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Sailing Droplets in Superheated Granular Layer

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We report instability of a superheated granular layer when a droplet is deposited on top of the layer. We find that the instability caused by evaporating vapor may trap or cause the droplet to sail away from the deposited position. The sailing motion is triggered by an unstable pressure distribution originated from fast fluidization of metallic grains. We provide a predictive model and experimental verification of the enabling conditions for sailing motion based on limiting criteria for fast fluidization.

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Fast evaporation of a droplet deposited on a superheated surface may allow the droplet to suspend on its own vapor, a phenomenon commonly known as the Leidenfrost effect [1,2]. During the two centuries since the effect was first reported, the seemingly straightforward interplays [3] among the superheated surface, evaporating liquid droplet, and generated vapor have been found as the origin of numerous fascinating phenomena. Most notably, it was found that Leidenfrost droplets could propel either by the internal flow [4] or by the surface's asymmetrical structures [5,6]. They could also get excited and oscillate [7,8], or perform radical maneuvers such as leaping away [9] or explode [10]. Surprising phenomena occur when the heated surfaces are allowed to deform, thus exert another degree of influence on the Leidenfrost droplets. These include Leidenfrost droplets sustaining in a liquid pool with negligibly small superheats [11] and robust self-propelled motions of oil droplets in an evaporating nitrogen pool [12].

Besides liquid, Leidenfrost surfaces can be expanded to include superheated granular media. In this case, strong gas-grain interactions around deposited droplets were observed in addition to the usual droplet-surface interactions [13,14]. Here, the vapor flow spontaneously generated from the evaporating droplet may be strong enough to fluidize the surrounding grains, allowing the droplet to sink into the granular layer. The behavior of the liquid droplet therefore is strongly affected by the fluidized granular flow. The grains may also be considered as the surface's *dynamic* roughness that affects the droplet's motion, as opposed to the *static* roughness, which has been exploited extensively in droplet's manipulation [5,15]. Nonetheless, the resulting droplet dynamics and how it depends on the intensity of fluidization remain elusive.

In this Letter, we report spontaneous motions of a liquid droplet deposited on a superheated granular layer. We find that the fluidized granular flow either traps the droplet or causes it to sail away from the deposited position. We investigate the trapping-sailing transition and its

dependence on fluidization instability. We then provide a predictive model and experimental validation of the trapping-sailing transition.

In our experiment, we use stainless-steel grains to prepare a granular layer on a sapphire plate. We use ethanol as the working liquid, although other liquids, e.g., deionized water, FC72, acetone and isopropyl alcohol, yield qualitatively similar behaviors. The grain diameters range from 10 to 70 μm with mean value $d = 30 \mu\text{m}$. Sufficiently small grain size ($d \lesssim 220 \mu\text{m}$) is required to prevent vapor from

FIG. 1. (a) Series of representative snapshots from the side and bottom views showing a droplet sailing on a heated granular layer. The droplet first sinks in the granular layer, then starts sailing away. The dashed lines indicate the droplet's deposited position; the dashed-dotted lines indicate the droplet's center. (b) A droplet in the trapping regime. The scale bars represent 2 mm.

escaping into the granular layer [16]. The thickness h_0 of the granular layer is varied from 0.35 to 3.50 mm; its top surface is flattened using a sharp blade before droplet deposition. The initial volume fraction ϕ_0 of the granular layer is 0.61 ± 0.01 . We vary the temperature T_w of the sapphire plate up to 380°C . The top surface temperature T_p of the granular layer is lower than T_w and is monitored by an infrared camera (ImageIR 8300 hp, InfraTec) [16]. For each experiment, once T_p is stabilized, we deposit an ethanol droplet with volume $V_0 = 14 \mu\text{l}$ on the granular layer and record its behavior from both the side view (with a viewing angle 14°) and the bottom view using two synchronous high-speed cameras (SA5 and SA-X2, Photron).

In Fig. 1(a), we show several representative snapshots from both the side and bottom views of a sailing droplet in a granular layer with $h_0 = 2.1 \text{ mm}$ and $T_w = 240^\circ\text{C}$. We observe that after deposition, the droplet sinks in the granular layer without any lateral motion. The sinking motion is accompanied by liquid vaporization and fluidization of grains due to flows of vapor evaporated from the droplet. The droplet reaches the bottom of the granular layer (although still separated from the sapphire surface by a vapor layer) at $t \approx 7.9 \text{ s}$, evidenced by the dark area in the bottom-view snapshot. From this moment, the fluidization intensity increases quickly, suggesting significantly higher vapor velocity. Subsequently, the droplet starts moving and passes the generated crater to sail away; its motion can be readily detected from both views. Surprisingly, a droplet may be trapped by either reducing h_0 or increasing T_w [Fig. 1(b)], suggesting that the transition between the sailing and trapping regimes crucially depends on the conditions of the heated granular layer.

We repeat the experiment numerous times to confirm that trajectories of droplets in the sailing regime display no directional preference, as shown in Fig. 2(a). From each trajectory, we extract the travel distance S and the corresponding base radius R_b as functions of time t [Fig. 2(b)]. Generally the average travel distance increases with the liquid volume. As a droplet in the sailing regime always starts moving as soon as it reaches the bottom substrate, we infer that the sinking stage sets the conditions to enable motions of sailing droplets.

We describe the sinking stage in analytically tractable terms as follows. An evaporating droplet with the initial radius $R_0 = 1.9 \text{ mm}$ reduces its radius to R by the time it reaches the bottom substrate. The granular grains in its sinking path are either entrained into the liquid or ejected upward by the vapor flow and settled around the rim of the droplet [Fig. 3(a)]. The crater containing the sinking droplet is shaped by an avalanche angle α [Fig. 3(a)], i.e., the largest angle that a granular material can make with the horizontal plane ($\alpha \approx 38^\circ$ in our study). We note that the star formations [23] of Leidenfrost droplets were not observed during the sinking stage. When the droplet reaches the substrate, the generated vapor flow fluidizes

FIG. 2. (a) Droplet trajectories in the sailing regime showing no directional preference. All droplets are deposited at the same position ($x = 0, y = 0$) on granular layers of the same thickness and temperature. The average travel distance is $\approx 3 \text{ mm}$; the velocity ranges from 0.4 to 1.4 mm s^{-1} . (b) Representative plots showing the base radius R_b (left axis) and the travel distance S (right axis) vs time t .

and spews up grains, creating a fluidized stream [Fig. 3(b)]. Subsequently the fluidized grains fall on the crater's side and slide down to replenish the fluidized stream. At this moment, the volume V_L of grains in the fluidized stream is estimated as the difference between the volume V_a of grains evacuated to make the crater and the volume V_b of grains either entrained into the liquid or ejected out during the sinking process [Fig. 3(a)] [24].

We highlight that the fluidized stream of a sailing droplet always has an uneven profile [side views in Fig. 1(a)] and the droplet always moves toward the side with larger profile height, as illustrated in the inset of Fig. 3(b). As a result, we hypothesize that grain fluidization causes an imbalance in pressure distribution, which results in an uneven profile of the fluidized grains and a net force that triggers the droplet motion.

From the close-up recording at the rim of the droplet [inset of Fig. 3(b)], we find no evidence of vapor moving through the granular layer in voids. Instead, the vapor flow continuously conveys grains from the droplet's base upward. The relatively high vapor velocity generated from Leidenfrost droplets ($u_v \gtrsim 1 \text{ ms}^{-1}$ [2]) and the observed characteristic behaviors suggest that fluidization at the rim of the droplet may be either fast fluidization or dilute phase flow [17]. The former one, typically occurs with relatively higher volume fraction of grains and lower gas velocity, is characterized by a negative correlation between the pressure drop ΔP associated with fluidization and the

FIG. 3. Schematic showing two stages of droplet dynamics. (a) Sinking: a droplet of radius R_0 sinks in the granular layer and reaches radius R at the bottom. (b) Fluidization: vapor flow coming from the gap e between the droplet and the substrate with velocity u_v accelerates grains to velocity u_p . Inset: snapshot showing fluidized streams of different heights ($h_L < h_R$) around a droplet moving from left to right. (c) Typical Zenz's type plot showing how the pressure drop ΔP depends on the vapor velocity u_v . The point where ΔP is minimum ($u^*, \Delta P^*$) separates fast fluidization from dilute phase flow.

gas velocity u_v [Fig. 3(c)]. The latter one occurs when u_v is higher causing most grains conveyed in the gas flow with lower volume fraction. This regime is characterized by a positive correlation between ΔP and u_v . The transition between the two regimes happens when u_v reaches a critical value u^* where ΔP is minimum [25,26].

The negative correlation between ΔP and u_v in the fast fluidization regime provides an unstable mechanism triggering the droplet's motion. For a stationary droplet initially subjected to zero net force, i.e., ΔP and u_v are initially uniform around the rim of the droplet [point A in Fig. 3(c)], a steady vapor generation rate at the droplet's bottom dictates that a decrease in u_v (and the corresponding increase in ΔP) at any point on the rim gives rise to an increase in u_v (and the associated decrease in ΔP) at another point on the rim. As a result, any deviation in u_v inevitably drives the imbalance in ΔP higher. Eventually, the difference in pressure drop around the rim of the droplet grows sufficiently large to displace the droplet. We conclude that droplet sailing is possible if the velocity u_v of vapor escaping from the bottom of the droplet causes fast fluidization of grains.

We note that the occasionally changes in moving direction of a sailing droplet [Fig. 2(a)] may reflect the unstable mechanism in generating the pressure imbalance around the droplet; this mechanism is sensitive to deviations from an uniform distribution of the escaping velocity u_v of vapor at the droplet's bottom. Since u_v is directly affected by the surrounding grains, the change in moving direction is most likely tied to the granular layer's intrinsic properties, e.g., random packing and grain size variation.

In contrast to the negative correlation between ΔP and u_v , the positive correlation in the dilute phase flow regime stabilizes deviation in ΔP around the rim of the droplet, hence suppresses any imbalance in ΔP around the rim. As a result, the droplet is trapped if u_v is sufficiently high to cause dilute phase flow around the droplet.

To formulate the transitional condition between sailing and trapping, we first establish how the layer's thickness h_0 and substrate temperature T_w affect the fluidized system's parameters at the end of the sinking stage, including the droplet volume V , vapor velocity u_v , grains velocity u_p , and volume fraction ϕ_f in the fluidized stream. We note that the energy transferred to the droplet during sinking consists of the sensible heat increase $E_s = \rho_l V_0 c_p^l (T_b - T_r)$, i.e., to heat the droplet to the boiling temperature T_b [27], and the latent heat of evaporation $E_l = \rho_l (V_0 - V) h_{fg}$, i.e., to vaporize and reduce the liquid volume from V_0 to V . Here ρ_l , c_p^l , and h_{fg} are the density, specific heat, and latent heat of liquid, respectively; $T_r = 25^\circ\text{C}$ is the room temperature, and $V = 4\pi R^3/3$ the volume of droplet when it reaches the bottom. The energy transferred to the droplet $E_s + E_l$ is balanced with the heat release $E_c = \phi_0 \rho_s V_b c_p^s (T_s - T_b)$ from cooling grains in the sinking path of the droplet from the granular layer's averaged temperature $T_s = 0.5(T_w + T_p)$ to T_b . Here, we denote ρ_s and c_p^s the density and the specific heat of solid, respectively [28]. As a result, we obtain the relation to determine how the droplet size R depends on h_0 and T_w :

$$E_s + E_l = E_c. \quad (1)$$

At the end of the sinking stage, the droplet reaches the substrate and its bottom surface is flattened with area $\pi R^2 (R/\lambda)^2$, where $\lambda = [\sigma/(\rho g)]^{1/2}$ is the capillary length [3,16]. The dependence of the vapor thickness e on R and surface temperature T_w is $e \approx (k\Delta T \eta \rho_l g)^{1/3} (h_{fg} \rho_v \sigma^2)^{-1/3} R^{4/3}$ [3,16], where k , η , and ρ_v are the thermal conductivity, viscosity, and density of vapor, respectively; $\Delta T = T_w - T_b$ is the substrate's superheat, σ the surface tension of liquid, and g the gravitational acceleration. Here, we use the properties of liquid at T_b , and the properties of vapor at T_w . Subsequently, the evaporating velocity of vapor from the droplet's bottom surface is $w = k\Delta T / (e h_{fg} \rho_v)$. Thus, the vapor flow responsible for

FIG. 4. Theoretical predictions of (a) ΔP vs u_v and (b) ΔP vs T_w for different thicknesses h_0 . For each value of h_0 , a critical point, $(u^*, \Delta P^*)$ in (a) and $(T^*, \Delta P^*)$ in (b), is found where ΔP is minimum. The locus of these critical points marks the transition between the sailing regime (shaded area) and the trapping regime. (c) Phase diagram showing experimentally observed behaviors: sailing (squares) and trapping (circles). The solid line is the theoretical prediction of the trapping-sailing transition. The scale bars represent 2 mm.

fluidizing the grains escapes from the gap between the droplet and the substrate with velocity $u_v = wR^2/(2\lambda e)$.

The vapor flow exerts a drag force on grains at the base of the crater and accelerates them to reach the velocity u_p [Fig. 3(b)]. With u_v estimated from 6 to 38 ms^{-1} , the Reynolds number $\text{Re} = \rho_v u_v d / \mu$ for the vapor flow around a grain varies from 23 to 49, indicating a laminar flow. Thus, the drag force acting on each grain is $F = (\pi/8)C_d \rho_v u_v^2 d^2$, where the drag coefficient is $C_d \approx 24 \text{Re}^{-1}(1 + 0.19 \text{Re}^{0.63})$ [17]. We note that the grains at the base of the crater are densely packed, implying that each grain is only accelerated within a distance of the order of the grain's size d . As a result, the spacing between grains after acceleration but before the fluidized stream is also d , giving the volume fraction $\phi_a = (\pi/6)d^3/(2d)^3 \approx 0.065$ [29]. The height h' of the fluidized stream [Fig. 3(b)] therefore results from balancing the kinetic energy $E_k = Fd$ that each grain gains after acceleration with the gravitational potential energy $E_g = (\pi/6)\rho_s d^3 gh'$, leading to $h' = (3/4)C_d \rho_v u_v^2 / (\rho_s g)$.

We now identify the relation between the thickness h_0 and temperature T_w at the trapping-sailing transition by determining the condition to minimize the pressure drop ΔP . We note that grains around the droplet essentially participate in a circulating fluidized layer that has two major functions: (i) sustaining grains in the fluidized stream until they fall back to the crater's slope, and (ii) accelerating

and injecting grains returned from the avalanche slope into the fluidized stream. As a result, the pressure drop ΔP is contributed by a static component ΔP_s to sustain grains in the fluidized stream, and a dynamic counterpart ΔP_a to accelerate grains into the fluidized stream [25]:

$$\Delta P = \Delta P_s + \Delta P_a. \quad (2)$$

We calculate the static pressure as $\Delta P_s = \phi_f \rho_s gh'$, where $\phi_f = \phi_0(h/h')^3$ assuming isotropic expansion of the grain stream from the initial volume fraction ϕ_0 . Here h is the hypothetical filling height of all grains in the fluidized stream if they settle in the gap between the droplet and the avalanche slope [30]. Subsequently, the dynamic pressure is $\Delta P_a = (1/2)\phi_a \rho_s u_p^2$, where u_p is the velocity of grain after accelerated by the vapor flow and can be related to the height h' of the fluidized stream as $u_p = (2gh')^{1/2}$.

Equation (2) establishes how the vapor velocity u_v affects ΔP [Fig. 3(c)], or equivalently how the granular layer's initial conditions, T_w and h_0 , affect ΔP . In Fig. 4(a), we show that for each value of h_0 , the dependence of ΔP on u_v indeed consists of the fast fluidization part (with negative correlation) and the dilute phase flow counterpart (with positive correlation). The trapping-sailing transition for such value of h_0 is found at $(u^*, \Delta P^*)$, where ΔP is minimized; the locus of $(u^*, \Delta P^*)$ forms the border between the sailing and the trapping regimes. We also show in Fig. 4(b) that the two regimes and their border can also be found in the diagram of ΔP versus T_w . Interestingly, there exists a maximum value of T_w beyond which a deposited droplet is always trapped regardless of h_0 . In Fig. 4(c), we show experimental data for the sailing and trapping regimes in the parameter space (T_w, h_0) . We also show the trapping-sailing transition predicted using h_0 and the corresponding values of T_w found by minimizing ΔP , confirming that the theory is consistent with the experimental data. Broadly speaking, the theory implies that within the tested temperature and granular thickness, sailing is only possible for $T_w < 366^\circ\text{C}$ and $h_0 > 0.7$ mm. Between these limits, the increase in T_w with h_0 at the transition signifies that adding more grains to the fluidized stream is more favorable to sailing.

In conclusion, we demonstrated that a droplet deposited on a superheated granular layer may be trapped or sail away. We identified fast fluidization and the associated unstable pressure distribution around the droplet as the required condition to trigger the sailing motion. More interestingly, we found that even though fluidization was required to destabilize and eventually cause the droplet to move, increasing fluidization intensity suppressed its motion. As a result, we theoretically derived a predictive model for trapping-sailing transition and experimentally verified that it indeed occurred when the system switched from dilute phase flow to fast fluidization. Our results indicate that fast fluidization induced by vapor flows may

play an important role in applications involving mass transport in granular media as it alleviates frictional constraints between moving objects and the surrounding grains. We also highlight that numerous questions remain open for this phenomenon, including the droplet's exact shape and how the droplet's internal flow characteristics influence its interactions with the granular media.

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- [28] The solid density is 8070 Kg m^{-3} and the specific heat of solid is $530 \text{ J Kg}^{-1} \text{ K}^{-1}$.
- [29] Since the grains are accelerated from 0 to u_p during the distance d , this gives a gap of d between the grains with velocity of u_s in the acceleration stream.
- [30] The grains in volume V_L are hypothetically piled up in the gap confined by a circular cylinder of radius R_b (the inner wall) and an inverted and truncated cone with angle α (the outer wall). The filling height h of all the grains in V_L therefore can be calculated from the equation $V_L = \pi/3 h \{ [h \cot(\alpha)]^2 + 3 \cot(\alpha) h R_b \}$.