Experimental study of evaporation of droplets of water ethanol solution at high relative air humidity

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Abstract. A change in the temperature of suspended droplets of a water solution of ethanol, evaporating at high relative humidity, is experimentally investigated using high-speed microphotography and infrared thermography. The data obtained for ethyl alcohol droplets show a significant dependence of the surface temperature of evaporating droplets on relative humidity of the ambient air. It should be noted that at high relative humidity, a significantly smaller decrease in the temperature of droplet surface than at low humidity was observed during evaporation. This relates to the processes of moisture absorption and condensation on the surface of an evaporating droplet of ethyl alcohol at high air humidity, accompanied by the release of heat.

1. Introduction
Evaporation of droplets of binary solutions of ethanol is of scientific interest and has a wide range of practical applications [1–3]. To date, various physical and mathematical calculation models on this issue have been proposed. Considering the existence of such works, their verification is of fundamental importance [4–6]. Therefore, experimental studies of evaporation of binary solutions play an important role. A significant part of the experimental work deals with the study of evaporation of sessile drops of a water solution of ethanol. The effect of surface material on the evaporation rate and change in the contact angle is studied in [7, 8]. The effect of solution concentration on the evaporation rate is considered in [9, 1]. A number of studies have analyzed a change in the temperature and geometric parameters of suspended droplets of binary solutions depending on the air flow temperature [11, 12]. A significant influence of environmental parameters on the process of evaporation of droplets of binary ethanol solutions is noted in [13–16]. A significant proportion of these experimental studies were carried out at relatively low values of relative humidity of the ambient air. At the same time, the process of evaporation of droplets of a water ethanol solution at high relative humidity is of certain scientific and practical interest. Since a water ethanol solution is a binary nonideal solution [17], concentrations of components in the droplet and in the environment are not the same and have a mutual influence. Therefore, the environment humidity affects significantly the composition and, accordingly, the process of droplet evaporation. Thus, the problem of experimental study of evaporation of droplets of a water solution of ethanol at high relative humidity of air is important.

2. Experimental setup
This work is a development of experimental studies on examination of evaporation of droplets of a water ethanol solution [18]. In contrast to previous studies, in this work evaporation of droplets at high relative humidity is considered in detail. Experimental studies were carried out for droplets of a water ethanol
solution with relative volumetric concentration of ethanol \( c_v = 0.96 \) (ethyl alcohol) with a volume of 5 μL. The experiments considered evaporation of droplets suspended on a polypropylene filament with a diameter of 150 μm in a sealed chamber with constant values of temperature \( t = 25^\circ C \) and relative air humidity \( \varphi = 95\% \) inside.

3. Measurement of geometric parameters of droplets

Experimental studies were carried out using high-speed microphotography to determine changes in the geometric parameters of evaporating droplets. Based on the sequences of micrographs obtained in the experiments, a change in the droplet diameter during evaporation was determined. The dependences of the square of relative diameter of ethyl alcohol droplet \( (d/d_0)^2 \) (\( d_0 \) is the initial diameter, \( d \) is the current diameter) on evaporation time \( \tau \), obtained after processing the experimental results, are presented in Fig. 1. Figure 1 also shows the data on a change in the square of the relative diameter for a water droplet of the same volume, obtained under similar conditions: temperature \( t = 25^\circ C \) and humidity \( \varphi = 95\% \) [18].

![Figure 1](image-url)

**Figure 1.** Change in the relative diameter of evaporating droplets at relative humidity of 95%:

1 – ethyl alcohol, 2 – water.

The data obtained show that at high relative humidity and the same ambient temperature, the nature of the change in relative diameter of ethyl alcohol \( (c_v = 0.96) \) and water \( (c_v = 0) \) droplets differs significantly. For a water drop, a linear character of a change in the square of the relative diameter is observed during the entire evaporation process, and for a drop of ethyl alcohol, the dependence of a change in the square of the relative diameter is nonlinear. Moreover, it should be noted that at the beginning of evaporation for about 120 s, the diameter of ethyl alcohol droplet changed hardly.

Then, a close to linear decrease in the square of the relative diameter was observed for a droplet of ethyl alcohol. At that, the slope of the \( (d/d_o)^2 - \tau \) dependence for a droplet of ethyl alcohol was significantly larger than for a water drop evaporating under the same conditions. This is explained by the fact that during ethyl alcohol evaporation, at the initial stage, the more volatile component of the solution is predominantly evaporated; it is ethanol whose evaporation rate is higher than that of water. Then, as the droplet evaporated, a gradual deviation from the initial linear dependence of the square of
the relative diameter was observed. Obviously, this was due to the fact that the ethanol content in the droplet decreased, and the evaporation rate of the droplet decreased gradually.

Approximately in 7000 seconds after the start of evaporation, with a decrease in the square of the relative droplet diameter to 0.35, the dependence of \((d/d_0)^2\) on \(\tau\) again took a linear character, and its slope angle corresponded to the slope of a similar dependence for a water drop. This indirectly indicates that, at this stage, the drop consisted mainly of water. The relative square of the water drop diameter of 0.35 corresponds to the volume of water of 1.1 μL. At the initial volumetric concentration of ethanol in the droplet \(c_v = 0.96\), the water content by volume in the droplet was 0.04, which corresponded to the volume of water in the droplet of 0.2 μL. Consequently, during evaporation of the ethyl alcohol droplet, the water content in the droplet increased in comparison with the initial content. Obviously, this can be associated with the absorption of water vapor from the ambient air due to ethanol hygroscopicity [19], as well as condensation of water from the air on the droplet surface when it is cooled due to evaporation [5].

4. Measurement of the droplet surface temperature

Experimental studies were carried out using infrared thermography. In the experiments, a thermal imaging camera NEC TH 7102WV, which allows recording the temperature distribution on the droplet surface with an accuracy of ± 0.2°C, was used. The measurements were carried out using a TH 71-377 microlens, which allowed determination of the temperature with a spatial resolution of 100 μm with an interval of 5 s. In the experiments, the thermograms of temperature distribution on the surface of evaporating droplets were recorded. The time dependences of changes in the average surface temperatures of evaporating droplets were determined via processing the sequences of thermograms obtained in the experiments. Figure 2 shows the experimental data on a change in the average temperature of droplet surface during evaporation at \(\phi = 95\%\), and similar data obtained previously at low values of relative air humidity [18].

![Figure 2](image_url)

**Figure 2.** Change in the surface temperature of droplets evaporating at different relative air humidity: ethyl alcohol 1) \(\phi = 5\%)\), 2) \(\phi = 25\%)\), 3) \(\phi = 95\%)\); water 4) \(\phi = 95\%)\).

The results obtained for a droplet of ethyl alcohol at relative air humidity of 95% show that at the initial stage of evaporation there was a sharp drop in temperature to 16.5°C. Subsequently, there was a smooth, gradually decelerating rise in the droplet temperature. At the final stage of evaporation, the surface temperature of ethyl alcohol droplet corresponded to the surface temperature of the water droplet evaporating under similar conditions. Obviously, this is explained by the fact that after intensive
evaporation of ethanol at the initial stage, its concentration in the droplet decreases, and at the final stage, evaporation occurs mainly due to water. The performed comparison shows that for all the considered values of relative air humidity, the form of the obtained dependences of a change in the surface temperature of ethyl alcohol droplets was similar; it included 3 stages noted earlier in [19].

According to the experimental results, shown in Fig. 2, a change in the temperature of suspended drops of ethyl alcohol depended significantly on the relative humidity of the ambient air. The lower the relative humidity of air, the lower the droplet temperature dropped, and the faster it evaporated. It should also be noted that in all the cases considered, the minimum droplet temperature during evaporation did not reach the adiabatic evaporation temperature of ethanol $t = 6.1^\circ C$ [20]. As it was noted earlier, this could be due to the supply of heat along the filament [18] and radiative heat exchange between the droplet and the environment [14, 15]. According to the performed estimates, the supply of heat along the filament to the droplets is insignificant and, for the conditions of experiments, it led to an increase in temperature by 0.1°C. Another possible reason why the droplet temperature did not reach the values of adiabatic evaporation of ethanol, in addition to radiation heat transfer, is the absorption of moisture from the ambient air due to ethanol hygroscopicity. At low values of relative air humidity $\varphi = 5\%$, the absorption of moisture by the drop is insignificant and it has little effect on the process of droplet evaporation and its temperature. At relative air humidity $\varphi = 25\%$, moisture absorption by a drop increases, and the effect of hygroscopicity on the evaporation process and drop temperature increases. At high relative air humidity $\varphi = 95\%$, the content of water vapor in the air is significant. As a result, the absorption of moisture by the droplet increases significantly due to hygroscopicity. For the experimental conditions ($t = 25^\circ C$, $\varphi = 95\%$), the dew point temperature was $t = 24.1^\circ C$. Thus, it can be noted that the droplet surface temperature decreased below the dew point of water vapor. As a result, in addition to moisture absorption due to hygroscopicity, water vapor condensed from the ambient air on the surface of evaporating droplet. Condensation was accompanied by the release of heat, which leads to an increase in the droplet temperature.

Analysis of the data obtained shows that evaporation of ethyl alcohol droplets depends significantly on relative humidity of the ambient air due to the possible supply of moisture into the droplet from the ambient air during its evaporation. At high air humidity, in addition to the absorption of water due to ethanol hygroscopicity, water vapor condenses on the droplet surface. In experiments using microphotography with 200x magnification, the appearance of condensate in the form of small droplets on the drop surface was directly recorded (Fig. 3).

![Figure 3. Micrograph of the surface of an ethyl alcohol droplet at relative air humidity of 95%: a) at the initial moment b) in 300 s after the start of evaporation.](image-url)
The data presented in Fig. 3 show that approximately in 300 s after the beginning of evaporation, small drops with a characteristic size of about 5 μm appeared on the surface of ethyl alcohol droplet at relative air humidity of 95%.

Conclusions
As a result of experimental studies, the data on a change in the diameter and temperature of the surface of evaporating drops of a water-ethanol solution, suspended on polypropylene filaments at high relative humidity, were obtained. The results obtained show that, at high relative humidity, the dependence of a change in the square of the relative diameter of a droplet of water-ethanol solution with ethanol concentration $c_v = 0.96$ is generally nonlinear. A significant dependence of the surface temperature of evaporating droplets on relative humidity of the ambient air, caused by moisture absorption from the ambient air due to ethanol hygroscopicity, has been experimentally shown. It should be noted that at high relative humidity, a significantly smaller decrease in the surface temperature of droplet during evaporation was observed than at low humidity. This is due to the processes of absorption and condensation of moisture on the surface of an evaporating drop of ethyl alcohol at high air humidity, accompanied by the release of heat.

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