Investigation of the effect of air humidity on the condensation growth of levitating liquid microdroplets

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Abstract. Two-dimensional structured arrays of liquid microdroplets levitated over a hot liquid surface have been investigated in several recent papers, but the nature of this phenomenon has not yet been fully understood. In this work we investigate the effect of air humidity on the condensation growth of levitating liquid microdroplets. It was found that the higher the relative humidity of the surrounding air, the lower the rate of the droplet growth.

1. Introduction
If one looks closely at a cup of hot coffee or tea, one can see a white mist floating above the surface. These are drops of condensate that can levitate over the surface of a hot liquid at the height comparable with the droplet size. Levitating droplets form an ordered triangular structure when they hang in the air. This phenomenon has important implications for the thermodynamics of evaporation, and can also have a range of applications from chemical manufacturing to medicine.

Schaefer was the first [1] who in 1971 qualitatively described the phenomenon of levitation of microdroplets near the surface of a heated liquid. The mechanism of droplet formation is associated with the upward movement of the hot vapor-air mixture (Stefan flow) to the lower temperature region, where condensate droplets are formed. These droplets continue to grow due to condensation and move downwards under the influence of gravity. At some point, the Stefan flow balances gravity, and the droplets eventually levitate over the surface, often creating large, ordered arrays that move randomly across the surface. The top view of such an array is shown in Figure 1.

In 2003, a similar phenomenon was registered in the study of photoinduced thermocapillary flows [2] and was called a drop cluster due to the fact that a localized heat source with a diameter of 1 mm was used in the experiment. The dynamics of extended arrays of microdroplets above the surface of the hot water layer was studied in [3]. It has been experimentally established [2,3] that an array of levitating microdroplets of liquid can be observed over different types of hot water solutions, such as tea, coffee, water with detergents, clean water, tap water, boiled and distilled water. This phenomenon can also be observed over a number of organic liquids such as glycerin and benzyl alcohol. The size of the droplets is on the order of 10 μm, the average size of the droplets increases as the temperature of the liquid increases (other things being equal). The height of levitation of the drops is comparable to the size of the drops. In [4], it was experimentally found that the velocity of the vapor-gas flow from the liquid surface is sufficient to compensate for the drop weight, which confirms the proposed Stokes mechanism of droplet levitation. In [5], using high-speed imaging, it was found that the droplet cluster “disappears” in time of about 3 ms as a result of the propagation of a capillary wave caused by the fall of a single drop (the "initiator"). In [6] for the first time the possibility of levitation and self-organization of microdroplets was shown not only over the liquid surface, but also over a solid substrate (subcooled to...
saturation point). In [6] the evolution of a 2D array consisting of thousands microdroplets over a wetted surface was studied. It was found that the number of droplets in the array, the size of the array and the interdroplet distance increase with substrate temperature. In [7], the dynamics of liquid microdops in the region of the gas – liquid – solid contact line was visualized for the first time using high-speed video shooting (5600 frames/s) with a high resolution (0.78 microns/pixel). It was found that the transition of microdroplets from liquid to a dry surface is accompanied by a significant change in the height of the drop levitation above the contact line. Based on the trajectories of microdroplets, the local velocities of the vapor-air flow were estimated and it was found that the evaporation intensity in the contact line region is several times greater than at a distance from it. In [6], an analytical model of microdroplet levitation over a dry surface was developed, based on the representation of a drop as a point evaporating source and the use of the image method to estimate the flow velocity around the drop. This model allows one to describe well the experimentally measured levitation height for relatively small drops. Taking into account the drop size and the inhomogeneity of its temperature in the model allowed the description of the levitation height for larger drops [8]. To describe the levitation of microdroplets over a liquid surface, a vapor flow from the liquid surface was added to the model [9]. A detailed review of the mechanisms of droplet levitation and the possibilities of self-organization of clouds of levitating droplets are presented in [10].

![Figure 1](image-url) A typical photograph of structured two-dimensional array of microdroplets levitating over hot water layer (top view). The thickness of the liquid layer is 0.5 mm, the substrate temperature is 71.7 °C, relative humidity and temperature of the surrounding air are 30% and 23°C, respectively.

In previous works of the authors, the growth of levitating droplets in time was studied. It was established that the diameter of levitating liquid microdroplets increases almost linearly with time. In present paper the growth of levitating droplets is studied for different humidity of the surrounding air.

2. Experimental setup

A scheme of the experimental setup is shown in Fig. 2. The test section is a copper rod that serves as a heating element. The diameter of the heated element is 3 mm. The thickness of the layer of the working liquid (degassed ultrapure Milli-Q water) was maintained constant during each series of the experiment with the help of a system of communicating vessels.

In order to reduce the influence of convective flows in the air, the test section was placed in a large transparent box with dimensions of 45x80x90 cm. The relative humidity in the box varied from 22% to 60%; for this, we used a vaporizer. The digital camera Nikon D500 is used for optical imaging from the
top. The parameters of the experiment, such as the thickness of the liquid layer and the temperature of the substrate, were maintained constant in each series of experiments.

Figure 2. The scheme of the experimental setup.

3. Experimental results
The microdroplets that make up the two-dimensional array are continuously increased in size due to vapour condensation. Figure 3 shows the relation between the droplet diameter and time. The graphs show data for different arrays with different amounts of microdroplets and at different relative humidity values (varied from 22% to 60%), but the substrate temperature value is the same and is equal to 72.5 °C and the thickness of the liquid layer is constant and is equal to 0.5 mm.

As it can be seen from Fig. 3, the droplets grow almost linearly over time. Similar result was obtained in our previous experiments. This result is quite unexpected, since in the classical model of droplet condensation growth (being determined by diffusion), the square of the radius should grow linearly rather than the radius. This discrepancy is perhaps due to the fact that when our droplets approach the heated liquid surface under the influence of gravity, the vapour concentration increases and as a result, the droplets condense more rapidly. Figure 4 shows the relation of the angular coefficient of the dependences from Fig. 3 to relative humidity. As it can be seen from Fig. 4, with an increase in relative humidity, the angular coefficient somewhat decreases. Figure 4 also contains experimental data from our previous experiments. This dependence can be explained by the fact that with increasing relative humidity, the Stefan flow from the liquid surface decreases. In this regard, the weaker the Stefan flow, the lower the growth rate of the droplets.
Figure 3. The relation between the diameter of the droplets (mm) and time (s). \( \rho \)- relative humidity value, \( N \)- the number of the droplets in the array, \( k \)- angular coefficient in the given linear equation.

Figure 4. Angular coefficient from Fig. 3 vs. relative humidity.

4. Summary
This paper presents new experimental data on condensation growth of microdroplets levitating over hot liquid, depending on the relative humidity of the surrounding air. It was found that the higher the relative humidity of the air, the lower the rate of the droplet growth. Further detailed experimental study as well as theoretical research are needed to explain this result.
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