The effect of air relative humidity on the intensity of evaporating of water–ethanol droplets

A N Sterlyagov*, M I Nizovtsev, V Yu Borodulin and V N Letushko
Kutateladze Institute of Thermophysics, 1 Ac. Lavrentyev Ave., Novosibirsk, Russia

*E-mail: sterlyagov@itp.nsc.ru

Abstract. The results of experimental studies of the evaporation of the water-ethanol droplets with various concentrations of ethanol suspended on a thread are presented. Using high-speed microphotography, we studied the dynamics of changes in the size of evaporating droplets at various relative humidity of the surrounding air. As a result of experiments, it was found that the relative humidity of the surrounding air had a significant effect on the process of droplet evaporation. For all the considered concentrations of ethanol, it was found that the higher the concentration, the shorter the evaporation time of the droplets. Generalization of the experimental data on the evaporation time of the water-ethanol droplets of the corresponding concentration of ethanol at a relative humidity of 95% was carried out.

1. Introduction
The phenomenon of evaporation of the binary solution droplets is the basis of various technological processes. Therefore, a significant number of numerical and experimental studies have been devoted to this issue. As compared to pure liquids, the process of evaporation of binary solutions is significantly complicated due to differences in the thermophysical characteristics of the components and their complex mutual influence. In most experimental and numerical studies of evaporation of the binary solution droplets the effect of the ethanol concentration on the intensity of the evaporation process is studied [1-6]. In [7-9] a significant effect of the concentration on the change in the volume and contact angle of lying droplets was shown. A number of studies have analyzed the changes in geometric parameters and temperature of the suspended droplets for various binary solutions depending on the temperature of the air flow [10-12]. It should be noted that a significant proportion of studies were carried out at high temperatures and at a fixed relative humidity of the surrounding air. In a number of works [13-15] it was noted that the relative humidity significantly affects the process of evaporation of droplets of water-ethanol solutions. However, in these works only lying droplets are considered. At the same time, the process of evaporation of free droplets is of certain scientific and practical interest. Thus, one of the important tasks is to study evaporation of free water-ethanol droplets at various relative humidity. The results of the experimental study of the effect of relative humidity on the evaporation of water-ethanol droplets suspended on the thread are presented in this work.

2. Experimental setup
This work is a continuation of the experimental studies on the evaporation of the water-ethanol droplets suspended on thread of a low-heat-conducting material, which allows a good approximation to the conditions of evaporation of the free droplets [15]. Unlike previous studies, the evaporation of a droplet occurred inside a sealed chamber. In the experiments, a drop of a water-ethanol solution was suspended...
on a thin polypropylene thread (thermal conductivity coefficient of 0.19 W/m°C) with a diameter of 150 μm. Evaporation of droplets of the water-ethanol solution with 5 μl volume was studied at various volume concentrations of ethanol $c_v$ (0, 0.25, 0.5, 0.75, and 0.96). In accordance with the estimates made, the concentration measurement uncertainty was ± 4%. Using a sorbent, a fixed constant value of relative humidity in the chamber was achieved. The control and measurement of the temperature and humidity of the air in the chamber were carried out using an Eclerk-USB-RHT-K1 thermohygrometer. The absolute error in measuring the temperature in the chamber was ± 1°C, relative humidity ± 2%. In experiments with a digital microscope, the change in the droplet size during evaporation was recorded, while the uncertainty in determining the droplet size was ± 7%. During the experiment, constant temperature and relative humidity were maintained inside the sealed chamber. In the experiments, droplets were evaporated at a constant temperature $t = 25°C$ and different relative humidity of the ambient air ($\varphi = 5\%, 25\%, 55\%$ and 95%).

3. Results of the experiments

Figure 1 shows the experimental results depending on the square of the relative diameter of the droplets $(d/d_0)^2$ as a function of time for droplets with various ethanol concentrations at different relative humidity. Here $d_0$ is the initial diameter of the droplet and $d$ is the current diameter.

![Graphs](image1)

**Figure 1.** The relative diameter of the suspended the water-ethanol droplets vs time:

- a) $c_v = 0$ (water),
- b) $c_v = 0.96$ (ethanol),
- c) $c_v = 0.75$,
- d) $c_v = 0.25$. 


The results in Figures 1(a, b) show that the square of the relative diameter of the droplets of water and ethanol decreased linearly with time for the whole considered range of relative humidity. This linear relationship which known as the Sreznevsky law (d2-low) is widely used to describe the process of evaporation of drops of pure liquids [6, 10-12]. The less the relative humidity of the air, the greater the slope of the line (d/d0)^2. This indicates the intensification of evaporation of the droplets.

Figures 1(c, d) show the (d/d0)^2 vs time for droplets with ethanol concentration of 0.75 and 0.25. It has a non-linear character. The higher the concentration of ethanol in the solution, the closer the evaporating character to the ethanol one. With a decrease in ethanol concentration, the character of evaporation was more similar to the evaporation of water droplets. At the initial stage of evaporation, the slope of the curve approached this for the ethanol droplets at the corresponding relative humidity. At the final stage of evaporation, the slope of the curve (d/d0)^2 approached to the slope for the water droplet at the corresponding relative humidity.

At the initial stage this is occurred due to evaporation of a more volatile component: ethanol. Then as the ethanol concentration decreased the evaporating of the droplet was mainly determined by water. A decrease in the rate of evaporation of the water – ethanol droplets at high relative humidity was noted earlier in [13–15]. However, in these articles evaporating of sessile droplets was considered.

Dependences of evaporation time of water-ethanol droplets on concentration at various relative air humidity were obtained (Figure 2) in the experiments.

![Figure 2](image.png)

**Figure 2.** Evaporation time of water-ethanol droplets vs ethanol concentration at various relative humidity.

Figure 2 shows that for the entire range of the studied relative humidity, the higher the concentration of ethanol, the shorter the evaporation time. Such effect of concentration on the evaporation time of water binary solutions was noted earlier in [6, 10]. However, the results of these studies were obtained only at a fixed relative humidity. The results of this work show that a similar pattern of a decrease in the evaporation time with increasing ethanol concentration is characteristic of various relative humidity. It should be also noted that with an increase in relative humidity the evaporation time increased for all
considered concentrations of water-ethanol solution. The dependence of evaporation time of suspended water-ethanol droplets on relative humidity is shown in Figure 3.

The data presented in Figure 3 show that the highest rate of an increase in the evaporation time with increasing relative humidity was observed for water droplets, and the lowest one was observed for ethanol. An intermediate situation was observed for droplets with ethanol concentrations $c_v = 0.25, 0.5, 0.75$.

**Figure 3.** The evaporation time of the suspended water-ethanol droplets vs the relative humidity.

**Figure 4.** The dimensionless evaporation time of water-ethanol droplets with various ethanol concentrations vs air relative humidity.
Figure 4 shows the dependence of the dimensionless evaporation time of water-ethanol droplets \( \tilde{\tau} = \tau/\tau_0 \), where \( \tau_0 \) is the evaporation time at the relative humidity of 95%. It can be seen that in this processing the experimental data are well generalized by the exponential dependence
\[
\tilde{\tau} = 0.034 + 0.004 \cdot e^{0.75 \phi}.
\]
Thus, the dependence can be used to determine the time of evaporation of water-ethanol droplets with different concentrations at various relative humidity.

**Conclusions**
As a result of the experimental studies the suspended droplet diameter as a function of time was determined at different relative humidity. The data showed that for droplets of pure liquids (water and ethanol) the square of the relative diameter \( (d/d_0)^2 \) decreased linearly over time at different relative humidity. For droplets with an intermediate concentration of ethanol two intervals can be distinguished. The first one is associated with the predominant evaporation of ethanol and another is associated with the evaporation of water. It is shown that with an increase in the relative humidity the evaporation time of droplets increases for all the considered concentrations of the water-ethanol solution. Generalization of the experimental data is carried out and it can be used in calculating the evaporation time of the water-ethanol droplets at different relative humidity.

**Acknowledgments**
This research was carried out under state contract with IT SB RAS (AAAA-A17-117022810196-0).

**References**
[1] Chandra S, Di Marzo M, Qiao Y M., Tartarini P. 1996 *Fire safety journal* 27(2) 141–58
[2] Sefiane K, David S, Shanahan M ER 2008 *The J. Physical Chemistry B* 112(36) 11317
[3] Zhang H, Law C K 2008 *Combustion and Flame* 153(4) 593–602
[4] Saverchenko V I, Fisenko S P, Khodyko Y A 2015 *Colloid Journal* 77(1) 71–6
[5] Kuchma A E, Mikheev A A, Shchekin A K, Esipova N E, Itskov S V 2017 *Colloid Journal* 79(6) 779–87
[6] Borodulin V Y, Letushko V N, Nizovtsev M I, Sterlyagov A N 2019 *Colloid Journal* 81(3) 219–25
[7] Sefiane K, Tadrist L, Douglas M 2003 *Int. J. Heat Mass Transfer* 46 4527
[8] Cheng A K H., Soolaman D M, Yu H Z 2006 *The J. Physical Chemistry B*. 110(23) 11267
[9] Shi L, Shen P, Zhang D, Lin Q, Jiang Q 2009 *Surf. Interface Analysis* 41 951–5
[10] Terekhov V I, Shishkin N E 2010 *Joural Polzunovsky Bulletin* 1 55–9
[11] Hallett W L H, Beauchamp-Kiss S 2010 *Fuel* 89(9) 2496–504
[12] Han K, Song G, Ma X, Yang B 2016 *Applied Thermal Engineering* 101 568–75
[13] Liu C, Bonaccurso E, Butt H J 2008 *Physical Chemistry Chemical Physics* 10(47) 7150
[14] Kuchma A E, Esipova N E, Shchekin A K, Itskov S V 2018 *Colloid Journal* 80(6) 640–7
[15] Oztürk T, Erbil H Y 2018 *Colloids and Surfaces A* 553 327–36