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# The effect of the thickness of the liquid layer and the relative humidity of the environment on the condensation growth of microdroplets levitating over a thin layer of liquid

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**Abstract.** Tests were carried out on levitating microdroplets in a test section comprising a cuvette containing a thin layer of liquid. At the base of the cuvette, there is a round heating element with a diameter of 3 mm that is flush-sealed. We investigated how the size of the droplets changed due to condensation under different conditions, such as the thickness of the liquid layer and the humidity of the surrounding air. Our results showed that increasing the thickness of the liquid layer did not affect the growth of the droplets, but increasing the humidity of the air caused them to grow at a slower rate.

## 1 Introduction

The phenomenon of microdroplet levitation is important for thermodynamics and can be applied in various fields, for example, in spray cooling [1] or medicine [2] (aerosols that are used in medicines to affect the respiratory tract). Schaefer [3] refers to the appearance of a white mist layer forming over a cup of hot coffee as an excellent illustration of micro-scale droplets being lifted by the flow of moist air originating from the evaporating surface of the liquid. As the moist air rises and moves away from the hot liquid surface, the droplets are formed naturally through the process of condensation. Similar phenomena were recorded in the case of droplets levitating over thin films of evaporating liquid on a heated base [4, 5, 6]. Also, ordered arrays of liquid micro-scale droplets were observed in configurations where heating was not localized. Thus, in article [7], a rectangular container with hot water was used, where the surface temperature of the liquid in the container is close to uniform; in this installation, levitating droplets still formed ordered arrays. In the works of the authors [6], a larger heating element (10 mm) was used. Thanks to this, it was possible to register large and well-ordered arrays of droplets and observe their collective movement. Figure 1 represents a typical photo of microdroplets levitating above thin layer of heated liquid. The size of particles is varied between 10 and 100 microns, and the levitation height is comparable to the droplet size.

In papers [6, 8] the self-organization mechanisms of levitating droplets have been examined. It is generally agreed that electrostatic attraction is not significant due to the limited electrical charges of the droplets. Instead, the repulsion force can be attributed to viscous effects as the flow between the droplets decreases when they approach one another. However, the attraction between droplets remains controversial. Authors in [8] suggest that the radial temperature gradients in the arrangement of droplet clusters could cause attraction, but this idea is challenged by observations of studies [6] and [7]. Recalling that droplets continuously condense, leading to vapor depletion and pressure reduction between them, this phenomenon may explain the levitation and self-organization of droplets into a monolayer. However, there is no precise quantitative theory accounting for this effect, despite extensive literature on microscale particles and droplets.

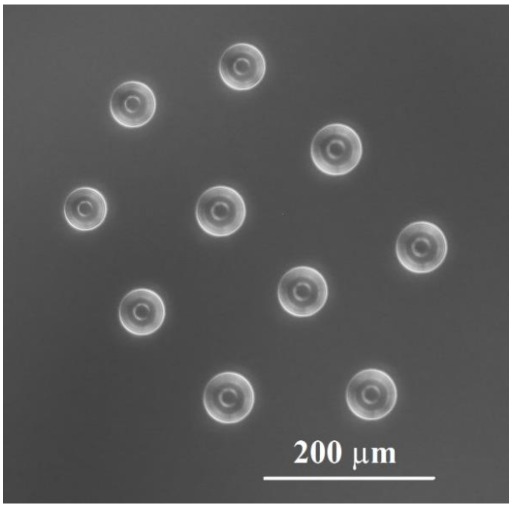

**Fig. 1.** Top view of levitating water droplets over heated liquid layer with temperature of the substrate Tw = 75 ºC, the thickness of thin liquid layer h = 0.6 mm and the relative humidity of the air φ = 33 %.

Also, the formation of hexagonal ordered structures, including self-organization, is observed in a dusty plasma [9]. Dusty plasma crystals were found in an inert gas low-pressure Radio Frequency Discharge, with

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multiple laboratories almost simultaneously discovering this phenomenon [10-13]. Typically, the micron-sized dust particles are suspended in the sheath located above the lower electrode due to a balance between various force types, including electrostatic force, force of gravity, and the ion drag force. Particles can form an organized structure containing numerous horizontally extended layers depending on specific conditions. Although the importance of electrical charges differs greatly between droplet monolayers and other systems, it is still possible to draw mathematical similarities by focusing on the hydrodynamic interaction of droplets instead of electrostatic effects.

According to models of water droplet levitation, the upward force created by the flow of moist air from the surface of the evaporating liquid can balance the weight of the drop [5, 14]. Droplet growth was observed in the clusters as a result of condensation, and it was observed that the distance between the droplets and the liquid surface decreased with increasing droplet size. Findings in [5] indicated that within the area where the droplets accumulate, the velocity of the mixture of air and water vapor is adequate to sustain the levitating droplets on the surface of liquid in accordance with the Stokes principle. In addition, it was found in [5] that the agreement between the measured and anticipated maximum droplet sizes is good at higher temperatures but not at lower ones. In [6], the levitation model took into account diffusion mass transport. An ongoing process of evaporation causes vapor to spread away from the interface due to a difference in concentration levels. This creates a gradient in the partial density of other components of air in the opposite direction, assuming that the overall gas density remains relatively even. While these components move towards the interface, they are unable to penetrate it. As a result, there must be a flow upward, known as Stefan flow, to balance out the diffusion fluxes in accordance with the law of mass conservation [15]. Thanks to this consideration of flow [6], the comparison between theory and experiment at low temperatures is greatly improved.

As we know, the weight of droplets occurring in 2D monolayer rises as a result of condensation. Moreover, in the paper [16], it was found that diameter of droplets linearly increases with time. It is known that in diffusion regime the square of radius grows linearly with time [17]. The deviation between the theory and experimentally obtained data is explained by the theoretical model, which was demonstrated in [18]. Current paper presents careful measurements of the change in the diameter of droplets over time as well as the effect of the main experimental parameters (the thickness of liquid layer and the relative humidity of the air) on the condensation growth of individual droplets.

## 2 Experimental setup

Figure 2 displays the scheme of the experimental installation. The test section consists of a cuvette with a thin layer of liquid, at the bottom of which there is a flush-sealed round heating element with a diameter of 3 mm. The heating element is made of copper and is electrically heated with a nichrome wire at the bottom, which is wound around a copper rod. The temperature of the heater surface (Tw) is measured in the center of the heater with a thermocouple (K-type) with an accuracy of 0.2 K. According to the measurements, the constant temperature condition, is satisfied along the copper surface. In the current experiment, the substrate temperature was kept constant Tw = 66 °C.

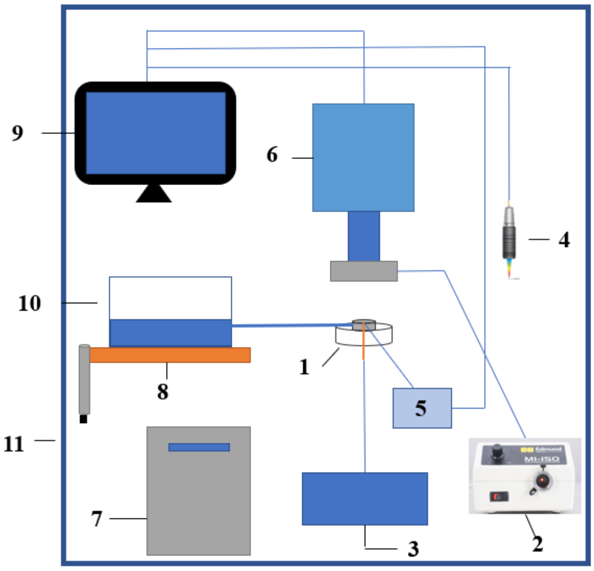


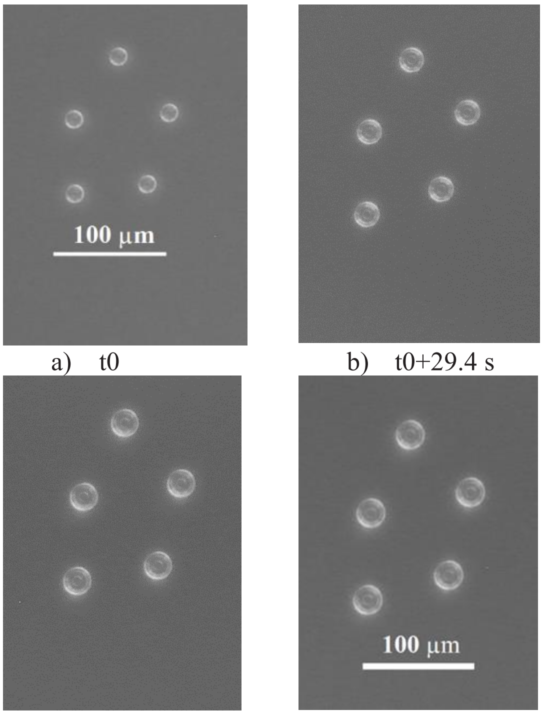
**Fig. 2.** The scheme of the experimental setup: 1 – test section, 2 – light source, 3 – power supply, 4 – confocal sensor, 5 – ADC 6 – digital camera, 7 – humidifier, 8 – table with micrometre, 9 – PC, 10 – container with working liquid, 11 – large transparent box.

**Fig. 3.** The photo of the experimental setup: 1 – digital camera, 2 – container with working liquid, 3 – light source, 4 – test section, 5 – confocal sensor.

The test section is located horizontally and is open to the atmosphere. The temperature of ambient air is 22 ºC ± 2 ºC. Milli-Q ultrapure distilled water is used as the working fluid. The liquid film thickness is measured using a Micro-Epsilon IFC2451 controller with an IFS2405 confocal chromatic sensor (with a measuring accuracy of about 1.5 µm). An optical recording is made by digital camera (Nikon D850 with resolution 3840 x 2160 pixels) equipped with a microscope lens of high-resolution power (Mitutoyo Plan Apo Infinity Corrected Long WD Objective with 10X magnification and numerical aperture 0.28). In the experiment, the highest resolution of the camera was 0.49 µm per pixel. A digital camera positioned vertically to the work area provides a top view of the levitating microdroplets over heated thin liquid film. Thanks to the system of communicating vessels (container with working liquid that is located on the table with a micrometer is connected to the working area through silicon tube) two parameters of the experiment such as thickness of thin liquid film (h) and the substrate temperature (Tw) are maintained constant during the experiment. The thickness of the liquid layer (h) varied from 0.14 mm to 1 mm. In order to reduce the influence of convective flows in the air, the working area was placed in a large transparent box measuring 45 x 80 x 90 cm. An air humidifier was used to regulate the humidity level inside the box, which ranged from 10% to 60%.

## 3 Results

Micro droplets of liquid levitating over a thin layer of liquid that make up a two-dimensional array increase in size due to condensation (fig.4). Figure 5 shows new experimental data on condensation growth. As we can see from the graph, the droplet size rises linearly over time, as was obtained in previous works [16]. The graph presents data for different arrays with different relative humidity values (varied between 13 % and 55 %), but the temperature of the substrate value is the same and is equal to 66 °C and the thickness of the liquid layer is constant and is equal to 0.6 mm.



a) t0 b) t0+29.4 s

c) t0+46.8 s d) t0+52.7 s

**Fig. 4.** Evolution of a two-dimensional array over time. Parameters of the experiment: Tw = 66 ºC, the relative humidity of the air is φ = 10 %, h = 0.92 mm.

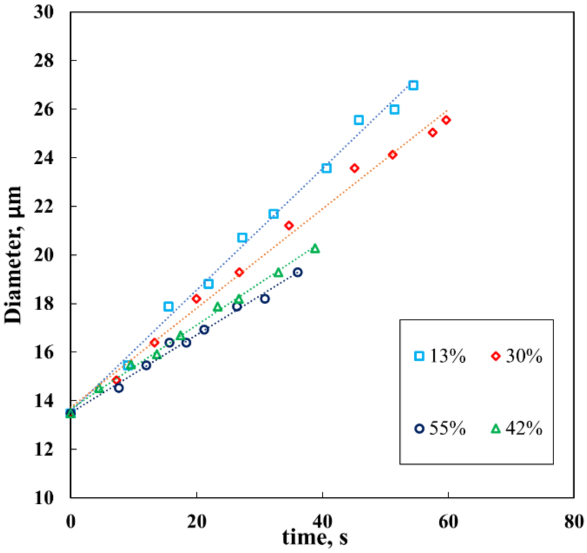


**Fig. 5.** The dependence of diameter of the droplet (µm) on time (s) for different relative humidity of the surrounding air (noted in the legend). Parameters of the experiment: Tw = 66 ºC, h = 0.6 mm.

Based on these data (fig.5), a graph of the dependence of the droplet growth rate on humidity was constructed (see fig.6). The droplet growth rate was determined as the coefficient of the angle of inclination of the dependence diameter of the droplet on time (fig.5). As we can see from the graph, the rate of change of the droplet diameter decreases with relative humidity of the air. This may be due to the fact that the higher the relative humidity of the air, the less intense is the evaporation of water from the liquid film and as a result, the droplets condense more slowly.

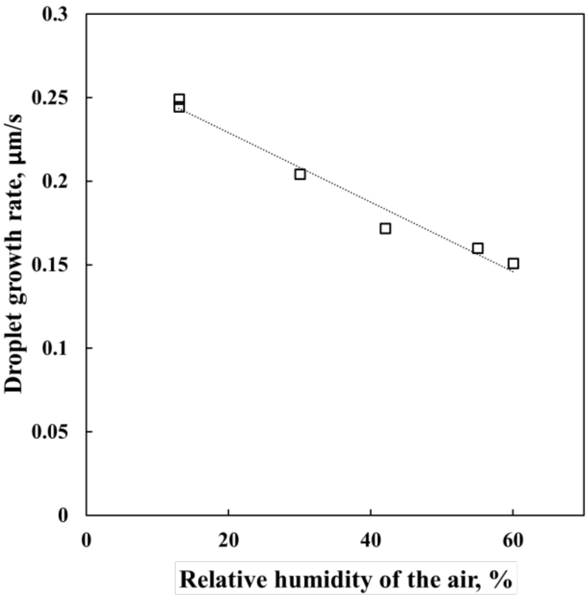


**Fig. 6.** The dependence of the droplet growth rate (µm/s) on relative humidity of the air. Parameters of the experiment: Tw = 66 ºC, h = 0.6 mm.

Figure 7 demonstrates the rate of change of the droplet (µm/s) versus the thickness of the liquid film (mm). It can be seen that the thickness of the liquid layer does not affect the condensation growth of microdroplets. This is probably due to the relatively low temperatures of the substrate (Tw = 66 ºC) and, as it was found out in previous experiments [19], the surface temperature of the film does not differ much from the substrate temperature.

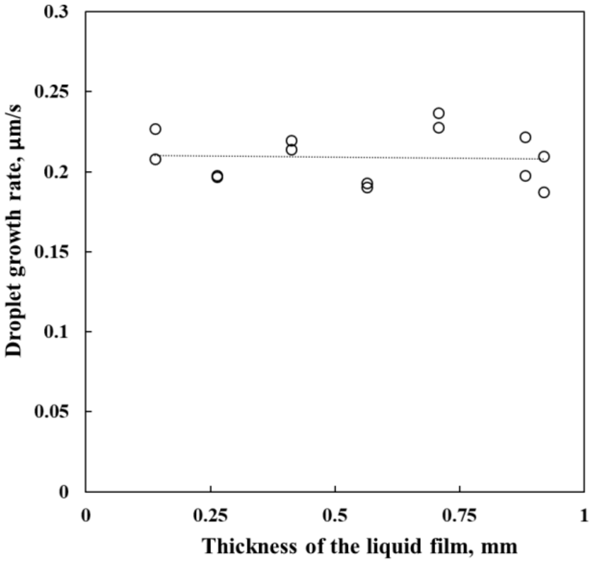


**Fig. 7.** The dependence of the droplet growth rate (m/s) on the thickness of the liquid film (mm). Parameters of the experiment: Tw = 66 ºC, the relative humidity of the air φ = 10 %.

## 4 Summary

An experimental study of the levitation of microdroplets over a thin evaporating liquid layer has been performed. Droplet diameters and droplet growth rates were measured at different experimental parameters. It was found that:

(1) with an increase in the thickness of the liquid layer, the condensation growth of droplets practically does not change.
(2) with an increase in the relative humidity of the ambient air, the condensation growth of droplets decreases.

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