Investigating The Dynamics of Leidenfrost Droplets

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The Leidenfrost phenomenon is an effect that happens when a liquid mass is placed on heated surface above the boiling point of the liquid mass. The result is that there is a vapor layer created by the evaporation of the lower surface of the liquid mass, and if the heated surface is asymmetrical the droplets will move. The velocities of these droplets are dependent on the topography and the temperature of the heated surface. This experiment used a heated block of brass with two different, ridged topographies to determine how the velocities of the Leidenfrost droplets would change, if at all, based on topographies and temperature. The results were that the velocity of the droplets on both of the different topographies peaked around 208°C and then decreased in velocity as the temperature increased. The maximum droplet velocity achieved in this experiment was 34.67 ± 0.01 cm/s.

I. INTRODUCTION

The Leidenfrost phenomenon is observed when a liquid mass is placed on a heated surface. If the surface is at a high enough temperature the droplet is supported by a vapor layer generated by the evaporation of the lower surface of the liquid mass [1]. The result is that the droplets evaporate very slowly. This phenomenon was first observed formally by Johann Gottlob Leidenfrost in 1756 in his book titled *A Tract About Some Qualities of Common Water*[1]. Working as a German medical doctor, Leidenfrost studied the boiling of small masses on heated surfaces. In his experiment Leidenfrost used a spoon of heated, glowing iron as his hot surface and distilled water as his liquid mass and released droplets of the water onto the heated spoon [1]. He discovered that the droplets took longer to evaporate as the temperature was increased; the longest times being around 34 or 35 seconds at the hottest of temperatures [1]. The Leidenfrost phenomenon is commonly seen in every day life in kitchens when dropping water on a hot pan to determine if it is hot enough to cook with.

Numerous contemporary scientific experiments have been done investigating the different characteristics of the Leidenfrost phenomenon including the heat transfer between the hot surface and the liquid, how the phenomenon varies with varying liquids and hot surfaces, and the underlying theory behind the phenomenon [2] [3]. Recent experiments have found that Leidenfrost droplets can have self-propelled movement if the heated surface is textured [4] [5]. A 2012 experiment on the movement of these droplets was performed by Dr. Kei Takashina at The University of Bath using a heated block of aluminum with a saw-tooth like topography. It was found that the asymmetry of the saw-tooth surface causes the vapor layer of the Leidenfrost droplets to flow out from the droplet non-uniformly, which induces a net lateral force on the droplet that allows it to be propelled [4] [5]. Dr. Takashina found that, if the surface is angled, the Leidenfrost droplets will actually move uphill [4]. Numerous independent variables can be tweaked in this type of experiment such as the topography of the surface, the temperature of the block, and the angle of elevation which will all cause the characteristics of the Leidenfrost droplets to change.

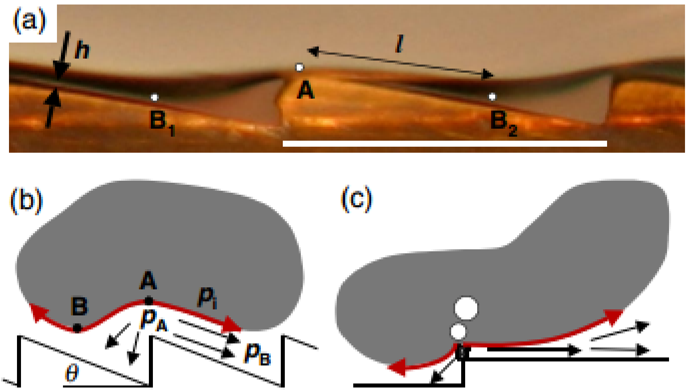

FIG. 1: (a) An image of a Leidenfrost droplet moving across a brass surface. Point A shows the droplet concave curvature, whereas at points B_1 and B_2 the droplet is convex. (b) A schematic of the outward pressure of the droplet on the brass block. The outward pressure of the droplet on the brass at point A is greater than the pressure at points B_1 and B_2. (c) a schematic of the pressure from point A to B_1 escaping along the sides of the ridges. This figure is reproduced from ref.5

II. THEORY

Currently, there is no agreed upon theory as to why Leidenfrost droplets will move on a ridged topography, as this feature of the phenomenon is relatively new. However, theories have arisen to attempt to explain the movements of these droplets; one of these theories comes from the Materials Science Institute and Physics Department at the University of Oregon, proposed by H. Linke et al., and will be the model used in this report. Their model proposes that as the Leidenfrost phenomenon takes effect, the vapor pressure that levitates the droplet will rush out of the droplet laterally as a vapor[5]. Viscous shearing will take place between the vapor and the actual droplet causing a lateral, net viscous force on the droplet [5]. The vapor flow and the pressure are caused by the heat coming off the block, which makes the Leidenfrost droplets, as stated by the H. Linke et al., "essentially heat engines" [5].

The Oregon model uses the fact that, as the droplet moves across the brass block, the droplet will curve convexly or concavely around the ridges, as shown in Fig.1. Because of this fact, it can be assumed that there is a variation in pressure on the block surface. The internal pressure of the droplet P_i is assumed to be constant along the bottom of the droplet, and the pressure caused by the vapor layer is approximated by the Laplace pressure $\Delta p = \gamma/R$, where R is the radius of curvature and γ is the surface tension. In reference to Fig.1, the curvature of the droplet at point A corresponds to a curvature less than zero, or $R_A < 0$, and the droplet at points B_1 and B_2 correspond to a curvature more than zero, or $R_{B_1} > 0$ and $R_{B_2} > 0$. At point A, the pressure exerted on the block by the vapor layer is greater than the internal pressure of the droplet, or $P_i < P_A$. Therefore, from the same logic, the pressure at points B_1 and B_2 are less than the internal pressure of the droplet, or $P_i > P_{B_1}$ and $P_i > P_{B_2}$. Because of this change in pressure there is an expected vapor flow from point A to both B_1 and B_2 [5]. Vapor flows from point A to point B_1 and a viscous shear force is generated from the pressure on the block reacting with the droplet itself, which results in a force on the droplet in the positive x direction; to the right in Fig. 1. Vapor from point A to point B_2, in contrast, flows backwards and is assumed to escape sideways along the grooves of the block because of a small flow resistance [5], as seen Fig. 1. Therefore, the droplet will move in the positive x direction, in accordance to Fig. 1.

The Oregon model proposes two components to the vapor force between points A and B_2 that cause the forward viscous force. The first component is a forward shear force that comes from Poiseuille vapor flow, and is a resultant of the different pressures on the different points. Poiseuille flow is the principle that a liquid or vapor will flow from areas of high pressure to low pressure in a time that is proportional to the difference in pressures and inversely proportional to the distance between the pressure points [6]. In the realm of self-propelled Leidenfrost droplets, the Poiseuille flow shows that the droplet will want to move, in accordance to Fig.1, from the high pressure of point A to the low pressure of point B_2. The second component of the vapor flow force is the viscous drag force, which is given by

$$F_{drag} = -\beta v_x = -\left(\eta A_{eff}/h\right) v_x. \tag{1}$$

The η in Eq. 1 is the vapor's viscosity, A_{eff} is the effective area of the droplet, h is the height of the vapor layer assumed to be between $10 - 100\mu$m [5], and v_x assumes that the droplet is moving in the positive x direction; Eq. 1 is negative because the drag force is acting against the forward momentum of the droplet.

The Leidenfrost droplets reach a terminal velocity after a brief acceleration period [5]. Again, using the Oregon model, the velocity $v_x(t)$ of these drops are described by the equation of motion

$$m(dv_x/dt) = -\beta v_x(t) + F, \tag{2}$$

whose solution, for a droplet of mass m, is given by

$$v_x(t) = \left(v_{0_x} - \frac{a}{\beta/m}\right) e^{-(\beta/m)t} + \frac{a}{\beta/m}. \tag{3}$$

The factor $(-\beta/v_x)$ in Eq. 2 is the velocity dependent drag force on the droplet, and F is the force propelling the droplet (Eq. 3). The terminal velocity is given by the factor $a/(\beta/m)$ in Eq.3, and v_0 is the initial velocity of the droplet [5].

III. PROCEDURE

This experiment was performed using a 14.7 cm by 4.4 cm by 2.3 cm block of brass, a hotplate capable of generating temperatures up to 400° C, a Casio Exilim high-speed camera, a type K thermocouple connected to a multimeter, a level, and a cup of tap water with a plastic syringe. One side of the brass block was oriented with shark tooth like ridges that were 1 mm by 0.58 mm in dimension, shown as Ridge 1 in Fig. 2, and the other side was oriented with shallower ridges that were 1 mm by 0.17 mm in dimension, shown as Ridge 2 in Fig.2. To take data the block of brass was placed on the hotplate and leveled to insure that the Leidenfrost droplets would not be encouraged to move a certain direction simply due to gravity. The hotplate was turned on and the thermocouple was set on top of the brass block so that the surface temperature of the block was always known, as shown in Fig. 3. As the temperature increased, drops of water were placed on the brass block with the plastic syringe to determine when the Leidenfrost phenomenon took effect. The phenomenon was determined by watching the droplets on the brass block; once they started to move fully across the block without evaporating away it was determined that the phenomenon had taken effect. It was found that the Leidenfrost phenomenon fully took effect near 180° C.

Once the Leidenfrost phenomenon was established a 240 frame per second video of the moving droplets was taken at varying temperatures up to 330° C with a Casio Exilim high-speed camera that was placed on a tri-pod and focused on the block. The video was taken at such a high frame rate to insure that the data were as precise as possible. The videos were analyzed in Capstone in a frame by frame manner that tracked the position of the droplet. This was done by creating X vs. Y dimensions in Capstone and tracking the droplet based on its X position, which was parallel to the block of brass, as shown in Fig. 4. Using the known length of the brass block as a reference of actual length the velocity of the droplets could be initially determined by taking the slope of the

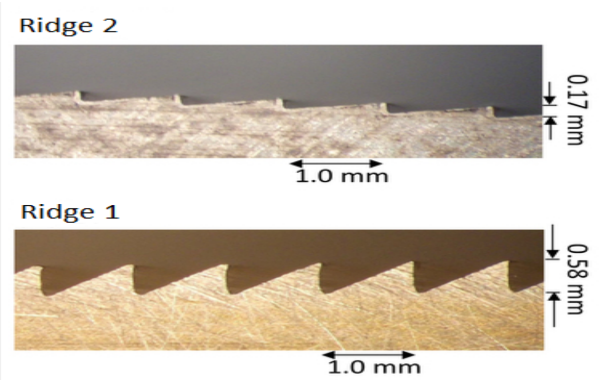

FIG. 2: A focused image on the ridges of Ridge 1 and Ridge 2. This image is reproduced from ref.[5], but the dimensions of the brass block used in the experiment are the same.

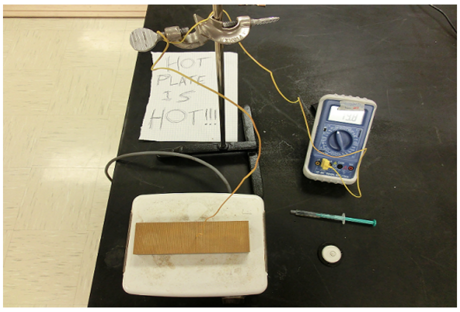

FIG. 3: An image of the set up of the experiment. There is a brass block, a hotplate, a type K thermocouple, a syringe, and a level. The camera was used to take the picture.

FIG. 4: A screenshot of the frame by frame video analysis technique in Capstone. The marks show where the droplet was tracked.

position of the droplet versus the time of the droplet on the brass block. Because Capstone assumes the frame rate is 30fps, the data were exported to Igor Pro to convert to the correct 240fps frame rate; this was done by dividing the time data by eight. This had to be done to find a real time velocity because, for example, a 40 second video at 240 fps is actually a 5 second video in standard time; if the time data were not standardized the velocities of the Leidenfrost droplets would be eight times greater. After the time was standardized, the slope

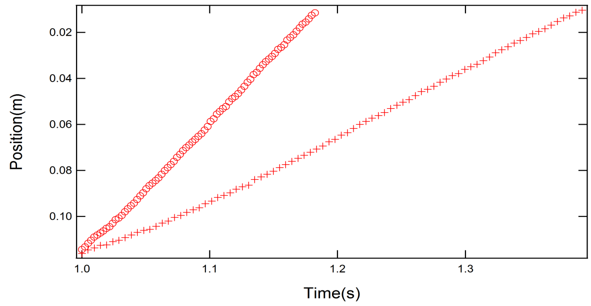

FIG. 5: A sample graph of the x-position versus time of two droplets at $210°C$ in Igor Pro.

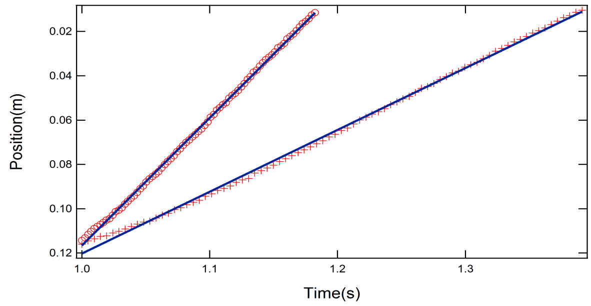

FIG. 6: A sample graph of the x-position versus time of two droplets at $210°C$ with fit lines in Igor Pro.

of the position versus the time on the block was found from graphs similar to Fig. 5 and Fig. 6 to determine the velocity of the Leidenfrost droplets at varying temperatures. This procedure was first completed with the Ridge 1 shark tooth ridges for two droplets, and then again with the Ridge 2 ridges for two droplets. The resulting two slopes for each temperature and ridge topography were then averaged and the uncertainty could then be calculated in Microsoft Excel.

IV. DATA AND ANALYSIS

After the data were taken and plotted against temperature for the respective ridges, seen in Fig. 7, the data showed that the velocity initially increased with temperature, but peaked and then decreased with increased temperatures. This result held true for both of the ridge topographies, as was expected. As the temperature increases, the vapor layer that levitates the droplet also increases in height, which results in a lower pressure on the brass block from the vapor layer, which results in a lower shear force and a lower velocity [4][5]. This fact can be explicitly shown in Eq. 1 where h is in the denominator of the fraction, showing that as the height of the vapor layer increases, the drag force against the droplet decreases. As seen in Fig. 7, the peak in the velocities both happened at the same temperature, which shows that the velocities of the droplets are temperature dependent, which is shown in Eq. 2. As knowledge of the

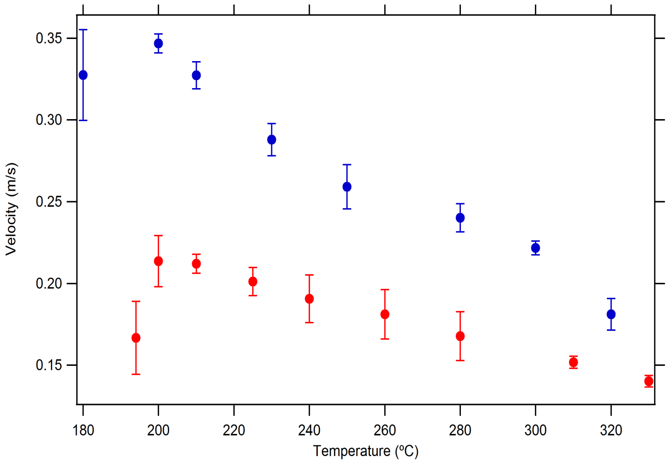

FIG. 7: Graph of Ridge 1 and Ridge 2 velocities based on temperature in degrees Celsius. The blue marks are from Ridge 2 and the red marks are from Ridge 1

velocities of Leidenfrost droplets increase there may be a larger temperature dependence in Eq. 2 than is seen currently.

It was found that the velocities for Ridge 2 were consistently higher than the velocities for Ridge 1 for the same temperatures. This is because there is more of a flat surface on Ridge 2 than Ridge 1, which creates a larger surface area for the Poiseuille flow force to take effect; this fact, in turn, increases the velocity of the droplets on Ridge 2. This came as a surprise, as it naively seems that the smaller ridges in Ridge 2 would slow the droplets down because the droplets would be moving on a flatter surface; analogous to a ball rolling down a steep hill (Ridge 1) and a ball rolling down a flatter hill (Ridge 2). But after checking the theory again after the data was taken, it was confirmed that Ridge 2 droplets should have a higher velocity than Ridge 1 velocities. Another possible explanation as to why the velocities are so different is that the topography on Ridge 1 is much more sharp than the topography on Ridge 2. This could mean that the topography on Ridge 1 pierces through the vapor layer more easily than the Ridge 2 topography, which would result in a increased drag force that slows down the velocities.

The uncertainty in the velocities were found by taking the difference between the velocities of two video recordings of droplets at the same temperature. The uncertainties are higher at lower temperatures because of the smaller height of the vapor layer that levitates the droplet. Because of this small height, there can be instances where the droplet touches the brass block and causes a quick boiling, which causes the droplets to slow down for a time, analogous to a speed bump. Also, with the smaller vapor height at lower temperatures the vapor flow is more susceptible to the microscopic cuts made from the construction of the ridges [5], which would could decrease or at least impact the velocities of the droplets. Because of these two theories there are increased fluctuations in the velocity of the droplets. At higher temperatures there is a smaller fluctuation in velocities as the vapor layer becomes greater and the height increases. The vapor flow from the droplets are then less concerned with the construction cuts, and the speed bumps caused by the droplet touching the brass block can be nearly ignored. Also, as the temperature increased above 300°C, the droplets took longer to start moving initially, like a car that is peeling out, because of the large vapor layer height. In investigating the movement of the droplets without formally recording, it was found that as the temperature was raised above 320°C the water droplets could be slid onto the block opposite the direction that the droplets were oriented to move by the block, and the droplet would slide, come to a stop, and then start moving along the block in the direction oriented by the block. This result was an interesting and fun characteristic of the droplets to find.

V. CONCLUSION

The velocity of self-propelled Leidenfrost droplets are dependent on temperature and topography of the heated surface. It was found that the velocity of these droplets peaked around $205 - 210$°C, and then decreased with an increase in temperature. The velocities of the droplets on Ridge 2 were found to be consistently higher than the velocities of the droplets on Ridge 1 because of a larger surface area for the vapor flow pressure to act upon. According to the Oregon model of the movements of the droplets, the vapor layer of the Leidenfrost droplets increased in height with an increase in temperature, which resulted in a decreased pressure on the brass block leading to a decreased velocity [5]. The maximum velocity for the Ridge 1 droplets was found to be 21.35 ± 0.02 cm/s and the maximum velocity for the Ridge 2 droplets was found to be 34.67 ± 0.01 cm/s.

VI. ACKNOWLEDGMENTS

I would like to thank Dr. Kei Takashina of the University of Bath for giving me initial ideas on how to perform the experiment.

I would also like to thank Tim Seigenthaler for making the ridges that I wanted in the block of brass.

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