The effect of air relative humidity on the evaporation temperature of water-ethanol droplets

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Abstract. Using the method of infrared thermography, an experimental study of the temperature of evaporating droplets of a water-ethanol solution of different concentrations suspended on polypropylene thread at different air relative humidity was carried out. It is shown that the amplitude of the diminution in droplet temperature during evaporation decreases with an increase in relative air humidity for all considered concentrations of the water-ethanol solution. It is shown that the pattern of decreasing the minimum temperature of cooling of the evaporating droplets with increasing ethanol concentration is characteristic of all the studied air relative humidity. The obtained experimental data are generalized and can be used when calculating the heat and mass transfer of evaporating droplets of the water-ethanol solution.

1. Introduction

In researches on the evaporation of the water-ethanol droplets, most often the main attention is paid to the effect of the solution concentration on the dynamics of evaporation [1-5]. In these works, the change in the geometric parameters of droplets was studied mainly, while the change in droplets temperature during evaporation was not considered. At the same time, several works showed a significant effect of thermal effects on the processes of evaporation of droplets of the binary solutions [4, 5]. It should also be noted that most studies consider the evaporation of water-ethanol droplets lying on the surface of the substrate, although the process of evaporation of free droplets is also of scientific and practical interest. An analysis of a change in the geometric parameters and surface temperature of suspended drops of binary solutions was carried out in [6-8]. However, these studies were conducted at certain air relative humidity. Moreover, it was noted in [9-11] that the humidity of the surrounding air, as well as the concentration of the solution is a significant factor that determines the evaporation process dynamics. Thus, the important task is to study the effect of the relative humidity on the evaporation of free water-ethanol droplets.

2. Experimental setup

This work is a continuation of a series of experimental studies of the evaporation of suspended drops of the water-ethanol solution [12]. The small diameter and the low thermal conductivity coefficient (0.19 W/m°C) made it possible to minimize the effect of the thread and obtain a good approximation to the evaporation conditions of free droplets. In contrast to previous studies, in this work, the evaporation of droplets is considered at various relative humidity. For this purpose, the test section of the experimental setup with a suspended drop was placed inside the sealed chamber (Figure 1).
Figure 1. Photo (a) and schema (b) of the experimental setup: 1 – polypropylene thread; 2 – droplet; 3 – digital microscope; 4 – infrared camera; 5 – sensor of the thermohygrometer; 6 – sealed chamber

During the experiment, constant temperature and relative humidity were maintained inside the sealed chamber. Using a sorbent, a set constant value of relative humidity in the chamber was achieved. The temperature and humidity in the chamber were measured using a thermo-hygrometer. A thermal imaging camera and a digital microscope were located on the side of the suspended droplet. The evaporation time, droplet diameter, and surface temperature were measured during the evaporation of a droplet. The surface temperature of the droplets was determined based on data obtained by the thermal imaging camera. In calibration experiments and when determining the emissivity of the surface of the droplets, the temperature of the droplets was additionally measured using a micro-thermocouple. In the experiments, two identical droplets with equal ethanol concentrations were suspended on a thread not far from each other. The temperature in one of the droplets was measurement by the micro-thermocouple. During the evaporation, both droplets were recorded using the thermal imaging camera. It should be noted that droplets with a thermocouple had an average temperature of 0.4 ÷ 0.9 °C higher than ones without the thermocouple. Obviously, this is explained by the supply of heat to the droplet through a micro-thermocouple. The data obtained for droplets with a micro-thermocouple were used for the only calibration and determining the emissivity of the droplet surface. In further analysis, we considered the temperature obtained using a thermal imaging camera for droplets without the thermocouple.

In the experiments, we studied the evaporation of droplets of the water-ethanol solution with different volume concentrations of ethanol $c_v$: 0, 0.25, 0.5, 0.75, and 0.96 (for brevity, below this value is designated as “ethanol”). In the experiments, evaporation of droplets with 5 μl volume were considered at a constant temperature $t = 25$ °C and various relative humidity ($\varphi = 5\%, 25\%, 55\%$, and $95\%)$.

3. Results of the experiments
As a result of processing the experimental data, the time dependences of the surface temperature of droplets of water-ethanol solution evaporating at various relative humidity were determined. Figure 2 shows the characteristic time-temperature dependences obtained for water droplets ($c_v = 0$) and ethanol droplets ($c_v = 0.96$) at air relative humidity of $\varphi = 5\%$ and $\varphi = 25\%$.

The data in Figure 2a show that for the water droplet at a relative humidity of 25% at the initial stage of evaporation, a sharp decrease in temperature to 14.2 °C was observed. Subsequently, the temperature of the droplet practically did not change during the main time of evaporation.
The droplet temperature rose to ambient temperature during the final stage of evaporation. At a relative humidity of 5%, the behavior of the temperature was similar, but the droplet cooled down to lower values of about 10 °C and the evaporation process was much faster. This indicates more intense evaporation at lower humidity. Under these experimental conditions (t = 25 °C), the temperature of the adiabatic evaporation of water was 9.5 °C with an air humidity of 5% and 13.5 °C with an air humidity of 25%. Thus, the experimental data show that upon evaporation of water droplets suspended on polypropylene thread, the minimum values of the droplet temperatures exceeded the corresponding adiabatic evaporation temperatures by about 0.5 °C. This was probably due to the supply of heat along the thread and the radiative heat transfer of the droplet in the environment [13]. According to estimates, the heat supply through the thread to the droplets was insignificant and under the conditions of the experiments, this resulted in a temperature increase of about 0.1 °C. The greatest effect was exerted by the radiative heat transfer of the droplet in the environment [14-16]. The data in Figure 2 show that the temperature change of the suspended ethanol droplets (c_v = 0.96) also depends on the relative humidity of the surrounding air. At a relative humidity of 5%, the ethanol droplet temperature decreased to lower values than at relative humidity of 25%, and evaporation occurred faster. The character of the temperature dependences was similar to one for water droplets, and also included the 3 stages of evaporation noted earlier in [16]. Under similar conditions, ethanol droplets evaporated faster than ones of water, and their temperature decreased to lower values, for example, at a relative humidity of 5% minimum temperature was 6.6 °C, and at a relative humidity of 25%, it was 9.5 °C. Under the experimental conditions (t = 25 °C), the temperature of the adiabatic evaporation of ethanol was 6.0 °C at the air relative humidity of 5% and 8.9 °C at the relative humidity of 25%. Thus, for the ethanol droplets, the minimum temperatures also exceeded the corresponding adiabatic evaporation temperatures. The reason of this is probably also due to radiative heat transfer.

Data analysis (Figures 2a and 2b) shows that the air relative humidity has a significant effect on the evaporation time and the minimum temperature of water and ethanol droplets. A similar effect of relative humidity was observed in experiments during the evaporation of the droplets of the water-alcohol solution with ethanol concentrations equal to c_v = 0.25, 0.5, 0.75. Figure 3 shows the dependences of the minimum temperature of the evaporating water-ethanol droplets on the concentrations of ethanol at different relative humidity.
Figure 3. The minimum temperature of water-ethanol droplets with different concentrations of ethanol evaporating at a different relative humidity.

The results presented in Figure 3 show that the minimum values of the droplet temperature increase with increasing relative humidity for all considered concentrations of the solution. The highest growth was observed for water droplets and the lowest – for ethanol ($c_v = 0.96$). An intermediate situation was observed for droplets with ethanol concentrations of 25%, 50%, and 75%. It should also be noted that the higher the ethanol concentration, the lower is the minimum droplet temperature during evaporation. This dependence is presented more clearly in Figure 4.

Figure 4. The minimum temperature of evaporating water-alcohol droplets vs the concentration of ethanol at a various relative humidity.
The results presented in Figure 4 show that within the all considered range of relative humidity, the higher the ethanol concentration, the lower is the minimum droplet temperature during evaporation. Such an effect of ethanol concentration on the adiabatic evaporation temperature of binary solutions was noted earlier in [17], and was observed for droplets of the water-ethanol solution in [8]. However, the results of these studies were obtained only at given relative humidity. The data obtained in the present work show that a similar pattern of decrease in the minimum droplet temperature with an increase in ethanol concentration is characteristic within the entire range of relative humidity. The generalized result of measurements of the surface temperature of the evaporating droplets of water-ethanol solutions in the relative form is presented in Figure 5.

![Graph showing the dependence of the dimensionless minimum temperature of evaporating water-ethanol droplets on the volume concentration of ethanol](image)

**Figure 5.** The dimensionless minimum temperature of evaporating water-alcohol droplets vs the concentration of ethanol at a various relative humidity.

Figure 5 shows the dependence of the dimensionless minimum temperature of evaporating water-ethanol droplets \( \tilde{T} = t/t_w \) on the volume concentration of ethanol. Here \( t_w \) is the minimum temperature of a water droplet of the same size as water-ethanol one at the corresponding relative humidity. In such processing, the obtained experimental data are well described by the dependence \( \tilde{T} = 1 - 0.88c_v + c_v^2 - 0.47c_v^3 \). The obtained dependence can be used to determine the minimum temperature of evaporating water-ethanol droplets with various concentrations of ethanol at different relative humidity.

**Conclusions**

As a result of the evaporation studies of the water-ethanol droplets suspended on polypropylene thread at different air relative humidity, experimental data were obtained on the surface temperature of droplets with various solution concentrations. These data showed that ethanol concentration and air humidity are decisive factors that determine the evaporation dynamics. It is shown that with an increase in the relative humidity of the air, the minimum temperature of the droplets increases for all the considered concentrations of the water-ethanol solution. The character of decreasing the minimum temperature of evaporating droplets with increasing ethanol concentration is the same within the entire studied range of the relative humidity. The obtained generalization of experimental data can be used when calculating the heat and mass transfer of evaporating drops of water-ethanol solutions.
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