Experimental study of the evaporation of suspended droplets of a water-ethanol solution

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Abstract. The dynamics of the geometric parameters of droplets of a water-ethanol solution suspended on polypropylene filaments was investigated using high-speed microphotography. It was found that all suspended droplets had a spherical shape during the main time of evaporation. The higher the concentration of ethanol in the drop, the faster the droplet evaporates. The dynamics of the temperature of droplets of a water-ethanol solution suspended on polypropylene filaments was investigated using the method of infrared thermography. Three stages of temperature change of evaporating droplets of a water-ethanol solution were found. At the initial stage of evaporation, the droplet temperature changed like the temperature of an ethanol droplet, and then its behavior was similar to the temperature change of water droplets. The higher the ethanol concentration in the drop, the more similar was the temperature change with a change in the ethanol droplet temperature.

1. Introduction
In recent years the investigation of binary solution droplet evaporation became significantly interesting. The results of the research have a wide field of practical applications, and therefore a large number of papers are devoted to this problem [1-3]. Mainly, in experiments, the change in the geometric parameters of evaporating droplets is considered [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. Using the noncontact infrared thermography method is very promising for the measuring droplet temperature [8, 9]. Evaporation of droplets with the use of infrared camera was investigated in this work.

2. Experimental setup
Experimental studies of evaporation of suspended droplets were carried out on experimental setup [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. The evaporation of droplets suspended on filaments of polypropylene with a thickness of 200 μm was considered in experiments. Polypropylene has a relatively low coefficient of thermal conductivity $\lambda = 0.19$ W / m°C. This experimental approach minimizes the influence of the filament and ensures good approximation to the conditions for evaporation of free drops. In experiments the evaporation of water-ethanol solution droplets with a different concentration (0% (water), 25%, 50%, 75%, 92% (ethanol)) was studied at constant temperature $t = 24^\circ$C, and constant relative humidity $\varphi = 24\%$. All droplets had the same volume (5 μl).
3. Measuring geometric parameters of evaporating droplets
Microphotographs of droplets were made during evaporation. This allows us to fix the shape of liquid droplets and determine their geometric parameters. Figure 1 shows microphotographs of evaporation of the water-ethanol droplets at different instants of time.

![Microphotographs of evaporation of water-ethanol droplets](image)

**Figure 1.** Micrograph of evaporating suspended droplets of water-ethanol solution with different concentrations.

Figure 1 shows that at the initial stage of evaporation all suspended droplets of a water-ethanol solution with different concentrations had a spherical shape. The diameter of the droplets decreased during the evaporation time, but the shape of droplets approximated a sphere. Not a spherical form of droplets was observed only at the final stage of evaporation. Thus, the droplets suspended on the filaments had a spherical shape during the main evaporation time.

The geometric parameters of the evaporating droplets were determined on the basis of microphotographs (figure 2).

![Temporal variations of droplet diameter and normalized squared droplet diameter](image)

**Figure 2.** Temporal variations of droplet diameter (a) and normalized squared droplet diameter (b) of a evaporating suspended drops of a water-ethanol solution with different concentrations.
Figure 2a shows that the initial droplet diameter was 2.1 mm. The droplet size at which the energy of its surface tension is balanced with the gravitational energy is characterized by the capillary constant \( a = \sqrt{2\sigma / g \rho} \) [10]. If the droplet size is less than the capillary constant, then the drop can be considered spherical. For water, the capillary constant is 3.8 mm, and for ethanol, it is 2.4 mm. Since the diameter of the droplets of the water-ethanol solution studied does not exceed the value of the capillary constant, their shape can be considered spherical. Figure 2a shows that the diameter of the ethanol droplet decreased significantly faster than that of the water droplet. For droplets with different ethanol concentrations, an intermediate situation was observed. The greater the ethanol concentration, the faster the decrease in droplet diameter.

Figure 2b shows evolutions of the normalized squared droplet diameter \( \frac{d^2}{d_0^2}\) versus the time for evaporating of suspended drops of a water-ethanol solution with different concentrations. During evaporation the normalized square of droplet diameter decreased linearly both for water and ethanol droplets. Thus, the evaporation of drops of the pure liquids considered is described by Sreznevsky’s law [1]. The behaviour of the normalized squared droplet diameter was different for droplets with intermediate concentrations of ethanol. The greater the ethanol concentration, the more the correspondence of evaporation of droplets to evaporation of droplets of pure ethanol, especially at the initial stage of evaporation. In this case, the change in the normalized squared droplet diameter is not linear. This indicates that for binary solution droplet the linear dependence of the surface change on time is not observed.

4. Measuring temperature of evaporating droplets

The method of infrared thermography was used to study experimentally 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. The value of the radiation coefficient for water was taken \( \varepsilon = 0.96 \) [7]. The droplet temperature was measured with a chromel-alumel microthermocouple 50 \( \mu \)m thick to determine the emissivity of ethanol simultaneously with thermal imaging. Figure 3 presents a photograph of the droplet in the experiment and the temperature of ethanol droplet.

![Figure 3](image)

**Figure 3.** Photograph of the droplet in the experiment at the initial stage of evaporation (a) and the temperature of a droplet of ethanol obtained by microthermocouples and infrared method (b).

Figure 3a shows that the droplet size was significantly larger than the thickness of the microthermocouple. This provided a relatively small influence of microthermocouple on evaporation at the initial stage. Figure 3b shows the droplet temperature obtained by microthermocouples and infrared method. The received data do not differ significantly. On the basis of the measurements, the value of the emissivity for ethanol was determined \( \varepsilon = 0.92 \); it corresponds to the data of other authors [8].
Figure 4 shows the thermograms of the surface of evaporating droplets of water and ethanol, 1 minute after the beginning of evaporation.

![Thermograms of droplets](image)

**Figure 4.** Thermograms of the suspended droplets (1 minute after the beginning of evaporation): a) a water droplet; b) an ethanol droplet.

It is seen that the surface temperature of the droplets was lower than the temperature of the substrate. The reason is due to the cooling of droplets due to evaporation processes. However, under identical conditions, the average temperature of the water droplet surface was $14^\circ$C, but that of ethanol was $9.5^\circ$C. This is evidently due to the varying intensity of evaporation of these liquids.

The time dependences of the 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).

![Temperature vs. time graph](image)

**Figure 5.** Surface temperature of evaporating suspended drops of a water-ethanol solution with different concentrations.

The temperature of the evaporating droplets was essentially dependent on the ethanol concentration (figure 5). At the initial stage of evaporation, a sharp decrease in temperature to $14^\circ$C was observed for the water droplets. Then, the droplet temperature remained practically unchanged for 2700 seconds, after that a sharp increase in the droplet temperature to the ambient air temperature was observed. The ethanol droplets cooled to lower temperature, about $9.5^\circ$C. The stage of constant temperature had duration of 460 sec. Then, as above, the sharp temperature increase was observed.
Under these conditions, the wet bulb temperature of water was 12.7 °C, and 8.2 °C for ethanol. The minimum droplet temperature was insignificantly higher than the corresponding wet bulb temperature. Obviously, this was due to the insignificant supply of heat from the filament to the drops. Thus, the evaporation of droplets suspended on polypropylene filament was a good approximation to the conditions of evaporation of free droplets. The behaviour of the surface temperature differed for the droplets with intermediate concentrations of ethanol. Firstly, this is the initial section of a sharp decrease in temperature. After that it is a stage of a gradual increase in droplet temperature to the ambient air temperature. The higher was the ethanol concentration in the droplet, the more similar was the temperature change with a change in the ethanol droplet temperature. At the initial stage of evaporation the temperature of the droplets with different ethanol concentrations changed like the temperature of an ethanol droplet. Then the temperature of the droplets changed like the temperature of a water droplet. Obviously, this behaviour was due to the fact that more volatile component (ethanol) evaporated predominantly [4, 6].

5. Conclusions
As a result of the performed experimental studies, at different concentrations of the water-ethanol solution data on the change in geometric parameters and average temperature of the surfaces of evaporating suspended droplets were obtained. The results obtained due to the microphotography showed that evaporating water-ethanol droplets suspended on the filaments had a spherical shape during the main evaporation time. During evaporation the normalized square of droplet diameter decreased linearly both for the water and ethanol droplets. For droplets with intermediate concentrations of ethanol, the change in the normalized squared droplet diameter is not linear. The data obtained by the method of infrared thermography showed that the dynamics of the change in the average surface temperature of the sessile droplets of the water-ethanol solution depended on the ethanol concentration. The nature of the change in surface temperature of water droplet and ethanol droplet has a stage of constant temperature, corresponding to the wet bulb temperature, and finally a stage of a sharp increase droplet temperature to the ambient air temperature. The behaviour of the surface temperature differed for the droplets with intermediate concentrations of ethanol. Firstly, this was the initial stage of a sharp decrease in temperature. After that it was a stage of a gradual increase in droplet temperature to the ambient air temperature. The higher was the ethanol concentration in the droplet, the more similar was the temperature change with a change in the ethanol droplet temperature.

Acknowledgments
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