Minimum and maximum size of levitating water droplets above the surface of a heated liquid layer

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Abstract. This work is devoted to the phenomenon of levitation of liquid microdroplets above hot liquid interfaces. The droplets levitate due to air-vapour upward flow from the liquid surface and grow in time due to condensation. It was found that the diameter of droplets linearly increases with time. The maximum possible and minimum possible droplet sizes were measured depending on the substrate temperature.

1. Introduction
Such an interesting phenomenon as levitation of microdroplets over a heated surface and their self-organization into two-dimensional (2D) arrays was first described in [1, 2]. Microdroplets of condensed liquid have the ability to levitate over hot liquid/gas interface due to the action of the air-vapor upward flow from the liquid interface. The height of levitation of microdroplets is on the order of the size of microdroplets and is ~10 μm. A typical photograph of such a 2D array is shown in figure 1.

Figure 1. A typical photograph of structured two-dimensional array of levitating microdroplets over water surface (top view). The substrate temperature is 79.6 °C, the thickness of the water layer is 0.5 mm.
It is known [1, 3] that this phenomenon can be observed over different types of liquid. For example, hot coffee, tea, tap water, pure and distilled water, glycerol, FC-72, benzyl alcohol. Also, an ordered array of microdroplets can be observed not only over a wetted surface, but also over a dry substrate [4, 5]. Investigation of liquid levitation over heated dry surface has been considered in many papers on the Leidenfrost effect [6, 7] but organization of liquid microdroplets into ordered structures has not studied earlier. Also in works [8, 9] the behavior of microdroplets moving over the contact line from a wetted zone to a dry surface was studied. In [4, 5] a mathematical model was developed to explain the mechanism of levitation of microdroplets over dry and liquid surfaces, which has a good agreement with experimental data.

Thus, the droplet levitation mechanism is basically known, but the mechanism of interaction of droplets with each other has not yet been elucidated. In previous works [10, 11], the dependences of the distance between drops in the array on the experimental parameters were investigated. In this article we investigate minimum and maximum size of levitating water droplets and the dimensional evolution of droplets.

2. Methods
A photograph of the experimental setup is shown in figure 2a. The test section is a cylinder made of polyamide-6 with flush-mounted copper rod in the center made serving as a heating element. The diameter of the copper rod is 3 mm. A thermocouple is set in the center of the heater to determine the substrate temperature. In our experiments, a K type thermocouple is used. The accuracy of determining the substrate temperature is ± 0.2 K. The test section is opened to the atmosphere. The working liquid is degassed ultrapure water Milli-Q. The thickness of the liquid layer and the substrate temperature is maintained constant in each series of experiments. The thickness of the liquid layer is 0.5-0.7 mm. To record the temperature distribution on the surface of the liquid layer, a Titanium 570M infrared camera manufactured by Flir Systems was used (typical temperature distribution over liquid surface is shown in figure 2b). It was found that the temperature of the liquid surface and temperature of the substrate are within ±1 K. Visualization of the droplets is made with digital camera Nikon D500.
Figure 2. a) Photo of the experimental setup, b) temperature distribution and temperature profile on the surface of the liquid layer, local thickness of the liquid layer $h_{loc}=0.5$ mm, substrate temperature $T_w = 56\ ^\circ C$.

The digital camera, which is located vertically to the working area, allows registering and measuring the diameter of droplets levitating above the heated surface, from the moment the droplet appears in a two-dimensional array (the minimum size of the droplet) to the moment the array merges with the liquid layer (the maximum droplet size). The absolute error in determining the drop diameter was about $\pm 2\ \mu$m.

Using the IFS 2405 confocal sensor, the immediate local thickness of the liquid layer in the centre of the test section was measured, figure 3. The principle of operation of the confocal sensor allows to define the local thickness of the liquid layer with an accuracy of about $1\ \mu$m.

Figure 3. Photo of an experimental stand with IR camera and confocal sensor.
Figure 4 shows the change in the thickness of the liquid layer in the center of the heater during a smooth increase in the substrate temperature. As can be seen from figure 4, in the temperature range from 20 to 85 °C, the thickness of the liquid layer varies from 0.8 mm to 0.7 mm (with a constant average thickness). This is due to the action of the thermocapillary effect.

![Figure 4. Change of the thickness of the liquid layer in the center of the test section depending on the substrate temperature.](image)

3. Experimental results

Microdroplets of the liquid in a two-dimensional array are subjected to continuous condensation growth. Figure 5 presents the droplet diameter as a function of time. This figure shows data for various substrate temperatures (Tw). From figure 5 one can see that the diameter of droplets linearly increases with time. It is known [12] that in the diffuse condensation mode, the surface area of the droplet (rather than its size) has a linear time-dependent relationship. But in our case, the diameter of the droplets is almost linearly time-dependent. This may be related to the fact that as the microdroplets approach under the effect of gravity to the heated surface, the vapor concentration increases and the droplets condense more rapidly.
Figure 5. Diameter of droplets depending on time. $T_w$ is substrate temperature.

Figure 6 shows a graph of the dependence of the maximum droplet diameter ($d_{\text{max}}$) and the minimum droplet diameter ($d_{\text{min}}$) on the substrate temperature. As can be seen from the graph, the range of variation of $d_{\text{max}}$ in the process of increasing the substrate temperature is significantly larger than the corresponding range of $d_{\text{min}}$. Figure 7 shows the corresponding frames of the monolayer at $d_{\text{min}}$ and $d_{\text{max}}$. The data obtained can be used in the future to build a theoretical model of the interaction of drops with each other in a two-dimensional array.

Figure 6. Dependence of the maximum and minimum drop diameter on the substrate temperature. Local thickness of the liquid layer in the center of the working area is $h_{\text{loc}}=0.5$ mm.
Figure 7. Video frames of the 2D arrays of the microdroplets. a) Tw= 78.9 °C, dmax= 60 μm, b) Tw= 82.1 °C, dmin= 13.5 μm.

In work [11], dimensionless relations were constructed for the dependence of the distance between the droplets on the size of the droplets. And the value of dmin/dmax were used as scales. Thus it is important to know the dependence of dmax and dmin on the parameters of the experiment, in particular, on the substrate temperature.

4. Conclusions
It has been found that the diameter of levitating microdroplets virtually linearly increases with time. Thus, the condensation growth of droplets cannot be explained by classical models where condensation is limited by diffusion. Further careful experimental and theoretical research is needed. It was found that the maximum possible and minimum possible droplet diameters grow with the substrate temperature. We expect that the presented results will be useful for testing the theoretical models under development.

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