Heat and mass transfer with evaporation cooling of a porous plate

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Abstract. In this paper the results of experimental and theoretical investigation of heat and mass transfer with adiabatic evaporation of bicomponent water/ethanol fluid to an air flow are presented. An innovative test section for the wind tunnel with an active thermal stabilization system, maintaining the cuvette temperature equal to the evaporation surface temperature, is used to provide the evaporation adiabatic conditions. The wall temperature obtained experimentally shows the presence of expressed quasi-stationary evaporation area, qualitatively similar to sublimation curves of volatile organometallic compounds. A theoretical model based on the similarity of heat and mass transfer processes for each of the evaporating solution component is suggested. This model allows to determine evaporation surface temperature (sublimation temperature) accounting for radiation effect.

1. Introduction

Transition-of-phase heat and mass transfer processes became a frequent practice in aeronautical and heat engineering. Suffice to point out evaporation and sublimation cooling processes, which are used as an effective thermal protection of gas-turbine engine blades. The important scientific and technical objective is rise in field reliability of cooled turbine blades.

Heat and mass transfer processes with evaporation of pure (single component) liquids at flat, cylindric and spherical surfaces are described in detail in the literature [1, 2]. At the same time, heat and mass transfer effects with bicomponent liquids evaporation are still poorly understood, despite their widespread use in technological processes. The problem becomes more complicated in case of binary liquid evaporation, as far as it is necessary to take into account the deviation from ideal mixture, azeotropism, compatibility of the liquid components, which are complex functions of temperature, pressure and composition. Apart from this, the concentration of easily volatile substance in the solution is decreasing more intensively in unsteady evaporation regime due to the difference of components fugacity. Evaporation of aqueous ethanol, methanol and acetone droplets results in temperature non-uniformity of a droplet surface with the passage of time [3]. It is necessary to take special actions to provide composition constancy of liquid mixture over time in steady evaporation regime. Steady evaporation of binary aqueous ethanol, methanol and acetone at a porous sphere surface in a continuous liquid phase feed regime is experimentally studied in [4]. There is suggested a correlation for dimensionless temperature of adiabatic binary liquid mixtures evaporation with temperatures of pure liquids adiabatic evaporation used as representative. The influence of
composition of bicomponent liquid film flowing on the inner wall of a vertical cylinder on heat and mass transfer intensity is studied numerically in [5]. It is shown an addition of methanol in very small quantities to benzene, results in a significant increase of the liquid evaporation intensity. The influence of evaporation surface geometry on heat transfer coefficients during flow of freons binary mixture film is considered in experimental studies [6-8]. It is observed that changing the nature of film wave flow at Reynolds numbers $Re>400$ leads to the intensification of heat transfer during evaporation at transversely finned surface compared with smooth and diamond surfaces. The heat transfer coefficient for surface with net coating in evaporation regime and nucleate boiling, is significantly higher than for smooth and structured surfaces.

Control of heat influx to evaporation surface during experimental studies under laboratory conditions is one of the problems to solve. Spurious radiative and conductive heat influxes emitted by components of an apparatus are comparable to convective heat fluxes under investigation when evaporation surface temperature decreases sufficiently, heat and diffusion flows are small. The important objective is elimination or accurate control of addition heat fluxes. Ideal study conditions are known as an adiabatic evaporation. The adiabatic evaporation regime in practice realizes by means of heat-reflecting shielding [4, 9], small area of evaporation surface (drops, wetted fibers) and minimal size of thermometric probes (0.05...0.2 mm) [10]. An investigation into the influence of flow dynamics in a boundary layer on heat and mass transfer processes during evaporation requires a large test section area. Providing adiabatic conditions with evaporation surface rise becomes sophisticated problem since contact area with metallic elements of the apparatus, and area of radiative and conductive heat transfer rise.

The thermocouple measurements of evaporation surface temperature of aqueous ethanol at a flat porous plate under conditions close to adiabatic were carried out in this paper. The innovative thermal stabilization system of the test section containing Peltier coolers with feedback is used. This system allows to maintain the temperature of liquid inside the plate to be equal to the temperature of evaporation surface temperature. The obtained thermograms are used for verifying the theoretical model of binary liquid evaporation based on the assumption of temperature distribution similarity of a vapor-air flow and mixture components concentration over the boundary layer thickness.

2. Experimental setup and measurement

Heat and mass transfer during evaporation of aqueous ethanol at the porous plate with dimensions 100x150x10 mm into the boundary layer of air is studied. The innovative thermal stabilization system of the test section is used. The system makes use of Peltier elements with feedback and allows the temperature of liquid inside the plate to be equal to the temperature of evaporation surface. The porous plates are made of TZMK-10 (super-pure amorphous quartz fiber) with porosity of 90...95% and thermal conductivity of 0.05 W/m·deg. The test section design appears in figure 1.

![Figure 1](image_url)

**Figure 1.** The test section design: 1 – porous plates; 2 – Peltier coolers; 3 – heatsinks; 4 – cooling fans; 5 – fluid inlet tube; 6 – commutator switch; 7 – cuvette; 8 – heat insulation; 9 – supply pipe; a – flow direction of evaporating fluid; b – main flow direction.

The high level of measurement automation achieved by using own software and modern set of sensors such as the relative humidity sensor SHT-15 (accuracy of at least 2%RH), absolute pressure...
sensor BMP180 (accuracy of at least 0.2%), multi-channel thermocouple measurement unit (TermoLab32 and ADC LCard 14-440. The Peltier coolers were controlled by remotely adjustable power supplies (four APS-7305L units). The location scheme of chromel-alumel microthermocouples and block diagram of the thermal stabilization system are displayed in figure 2. The average temperature of bottom cuvette wall determined by means of thermocouples \( p_1, \ldots, p_6 \) is maintained equal to the average temperature of evaporation surface obtained from thermocouples \( s_1, \ldots, s_6 \) when the thermal stabilization system is turned on.

![Figure 2. The location scheme of thermo-couples in porous plate (a): \( P_1, \ldots, P_6 \) – set of Peltier elements with feedback by dint of thermocouples \( s_1, p_1, \ldots, s_6, p_6 \); \( a_1, \ldots, a_6 \) – measuring thermocouples; block diagram of thermal stabilization system (b).](image)

The experiments were carried out using an open-circuit subsonic wind tunnel with cross-section at a nozzle exit with dimensions 108x108 mm. The flow velocity at the nozzle was maintained at 2 m/s. Pre-measured by LDA turbulence at the given flow velocity doesn’t exceed 2%. The relative humidity of air didn’t exceed 0.5%RH. Preliminary experiments have shown there is a significant error in measurements when the thermal stabilization system is turned off. The error in the determination of surface evaporation temperature in the conducted experiments is able to rise up to 50%.

3. Results and discussion

Series of measurements of aqueous ethanol evaporation at the high-porous plate interface in dry air was conducted. The surface evaporation temperature at different points of the porous plate depending on time is obtained. The data on temperature change during evaporation of a solution with mass ethanol concentration of 93.1 % are displayed in figure 3.

![Figure 3. Temperature change at various surface points of the porous plate depending on time. The data referred to the evaporation process of water/ethanol solution with a mass concentration of ethanol of 93.1%.](image)
There are three sections on the thermogram curve: the initial section corresponding to liquid cooling from room temperature to the temperature of steady evaporation regime; the section corresponding to porous wall heating up to room temperature when evaporation process is over. The quasi-stationary evaporation regime occupies more than 3 hours, and the temperature exhibits a minimum at all thermocouple readings on this section. The equal temperature values fixed by thermocouples installed streamwise show that the composition of liquid mixture changes insignificantly and evaporation conditions are adiabatic on this section. The surface temperature obtained in experiment on this section is thus the adiabatic evaporation temperature of binary liquid with predetermined composition. The study results for mass ethanol concentration \( K_L \) in the solution of 0; 46.8; 75.5; 93.1% are listed in Table 1 (the temperatures indicated in centigrade degrees, °C).

Table 1. The experimental conditions and study results for water/ethanol solutions.

| \( K_L, \% \) | \( t_0 \) | \( t_e \) | \( t_w \) | \( t_w^{sym} \) | \( \delta^*, ° \) | \( t_w' \) |
|---|---|---|---|---|---|---|
| 0   | 21.0 | 26.4 | 8.8  | 5.5  | 968 | 9.0 |
| 46.8| 21.4 | 25.4 | 3.0  | -0.1 | 749 | 4.5 |
| 75.6| 22.6 | 26.4 | 4.7  | 1.5  | 422 | 4.7 |
| 93.1| 21.5 | 26.2 | 4.5  | 1.7  | 397 | 5.6 |
| 93.1| 24.5 | 29.8 | 6.6  | 2.9  | 330 | 6.2 |

The upper limit of concentration is governed by the azeotropic solution point at standard pressure. Figure 3 and Table 1 show experimental values of surface evaporation temperature \( t_w' \) distinguish from the temperature \( t_w^{sym} \) values, calculated using similarity of heat and mass transfer processes [11]. According to [12] the heat addition due to radiation sometimes significantly affects the surface evaporation temperature. The temperature of structural components near the test section was \( t_e \) during the experiments. The radiation influence in heat and mass transfer principles similarity [11] may be considered as:

\[
t_w' = t_0 - \left( K_{lw} L e_i' \rho_{lw} / K_{lw} + K_{lw} L e_i' \rho_{lw} / K_{lw} \right) \left( r / c_{p0} - \delta^* \right)
\]

in this equation \( \delta^* = \epsilon_{ef} \sigma \left( T_w' - T_e' \right) / J_w c_{p0} \) – the correction factor, depending on radiative heat transfer intensity and evaporation intensity, \( \epsilon_{ef} = 0.9 \) – the reduced emissivity factor, calculated using emissivity factor of porous quartz, ethanol and surrounding surfaces, covered with organic dyes, \( \sigma = 5.67 \times 10^{-8} \) W/m²·deg⁴ – blackbody emission coefficient. To calculate the surface temperature \( t_w' \) we derived the average evaporation intensity \( j_w \) from experimental data as a ratio of the initial mass of solution, filled in cuvette, to the evaporation surface area and to solution complete evaporation time. The complete evaporation time of solution was determined by the thermograms. The moment of time when surface temperature exceeds the main flow temperature and variation of the average surface temperature over the past 10 minutes doesn’t exceed 0.5 deg. is considered the evaporation process end. The average evaporation intensity over plate area can be determined theoretically using mass transfer principles for components of the mixture under standard conditions. In laminar flow regime \( A=0.664; n=0.5; m=2/3 \):

\[
\frac{j_w}{\rho \mu_0} = \frac{A}{Re_{lw}} \left( \frac{K_{lw} + K_{lw}}{K_{lw} \sigma_{cw} + K_{lw} \sigma_{cw}} \right)
\]

Figures 4 and 5 show the evaporation surface temperature depending on the water/ethanol fluid composition. Figure 4 shows the experimental points for adiabatic evaporation surface temperature.
distribution of water and aqueous ethanol with azeotropic composition over the length of plate. Note, the experimental data are almost identical with the results of heat and mass transfer numerical simulation computed considering the radiative heat fluxes according to [11]. In this case, wetted wall temperature rises over the length of plate. The evaporation surface temperature remains constant over the entire length in the absence of radiative heat transfer. In this case the calculated value of temperature is significantly below the experimental data.

Figure 4. The temperature of porous plate surface depending on the length of plate in comparison with simulation data [11].

Figure 5. The temperature of porous plate surface plotted against binary liquid composition.

Figure 5 shows $t_{w}^{sym}$ calculated by means of a formula (1) excluding the impact of $\delta'$. Here we can see lower values of the evaporation surface temperature. The data calculated with formulas (1) and (2) considering the radiation effect at the main air flow temperature of $t_{0} = 22 \degree C$ and room temperature of $t_{r} = 26 \degree C$ (dash line $t_{w}'$ in figure 5) describe experimental data more accurately. The temperature reaches minimum value when mass content of ethanol in the solution is about 40%.

4. Conclusions
The conducted experiments showed an applicability of the developed equipment for study of heat and mass transfer during evaporation of binary liquid. The simple ratio for determining the temperature of wetted wall during evaporation of binary liquid was derived. The surface temperatures of aqueous ethanol evaporation calculated with account for radiation are close to ones obtained experimentally and by numerical simulation.

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