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Micro-droplet cluster dynamics in a heated layer of liquid at dry spots formation

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Abstract. Organization of a cloud of micro-droplets of condensate into an ordered hexagonal structure levitating over a heated layer of liquid (the so called micro-droplet cluster) has been observed in several recent experimental works, however the nature of this phenomenon is still not completely understood. In the present paper the micro-droplet cluster is studied on a test section with relatively large heating area, under the condition when the liquid layer ruptures and dry spots form on the heater. It has been found, that the micro-droplets can levitate not only over the heated liquid surface, but also over a dry surface of the heater, following the rupture of the liquid layer. The micro-droplets can move over the dry surface as far as 3 mm away from the contact line, and can exist for up to 3.5 seconds after the rupture.

1 Introduction

A micro-droplet cluster is a spatially ordered structure of micro-droplets, discovered in [1] over the surface of liquid layer spot-heated from below. The cluster consists of several of hundreds of drops packed into one layer, forming a hexagonal structure. The drop diameter is on the order of 10 microns; the distance between the drops is of several drop diameters, while the drops levitation height above the liquid surface is comparable to the drop diameter. The possible mechanism of drops levitation is the Stokes force acting onto a drop from the steam flow arising from the heated liquid surface [2,3].

Among the effective solutions for removing high heat fluxes, there are systems of spray cooling [4] as well as the systems using stratified two-phase flows in microchannels [5,6]. Under the certain conditions, heat in these systems is removed due to evaporation of liquid microdroplets that are in contact with the surface [7,8]. However, the phenomenon of droplet levitation above a heated surface may have a significant effect on operation efficiency of the two-phase cooling systems, since the evaporation rate of levitated droplets is much lower than that of droplets in contact with the heated surface.

In this paper the micro-droplet cluster is studied at a relatively large heater of size 1×1 cm^2, (in works [1-3] the size of the heater was around 1 mm) under the condition when the liquid layer ruptures and the micro-droplets move onto the dry surface of the heater.

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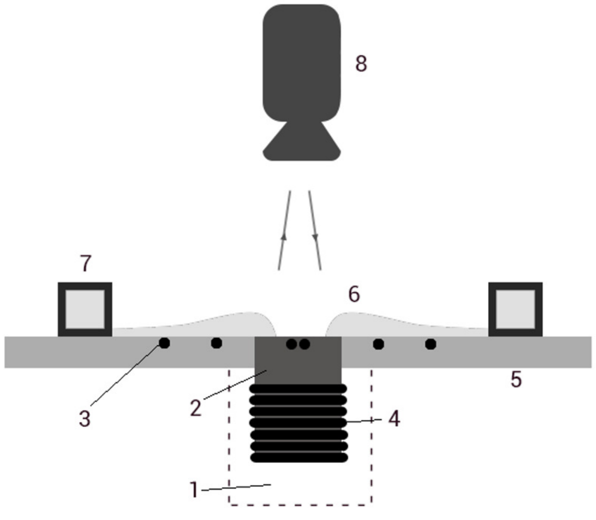
2 Experimental setup

Schematic and photograph of the experimental setup is presented in Fig. 1. The main part of the test section is a 3 mm thick stainless steel plate with a flush-mounted copper rod. At the working surface the rod has a 1×1 cm^2 square head. The rod is heated by a heating spiral coiled around its lower part. A layer of insulation material (mineral wool) is superimposed over the spiral. The heater surface temperature, T_w, and surface temperature of stainless steel plate are measured at several points by thermocouples. The heat flux, q, is determined by the electric power released at the spiral. Ultra-pure degassed distilled water with the initial temperature of 25°C is used as the working liquid. The test section is open to the atmosphere; the temperature of ambient air is 23±2°C. The test section is installed horizontally, and a square cooper cooling circuit is mounted on the working surface, so that the heater is in its centre. The inner size of the circuit is 40×40 mm^2. Water with the temperature of 25°C is pumped through the circuit. Before conducting experiment, a given volume of liquid is put onto the working surface by means of a syringe. The initial thickness of the liquid layer is h_0=0.40 mm. To register dynamics of cluster formation, the high-speed camera FASTCAM SA1.1 (5400 fps, resolution of 1024x1024 pixel, optical resolution of up to 1 micron/pixel) is used.

The working surface of the test section was mechanically polished. The morphology of the surface was analysed using scanning electron microscope (JEOL JSM6700F) and atomic force microscope (Solver Pro NT MDT). The root mean square (RMS) surface roughness, measured on a 22 μm^2 area of the heater surface, was found to be 790 nm.

The equilibrium contact angle on the working surface at different points was measured by the method of a sessile drop at the room temperature of 23 ± 2°C. To obtain the profile of the drop surface, the shadow method was used with a collimated light source and digital camera Nikon D800 with resolution of 6 micron/pixel. The resulting images were processed using the software by KRUSS. The advanced static contact angle measured at different points over the surface of the copper heater was 74±9°.

During the experiment the heat flux increased with small steps up to a threshold value of q=27 W/cm^2, when a dry spot was formed on the heater. Several runs were made. At the moment of the layer rupture the temperature of the heater surface was T_w=85±3°C.



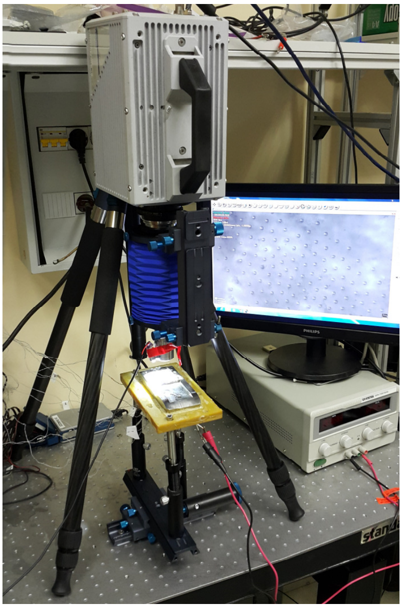


Figure 1. Schematic and photograph of the experimental setup. 1 – heat-insulating material, 2 – copper rod, 3 – thermocouple, 4 – nichrome spiral, 5 – stainless steel plate, 6 – liquid, 7 – cooling circuit, 8 – high-speed camera.

3 Experimental results

Increase of the heat flux induces formation of the cluster of micro-drops levitating over the heated layer (Fig. 2a). Usually, the cluster was of an elliptical shape. The average size of the cluster (defined as the mean between minor and major diameters of the ellipse inscribed in the array of micro-droplets) was found to be approximately from 500 to 4000 µm. Figure 3 represents variation of the average size of the cluster with time for 5 different runs (zero time corresponds to the beginning of recording, the last point in each run corresponds to the moment when the cluster coalescences with liquid; for mechanism of the coalescence refer to [3]). No cluster with an average size higher than approximately 4000 µm was observed. In most of previous studies [1-3] the authors use the term 'droplet cluster', meaning that the droplets form a localized one-layer array. However, the cluster in their experiments is localized due to the use of localized heating (the size of the heater is around 1 mm), and as such the size of the cluster is roughly coincides with the size of the heater. In contrast, we use a heater having size much larger than typical size of the cluster, which allows us to obtain larger arrays of droplets and measure their size.

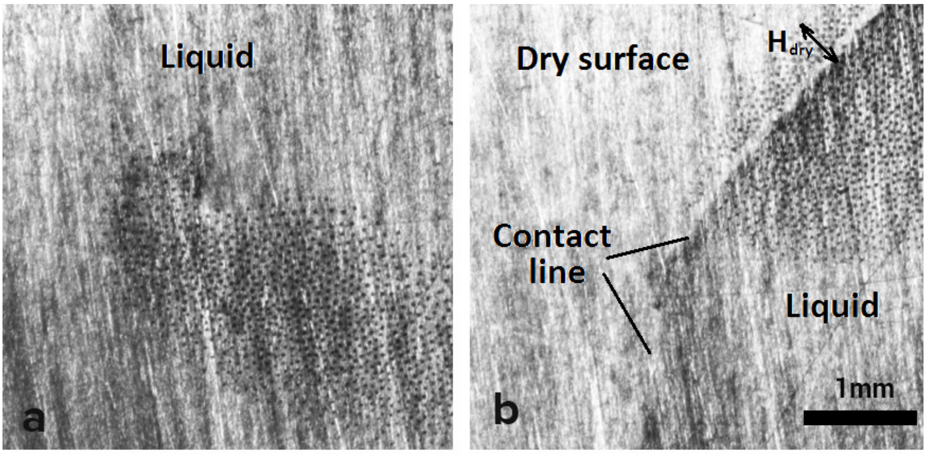


Figure 2: Array of micro-drops levitating over a water layer heated from below (the heat flux is 27.0 W/cm^2, the heater surface temperature is 83±3°C). Central area of the heater is shown. a) Before the rupture of liquid layer; b) just after the rupture.

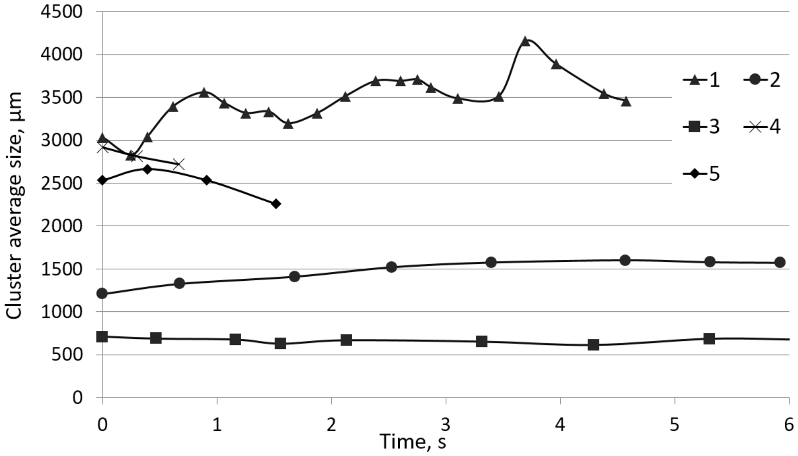


Figure 3: Time variation of the average size of the micro-drop cluster over heated layer of liquid for 5 different runs. The heat flux is 27.0 W/cm^2, the heater surface temperature is 70-83°C.

Figure 4 show the average distance between centre s of micro-drops in the cluster for two runs presented in Fig. 3 (runs 1 and 3). It is seen that in spite the fact that the size of the cluster differs roughly 7 times for these runs, the average distance between the micro-drops is close (around 175-200 µm, which is in good agreement with results of [1-2]).

Upon the rupture of liquid layer (at a threshold heat flux) the levitating micro-drops move to the dry spot. It has been found out that usually micro-droplets do not touch the heater surface, but levitate over the surface at some distance, Fig. 2b. Due to evaporation, the droplet size decreases with time. The drops can move over the dry surface as far as 3 mm away from the contact line, and can exist for up to 3.5 seconds after the rupture, Fig. 5. It should be noted, that the evaporation rate of levitating micro-droplets is much less as compared to the micro-droplets that fall down the heater surface. As soon as a micro-droplet touches the heater surface, it disappears within a fraction of a second (less than 0.1 s). Thus, the phenomenon of micro-droplet levitation may have a significant effect on operation efficiency of the two-phase cooling systems.

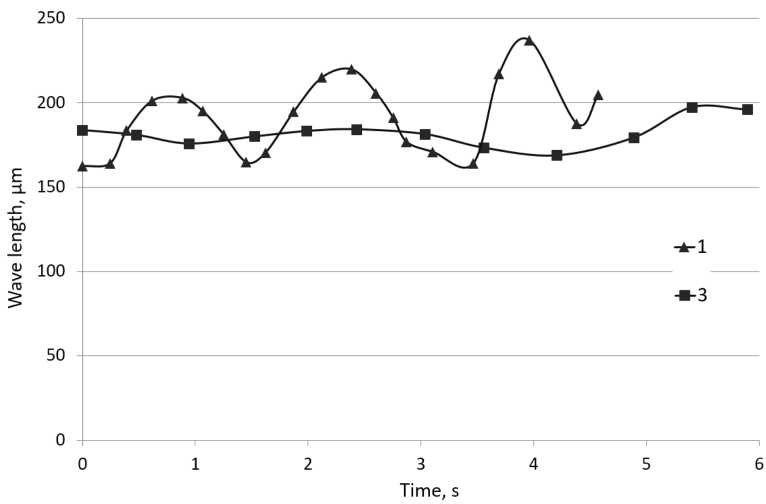


Figure 4: The average distance between centres of micro-drops in the cluster for runs 1 and 3 from Fig. 3.

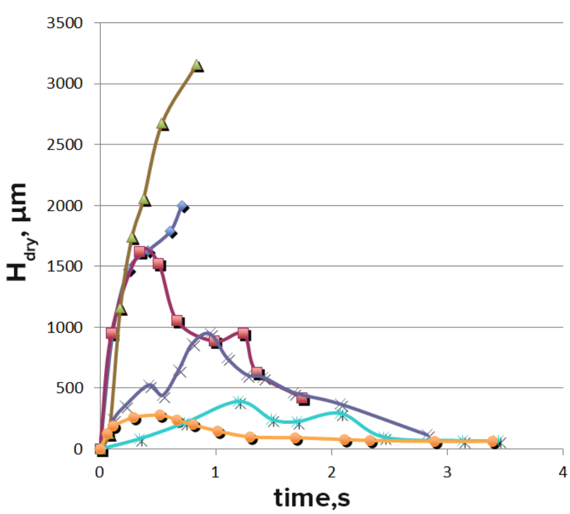


Figure 5: Distance from the contact line to the boarder of the array of micro-drops levitating over the dry surface of the heater (see Fig. 2b), versus time. Data are prasented for 6 runs. Zero time corresponds to the moment of the layer rupture. The heat flux is 27.0 W/cm^2, the heater surface temperature is 83±3°C.

4 Conclusions

The micro-droplet cluster has been studied on the heater having size greater than typical size of the cluster. The average size of the cluster was found to vary from approximately 500 to 4000 μm, with the distance between micro-drops being around 175-200 μm. It has been found, that the micro-droplets can levitate not only over the heated liquid surface, but also over a dry surface of the heater, following the rupture of the liquid layer. The micro-droplets can move over the dry surface as far as 3 mm away from the contact line, and can exist for up to 3.5 seconds after the rupture.

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