Water droplet evaporation and dynamics in a mini-channel under action of the gas flow

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Abstract. An experimental setup was developed to study the vaporization and dynamics of liquid droplets, blown by the gas flow in a mini-channel. The shadow method was the main method of measurement; a drop was also observed from the top. A series of experiments was carried out with single water drops with volumes varying from 60 to 150 µl in the channel of 6 mm height on the polished stainless steel substrate. The experiments have resulted in the dependences of evaporation rate in the temperature range of the substrate surface from 25 to 70°C and Reynolds numbers of the gas flow from 0 to 2500. The advancing and receding contact angles were measured depending on the Re number of the gas flow. The gas flow rate at which the droplet motion over the substrate starts was determined depending on the surface temperature at different drop volumes.

1. Introduction
The development of microelectronics is closely related to the problem of heat removal. Heat generation rate in microprocessors of modern computers reaches 100-200 W/cm², which is the limit of air cooling systems. Therefore, the most perspective appear to be liquid, two-phase and evaporative cooling systems. To date, the most affective are the systems based on impact jets and sprays, two-phase flows in mini-channels and fluid flows in micro-channels. At cooling microelectronic equipment, these systems enable removal of heat fluxes of up to 500-800 W/cm² [1, 2, 3, 4, 5]. However, already now the electronic industry is ready to produce components where the heat flux density can reach values of 1-2 kW/cm² and higher [6]. Even the most effective systems that use the two-phase flows are unable to cool such components, which is a technological barrier to the further development of microelectronic systems. One of the technical solutions to achieve significant intensification of heat transfer and, accordingly, an affective cooling of microelectronic equipment with local heat generation is a device, forming near-wall droplet flows in micro- and mini-channels. The transition from a continuous film flow to the droplet flow with an increase in the length of the contact lines leads to the intensification of heat transfer at evaporation [7]. Droplet evaporation has been widely studied numerically and experimentally, but mostly in still air [8,9, 10]. There are a few works studying the dynamics of single liquid droplets in rather high channels [11], but the existing data are not sufficient.

The objectives of this work are as follows:
•the evaporation of a single water droplet placed on a heated substrate in a flat channel under the influence of the laminar air flow;
•the dynamics of a single water droplet, moving on cold and hot surfaces.

2. Describing the experimental setup and measurement methods

The scheme of the experimental setup is shown in figure 1. It includes a channel with height varying from 4 mm to 20 mm, removable substrates, the substrate temperature control, and the air supply system. The side walls and the top cover are equipped with optical windows for visualization. The aim of this work is to study the influence of substrate temperature and Reynolds number of the air flow on the drop evaporation rate in a channel of 6 mm height. The used working fluid was ultrapure water, obtained with the use of Milli-Q system. The drop was placed into the channel with a syringe. All experiments were realized on a substrate of stainless steel with polished surface. The Reynolds number of the gas flow was varied from 0 to 2500. The gas temperature was maintained equal to 25°C using a system of thermoregulation. The substrate was heated by Peltier elements, installed in contact with the substrate. The substrate temperature during the experiment was regulated with a precision of 0.2°C using the PR-59 controller.

To register the contour of a sessile drop on the solid substrate the shadow method was used. Its principle is based on the fact that the physical object is illuminated by a parallel light beam, and its shadow is recorded by the camera, as shown in Fig. 2. Optical equipment allows obtaining images with a resolution of 6 µm/pixel (see Fig. 3 and 7). The obtained images were processed by different methods with the help of software (the Drop Shape Analysis by KRÜSS). The most suitable for measuring the contact angle of wetting in the experiments was the tangential method, since the drop had an asymmetric shape due to the impact of air flow. The principle of the tangential method is based on adapting the contour to the equation of the conic sectors. Then, the derivative of this equation equal to the wetting angle was taken at the point of intersection of the contour line and the baseline. Before the experiments, the hysteresis of the contact angle on the substrate was measured. The advancing angle of wetting was around 80 degrees, and the receding angle was around 50 degrees.
3. Results

3.1. Evaporation of a sessile drop

Figure 3 shows photographs of droplets at different substrate temperatures and times. Images were registered with an interval of 10 seconds. Analyzing the results of the experiment given in Figs. 4, 5 and 6, we can draw the following conclusions: the rate of evaporation is determined by the substrate temperature; the gas flow rate also affects the evaporation, and this affect is maximal at the initial moment of time. The change of drop volume is well approximated by a parabolic profile (see Fig. 4). Figure 5 shows data for the evaporation rate J related to the droplet surface area depending on the droplet size. The graph shows that the evaporation rate changes several times and has a local minimum. The explanation for this is the fact that in the first moment of time the drop remains similar, i.e. the ratio of height to diameter of the droplet remains unchanged (see Fig. 6). Since the gas velocity in a flat channel has a parabolic profile, the velocity of drop blowing decreases with reduction in the drop height; this explains the local minimum. As soon as the drop becomes flat, i.e. the ratio of the drop contact area to the substrate surface area from which evaporation begins starts growing. The same tendency of increasing of J was observed in [10] for sessile droplet in motionless air (see ref [10]).
Figure 4. The change of drop volume during evaporation for different experimental conditions.

Figure 5. The rate of evaporation versus the droplet diameter.

Figure 6. The ratio of height to the droplet diameter versus time.
3.2 Droplet dynamics
At an increased velocity of the gas flow, a drop lost symmetry (see Fig. 7), and at some velocity values it started moving over the substrate (see Fig. 8). It should be noted that increasing temperature of the substrate surface, leads a decrease in the receding contact angle; in other words, the stack to the surface. One of the explanations that must be taken into consideration is that the viscosity and the surface tension of water significantly depend on temperature.

![Figure 7. Droplet dynamics](image)

Figure 7. Droplet dynamics Flow rate: (a) 0 l/min, (b) 90 l/min, (c) 100 l/min, (d) 120 l/min, (e) 135 l/min.

Figure 8 shows the friction force affecting the contact line. It was determined by the formula 
\[ \sigma (\cos(A) - \cos(R)) \]
where \( \sigma \) is the surface tension, and the angles \( A \) and \( R \), \( r \) are shown in Fig. 2. The larger symbols correspond to the values at which the drop began its motion. The work [11] studied the dynamics of different droplet on the silane substrates. The values of velocity required to move droplet and correspondent friction forces in [11] were very similar to those obtained in our work. The effect of heating on the dynamics of droplets in [11] was not taken into account. In our work it was found that with increasing temperature the drop motion starts at somewhat larger gas flows, and the friction force affecting the drop on the heated surface, calculated by the above formula, is a few times larger than in the case without heating.

4. Conclusion
In this paper, we have carried out a detailed study of the evaporation of a single droplet in the 6 mm channel. With this view, the images of the drops were recorded with an interval of 10 sec and analyzed. It has been experimentally found out that the evaporation rate is determined by the temperature of the substrate surface, and the velocity of the gas flow blowing the drop also affects evaporation. It is found local minimum on evaporation rate curves. New data on the dynamics of water drops on a heated surface have been obtained. It has been found that with increasing temperature, the droplet starts to stick to the substrate surface.

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Figure 8. Friction force affecting the drop contact line, depending on the air flow rate and substrate temperature.

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