Effect of the surface wettability on water droplet evaporation

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Abstract. Experimental studies of evaporation of water droplets lying on hydrophobic surfaces were carried out using non-contact measurement methods. The behavior of a contact angle and contact spot size was investigated using high-speed micro photography. The dynamics of the change in an average temperature of the surface of evaporating droplets was studied by the method of infrared thermography. For a theoretical study of the evaporation of liquid droplets, the previously developed emission-diffusion model, which takes into account the influence of the contact angle on the droplet evaporation rate, was used. The results of computations and experiments were compared and satisfactory agreement was obtained.

1. Introduction
The process of evaporation of liquid droplets lying on hydrophobic surfaces has a wide range of practical applications, and therefore a large number of papers are devoted to this problem [1-3]. To model heat and mass transfer in liquid droplets at evaporating, various physical models are used [4, 5]. In most studies, as a rule, changes in the geometric parameters of evaporating droplets are studied, and temperature measurements are performed with thermocouples [6-8]. However, contact temperature measurements affect the evaporation of droplets and do not provide data on the temperature distribution at the droplet surface. The use of infrared technology is very promising for the experimental study of evaporation of liquid droplets [9, 10].

2. Experimental studies

2.1. Experimental setup
For experimental studies of evaporation of drops lying on the surface, a special experimental setup was used [11]. Samples with a hydrophobic surface were placed on the working site. An infrared camera was placed above the working site. A digital microscope was installed on the side from the working site. The temperature and humidity of the ambient air were measured with a thermohygrometer.

In the experiments, the droplet evaporation process was recorded with a digital microscope and infrared camera NEC TH 7102WV. The infrared camera was additionally equipped with the micro-lens TH 71-377, which allowed us to measure the temperature with a spatial resolution of 100 μm and sensitivity of 0.1 °C. Contact measurements of substrate temperature were additionally performed for calibration and determining an emissivity of the surface. To form the droplets, a drip dispenser "Thermo Scientific" was used, which makes it possible to obtain droplets of a given volume with an accuracy of 0.1 μl. In all experiments, droplets of distilled water with a volume of 5 μl were investigated. The differences in the initial volume of droplets did not exceed 2%.
The experiments were carried out at constant temperature and humidity of the ambient air, \( t_a = 24^\circ\text{C}, \varphi = 24\% \). Samples from organosilicon rubber SHL-1A (synthetic heat-resistant and low-molecular rubber) with various content of silicone oil PMS-10 (polymethylsiloxane) were used as hydrophobic surfaces. Four samples were made in the form of plates 20 mm thick with different oil content: 50%, 66%, 75%, and 80%.

2.2. High-speed microphotography
During the evaporation of water droplets microphotography was performed to record the shape of liquid droplets. As a result, it turned out that the more oil there in the material, the less a drop of water spread over the surface. Geometric parameters of the evaporating droplets lying on the silicone rubber plates with different oil content were obtained by image processing.

![Figure 1](image1.png)

**Figure 1.** Behavior of the geometric parameters of evaporating water droplets lying on surface of silicone rubber with different oil content: (a) the contact angle \( \theta \), (b) the diameter of the contact spot \( d \)

As seen from the image in figure 1a, the surfaces under investigation can be referred to as hydrophobic, since the initial wetting angle \( \theta \) exceeds 90\(^\circ\). The greatest initial angle \( \theta = 111^\circ \) was observed at the surface with the largest 80% oil content in the material. The smallest angle \( \theta = 99^\circ \) was observed at the surface with an oil content of 50%. The behavior of the contact angle \( \theta \) during the evaporation of drops lying on all the surfaces under study was similar. There are three stages of variation of the contact angle \( \theta \): 1) relatively rapid decrease in the angle at the onset of evaporation to about 90\(^\circ\); 2) smoother decrease to about 70\(^\circ\); 3) sharp decrease at the final of evaporation.

Figure 1b shows that at the initial stage for evaporating water droplets the diameter of the contact spot \( d \) changes little. The larger was the oil content in the material, the longer the spot diameter \( d \) remained constant. Thus, at evaporation of water droplets on a hydrophobic surface, the evaporation regime with a constant contact line-the pinning regime-was realized at the initial stage. Then a mixed mode was observed, when the contact line moved and the contact angle \( \theta \) decreased.

Figure 2a shows the change in the contact area \( S \) of water droplets with a hydrophobic surface during evaporation. The smallest area of a contact spot was observed on the surface of the material with an oil content of 80%, and it did not practically change during a half of the entire time of evaporation. The greater was the oil content of the material, the longer the contact spot area of the droplet remained constant. Figure 2b presents data on the change in the evaporation surface of droplets \( S_1 \) on different samples over time. It can be seen that droplets on more hydrophobic surfaces had a large evaporation surface. In this case, the change in the evaporation area \( S_1 \) occurred practically linearly for all hydrophobic surfaces investigated.
Figure 2. The area of the contact spot $S$ (a) and the surface $S_1$ (b) of evaporating water droplets lying on a substrate of silicone rubber with different oil content as a function of time.

2.3. Infrared thermography

For the experimental study of the droplet temperature during evaporation, the method of infrared thermography was used. The infrared camera recorded thermograms of the evaporating droplet surface with an interval of 5 seconds. As a result, the time dependences of the average temperatures of evaporating water droplets lying on the surface of silicone rubber were determined (figure 3).

Figure 3. The temperature of the surface of water droplets on the surface of silicone rubber with different oil contents as a function of time.

From the analysis of the obtained data it follows that the dynamics of the temperature change of water droplets lying on the surfaces of different samples were generally similar. At the initial stage of evaporation, a sharp decrease in temperature to $20.5\, ^\circ C$ was observed. Subsequently, the temperature of the droplet practically did not change for about 1000 seconds, and then a gradual increase in the droplet temperature and its sharp increase to the ambient air temperature at the final stage were observed. The higher was the hydrophobicity of the surface, the earlier the droplet temperature began to rise, and consequently the less was time its evaporation.
The data presented in figure 3 show that the surface droplet temperature was below the temperature of the sample surface \( t_s = 24 \degree \text{C} \), but it exceeded the adiabatic evaporation temperature of \( t_m = 12.7 \degree \text{C} \) for the experimental conditions. Obviously, this was due to the heat input from the plate surface to the droplet, which has a significant effect on the evaporation of droplets [9, 10].

3. Modelling of droplet evaporation

To model the evaporation of liquid droplets lying on hydrophobic surfaces, an emission-diffusion model of evaporation of droplets is proposed. The model considers sessile droplets. The droplet form is assumed to be a spherical segment. The model takes into account the influence of the contact angle on the rate of evaporation. The model considers three modes of evaporation of droplets: evaporation at constant contact angle, evaporation at a constant radius of a contact spot and an arbitrary alternation of the first two regimes with each other. The emission-diffusion model of evaporation of free droplets [11] is taken as the basis of concept of the evaporation process. Its essence is reduced to the fact that evaporation is determined by the dynamic balance between the matter emitted from the interphase surface and the flow carried away from it by diffusion and convection. Equality of flows is ensured by introducing some intermediate vapor layer. As a result, two cases of evaporation are possible. In one case, evaporation is controlled by diffusion-convective transfer. In another case, under the so-called depletion regime, the evaporation is controlled by the emission of molecules from the interphase surface. The equality between the convective-diffusion flux from the droplet surface and the molecular emission flux makes it possible to determine the unknown relative humidity value for the intermediate vapor layer. This value is used to calculate the resulting rate of evaporation. It should also be noted that the saturated vapor pressure in the layer is taken at the droplet surface temperature. This assumption is valid for some practically important cases of evaporation, since the temperature difference at the boundaries of the layer is insignificant.

The solution of the system of differential equations was carried out by the fifth-order Runge-Kutta-Merson method with correction of the calculation step at each computational stage. The relative humidity value for the vapor layer near the droplet surface was determined at each moment of time by the solution of the nonlinear equation by the Newton method. To calculate the process of evaporation of lying drops of liquid, a computer program was developed.

To compare the results of the calculations and the experiments, two surfaces of silicone rubber with an oil content of 50% and 80% were chosen. On the surface with an oil content of 80%, the initial contact angle of the droplets was 111°, and a stable pinning regime was observed with an unchanged position of the contact line.

![Figure 4. The surface temperature of the droplet lying on the hydrophobic substrate as a function of time.](image-url)
For droplets on a surface with an oil content of 50\%, the initial contact angle was 99°. In this case a mixed evaporation regime with simultaneous movement of the contact line and change in the contact angle was observed. The simulation of the mixed evaporation process was carried out by periodic switching of the evaporation mode. The calculation results and experimental data presented in figure 4 demonstrate a satisfactory agreement of the temperature of the droplet surface at the initial evaporation period. In the initial period under consideration, the droplet temperature decreased sharply to a certain minimum value and then it changed little over a long period of time. The temperature of the droplets with smaller initial contact angles was slightly higher than the droplet temperature with large initial contact angles. Further refinement of the model is necessary for describing the entire process of evaporation on a hydrophobic surface from start to end.

4. Conclusions
The geometric parameters of evaporating water droplets lying on silicone rubber substrates with different oil content were obtained using digital microscopy. The investigated surfaces can be referred to hydrophobic, since the initial contact angle was more than 90°. The nature of the change in the contact angle during evaporation for all investigated surfaces was similar. There was a relatively rapid decrease in the angle at the beginning of evaporation to about 90°, then a gradual decrease to about 70°, and a sharp decline at the final stage. Experimental data on the dynamics of changes in droplet temperature were obtained using the infrared thermography method. After the sharp decline in the droplet temperature at the beginning of evaporation, the constant droplet temperature stage was observed on all surfaces. After that, the temperature of the droplets increased to the ambient air temperature. A comparison of the results of calculations on the emission-diffusion model with the experiments was carried out. For the beginning stage of evaporation a satisfactory agreement was obtained.

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