Experimental study of evaporation of sessile droplets of the water-ethanol solution with different concentrations

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Abstract. The dynamics of the geometric parameters of droplets of a water-ethanol solution lying on a Teflon plate was investigated using high-speed microphotography. It was found that the evaporation of water droplets occurred with a constant contact line, and the evaporation of droplets of a water-ethanol solution was accompanied by its movement. At the initial stage of evaporation, the higher the concentration of ethanol in the drop was, the greater was the change in the contact spot diameter, corresponding to the change in the diameter of the spot of ethanol. Using the method of infrared thermography, three stages of temperature change of evaporating droplets were found. The first stage corresponds to the initial sharp decrease in temperature. The second stage is a process at a constant temperature. And finally, the third stage is the stage of its smooth growth to the ambient air temperature. A similar pattern with some features was observed for droplets with different concentrations of ethanol. At the initial stage of evaporation, the droplet temperature changed like the temperature of ethanol droplet, and then its behavior was similar to the temperature change of water droplets. The higher the ethanol concentration in the droplet was, the larger the change in temperature was, similar to the change in the temperature of the ethanol droplet.

1. Introduction
There has been significant interest in investigation of binary solution droplet evaporation in recent years. The research results have a wide field of practical applications, and therefore a large number of papers are devoted to this problem [1-3]. Experimental works mainly focuses on the change in the geometric parameters of evaporating droplets [4, 5]. In a number of studies, the temperature of evaporating droplet was measured by means of thermocouples [6, 7]. However, contact measurements affect the evaporation of droplets through additional heat input and do not provide information on the temperature distribution on the droplet surface. Using the infrared thermography method is very promising for the experimental studies [8, 9].

2. Experimental setup
Experimental studies of evaporation of sessile droplets were carried out on a special experimental stand [9]. The infrared camera was located in an upright position above the working site of the experimental stand. The digital microscope was located on the side of the working area in a horizontal position. In experiments the evaporation of water-ethanol solution droplets with a different concentration (0% (water), 25%, 50%, 75%, 92% (ethanol)) was studied at a constant temperature $t = 24 \, ^\circ C$, and at constant relative humidity $\varphi = 24\%$. All droplets had the same volume (5 μl). A Teflon plate with a thickness of 3 mm with thermal conductivity $\lambda = 0.25 \, \text{W/(m}\cdot\text{\degree C})$ was used as a substrate.
3. Measuring geometric parameters of droplets

The wettability of the Teflon surface with water and ethanol has been investigated earlier. Figure 1 demonstrates the microphotographs of water and ethanol droplets with a volume of 5 μl lying on the Teflon plate surface at the initial instant of time.

The resulting images were processed using KRUSS software to measure the contact angle of the wetting. For droplets of ethanol, the contact angle of wetting was about 30 ÷ 31.8, for water it was about 88.7 ÷ 91. The data obtained in experiments show that droplets of ethanol and of water have different forms. Due to high wettability, ethanol droplets spread on the Teflon substrate further than water droplets. For an equal volume of droplets, the contact spot area and the evaporation surface area of the ethanol droplets are greater than those of water droplets.

Microphotographs of droplets were made during evaporation. This allowed us to fix the shape of liquid droplets and to determine their geometric parameters. Figure 2 shows microphotographs of evaporation of the water-ethanol droplets at different instants of time.

Figure 2 shows that the shape of evaporating droplets lying on the substrate depends on the ethanol concentration. The area of the contact spot and the rate of evaporation increased with the concentration of ethanol in the mixture.

The behavior of the geometric parameters of the evaporating droplets was determined on the basis of micrographs (figure 3).

Figure 1. Microphotographs of liquid droplets lying on a Teflon plate: a) water; b) ethanol.

Figure 2. 5 μl droplets of water-ethanol mixture with different concentration, evaporating on the Teflon substrate.
Data given in figure 3a show that diameters of contact spots of water droplets change little, especially at the initial stage. The pinning regime is realized at evaporation of water droplets. During evaporation, the contact lines of the ethanol droplets moved toward the center of the contact spot. These droplets evaporated with depinning. A different behavior of the diameter of the contact spot was observed for droplets with intermediate concentrations of ethanol. The greater the ethanol concentration, the less the evaporation time. In addition, behavior of the contact spot diameter more corresponds to the evaporation of droplets of pure ethanol, especially at the initial stage of evaporation. The results obtained from measurements of the contact spot diameter are in good agreement with data of other researchers [5, 7].

Figure 3b shows the change in the height of the droplets of the solution during evaporation. The water droplet is seen to have the largest height at the initial stage. During evaporation its height decreases linearly with time. The initial height of the ethanol droplet was the lowest and in the evaporation process it decreased faster than that for droplet of water. The curves $h(t)$ for mixtures lie between the curves for water and ethanol.

4. Measuring the droplet surface temperature

The method of infrared thermography was used to experimentally study the surface temperature of the evaporating droplets. The infrared camera NEC TH 7102WV was used for temperature measurement. During the experiments, the thermograms were recorded with an interval of 5 seconds.

Figure 4 shows thermograms of the surface of evaporating drops of water and ethanol, made 1 minute after the beginning of evaporation. It is seen that the surface temperature of the droplets was lower than the temperature of the substrate. This was due to the droplet cooling during evaporation processes. However, under identical conditions, the average temperature of the water droplet surface was 21.5 °C, but that of ethanol was 19.5 °C. This was evidently conditioned by the varying intensity of evaporation of these liquids.

Time dependences of average temperatures of evaporating droplets with different ethanol concentrations were determined on the basis of processing the thermogram sequences obtained in the experiments (figure 5).

The behavior of the temperature of evaporating droplets is essentially dependent on the ethanol concentration (figure 5). At the initial stage of evaporation, sharp decrease in temperature to 21.5 °C was observed for the water droplets. Then the droplet temperature remained practically unchanged for 700 seconds, after that a gradual increase in the droplet temperature to the ambient air temperature was
observed. The ethanol droplets cooled to lower temperature, about 19.5°C. The stage of constant temperature lasted for 60 sec. Then, similar to above, the sharp temperature increase was observed.

Under these conditions, the wet bulb temperature of water was 12.7°C, and that of ethanol was 8.2°C. The lowest droplet temperature was more than the wet bulb temperature for a given liquid. Obviously, this temperature difference was due to the heat flux from the substrate. As noted in works [7, 8, 9] the heat flux has a significant effect on the evaporation of droplets.

As discussed in [10], the nature of the change in surface temperature of evaporating droplets has three stages [10]: the initial section of a sharp temperature increase; a stage of constant temperature; and a final stage of a gradual increase in droplet temperature to the ambient air temperature. The temperature of the droplets with different ethanol concentrations at the initial stage of evaporation changed similar to the temperature of an ethanol droplet, and then as a water droplet temperature. Obviously, this behavior is due to the fact that at the initial stage, the more volatile component (ethanol) predominantly evaporates [4, 6]. The larger the ethanol concentration was, the higher the temperature of the droplet surface was similar to the temperature of the ethanol droplet.

![Figure 4](image)

**Figure 4.** Thermograms of the droplet surface lying on the Teflon substrate (1 minute after the beginning of evaporation): a) water droplet; b) ethanol droplet.

![Figure 5](image)

**Figure 5.** Surface temperature of evaporating drops of a water-ethanol solution with different concentrations (Teflon substrate).
5. Conclusions
The performed experimental studies have resulted in obtaining data on the change in geometric parameters and average temperature of the surfaces of evaporating sessile droplets at different concentrations of the water-ethanol mixtures. The results obtained due to the microphotography show that the shape of the evaporating water-ethanol droplets lying on the surface of the Teflon plate differ substantially depending on the ethanol concentration. The higher the ethanol concentration is in the droplet, the greater the contact spot area is on the Teflon surface, and the faster the evaporation is. The data of infrared thermography show that the dynamics of the change in the average surface temperature of the sessile droplets of the two-component water-ethanol mixture depend on the ethanol concentration. The change in the temperature of the evaporating droplet of the mixture also occurs in three stages. The initial stage is characterized by a sharp decrease in the temperature of the droplet surface. During the second stage, the temperature remains constant. At the last stage, the temperature of the droplet surface gradually rises to the ambient air temperature. The higher the ethanol concentration in the mixture is, the smaller the difference between the temperature of a droplet of a water-ethanol mixture and of a pure ethanol.

Acknowledgments
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