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An experimental and theoretical study of the evaporation of non-ideal solutions droplets

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Abstract. This work presents the results of an experimental study of the dynamics of evaporation of suspended droplets in the air stream. Droplets of pure liquids (water, ethanol) and their mixtures of various compositions are considered. Dependences of the size of droplets and their surface temperature on time in a wide range of velocities of the flowing stream and its temperature, as well as the variation of the composition of the droplets, are obtained. The paper presents a mathematical model used to compare the experimental data.

1 Introduction

The evaporation of liquid droplets is applied in thermal power engineering, mechanical engineering, constructing, food processing and chemical industries. It is the foundation to steam power engineering, working refrigeration, evaporators, heat exchangers and other installations, and to all processes of drying materials. Investigations of the process and attempts to intensify and improve the efficiency of power units are extremely important [1-4]. At the same time, the solution of the problems that arise when designing devices using drop evaporation is a difficult task because it requires solving the problems of gas dynamics and heat and mass transfer in a multiphase flow with phase transformations. Evaporation of a single droplet has been studied by many authors [1-5], but establishment of the laws that allow precise calculation is an urgent task. There is no unified theory of evaporation of droplets of multicomponent mixtures that would reflect all the patterns and effects, observed in experiments.

In the present work, the process of evaporation of non ideal solutions droplets, streamlined by the gas flow, was studied theoretically and experimentally.

2 Experimental

The experimental part of this work was carried out on the setup (Fig. 1). The gas flow was formed by laminar flow due to the structural elements of the experimental stand. The flow velocity and temperature can be set in a wide range of values (0.1…5 m/s, 22…200 ^{0}C) and are constant during the experiment.

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At the height of about 2 cm from the nozzle, a droplet was suspended on a holder, which was a thread of glass fiber impregnated with wax of about 100 μm. Data on dynamics of the droplet size were obtained by the digital microscope, and the surface temperature of a droplet was measured by the thermal imager. The size of the droplets was ~ 2 mm, and the measurements were performed up to 0.3d.

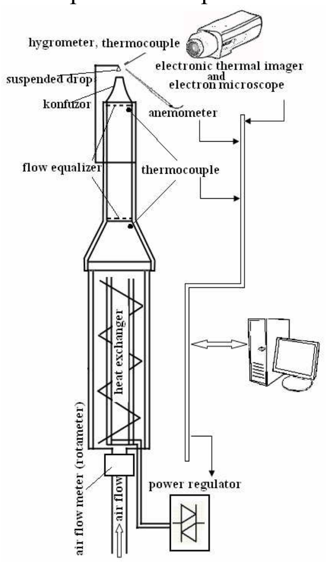

Fig. 1. The scheme of the experimental setup.

The experiments were carried out at atmospheric pressure, and the relative humidity of the air in the stream did not exceed 3%. Mixtures of working fluids were prepared by means of electronic weights using the mass ratio of the components.

3 Theoretical

As described above, in the present experiments, the drop was located on the holder, which was the main source of heat loss from the drop. The purpose of the simulation was to estimate the magnitude of these losses. The mathematical model was based on the balance of heat and mass at the drop surface. It was assumed that the temperature inside the droplet is uniform. In adiabatic conditions, the change in temperature during evaporation is the supplied heat from the gas minus the heat of the phase transformation.

$$\rho_l c_{pl} \frac{dT_l}{dt} = j \frac{c_{pg}\left(T_g - T_l\right)}{B_T} - jL \ , \tag{1}$$

where B_T is the thermal Spalding number. In the case of non-adiabatic evaporation, an additional term is added to the right-hand side of (1) to account for heat losses. In this paper, it was made in the form of $\alpha\left(T_g - T_l\right)$. Note that for all the calculations performed, the heat transfer coefficient α was assumed to be constant.

Mass flux of vapor is evaluated as:

$$j = 2\pi\rho_g D_g ShR \ln\left(1 + B_M\right), \tag{2}$$

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where B_M is the mass Spalding number. In order to determine the heat, Spalding used hypothesis about the similarity of heat and mass transfer:

$$B_T = (1+B_M)^{\phi} - 1 \ , \ \phi = \frac{c_{pf}}{c_p}\frac{Sh}{Nu}\frac{1}{Le} \tag{3}$$

Note that the Sherwood and Nusselt numbers are functions of the Spalding numbers, so they are evaluated by iteration. The Nusselt and Schmidt numbers were determined from the known dependences Nu=Nu(Re, B_T) for the sphere [5]:

$$Nu = 1 + \frac{(1+\mathrm{Re}\,\mathrm{Pr})^{1/3}\max\left[\mathrm{Re}^{0.077},1\right]-1}{2F(B_T)} \tag{4}$$

Identical depending Sh=Sh(Re, Sc, B_M) used to determine the rate of mass transfer. The system of equations was closed using the law of liquid-vapor equilibrium. The partial vapor pressure at the surface could be evaluated using an ideal model or non ideal one, taking into account the activity coefficients.

Thus temporal changes of droplet size:

$$\frac{dR}{dt} = -\frac{j}{4\pi\rho_l R^2} \tag{5}$$

4 Results and discussion

The obtained results of evaporation of water droplets are compared with the experimental work [3] in Fig. 2. The experimental data correlate well with the data of [3].

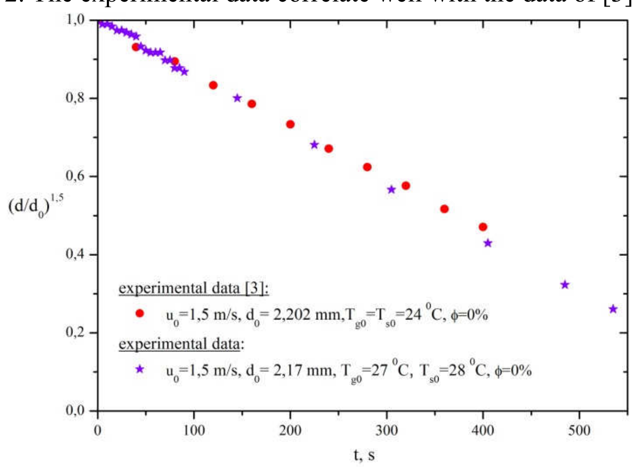

Fig. 2. The dependence of water droplet diameter on time.

Experiments and numerical simulation for water, ethanol and their mixtures in various proportions have been carried out. As it may be expected, evaporation of water occurs much slower than ethanol, evaporation of mixtures water and ethanol correspondingly are between them (Fig. 3). In this case, the surface temperature of the drop of ethanol, at the initial stage of evaporation (less than 50 s), respectively, is lower. Later, the temperature increases, due to the supply of heat through the holder.

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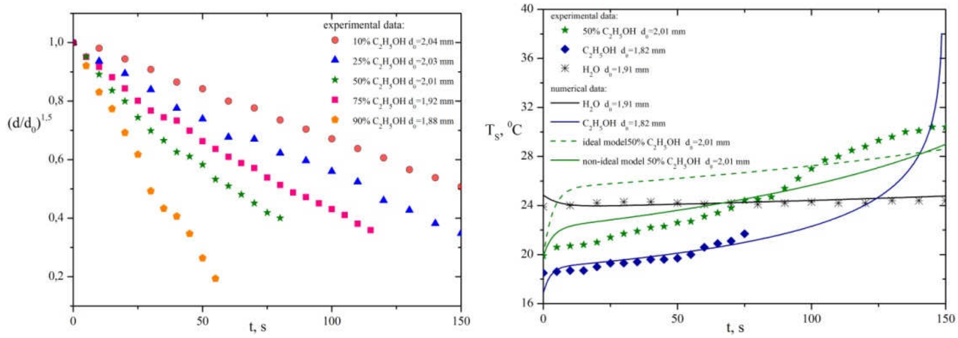

Fig. 3. Evaporation characteristics of droplets in experimental conditions: u_0=0.1 m/s, t_{0g}=47.6 ^{0}C, t_{0s}=22 ^{0}C, φ =3%.

From the temperature distribution it can be seen that the heat losses in the holder have a significant effect. This effect is most noticeable when the droplet size is reduced (see the Fig. 3a). Note that due to heat losses, the effect is observed: the temperature of the drop surface of the ethanol-water mixture and ethanol exceeds the temperature for the water drop. This is due to the fact that at the same time a drop of the mixture (or ethanol) is much smaller than a drop of water (see the Fig. 3a). In this case, the effect of heat supply through the holder is more significant, since the magnitude of the heat flux does not depend on the characteristics of the droplet.

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