Leidenfrost Drop
Ratchet Impact Dynamics

By

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Abstract

A drop deposited on a sufficiently hot substrate generates its own vapor cushion preventing contact with the surface. This vapor layer is responsible for the low friction and long lifetime of the drop. Falling water droplets will even bounce on their own vapor layer. By varying the geometry of a surface at the micro-scale, it is possible to control the movement of impacting droplets in this Leidenfrost state. We propose a model for the behavior of droplets impacting a micro scale ratchet structure. In particular, we theorize that surface roughness can lead to an inconsistent vapor layer, allowing for propulsion resulting from contact boiling. Additionally, pressure differences in the vapor layer can drive a convective vapor flow that can drag the drop along. In this study, we examine the horizontal velocity of water dropped on a ratchet surface with varying temperature, impact velocity, and ratchet geometry. We provide a new explanation—involving both propulsion from contact boiling as well as convective vapor flow—for why droplets move in the direction they do.

Introduction

As first described by Boerhaave and later by Leidenfrost, a drop deposited on a sufficiently hot substrate generates its own vapor cushion preventing contact with the surface [1,2]. This vapor layer is responsible for the low friction and long lifetime of the drop.

By altering the surface geometry, Linke *et al*. have found ways to control the movement of droplets along a surface while the drops are in the Leidenfrost state [3]. In particular, they have experimented with the dynamics of a drop gently deposited on a rachet surface. They discovered that the deposited droplets self-propel in the direction of the downward-sloping ratchet surface, as shown in Figure 1, and rationalize this motion by considering that viscous shear forces from the vapor layer drag the droplets along.

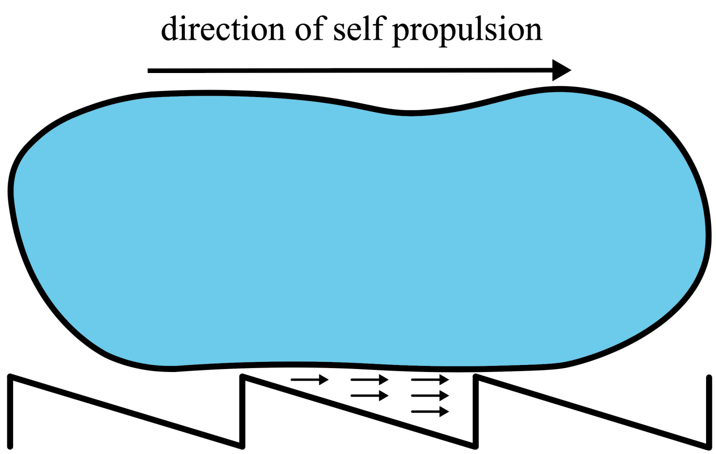

Figure 1. The direction of the droplet's self-propulsion relative to the ratchet, and viscous drag acting within the vapor layer. The illustration is roughly to scale of the experiments in [3].

In this study, we replicate this experiment with smaller scale ratchet structures, one tenth the size.

Tran *et al*., have investigated the dynamics of a drop upon vertical impact with a flat hot surface [4]. These impacts show separation into three regimes: contact boiling; gentle film boiling; and spraying film boiling. In contact boiling, the surface is not hot enough for a vapor layer to form and the droplet quickly makes contact with and boils on the surface. In gentle film boiling, a vapor layer is formed and the droplet can gently bounce off this layer. Spraying film boiling combines these two regimes; the impact speed is sufficiently high to partially pierce through the vapor layer, causing some boiling as enough heat can conduct through the thin compressed layer.

In this paper, we present an experiment that juxtaposes these two phenomena at a smaller scale. Namely, we study the dynamics of a droplet upon vertical impact with rachet surfaces at the micro-scale. The ratchets are manufactured using laser etching on a brass sheet, and heated above the Leidenfrost point. We propose a model wherein, upon contact, the vapor layer does not fully contact the bottom of the droplet due to the surface roughness. Accordingly, a combination of contact boiling and film boiling occurs, which compete to propel and pull the drop in both the upward-sloping and downward-sloping directions. By examining the resulting horizontal velocity of the droplet, we estimate the relative effect of the two regimes as temperature and surface geometry vary.

Research Review

Droplet Impact

Tran *et al*. have studied the dynamics of a droplet impact on a silicon plate above the Leidenfrost temperature and divided this impact into three regimes: contact boiling; gentle film boiling; and spraying film boiling [4]. In contact boiling, the surface is not hot enough for a vapor layer to form and the droplet quickly makes contact with and boils on the surface. Meanwhile, in gentle film boiling, a vapor layer is formed and the droplet can gently bounce off this layer. Spraying film boiling combines these two regimes; the Weber number, controlled by the impact speed, is sufficiently high for the droplets to partially pierce through the vapor layer, which allows spraying boiling to occur. Although this paper does not provide a quantitative relationship to predict which regime a droplet may fall in, it provides hints as to how water droplets may impact our ratchet surface.

Micropillars

Van der Veen *et al*. have studied the impact of water droplets on micropillar structures with pins around 10 μm in diameter, albeit below the Leidenfrost temperature [5]. They show how the 3D nature of a drop coupled with the geometry of a surface can affect the air layer that forms prior to wetting. In the case of Leidenfrost temperature, this still applies as the air layer formed before impact should only depend on the geometry of the drop—not the temperature of the surface. Below the Leidenfrost point, the air layer is thinnest at the top of the pillars and also becomes the first part to get wet. A similar behavior may occur on our ratchets as the tops of the ratchet teeth behave like pillars.

Another study by Tran *et al*. has observed the effect micropillar structures have on the dynamic Leidenfrost temperature [6], where the *dynamic* Leidenfrost temperature is defined the temperature at which impact droplets change from the contact boiling regime to the film boiling regime. Increasing the pillar heights decreases the dynamic Leidenfrost temperature. In all cases, this temperature is less than that of a flat surface. An example of these surfaces is illustrated in Figure 2.

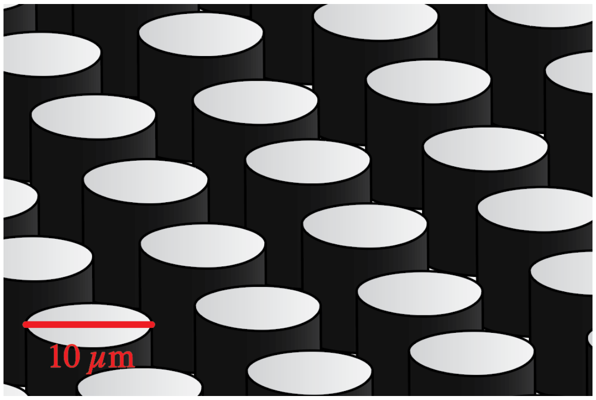

Figure 2. An illustration of the micropillar structures studied in [5].

Leidenfrost Ratchet Effects

Linke *et al*. have studied the dynamics of a droplet deposited gently on a ratchet surface above the Leidenfrost temperature [3]. No dependence of horizontal velocity on ratchet material choice has been observed, and the motion of the deposited droplets has been reported to follow the downward-sloping direction of the ratchet. It is noted that the Leidenfrost point on these surfaces depends largely on roughness and contamination. The ratchets we study are around ten times smaller than the ones studied here.

Marín *et al*. largely confirm Linke's findings, providing more analysis of the viscous drag mechanism that causes the droplets to move [7]. In particular, Marín derives a viscous drag force of

$$F \propto Mg\theta, \tag{1}$$

where M is the mass of the droplet and θ is the pitch of the ratchet, shown in Figure 3.

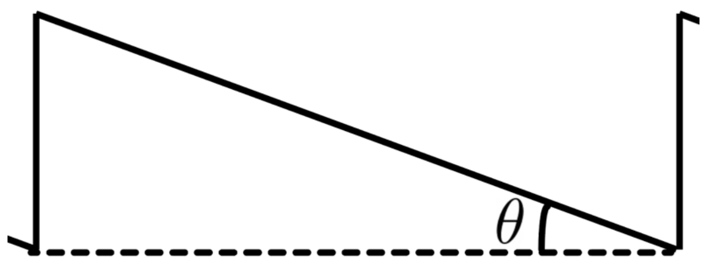

Figure 3. θ, as it appears in Eqn. (1).

Interestingly, equation (1) is independent of on the temperature gradient ΔT and the thickness of the air layer; a thicker layer creating lower viscous drag and a larger temperature gradient creating higher viscous drag cancel each other out.

Lagubeau *et al.* propose a different, rocket-like, mechanism, equating the rate at which vapor is produced and the rate at which it can escape [8]. Using an escape rate of $1\ \mathrm{m/s}$, they obtain an equation that gives

$$F \propto \Delta T^{5/4}. \tag{2}$$

This is an inertial force resulting from momentum conservation, rather than one driven by viscous drag.

Additional experiments have been done involving dry ice to try to prove these theories. Since the dry ice behaves as a solid, these experiments confirm that the horizontal movement is due to vapor production and not the dynamics of fluid deformation. Dupeux *et al*. suggest the viscous drag mechanism to be dominant [9].

A third mechanism has been suggested by Würger *et al*., in which thermal gradients drag drops along [10]. However, this has been refuted in [7] for requiring too large of thermal gradients to be reasonable.

Summary

Previous droplet impact research demonstrates that higher impact speed enables a compression of the vapor layer that can in turn lead to a higher rate of vaporization. Additionally, previous impact research on rough surfaces reveals that these vapor layers themselves may be inconsistent, and potentially even nonexistent.

At the same time, droplet movement mechanisms on Leidenfrost ratchets are not fully understood. There are possibly several mechanisms occurring at the same time, but they all suggest the same, downward-sloping, direction of movement along the ratchet surface. However, the competing theories each suggest a different scaling of droplet movement.

Experimental Setup

Our ratchets are produced using laser etching on 1 mm thick brass sheets. This is done by Professor Konishi and Doctor Sakurai from the Institute for Photon Science and Technology at the University of Tokyo. They are then cut to 1 cm x 2 cm. After heating these samples above the Leidenfrost temperature, a 2 mm diameter water droplet is dropped and the impact is recorded from the side with a high-speed camera (Nova FASTCAM) at 2000 fps, shown in Figure 4. We record the moments surrounding the impact of a droplet, illustrated in Figure 5. The drop dynamics are extracted from the videos, shown in Figure 6. The code to analyze these videos is in large part courtesy of master's student Kunhak Lee.

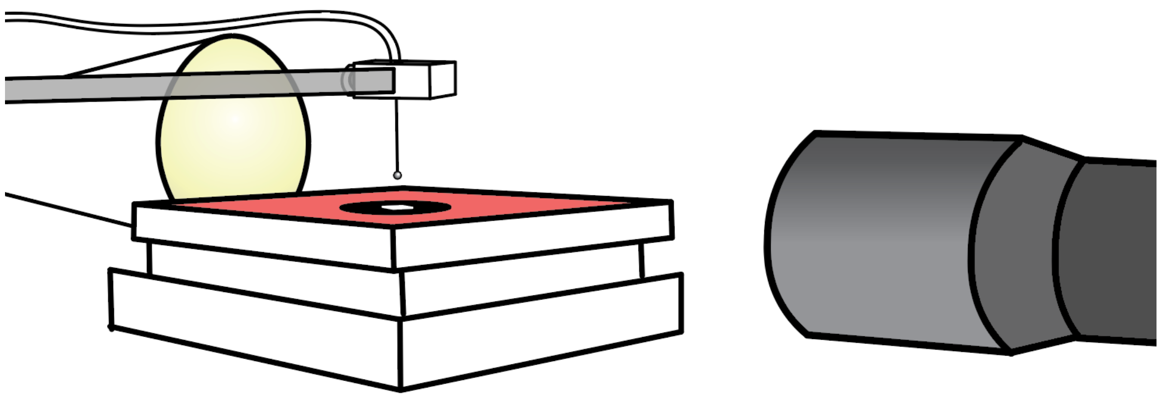

Figure 4. A high-speed camera records the impact of the 2 mm water droplet from the side. The sample is placed atop a silicon wafer on the hot plate to serve as a hydrophilic surface for escaping droplets. The setup is backlit to aid the necessary fast shutter speeds.

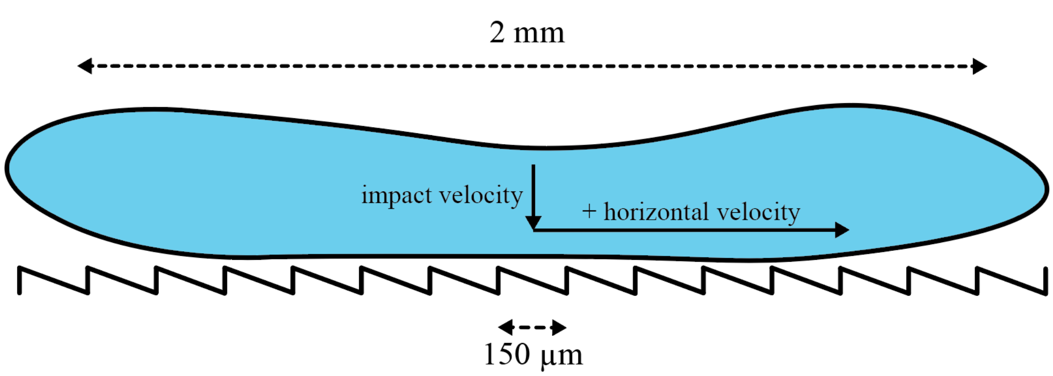

Figure 5. Illustration of droplet impact, drawn to scale, with the positive horizontal velocity direction shown. Current literature suggests that deposited drops always travel in the positive direction.

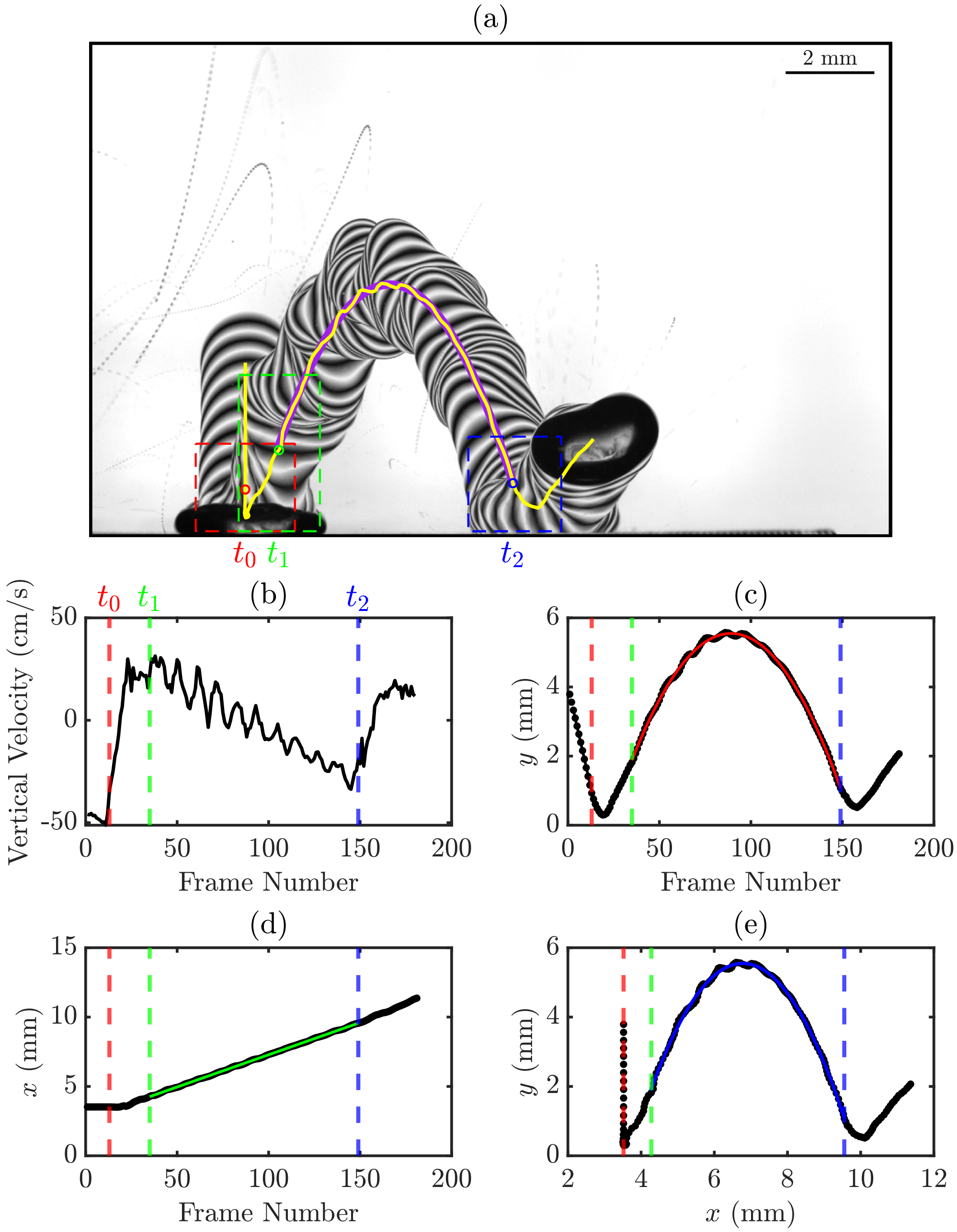

Figure 6. An example of the video analysis. In (a), the video is cropped so that the bottom of the frame aligns with the top of the ratchet. The droplet is detected and a bounding box is drawn around it. The times of the first and last contact, t_0 and t_1, of the first bounce, as well as the time of the first contact of the second bounce, t_2, are detected. In (b), the vertical velocity of the drop is shown. In (c), the center y-coordinates of the droplet from t_1 to t_2 are fit by a parabola. In (d), the horizontal velocity of the droplet between these bounces is determined by fitting the center x-coordinates of the droplet from t_1 to t_2 with a line. In (e), the center x-coordinates and y-coordinates are fit by a parabola describing the motion of the drop.

For each impact, five videos are recorded from the droplet's first impact with the ratchet to its second.

Sample Sensitivity

The ratchets are highly sensitive to contamination. To avoid contamination to the surface that results in drastic changes in the droplet dynamics, trials are performed on the same day and same sample whenever possible. Additionally, the samples must be handled with care to not be scratched, damaged, or contaminated. Contamination can come from the process used to clean the samples after etching. These samples were checked visually for a clean surface, as well as tested visually for consistency in drop dynamics when droplets are deposited on different areas of the ratchet surface. Out of eight samples, only three were found to be reliable and clean enough to conduct experiments with.

Notably, with a new set of ratchets, the behavior changed throughout the first month of use. While we performed no specific study on this change, we note that new samples may undergo changes in wettability from the environment. These changes may come from hydrocarbon deposition onto the ratchet surface during the first few weeks after manufacturing. Surface wettability is known to have a substantial effect on the Leidenfrost point [11].

We have observed that rapid heating and cooling cycles create inconsistent, hysteresis behavior around the Leidenfrost point of our samples. For example, the sample at 250 °C behaves differently when heated to 400 °C and cooled back down to 250 °C. To account for this, all trials are preformed through slowly increasing the temperature from the lowest to highest temperature.

Sample and Droplet Geometry

The samples that were deemed reliable, henceforth referred to as samples A1, A3, A7, have geometries as indicated in Figure 7. The droplets are produced using a 0.26 mm needle that results in droplets with diameter 2 mm.

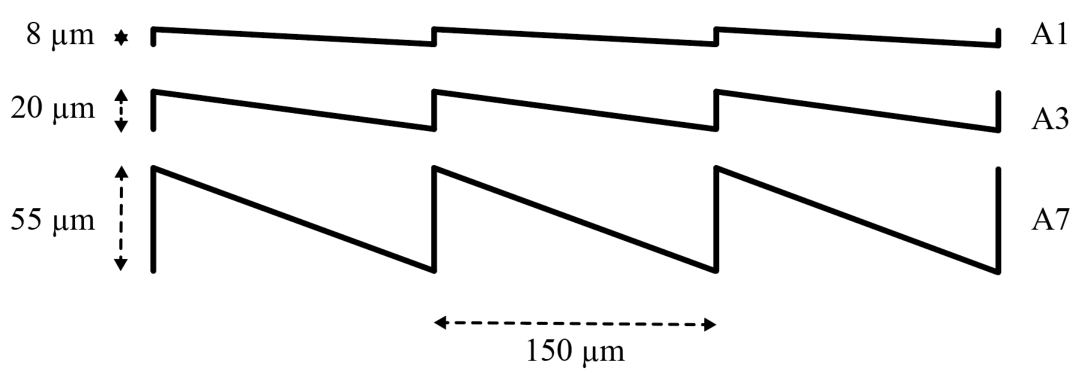

Figure 7. The geometries of the three samples used. Note the scale (also shown in Fig. 5), wherein the pitch is only 150 µm but the

droplet diameter is 2 mm. The pitch angles are 3.1°, 7.5°, and 20.1°, respectively.

Setup Limitations

The setup has several limitations. Mainly, it is very difficult to analyze the thin, micrometer scale, vapor layer that forms beneath the drop when recorded from the side. Many other experiments are done on glass or another surface that allows for vertical recording from beneath that can help to visualize the vapor layer. Because of the ratchet geometry, that is not doable here.

It is also important to note that our videos only capture one dimension of the movement, in the axis perpendicular to the ratchet. In reality, the droplet sometimes moves in a direction not truly perpendicular to the direction of the ratchet. To account for this, a second angle of the drop can be captured from the top or the orthogonal side to be cross referenced. In this experiment, we checked visually that the droplets were bouncing mostly in the direction perpendicular to the camera.

Results

We present both the effects of varying temperature with a fixed rachet geometry as well as varying the ratchet geometry with a fixed temperature. The videos were captured by intern Mari Chikaarashi.

Fixed Temperature

The temperature is fixed and the three samples A1, A3, and A7 are used to collect data at six impact heights. This is repeated for three surface temperatures: 250 °C, 350 °C, and 400 °C. The horizontal velocities are shown in Figure 8. Each set of data has a line best fit and the slopes of these lines are given in Table 1.

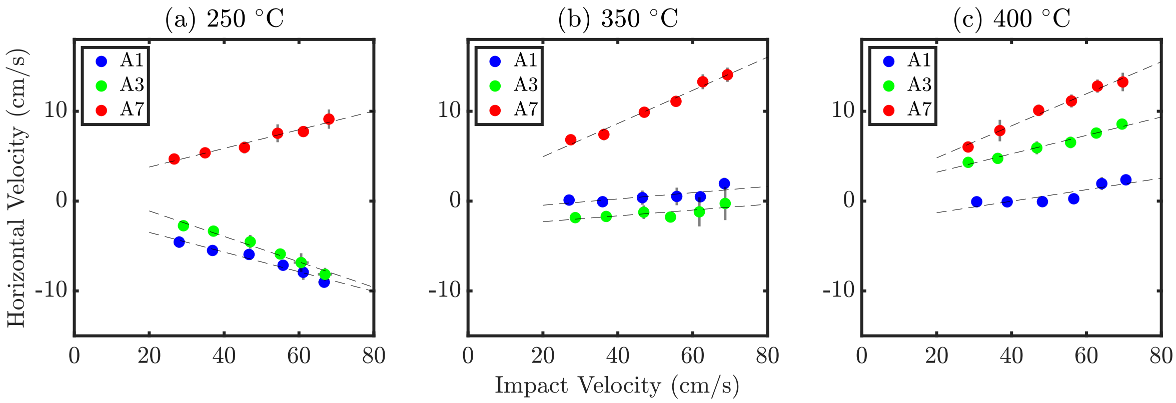

Figure 8. Plots (a), (b), and (c) show the horizontal velocities that result from varying impact velocities on the three samples at surface temperatures 250 °C, 350 °C, and 400 °C, respectively. All droplets are 2 mm in diameter. A line is best fit to each set of data, shown as a dashed line in each case.

	250 °C	350 °C	400 °C
A1	-0.110	0.035	0.064
A3	-0.142	0.032	0.103
A7	0.104	0.185	0.178

Table 1. The slopes of the best fit lines of each set of data in Fig. 8.

We notice sets of droplets that bounce in the *negative* direction. No previous research has reported this phenomenon. We believe it is due to a new propulsion mechanism, and we have even observed it in the case of gentle deposition. In [7], the vapor layer is consistent and thus viscous drag entrains the full bottom surface of the drop. In contrast, we suggest that the smaller-scale ratchet structure and roughness of our surfaces make for a less reliable Leidenfrost vapor layer, where the falling droplet can *completely* pierce the vapor layer at the peaks of the ratchet. This induces contact boiling that creates a large amount of vapor expulsion. For lower ratchet pitch angles, we suggest larger contact areas, further increasing the magnitude of this expulsion. Due to the pressure gradient down the ratchet, this vapor escapes in the positive direction and propels the droplet through momentum conservation in the negative direction. Figure 9 compares the theory in [7] to this new theory we propose.

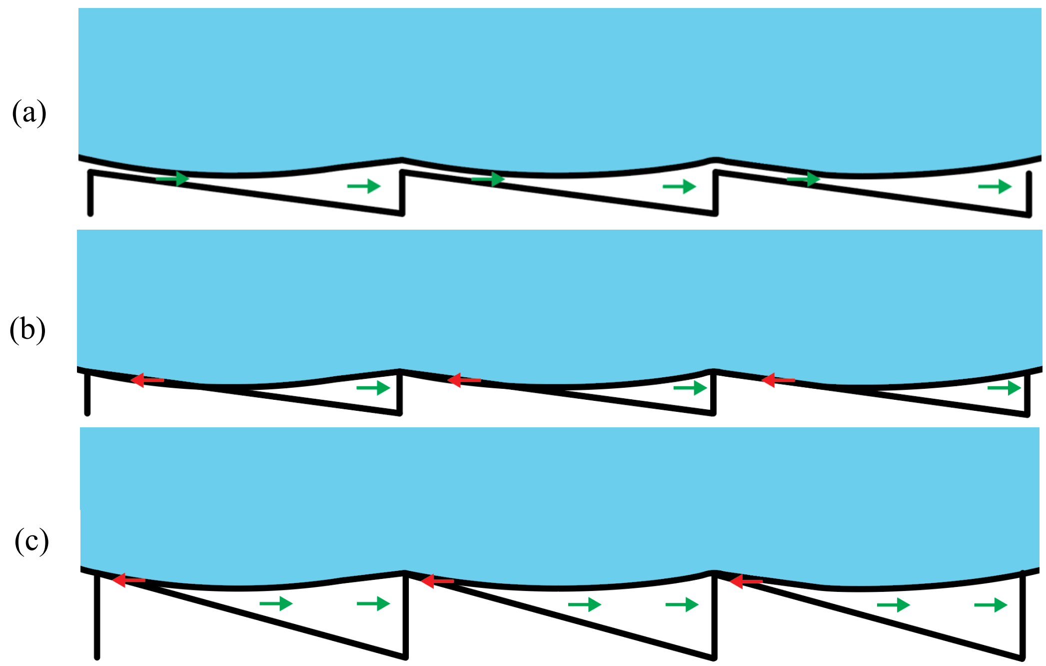

Figure 9. An illustration of the model proposed in previous research (a) along with the model we propose (b,c). The arrows show the two phenomena we describe occurring simultaneously. The green arrows show the convective vapor movement, which drags the drop along in the positive direction. The red arrows show complete contact with the surface, causing rapid vapor generation and expulsion in the positive direction. This pushes the droplet in the negative direction by momentum conservation. These two effects act in opposition. Note that the scenario in (b) may turn into the scenario in (a) as the temperature is increased. (c) shows the effect of an increase in pitch angle; namely, there is less contact area as pitch angle is increased. This causes more viscous drag and less propulsion, so the droplet experiences more positive horizontal velocity than in (b).

Although the plots in Figure 8 only describe the droplet until the second bounce, at 250 °C this negative direction is also indicative of the direction that the droplet continues in; it does not turn around. However, the drops with close to zero horizontal velocity for their first bounce (at 350 °C and 400 °C) do sometimes eventually go in a direction that does not necessarily match their first bounce.

In (8a), all three samples each individually follow a clear trend. For A1 and A3, the propulsion regime is comfortably dominant, moving the droplet in the negative direction, while for A7 viscous drag is comfortably dominant, moving the droplet in the positive direction. In this case, increasing the impact velocity does not change the dominant effect, but rather just increases the magnitude of the horizontal velocity. In (8b), for A7 viscous drag is still comfortably dominant, by A1 and A3 only weakly show a dominant regime. In this case, as the impact velocity is increased, the droplets start to move toward the viscous drag regime. In (8c), the viscous drag regime is comfortably dominant for A7 and A3, and A1 shows similar behavior to (8b).

Given this propulsion regime, the order of magnitude of the vapor exit velocity may be approximated. For a 1 mm radius droplet, the direct contact area is on the order of $5 \times 10^{-6}\ \mathrm{m}^2$. With critical heat flux around $10^6\ \mathrm{W/m}^2$, the total flux is on the order of 5 W [12]. With measured contact time around 10^{-2} s and latent heat of vaporization around $2 \times 10^6\ \mathrm{J/kg}$, the vaporized mass is 2.5×10^{-8} kg [12]. As the mass of the drop is around 5×10^{-6} kg, the exit velocity of the vapor must be $10\ \mathrm{m/s}$ to achieve the droplet propulsion of $-0.05\ \mathrm{m/s}$ that we see. This is realistic.

This rocket-like mechanism is similar to the inertial theory provided in [8], except our direction of escape is the opposite.

Fixed Geometry

To isolate the effect of temperature on the droplet impact dynamics, experiments have been conducted with fixed impact velocity (around 36 cm/s) and temperature varying from 210 °C to 420 °C. The horizontal velocities are shown in Figure 10.

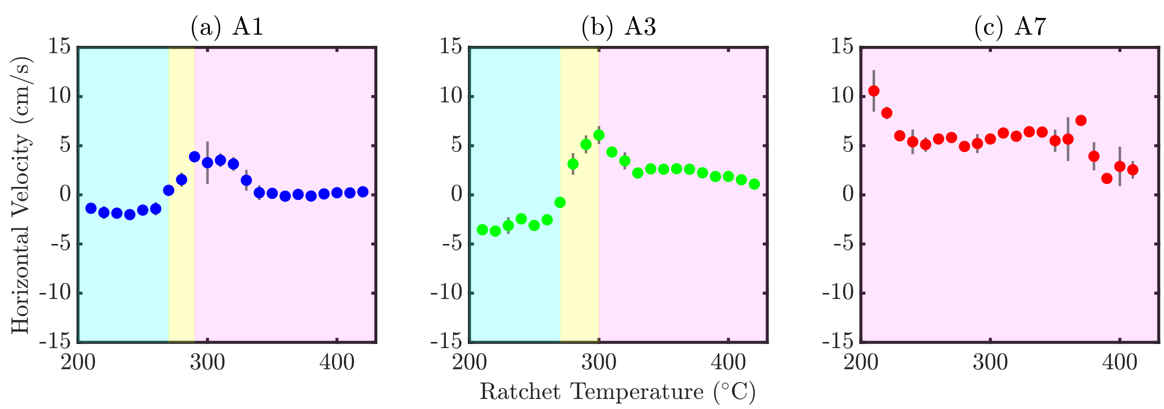

Figure 10. The effect of varying temperature while fixing impact velocity (around 36 cm/s) and geometry. Plots (a), (b), and (c) show experiments done on samples A1, A3 and A7, respectively. The shaded colors—cyan, yellow, and magenta—correspond to the three regimes described below.

With samples A1 and A3, we see three regimes. Below 270 °C, the droplets move in the negative direction predominantly from the propulsion regime. This is shown with the cyan background. From around 270 °C to 300 °C, they go through a transition regime, in which the propulsion and viscous drag effects are roughly in balance. This is shown with the yellow background. From 300 °C, they start to move in the positive direction predominantly from the viscous drag regime. This is shown with the magenta background. Further, the horizontal velocity slows as the temperature further increases. This is explained as the vapor layer thickens and there is less friction to drag the drop in the positive direction. However, recall that in the static case, as a consequence of the temperature gradient balancing the vapor layer thickness, the viscous drag force does not depend on ΔT. Because it appears to depend on ΔT here, it suggests that there is still some propulsion and the amount of propulsion continues to decrease as the temperature difference increases.

With sample A7, we observe something different. In particular, the sample appears to start in the viscous drag regime and stay in it from 230 °C all the way through 400 °C. The more aggressive geometry seems to command a lower threshold temperature for viscous drag effects to dominate, as well as allowing the vapor layer to stay thin enough for the viscous drag to remain effective for a larger range of temperatures. This seems to agree with the findings in [6], as the taller structure should make for a lower dynamic Leidenfrost temperature.

Conclusions

We examined the behavior of impacting Leidenfrost droplets on ratchet surfaces. Our results both build on and challenge the findings of Linke *et al*. and Dupeux *et al*. [3,9]. We propose a new mechanism similar to the rocket-like mechanism proposed in [8], only with the opposite direction of propulsion. This mechanism, we propose, works in combination with the viscous drag mechanism to produce the dynamics of the impacting drop. We suggest that lower temperatures cause less consistent Leidenfrost layers, which in turn lead to rocket-like propulsion in the negative direction of a ratchet. Higher temperatures or more aggressive ratchet geometry allow for a thicker vapor layer to form and a pressure-driven viscous drag mechanism to dominate the dynamics. Increasing the impact velocity increases the resulting horizontal velocity in both of these regimes.

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