaces in the film boiling regime collapse on a horizontal line (Fig. 6b), implying that in this low velocity regime the impact velocity is an insignificant contributing factor to variations of the residence time. Further, the measured residence time on Leidenfrost surfaces is consistent with τ_0 for different drop sizes (as shown in the inset of Fig. 6). Thus, we conclude that the residence time of droplet impact on surfaces in the film boiling regime can be approximated by the period of a freely oscillating drop and is insensitive to the surface temperature, the impact velocity, and the structure's geometry.

Film boiling regime: spreading dynamics

In this section, we focus on the deformation of droplets impacting on superheated surfaces in the film boiling regime without splashing and how it is affected by the structure's geometry and surface temperature. Upon impact, these drops spread and then retract. These deformation processes are best quantified using the diameter D of the deforming drop. Note again that the drop does not touch the solid surface, as shown in the interferometric observations in Fig. 3b. In Fig. 7, we show a plot of D/D_0 as a function of time t for different structured surfaces. The surface temperature was set at T = 400 °C and the Weber number at We = 33, for which impacting droplets on all surfaces were in the film boiling regime. We also show the data measured for impacting water droplets (with the same impact conditions) on an unheated superhydrophobic surface as a comparison. For impact on superheated surfaces, D/D_0 is not affected by changes in structured surfaces. However, compared to the spreading on unheated surfaces, it is significantly larger around the peak although the expansion time, defined as the time for the contact diameter to reach its maximum value, is



Fig. 8 Spreading factor D_m/D_0 versus Weber number for different structured surfaces and different temperatures in the film boiling regime. (a) Spreading factor measured for surfaces with pillar interspacing $I = 20 \ \mu\text{m}$. For each surface, we group data for different temperatures into two sets: ΔT_1 (240 °C $\leq T < 315$ °C), and ΔT_2 (315 °C $\leq T < 390$ °C). (b) Spreading factor measured for surfaces with pillar interspacing $I = 4 \ \mu\text{m}$. Data for each surface are grouped into four sets: ΔT_1 (240 °C $\leq T < 315 \ ^{\circ}$ C), ΔT_2 (315 °C $\leq T < 390 \ ^{\circ}$ C). (b) Spreading factor measured for surfaces with pillar interspacing $I = 4 \ \mu\text{m}$. Data for each surface are grouped into four sets: ΔT_1 (240 °C $\leq T < 315 \ ^{\circ}$ C), ΔT_2 (315 °C $\leq T < 390 \ ^{\circ}$ C), ΔT_3 (390 °C $\leq T < 465 \ ^{\circ}$ C) and ΔT_4 (465 °C $\leq T < 540 \ ^{\circ}$ C). We show the data in two figures for better clarification. All the data however collapse on a master curve as shown in Fig. 9.



Fig. 9 Spreading factor D_m/D_0 for droplet impact on different structured surfaces in the film boiling regime. We also show the spreading factor for impact on smooth Leidenfrost surfaces as a comparison.¹⁰ The dashed line represents the scaling $D_m/D_0 \sim We^{1/4}$, which holds for unheated surfaces. The solid line represents the scaling $D_m/D_0 \sim We^{3/10}$ resulting from the vapor-induced spreading mechanism eqn (11). The dashed-dotted line represents the scaling $D_m/D_0 \sim We^{1/2}$ resulting from the balance between the drop's initial kinetic energy and the change in its surface energy at maximum deformation.

only slightly larger. As a result, it is suggested that the maximum spreading diameter of impacting droplets on superheated surfaces in the film boiling regime is not strongly influenced by the structure's geometry and is higher than that on unheated surfaces.

We now verify the independence of the maximum spreading diameter D_m on the structure's geometry for droplets impacting on Leidenfrost surfaces with varying Weber numbers. Indeed, measurements of the spreading factor $\Gamma = D_{\rm m}/D_0$ in the film boiling regime (Fig. 8) clearly show that it is not only independent of the structure's geometry, but also of the surface temperature. In Fig. 9, we show a log-log plot of $D_{\rm m}/D_0$ versus We for droplet impact in the film boiling regime. The plot includes six sets of data obtained on six different structured surfaces (Table 1) and one on smooth surfaces.¹⁰ All the data fall on the same curve despite wide variations in structured surfaces and temperature. Compared to the case of impact on unheated surfaces, the scaling of the maximum spreading diameter on Leidenfrost surfaces is steeper than the 1/4-scaling, which holds for unheated surfaces of various wettability and roughness.²⁶⁻²⁸ Note that a scaling argument for the maximum spreading diameter of impacting droplets on an unheated post of the same diameter was also reported with experimental support and is of the form $D_{\rm m}/D_0 - 1 \sim {\rm We}^{1/2}$.²⁹

To explain this universal behavior in our case, we seek to derive the spreading factor $\Gamma = D_m/D_0$ of droplets impacting on solid surfaces in the film boiling regime. The liquid during its impact upon surfaces is modeled as a disc and spreads on a vapor layer generated by the liquid evaporating from the bottom of the disc (see Fig. 10). If we further assume that the heat required to evaporate the liquid is conducted through the vapor layer of thickness $\sim h$ and area $\sim D_m^2$, it is then possible to approximate the rate of heat transfer to the liquid using

Fourier's law: $\dot{Q} = k_v \Delta T D_m^2 / h$, where k_v is the thermal conductivity of the vapor, and ΔT is the temperature difference between the solid and the liquid surfaces (the liquid surface is assumed at boiling temperature). The rate of vapor generation is then $\dot{m} \sim \dot{Q}/L \sim k_v \Delta T D_m^2 / L h$, where *L* is the latent heat of evaporation. This generation rate balances with the rate of vapor escaping the gap between the liquid and the solid surfaces, $\dot{m} \sim \rho_v U h D_m$, where ρ_v is the vapor density, and *U* is the radial velocity of the vapor flow. Hence:

$$\frac{k_{\rm v}\Delta T}{Lh} D_{\rm m}^{2} \sim \rho_{\rm v} Uh D_{\rm m}.$$
(2)

The vapor flow is driven by a pressure increase ΔP under the drop. For an impacting droplet we take the dynamic pressure $\Delta P \sim \rho_1 V_0^2$. Since the vapor thickness is very small (for a droplet impacting with We \approx 3, the vapor thickness is roughly 3 µm (ref. 10)), the vapor flow is viscous and can be described by the lubrication approximation $\partial_x P \sim \mu_v \partial_z^2 U$, where ∂_x and ∂_z are derivatives in the radial and vertical directions, respectively, and μ_v is the viscosity of the vapor. By taking into consideration $D_{\rm m}$ and *h*, the typical length scales in the horizontal and vertical directions respectively, we thus have:

$$\frac{\rho_{\rm l} V_0^2}{D_{\rm m}} \sim \mu_{\rm v} \frac{U}{h^2}.$$
 (3)

The viscous vapor flow exerts a drag force on the liquid. This drag force can be approximated as $\tau_v D_m^2 \sim \mu_v (U/h) D_m^2$, where τ_v is the viscous shear stress of the vapor flow. The drag force is then balanced by capillarity, $(\sigma/H_m)D_m^2$. Here, H_m is the thickness of the liquid pancake at its maximum spreading and is related to the maximum diameter D_m by volume conservation, $H_m D_m^2 \sim D_0^{-3}$. Hence, the force balance becomes:

$$\sigma \frac{D_{\rm m}^2}{D_0^3} \sim \mu_{\rm v} \frac{U}{h}.\tag{4}$$



Fig. 10 Schematic to derive the spreading factor. A drop of diameter D_0 and impact velocity V_0 falls on a heated surface with temperature *T*. The drop spreads on a vapor layer of thickness *h* and takes the shape of a pancake. The vapor flows radially outward with velocity *U* due to the pressure increase ΔP (as compared to outside ambient pressure) and drags the liquid along. At maximum spreading, the diameter and thickness of this pancake are D_m and *H* respectively.

The three equations eqn (2)-(4) allow us to determine the three unknowns $D_{\rm m}$, U, and h. We can rewrite these equations in non-dimensional forms using the dimensionless variables $\Gamma = D_{\rm m}/D_0$, $\tilde{U} = U/V_0$, and $\tilde{h} = h/D_0$. The relevant dimensionless numbers are the Weber number We, the Stokes number St = $\rho_1 D_0 V_0 / \mu_v$, and the "Peclet" number Pe = $\rho_v L D_0 V_0 / k_v \Delta T$. The mass balance (eqn (2)) together with eqn (3) become

$$\Gamma^2 \sim \tilde{h}^4 \text{St} \times \text{Pe},$$
 (5)

the lubrication approximation (eqn (3))

$$\Gamma \tilde{U} \sim \text{St} \times \tilde{h}^2,$$
 (6)

and finally the force balance (eqn (4)) and eqn (3) lead to

$$\tilde{U} \sim \frac{\mathrm{St}}{\mathrm{We}} \Gamma^2 \tilde{h}.$$
(7)

This system of equations can be solved to obtain the final result

$$\Gamma \sim \frac{W e^{2/5}}{S t^{1/10} P e^{1/10}},$$
(8)

$$\tilde{h} \sim \frac{\mathrm{We}^{1/5}}{\mathrm{St}^{3/10}\mathrm{Pe}^{3/10}},$$
 (9)

$$\tilde{U} \sim \frac{\mathrm{St}^{1/2}}{\mathrm{Pe}^{1/2}}.$$
 (10)

If we now assume that all the dimensionless numbers are varied only by changing the impact velocity V_0 , then the velocity dependence of Γ , \tilde{h} , and \tilde{U} can be expressed through the Weber number, resulting in

$$\Gamma \sim \left(\frac{\mu_{\rm v} k_{\rm v} \Delta T}{\rho_{\rm v} \sigma L D_0}\right)^{1/10} \mathrm{W} \mathrm{e}^{3/10} = \beta \mathrm{W} \mathrm{e}^{3/10}, \tag{11}$$

$$\tilde{h} \sim \beta^3 \mathrm{We}^{-1/10},\tag{12}$$

$$\tilde{U} \sim \left(\frac{\rho_{\rm l} k_{\rm v} \Delta T}{\rho_{\rm v} \mu_{\rm v} L}\right)^{1/2},\tag{13}$$

where β in eqn (11) and (12) is a pre-factor that depends on the drop size D_0 , among other parameters. The dependence of β on D_0 is however very weak, and hence a small change in the drop size can be assumed not to affect the scaling law for the dependence of Γ on the Weber number (in our experiments, the mean diameter of droplets is 2.2 mm, with a standard deviation $\approx 10\%$). For large We, the experimental result is consistent with the scaling exponent 3/10 for the spreading factor Γ (see Fig. 7), whereas for smaller We, it deviates from the 3/10-scaling and in fact is closer to the 1/4-scaling for unheated surfaces. We attribute the discrepancy between the experimental data at low Weber numbers and the 3/10-scaling to the fact that the drag force induced by the vapor flow is less dominant if the liquid is not strongly forced against the solid surface, which is the case in this low Weber regime.



Fig. 11 Jet formation during the impact of a water droplet on a structured surface ($l = 4 \,\mu\text{m}$, $H = 2 \,\mu\text{m}$) heated to 300 °C. The diameter of the drop is 2.2 mm, and the impact velocity is 1.3 m s⁻¹.

Let us discuss the dependence of the spreading factor Γ on the superheat $\Delta T = T - T_{\rm b}$, where $T_{\rm b}$ is the boiling point of the liquid. In our experiments, the surface temperature *T* is varied between 240 °C and 540 °C. Correspondingly, ΔT is varied from 140 K to 440 K. It is then predicted by eqn (11) that increasing ΔT from 140 K to 440 K only causes Γ to increase by 12%. This variation is within the experimental scatter of the data (see Fig. 9), and hence is consistent with the weak dependence of Γ on the surface temperature that is observed experimentally.

The scaling laws for the normalized vapor thickness h and the vapor velocity \tilde{U} (eqn (9) and (10), respectively) are of great



Fig. 12 (a) Jet height of droplets impacting structured surfaces in the contact boiling regime *versus* the pillar height *H* of the structure. The impact velocity $V_0 = 1.65 \text{ m s}^{-1}$ (We = 88) and the surface temperature T = 300 °C were kept fixed. The error bars for each surface represent the standard deviation of 25 experiments of the same impact conditions. (b) Jet height *versus* the ratio *H*/*I* for all surfaces. (c) Schematic showing the structure's geometry.

importance as they explicitly reveal the role of different parameters involved in the vapor flow dynamics. For instance, it is predicted by eqn (10) and the resulting eqn (13) that the vapor velocity U does not depend on the diameter of the drop and is linearly proportional to the impact velocity V_0 . This is a crucial prediction for applications such as cleaning of hot metals using sprays.

Contact boiling regime: jet formation

In this section, we describe the surprising formation of upwarddirected liquid jets that emerge during the spreading phase of the droplets in the contact boiling regime on structured surfaces. We never observed similar jets in the case of a smooth surface. The occurrence of the jet and its velocity vary depending on the surface structures, surface temperature, and impact velocity. That this type of jets occurs during the spreading stage makes the phenomenon very different from those that occur during the retracting stage of impact on unheated surfaces.³⁰ In Fig. 11, we show a series of images taken during the impact of a water droplet falling with a velocity of 1.3 m s^{-1} on a structured surface heated to 300 °C (the time origin t = 0 ms is taken as the moment the drop first touches the surface). Shortly after the initial contact, the liquid at the bottom of the droplet spreads out horizontally, whereas the top surface still remains spherical. At the same time, a stream of small droplets shoots up from the base of the spherical cap as shown in the image taken at t = 0.83ms. These droplets are presumably caused by the bursting of vapor bubbles forming on the lower liquid surface.

The ejection of small droplets is then followed by a liquid jet shooting vertically upward from the center of the flattened drop. One possible explanation is that the expansion of vapor bubbles underneath the spreading drop applies a collective pressure to the liquid bulk and eventually causes the liquid in the middle to shoot up. On the other hand, the shape of the jet may suggest that it is caused by a converging liquid motion toward the axis of the flattened drop. A possible cause is the formation of vapor bubbles on the pillars which might penetrate through the lower surface of the liquid. Since, due to the geometry, more pillars would penetrate the liquid with increasing distance from the axis of the drop, a pressure gradient favoring an inward motion of the liquid might be generated in this way. Both mechanisms lead to the conclusion that the effect is more pronounced with increasing pillar height and decreasing spacing. These expectations are supported by Fig. 12, which shows the maximum jet height h_{iet} for impacting droplets on different structured surfaces. The surface temperature and impact velocity are kept fixed. For the same interspacing, it is evident that the jet height increases as the pillar height is increased. Further, when the jet height is plotted against the aspect ratio H/I of all the structured surfaces (see Fig. 12b), it is shown that h_{iet} increases with H/I.

Conclusions

In the present study, we have determined the dynamic Leidenfrost temperature for various structured surfaces and compared it with that for smooth surfaces. For a fixed interspacing and pillar width, the dynamic Leidenfrost temperature decreases with increasing pillar height. This result shows that it is possible to control the dynamic Leidenfrost temperature of impacting droplets, hence their characteristic boiling behaviors, using structured surfaces.

We also investigated the hydrodynamic behaviors of impacting droplets on these structured surfaces in the film boiling regime. We show that the residence time of droplets is independent of the impact velocity, structures, or surface temperatures and can be approximated by Rayleigh's result for the period of a freely oscillating droplet, eqn (1).

Regarding the spreading dynamics above the dynamic Leidenfrost temperature, we show experimentally that the maximum spreading factor follows a universal behavior regardless of changes in the surface temperature and structure geometry. We theoretically derive scaling laws for the spreading factor, the vapor thickness and velocity with the main assumption that the vapor escaping from the gap between the liquid and the solid surfaces drags the liquid radially outward. The scaling law for the spreading factor $\Gamma \sim \text{We}^{3/10}$ was shown to be in accord with the experimental data at high Weber numbers where the vapor-induced mechanism becomes dominant. The scaling laws for the vapor thickness are still open to be tested experimentally as they may hold important implications for applications that utilize vapor flows.

In the contact boiling regime, the emergence of liquid jets shooting vertically upward is a surprising feature of impacting droplets on structured surfaces. We provide a detailed description of these liquid jets, and show that for a fixed temperature and Weber number, the jet shoots higher with increasing pillar height. The mechanism of the jet formation as well as the dependence of its intensity on the impact conditions, however, still remains as open questions and need further investigation.

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