



Heat transfer of aqueous salt solutions during evaporation on a structured heated wall

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ABSTRACT

Evaporation and heat transfer of the layers of water and aqueous salt solutions ($\text{H}_2\text{O}/\text{LiBr}$, $\text{H}_2\text{O}/\text{CaCl}_2$, $\text{H}_2\text{O}/\text{LiCl}$) have been studied experimentally. Evaporation rate is greater for a structured wall than for a smooth one. When simulating droplet evaporation and heat transfer, it is necessary to take into account free convection of air and vapor. There is a change of the heat transfer coefficient for salt solutions layers on the structured surface with the presence of an extremum. The largest value of the heat transfer coefficient α on the structured surface corresponds to water for the final stage of evaporation. For salt solutions, α is lower than that of water. The maximum excess of heat transfer coefficient of micro-structured wall above the smooth wall (20–25%) corresponds to the maximum height of the liquid layer for the initial period of evaporation. With increasing time, the excess is reduced.

1. Introduction

The evaporation of water is important for temperature control of plants and mammals, and for earth climate. Droplet evaporation is very important in engineering fields: microelectronics (droplets deposited on a surface by nanodispersing techniques) [1], inkjet printing and liquid lithography techniques [2], the control of droplet evaporation rate for the self-assembly of nanoparticles [3] and DNA macromolecules [4], spray cooling [5], fabrication of microlenses from polymers [6], and ice production [7]. Analysis of an evaporative cooling system with droplet evaporation for cooling microprocessors is considered in [8]. The studies of droplets evaporation in a wide range of their diameters are interesting in terms of theory and practice. At high wall superheating and for thin-walled heat exchangers, an increase in the droplet diameter leads to a significant change in wall cooling, and this results in a shift in the boiling regime [9].

The wall roughness affects the Leidenfrost temperature of droplets. One important aspect regarding heat transfer is the application of nanotubes, that limit heat flux into the wall and lead to boiling crisis in nuclear power plants utilizing nanotube-clad parts in the reactor [10]. The low heat transfer coefficient between water droplet and carbon nanotube porous films is observed [11]. When stretching the droplet on the wall, wettability plays an important role [12]. Gas droplet flows are widely used in power engineering [13, 14]. When burning coal, sulfur and nitrogen oxides are considered the most dangerous anthropogenic

emissions. Temperature measurement in the trace of water droplet are formed in Ref. [14]. The water droplet evaporation according to diffusion and emission-diffusion models are compared in Ref. [15]. The flow of vapor and fine droplets is formed when burning methane hydrate, which leads to a decrease in the combustion temperature of the fuel [16, 17]. Droplets, falling on the wall surface, move along the surface, interact and merge with each other. As a result, the wall is cooled both by the small and large droplets. The large droplets interact and form a thin liquid film that demonstrates the meaninglessness to increase a droplet concentration in a vapor-gas curtain because this leads to film thickening and heat flux reduction. Gas convection intensifies the process of sessile droplet drying. It is assumed that a change in the law of evaporation is caused by a change in natural convection, which is characterized by the Rayleigh number [18]. 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 [19].

Evaporation of salt solutions is widely observed in biology, medicine and nature. The salt solutions behavior differs from the behavior of one-component liquids. At evaporation of aqueous salt solutions only water evaporates, and the salt remains in liquid. At high-temperature non-stationary evaporation, time dependence of salt concentration, evaporation heat, and diffusion coefficient is formed. Absorption and desorption of aqueous salt solutions ($\text{H}_2\text{O}/\text{LiBr}$, $\text{H}_2\text{O}/\text{CaCl}_2$, $\text{H}_2\text{O}/\text{LiCl}$) are used in absorption heat pumps. At nucleate boiling in a salt solution

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it is incorrect to simulate the droplet evaporation and the heat transfer in quasi-stationary approximation. The evaporation at nucleate boiling in a droplet is divided into several characteristic time intervals [20]. Each of these intervals is characterized by a noticeable change in both the evaporation rate and the convection role. Thermodynamic and thermal-physical properties of salt solutions are considered in Ref. [21–23]. The effect of wettability on droplet evaporation and crystallization was considered in [24–26]. Experimental assessment of a hydrophobic membrane-based desorber/condenser with LiBr aqueous salt solution for absorption systems was presented in [27]. Prediction of heat transfer conditions in lubricant emulsions was considered in [28].

Thus, when simulating the non-isothermal evaporation and the non-stationary heat and mass transfer it is important to know the dependence of the change in the heat transfer coefficient with time during a continuous change in the salt concentration. It is also important to know the effect of wettability and wall roughness on the heat and mass transfer. In problems associated with droplet and layer evaporation of an aqueous salt solution, the character of non-isothermal evaporation fundamentally differs from single-component liquids. Studying the behavior of heat transfer and evaporation on a structured wall is also an important scientific task.

2. Experimental data and analysis

2.1. Experimental methods for droplets

The experimental research was carried out on two horizontal surfaces: smooth and structured wall surfaces at air temperature of 23 °C and air pressure of 1 bar. External air humidity was 45%. The initial temperature of the liquid droplet was 23 °C (before placing the droplet on the heated wall). Measurements of wall roughness and surface topography were recorded with the help of optical profilometer “Zygo” (measurement uncertainty of ± 15 nm). Imaging was processed using 3D imaging software. The droplets were located on a horizontal heated wall of the duralumin cylindrical working section. The cylinder height was 50 mm and its diameter was 90 mm. The wall surface was cleaned ethanol, followed by acetone left overnight before experiments. Surface roughness was monitored before and after each experiment with the profilometer. Measuring thermocouples were located near the wall surface. The wall temperature was kept constant with the accuracy within 0.5 °C. The liquid surface temperature T_s was determined by the thermal imager (NEC-San Instruments, 640×512 pixels, the resolution is 10 μm). The spectral bandwidth of the infrared camera that is working in short wave range was 3–5 μm . The measurement error of the infrared camera was within 1 °C. The droplets were formed by the dispenser with the maximal relative volume error of 0.5%. The process of water separation from the dispenser occurred without the droplet fall, i.e., the dispenser was near the wall surface and it was located normally to the wall. Photographic measurements of a static contact angle θ_0 and area F of the sessile droplet bottom have shown good reproducibility in repeated experiments. The average values of a droplet diameter d_0 , θ_0 and area F were determined by the data of 3–4 experiments. Scattering of a droplet diameter and a droplet area did not exceed 3–5% of the average value. To measure droplet contact angle θ_0 and interface temperature T_s , the measurement system, shown in Fig. 1(a) was used. The relative error of static contact angle was below 5% and corresponded to high angles of 60–90° (the range of experimentally measured angles θ_0).

In experiments, the wall surfaces of two types were used: the smooth surface with rms roughness of about 1–2 μm and the structured surface with rms of 1–1.5 (see Fig. 1(b)) and with two typical transverse and longitudinal dimensions of the “wave” profile: profile height h_s and profile period l_s (Fig. 1(c)).

2.2. Experimental methods for layers of water and salt solutions

The scheme of the experimental setup for carrying out experiments with an aqueous salt solution is shown in Fig. 2. The initial height of the salt solution layer (5) for all experiments was 2.9 mm. Measurements were carried at air temperature 23 °C and air pressure 1 bar. External air humidity was 45%. The initial temperature of the liquid was 23 °C (before placing the liquid on the heated wall). The height of cylinder was 40 mm and its diameter was 70 mm. The heater (cylindrical working section) (3) was made from titanium alloy. The wall temperature T_w was kept constant automatically. The value of initial mass salt concentrations of aqueous salt solutions (C_{01}) was determined using densimeters. Current salt concentrations of aqueous salt solutions C_i were determined by a weight method. The setup was placed on the precision balance (1). Since the salt mass does not change with time, it is easy to determine the current values of salt concentration. The maximum error of the evaporation rate $j = \Delta m / \Delta t$ (m is the liquid mass, t is time) was 10–12% before crystallization at low evaporation rate. The liquid surface temperature T_s was determined by the thermal imager (NEC-San Instrument (6) Fig. 2). In the wall of the working section (3) there were several thermocouples (4), evenly placed over the surface to measure the average surface temperature across the wall (T_w). In the experiments, we used liquids: water and salt solutions of LiBr, CaCl_2 , and LiCl.

2.3. The droplet evaporation

Wettability affects both the drop contact angle and the diameter of droplet spreading on the wall surface in accordance with the balance of the forces applied to the triple contact line of the droplet. The base diameter of a droplet on highly hydrophilic and highly hydrophobic surfaces will differ markedly. Obviously, different diameters will result in different mass flows due to evaporation. The fabricated structured wall (Fig. 2(b)) has hydrophilic properties. The wetted diameter for a structured surface increases compared to a smooth wall.

Consider the drop evaporation of water and aqueous salt solution on a structured surface. The droplet evaporates on a heated horizontal surface, when the wall diameter of the heater substantially exceeds the diameter of the drop. In connection with the evaporation of water, the current salt concentration in the drop continuously increases, which leads to a change in the evaporation rate with time. Fig. 3 demonstrates experimental and calculated data for the evaporation rate of water drops and for drops of aqueous salt solutions. The evaporation rate was derived by the weight method $j = \Delta m / \Delta t$.

The experimental data correspond to curves 1–3, and curves 4–6 were obtained by calculation (6) (points 1, 4 – for water; curves 2, 5 – for the aqueous salt solution of $\text{H}_2\text{O}/\text{LiBr}$ and curves 3, 6 – for the aqueous salt solution of $\text{H}_2\text{O}/\text{CaCl}_2$). The evaporation rate $j = \Delta m / \Delta t$ for water drop slightly increases with time, as with a significant reduction of the droplet height the temperature T_s increases by several degrees. Despite the growth of the free surface temperature (T_s) for aqueous salt solutions j for curves 2, 3 decreases over time. The temperature T_s of the solution increases with time by 7–8 °C (from 66 to 67 °C to 73–75 °C), and the difference $\Delta T_w = T_w - T_s$ (T_w is the wall temperature under the drop) drops to 2–4° before crystallization. The difference ΔT_w at initial times is equal to 10–11°. Regions 1 and 2 are separated by a vertical dotted line. For region 1, the evaporation rate j is higher for the aqueous salt solution of LiBr, and for region 2, on the contrary, the aqueous salt solution of CaCl_2 has higher values of j . It is generally accepted that the lowest evaporation rate corresponds to the $\text{H}_2\text{O}/\text{LiBr}$ aqueous salt solution, as this salt has the highest absorption capacity. However, as can be seen from the Fig. 3, the evaporation rate (an absorption efficiency of a heat pump) of the aqueous salt solution depends on the current salt concentration. Before the time of 400 s (the salt concentration corresponds to the values of about 45%) the aqueous salt solution of $\text{H}_2\text{O}/\text{LiBr}$ evaporates faster than the solution of $\text{H}_2\text{O}/$

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