Study of levitating microdroplets of water condensate over wet and dry heated substrates

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Abstract. The purpose of this work was to study the levitation of microdroplets of water condensate (about 10 µm in size) above a liquid surface and above a dry surface in a wide range of experimental parameters (microdroplets of condensate levitate due to the Stefan flow). The assigned tasks were studied using experimental methods. It was found that with increasing substrate temperature, the rate of droplet condensation and the rate of droplet evaporation increases. The rate of droplet evaporation over a dry substrate is much higher than the rate of droplet condensation over a wetted surface. The dependences of the height of levitation to the center of the drop on the radius of the drop levitating above the liquid layer at different values of the substrate temperature were also studied.

1 Introduction

To date, spray cooling [1] is, according to a number of experts, one of the most effective cooling methods, it is capable of diverting heat flows up to 1 kW/cm^2 at relatively low liquid flow rates. On the other hand, when spray cooling is carried out, the droplet flow encounters an oncoming flow of liquid evaporating from the surface, as a result of which the droplets may not reach the cooled surface, which generally reduces the efficiency of such a system. Thus, finding out the conditions of microdroplet levitation near heated liquid and solid surfaces can have an impact on the development of spray cooling systems. Also, as demonstrated in [2], levitating microdroplets of liquid can serve as tracers for visualizing microscale flows in a vapor-gas environment near the liquid-vapor/gas interface, a region where traditional PIV methods are challenging or impractical to apply. In addition, the study of levitation of microdroplets over various surfaces becomes relevant in connection with the problem of the spread of acute respiratory viral infections. Microdroplets of liquid containing the virus can levitate for some time near the surface of liquids and solid surfaces, which can significantly increase the risk of infection [3].

The first observation of levitating microdroplets of liquid was first published in 1971 by V. Schaefer [4]: a layer of white mist—tiny droplets of water—forming over a cup of hot tea or coffee. However, with multiple magnifications, you can see that this fog consists of individual microdroplets. The mechanism of droplet formation is associated with the upward movement of a hot steam-air mixture (Stephen flow) into an area of lower temperature, where condensate drops are formed. These droplets continue to grow through

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condensation and move downward under the influence of gravity. At some point, Stefan's flow balances gravity and the droplets end up levitating above the surface, often creating large, ordered arrays. In 2003, A. Fedorets [5] observed a similar phenomenon while studying photo-induced thermocapillary flows and was termed a droplet cluster because a localized heat source was utilized in the experiment. Also, in [6] the levitation of microdroplets over a solid heated surface and over a liquid film was considered. The authors were the first to experimentally demonstrate that a two-dimensional ordered array of levitating microdroplets can form above a dry heated substrate. The phenomenon of levitation and evaporation of water droplets occurred well below the Leidenfrost point and below the saturation temperature, the levitation height was of the order of the droplet size or higher. Despite great progress in understanding the mechanism of levitation of microdroplets, the mechanism of interaction between microdroplets, which is responsible for the self-organization of droplets, currently remains unclear. In this regard, the subject of this study is an array of microdroplets levitating above wet and dry heated surfaces. The aim of this work was to study the levitation of microdroplets of liquid with a size of about 10 μm above the surface of a liquid and above a dry surface at different values of the substrate temperature.

2 Experimental setup

In figure 1 a photograph of the experimental stand is presented. The working section, which is a cylinder made of a fiberglass base with a diameter of 24 mm, in the center of which a copper round cross-section rod with a diameter of 3 mm is pressed. This rod serves as a heating element. Ultrapure, degassed MilliQ water was used in the experiments. A thermocouple was installed in the center of the heater, in its upper part, to measure the heater surface temperature.

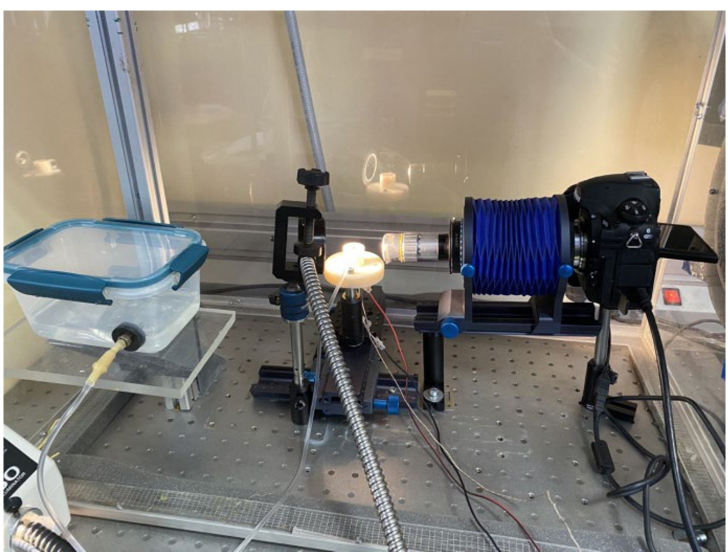

Fig. 1. The photo of experimental setup.

The test site is located horizontally and opened to the atmosphere. The ambient temperature is 22 ± 2 ºC. Ultrapure distilled water is used as a working fluid. Due to the system of communicating vessels (a container with working liquid placed on the table and connected to the working area via a silicon tube), two experimental parameters—the thickness of the thin liquid film (h) and the substrate temperature (Tw)—are kept constant throughout the experiment. The thickness of the liquid film is measured with the help of the Micro-Epsilon IFC2451 controller with the confocal chromatic sensor IFS2405 (measurement accuracy is about 1.5 microns). Optical recording is made by digital camera (Nikon D850 with a resolution of 3840x2160 pixels), equipped with a high-resolution microscope lens (Mitutoyo Plan Apo with 10X magnification). To minimize the influence of convective air flows, the working area was enclosed in a large transparent box measuring 45x80x90 cm.

To study the levitation of droplets over a dry heated substrate, the experimental procedure was as follows: first, a thin layer of liquid with a specified thickness is formed. Next, the heater is turned on, and once the substrate temperature exceeds 50 degrees Celsius, microdroplets of condensate begin to form. Then, a dry spot approximately 0.5 to 1 mm in size is created on the copper surface using a short pulse of air flow. Finally, under the influence of gravity, the droplet array moves down the slope of the interface towards the dry spot, where it levitates above the dry substrate.

3 Results

Microdroplets of liquid above the heated liquid layer continuously grow through condensation until they reach a critical size, at which point they merge with the thin liquid layer. Figure 2 presents a series of photographs showing microdroplets of varying sizes levitating above the liquid surface (side view).

The photograph shows real drops (top) and their reflections from a liquid (bottom). The side view allows you to measure the levitation height of micro-droplets, as well as obtain the dependence of the levitation height on the droplet size.

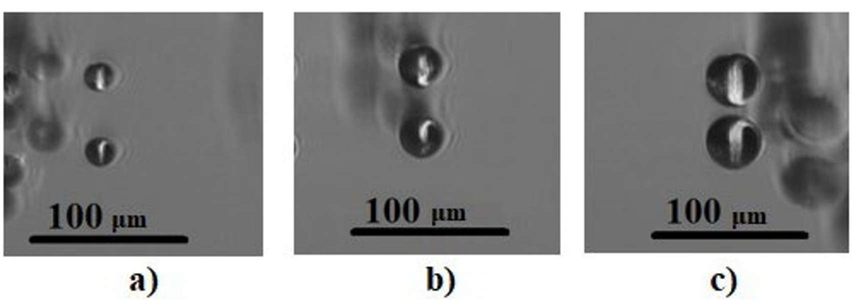

Fig.2. Condensation growth of a levitating microdrop above the surface of a liquid, side view. Experiment parameters: substrate temperature Tw= 85 ºC, relative humidity 33%.

Figure 3 shows a graph of the dependence of the height of levitation to the center of the drop on the radius of the drop levitating above the liquid layer at different values of the substrate temperature. The substrate temperature varies from 70 ºC to 92 ºC.

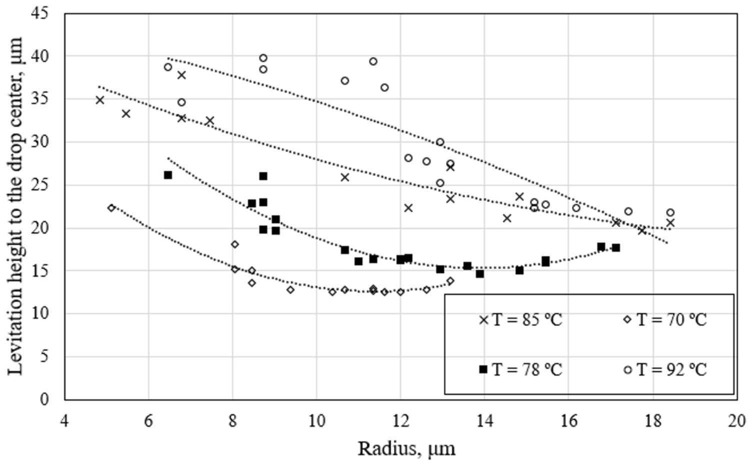

Fig. 3. Dependence of the height of levitation to the center of a microdroplet on the radius of a droplet levitating above a wetted surface at different temperatures of the substrate.

Figure 4 shows a graph of the dependence of the gap between a drop and the surface of the liquid on the radius of the drops at different values of the substrate temperature.

As can be seen from the graph, the height of the center of the drop above the surface of the liquid changes slightly with time (during the process of condensation growth of the drop), while the vapor-air gap between the drop and the surface of the liquid decreases significantly (until the drop coalesces with the layer liquid).

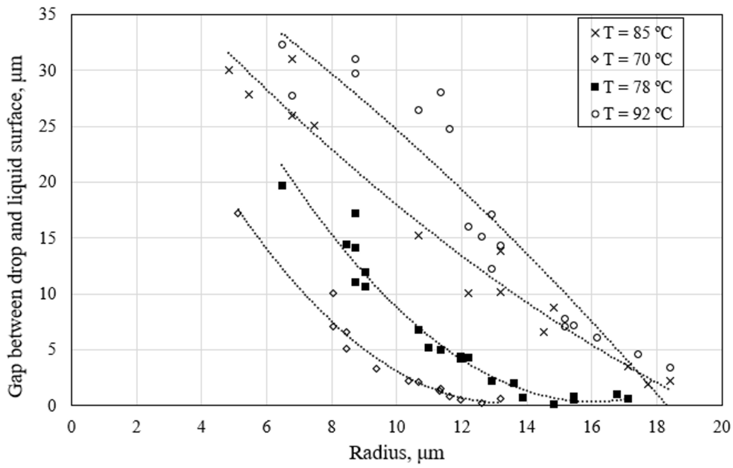

Fig.4. Dependence of the gap between the drop and the surface of the liquid on the radius of the drops at different values of the substrate temperature.

As mentioned earlier, microdroplets levitating above a wetted surface undergo constant condensation growth until the droplet size reaches a critical value at which the droplets coalesce with the liquid layer. Figure 5 shows a graph of the dependence of the droplet growth rate on the substrate temperature.

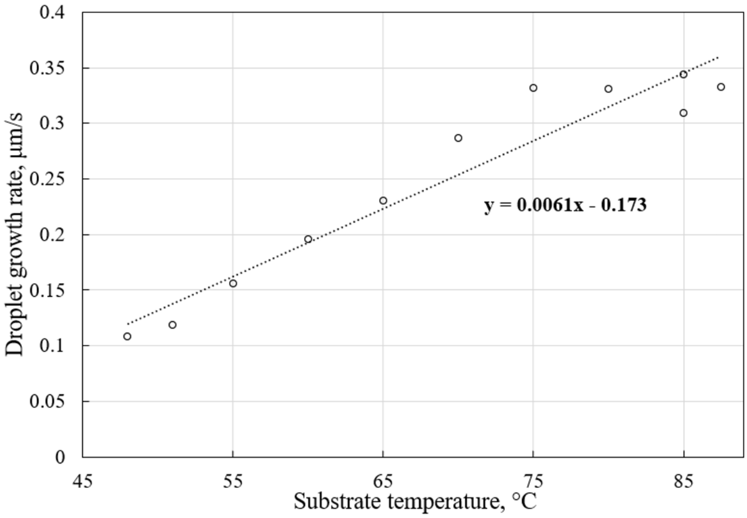

Fig.5. Dependence of the droplet growth rate on the substrate temperature (above the wetted surface). Experiment parameters: relative air humidity 33%, h = 0.6 mm.

As can be seen from the graph, the growth rate of droplets is directly proportional to the substrate temperature. This is due to the fact that with increasing temperature of the substrate, the intensity of evaporation of the liquid layer increases and, as a result, the droplets condense faster. When a liquid film with a dry spot is heated, microdrops of condensate form above its surface, which roll into the dry area of the substrate and levitate for some time (about one second) over a dry surface until they evaporate completely. Figure 6 shows a graph of the dependence of the droplet evaporation rate on the substrate temperature. As can be seen from the graph, with increasing substrate temperature, the rate of droplet evaporation increases. As can be seen from the angular coefficients of the linear approximation of experimental data, the rate of evaporation of droplets over a dry substrate is much higher than the rate of condensation of droplets over a wetted surface.

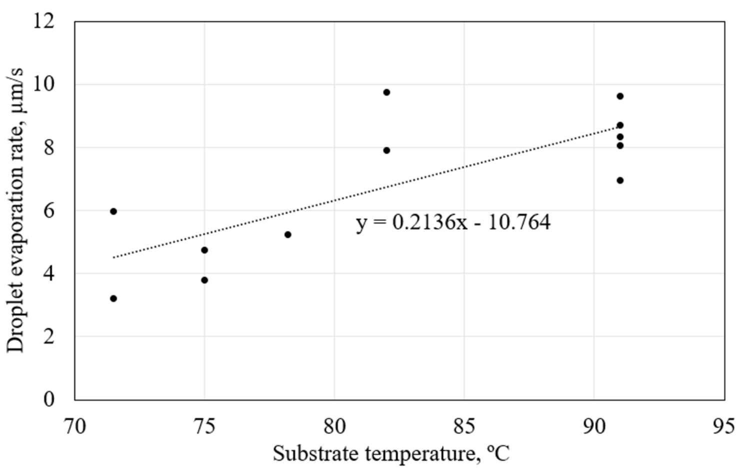

Fig.6. Dependence of the droplet evaporation rate on the substrate temperature (above a dry surface). Experiment parameters: relative humidity 30%.

4 Summary

An experimental study was carried out on the levitation of condensate microdroplets (about 10 μm in size) over a thin evaporating layer of water, as well as over a dry heated surface. The levitation height, as well as the droplet growth and evaporation rates were measured as the substrate temperature changed.

It has been established that with increasing substrate temperature, the rate of condensation growth of microdroplets above the liquid layer, as well as the rate of evaporation of microdroplets above a dry surface, increase.

It was found that, the height of the center of the drop above the surface of the liquid changes slightly with time (during the process of condensation growth of the drop), while the vapor-air gap between the drop and the surface of the liquid decreases significantly (until the drop coalesces with the layer liquid).

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Link to project information: https://rscf.ru/project/23-29-00982

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