Evaporation of micro-sized droplets on a heated silicon substrate

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Abstract. The present research is devoted to the evaporation of micro-sized water droplets on a smooth silicon substrate heated from below. The study of this process is relevant for the development of spray cooling systems. Due to the extreme complexity of this phenomenon the mechanism of spray cooling is not fully understood yet. In our experiment the silicon substrate is open to the atmosphere. Evaporation of sessile droplets with the size of the order of 10 µm is studied at the substrate temperature ranging from 23 to 100°C. A shadow method coupled with a high-speed camera is used in the experiment to determine the geometric characteristics of the droplet profile and to calculate the droplet evaporation rate.

1. Introduction
Liquid and two-phase cooling systems that can effectively remove heat from electronic equipment are becoming more and more popular. Relatively high efficiency of removing high heat flux densities is shown by the system with gas-droplets flows or sprays [1]. Spray cooling is widely used in many industrial applications such as steel-rolling industry, cooling of power electronics and LED devices. Due to the extreme complexity of this phenomenon, the mechanism of spray cooling is still undersinvestigated. Numerous scientific papers have been devoted to the study of the influence of various spray parameters and surface morphology on the cooling efficiency [2]. However, there is yet no satisfactory agreement between the researchers regarding the influence of various important parameters. The cooling process itself can be caused by the evaporation of single droplets as well as by the film evaporation created under the influence of the spray on the surface of the cooled sample, which is insufficiently studied either. In addition, the influence of various parameters on the cooling process depends on the dominant mechanisms of heat transfer, including convection, evaporation of liquid film, evaporation near the contact line, and nucleate boiling.
Fig. 1 presents typical cases with significant effects in the contact line region: (a) an isolated bubble formed on a heated substrate, b) an evaporating meniscus in a groove or corner, c) a dry spot formed by a thin liquid film on a heated surface, d) an evaporating drop [3]. Evaporation of a sessile droplet was studied in [4]. The authors have obtained the evaporation rate (mass flow per unit surface area) by measuring changes in the weight of water droplets on a glass surface and have concluded that for most of the time during the evaporation the evaporation rate remains constant.

The diffusion equation solution obtained under the assumption of liquid quiescence leads to a change in the vertical profile of gas density. This profile becomes unstable under normal gravity conditions when evaporation is rather strong and results in transition to the convective flow. The value of this flow is controlled by the Grashof concentration number. The study of droplet evaporation for several liquids and for different Grashof numbers [5] shows that free convection for millimeter-sized droplets can lead to evaporation with the rate several times higher than that predicted by the vapor diffusion model.

In the experimental study [6] the behavior of the heated contact line was studied for a pure liquid and a mixture of liquids in microgravity. Experiments were performed in a small heat pipe. At the microscopic level, capillary and Marangoni flows were observed. The two-dimensional profile of the thickness of the liquid film that was formed on the edges of the meniscus in the heat pipe in microgravity was measured. The data allowed obtaining an accurate curvature gradient of the liquid-vapor interface. The results have shown that the curvature gradient is the function of heat flux and concentration. Droplet evaporation was also considered in the levitating conditions in [7].

Experimental and theoretical investigations of the atmosphere effect on the evaporation of the pinned sessile water droplet were performed in [8]. In [7, 9] authors studied the behavior of small condensate microdrops in the gas phase near the contact line region, formed on a heated substrate in a dry spot. Each drop was tracked and its coordinates were recorded at regular intervals [7]. The drop moved over the contact line along a circle. At the beginning, the drop flowing over the contact line accelerated. Then it slowed abruptly approaching a dry surface. According to the analysis, for the flow near the contact line the vertical velocity component was much larger than the horizontal one. There was also an increase in the flow velocity near the contact line. The velocity gradient in the vertical direction was approximately constant in the area of strong evaporation. An increase in surface temperature led to an increase in the flow velocity, because evaporation became more intense.

It was found that the diffusive evaporation rates depend on contact angle [10]. In [11] experiments were performed with a water drop under atmospheric conditions, when the temperature difference between the ambient air and the solid substrate was about 40°C. Using substrates with different wettability all three modes of droplet evaporation were studied: pinning mode, partial pinning mode,
and depinning mode. One of the most important results was that at the last stage of the drop's life the specific evaporation rate increased sharply, especially for drops with a small and medium contact angle hysteresis. The heat exchange between the drop and the gas phase had a significant effect on the temperature distribution on the drop surface. The evaporation of sessile water drops on substrates with micro- and nano-coatings with different wettability were also studied in [11] at a temperature difference between the solid surface and the surrounding atmosphere from 30 to 60 °C. When the volume of the drop decreased, the specific evaporation rate was found to increase, especially at the last stage of the drop evaporation. The similar increase in the specific evaporation rate at the last stage of evaporation on the substrate without heating was demonstrated in [12]. In [13] the authors conducted experiments on drop evaporation on a Teflon heated substrate and demonstrated that the higher was the temperature, the greater was the evaporation rate.

2. Experimental setup

The experimental set up included a smooth silicon substrate as a working surface. The surface structure was studied by atomic force microscope; and the mean square roughness of the substrate was 0.15 nm. The 40x20 mm² Peltier element with 0.8 Ohm resistance from Kryotherm was used as a heating element. It allowed supplying current up to 11.3 A and a voltage of 12.3 V with a maximum permissible operating temperature of 120°C. The Peltier element was attached to a holder, and the silicon substrate was glued to its top using the heat-resistant sealant. The scheme of experimental setup is shown in Fig. 2. The relative humidity of the ambient air was about 35%. The microdroplets were sprayed manually by means of a medical syringe with a needle with internal diameter of 0.5 mm.

In the experiment a high-speed FASTCAM SA1.1 camera with a resolution of 1024 × 1024 pixels, frequency of 250 to 5400 frames per second and microscopic lenses with high resolution (Mitutoyo Plan Apo Infinity Corrected objects) was used. Its maximum resolution was 391 nm per pixel (the field of view of the camera was 400 mm²). To provide a maximum illumination intensity, a LED light source was placed just behind the substrate.

![Figure 2. Scheme of the experiment.](image)

3. Experimental methods

In the experiment, the shadow method was applied. A beam of light parallel to the substrate was directed to the water drop lying on the surface. After interacting with the droplet, some of the light was scattered and the unscattered light was captured by the camera.
To show the dependence of specific evaporation intensity on time the following equation was used:

\[ f(t) = \frac{\Delta M}{S \cdot \Delta t} \]  

(1)

where \( \Delta M \) is the change in the drop mass over time \( \Delta t \), \( S \) is the average droplet area at two neighboring times and \( \Delta t \) is the time passed between two neighboring frames. The mass of a droplet was obtained from the measurements of its geometric parameters: the width and height of the drop were measured first in pixels and then converted into micrometers by multiplying by a coefficient of 0.4 since the camera resolution in the experiment was 391 nm per pixel. Then the obtained parameters were substituted into the equation for calculating the spherical cap volume:

\[ V = \pi h(3a^2 + h^2)/6 \]  

(2)

where \( a \) is the radius of the base of the cap, and \( h \) is the height of the cap.

The experiment was conducted at room temperature 23±2°C and at atmospheric pressure. Water of room temperature was used as a working fluid. During the experiment, the humidity in the room was 33-34%, and the size of the droplets varied from 14 to 100 microns. The Peltier element was supplied with a voltage from 1 to 6 V and a current from 1.5 to 4 A. The maximum temperature that allowed conducting the successful experiment was 101°C. The substrate was mounted horizontally.

4. Results and discussion
In the experiment, the evaporation of micro-sized droplets on a silicon heated substrate was considered (we also conducted experiments without heating).

![Figure 3. Droplet diameter evolution (without heating).](image-url)
Figure 4. Droplet volume evolution (without heating).

For microdroplets of various initial sizes (20-80 microns) the following dependences are observed without heating the substrate (see Fig. 3). It is clear from the figure that the pinning mode takes place at the initial stage of evaporation, when the volume (Fig. 4) and the height (Fig. 5) decrease quite sharply, and then the decrease of measured parameters looks almost uniform.

Figure 5. Droplet height evolution (without heating).

Figure 6. Specific evaporation rate (without heating).
For all droplets that evaporate at room temperature without heating at the initial stage the max value of the specific evaporation rate was characteristic (Fig. 6). It could be related to the process unsteadiness that happened immediately after the drop falling. At the last stage the specific evaporation rate increased slightly. At the intermediate stage there were small decreases and increases in intensity. High peaks at the intermediate stage are most often associated with drop depinning.

After heating the substrate to 30˚C the maximum value of the specific evaporation rate was still observed at the initial stage but this effect disappeared with further heating.

Figure 7. Specific evaporation rate (with heating).

Graphs of the specific evaporation rate at the substrate temperature from 33˚C and above (Fig. 7) show a typical sharp rise at the last stage of evaporation, which is consistent with the results obtained earlier in [9], [11] and [13]. High values as in the case of room temperature at the initial stage are not observed. Peaks at the intermediate stages can be also explained by drop depinning.

The evolution of the diameter at the initial stage shows the drop pinning (as in the case without heating) but then the diameter of the drop begins to decrease much faster than in the case of a non-heated substrate. The pattern of changes in height and volume is similar to that for non-heated microdroplets.

Conclusions
An experimental study has been performed. An evaporation of micro-sized water droplets lying on a silicon heated substrate has been studied. It has been established that:
1) at a substrate temperature comparable to the ambient temperature (23˚C), the maximum specific evaporation rate from the surface of the drop occurs at the initial stage of its evaporation;
2) at substrate temperatures from 30 to 100˚C there is a sharp rise in the specific evaporation rate at the last stage of the droplet evaporation, which is consistent with the previous results [9], [11] and [13].

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