Evaporation of aqueous solution of ethanol into an accelerated laminar boundary layer of air

M S Makarov\textsuperscript{1,2} and S N Makarova\textsuperscript{2}

\textsuperscript{1}Novosibirsk State Technical University NETI, K. Marks ave. 20, Novosibirsk, Russia, 630073
\textsuperscript{2}Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Sciences, 1 Ac. Lavrentyev Ave., Novosibirsk, Russia, 630090

E-mail: msmakarov@itp.nsc.ru

Abstract. The results of numerical studies of heat and mass transfer during adiabatic evaporation of an aqueous solution of ethanol into an accelerated steam-air laminar boundary layer on a flat wetted plate are presented. The flow acceleration is realized due to the inclination of the upper channel wall, which ensures the constancy of the Kays acceleration parameter. The dependences of the evaporation intensity of the components of solutions of various compositions are obtained for the acceleration parameter 0 and $10^{-6}$ for the flow temperature from 20 to 50 °C. A significant effect of the accelerating pressure gradient on the evaporation intensity and its weak effect on the equilibrium wall temperature are shown.

1. Introduction
Evaporation of liquid mixtures (solutions) is the basis of many technological processes in the industry. The interest of researchers in recent years has been focused on the development of technologies for obtaining fuels from renewable sources of raw materials, i.e., biofuels, the main combustible components of which are alcohols, benzene and other hydrocarbon compounds of organic origin [1]. The production of biofuels that can compete with traditional types of liquid fuels, obtained from fossil raw materials, in terms of production costs is associated with the enhancement of distillation and rectification processes. The main directions of the development of distillation columns are intensifying the mass transfer processes due to the development of the surface of the nozzles, the shape of which contributes to the intensive interaction of the steam flow with a thin film of liquid (solution), and ensuring the uniformity of the nozzle irrigation with a liquid flow [2]. In addition, various methods of modifying the nozzle surfaces are actively developing, which leads to the intensification of evaporation due to the formation of areas with ultra-thin layers of liquid (microrregions) [3, 4].

One of the ways to increase the intensity of heat and mass transfer processes on a solid surface is the effect of an accelerating pressure gradient on the gas flow. When a wetted wall is washed by an air or steam flow without acceleration, due to an increase in the thickness of the dynamic and diffusion boundary layers, the intensity of heat supply to the liquid and that of evaporation decrease. The accelerating pressure gradient suppresses the growth of the boundary layer thickness [5] and increases the diffusion steam flows from the wall to the external flow.

Stationary evaporation of aqueous solutions of alcohols and acetone in a gradient-free flow (with a constant velocity of the incoming flow) at a continuous liquid supply was studied in [6, 7]. A formula for calculating the temperature of adiabatic evaporation of the studied solutions was proposed. It was
shown in [8] that during the evaporation of a two-component liquid film, the addition of methanol to benzene led to an increase in the evaporation intensity. The papers [9-16] studied the phenomenon of inversion of the evaporation intensity of pure liquids and their solutions at an increase in the temperature of the air flow and superheated steam, flowing about the wall, above the boiling point of the corresponding liquid. The existence of the inversion temperature during the evaporation of volatile liquids (ethanol, acetone, benzene) was shown in [13, 14]. The inversion temperature during evaporation of aqueous solutions of ethanol and acetone into a laminar and turbulent boundary layer was considered in [15, 16].

This paper presents the results of numerical simulation of the adiabatic evaporation of an aqueous ethanol solution into an accelerated air flow (a vapor-air mixture with low vapor content) at a concentration of ethanol in water of 50% by weight at atmospheric pressure at the entrance to the narrowing channel.

2. Problem statement and solution method

A stationary laminar boundary layer on a flat plate is considered. The flow around the plate is a three-component gas, a mixture of water and ethanol vapors with air. However, the mass concentrations of water vapor and ethanol in the flow are assumed to be small (0.1% each). For simplicity of calculations, the properties of air are replaced by the properties of nitrogen [15]. The temperature of the flow around the wall varies from 20 to 50 °C, the flow rate at the entrance to the channel is 10 m/s, and at the exit, depending on the angle of inclination of the upper wall (acceleration parameter $K$) the velocity varies from 10 to 130 m/s.

The flow diagram and the main parameters of the problem are presented in Fig. 1. For the formation of a dynamic boundary layer with the developed laminar velocity profile, there is an initial adiabatic section with length $L_0$, followed by a section with flow acceleration over a wetted wall with length $L$ and an adiabatic section of flow relaxation with length $L_1$. In the wetted area, the heat supply to the surface is carried out only by convection – the conditions of adiabatic evaporation are met. The acceleration of the flow with a constant Kays parameter [5] $K = \frac{\sqrt{\nu (du_\gamma /dx)}}{u_\gamma}$ is realized due to the inclined upper wall. The relation of the inclination angle to the acceleration parameter can be written as follows: $K = \frac{\tan \alpha}{Re_0}$, $Re_0 = u_\gamma h_0/\nu$.

![Figure 1](image)

**Figure 1.** The scheme of a laminar boundary layer on a flat wall with adiabatic evaporation of a two-component liquid into the accelerated flow of the vapor-air mixture.

The problem was solved by numerical methods based on a system of differential equations of a two-dimensional boundary layer in physical coordinates. For the flow of a multi-component gas, the system of equations of continuity, motion, energy and diffusion was written as follows:
\[ \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0, \]

\[ \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) - \frac{dp}{dx}, \]

\[ \rho u \frac{\partial T}{\partial x} + \rho v \frac{\partial T}{\partial y} = \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) - \sum_{i,j} J_{(i,j)} \frac{\partial T}{\partial y} + \mu \left( \frac{\partial u}{\partial y} \right)^2 + u \frac{dp}{dx}, \]

\[ \rho u \frac{\partial K_{(i,j)}}{\partial y} = \frac{\partial}{\partial y} \left( -J_{(i,j)} \right); \quad K_{(s)} = 1 - \sum_{i,j} K_{(i,j)}, \]

where: \( 1 - \text{H}_2\text{O}, \ 2 - \text{C}_2\text{H}_5\text{OH}, \) and \( 3 - \text{air}. \) Thermal diffusion and the diffusion thermal effect were not taken into account in the calculations. The pressure gradient was determined by the Bernoulli equation as a function of the flow velocity at the outer boundary of the boundary layer \(-dp/dx = \rho u \frac{du}{dx} = \rho u^2 K/\nu\). The kinetic energy dissipation of the flow \( \mu (\partial u/\partial y)^2 \) was taken into account in the calculations, but in all the cases considered, its contribution to the thermal balance on the wall was negligible. In the gas phase, the diffusion fluxes of individual components in a mixture of others were calculated using the effective diffusion coefficient determined by the Wilke model [17]:

\[ J_{(i)} = -\rho D^0_{(i)} \frac{\partial K_{(i)}}{\partial y}; \quad D^0_{(i)} = \sum_{j=1} \frac{K_j}{M_j} / \sum_{j=1} \frac{K_j D_j}{M_j}, \]

where: \( D_{ij} \) the coefficients of binary diffusion of the mixture components.

Boundary conditions were set for the closure of the system of equations (1) – (5).

At the outer boundary of the boundary layer, the longitudinal flow velocity was set: constant in adiabatic sections of the wall and varying according to the Bernoulli equation when \( K = \text{const} \) over the wetted part of the wall. A zero transverse temperature gradient and a constant composition of the vapor-gas flow were set.

The longitudinal velocity component on the walls and the evaporation surface \( u_w = 0 \). The diffusion equation (4), written on the wall, taking into account the generation of vapors of the solution components on the evaporation surface (at \( y = 0 \)), may be written as:

\[ \rho_w v_w K_{w(i)} = -J_{w(i)} + \tilde{K}_{w(i)}, \]

where: \( \tilde{K}_{w(i)} \) is the specific evaporation intensity, which is determined in the calculation by the known equilibrium concentration of the \( i \)-component vapor over a solution of a given composition, as presented in [16]. Obviously, for air \( \tilde{K}_{w(3)} = 0 \). Summation of equations (6) by \( i \) gives a known relation for determining the convective flow of matter from the evaporation surface:

\[ \rho_w v_w \sum_{i=1}^3 K_{w(i)} = -\sum_{i=1}^3 J_{w(i)} + \sum_{i=1}^3 \tilde{K}_{w(i)} \], или \( j_w = \rho_w v_w = \sum_{i=1}^3 \tilde{K}_{w(i)}. \)

Writing equation (6) for air, we obtain an expression that determines the transverse component of the flow velocity:

\[ v_w = \frac{1}{\rho_w} \frac{1}{1 - \sum_{i=1}^3 K_{w(i)}}. \]

Adiabatic evaporation from the wetted part of the plate occurs only due to the convective heat supply from the external gas flow. We define the boundary conditions on the evaporation surface for the energy equation based on the balance of heat fluxes arising due to all the mechanisms of transfer and...
phase transition. Using the definition of the enthalpy of a gas mixture, we can obtain
\[ c_p \frac{\partial T}{\partial x} = \frac{\partial h}{\partial x} - \sum_{i=1}^{m} h_i \frac{\partial K}{\partial x}; \quad c_f \frac{\partial T}{\partial y} = \frac{\partial h}{\partial y} - \sum_{i=1}^{m} h_i \frac{\partial K}{\partial y}, \]
and equation (3) can be easily reduced to the form:
\[ \frac{\partial (\rho w h)}{\partial x} + \frac{\partial (\rho v h)}{\partial y} = \rho \left( \frac{\partial T}{\partial y} \right) - \sum_{i=1}^{m} \left( \frac{\partial (J_i h_i)}{\partial y} \right). \]
Equation (9), written on the wall, is
\[ \rho \nu \nu_i h_i = \lambda (\partial T/\partial y)_w - \sum_{i=1}^{m} J_{w(i)} h_{w(i)} \]
Let us multiply the left and right parts of equations (6) by the enthalpy of the corresponding component of the mixture in the gas phase and sum the equations by the component number:
\[ \rho \nu \nu_i h_i = -\sum_{i=1}^{m} J_{w(i)} h_{w(i)} + \sum_{i=1}^{m} K_{w(i)} h_{w(i)} \]
then the boundary condition for the equation of energy on the evaporation surface, taking into account that for air \( \dot{K}_{w(3)} = 0 \), will take the form:
\[ \lambda (\partial T/\partial y)_w = \sum_{i=1}^{m} \dot{K}_{w(i)} h_{w(i)} \]
The resulting ratio has a simple explanation. The heat supplied to the evaporation surface, due to the temperature gradient arising in the boundary layer, is spent on the formation of vapors of the solution components with a corresponding increase in the enthalpy of the vapor-gas mixture. The vapor enthalpy of the solution components can be expressed in terms of the enthalpy of the components in the liquid phase and the heat of the phase transition \( h_{w(i)} = h_{x(i)} + r_{w(i)} \). The heat of the phase transition for the aqueous ethanol solution under consideration may include the heat of dissolution, which depends on the composition of the liquid. However, the specific enthalpy of dissolution does not exceed 2% of the enthalpy of vaporization, and its contribution to the enthalpy balance can be neglected. If the liquid has a temperature equal to that of the evaporation surface, then the enthalpy of the liquid in the balance (11) can be neglected, and then, taking into account (6) and (7), we can write:
\[ \lambda (\partial T/\partial y)_w = \sum_{i=1}^{m} \left( j_i K_{w(i)} + J_{w(i)} \right) r_{w(i)} \]
### 3. Results and discussion
Figure 2a shows the results of calculating the local specific intensity of evaporation of an aqueous ethanol solution into dry air when the streamlining flow is accelerated with an acceleration parameter \( K=10^6 \) in comparison with the data obtained without flow acceleration. The effect of acceleration on the evaporation intensity can be divided into three regions along the length. For the considered narrowing channel with a length of 1.4 m, the first region is limited to the initial section from 0.1 to 0.3 m. In this region, the evaporation intensity practically does not differ from that in the flow without a pressure gradient. The dynamic and diffusive boundary layers increase, and the evaporation intensity decreases. The influence of the incoming flow temperature on the evaporation intensity is insignificant. Downstream from 0.3 to 0.7, there is a stabilization of the evaporation intensity in the accelerated flow, while in the flow without acceleration, evaporation is significantly suppressed. Acceleration leads to a decrease in the thickness of the diffusive boundary layers, which reduces their resistance to mass transfer from the wetted wall to the external flow. In this area, the influence of the temperature of the incoming flow on the evaporation intensity is clearly expressed. Thus, at 50°C, the evaporation intensity is two times as high as the evaporation intensity at 20°C. In the third region, from 0.7 to 1.4 m, the evaporation intensity increases, but for different temperatures of the incoming flow at different rates. So, for a flow with a temperature of 20°C, the increase in the evaporation intensity is the greatest, while for a flow with a temperature of 50°C, the evaporation intensity almost does not change. This region is characterized by a constant coefficient of friction along the length [5]. The different ef-
The effect of acceleration on evaporation is also due to the fact that with a constant Kays parameter, the maximum velocities at the exit from the narrowing channel significantly depend on the flow temperature, more precisely, on its density. Thus, at 20 °C, the flow velocity at the outlet is 130 m/s, and at 50°C it is only 45 m/s, i.e. at the same length, the flow velocity at 20°C increases 13 times, and at 50°C, only 4.5 times.

Figure 2. The local evaporation rate (a) and surface temperature (b) of an aqueous solution of ethanol in the area with air flow acceleration at different temperatures for the mass content of ethanol in the liquid of 50%: the dotted lines show calculations of the temperature of the wet thermometer by the theory of similarity [7], for the temperature of the incoming flow from the bottom upwards of 20, 30, 40 and 50 °C.

Figure 2b shows the surface temperature distribution on adiabatic sections and on a section with a wetted wall. The temperature practically does not change along the length of the wetted wall. We can only note a slight decrease in temperature near the outlet of the narrowing channel, associated with a decrease in the flow pressure due to acceleration. The adiabatic wall temperature obtained in this work is slightly higher than the temperature of the wet thermometer, determined for the solution under consideration according to the method from [7], but is closer to the data of experimental studies [6]. Thus, for the mass concentration of ethanol 0.718 (0.5 by mole fractions) at a dry air temperature of 23.5 °C, the temperature of the wet thermometer in the experiment is 4.6 °C, in these calculations it is 3.6 °C, and according to the similarity theory for the laminar flow regime without acceleration it equals 2.7 °C. Although the difference in the obtained temperatures is not large, according to the authors, it is due to the fundamental failure to take into account the similarity theory of the diffusion enthalpy transfer (see Equation 12).

Figure 3 shows data on the integral mass entrainment for the components of an aqueous ethanol solution (see Equation 12) along the wetted wall during flow acceleration. The width of the walls over the coordinate \( z \) is assumed to be equal to 1 m. So, for the geometry under consideration and the conditions of evaporation in a gradient-free flow, the water entrainment is 39 mcg/s at 20 °C and 92 mcg/s at 50 °C, and in an accelerated flow it is 86 mcg/s and 160 mcg/s, respectively. For ethanol in a gradient-free flow it is 127 mcg/s and 256 mcg/s, and in an accelerated flow it is 293 and 460 mcg/s, respectively. It may be stated that for the conditions under consideration, the influence of temperature is comparable to the influence of the pressure gradient on the intensification of evaporation.
Figure 3. Changes in the integral mass entrainment for the components of the aqueous ethanol solution along the wetted wall with flow acceleration (squares) and without acceleration (circles): the red dots show the data for ethanol, the blue dots – for water.

From the given numerical values of the integral intensity of evaporation of water and ethanol from the solution, it may be seen that ethanol evaporates more intensively than water, which should lead to the solution depletion with ethanol and enrichment with water during the process development over time.

Conclusions
Studies of heat and mass transfer during adiabatic evaporation of an aqueous solution of ethanol into an accelerated steam-air laminar boundary layer on a flat wetted plate have been carried out. The obtained dependences for the local and integral evaporation intensities of the solution components in the temperature range of the incoming flow from 20 to 50°C have shown that the accelerating pressure gradient enhances evaporation almost two times at $K=10^6$. In this case, the pressure gradient has a weak effect on the equilibrium temperature of the wall up to the flow rates of 130 m/s. The obtained results may be used in the development of effective technologies for the separation of mixtures (solutions) containing water and ethanol, in biofuel production technologies, absorption systems of refrigeration equipment, in evaporative cooling systems, during rectification or in drying processes.

Nomenclature

- $c_p$ – specific mass isobaric heat capacity, J/kg·K;
- $\delta$ – thickness of boundary layer, m;
- $D^0$ – effective diffusion coefficient, m$^2$/s;
- $J$ – diffusion flux, kg/m$^2$/s;
- $j_e = \rho_e v_e$ – evaporation intensity, kg/m$^2$/s;
- $h$ – enthalpy, J;
- $h_0$ – inlet height of channel, m;
- $K$ – Kays parameter;
- $K^{(i)}$ – mass fraction of $i$ component;
- $K_{ev(i)}$ – evaporation rate of $i$ component, kg/m$^2$/s;
- $L, L_0, L_1$ – length of the plate and lengths of non-wetted isothermal sections, m;
- $p$ – pressure, Pa;
- $Pr$ – Prandtl number;
- $q$ – heat flux, W/m$^2$;
- $r$ – specific heat of vaporization, J/kg;
- $Re$ – Reynolds number;
- $t$ – temperature, °C;
- $T$ – absolute temperature, K;
- $u, v$ – longitudinal and transverse components of the flow velocity vector, m/s;
- $x, y$ – longitudinal and transverse coordinate, m;
$X_{(i)}$ – mol fraction of $i$ component;  
$M$ – molar mass, kg/kmol;  
$\rho$ – density, kg/m$^3$;  
$\mu$ – dynamic viscosity, Pa·s;  
$\nu$ – kinematic viscosity, m$^2$/s;  
$\lambda$ – heat conductivity, W/m·K;  

bottom indexes:  
$0$ – inlet flow;  
$e$ – external flow;  
$i, j$ – component number  
in the vapor mixture or in the liquid solution;  
$L$ – liquid;  
$w$ – evaporation surface or wall.

Acknowledgments

The testing of numerical model was carried out under state contract with IT SB RAS, the parametric study of evaporation processes was financially supported by RFBR (Project No. 20-08-00717), and conducted at core facility "Structure, mechanical and physical properties of materials".

References

[1] Markov V A and Patrakhaltsev N N Alcohol fuels for diesel engines 2010 Transport na Alternativnom Toplive 1(22) [In Russian]
[2] Pavlenko A N, Zhukov V E, Pecherkin N I and Slesareva E Y 2020 Journal of Engineering Thermophysics 29(2) 195
[3] Zhukov V I, Pavlenko A N, Shvetsov D A 2020 Int. J. Heat Mass Transf. 163 120488
[4] Lyulin Y V, Kabov O A, Feoktistov D V, Kuznetsov G V, Ponomarev K O 2020 Thermophysics and Aeromechanics 27(1) 117
[5] Makarov M S, Sakhnov A Yu 2016 Int. J. Heat Mass Transf. 92 1018
[6] Terekhov V I and Shishkin N E 2009 Thermophysics and Aeromechanics 16(2) 239
[7] Makarov M S and Makarova S N 2016 Thermophysics and Aeromechanics 23(1) 23
[8] Baumann W W and Thiele F 1990 Int. J. Heat Mass Transf. 33 267
[9] Chu J C, Lane A M, and Conklin D 1953 Ind. Eng. Chem 45(7) 1586–91
[10] Schwartz J P and Brocker S 2000 Int. J. Heat Mass Transfer 43(10) 1791–800
[11] Sghaier J, Ben Abdelhamid M, Lecomte D and Belghith A and Sammouda H 2009 Int. Review of Mechanical Engineering 3(1) 64–73
[12] Chen J, Ma X, Bai L and Wang J 2010 Chemical Engineering (China) 38(1) 14–7
[13] Volchkov E P, Leontiev A I and Makarova S N 2007 Int. J. Heat Mass Transf. 50 2101
[14] Volchkov E P, Leontiev A I and Makarova S N 2007 Thermophysics and Aeromechanics 14(4) 493
[15] Makarov M S and Makarova S N 2019 Journal of Physics: Conference Series 1369 012056
[16] Makarov M S and Makarova S N 2020 Journal of Physics: Conference Series 1675 012054
[17] Wilke C R 1950 Chemical Engineering Progress 46 95