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Leidenfrost effect on strings

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New manifestations of the Leidenfrost effect (levitation of limited volumes of liquid over an overheated surface) on smooth and morphologically complex thin metal strings are described for the first time. Various dynamic modes of Leidenfrost levitation are presented, including a new one — a combined thermohydrodynamic mechanism of levitation as a sum of the effects of a viscous vapor flow under a drop and a convective flow around a drop with a mixture of vapor + air due to natural convection.

Keywords: Leidenfrost effect, thin strings, surface morphology, levitation mechanism, steam layer.

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The results of studies into stream–droplet flows find practical applications in the development of alternative energy systems, techniques for synthesis of new materials, and active thermal management solutions. If a solid surface is sufficiently overheated, liquid does not come into contact with it: a viscous vapor flow under droplets creates a lifting force that counteracts the weight of droplets [1–3]. A viscous flow is induced by vapor spreading along the surface, which establishes the lifting mechanism. Although this mechanism undergoes certain modifications in the case of weakly nonuniform surfaces (meso-, micro-, or nanostructured surfaces), it is still preserved in general. The impact of liquid droplets on overheated metal wires has been examined for the first time in [4], but no levitation (even quasi-steady one) was reported. The present study is the first to demonstrate that the Leidenfrost effect may be observed both on smooth thin metal strings and on morphologically complex strings (e.g., strings with winding or deposited nanostructures). The results of calculations revealed that a viscous vapor flow under a droplet generates only a fraction of the levitation force; the remaining part of the overall lifting force is provided by droplet „floating" due to natural convection of a vapor + air mixture and a vapor flow along the strings, which stabilizes the process.

The key elements of the experimental setup are two sections of one and the same nickel–chromium string stretched parallel to each other between ceramic holders with guiding grooves cut with a spacing of 1 mm. The ends of this string are secured to a screw tension system on ceramic insulators.

Strings are heated by applying a potential difference to them. The ends of a string secured to the screw tension system are connected for this purpose to an electrical circuit containing a reducing transformer and a laboratory adjustable-ratio autotransformer. The tension system is needed due to the fact that a metal string sags under heating. Droplets of a given volume (from 3 to 5 μl) are deposited onto strings from a height of 3–5 cm with the use of an injector.

The behavior of droplets on strings of the following configurations was studied: (1) smooth; (2) with intermittent winding; (3) with tight winding (Fig. 1, *a*). The diameter of primary (axial) strings was 0.4 mm. The diameter of nickel–chromium wire used to produce a surface relief was 0.1 mm. Turns of this wire were wound with a pitch of 0.1 mm and side by side to produce strings with intermittent and tight winding, respectively. The heated section length was 3.3 cm. Figure. 1, *b* shows a droplet levitating on overheated smooth strings imaged with a Point Grey Flea3 camera. Figure 1, *c* presents the variation of temperature of strings of different configurations (measured with Cr/Al thermocouples) with applied voltage. According to this plot, the voltage needed to heat strings with winding to a certain temperature was higher than the one required for smooth strings. This is probably attributable to an increase in heat dissipation area and provides an opportunity to perform a finer temperature adjustment.

At room temperature, two types of interaction between droplets and strings are possible: wetting from the top and sinking below the strings. These regimes are established depending on the distance between strings and the droplet volume. Note that the contact Young mode (wetting on smooth surfaces) is seen clearly for smooth strings, while the presence of the wetting mode in experiments with nonuniform strings with winding could not be established (in our view, however, this is the Wentzel mode below the Leidenfrost temperature) [5]. Since both types of interaction were observed only when a droplet was in contact with two strings, a similar interaction is considered below.

Further experiments were carried out with strings of the three mentioned types heated to temperatures above the Leidenfrost one. The Leidenfrost effect was observed within the entire temperature range (300–590°C) for smooth

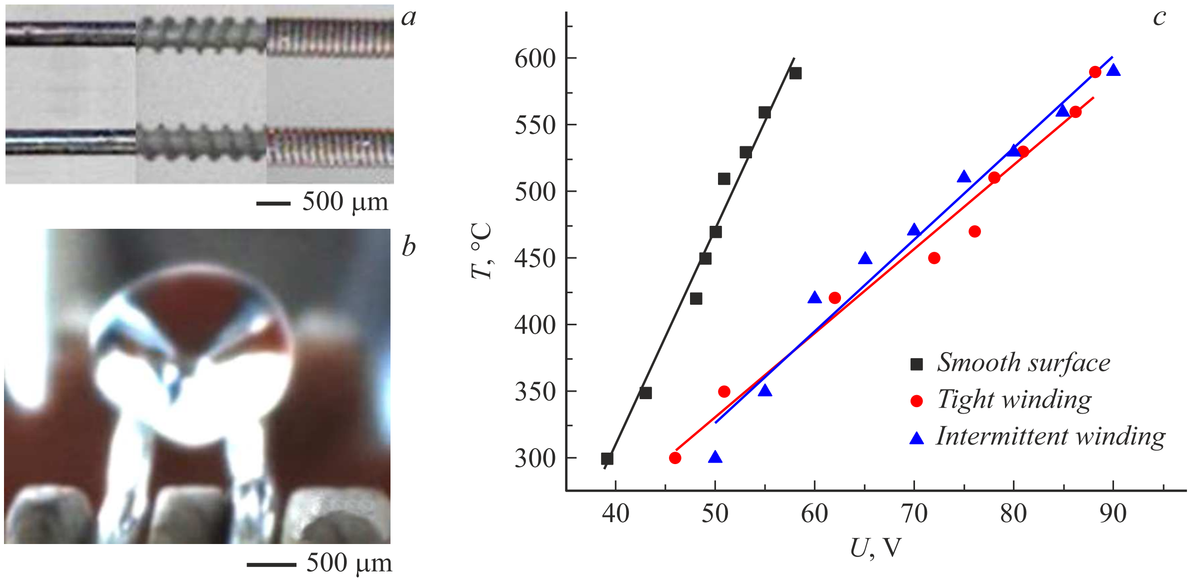

Figure 1. Leidenfrost effect on strings. *a* — Metal strings (smooth and with intermittent and tight winding); *b* — image of a droplet on overheated smooth strings; *c* — dependence of the temperature of strings on their configuration and the applied voltage.

strings; a droplet was either at rest or in chaotic oscillatory motion along strings. Its diameter decreased as a result of evaporation. Having reached a size approximately equal to the distance between strings, it sank down between them. The Leidenfrost effect was not observed on strings with tight winding at temperatures of 300–350°C: a droplet evaporated on contact with strings. Levitation was noted when the string temperature increased to 420°C. This effect was seen fairly clearly: droplets on strings were motionless below the Leidenfrost temperature and moved fast along strings (with characteristic velocities on the order of tens of cm/s) at temperatures above the film boiling one. According to observational data, droplets move in these conditions along the given direction in approximately 2/3 of all cases and sink down in the remaining 1/3 of experiments. The stability of retention of droplets on strings increased ($\sim 90\%$) with a further increase in temperature.

The obtained experimental data confirm that droplets levitate above stretched metal strings. At the same time, if one considers the classical mechanism of droplet levitation in the Leidenfrost effect, where the leading part is played by a viscous vapor flow under a droplet that creates the lifting force and counteracts the droplet weight, it becomes apparent that the overall force is related to the droplet area exposed to a viscous vapor flow.

The existing models of the viscous levitation regime [1–3,6] do not provide an explanation for the droplet levitation, since the substrate area is significantly smaller than the one found in the case of a plane heated surface. The results of calculations within these models demonstrate that a lifting force of just 60–70% of the one needed to counteract the droplet weight is provided by introducing the area of contact between a droplet and the vapor flow across strings into calculations. The question of character of the additional force contributing to levitation is the key one arising in the study of the Leidenfrost effect on thin strings. The overall force balance (Fig. 2, *a*) may be written in this case in the following way:

$$(\rho_l - \rho_v)V_g = 2\pi \oint_S [p_{eff}(r) + p_{conv}(r)]dr$$

$$\approx 2 \int_0^{r_{eff}} (r) + \int_0^{r_{conv}} P_{conv}(r)dr. \quad (1)$$

Here, r_{eff} is the radius of effective evaporation surface, which is close to the radius of an individual string, and r_{conv} is the region of convective heat exchange (approximately corresponding to the mean distance between strings). Owing to the high temperature of strings, a sufficient hot zone forms under a droplet, and natural convection emerges, producing an additional pressure of hot gas (air + vapor) under a droplet. This pressure is the second term in relation (1). Note that a third term supporting levitation (evaporative pressure, which is a reaction impulse produced upon droplet evaporation) may emerge if droplets are sufficiently small. The contribution of a viscous vapor flow along strings under a droplet was also taken into account (for a $3.5\,\mu$l droplet; see Fig. 2, *b*). Radial and axial vapor flows induce pressure, which may be calculated as

$$p(r) = 6[(j_m v_v)/(\rho_v \delta^3)]\left\{r_{eff}^2 - r^2\right\}. \quad (2)$$

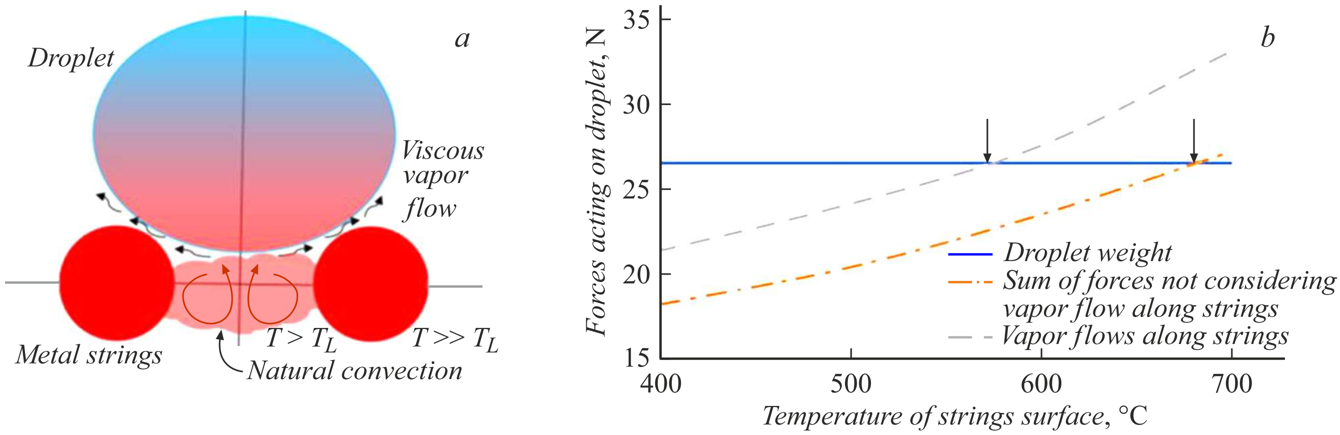

Figure 2. Levitation on strings. *a* — Diagram; *b* — balance of forces as a function of temperature.

Here, j_m, v_v, and δ are the mass flow of vapor, the velocity of vapor flow, and the vapor layer thickness, which may be calculated using standard algorithms [1,3].

The relations for convective heat exchange under natural convection from a cylinder may be used to calculate the pressure exerted on a droplet by a convective flow. Naturally, the numerical problem of vapor and air distribution needs to be solved in the general case, but simple empirical relations for natural convection from a heated cylinder are sufficient to obtain estimates [7].

It is seen clearly in Fig. 2, *b* that the levitation force and the droplet weight come into balance only at temperatures above 690°C (indicated with arrows) if the spread of vapor along strings is neglected. At the same time, if the vapor flow along strings is taken into account, an additional force from viscous flow emerges and induces levitation at temperatures above 580°C. This pattern agrees closely with the one seen in experiments.

Note that experiments with varying diameters and numbers of strings were carried out [8,9]. The obtained data essentially confirmed the validity of key findings reported in the present study.

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Conflict of interest

The authors declare that they have no conflict of interest.

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