Heat and mass transfer in the boundary layer during evaporation of aqueous solutions of ethanol and acetone into air and superheated vapor components of solutions

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Abstract. A stationary flow of three-component gas in a laminar boundary layer on a flat plate is considered at adiabatic evaporation of a two-component liquid film. Numerical modelling were carried out at atmospheric pressure, air flow velocity of 2 m/s and temperature from 20 to 500 °C in the whole range of concentrations of a low-boiling component of binary solutions: ethanol/water, acetone/water, and acetone/ethanol. Data on the local specific evaporation rate of ethanol/water and acetone/water solutions into dry air and superheated mixture of ethanol, acetone and water vapors were obtained depending on the temperature of the inlet flow. Composition of superheated vapor mixture was taken to be equilibrium relative to the liquid solution. With an increase in the molar fraction of ethanol or acetone in the water solution, the evaporation rate increases, and when evaporated into superheated vapor, the growth of evaporation rate with increasing vapor temperature is significantly higher than at evaporation into air. With an increase in ethanol or acetone concentration in the liquid solution, the inversion temperature decreases from down to 155...165°C.

1. Introduction

It is necessary to take into account the heat and mass transfer processes with phase and chemical transformations to designing the power equipment [1, 2]. The describing of the process of liquid mixture evaporation as a part of heat and mass transfer problem is of interest to a number of modern technologies. To obtain a new energy carrier (alternative to oil and gas) in the fuel industry the mixtures of liquid are used [3]. For example, ethanol and methanol are added to gasoline. The fuel companies develop the biofuel, whose advantage is renewability of the raw materials base. The evaporative cooling is important for the chemical industry, when preparing the supersaturated water solutions in a new method of nanoparticles production [4, 5]. Advance of distillation devices of chemical technologies depends on optimization of evaporation process, which in turn depends on the geometry, thermodynamic parameters, composition of liquid and gas phases, etc.

The heat and mass transfer dependencies during evaporation of pure liquids are widely known. The current state of the problem is set out in a number of reviews and monographs [6-7]. At the same time, the effects of heat and mass transfer at evaporation of liquid mixtures poorly understood despite their widespread in industrial processes. The task becomes more complicated at evaporation of liquid mixtures because it is necessary to account for the non-ideality, azeotropy, and mutual miscibility of liquid components. All of these factors are dependent on temperature, pressure and composition. In the transient regime, a more intensive decrease in concentration of volatile substances in solution occurs.
due to the difference of component fugacity. The droplets of ethanol/water, methanol/water, and acetone/water evaporate with temperature maldistribution over the droplet surface [8]. The additional actions are taken to ensure the constancy of liquid mixture composition in time. In [9], steady evaporation of ethanol/water, methanol/water and acetone/water from the porous sphere are studied experimentally at continuous supply of the liquid phase. New correlation for temperature of adiabatic evaporation of binary liquid is proposed. The two-component liquid film flowing on the inner wall of a vertical cylinder is investigated numerically in [10]. It is shown that the addition of methanol to benzene less to an increase in evaporation. The influence of geometry of evaporation surface on the heat transfer coefficients in the flow of the film of a binary Freon mixture is presented in experimental works [11, 12]. It is found out that at evaporation in the region of nucleate boiling development, the heat transfer coefficient for the surface with a mesh coating is higher than that for the smooth surfaces.

Heat and mass transfer at evaporation of mixtures is often simulated using the Raoult law. For example, in [13-15] the evaporation of a thin film of an idealized water/ethylene glycol solution to the laminar boundary layer on the vertical or horizontal surfaces are simulated numerically. It is shown that with increasing concentration of ethylene glycol, the temperature of evaporation surface increases due to the less fugacity of its vapors. The existence of inversion temperature at evaporation of binary liquid, observed previously only at evaporation of pure liquids [16, 17], is confirmed. In [18] the heat and mass transfer in a laminar boundary layer on a flat plate at stationary adiabatic evaporation of binary liquid mixtures was simulated numerically. Evaporation of mixtures with the properties of perfect solution and real zeotropic solution with positive deviation from the Raoult law was considered. For the real solutions, equilibrium between liquid and vapor is described using the Carlson-Colburn correlation. It is shown that at adiabatic evaporation of binary liquids, the wall temperature can be determined based on the similarity of heat and mass transfer for each component of the mixture. The calculation method was proposed for the engineering analysis of the processes of adiabatic evaporation of non-ideal binary liquids.

In this work, heat and mass transfer in a laminar boundary layer on a flat plate at stationary adiabatic evaporation of binary liquids of water, ethanol and acetone was simulated numerically at atmospheric pressure and temperature up to 500 °C. The data on the evaporation rate of ethanol/water, acetone/water, acetone/ethanol solutions into dry air and superheated mixture of ethanol, acetone and water vapors were obtained depending on the temperature of the inlet flow to determine the inversion temperature.

2. Problem statement and solution method
The scheme of the flow and the main parameters of the problem are presented in figure 1. Calculations were carried out at atmospheric pressure, air flow velocity of 2 m/s and temperature from 20 to 500 °C in the whole range of concentrations of a low-boiling component of binary solutions: ethanol/water, acetone/water, and acetone/ethanol.

![Figure 1](image-url)
Composition of the vapor-gas mixture at the interface was determined according to the Dalton law and equation of state of an ideal gas. The pressure of saturated vapor of components was determined from relationships based on the Margules equations: formulas of S E Harin [19] and I A Semyonov [20]. The results of calculations were verified by the known experimental data (figure 2).

![Figure 2. Saturated vapor pressure of the ethanol/water and acetone/water solution mixture at 30°C calculated by various models.](image)

The problem was solved by the numerical methods based on the system of differential equations of the two-dimensional boundary layer in physical coordinates. The secondary effects, such as thermal diffusion and diffusion thermal effect, are not taken into account. To close the system of differential equations, the boundary conditions are set at the interface and in the inlet flow. Based on the condition of viscous gas adhesion, the longitudinal velocity component on the evaporation surface is equal to zero. The transverse velocity component and heat flux at the gas-liquid interface is expressed through the balance of matter and energy at adiabatic conditions. More detail of the equations, boundary conditions, and solution method is presented in [18].

3. Results and discussion
Data on the local specific evaporation rate of ethanol/water, acetone/water, and acetone/ethanol solution into dry air and superheated mixture of its vapors were obtained depending on the temperature of the inlet flow. Composition of superheated vapors mixtures was taken to be equilibrium relative to the solutions.

As it show in figure 3, with an increase in the molar fraction of ethanol in the solution, the evaporation rate increases, and when evaporated into superheated vapor, the growth of evaporation rate with increasing vapor temperature is significantly higher than at evaporation into air. Equality of the rate of evaporation into superheated vapor and dry air occurs at a certain temperature: the temperature of inversion, which depends on the composition of solution, and for an aqueous solution of ethanol, it does not depend on the evaporation rate or local coordinate. With an increase in ethanol fraction in the solution, the inversion temperature decreases from 460 to 166°C.

For an aqueous solution of acetone, it is shown that the inversion temperature decreases slightly along the plate length, which may be related to a larger temperature gradient across the boundary layer thickness, which increases the effect of acetone vapors on the density and viscosity of mixture near the evaporation surface (figure 4). With an increase in the fraction of acetone, the average-length inversion temperature decreases from 460 to 154°C.
Figure 3. Evaporation rate depending on the inlet temperature of dry air and superheated vapor with an equilibrium concentration corresponding to the molar fraction of ethanol in liquid solution ethanol/water (the dash line shows the inversion temperature).

Figure 4. Evaporation rate depending on the inlet temperature for acetone/water solution.

Figure 5. The relative inversion and boiling temperatures depending on the molar fraction of the light-boiling component of liquid for acetone/water and ethanol/water solutions.
A decrease in the boiling point of solution correlates with a decrease in the inversion temperature as it shown in figure 5 in the dimensionless form. It should be mentioned that the correlation of the inversion temperature with the boiling temperature was noted earlier in [17], where the influence of the pressure of the drying medium on the intensity of water evaporation into the steam-air mixture was studied.

**Figure 6.** Evaporation rate depending on the inlet temperature for acetone/ethanol solution.

The obtained data on the rate of evaporation of the acetone/ethanol mixture show in figure 6. The boiling points of components are close (78.3 for ethanol and 56.3 for acetone); the heat capacities of liquids are close to. With an increase in ethanol concentration, the inversion temperature increases slightly from 155 to 165°C, which, as in previous cases, is consistent with an increase in the boiling point of the solution.

4. Conclusions
The heat and mass transfer on the wetted plate with adiabatic evaporation of ethanol/water, acetone/water, and acetone/ethanol binary solutions into the laminar boundary layer of the vapor-air mixture was studied. The values of the inversion temperature for the binary solutions under study were determined. It is shown that the dependence of the inversion temperature for water on the boiling point obtained earlier is maintained for solutions in which the boiling point changes due to changes in composition. An increase in the boiling point leads to an increase in the inversion temperature. The minimum value of the inversion temperature at atmospheric pressure for the solutions under studies is about 150 °C, which is significantly less than that of water. Lowering the pressure should also contribute to lowering the temperature of the inversion. The obtained results can be used in the development of effective technologies for separation of mixtures containing these components, in the absorption systems of refrigeration equipment, or in evaporative cooling systems.

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