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Study of the influence of different parameters on the flight of microdroples over the contact line in a liquid film heated from below

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Abstract. In this work, experimental studies were carried out on the flight of levitating liquid microdrops over the contact line around a dry patch formed in the horizontal liquid film heated from below in the temperature range of 52°C - 77°C. The working area is a textolite base, in the center of which a copper rod of a circular cross section with a diameter of 3 mm is pressed. The copper rod serves as a heating element. It was found that with an increase in the substrate temperature and decrease in the diameter of the microdroplets the height of the flight increases.

1 Introduction

Liquid microdroplets are an important element in a wide range of technical applications, such as inkjet printing, pesticide spraying, micro- and nanofabrication, thin-film coatings, bio-chemical analyzes, DNA/RNA microarraying, the production of new optical and electronic materials, and also cooling of microelectronics and power electronic devices. The constant growth in the power of electronic devices requires an increase in cooling efficiency. Liquid cooling systems are popular in the industry, as they allow you to effectively remove heat from various elements of electronic devices (for example, from microchips, processors, etc.). Systems using gas-drop flows or sprays are effective for removing high heat flux densities. The phenomenon of droplet levitation at sufficiently low temperatures can have a significant impact on the efficiency of cooling systems. To improve cooling systems, it is necessary to conduct fundamental research and describe in detail the processes that occur during heat removal.

During heating and evaporation of a liquid layer near the liquid-gas interface, one can observe suspended liquid microdroplets, which can be organized into arrays ordered in the form of a hexagonal structure. The droplet formation mechanism is associated with an upward flow of a hot vapor-air mixture. When the liquid layer evaporates, the vapor-air mixture moves upwards to the region of lower temperatures, where condensation occurs, then the drops move downwards under the action of gravity until gravity is balanced by the Stefan flow, after which the drops begin to levitate above the surface. A monolayer of levitating microdroplets, depending on the conditions, may have a dense hexagonal packing or may not have a clear structure. The “lifetime” of a monolayer can be minutes, and in some cases even hours. At a certain moment, the monolayer coagulates with the surface within a few microseconds. In 1971, Vincent Schaefer wrote a short article in which he spoke in detail about the mechanism of the formation of a layer of white fog over a cup of hot tea or coffee [1].

In 2003, a similar phenomenon was registered in the study of photoinduced thermocapillary flows [2] and was called a drop cluster in connection with the use of a localized heat source 1 mm in diameter in the experiment. The dynamics of extended arrays of microdroplets above the surface of a hot water layer was studied in [3]. It has been experimentally established that an array of levitating liquid microdrops can be observed over various types of hot aqueous solutions, such as tea, coffee, water with detergents, clean water, tap, boiled and distilled water. Also, this phenomenon can be observed over a number of organic liquids such as glycerin and benzyl alcohol. The droplet size is on the order of 10 μm, the average droplet size increases as the temperature of the liquid increases. The droplet levitation height is comparable to the droplet size.

In [4], it was experimentally established that the velocity of the vapor-gas flow from the liquid surface is sufficient to compensate for the weight of the drop, which confirms the proposed Stokes mechanism of drop levitation. In [5], with the help of high-speed shooting, it was found that the cluster "disappears" in a time of about 3 ms as a result of the propagation of a capillary wave caused by the fall of one drop - the drop of the "initiator". In [6-8], it was experimentally established that infrared irradiation of a drop cluster levitating above the water surface reduces the rate of condensation growth of liquid microdroplets and the subsequent merging of the drop cluster with a water layer. As a result, irradiation can be used to stabilize levitating clusters for a long time. The power of infrared radiation required for this turned out to be approximately proportional to the power of the laser used to heat the water layer.

In contrast to the observational experiments carried out in earlier works, in the studies [9-10] a precision experimental measuring technique was proposed. For the first time, the possibility of levitation and self-organization of microdroplets not only above the surface of a liquid, but also above a solid substrate (subcooled to the saturation temperature) has been shown. It has been established that the transition of microdroplets from a wetted to a dry surface is accompanied by a significant change in the droplet levitation height above the contact line. Based on the trajectories of micro-droplets, an estimate of the local velocities of the vapor-air flow was made and it was found that the intensity of evaporation in the region of the contact line is several times greater than at a distance from it. An analytical model of microdroplet levitation over a dry surface has been developed, based on the representation of the droplet as a point evaporating source and the use of the imaging method to estimate the flow velocity around the droplet. This model allows a good description of the experimentally measured levitation height for relatively small drops [10]. Taking into account the size of the drop and the inhomogeneity of its temperature in the model made it possible to describe the levitation height for larger drops as well [11]. To describe the levitation of microdroplets over a liquid film, a vapor flow from a liquid surface was added to the model [12]. A detailed review of the mechanisms of drop levitation and the possibilities of self-organization of clouds of levitating drops is presented in [13].

Near the contact line there is a narrow dry area where levitating microdroplets are not observed. The width of this region increases significantly with increasing substrate temperature [14]. In [15], water microdrops were studied near the contact line, which is the interface between a dry spot and a liquid layer on a heated horizontal substrate. Time-dependent data on the trajectories of droplets are used to obtain detailed information about the steady-state distributions of air velocity near the contact line. With the help of the Savitsky-Golay method, an accurate estimate of the velocities and accelerations of the drops is made. Using data on drop trajectories, the local flow velocity near the contact line is calculated. A higher substrate temperature results in an increase in flow rate as evaporation becomes more intense.

The contact line is a key object in many processes accompanied by evaporation. It is known that the maximum evaporation rates are achieved in the microregion near the contact line due to the low thermal resistance when heat is supplied to the evaporation area.

2 Experimental setup

The working area is a textolite base, in the center of which a copper rod of a circular cross section with a diameter of 3 mm is pressed. The copper rod serves as a heating element. A thin layer of liquid is created on the surface of the heater and a dry spot is formed by hand. Milli-Q ultrapure, nanofiltered and degassed water is used as the working fluid. A monolayer of levitating microdroplets is formed above the liquid layer and passes to a dry surface. The flight of microdroplets is recorded using a high-speed Fastcam SA 1.1 Photron camera with a resolution of 1024x1024 pixels and a shooting speed of up to 5400 fps. The optical resolution of the system in the experiment was 1.03 μm/pixel, the recording rate was 500 frames/s. Mitutoyo Plan Apo Long WD microscope objectives with 10X and 20X magnifications were used in the work. The optical system uses a parallel beam of light (the principle of the Schlieren system), which allows you to get good quality imaging. Experiments were carried out in the temperature range 52ºC - 77ºC, as well as with a change in the contact angle of wetting. The scheme of the experimental stand is shown in Fig. 1, a photo of the stand is shown in Fig. 2.

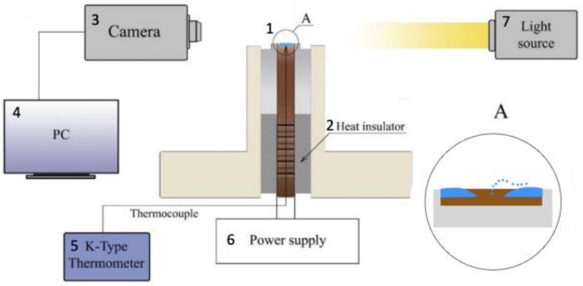

Fig. 1. Scheme of the experimental stand. 1 - copper rod of a circular cross section with a diameter of 3 mm, 2 - heat insulator, 3 - camera, 4 - PC, 5 - k-type thermocouple, 6 - power supply, 7 - light source.

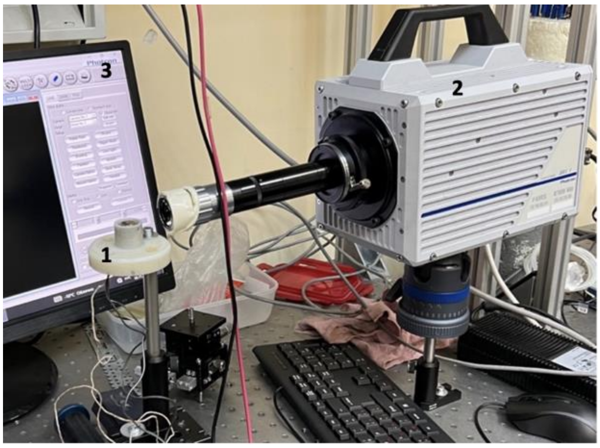

Fig. 2. Photo of the experimental stand. 1 - test cell, 2 - camera, 3 - PC.

3 Results and discussion

In the course of research on the flight of microdroplets over the contact line, the following results were obtained. Experiments were carried out in the temperature range 52ºC - 77ºC, as well as with a change in the contact angle of wetting.

Graph in Fig. 3 shows the flight of microdroplets of different diameters at the same substrate temperature T = 52ºC. To the right of the graph is a liquid layer, to the left is a dry surface, the contact line is at the origin. A photo of the flight process from a high-speed camera is shown in Fig. 4. The flight time for a drop with a diameter of 17.5 microns was 0.122 s, for a drop with a diameter of 15.4 microns: 0.18 s, for a drop with a diameter of 14.4 microns: 0.22 s.

The droplet diameters are 14.4 µm, 15.4 µm, 17.5 µm. The smaller the droplet diameter, the higher its trajectory goes. The maximum height to which drops fly up at a temperature of 52°C is 143.1 microns.

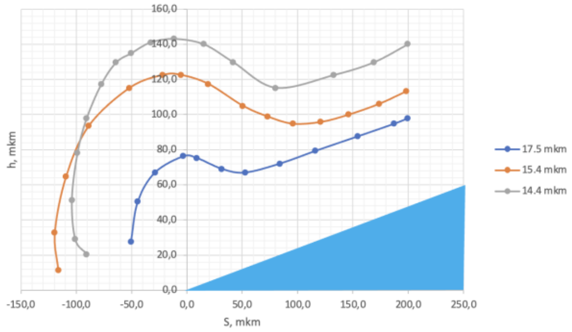

Fig. 3. Flight of microdroplets over the contact line (right-liquid, left-dry spot, contact line - origin). On the right is the size of the microdroplets. T = 52°C

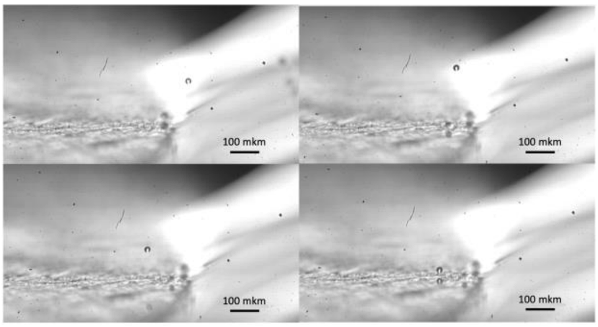

Fig. 4. Photo of the flight of microdroplets over the contact line. T = 52 °C.

Graph in Fig. 5 shows the flight of microdroplets at the substrate temperature T = 63°C. The droplet diameters are 20.6 µm (2 drops), 22.7 µm (3 drops). Some droplets demonstrate a flight scenario with swirling in the area of the contact line. The prerelease height also increases with the droplet diameter. The flight time for a drop with a diameter of 22.7 µm (blue) was 0.112 s, for a drop with a diameter of 22.7 µm (orange): 0.11 s, for a drop with a diameter of 20.6 µm (gray): 0.426 s, for a drop with a diameter 20.6 µm (yellow): 0.412 s, for a 22.7 µm drop (cyan): 0.278 s.

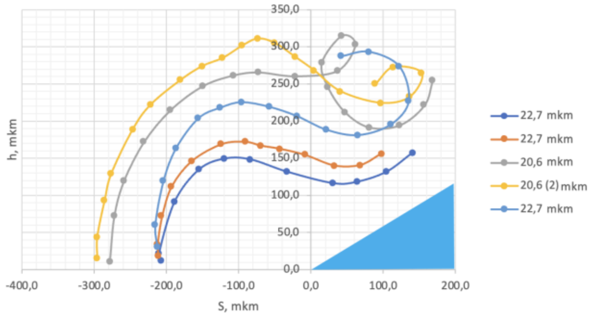

Fig. 5. Flight of microdroplets over the contact line. T = 63°C.

At a temperature of 60°C, the flight of microdroplets over the contact line was studied at various values of the wetting angle. In Fig. 6, the flight at CA = 15°, in Fig. 7 at CA = 30°.

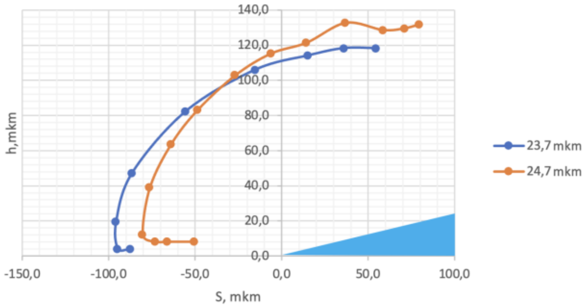

Fig 6. Flight of microdroplets over the contact line. T = 60°C. SA = 15°.

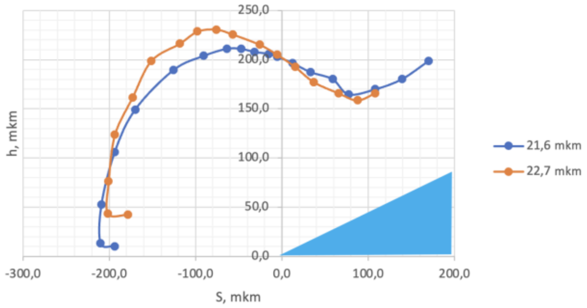

Fig 7. Flight of microdroplets over the contact line. T = 60°C. SA = 30°.

At CA = 30° the trajectory of microdroplets passes higher. The maximum height of approach of microdroplets is 230.7 µm. The flight time for a drop with a diameter of 21.6 µm was 0.14 s, for a drop with a diameter of 22.7 µm: 0.102 s.

At CA = 15° the droplets do not rise above 120 µm. The flight time for a drop with a diameter of 23.7 µm was 0.052 s, for a drop with a diameter of 24.7 µm: 0.074 s. After landing in the area of the dry spot, the droplets evaporate, continuing to levitate and, at the same time, are pulled closer to the contact line.

Graph 8 shows a scenario where two droplets coalesce and continue to fly over the contact line. Surface temperature T = 71°C. The maximum flight height is 287.3 microns. The flight time for a drop over the contact line was 0.184 s. Photo of the flight process from a high-speed camera at a surface temperature T = 71°C is shown in Fig. 9.

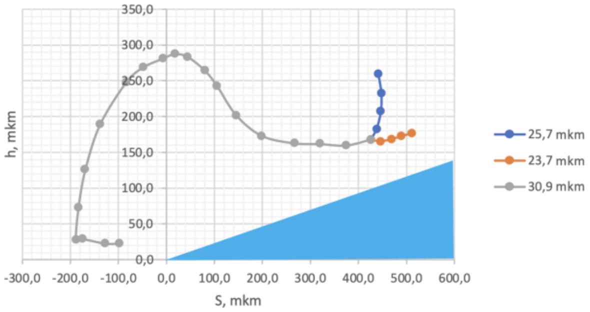

Fig. 8. Merging of two microdroplets. T = 71°C.

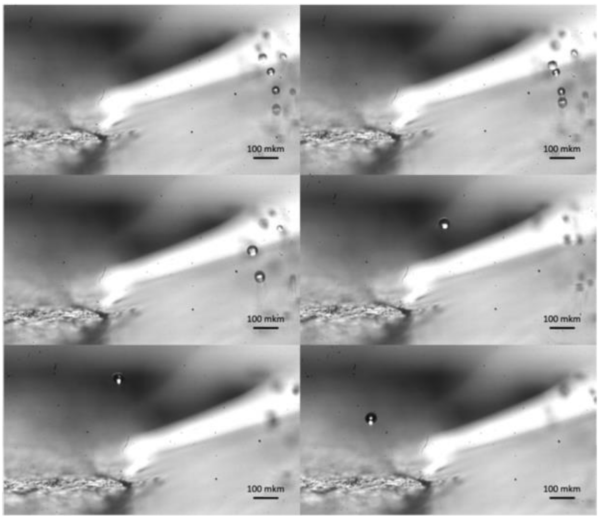

Fig. 9. Photo of merging and flight of microdroplets over the contact line. T = 71ºC.

Graph 10 shows the flight of microdroplets at the surface temperature T=70ºC. Drops with a diameter of 29.9 µm (green on the graph) and 30.9 µm (dark blue) collide, one drop flies over the contact line after the collision, the second one continues to rotate in the area of the contact line. Two pairs of droplets demonstrate the scenario of coalescence during the flight. A drop with a minimum diameter of 26.8 µm has a maximum flight height at a given temperature of 394.4 µm. The flight time for a drop with a diameter of 39.1 µm (gray) was 0.104 s, for a drop with a diameter of 28.8 µm (yellow): 0.272 s, for a drop with a diameter of 26.8 µm (cyan): 0.368 s, for a drop with a diameter of 29, 9 µm (green): 0.238 s, for a 38.1 µm drop (brown): 0.05 s.

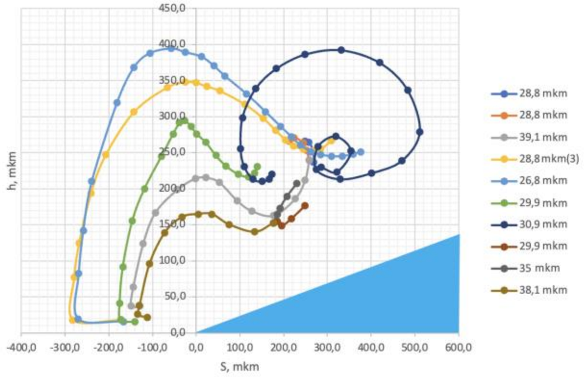

Fig. 10. Flight of microdroplets. T = 70ºC.

Graph 11 shows the flight of microdroplets at the surface temperature T = 77ºC.

A droplet with a diameter of 43.3 µm is also the result of the coalescence of two drops. The maximum drop height at this temperature was 417.1 µm. The flight time for a drop with a diameter of 43.3 µm was 0.088 s, for a drop with a diameter of 26.8 µm: 0.202 s. A photo of the flight process from a high-speed camera at a surface temperature T = 77°C is shown in Fig. 12.

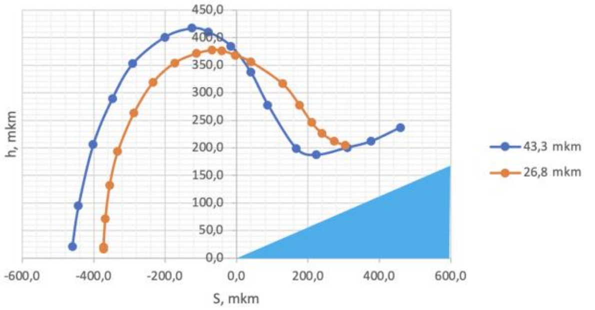

Fig. 11. Flight of microdroplets. T = 77ºC.

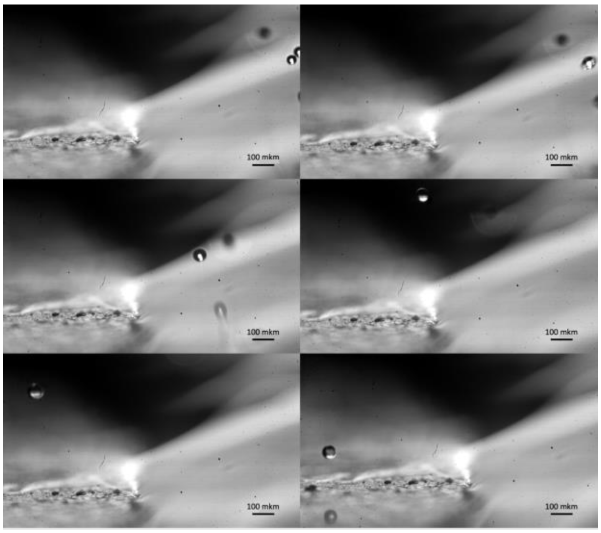

Fig. 12. Photo of merging and flight of microdroplets over the contact line. T = 77ºC.

Graph 13 shows the dependence of the maximum height reached by a drop during flight on the microdroplet diameter at various surface temperatures.

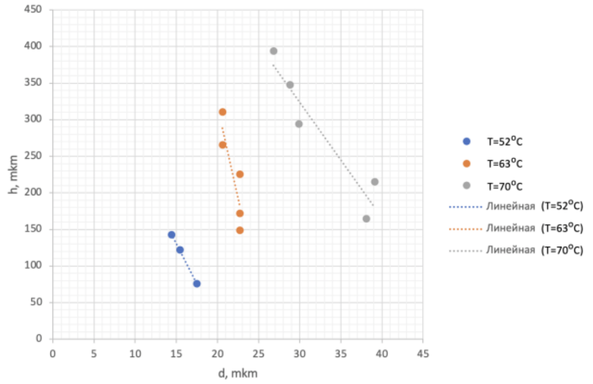

Fig. 13. Dependence of the maximum flight height on the droplet diameter at various surface temperatures.

Dependence of the maximum flight height on the droplet diameter at various surface temperatures.

Conclusions

The flight of levitating liquid microdrops over the contact line from the wetted surface to the dry spot area in the temperature range 52ºC – 77ºC was studied. It is shown that with an increase in the contact angle, the droplet trajectory is higher. With an increase in the substrate temperature and decrease in the diameter of the microdroplets the height of the flight increases.

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