Evolution of a structured monolayer of levitating microdroplets over a heated horizontal liquid film

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Abstract. Structured arrays of liquid microdroplets levitating over the surface of hot liquid have been observed in several recent experimental works, however the nature of this phenomenon is still not completely understood. In the present paper, we study the peculiarities of formation and evolution of a structured monolayer consisting of several thousands of microdroplets levitating over the water film heated from below. It was found that with the increase of the substrate temperature, the number of droplets in the monolayer increases to a certain value, after which the number practically does not change. The size of the monolayer increases linearly with temperature from approximately 1 mm to 3 mm. The average distance between the microdroplets increases with the substrate temperature, with the droplet size, and also with the distance from the center of the monolayer.

1. Introduction
It is known that with intensive heating of liquid a structured monolayer which consists of hundreds or thousands of microdroplets levitating over liquid surface can form [1, 2]. The study of levitation of microdroplets near interfaces is important for some applications. For example, when delivering drugs using sprays, it is very important to know under what conditions the drops levitate, that is, do not touch the surface of the body [3]. The study of levitation of microdroplets is also important for spray cooling, when a flow of liquid microdroplets is directed to a heated surface [4]. Also microdroplets can be used as tracers. On the base of the trajectories of microdroplets, it is possible to reconstruct microscale gas-vapor flows near the hot liquid-gas interface [5, 6]. It is known that the levitating microdroplets are initially drops of condensate arising from the evaporation of the heated liquid. After gaining enough mass they fall down and find themselves levitating over the heated liquid (supported by the flow originated at the interface, as discussed in [2]) forming a highly ordered triangular structure. The typical size of droplets in a monolayer is 10-100 μm, the height of levitation is comparable to the diameter of droplets. Structured arrays of levitating microdroplets can be observed over tea, coffee, tap water, and some other liquids [7, 8]. It is also known that destruction of the monolayer is due to the fact that the first drop touches the liquid surface and induces a capillary wave that destroys the neighboring drops [9]. In papers [5, 6, 10], the behavior of levitating droplets was studied near the region of high evaporation near the contact line at the border of a dry patch. It was found that when approaching the contact line, the droplet levitation height increases several times, which most likely indicates the existence of intense evaporation in the region of the contact line. Three scenarios for the migration of microdroplets to the dry spot area were identified: a) the droplet flies through the contact line with a
change in the levitation altitude, b) the droplet travels along a circular path near the contact line with one or more complete rotations and falls on the dry surface, c) the droplet levitates at a fixed location. Furthermore, there is a "forbidden zone" over a dry surface where levitating drops are not observed. The width of the forbidden zone is from 25 to 75 μm, and it increases with temperature due to increasing the evaporation rate. In [2, 11, 12], levitation and self-organization of water microdroplets over a dry surface were studied. Levitation of drops over a dry heated surface was observed in numerous experimental studies on the Leidenfrost effect [13, 14], but self-organization of microdroplets into structures, as described in [2], was not observed before. In addition, Leidenfrost's levitation model is not applicable to the case of [2, 11, 12], because the substrate temperature in [2, 11, 12] was much lower (as low as 55°C) than the Leidenfrost temperature (about 200°C for water). A theoretical model was proposed that satisfactorily described the dependence of the levitation height of the liquid microdroplets on the droplet size.

In this paper we investigate formation and evolution of the monolayer of microdroplets levitating over a horizontal water film heated from below. We measure the size of the monolayer, the distance between drops in the monolayer and the size of droplets, depending on the main experimental parameters.

2. Experimental setup

The test section is a textolite base in the centre of which a copper rod with diameter of 12 mm is pressed, which serves as a heating element. Thermocouples were installed to measure the temperature of the copper rod surface. A glass cylinder was installed on the textolite base to reduce external air flows. The scheme of the experimental setup is shown in figure 1.

The test section is oriented horizontally and open to the atmosphere. The ambient temperature is 20-25°C. As a working fluid ultra-pure, nanofiltered water Milli-Q is used. The optical system consisting of lenses, a semi-transparent mirror and digital camera Nikon D500 was used. The images were analyzed using image processing software ImageJ.

The experimental procedure is as follows:
1) The specified volume of the working fluid is supplied by means of a syringe to the working surface with the formation of a liquid film. The thickness of the film is calculated by the volume of the liquid to be filled. The film thickness varied from 0.5 to 1 mm.
2) The heater is switched on, which induces the formation of microdroplets levitating over the heated liquid film.
3) At the same time, the image recording is started.

Figure 1. The scheme of experimental setup.
3. Results and Discussion

In most cases, the number of droplets increases with increasing temperature and then reaches a certain value. After that in most cases the number of drops ceases to grow. Figure 2 shows the dependence of the number of droplets on the substrate temperature. The three lines correspond to three different monolayers. Figure 3 shows the dependence of the average diameter of the monolayer on the substrate temperature. As can be seen from figure 3, the average diameter of the monolayer linearly increases with increasing temperature. The data correspond to the same three monolayers as in figure 2.

**Figure 2.** The number of droplets vs. the substrate temperature. Thickness of the liquid film $h$ is indicated.

**Figure 3.** The average diameter of the monolayer vs. the substrate temperature.
Figure 4 shows the dependence of the average distance between microdroplets on the substrate temperature. As can be seen from figures 2-4, the monolayer size increases both due to increasing the number of droplets and due to increasing the distance between the drops. Figure 5 shows a plot of the distance between droplets as a function of the droplet size. It can be seen that the larger the droplet size, the greater the distance between them. The peculiarity of this graph is that the processing was carried out using one image only (see figure 6), i.e. all parameters are the same.
Figure 6. The photo of monolayer (top view). Parameters $h = 1 \text{ mm}, T = 84 \, ^\circ C$.

Figure 7. Average distance between the droplets vs. distance from the monolayer center.

Figure 7 shows dependence of the distance between droplets on the distance from the center of the monolayer. When approaching the periphery of the monolayer, the distance between the droplets increases. Three lines in figure 7 correspond to the same three monolayers, as in figure 2-4.

4. Summary
With increasing the substrate temperature, the amount of droplets in the monolayer increases up to a certain value, after which it practically does not change. The size of the monolayer increases linearly with temperature. The average diameter of the monolayer varies from about 1 mm to 3 mm. The distance between the microdrops increases with the substrate temperature, with the droplet size, and also with
increasing distance from the center of the monolayer. The average distance between the drops increases from 20 to 40 μm.

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