Study of the Leidenfrost Effect on Heterogeneous Surfaces of Complex Structure

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Abstract. This work is devoted to a research of water droplets that are put in-between two parallel metal strings the distance between which is comparable to linear size of the droplet. Strings are heated by Joule heating to temperatures that exceed critical temperatures of nucleate and film boiling. Different configurations of strings’ side surface have been tested: smooth and with winding made of the same material (intermittent and uninterrupted). Experiments have shown that droplets on these types of surface do not boil away quickly or fall down. Instead they displayed behavior that can be described as floating, either stable or with directed motion, depending on surface structure or relief. Multiple experiments have shown that it is quite similar to Leidenfrost effect demonstrated on a flat overheated surface by liquids.

1. Introduction

The Leidenfrost effect is known since the middle of XVIII century. It consists in, when liquid is placed on a surface, heated to temperatures greatly exceeding boiling point, immediate evaporation of the lower part of droplet, being the closest region to surface. The resulting vapour supports the remainder of the droplet above it, preventing further direct contact between liquid and hot object. It was shown, that vapor, that supports droplet in levitating position, is generated most intensively in center of droplet [1-2].

Among other features Leidenfrost effect can also cause a direct or erratic movement of a droplet along overheated surface. For the last couple of decades, it grew into discrete branch if researches [3].

Previously it was assumed that, in most cases, gravity is the cause of the droplets' movement. In addition, the unsteady behavior of a drop can be caused by the Marangoni effect [4]. The essence of the effect is as follows: drops on the surface of liquid with a non-uniform distribution of the surface tension coefficient begin to shift to the region where this value has a maximum.

In [3] a self-propelled transportation of a droplet on a ratchet-structured brass heated surface was studied. Droplets of R-134a freon of millimeter diameter began to accelerate directionally with an acceleration of 1–2 m/s², after some time acquiring a constant speed of 5 cm/s. Later scientists from the Ecole Polytechnique and the Laboratory of Physics and Mechanics of Inhomogeneous Media in Paris investigated the phenomenon described above for the ethanol droplets in more detail [5].

A congregate classification of main reasons that can cause displacement was formulated:
1) the Laplace pressure gradient caused by the inhomogeneity of the radius of curvature of the drop;
2) processes of matter transfer from the back of the droplet to the front (waves), generating the motion of the droplet;
3) spontaneous droplet oscillations due to the inhomogeneous thickness of the vapor layer are capable to be transformed into kinetic energy of directed motion;
4) the Marangoni effect: the surface tension coefficient has a temperature dependence, and therefore a possible uneven temperature can provoke its inhomogeneous distribution, and hence droplet displacement.
5) while the surface on which the Leidenfrost drop is located is smooth, vapor flows out from under the drop uniformly and isotropically (equally in all directions). If the surface is corrugated, the vapor flow becomes anisotropic, acquiring a certain direction.

It should be noted that the characteristics of the droplet motion also depend on geometric parameters of the substrate relief. According to [5] if radius of drop does not exceed distance between teeth of the corrugated surface, the Leidenfrost effect is not able to move drop. At a larger size, as follows from the theory developed by the authors of the article, droplet’s velocity is proportional to the square root of the ratio of distance between surface teeth and its height.

A self-centering movement and transportation of droplets with low friction using a herringbone structure heated to the Leidenfrost temperature was investigated by Linzi E. Dodd, Prashant Agrawal, Matthew T. Parnell in 2019 [6]. Within the framework of this work, scientists for the first time managed to obtain a directed self-centering motion of a drop with the Leidenfrost effect. They used a surface structure resembling surface used in Linke's work, but the difference was it was inhomogeneous forming a herringbone-shaped mirror structure.

The study of droplet dynamics is also of great practical importance: its results are used in lab on a chip technology, inkjet printing, spray cooling and even in such a mundane process as painting.

Transporting droplets in a controlled and energy efficient manner can also play an important role in some engineering applications such as low resistance fluid transport, water basins, and advanced microfluidic devices.

2. Methods and materials
Investigation of Leidenfrost effect was held on experimental stand (figure 1) that was setup particularly for that occasion.

![Figure 1. Experimental setup scheme.](image1)

2.1. Experimental stand
Two parallel strings (1) are stretched between two vertically aligned ceramic tiles (2) acting as supports. Strings lay in grooves that are chiselled on upper sides of tiles. The distance between centers of grooves is 2 mm. Strings are made of nichrome – an alloy, that is characterized by high operating temperatures (up to 1100 °C) and mechanical strength (tensile strength 0.65-0.70 GPa). We chose ceramic tiles as supports for stretching strings because of its great heat and electrical insulation properties and availability. Tiles are set vertically on a platform made of composite epoxy material (CEM) (3). There is a tensioning system (4) fixed on a platform aside from tiles. It provides ability to
stretch strings with tension, because strings can sag when heated due to nichrome’s high coefficient of linear thermal expansion (18×10⁻⁶K⁻¹). The system consists of a bar that is mobile controllably in vertical dimension, on which two ceramic insulators (5) are nailed down. Strings are rigidly fixed on these insulators. Platform 3 is installed under optical microscope (6), thereby its vertical position could be regulated by microscope’s adjusting wheel (7), helping us to get clear view of droplets from above.

Strings are heated by potential difference. Its value is controlled by a set of transformers, variable autotransformer (8) in particular, connected to 220 V electrical network. Step-down transformer (9) is also in circuit. Amperage is controlled by ammeter (10) connected in series. Next step in the circuit – metal strings, connected by pin clips (11).

Distilled water, dosed to 4 μl droplets, is supplied onto strings via stated on a rack dispenser (12).

2.2. Studied surfaces

Metal strings had different configurations: smooth nichrome wire, diameter 0.4 mm (figure 2a); wire with intermittent winding (figure 2b); wire with uninterrupted winding (figure 2c):

![Figure 2. Nichrome strings: a) smooth; b) with intermittent winding; c) with uninterrupted winding.](image)

In case of a winded strings second wire of 0.1 mm diameter is wound around the first one. Both wires are made of nichrome. Winding was done using electric motor: its shaft has been mounted coaxially with a main string attached to the shaft. Constant thread of 0.1 mm was ensured by clamp and fixed rotation speed of the shaft. Direction of the winding on two strings was oppositely directed, so one string with a winding was a mirror image of the other, so that the projection in the top view was a "herringbone". For uninterrupted winding a set of components is the same as in previous configuration. The difference is that in this case there is no thread – every other turn of winding lays back to back to previous one.

3. Experiments

Voltage was applied to strings according to the scheme shown in Figure 1. Due to Joule heating, because of the finite resistance of the conductor, strings began to heat up. Introduction of winding reduces heating rate of strings, i.e. to reach the same temperature, strings with a winding required higher voltage than strings without it. One of the reasons is the increase in the heat dissipating area. Thanks to this property, a finer temperature setting can be achieved (figure 3).
3.1. Smooth strings
Putting droplets on different configurations of strings gave different results. In particular, on smooth nichrome wires the profile of droplet looked as shown on Figure 4a. Droplet was either still or wobbled around stable position. It stayed upon strings until its diameter became smaller than distance between strings (figure 4b).

![Figure 4. Droplet on smooth strings at the initial (a) and final (b) moments of its lifetime.](image)

During first series of experiments voltage was adjusted to set of values from 40 V to 60 V, which corresponded to temperatures from 300 °C to 600 °C (Figure 3). For every temperature a lifetime of a droplet on strings was measured. Based on results obtained, the following graph was constructed for the dependence of lifetime of droplets from surface temperature of strings (figure 5):
Figure 5. Temperature of smooth strings affect lifetime of water droplets.

According to this dependence, we can conclude that the higher surface temperature of strings was set, the shorter average lifetime of droplet became. It was also noticed that at lower temperatures periods of chaotic oscillations of droplets were observably shorter than the whole lifetime. But starting from 470 °C almost all the time that droplets spent on strings they wobbled. It is worth noticing that droplets explosively evaporate away just as they touch ceramic walls of supporting tiles.

It can be assumed that the lifetime decreases due to the fact that with increasing temperature of the superheated surface, the intensity of vaporization increases, which leads to a more rapid evaporation of the droplet.

3.2. Strings with constant-stepped winding

The second part of research consisted in experiments with nichrome strings of a 0.4 mm diameter with intermittent winding (0.1 mm spacing between coils). At temperatures of 300 °C and 350 °C, droplets evaporate immediately when in contact with strings. When the temperature of strings was increased up to 420 °C, the Leidenfrost effect occurs in nearly half of all of cases, drops kept stationary (Figure 6).

Figure 6. Droplet staying on strings with constant-stepped winding: a) floating on them, front and b) side view; c) hanging under strings.

As droplets stayed on strings they kept evaporating. The volume of liquid, that was held above the strings, decreased and droplets’ center of gravity shifted lower until the drop ceased to be held above the strings. However, unlike in the case of ordinary strings, droplets did not fall down, but they hung on strings from below, continuing to evaporate (Figure 6c).
Also, at this temperature, droplets were seen to explode or jump back onto dispenser needle once touching heated strings. In the remaining 50% of cases, the drop evaporated.

With temperature increasing up to 450 °C, in 10% of cases a directed motion of a drop along the surface of strings was observed. In the remaining 90%, droplets remained stationary above strings. With further increase of strings’ temperature, the ratio of number of moving droplets to stationary increases. For example, at 590 °C, 100% of the droplets move. Possible explanation: due to ribbed structure of strings some amount of vapor flows away along winding near the droplet, thus decreasing effective vapor “cushion” that holds droplet above strings. Hence difference of graphs on Figure 6 and Figure 7. The higher temperature of superheated strings with constant-stepped winding is, the more vapor is being exhaled from under the droplet, which helps to compensate vapor escaping through winding. Because of the geometry of the surface droplets tend to move. Thus, the higher the surface temperature is, the less ratio of vapor escapes, the thicker the vapor layer becomes and the greater reactive forces, acting from the superheated surface perpendicular to the drop center, are (Figure 7):

![Figure 7](image)

**Figure 7.** Temperature of strings with intermittent winding affect lifetime of water droplets.

3.3. **Strings without spacing between coils**

For strings with uninterrupted winding it was observed that for interval of temperatures from 300 °C to 350 °C, the Leidenfrost effect is not present – the drop evaporates instantly once touching strings. But with further increasing temperature up to 420 °C and higher, the Leidenfrost effect appears (figure 8).

![Figure 8](image)

**Figure 8.** Droplet floating on uninterrupted hot nichrome strings: a) front and b) side views.
According to results of observations, the drop "moves" along the direction of the strings nearly in every two out of three cases of contact with strings at 420 °C. In the remaining one third of all cases, droplets dripped down from strings. With further increase of the temperature of strings number of "moving" drops increases. For example, at 560 °C, almost all of the droplets "move". In contrast with two previous parts of the experiment, droplets on uninterrupted winding of strings did not rest steady. Therefore, in this part of the research, there was no possibility to measure lifetime of droplets.

4. Conclusion
Experiments have shown that droplets on two heated parallel metal strings, the distance between which is comparable to linear size of the droplet, do not boil away quickly or fall down. Instead they displayed behavior that can be described as floating, either stable or with directed motion, depending on surface structure or relief. Multiple experiments have shown that it is quite similar to Leidenfrost effect demonstrated on a flat overheated surface by liquids.

On smooth nichrome strings without winding droplets either float still or wobble around stable position and fall off only when droplet's diameter becomes smaller than distance between strings. The higher surface temperature of strings was, the shorter average lifetime of droplet became.

On strings with intermittent winding a process observed depended on temperature quite strongly. On strings heated up to 420 °C nearly half of droplets falls off, another half floats stationary. At 450 °C 9 out 10 droplets slowly evaporate away steady, 1 out of 10 begin to move. This proportion changes with temperature's increase. At 590 °C 10 out of 10 droplets began to move.

On strings with uninterrupted winding situation with temperature dependence was almost the same except that no stationary floating of droplets was observed. They either drip down or display constant movement.

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