



Heat transfer of aqueous salt solution layers

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ABSTRACT

Heat transfer and evaporation of layers of water and aqueous solutions of salts on a heated horizontal wall were studied experimentally. Aqueous solutions of salts can be divided into two characteristic groups. For the first group of salts, the evaporation rates and heat transfer coefficients increase with time. For the second group, the rate of evaporation falls sharply with increasing salt concentration and with decreasing liquid layer height. This difference in salts' behavior is determined by the difference in equilibrium curves and in physical and chemical properties of salts. The heat transfer coefficient for water and salt solutions increases when the layer height becomes less than 1.2–1.5 mm. With increasing concentration of salt and when approaching the crystallization point the role of free convection in the liquid phase decreases sharply, and the Nusselt number approaches 1. For salt solutions (LiBr, CaCl₂ and LiCl), a significant excess of convection (α) over the conductive heat transfer (λ) is observed for the layer height δ over 1.8–2.0 mm. For pure water, convective and conductive components are comparable even for $\delta = 3$ mm. This difference for salts is associated with substantial intensification of heat transfer, which is probably caused by the concentration flow of Marangoni Ma_c . Strong influence of Ma_c on heat and mass transfer in a thin layer and at high temperatures is detected for the first time and is extremely important for accurate modeling in unsteady and non-isothermal processes. Experimental data show a surprising result. The free liquid convection for salt solutions significantly exceeds the convection in the water layer for the most part of the evaporation time.

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1. Introduction

Evaporation of aqueous salt solutions is widely observed in nature, biology and medicine. Evaporation of highly concentrated salt solutions is accompanied by appearance of a new crystalline phase in the form of crystalline hydrates and salt crystals [1,2]. High-temperature evaporation of LiBr salt solutions results in formation of salt crystalline hydrates and may lead to crystalline plugs. Evaporation and absorption of water in aqueous salt solutions of LiBr; CaCl₂; LiCl are used in desorbers and absorbers of heat pumps [3].

The evaporation rate of solutions depends on many factors: the temperature of the free surface of the liquid, the concentration of the components, the thermophysical properties of the wall heater [4], wettability [5], the pressure of the external medium [6], as well as on the convection in the gas and liquid phase [7]. Thermophysical features of convection in gas and evaporation were presented in [8]. At evaporation of a thin layer on a heated wall, the important role is played by gas convection and external turbulence,

which accelerates drying and intensifies heat and mass transfer [9]. A structural wall influences evaporation and convection in a liquid layer [5]. Stability and break-up of a thin liquid film on structured surface is discussed in [10]. The effect of wettability on evaporation and crystallization was considered in [11–13].

The behavior of aqueous salt solutions significantly differs from the behavior of multicomponent volatile liquids [14,15]. At evaporation of aqueous salt solutions only water evaporates, and salts remain in the solution. The rate of evaporation of water solutions of salts decreases with time due to the increase in salt concentration. In most studies the numerical simulation of heat and mass transfer processes in a thin film of aqueous salt solutions does not take into account convection in the gas and liquid phases [16–18]. Modeling of heat transfer conditions in lubricant emulsions was considered in [19]. The dependence of the physical properties of solutions on concentration of salts is discussed in [20–23]. Experimental assessment of a hydrophobic membrane-based desorber/condenser with LiBr aqueous salt solution for absorption systems was presented in [24]. The efficiency of transfer processes in the adsorbers of heat pumps depends on the Marangoni flow. The addition of low concentrations of the surfactant leads to a sharp increase in convection in a thin layer of aqueous solution of LiBr

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[25,26]. The Marangoni flow leads to a film rupture in the absorber and to a decrease in the efficiency of heat transfer [27].

Thus, most studies of absorption and evaporation related to the salt LiBr and, partly, to salts CaCl_2 and LiCl, used in absorption heat pumps. Previously, we studied high-temperature evaporation of drops of these salts. In the literature, there is very little data on non-isothermal evaporation of fixed layers when the layer height and salt concentration change several times. Of course, the description of droplets and films is significantly different. In drops, the temperature gradient on the interface and the characteristic size of the convective motion are more clearly determined. In the layers, in addition to the layer height, there is a longitudinal size of the circulation motion, which can significantly differ from the layer length (the heater radius). Thus, experimental data are needed to determine the characteristic convective dimensions and Marangoni numbers for fixed layers. In addition, there is no comprehensive systematic study of a wide range of salts in the literature, when heat transfer and evaporation of aqueous solutions of salts with a strong change in physical and chemical properties are studied in one experiment. Studies of this article help to determine the key parameters that affect the behavior of different salt solutions.

Based on the above the following conclusions may be drawn. The lack of local data on heat and mass transfer of thin layers and films of the salt solutions significantly complicates the development of adequate physical models. Typically, the profiles of concentration, velocity and temperature do not take into account the change of the film thickness and concentration over time. The present work analyzes the impact of various key factors on the heat and mass transfer in a thin layer, when the salt concentration and the layer height change many times.

2. Measuring technique

For the experiments we used aqueous salt solutions: LiBr, CaCl_2 , LiCl, NaCl, CsCl, BaCl_2 , and MgCl_2 . The initial height of the solutions was 3 ± 0.1 mm. The experiments were carried out at ambient air temperature of 24°C ; relative air humidity of 40%; and ambient air pressure of 1 bar. The working section (1) was titanium alloy with diameter $d = 70$ mm (Fig. 1).

The aqueous salt solutions (3) were placed on a horizontal heated wall of the working section. The experimental setup was located in a box with dimensions: $1\text{ m} \times 1\text{ m} \times 1\text{ m}$. The upper part of the box was open to prevent changes in air humidity. The side-walls of the box prevented the effect of convection of external air in the room and made the measurements more time-stable. The measurement of external humidity and ambient temperature showed no change in time.

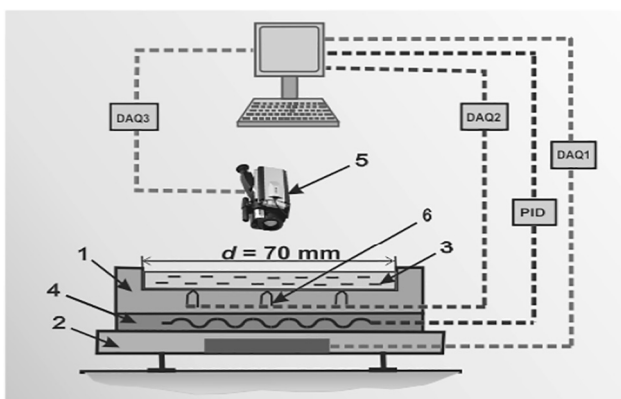


Fig. 1. The experimental setup: 1 – titanium working section; 2 – electronic balance; 3 – liquid; 4 – heater; 5 – thermal imager; 6 – thermocouple.

Thermocouples (6) for wall temperature measurement were located near the wall surface (0.5 mm from the wall surface). The wall temperature T_w was kept constant in an automatic regime with accuracy within $\pm 0.5^\circ\text{C}$ using PID and DAQ. The proportional-integral-derivative controller (PID) allows regulation of the heater power aimed at the achievement of the quasi-permanent wall temperature T_w . The values of the wall temperature are sent by thermocouples (6) to the data acquisition system (DAQ2) and then to the PC and PID. The wall temperature was kept constant automatically with the accuracy of $\pm 0.5^\circ\text{C}$. DAQ1 is designed to receive and process data on the droplet mass (a change in the droplet mass is recorded by the scales and the analog signal from the scales (2) is sent to the DAQ1 and PC.) The DAQ3-PC-thermal imager (5) is designed for measuring the temperature of the droplet surface T_s and processing data in the PC using special software that allows determination of the average temperature of a droplet surface. The interfacial temperature of liquid was determined with the help of thermal imager NEC R500 (5) (resolution of infrared camera was 640×512 pixels). The spectral bandwidth of infrared camera in short wave range (SW) was $3\text{--}5\ \mu\text{m}$. Before the experiments tests were carried out to evaluate the influence of salt concentration on the thermal imager measuring. The error of thermal imaging measurements associated with a change in salt concentration from 10% to 60–65% was 1–2%. Thus, a change in salt concentration did not affect the temperature measurements. The value of initial mass concentrations of salt in aqueous salt solutions (C_{01}) was determined using the densimeters. Current salt concentrations C_{1i} of the aqueous salt solutions were determined by a weight method. The setup was placed on the accurate balance (2). Since the salt mass does not change with time, it was easy to determine the current concentration values. As the salt concentration grows with time, the water concentration, on the contrary, decreases over time ($C_2 - C_{\text{H}_2\text{O}} = 1 - C_1$; where $C_{\text{H}_2\text{O}} = m_{\text{H}_2\text{O}}/m$; $C_1 = C_{\text{sol}} = m_{\text{sol}}/m$; $m_{\text{H}_2\text{O}}$, m_{sol} , m ($m = m_{\text{H}_2\text{O}} + m_{\text{sol}}$) are the mass of water, salt and aqueous salt solution). The increase in salt concentration leads to the change of the equilibrium partial vapor pressure p_s at the interfacial surface as well. At the known equilibrium values of temperature T_s and equilibrium vapor concentration C_s , the equilibrium vapor density ρ_s is uniquely determined by the equilibrium curves. The maximum error of evaporation rate was 11–12% for large times, when there was low evaporation rate. Experimental study of evaporation rates was conducted before the occurrence of crystallization.

3. Evaporation and heat transfer of aqueous salt solutions

The evaporation rate of the solution layer j was determined for narrow time intervals $\Delta t = t_{i+1} - t_i$ ($j_i = dm_i/dt_i \approx \Delta m_i/\Delta t_i$ (kg/s), where m_i is the current mass of liquid. Experimental data on evap-

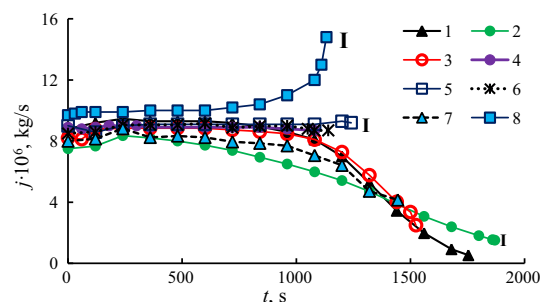


Fig. 2. Evaporation rate of aqueous salt solutions (initial salt concentration $C_{01} = 10\%$; $T_w = 80^\circ\text{C}$): 1 – LiBr; 2 – LiCl; 3 – CaCl_2 ; 4 – NaCl; 5 – CsCl; 6 – BaCl_2 ; 7 – MgCl_2 ; 8 – H_2O .

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