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Droplet oscillation and pattern formation during Leidenfrost phenomenon

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ABSTRACT

The unique dynamics of a water droplet over a hot copper substrate due to Leidenfrost evaporation has been reported here. The phenomenon is captured by a high speed camera and analyzed by image processing. During its entire lifetime, the droplet is observed to undergo several shape changes accompanied by simultaneous oscillation and rotation. Further the effect of depletion of droplet volume and substrate temperature on Leidenfrost phenomenon has also been reported.

1. Introduction

The process of heat transfer during boiling of fluids is complex, but of considerable technical importance. Boiling and evaporation of liquid droplets and its consequences are an appealing problem and have attracted immense attention over the years. If liquid droplets are exposed to a surface heated to a temperature close to its boiling point, the drop evaporates and vanishes very rapidly. However, if the temperature of the solid surface is much higher compared to the saturation temperature of the liquid, the droplet levitates above a vapor cushion formed at the solid–liquid interface. As a result the droplets take a longer period to evaporate often exhibiting certain special characteristics. The associated phenomenon is known as the Leidenfrost effect [1] which is basically film boiling of droplets. The first account of the effect was given in the scientific literature by Boerhaave in 1732, some 24 years before the more complete account by Leidenfrost [2]. A summary of the past investigations has been given by Gottfried et al. [3]. The study of drop evaporation was not intensified until the last 40 years when it became more and more important to technical processes. The phenomena of evaporative liquid droplets impacting solid objects of high-temperature are of great importance in many technical applications, such as spray cooling in the heat treatment of metallic alloys, impingement of oil droplets on turbine engines, and re-wetting of fuel rod in nuclear reactor. Leidenfrost effect is one such phenomenon which is encountered in all nuclear reactor cooling processes as during the quenching of the reactor rods from very high temperatures this effect cannot be avoided. Hence there is a fundamental need of understanding the dynamics of Leidenfrost phenomenon.

The ability to control the movement of liquid droplets is crucial in many of the cutting edge applications. Movement and manipulation of particularly very small droplets constitutes a new branch of technology namely, droplet microfluidics. In droplet microfluidics, droplet motion may be achieved by a variety of techniques, namely surface tension forces [3–5], chemical effect [6–11], thermal actuation [7,12], electrical field [13], magnetic field, acoustics, mechanical vibration, etc. The phenomenon in which the droplet motion is actuated by thermal gradient is known as Leidenfrost phenomena [1]. After the first observation of this film boiling phenomenon of liquid droplets by Leidenfrost in 1756 [1], a more systematic study was carried out by Tamura and Tanasawa [14]. The authors called the film boiling phenomena as spheroidal vaporization. Since then, extensive effort has been put forward to study the various factors that affect the drop dynamics. These include experimental studies, as well as analytical and numerical analyses on the effect of ambient pressure, types of liquids, surface conditions (roughness, temperature and material) and initial drop sizes.

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The behavior of droplets on a heated surface was observed by using high-speed photography [15], and the vaporization of spheroidal drops undergoing film boiling was investigated [16]. The total evaporation times for different liquids, such as water, carbon tetrachloride, ethanol, benzene, and n-octane, on a stainless-steel plate at surface temperatures ranging from 150 °C to 500 °C were determined [3]. Due to the low boiling temperature, the Leidenfrost phenomena for cryogens are quite common and have also been studied for liquid nitrogen [17] and liquid helium [18]. The forces and associated governing equations for isothermal and non-isothermal spheres floating on the surface of liquid nitrogen were studied [19]. Many researchers observed different vibrating shapes in the Leidenfrost drops which were of the form of rosettes/stars/chimneys. The observation of vibrating Leidenfrost drops and the subsequent stars were first reported in the early fifties by [20], with a tentative theoretical explanation by Gouin and Casal [21]. It may be noted that vibrations of droplets undergoing Leidenfrost effect are self-generated and are not actuated by any external forcing field. As the Leidenfrost drop continuously loses mass by evaporation, the frequency of oscillation is not constant and the phenomenon is not only dynamic but also transient. Biance et al. [22] investigated Leidenfrost drops under steady dynamic conditions, i.e. by feeding drop with water at the same rate as evaporation, and focused on the vapor layer. They did observe drop vibrations leading to stars as well as 'chimney' instability. The latter is manifestly different from the star instability, and occurs as the drop exceeds a certain size. The authors attributed these chimneys to the growth and rise of a vapor bubble at the center of the drop, due to Rayleigh–Taylor instability [22,23]. However, though several studies have been conducted by researchers across the globe to understand the Leidenfrost phenomena of droplets, many aspects still remain to be unveiled and the exact physical mechanism underlying the phenomena is far from being understood.

The present work aims to investigate some unique aspects of Leidenfrost phenomena. In most of the earlier works, studies were made with small initial droplet volumes giving rise to hemispherical or spherical droplets levitated over a vapor cushion. The larger droplet volumes considered in the present work generated saucer-shaped liquid rafts which exhibited unique dynamics and shape formation. The droplet evaporation characteristics as a function of its projected footprint with time have been investigated extensively. The effect of droplet volume and substrate temperature on the lifetime of the droplet undergoing Leidenfrost phenomenon has been studied in the present investigation. The oscillation and rotation characteristics of the bimodal shape of the levitating droplet have been extensively analyzed from the captured images based on the azimuthal position of the droplet axes. This easy yet effective way of analysis helps to understand the complex dynamics of the droplets.

2. Experimental facility

The indigenously developed experimental facility used to investigate the Leidenfrost phenomena of droplets consists of the substrate with heating arrangement, the arrangement for dispensing liquid drops and the facility for visualization along with illumination. The line diagram of the experimental facility is shown in Fig. 1. The images used in this diagram are representative only and are taken from www.google.com.

2.1. Heating system

It is one of the major components in the test facility which is capable of heating the substrate to a maximum temperature 600 °C. It consists of the following sub components:

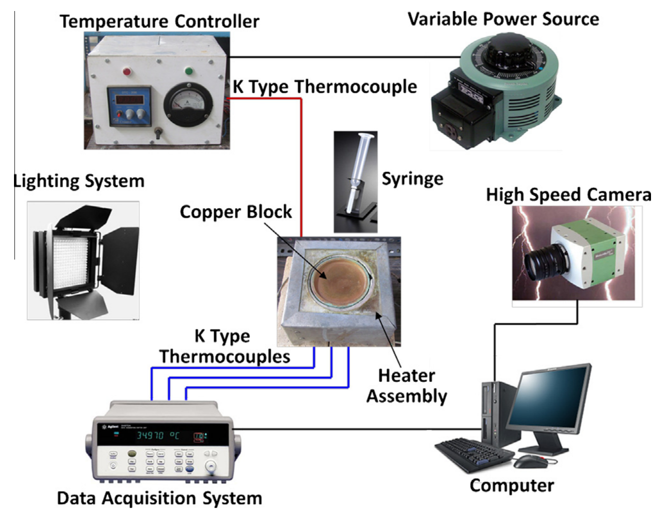

Fig. 1. Schematic diagram of the experimental test facility. The diagram is not to scale. The images shown in this diagram are representative only and are taken from www.google.com.

2.1.1. Heater assembly

The heater assembly consists of an array of Nichrome heating coils that is used to attain the desired temperature (shown in Fig. 2a). The heating coils are appropriately placed within an assembly of thick asbestos plates. A sample asbestos plate is shown in Fig. 2b. Each of the asbestos plates has been machined to appropriately fit the heating coils according to the design. After machining, the coils are placed within the asbestos plate assembly (Fig. 2c) and bolted together (Fig. 2d). This heating system assembly is adequately insulated by glass wool to minimize heat losses and enclosed by an aluminum cover. The inner diameter of the cavity where the copper plate is to be placed is provided with a 5 mm clearance for smooth placement and removal of the block.

2.1.2. Temperature controller

The heating chamber is connected to the temperature controller (Fig. 1) by a K-type thermocouple. The desired temperature can be set at the temperature controller and as the temperature is reached, the temperature controller automatically cuts off. A temperature feedback to the controller initiates the heating coils as the temperature falls below the desired set temperature.

2.1.3. Variable power source

The heating coils are provided power through the temperature controller by a variable power source (shown in Fig. 1) which in turn is connected to the supply mains.

2.2. The substrate

The substrate made from a copper block, has an outer diameter of 90 mm and is placed inside the cavity of the heating chamber for carrying out the experimental study. The inner diameter of the copper block is 80 mm over which area the experiments are carried out. During Leidenfrost phenomenon, as the droplet floats over a vapor cushion, it is seldom stationary (unless the droplet volume is extremely small). Levitation of a liquid mass over the low density vapor is inherently unstable and a slight perturbation can drive the droplet away from the heater. To avoid the spilling of the droplets during experiment, the copper block is designed with a rim of height 5 mm and the top surface of the substrate has been provided with marginal concavity (equivalent slope 1:20), as shown in Fig. 3a. It may be noted that to restrict the unwanted random

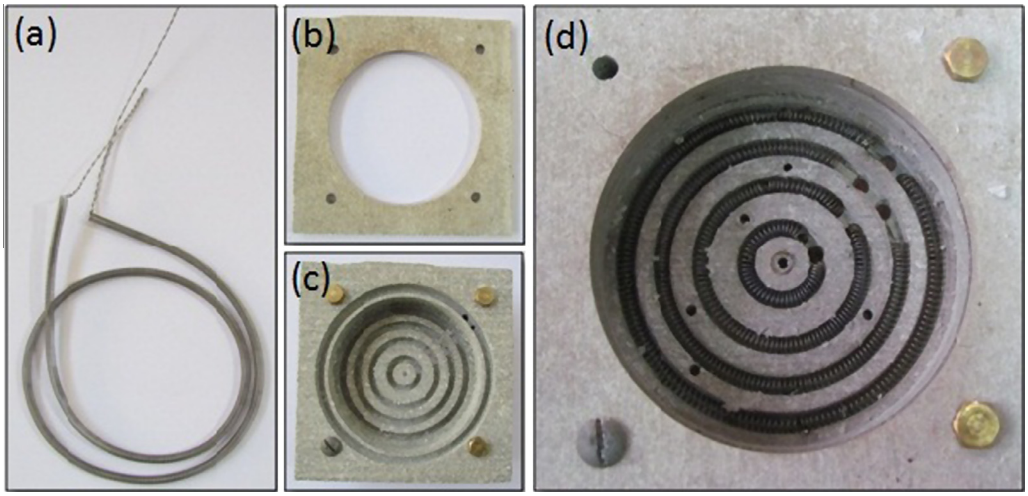

Fig. 2. (a) Nichrome heating coils, (b) a single asbestos plate, (c) assembly of the asbestos plates and (d) heater assembly with the coils in position.

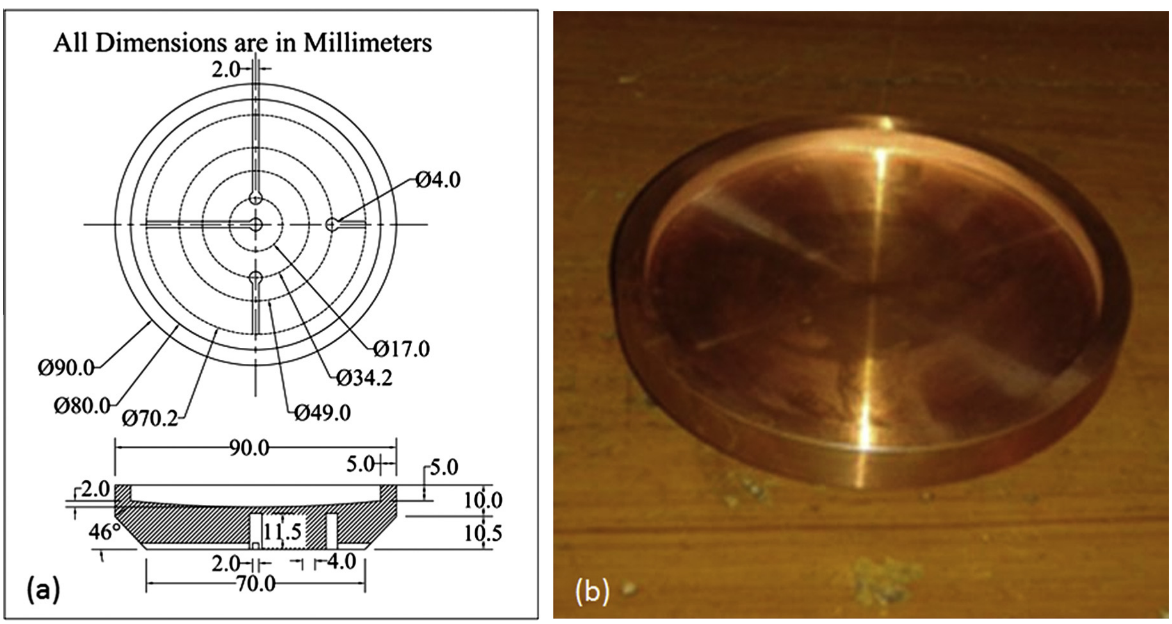

Fig. 3. (a) Schematic and (b) photographic view of the copper block.

motion of Leidenfrost droplets has been a major concern in many of the reported investigations. Accordingly different techniques have been adopted time to time. Concavity similar to that of the present test substrate has been utilized by several researchers [2,3,28,29]. Other methods which are devised for restricting the droplet spillage are by pinning the droplet using a needle [30] and by placing the drop in a Hele–Shaw cell [31]. It is expected that such restrictions guards the droplet against any random motion while having a negligible effect on its natural movement.

The dimensions of the copper block are shown in Fig. 3a and a photograph of the same is shown in Fig. 3b. Four 4 mm diameter holes are drilled at the bottom surface of the block to insert K-type thermocouples to measure the surface temperature of the block. The surface roughness of the machined copper substrate is ~0.5 μm.

2.3. Drop injection system

A syringe clamped to a stand is used for drop deposition of the liquid drops on the copper block. Several syringes of different volumes are used for this purpose.

2.4. Visualization system

A high-speed camera (make: Motion Blitz) has been used to record the evaporation time and shape change of droplets observed during Leidenfrost phenomenon. To facilitate photographic recording a mirror was placed at an angle of 45° with the horizontal above the copper block. The high-speed camera was focused in order to record the top view of the phenomena. A schematic line diagram of the experimental facility with the high-speed camera and mirror in position is shown in Fig. 4. The dynamics of the Leidenfrost drops were recorded at a speed of 100 fps. The videos have been processed and analyzed using Image Pro 6.0 software. The recorded videographs were divided into single frames and by proper segmentation and filtering the required outline of the droplets were traced. The required parameters for analysis were extracted by the help of the software.

3. Results and discussion

In this study, the phenomenon and modes of droplet evaporation impinging on a hot surface have been investigated and the

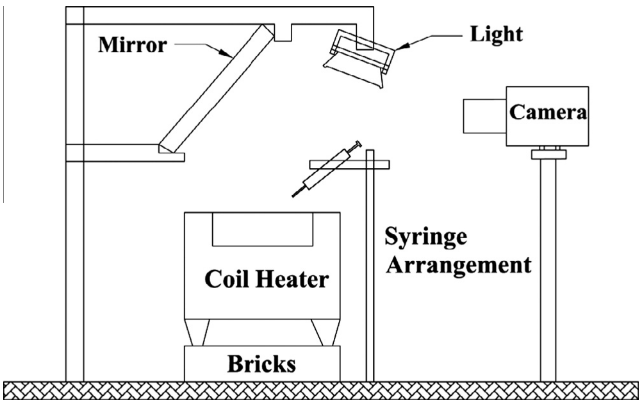

Fig. 4. Schematic diagram of the experimental setup.

droplet lifetimes have been measured. The evaporation phenomenon of droplets is found to be dependent on the initial volume of droplets and substrate temperature. However, during Leidenfrost phenomenon we have observed the formation of different shapes. The droplets have been observed to oscillate and rotate simultaneously. A detailed discussion on the above is given in the following sections.

3.1. Droplet evaporation phenomenon

The copper substrate was heated to 400 °C and the total evaporation time of droplets with initial volumes 1.0, 2.0, and 3.0 ml have been recorded. Image processing of the data captured by high-speed camera shows how the shape and size of droplets evolve with time (shown in Fig. 5). In this figure the different shapes of the droplets are also shown. From Fig. 5 it is evident that

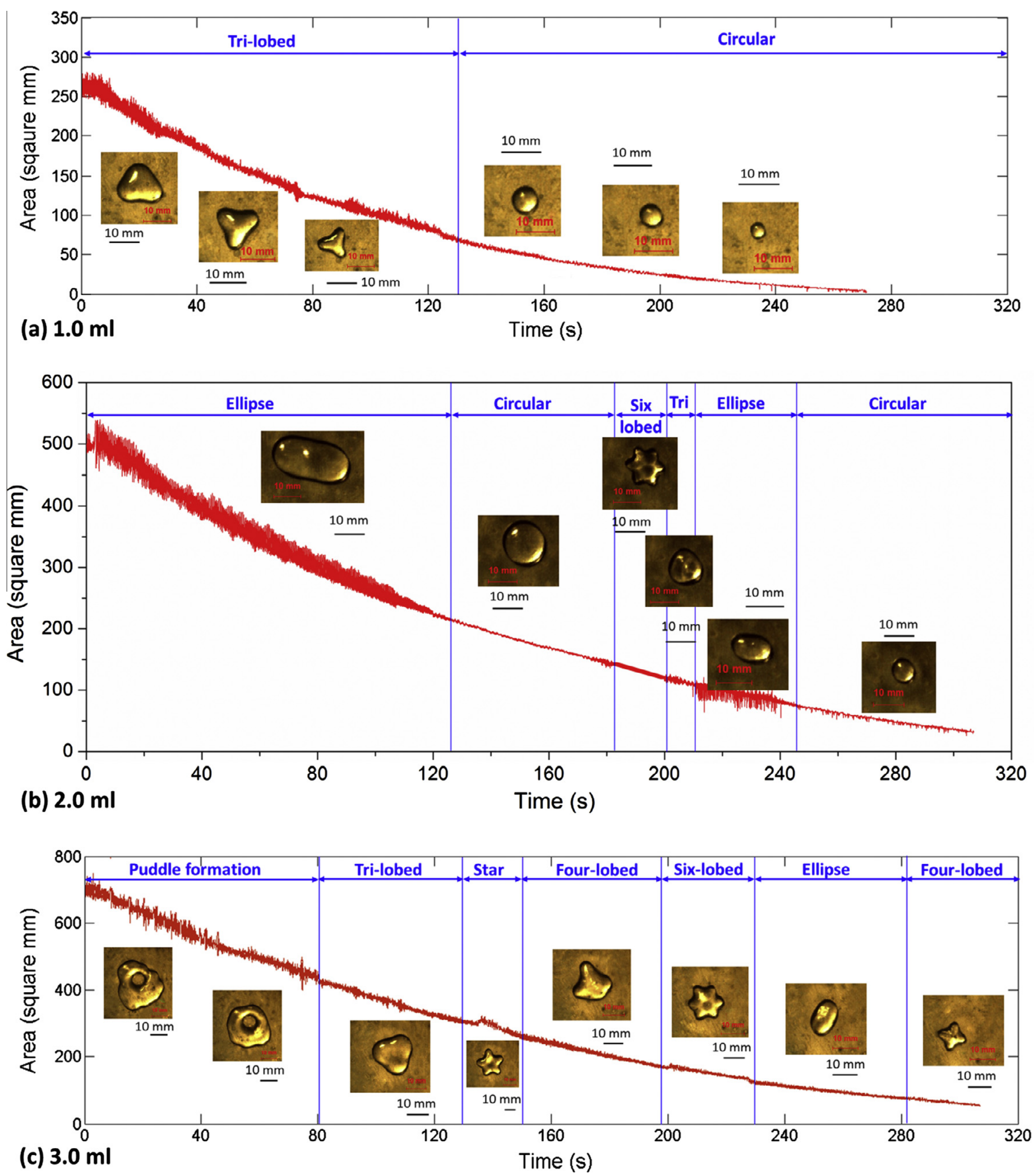

Fig. 5. Evolution of the shape and size of Leidenfrost drops with time for a substrate temperature of 400 °C having initial volume (a) 1.0 ml, (b) 2.0 ml and (c) 3.0 ml.

the projected area of the droplets changes non-linearly with time. It can be seen that for the droplet with initial volume 1.0 ml, shown in Fig. 5a, the shape of the droplets change continuously. The initial droplet takes the shape of a tri-lobed petal, the size of which continuously decreases. Finally, after certain period of time, the shape changes to that of a hemisphere and consequently to a sphere. For a 2.0 ml initial volume droplet, various shapes were observed in the process of droplet evaporation as shown in Fig. 5b. The different shapes were ellipsoidal, six-lobed petal, triangular and spherical. In a similar fashion for a 3.0 ml initial volume droplet, at the onset of evaporation several puddles were observed to form at regular intervals. During formation of puddles, layers of vapor blankets in the shape of hemispherical domes were formed which erupted after certain period of time. As the drop further evaporated and the projected area decreased, shapes resembling that of a tri-lobed structure, five-petal star, six-lobed flower, ellipse and four-lobed petals were observed, sequentially (Fig. 5c). A superimposed plot of the areas of the droplets with initial volumes 1.0, 2.0 and 3.0 ml, respectively is shown in Fig. 6a. From the superimposed plot of droplet areas (Fig. 6a), one can be estimate the time taken by a droplet of a given volume to reduce to a lower volume by evaporation. For example, for a droplet of initial volume of 3.0 ml, while it takes around 40 s to reduce to a volume of 2.0 ml, it takes another 100 s for the same droplet to evaporate to 1.0 ml. Towards the final stages of the evaporation process, the droplet volume decreases and it forms a spherical shape. Due to this the contact area in the proximity of the heated substrate decreases considerably which in turn decreases the evaporation rate of the droplet. Thus, it may be summarized that though the droplet evaporation is rapid at the beginning, it slows down towards the end. Another important fact that may be inferred from Fig. 6a is that the droplet evaporation profiles for all the three initial volumes show a matching trend with acceptable errors.

Fig. 6b shows the variation of area of the droplet with time for three different initial volumes of Leidenfrost droplets in contact

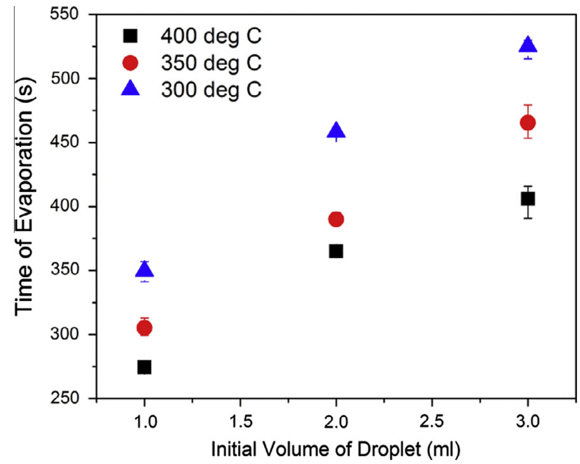

Fig. 7. Evaporation time of Leidenfrost drops over a copper substrate heated to different temperatures.

with the copper substrate heated to 400 °C. The area of the droplet gradually decreases with time while hovering over the vapor layer due to continuous evaporation. The evaporation rate of the droplets as observed from Fig. 5 exhibits an exponential nature. In view of this the variation of the projected area of the droplet is best fitted by regression analysis and is observed to follow an exponential relationship with the evaporation time which can be described by the following equation:

$$A(t) = 1.44 \times 10^{-5} - 43.4V_0 + 1.16A_0 \times 0.994^t \quad (1)$$

where $A(t)$ is the instantaneous area of the droplet at time t in m^2, V_0 is the initial volume of the droplet in m^3, and A_0 is the initial area of the droplet in m^2. It may be noted that the same equation can be utilized to describe the evaporation of Leidenfrost droplets with

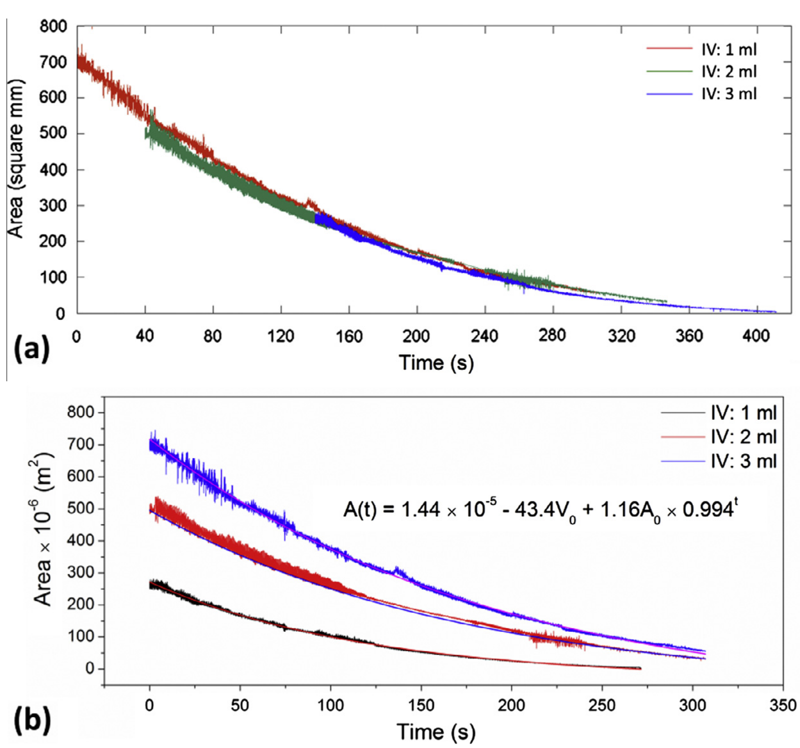

Fig. 6. Area regime map of Leidenfrost drops with initial volume 1.0 ml, 2.0 ml and 3.0 ml over a copper substrate heated to 400 °C (a) superposed on each other and (b) fitted by an exponential equation.

different initial volume. This leads to the observation that the area-time relationship follows the same trend for different volumes of droplets exposed to the same temperature. However, it should be noted that this fitted equation is particularly valid for the present set of experiments within acceptable error limits.

3.2. Effect of initial droplet volume and substrate temperature on evaporation time

Fig. 7 shows the effect of initial volume of the Leidenfrost droplet on the total evaporation time at different temperatures. In this study, the initial temperature of the copper substrate was varied between a temperature range of 300–400 °C with a step of 50 °C. The lower temperature was chosen as 300 °C since below a temperature ~250 °C, droplet sputtering was prevalent as it entered the nucleate boiling regime and the droplet evaporated within seconds. The temperature range being selected, the copper substrate was heated to a particular temperature and the total evaporation duration of droplets with three different initial volumes (1.0, 2.0, and 3.0 ml, respectively) were noted with the help of a high precision stop watch. From the graph shown in Fig. 7 it may be observed that the droplet evaporation time increased almost linearly as droplet volume was increased. The experiments at each initial volume were repeated four times to ensure the repeatability of the tests and no appreciable discrepancy was observed. It was also observed from Fig. 7 that the droplet evaporation time for the same initial volume increased as the temperature of the copper substrate was decreased. Thus there is an inverse proportionality between the droplet evaporation time and substrate temperature if the droplet initial volume is kept constant. The initial radius of a 2.0 ml initial volume water droplet is observed to be ~12 mm. The droplet evaporation lifetime for a 12 mm initial droplet size exposed to copper substrate heated to 300 °C (Fig. 7) is 458 s which fairly matches with an equivalent droplet exposed to duralumin substrate heated to 300 °C as studied by Biance et al. [22].

3.3. Leidenfrost droplet shapes

A thin layer of vapor phase supports the evaporating Leidenfrost drop thus resulting in fundamental instability. The levitating droplet is weakly pinned on the substrate and hence experiences a shape transition from axisymmetric to that having a finite azimuthal wave number. This results in the formation of different star shapes of the droplet extensively due to parametric forcing. In this case, the motion of the droplet is purely driven by thermal effects and the droplet constantly loses mass by evaporation. So it may be presumably explained that the evaporation of the droplet acts as the driving force for the origination of the vibration and different shape formation of droplets. The thickness of the vapor layer beneath the droplet is non-uniform and the vibration of the droplets originates from the undulations in the vapor layer which gradually transmit to the edges and forces the droplet to take different shapes. Some of these observed shapes are shown in Fig. 8. The modes of vibration of the droplets start at two and show multiple lobes as evident from Fig. 8. The various shapes observed are those of ellipsoidal (Fig. 8a), heart-shaped (Fig. 8b), four-lobed (Fig. 8c), diamond-shaped (Fig. 8d), stars having five and six lobes (Fig. 8e and Fig. 8f, respectively), floral shaped (Fig. 8g), and multi lobed (Fig. 8h). Though the multiple lobes of the droplet are not clearly distinguishable the authors took the liberty of presenting the image as a representative. Formation of similar patterns during Leidenfrost phenomena as well as other droplets levitated by air cushion has been reported by several researchers [20,24–27]. It is important to note that although the formation of different shapes of the levitating drop is apparently due to parametric forcing, the mechanism of spontaneous periodic oscillations of the drop is far from being completely understood.

3.4. Analysis of the bi-modal shaped droplet oscillation and rotation

The different modes of vibration of the droplets undergoing Leidenfrost phenomena are observed in Fig. 8. During evaporation the droplet is observed to undergo spontaneous oscillations and several patterns develop with time. To analyze and study this nature of oscillation and rotation, the lowest mode of vibration, i.e. the ellipsoidal shape has been chosen. When a droplet of initial volume 2.0 ml was exposed to a substrate heated to 400 °C the ellipsoidal mode of oscillation was observed. By analysis of the frame-by-frame sequence of a high-speed video it has been observed that the droplets undergo oscillation and rotation consecutively. To analyze the oscillation and rotation pattern, the angle subtended by the major axis of the ellipsoidal droplet with the vertical has

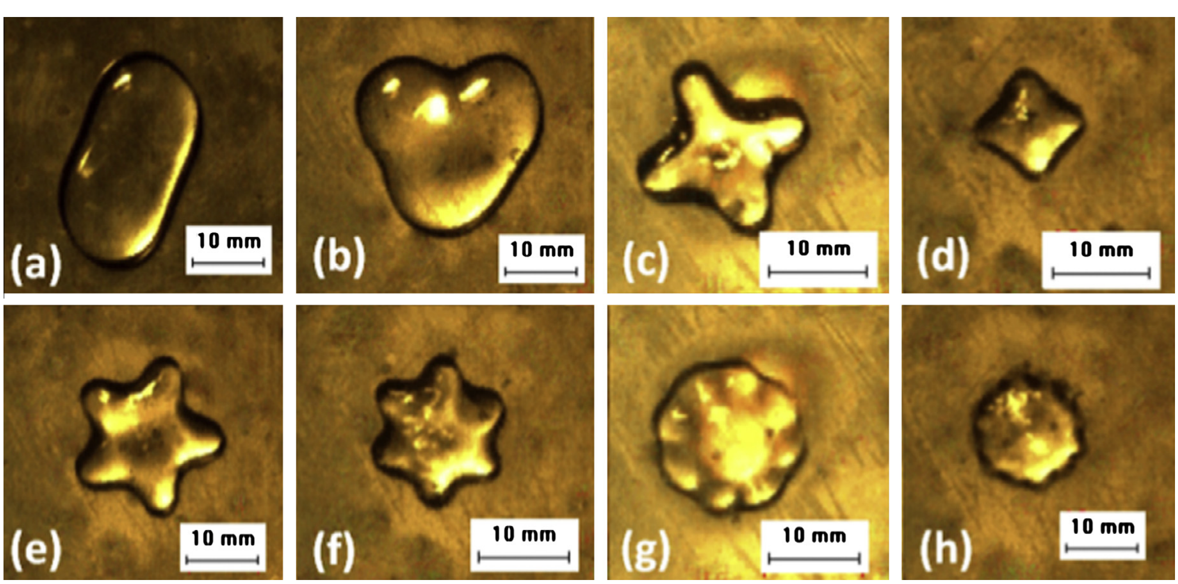

Fig. 8. Different shapes observed during droplet evaporation in Leidenfrost phenomena (a) bi-lobed (ellipsoidal), (b) tri-lobed (heart), (c) four-lobed, (d) four-lobed (diamond), (e) five-lobed (star), (f) six-lobed (petals), (g) eight-lobed (floral) and (h) multi-lobed petals.

been measured at each frame and plotted with time, as shown in Fig. 9a. From Fig. 9a it may be observed that the droplets undergo rotation under oscillating condition and the phenomena is repeated periodically. As the droplet is oscillating about the vertical axis, after every oscillation the angle subtended with the vertical increases (Fig. 9a) indicating the rotational motion of

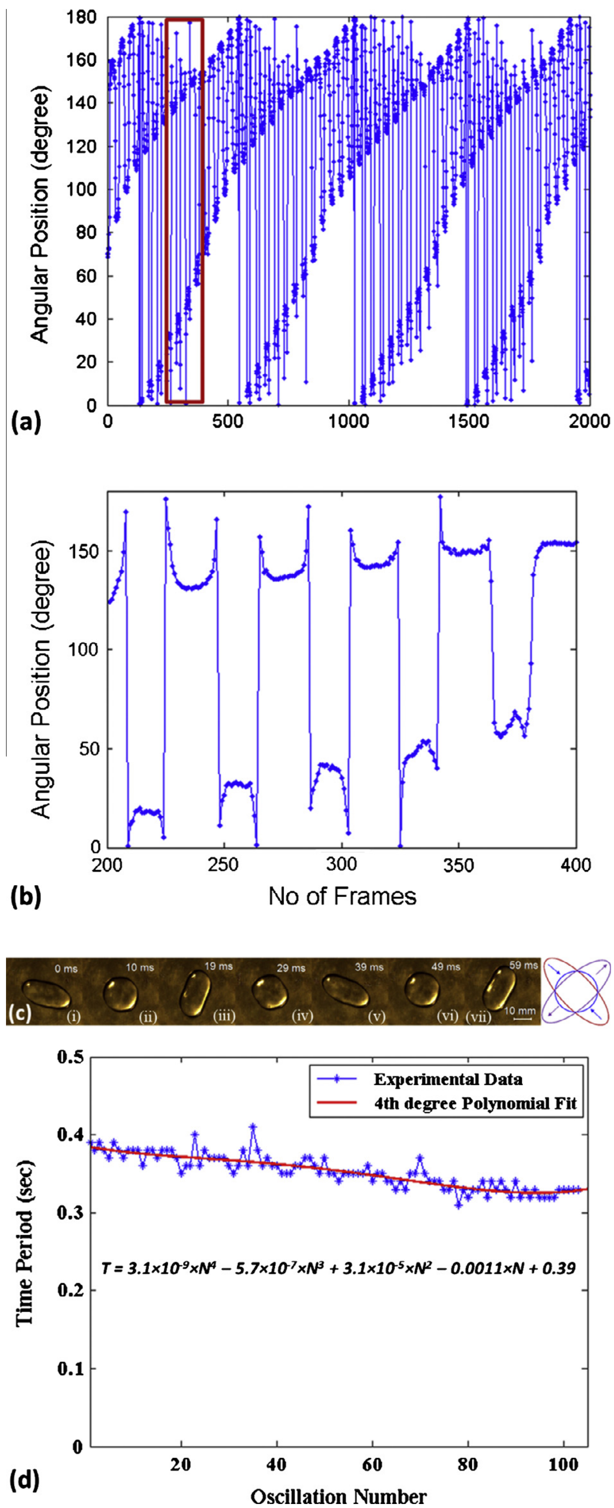

Fig. 9. (a) Variation of angle subtended by the major axis of the ellipsoidal droplet with the vertical, (b) oscillation pattern of the ellipsoidal droplet, (c) oscillation sequence of the ellipse shape of a Leidenfrost drop of initial volume 2.0 ml over a copper substrate heated to 400 °C and (d) time period of oscillation of the droplets.

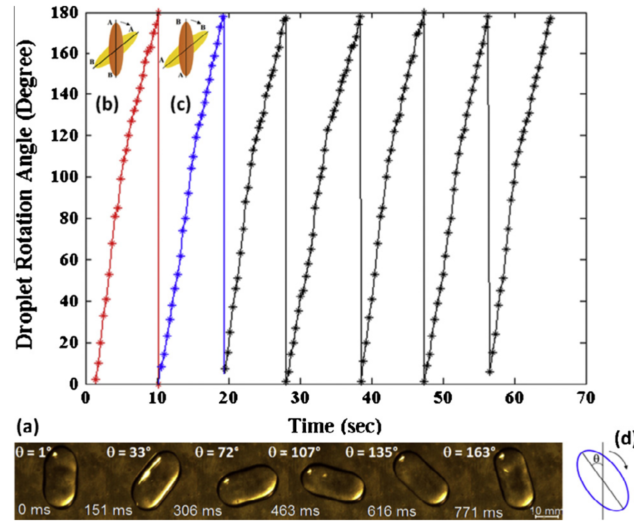

Fig. 10. (a) Angular rotation of an ellipsoidal droplet for time duration of 65 s of initial droplet volume 2.0 ml heated to 400 °C. (b) Schematic for first 180° rotation of the droplet. (c) Schematic for the next 180° rotation of the droplet and (d) photographic sequence of the rotation of droplet for a span of 180°.

the droplets. The oscillation pattern is categorically shown by exaggerating the portion marked by the red[1] box in Fig. 9a and is shown in Fig. 9b. A photographic sequence of the oscillation of droplets is shown in Fig. 9c. In a particular oscillation sequence (Fig. 9c) the droplet first elongates (Fig. 9c-i) and then squeezes along the major axis direction assuming almost a spherical shape (Fig. 9c-ii). Following this the droplet again elongates to the maximum ellipsoidal shape (Fig. 9c-iii) and the sequence is repeated. A schematic of the same is shown in Fig. 9c. From Fig. 9c-i and c-v, it may be observed that the angle subtended by the droplets with the vertical after a complete oscillation changes substantially indicating that the droplet undergoes rotation. The time period of each of the droplets is determined from Fig. 9b, and is plotted in Fig. 9d. It is observed from Fig. 9d that as the number of oscillations increase, the time period taken for each oscillation decreases. The relationship between time period of oscillation and number of oscillations is best fitted by regression analysis with a fourth order polynomial which is described by the following equation:

$$T = 3.1\times10^{-9}\times N^4 - 5.7\times10^{-7}\times N^3 + 3.1\times10^{-5}\times N^2 - 1.1\times10^{-3}\times N + 0.39 \quad (2)$$

where T is the time period of oscillation is s and N is the number of oscillations.

The angle subtended by the maximum elongated droplets at the same orientation at each oscillation sequence is taken as the reference angle for determining the rotation sequence and is plotted in Fig. 10a. From this figure it is evident that as the droplet undergoes rotation; its angle subtended with the vertical increases and can reach a maximum of 180°. As the angular position is analyzed by the Image Pro Plus software and the software detects the angle as that subtended by the major axis with the vertical, as the droplets crosses the 180° value the angle detected again changes to an acute angle. This fact is explained in Fig. 10a–c, respectively. Fig. 10b schematically represents the droplet rotation domain for the first 180°, the angular position of which is marked with red in Fig. 10a. In the next 180° rotation, schematically represented

[1] For interpretation of color in Figs. 9 and 10, the reader is referred to the web version of this article.

in Fig. 10c, the droplet changes position as shown in the figure where the positions of A and B are interchanged. The angular positions of the droplet for the second 180° rotation is marked in blue in Fig. 10a. Hence two half cycles (marked in red and blue in Fig. 10a) constitute a complete 360° rotation of the droplet. A photographic sequence of the angular position of droplet for a 180° rotation at different instants is shown in Fig. 10d.

4. Conclusions

The involvement of many factors in Leidenfrost evaporation of droplets makes the phenomenon a complicated one. Although complete understanding of the parameters affecting the phenomenon remains elusive at present, the general dependence of temperature and initial droplet volume on the evaporation phenomenon has been studied in this work. Further investigation is indispensable to have a clear picture of this important heat transfer phenomenon. The fundamental understandings at the moment are summarized as below:

- The evaporation time of droplets is non-linearly dependent on the initial volume of the droplets. The droplet projected area has been observed to decrease rapidly in the beginning while it slows down towards the end of the evaporation process.
- The evaporation lifetime of droplets is directly proportional to the initial volume of droplets and inversely proportional to the substrate temperature.
- During evaporation the droplet did not remain stationary and was observed to undergo several shape changes under dynamic conditions.
- Each shape of the droplet was observed to undergo periodic oscillation and rotation simultaneously.
- Analysis of the oscillation and rotation characteristics of the ellipsoidal mode of vibration shows that the time period of oscillation decreases as the number of oscillations increases.
- This report of the phenomenon of droplet oscillation and rotation and the analysis of the same is a new frontier in this domain of Leidenfrost film boiling. However, the mechanism of the oscillation and rotation characteristics and related mathematical model need further insight and investigation to completely understand the phenomenon.

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