Evaporation of levitating liquid microdroplets over a dry heated surface

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Abstract. The present work is devoted to the study of the evaporation process of micro-sized water droplets levitating over a heated dry substrate. The study of this process is relevant in connection with the development of spray cooling systems. Due to the extreme complexity of this phenomenon the mechanism of spray cooling is still not fully understood. In this work we studied the evaporation of micro-sized water droplets levitating over a dry substrate heated from below. The working area was open to the atmosphere. Evaporation was studied in the temperature substrate range from 23 to 95°C. During the experiment local values of the substrate temperature and geometric characteristics of the drop were determined. In the experiment a shadow method with high spatial resolution was used, shooting was performed with a high-speed camera.

1. Introduction

Spray cooling is widely used in numerous industrial applications, including the steel rolling industry and the cooling of power electronics [1]. Due to the extreme complexity of this phenomenon, the mechanism of spray cooling is still not fully understood [1-3]. For example, with this method of cooling, the microdroplets of the liquid may not reach the heating surface, which affects the cooling capacity and can lead to severe overheating of the cooled device. An analysis of the scientific literature showed that the behavior of liquid microdroplets that fall on a solid surface with a temperature of up to the Leidenfrost point has not been sufficiently studied [4].

Droplet levitation over solid super-heated surfaces has been studied in the numerous papers devoted to the Leidenfrost phenomena [5-7]. In [6], the authors found out that at the last stage of evaporation, when the radius of the droplet becomes less than a certain value, the distance between the droplet and the substrate instantly increases, reaching a height that is many times greater than the droplet radius. In the intermediate mode, when the droplet radius is greater than the minimum critical radius (when the drop sharply gains height), but less than the maximum critical radius (when the drop falls on the substrate), the thickness of the vapor film between the drop and the substrate increases as the drop radius decreases.

V. Schaefer in 1971 for the first-time has published [8] observations that microscale droplets of condensed liquid may levitate over a hot liquid-gas interface. Decades later, after conducting several experimental studies of this phenomenon [9], it was found that due to intensive local heating the levitating microdroplets may organize themselves into regular structures, the so called “droplet clusters” [9,10]. In [11,12] the authors conducted a detailed analysis of trajectories of levitating microdroplets above a heated liquid layer with a dry patch. The obtained results allowed determination of local velocities of moist air in a vicinity of the contact line at the dry patch.
The authors of [13,14] for the first time have shown experimentally that an ordered array of levitating microdroplets can appear not only at the liquid-gas interface but also over a dry substrate. To develop a theoretical model [13], explaining this phenomenon, for the sake of simplification, it was assumed that the size of the droplets is significantly smaller than the distance between the droplet and the substrate \( h \), also non-stationary effects and convective mass transfer were considered as the least significant for a system of this size. Taking into account these assumptions the local distribution of the vapor layer density between the drop and the heated surface was described by the stationary diffusion equation. It is the diffusion around the droplet that leads to the movement of the liquid also known as the Stefan flow. The relative height of the droplet levitation in the experiments approximately followed the power law \( R^{-3/2} \), which is consistent with the developed theoretical model for describing droplets in the Stefan flow (Fig. 1). Taking into account in the model the droplet size and inhomogeneity of its temperature allowed the description of the levitation height for larger droplets [15]. To describe the levitation of larger droplets above the liquid film, a vapor flow from the liquid surface was added to the model [16].

![Figure 1. Comparison between experimental results (three different droplets at the same substrate temperature of 85°C) and theory \( h/R \sim R^{-3/2} \), solid line] for droplets levitating over a dry heated substrate [13].

In the current paper, we built new experimental setup to conduct the experiment under more controlled conditions as compared to previous works [11-13]: communicating vessels were used to maintain the required liquid level on the substrate, \( T=\text{const} \), also we made a groove on the surface of the substrate in order to keep a dry spot, since the purpose of the work was to study the evaporation of microdroplets levitating directly over a dry heated surface. In the experiment we used optics with a high spatial resolution (400 nm/pixel), 2 times higher than that used previously for the similar experiments.

2. Experimental setup and methods

The experimental set up includes a stainless steel cylinder with a diameter of 18 mm and a copper rod with a diameter of 3 mm pressed into it, which acts as a heating element. The cylinder is mounted in a fiberglass base with a diameter of 24 mm. The source of heat is a nichrome spiral wound on the
free part of the rod. The spiral is covered with a layer of thermal insulation material. The scheme of the experimental set up is shown in Fig. 2.

![Experimental Setup Diagram]

**Figure 2.** The scheme of the experiment.

In order to keep the dry patch on the substrate stable, we have made a circle groove with a diameter of 1.3 mm at the substrate. This configuration allows us to study levitation of microdroplets over a dry surface using optics with high magnification. A K-type thermocouple was connected to the substrate to measure the temperature. The experiment was conducted at room temperature of 23±2°C, at atmospheric pressure. Room temperature ultra-pure Milli-Q water was used as a working fluid. During the experiment, the humidity in the room was 31-32%, the initial size of the droplets varied from 4 to 15 microns. The heating element was supplied with a voltage from 2 to 3 V and a current from 0.8 to 1.5 A. The max temperature that allowed the successful experiment was 95°C. The substrate was mounted horizontally.

For visualization we used a high-speed FASTCAM SA1.1 camera with a resolution of 1024 × 1024 pixels and a frequency of 250 to 5400 fps, and two high-resolution microscopic lenses (Mitutoyo Plan Apo Infinity Corrected Objects) with magnification of 20x and 50x. The maximum resolution of the camera with a 50x lens was 391 nm/pixel (the field of view of the camera is 400 microns wide) and 600 nm/pixel for a 20x lens. In this experiment the diameter and the height of the droplet levitation were measured. To maintain the required liquid level and substrate temperature in the cuvette we used a system of communicating vessels: a container with the working liquid was connected to the hole in the working area using a silicone tube. The dry patch in the liquid film was created with a help of a syringe filled with air and held by a groove.

In the experiment the shadow method was used. The distance between the levitating droplet center and the substrate, h, was calculated as half the distance between the real droplet and its reflection from the substrate. In order to increase the measurement accuracy, the image was first enlarged by 8 times, so the radius and the height of the droplets were measured at 0.125 of pixel, then these values were converted to micrometers by multiplying by a factor of 0.05 in the case of shooting with a 50x lens (camera resolution 391 nm/pixel) and by a factor of 0.075 for images taken with a 20x magnification lens (camera resolution 600 nm/pixel).

### 3. Results and discussion

In the experiment the evaporation of levitating micro-sized droplets over a dry heated surface was considered. During the heating of the liquid film, microdroplets formed above its surface and
subsequently rolled into the dry area of the substrate and levitated over the dry surface. The first levitating microdroplets in the experiment appeared at a temperature of 51°C.

Figure 3 shows photos of levitating droplets of different sizes and their reflections from the substrate at different substrate temperatures. Due to evaporation the drop size decreases over time. During evaporation the shape of the drop does not change and remains perfectly spherical.

Figure 3. Image of the levitating microdroplets (a) r = 5 μm, h = 7.6 μm, T = 78°C; (b) r = 5.05 μm, h = 4.2 μm, T = 65°C; (c) r = 4.2 μm, h = 5.2 μm, T = 83°C.

The dependence of the nondimensional form of levitation height $h^* = h/r$ on the droplet radius for different surface temperatures is shown in Fig. 4. According to the theoretical model [13] the dependence of the droplets levitation height on their radius is presented in dimensionless form as the following power law: $h/r \sim r^{-3/2}$. Comparing the exponents in generalizing dependences in Fig. 4 with 3/2 we may conclude that our results are in good agreement with the theory from [11].

Figure 4. Dimensionless levitation height of droplets, $h^* = h/r$ , as a function of their radii, for different surface temperatures. Solid lines – approximations of the experimental data.
4. Summary
An experimental study of evaporation of micro-sized water droplets levitating over a dry heated substrate was performed. The use of more powerful optics allowed verification of the theoretical model [13] in a wide temperature range. According to this model the dependence of the dimensionless levitation height on the droplet radius is represented as the following power-law: \( h/r \sim r^{-3/2} \).

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