The influence of various factors on the droplet desorption

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Abstract. Experimental data on sessile droplet desorption of aqueous salt solution of LiBr on a heated wall were implemented. High-temperature desorption of water-salt solutions in air atmosphere leads to significant difficulties at modeling heat and mass transfer. In this case, the evaporation rate multiply decreases with time and the diffusion coefficient, the desorption heat and the salt concentration change significantly. With the growth of salt concentration in solution from 10 % to 65 %, the steam partial pressure at the interface falls by dozens of times. In this study, we performed experiments in a wide range of salt concentrations and proposed a simple estimated method for calculating the mass flow. The resulting technique can predict the droplet solution behavior with a significant change in the partial vapor pressure on the droplet interphase with time.

1. Introduction
The Spray cooling are used in heat exchangers and small devices to improve the efficiency of heat transfer. The problems of combustion and dissociation are also closely related to gas-droplet flows. For example, burning of fuel droplets in a moving flow [1] and the formation of water droplets, vapor and gas methane during the combustion of methane hydrate [2, 3]. The size of constructions and energy costs depend on cooling efficiency. Droplet evaporation of single-component liquids on the hydrophilic surfaces was investigated in Refs. [4-8]. The droplet behavior on hydrophobic surfaces is studied in Refs. [9, 10]. Boiling of the gas-drop flow is considered in Refs. [11]. At brine evaporation, salt concentration in liquid increases. Desorption processes are accompanied by additional dissolution heat because concentrations of components in solution change. Desorption of aqueous salt solutions is used in desorbers of thermotransformers. One of the way to increase the heat pump efficiency is increasing wall superheating, which allows a reduction in desorption time and an increase in heat transfer coefficient. The diffusion equation is important for salt solutions modeling. If we neglect diffusion, this can lead to overstating the absorption rate more than twice [12]. Thermodynamic and thermal-physical properties of salt solutions are considered in Ref. [13, 14]. An increase in salt concentration leads to an increase in desorption heat and repeated decrease in the desorption rate. There is a strong non-linearity of the density of steam mass flux vs. time [15]. An increase in the heat flux in a salt solution droplet leads to a transitional regime of boiling crisis [16]. Formation of crystalline hydrates in technical devices can lead to crystal plugs and cessation of the mixture flow in the channel. The high-temperature flow of salt solution in minichannels results in formation of emulsion multiphase flow. The crystalline film is formed on the wall. This flow is unstable and the flow is oscillatory in nature [17, 18]. In contrast to the single-component liquids, the Marangoni flow...
in the salt solution droplets is formed due to the concentration gradient, which affects the bubble microlayer dynamics [19]. The combined effect of boiling and free convection is considered in Ref. [20]. In the last decades, the attention to the construction of the models, taking into account the combined effect of the natural convection in liquid and gas, has increased. An increase in the droplet diameter and Rayleigh number leads to a multiple increase in the evaporation rate for liquids [21, 22].

Thus, droplets desorption of aqueous salt solutions is characterized by continuous decrease in the desorption rate and the partial vapor pressure. The purpose of this study is to carry out the experimental research for the desorption of aqueous salt solutions of LiBr in a wide range of a change in salt concentration with time from 10 to 60 %.

2. Experimental method and analysis
The droplet of aqueous salt solutions of LiBr was located on the metallic horizontal heated cylinder. The cylinder was made from titanium (Fig. 1). All experiments were carried out at the air temperature of 21 °C and air pressure of 1 atm. The initial droplet temperature was equal to the ambient air temperature (21 °C). Relative air humidity was 30-40 %. The cylinder diameter was 80 mm and its height was 65 mm. The wall temperature under the droplet was measured by a thermocouple and this temperature was kept constant automatically. The liquid surface temperature was determined by the thermal imager. The values of initial mass salt concentrations of $C_{0i}$ were determined by the densimeters. Current mass salt concentration $C_{1i}$ was determined using the weight methods (Fig. 1). The water mass concentration is $C_2=1-C_1$.

![Figure 1. Principle scheme of setup:](image)

A – working heating surface; 1 – titanium cylinder; 2 – electric heater; 3 – multilayer screen thermal insulation; 4 – adjustable supports; 5 – analytical balance; 6 – thermocouples; 7 – flexible detachable element of thermocouple; 8 – Dewar vessel with ice; 9 – thermocouple switch; 10 – millivoltmeter; 11 – flexible detachable element of electric wiring; 12 – laboratory thermotransformer; 13 – temperature regulator; V and A – voltmeter and ammeter; 14 – puller ear; 15 – metering device; 16 – protecting screen; 17 – video and shooting cameras, thermal imager

The maximum relative error of the mass flow measurements was in the range of 8-10%. With time a change in the interfacial temperature will lead to a shift of the point on the equilibrium curve from $(C_0, T_{s0})$ to point $(C_{si}, T_{si})$, at that, the driving force of absorption (desorption) will decrease $\Delta C_{nis}=C_{si}-C_{s0}$. 
and \(\Delta C_{n_{0n}}\) for the non-isothermal case will be significantly less than \(\Delta C_{i_{0n}}\) for the isothermal problem. For the case of isothermal desorption, when the Stefan flow is taken into account (interface moves with velocity \(V\)), the expression for the water mass flow density \(J_2\) will take form (1) [12].

\[
J_2 = \frac{-\rho D}{1-C_{02}} \frac{\partial C}{\partial y}, \quad y=0 = \frac{\rho \sqrt[4]{T(C_{02}-C_{02})}}{\sqrt{\eta t}} \frac{1}{1-C_{02}} \tag{1}
\]

For the infinitely large layer of solution at \(y \to \infty\), \(T = T_0 = T_w\), \(C = C_{02}\). It is also necessary to write down the interface conditions. Desorption heat is spent for liquid heating \(r_d\delta y = -A \frac{\partial T}{\partial y}\). At that, free convection in gas and liquid is neglected. In a small alteration range of equilibrium water concentration \(C_{2i}\) for the interface, temperature dependence of concentration can be presented in the linear form \(C_{2i} = k_1 + k_2 T_{si}\), where coefficients \(k\) are functions of pressure \(p\). Expression (2) for consideration of for non-isothermal nature is proposed in Ref. [12]

\[
J_2 = -\frac{\rho D}{1-C_{02}} \frac{\partial C}{\partial y}, \quad y=0 = \frac{\rho \sqrt[4]{T(C_{02}-C_{02})}}{\sqrt{\eta t}} f_1, \tag{2}
\]

where \(f_1\) is function taking into account non-isothermal nature (desorption heat \(r\)),

\[
f_1 = \frac{1}{1+(C_{02}-C_{02})K\sqrt{T_e}}, \quad K = \frac{r}{C_0(T_u-T_{0i})}, \quad L_e = \frac{D}{a},
\]

where \(D\), \(a\) are the coefficients of diffusion and thermal diffusivity in solution, \(C_0\) is heat capacity of liquid. The average temperature vs. time for the droplet surface is approximately

\[
T_s = \frac{T_{s1}+T_{s2}}{2} = \frac{T_w(15)+T_w(7)}{2} = T_w - 11.
\]

The average partial pressure is determined as

\[
\frac{p_{si}}{2} = \frac{p_{si0}+p_{act}}{2},
\]

where \(p_{si0}\) is initial equilibrium vapor pressure near the liquid surface, corresponding to initial concentration, \(p_{act}\) is vapor pressure before crystallization beginning. Then, \(C_{2i}\) corresponds to point \((T_{si1}, p_{si2})\). Thus, the nonstationary problem of the equilibrium pressure is reduced to the problem with stationary boundary conditions \((p_{si0}=\text{const}, T_{si0}=\text{const})\). Moreover, this problem can be considered as the quasi-isothermal because \(T_s\) increases with time slightly for most of the desorption time.

The mass change is determined by time integration of the flow density \(G = F \int J_2 \, dt = 2J_2 F t\), \(F\) is average area of the droplet free surface, \(F = (F_{in}+F_{fin})/2\), \(F_{in}\) is initial area of the liquid free surface after droplet placement on the wall, \(F_{fin}\) is final area before crystallization. Data for the water mass change for \((T_{si1}, p_{si2})\) are shown in Fig. 2.

![Figure 2](image_url)

**Figure 2.** The water mass change (the initial mass salt concentration of LiBr is \(C_{01} = 55\%\), \(T_w = 85^\circ C\), \(V_0 = 250\mu l\)): 1 – simulation by (1) without interface transportation \((V = 0)\); 2 – simulation with consideration of \(V\) by (1); 3 – experimental data.
As it can be seen from Fig. 2, the largest deviation of simulation from the experiment corresponds to the period of droplet heating and with constant concentration \( C_{i1} = C_{01} = \text{const} \). This model is not designed to calculate the initial warm-up period. For the next quasi-isothermal interval, the calculation curve (2) is in satisfactory agreement with the experimental data (3).

**Conclusion**

Thus, the mass flow can be estimated by the simplified procedure, when an unknown point on the equilibrium curve is defined as the average value of the equilibrium vapor pressure. The mass flow, taking into account the velocity of free surface transportation, shows a satisfactory agreement with the experimental data, except the initial period of heating.

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