Investigation of structured 2D arrays of microdroplets levitating above the surface of hot liquid

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Abstract. This work presents new experimental data on the evolution of two-dimensional (2D) ordered arrays of microdroplets levitating over a heated liquid surface. It was found that the average distance between the centers of the droplets in the array increases with the droplet diameter, being practically independent of the number of droplets in the array and substrate temperature. Dimensionless correlation ratios for the distance between the droplets were obtained, which can be used to verify the theoretical models under development.

1. Introduction

It is notable that some physical phenomena, for which no mathematical description is known, are regularly reproduced by many people in their daily lives. For example, on the surface of hot coffee/tea, one can see the characteristic white spots. Under higher optical magnification, it is clear that these spots are composed of a huge amount of microdroplets of liquid levitating over the drink surface. This phenomenon was first described by Schaefer in 1971 [1]. In 2003 a similar phenomenon was accidentally registered during a study of photoinduced thermocapillary flows [2], and was called a droplet cluster, due to the fact that a localized heat source with a diameter of 1 mm was used in the experiment. A typical photograph of the 2D microdroplet array is presented in figure 1.

![Figure 1](image.png)

Figure 1. A typical photograph of structured two-dimensional array of levitating microdroplets over water surface (top view). The substrate temperature is 67 °C, the thickness of the water layer is 0.5 mm.
It is experimentally established [1-4] that the 2D array is insensitive to the purity of water and to the type of water solutions, i.e. an array of liquid droplets can be observed over different kinds of hot water solutions, such as tea, coffee, water with detergents, pure water, boiled and distilled Milli-Q water. This phenomenon can also be observed over a number of organic liquids such as glycerol and benzyl alcohol. The size of the drops is on the order of 10 μm, and the average size of the drops increases as the temperature of the liquid increases. The droplet levitation height is comparable to the size of the droplets.

The coalescence of the microdroplet array with the liquid layer was also studied in [5]. Spontaneous destruction of the array can be easily tracked with high speed video shooting. It was discovered that the entire 2D array "disappears" after 3 ms in consequence of the fall of an individual drop -- the "initiator" drop. Drops merge with the liquid layer, leaving specific "cold" marks on the interface. Concentric symmetry and the propagation velocity of the array destruction front (~ 70 cm/s) prove that the destruction is caused by a capillary wave on the interface surface.

In [6, 7] the behavior of levitating microdroplets was considered when they approach the area of high evaporation near the contact line, that is, the line where the liquid–vapor or liquid–air interface comes into contact with a solid substrate. It was found that microdroplets sharply increase the height of levitation as they approach the three-phase interface, and eventually end up above a solid substrate. These processes were recorded using high-speed video shooting. The maximum height for droplets flying over the contact line can be an order of magnitude higher than their size. Also, in [6,7], the analysis of droplet trajectories was used to calculate the flow of moist air near the contact line. In [8-10] for the first time, self-organization and levitation of liquid droplets over a dry heated solid surface was registered. The microdrops levitate above the solid, losing their mass in consequence of evaporation.

The typical drop lifetime varies from 0.5 to 3 seconds, depending on the initial drop size and substrate temperature. It was discovered that the minimum substrate temperature at which microdroplets of water levitate is about 50 °C. Note that the levitation of microdroplets over dry heated surfaces was considered in a number of experimental investigations on the Leidenfrost effect [11,12], but the self-organization of droplets into ordered structures has not been observed before. In addition, well-developed models of levitation of Leidenfrost droplets are unworkable in the actual context, so far as the substrate temperature in experiments [8-10] is significantly lower than the Leidenfrost point (about 200 °C for water). In this regard, a mathematical model was created that explains the mechanism of droplet levitation at substrate temperatures lower than the Leidenfrost (and saturation) temperature. Taking into account Stefan flows, a new power-laws were constructed for both cases of levitation over solid and liquid surfaces, which are in good agreement with new experimental data [9, 10] as well as with previously published data for the levitation of the localized “droplet cluster” [13].

But several points about this phenomenon are far from being completely understood, including the mechanism of interaction of microdroplets between each other. In this instance, the purpose of our study is to define the relation between the interdroplet distance, droplet size and number of droplets in the array. In previous studies [10, 14], these relations were obtained, but those investigations were performed under non-stationary experimental circumstances (the temperature of the substrate increased and the liquid layer thickness decreased during each series of experiments), which did not allow establishing an unambiguous relationship between the data obtained. To eliminate this ambiguity, a new experimental installation was created to maintain such parameters as the liquid layer thickness and substrate temperature constant during each cycle of experiments.

2. Methods
A 24 mm diameter cylinder made of Capron (polyamide-6), with a 3 mm diameter copper rod installed in the center, is used as the working section. The copper rod is electrically heated from below. A scheme and photograph of the setup are shown in figures 2, 3. In the experiments, ultrapure degassed Milli-Q water was used as the working liquid. A thermocouple was installed in the center of the heater to determine its surface temperature. The ambient air temperature was within 20–25 °C. A Nikon D500 camera with censor resolution of 5568 x 3712 pixels was applied to record the organization and growth of the microdroplet array. The camera was equipped with a 10X Mitutoyo Plan Apo Infinity Corrected
Long WD microscopic objective together with a 200 mm tube lens, providing uncertainty in droplet diameter measurement of about 1 μm. A system of communicating vessels was used: a container with working fluid placed on a table with a micrometer was attached to the working area using a silicone tube (figure 2). For any cycle of experiments this allowed maintaining virtually constant, not only the temperature of the heater, but also the fluid layer thickness (the area of the container is about 35 times larger than the area of the fluid layer in the working section).

![Figure 2. Schematic of experimental setup.](image)

A Titanium 570M infrared camera manufactured by Flir Systems was used for recording the temperature distribution on the surface of the liquid layer. The instantaneous local thickness of the liquid layer (in the center of the working section) was measured using the IFS 2405 confocal sensor manufactured by Micro Epsilon. The confocal principle of operation of the sensor allows determining the local thickness of the liquid layer with the accuracy of less than 1 micron. Figure 4 shows data on the surface temperatures of the liquid layer for corresponding substrate temperatures and for different thicknesses of the liquid layer (all measured in the center of the working section). From the graph one can see that the liquid surface temperature is within ±2K of the substrate temperature for the entire
ranges of the liquid layer thickness and substrate temperature studied. In the current work, levitation of microdroplets is studied for the fixed liquid layer thickness $h_{loc} = 0.5$ mm (in the center of the working section) in the range of the substrate temperatures $T_w = 66$-82 °C.

**Figure 4.** Liquid surface temperature (in the center of the working section) and corresponding substrate temperature, vs. local liquid layer thickness (in the center of the working section).

3. Experimental results

Even though the liquid layer thickness and heater temperature are kept constant throughout each series of the experiment, the levitating microdroplets are growing in time due to condensation of upward vapor flow, and after several minutes of growth they usually get critical mass and merge with the liquid layer. The distance between the droplets increases as the droplets grow. Figure 5 shows the average interdroplet distance (distance between the centers of the drops) in the array, depending on the average diameter of the drops in the array. Data are obtained for arrays with different number of drops (N) and for different substrate temperatures ($T_w$). The graph shows two approximating lines: 1) for 4 different arrays at $T_w = 66$ °C (N = 2, 6, 8, 12) and 2) for 3 arrays at $T_w$=79.8 °C (N=8, 29) and $T_w$=73.6-76.3 °C (N=12).

From figure 5 it is seen that the average distance between the centers of drops $L$ increases with the average diameter of drops $d$, as $L \sim d^{0.5}$, but it virtually does not depend on the number of droplets in the array (in the range of N = 2-29) as well as on the temperature of the heater surface (in the range of $T_w$=66-79.8°C). Based on this dependence, a dimensionless relation was constructed:

$$
\frac{L}{d_{\text{min}}} = \left( \frac{d_{\text{min}}}{d} \right)^{0.5},
$$

where $L$ and $d$ are scaled by the diameter of the initial condensed droplets that come to the liquid surface from above, $d_{\text{min}}$. In other words, $d_{\text{min}}$ is the minimum droplet diameter for a given substrate temperature. Figure 6 presents the dependence of this dimensionless ratio on the number of drops N. This graph also includes data from our previous experiment [10, 14] with a larger heating element (12 mm in diameter). As can be seen from figure 6, the dimensionless ratio varies slightly in the diapason N from 2 to about 7 being approximately equal to 6.3, while at N>7, it begins to decrease with N.

A similar dimensionless relation can be constructed, where the maximum droplet diameter for a given substrate temperature, $d_{\text{max}}$, is used for scaling (instead of $d_{\text{min}}$). Figure 7 shows this ratio versus the number of drops (including previously obtained data [10, 14]). From figure 7 it follows that for N = 2-
7, the ratio is approximately 2.9, while for $N > 7$ the ratio begins to decrease with an increase of the number of the microdroplets in the array.

The obtained dimensionless correlations for the distance between the droplets can be useful in verifying theoretical models on interaction of levitating microdroplets between each other.

**Figure 5.** Average distance between the centers of the microdroplets vs. average diameter of the microdroplets, for different number of microdroplets in the array, $N$, and for different substrate temperatures, $T_w$. The local thickness of the liquid layer below the array is about 0.5 mm. Two approximating lines are shown: 1) for 4 different arrays ($N = 2, 6, 8, 12$) at $T_w = 66$ °C, and 2) for 3 arrays at $T_w = 79.8$ °C ($N = 8, 29$) and $T_w = 73.6 - 76.3$ °C ($N = 12$).
**Figure 6.** Dimensionless interdroplet distance (scaled by \(d_{\text{min}}\)) vs. number of drops in the array. The graph includes data from our previous research [10, 14] with heating element of 12 mm in diameter.

**Figure 7.** Dimensionless interdroplet distance (scaled by \(d_{\text{max}}\)) vs. number of drops in the array.
Conclusions
In our study we have investigated the evolution of the array of condensed microdroplets levitating over a liquid layer heated from below. The average distance between the centers of the droplets in the array is found to increase with the average diameter of the droplets as $L \sim d^{0.5}$. Also, we have created non-dimensional ratios for the distance between the droplets that is equal to a constant value for small arrays (with number of droplets $N=2-7$). These findings can be useful for testing theoretical models that attempt to describe the interaction of two or several levitating microdroplets.

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