The influence of surface structuring on evaporation of sessile drops of water

V Yu Borodulin, V N Letushko, M I Nizovtsev and A N Sterlyagov

Kutateladze Institute of Thermophysics, 1 Ac. Lavrentyev ave., Novosibirsk, Russia

E-mail: sterlyagov@itp.nsc.ru

Abstract. The paper presents the results of experimental studies of the evaporation of sessile water droplets on smooth and structured surfaces of Teflon fluoropolymer. Using high-speed microphotographs, data were obtained on the change in the contact angle and the diameter of the contact spot of water droplets during evaporation on smooth and structured surfaces. Using the method of infrared thermography, the dynamics of changes in the average temperature of water droplets during evaporation was investigated. The results show that the structure of the surface has a decisive influence on the change in the geometric parameters and temperature of the sessile water droplets.

1. Introduction

At present time, much attention is paid to the study of the evaporation of sessile liquid droplets on structured surfaces. In studies of the evaporation of liquid droplets on nano- and micro-structured surfaces [1, 2], it was found that such surfaces, with certain characteristics of the structure, have superhydrophobic properties (wetting angle more than 150°). In studies on the evaporation of liquid droplets on a copper plate with different surface structures [3], it was experimentally established that the surface structure determines the movement of the contact line on the surface, which, in turn, strongly influences the entire process of evaporation of droplets. Studies of the influence of surface properties (roughness and surface energy) on the evaporation process using various nano- and micro-coatings [4] show that the rate of evaporation of droplets depends on the dynamics of changes in the radius of the contact spot. It should be noted that in most experimental studies, as a rule, only a change in the geometric parameters of the droplets is considered. However, to analyze the process of evaporation of droplets, it is also necessary to record the change in temperature. A promising method for measuring the temperature of evaporating droplets is the infrared thermography method [5, 6].

2. Experimental study

A study of the evaporation of sessile water droplets was performed on an experimental setup [7]. A Teflon AF 1600 fluoropolymer plate was used as a surface on which droplets were studied. This material has a low surface energy (15.7 mN/m) and is hydrophobic (wetting angle 104°) [8]. A structured surface was created on a fluoropolymer plate using nanolithography [9].
Figure 1. Image of Teflon AF 1600 fluoropolymer structured surface.

Figure 1 shows the Teflon AF 1600 fluoropolymer surface structure image obtained using a scanning electron microscope. It can be seen that the surface is unordered in the form of cylindrical columns with a diameter of about 1 μm and a height of 2 ÷ 4 μm.

2.1. Changing the geometric parameters of droplets

During the experiment, the process of droplet evaporation was recorded with a KS-is Digiscope II digital microscope and a NEC TH 7102WV infrared imaging camera. Figure 2 shows microphotographs of sessile water droplets with a volume of 5 µl at the initial moment of time on a smooth surface (a) and on a structured surface of Teflon AF 1600 fluoropolymer (b).

Figure 2. Microphotographs of 5 µl droplets of sessile water on a Teflon AF 1600 fluoropolymer plate: a) a smooth surface; b) structured surface

The data show that the shapes of water sessile droplets on smooth and structured surfaces significantly differ. On a smooth surface, the wetting angle was 104°, and on a structured surface it was
Thus, at the same volume of droplets, the contact area of a water drop on a smooth surface was larger than on a structured one. The experiments were carried out at a constant temperature and humidity of the surrounding air: $t_{\text{air}} = 24^\circ \text{C}$, $\varphi = 26\%$. For these experimental conditions, the adiabatic evaporation temperature was $t_{\text{ad}} = 12.7^\circ \text{C}$.

Based on the obtained microphotographs, the change in the geometric parameters of evaporating sessile droplets on the plates with a smooth and structured surface (figure 3) was determined.

![Figure 3](image)

**Figure 3.** Geometric characteristics of evaporating water droplets on smooth and structured surfaces of Teflon AF 1600 fluoropolymer: a) the wetting angle; b) the diameter of the contact spot

The data in figure 3 (a) show that both surfaces can be classified as hydrophobic, since the wetting angle of the droplets exceeded $90^\circ$. At the same time, the dynamics of changes in the geometric parameters of water droplets sessile on different surfaces differed. The initial contact angle was $104^\circ$ for sessile water droplets on the smooth surface of Teflon AF 1600 fluoropolymer. It gradually decreased during the main evaporation time (about 1500 seconds) and sharply decreased at the final stage of evaporation. A droplet of water sessile on a structured surface had the largest initial angle of $141^\circ$, which decreased linearly during the main evaporation time (about 2000 seconds).

The data in fig. 3b show that for sessile water droplets on both smooth and structured surfaces the diameter of the contact patch changes slightly at the initial stage. Thus a pinning mode was realized on both surfaces. However, on a smooth surface, the diameter of the contact spot was about 2.1 mm, and on a structured surface it was 1.1 mm. In addition, on a structured surface, the spot diameter remained constant longer than on a smooth surface. According to the results of digital microscopy, the time of evaporation of a drop on a structured surface was longer than on a smooth surface. The dynamic of geometric parameters of evaporating water droplets qualitatively agree with the data on the evaporation of droplets on structured superhydrophobic surfaces [1-3].

2.2. **Droplets temperature change**

During evaporation the temperature distribution on the droplet surface was determined by infrared thermography at various moments in time. Based on the performed experiments, the dependences of the change in temperature of sessile water droplets on different surfaces (figure 4) were obtained.
Figure 4. Surface temperature of sessile water droplets on smooth and structured surfaces of Teflon AF 1600 fluoropolymer

Analysis of the data presented in figure 4, shows the distinction in the dynamics of temperature variation of the sessile water droplets on different surfaces. Moreover, in the nature of the change in surface temperature for smooth and structured surfaces, we can conditionally distinguish three stages. The initial one is the stage of a sharp temperature decrease. The next stage is the stage of constant temperature. And the final stage is the stage of a gradual increase to ambient temperature. With the same volume, a drop of water on a smooth surface evaporated in 2100 seconds and on a structured surface in 2620 seconds. The results show that during the evaporation, the droplet surface temperatures differed at a stage with a constant temperature: for a smooth surface, this temperature was about 18.2 °C, for a structured one was about 17.0 °C. Since the droplet shapes were significantly different, this influenced the heat supply to the droplets. The larger was the area of the contact spot, the greater was the supply of heat to the droplet from the surface, and the higher was the temperature at the second stage. The data presented in figure 4 show that the surface temperature of water droplets was below the surface temperature of the substrate material, but exceeded the adiabatic evaporation temperature for the experimental conditions of 12.7 °C. Obviously, it was due to the supply of heat from the substrate. As noted in a number of works [7, 10, 11] it has a significant effect on the droplet evaporation.

Conclusions
An experimental study of the evaporation of sessile water droplets on a smooth and structured surface of Teflon AF 1600 fluoropolymer was carried out using contactless methods. The results have shown that the dynamics of changes in geometric parameters and temperature of sessile water droplets on smooth and structured surfaces was different. On a smooth surface, the contact angle for a water droplet was 104°, and on a structured one it was 141°. For both surfaces, the evaporation mode with a constant contact line was realized. However, on a smooth surface the contact spot diameter was about 2.1 mm, and on a structured surface it was 1.1 mm. In this paper, new data were obtained on the dynamics of changes in the temperature of water droplets during evaporation on surfaces with different structures using the method of infrared thermography. It is shown that the structure of the surface affects the change in the geometric parameters and the temperature of the droplet during evaporation. In the nature of the change in temperature of water droplets on smooth and structured surfaces after a sharp decrease in the droplet temperature at the initial evaporation stage, a constant temperature stage was observed. Then, at the final stage, the droplet temperature increased to the ambient temperature. The differences consisted
in that for a smooth surface the temperature decreased to 18.2 °C and for a structured one – to 17.0 °C. The droplet evaporation time on a structured surface was about 20% longer than on a smooth one.

References
[1] Choi C H, Kim C J 2009 Langmuir 25 (13) 7561–67
[2] Shin D H et al. 2010 J. Micromech. and Microeng. 20 (5) 055021
[3] Lee C Y et al. 2012 Int. J. Heat Mass Transfer 55 2151–59
[4] Sobac B, Brutin D 2011 Langmuir 27 14999–15007
[5] Brutin D et al. 2011 Experimental thermal and fluid science 35 (3) 521–30
[6] Tarozzi L, Muscio A, Tartarini P 2007 Experimental thermal and fluid science 31 (8) 857–65
[7] Borodulin V Y et al. 2017 MATEC Web of Conf. 115 08005
[8] Resnick P R, Buck W H 1997 Teflon AF amorphous fluoropolymers Modern Fluoropolymers (ed J Wiley and Sons) pp 397–419
[9] Korneev I A et al. 2017 Nanotechnologies in Russia 12 (9–10) 485
[10] Dunn G J et al. 2009 Journal of Fluid Mechanics. 623 329–51
[11] Bazargan V, Stoeber B 2016 Physical Review E. 94 (3) 033103