Investigation of heat transfer during evaporation of droplets of Fe₃O₄ nanofluids from biphilic surfaces

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Abstract. In this work, unique biphilic substrates were prepared with a sharp spatial gradient of the contact angle of wetting. Experimental studies of the process of evaporation of liquid droplets lying on the structured surfaces have been carried out. In the experiment, the dynamics of the temperature of an evaporating droplet was compared depending on its orientation in space. It was found that suspended droplets of 0.1 wt % Fe₃O₄ nanofluid have a higher evaporation temperature and a higher evaporation rate compared to sessile droplets.

1. Introduction
The evaporation of droplets from hard surfaces is an important fundamental process used in a variety of applications, including phase change cooling of surfaces, inkjet printing, controlled application of self-organizing surface coatings, and many others [1]. Research of this kind is important as a fundamental basis for the development of methods for the deposition of nanoparticles on solid surfaces due to evaporation of drops of colloidal solutions and can be used as a recommendation base for solving various problems in a wide range of technological applications [2]. However, the joint problem of the effect of gravitational forces, surface wettability, and nonsphericity of droplets on the evaporation efficiency makes it even more difficult to understand the deposition processes [3].

The dynamics of evaporation of a sessile and suspended droplet differ significantly [4] from each other, which is usually associated with the effect of vapor retention near the suspended droplet. The data obtained on the dynamics of evaporation confirm the above statement; indeed, evaporation from an inverted substrate occurs faster than that of a sessile droplet. However, some authors believe that a more important factor is the difference in the motion of the contact line between suspended and sessile drops [5]. In the case of evaporation on a surface with contrasting wettability, this factor can be neglected.

Despite many available theoretical and experimental works devoted to the study of evaporation of nanofluids, this area of modeling is far from complete. The aim of this work was to study experimentally the temperature of droplets of water and nanofluid Fe₃O₄ 0.1 wt%, depending on droplet orientation.

2. Experimental setup
The installation is a copper plate on which the substrate is fixed (Figure 1). The design of installation ensures uniformity of conditions during the experiment. The installed rotary mechanism allows you to...
set any angle of rotation of the substrate relative to the horizon. To measure the temperature of the drop, a non-contact method of infrared thermography was used.

**Figure 1.** Installation diagram, where 1 - thermal imaging camera, 2 - camera for fixing the droplet size, 3 - digital microscope, 4 - hot-wire anemometer, 5 - investigated liquid drop, 6 - substrate with a seat, 7 - copper plate, 8 - rotary mechanism.

Distilled water was used as the base liquid, to which spherical Fe₃O₄ nanoparticles with an average particle diameter of 12 nm were added. The choice of these nanoparticles is determined by the fact that Fe₃O₄ nanopowders are widely used in various fields of industry. To prepare a nanofluid of a certain mass concentration, the components were weighed on an electronic balance. To obtain a stable homogeneous mixture with a minimum degree of particle agglomeration, sonication was used [6].

The creation of unique substrates is based on a combination of laser processing and HW CVD (Hot Wire Chemical Vapor Deposition) method. The superhydrophilicity effect was achieved on the surface of monocrystalline silicon using laser irradiation. For this purpose, the silicon wafer was treated with the fundamental harmonic of a Nd: YAG laser with wavelength of 1064 nm, pulse duration of 9 ns, and Gaussian spatial profile. To achieve the effect of superhydrophilicity, the silicon surface was irradiated with 40,000 laser pulses with a frequency of 5 Hz. Next, a fluoropolymer coating was applied to the obtained superhydrophilic surface using the HW CVD method. The essence of the method is to activate the precursor gas flow with a hot (670°C) wire nichrome catalyst, followed by the deposition and polymerization of the formed free radicals on the substrate surface. Hexafluoropropylene oxide was used as the precursor gas. At the last stage, “landing” places were created, on which the investigated droplets were fixed (Figure 2). For this, the obtained sample with fluoropolymer deposition was locally irradiated with laser pulses.
3. Results and discussions

In the course of the experimental study, the dynamics of evaporation of a water and nanofluid Fe$_3$O$_4$ 0.1 wt% droplets was compared depending on the droplet orientation in space. The experiments were carried out under normal conditions (the initial conditions for each fluid are labeled in Figure 3).

During the evaporation of water droplets, the temperature ($T$) and humidity ($\varphi$) of the ambient air were equal to $T_g = 24.6$ °C and $\varphi = 20.7\%$, respectively. During the evaporation of nanofluid droplets, the temperature and humidity of the ambient air were equal to $T_g = 28.2$ °C and $\varphi = 28.4\%$, respectively. The initial temperatures of droplet ($T_{0d}$), substrate, and ambient air ($T_{0g}$) were the same for all experiments performed. Here, $T_s$ is the surface temperature.

Figure 3. Droplet temperature dynamics: a) water; b) nanofluid Fe$_3$O$_4$ 0.1 wt. %.

It can be seen that the water temperature monotonically increases regardless of the orientation of the substrate. This phenomenon can be explained by the constant heat flux into the droplet from the substrate. It should be noted that at the initial stages of evaporation, the temperature of the suspended
water droplet has a lower value. At the last stages of evaporation, the suspended water drop warms up more intensively than the sessile drop.

The dynamics of the temperature of a nanofluid droplet has several important differences as compared to water droplets. First, there is some difference in the temperature of the ambient air in which the experiments were carried out. Accordingly, this affects the minimum and maximum evaporation temperatures. However, this difference in ambient temperature does not explain the different behaviors of evaporating droplets. Second, it is worth noting the difference between the minimum and maximum temperatures for water and nanofluids. This difference is 5.3°C for water and 1.9°C for nanofluid. It can be assumed that, at such values, the nanofluid droplet should evaporate much longer, but in reality this is not the case. Perhaps this is due to the fact that only the liquid evaporates in the nanofluid droplets, while the nanoparticles remain until complete drying. Accordingly, the occupied volume of water in the nanofluid is less than that of pure water. This is probably why nanofluid droplets have a higher evaporation rate. It is also worth noting that the dynamics of the temperature of a sessile droplet of nanofluid changes only slightly, in contrast to water. An increase in temperature for a sessile nanofluid droplet is observed only at the last stage of evaporation. The evaporation temperature of a suspended nanofluid droplet increases monotonically and reaches its maximum value much faster than that of a sessile droplet.

4. Conclusion
In this work, the dynamics of the evaporation temperature of water and nanofluid droplets at different orientations of the surface were compared. The experiments were carried out under the natural conditions. The liquid droplets evaporated from the biphilic surfaces. From the results of the study, it can be concluded that nanofluid droplets evaporate faster than the base liquid and have a higher evaporation temperature.

It was found that the water temperature monotonically increases regardless of the orientation of the substrate. It was found that at the initial stages of evaporation, the temperature of the suspended water droplet is lower. It is also worth noting that the dynamics of the temperature of a sessile droplet of nanofluid changes only slightly, in contrast to water.

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