Integrated experimental and theoretical study of evaporation process of nonideal solutions

E M Bochkareva, V V Terekhov, A D Nazarov and N B Miskiv

Kutateladze Institute of Thermophysics, Siberian Branch of the RAS
Russia, 630090 Novosibirsk, Ac. Lavrentieva ave., 1

Abstract. An experimental and numerical process simulation of evaporation of a suspended droplet of a non-ideal solution liquid streamlined by a gas flow was carried out in this paper. For analyze the heat and mass transfer of an evaporating droplet a mathematical model is given, which makes it possible to calculate both ideal and non-ideal solutions and takes into account the thermal losses in the holder. The experimental part of the study contains data on the evaporation of droplets of various compositions. The experimental data obtained by the authors were compared with the developed numerical model in the research.

1. Introduction
The processes of movement, interaction, and evaporation of liquid droplets in gas flows are of great practical interest [1-10]. More recently, aerosols are applied in heat power engineering, aircraft and machine building, and used in construction, food and chemical industries. An accurate predict of the heating and evaporation of the droplet is an important component in the research of spray modeling in the injection of liquid fuels, fire extinguishing, many other engineering applications and environmental phenomena. However, designing devices using droplet evaporation is difficult task, because it requires a compound solution of the problems of gas dynamics and heat and mass transfer in a multiphase flow with phase transformations.

A literature review on the theoretical research of this problem has shown that there are many numerical models [11-14, 16-17], with one or another assumptions being used in most cases. This is explained by heat transfer during the evaporation of liquid droplets is a complex process associated with the simultaneous transfer of heat and mass of the substance and a change in the phase state. The combination of simplicity and precise forecasting of dynamics is a priority for studying evaporation processes with a large number of drops [2, 15]. Whereas, there are many investigations devoted to the experimental study of the evaporation process [1-10, 19]. However, an analysis of the studies on drop cooling showed that the results of experiments are often contradictory and disjointed. This is largely due to the fact that the study of the rate of evaporation is quite a challenge. A number of studies have been devoted to the study of a single drop in a gas flow [1, 4-10, 16, 19], but the results obtained do not always correlate with the theory and have some peculiarities due to differences in the methods of conducting and analyzing experimental data. Also in the modeling of aerosol sputtering in this manner, a number of difficulties arise, which must be taken into account [10]. There are studies on the cooling of the surface by various methods [2-3, 15], mainly drip, film and jet cooling. Despite the different approaches, the essence of the work can be generalized as the investigation of the heat removal from the surface, varying the intensity of the spray, the geometry of the arrangement of the
nozzles in the heat exchanger, and etc. Since the noted features of heat and mass transfer processes in aerosol cooling remain poorly understood, it is necessary to develop research in this direction. Therefore, the purpose of this paper was to perform a complex experimental and theoretical investigation of the process of evaporation of suspended droplets of liquids of a nonideal solution flowed by a gas stream.

2. Model description

The mathematical model is based on the approach by Abramzon-Sirignano [12]. The developed methodology is based on a one-dimensional, spherically symmetric approximation, integral heat and mass transfer laws, the liquid-vapor equilibrium law, and a database of thermophysical properties of mixtures of gases and liquids. These equations and their approximations, where appropriate, are presented and discussed below.

![Figure 1. The balance of heat and mass at the drop surface.](image)

The liquid phase modeling includes the internal heat balance of the evaporating droplet. Therefore, the evaporation rate is determined by the surface temperature which may be different from the volume-average one when a significant temperature gradient develops. In the main a distribution of the temperature inside the droplet is assumed to be uniform. Thus, the heat balance equation on the droplet surface can be written as:

\[ Q_{\text{conv}} = Q_{\text{heat}} + Q_L \]  \hspace{1cm} (1)

The droplet’s heating rate is calculated as:

\[ Q_{\text{heat}} = Q_{\text{conv}} - \sum J_s \cdot \Delta h_{\text{vap}}(T_s) \]  \hspace{1cm} (2)

where \( \Delta h_{\text{vap}}(T_s) \) – heat of evaporation with droplet temperature \( T_s \).

The convective heat flux around the droplet is approximately taken into account by introducing the Sherwood and Nusselt numbers, which estimate the empirical relationships as a function of the Reynolds number in the flow. These relationships are necessary to consider the evaporation of liquid droplets streamlined by the gas flow.

\[ Q_{\text{conv}} = \sum J_s \cdot c_{pg} \cdot \frac{(T_g - T_s)}{B_T} \]  \hspace{1cm} (3)

where \( B_T \) – is the thermal Spalding number:

\[ B_T = \frac{c_{pg} \cdot (T_g - T_s)}{\Delta h_{\text{vap}}(T_s) - Q_{\text{heat}}/\dot{m}} \]  \hspace{1cm} (4)

Mass flux of vapor is evaluated as:
\[ J_s = 2\pi \cdot R \cdot (\rho \cdot D) \cdot Sh \cdot \ln(1 + B_M) \]  

(5)

where \( B_M \) – is the mass Spalding number:

\[ B_M = \frac{Y_{vap,s} - Y_{vap,g}}{1 - Y_{vap,s}} \]  

(6)

In order to determine the heat, Spalding used hypothesis about the similarity of heat and mass transfer:

\[ B_T = (1 + B_M)\phi - 1 \]  

(7)

where \( \phi \):

\[ \phi = \frac{c_{pg} \cdot Sh}{c_p \cdot Nu \cdot Le} \]  

(8)

Note that the Sherwood and Nusselt numbers are functions of the Spalding numbers, so they are evaluated by iteration. The Nusselt number was determined from the known dependences for the sphere [13]:

\[ Nu = 1 + \frac{(1 + Re \cdot Pr)^{0.333} \cdot \max\left[Re^{0.077}, 1\right]}{2 \cdot F(B_T)} - 1 \]  

(9)

Identical depending used to determine the rate of mass transfer.

For a single droplet, modelling of gas phase is based on analytical solutions of the vapor mass and energy conservation equations [11-12, 17]. These solutions are obtained assuming spherical symmetry and produce explicit expressions for droplet evaporation rate. The system of equations was closed using hypothesis about the similarity of heat and mass transfer and 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. The saturation vapor pressure was found according to [18]; from this same source, data on the thermophysical properties of the substances under investigation were taken. Despite the simplicity of the model, it effectively solves the problems of gas dynamics with two-phase flows for bi-component liquids.

3. Experimental setup

The scheme of the experimental setup designed to study the evaporation of liquid droplets is shown in Fig. 2. The setup consists of the following main elements: a vertical stainless steel pipe 0.5 m long with diameter of 50 mm and with output confusor diameter of 10 mm, a heat exchanger with an electrical heater located over the entire length of the device and a thyristor power controller. To reduce heat losses the heat exchanger and the pipe are covered with thermal insulation. To form a laminar flow honeycombs are used. The flow rate is regulated by a valve at the input of the heating system in the range from 0.1 m/s to 3 m/s with an accuracy of 0.01 m/s. The heat exchanger with the power regulator heats the air flow in the range of 22 \(^\circ\)C to 200 \(^\circ\)C. At the height of about 2 cm from the confusor, required to ensure the uniform air flow, a droplet is suspended on a holder, which is a polyvinyl chloride fiber with a diameter of 0.3 mm. When a droplet enters the stream, its size and the surface temperature are recorded by two cameras: a digital microscope and a thermal imaging camera.
The experiments were carried out at atmospheric pressure and the relative humidity of the air in the stream did not exceed 1%. Temperature, flow velocity and humidity monitoring were carried out using a special automated system. Mixtures of working liquids were prepared by the ratio of the mass of the components.

4. Results
Experiments and numerical simulations for pure water and ethanol, and water-ethanol solution have been carried out. The time dependence of the droplet surface temperatures for different ethanol mass fraction is shown in Figs. 3. Comparison between the numerical simulations and the measurements, temporal evolutions of the droplet temperature are displayed. Comparison to the numerical simulation results for ideal and non ideal mixture hypothesis is shown.

Figure 2. The scheme of the experimental setup.
Figure 3. The time evolution of the droplet surface temperature in experimental conditions: \( u_0 = 0.1 \) m/s, \( T_{0g} = 47.6 \, ^\circ C \), \( T_{0s} = 22 \, ^\circ C \), \( \varphi = 3\% \).

From the temperature distribution it can be seen that effect of heat conduction through the fiber is weaker for pure ethanol and water-ethanol solution. This effect is most noticeable when the droplet size is reduced until \( \approx 1.5 \) d of fiber. 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. In this case, the contact area of the droplet with the holder increases, since the surface tensions begin to exert a significant influence than gravitational forces. Note that due to heat losses, the effect is observed: the droplet surface temperature of the ethanol-water mixture and pure ethanol exceeds the droplet surface temperature for pure water. This is due to the fact that a droplet of the mixture (or pure ethanol) much faster evaporates and correspondingly at one and the same time point it is smaller in size than a droplet of water. 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. The experimental results on the evaporation of droplets of pure liquids correlate well with numerical calculations. A comparison of the experimental data of the ethanol-water solution with mathematical model showed that developed methodology takes into account the non ideal mixture hypothesis gives improved prediction. Combination of model simplicity and capability to accurately predict droplet surface temperature is crucial for efficient use in a CFD spray model which deals with a very large number of droplets.

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