

# Non-isothermal evaporation in a sessile droplet of water-salt solution



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## ABSTRACT

Experimental data on nonisothermal evaporation of sessile droplets of water-salt solutions (LiBr + H<sub>2</sub>O; CaCl<sub>2</sub> + H<sub>2</sub>O) were obtained. Evaporation of droplets of volatile liquids occurs with almost constant evaporation rate, and the problem is solved in a stationary approximation. High-temperature evaporation of water-salt solutions leads to significant difficulties at modeling the heat and mass transfer. In this case, the evaporation rate substantially decreases with time. With the growth of salt concentration in the solution from 11% to 60%, the partial pressure of water vapor at the interface falls by an order of magnitude. In this work, we have performed simulation, considering diffusion in solutions, a non-isothermal character, and the Stefan flow, and proposed a simple method for calculating the mass flow. The resulting technique can qualitatively and quantitatively predict the solution behavior with a significant change in the external boundary conditions in time.

## 1. Introduction

Droplet evaporation is widely observed in nature, biology and medicine. Intense cooling at fast droplet evaporation is used in practice at power installations. Spray and film cooling are used in small heat exchangers and small devices to improve the efficiency of heat transfer. The size of constructions, energy and technology costs depend on the cooling efficiency. Evaporation of sessile droplets of single-component liquids on hydrophilic surfaces was investigated in Refs. [1–8]. The rate of evaporation increases with decreasing external gas pressure [1] and depends on the material of the wall and the droplet size [5,6]. Heat transfer and droplet evaporation are highly dependent on the wall wettability and significantly differ for hydrophilic and hydrophobic surfaces. The wettability is influenced not only by the physical properties of liquid and wall material, but also by the surface topology. The impact of the structured wall on the evaporation rate and heat transfer inside the drop is considered in Ref. [7]. The droplet behavior on hydrophobic surfaces is studied in Refs. [8,9]. In the distribution of a drop on the wall it is important to consider the contact angle [10–13]. At the attached contact line of the evaporating droplet, the contact angle decreases and its value affects the evaporation rate and the Marangoni flow inside the drop [14].

At brine evaporation (evaporation of aqueous salt solutions is usually called “desorption;” and further for convenience we will refer to this process as “evaporation”) salt concentration in liquid increases. Evaporation processes are accompanied by additional dissolution heat because concentrations of components in a solution change. Another

important difference of salt solutions from completely volatile liquids is formation of crystals and crystalline hydrates of different structures; at that, additional heat is released at crystallization, which must be taken into account in the energy balance. Desorption and absorption of water solutions of LiBr (CaCl<sub>2</sub>) are used in desorbers and absorbers of lithium-bromide thermotransformers. One of the methods to increase the efficiency of heat pump is increasing the wall superheating, which allows reducing evaporation time and increasing the heat transfer coefficient. In contrast to single-component liquids, the evaporation process in salt solutions is determined not only by the pressure, temperature and superheating, but also by salt concentration, which changes in time. The diffusion equation is also important for salt solutions. It is not sufficient to solve only the equations of energy and momentum transfer. If we neglect diffusion, this can lead to overstating absorption rate more than twice [15]. To correctly determine the mass flux density at absorption, it is necessary to consider both the heat flux of absorption (liquid heating) and the Stefan flow [15,16]. Thermodynamic and thermal-physical properties of salt solutions are considered in Refs. [17–20]. The regime of constant contact angle (droplet radius decreases) or the regime of constant radius (the contact angle decreases) may be used for the single-component volatile liquid, depending on the droplet wettability. Evaporation of droplets of single-component volatile liquids is characterized by the quasi-constant evaporation rate. The law of evaporation for the droplets of water-salt solution is fundamentally different from absolutely volatile liquids. Firstly, there is always the regime of the fixed contact line. With increasing time of evaporation, the salt concentration near the contact line rapidly increases, and the

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**Nomenclature**

$a$	thermal diffusivity
$C$	mass concentration
$c_p$	heat capacity of liquid
$D$	diffusion coefficient of liquid
$d$	droplet diameter
$F$	area of droplet free surface
$G$	change in a droplet mass
$K$	$K = r/(c_p(T_w - T_{s0}))$ – similarity criterion
$Le$	Lewis number
$m$	droplet mass
$p$	water vapor pressure
$r$	latent evaporation heat
$t$	time
$T$	temperature
$j$	evaporation rate
$V_0$	initial droplet volume
$V$	speed of interfacial surface

$y$  transverse coordinate

*Greek symbols*

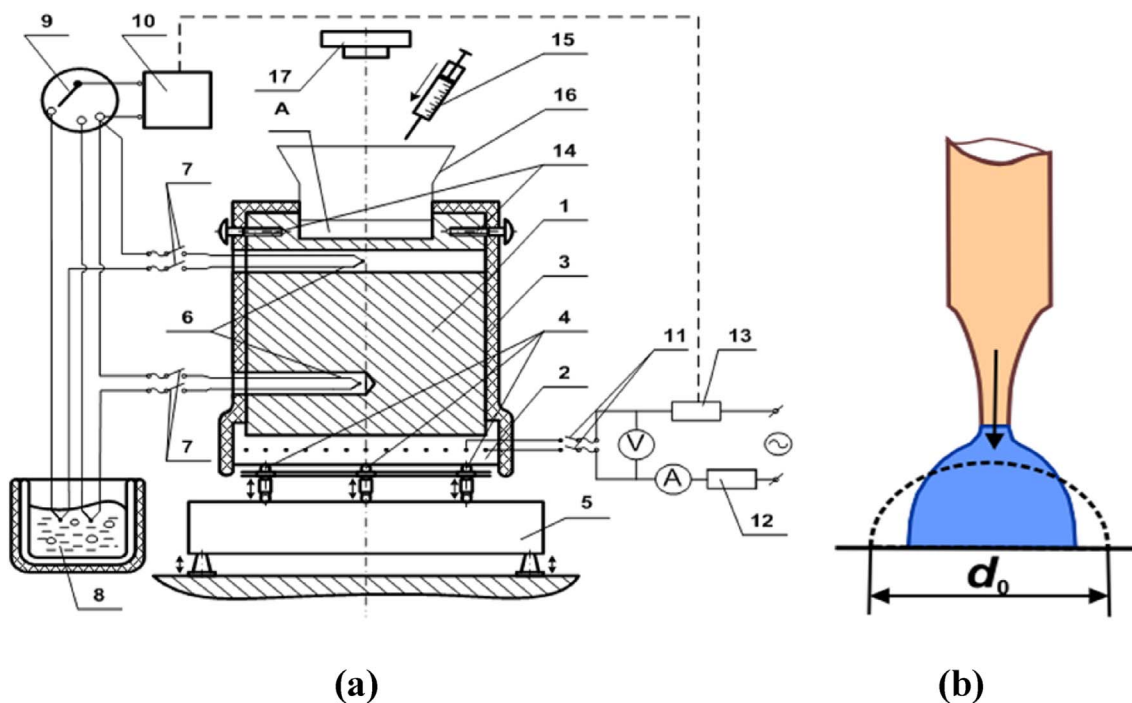
$\lambda$	thermal conductivity of liquid
$\rho$	density

*Subscripts*

0	initial value ( $t = 0$ )
$cr$	crystallization
$l$	liquid
$s$	droplet free surface
$w$	wall
$\nu$	vapor
$i$	current value
$m$	measurements
$e$	experiment

adhesive force between the wall and liquid increases as well, thus increasing the potential energy barrier of the contact line. Secondly, an increase in salt concentration leads to an increase in evaporation heat and repeated decrease in the rate of evaporation. As a result, there is a strong non-linearity of the density of water mass flux vs. time [21]. At high evaporation rates, the local areas of crystallization can occur in areas with the highest rate of evaporation. Crystalline hydrates are formed at the droplet edges, and the crystalline film moves from the droplet edge to the center [21–23]. Formation of crystals and their subsequent behavior in the droplets of water solutions of NaCl and CaSO<sub>4</sub> are controlled by wettability [24]. An increase in the heat flux in a droplet of the salt solution leads to a transitional regime of boiling crisis, when stable vapor film does not form under the droplet. High-frequency contact between the droplet and the wall leads to rapid

evaporation of the droplet and formation of a crystalline-hydrate film on the wall, which dramatically changes the boundary conditions: high wall roughness, low thermal conductivity of the crystalline film, formed on the wall, and sharp change in wall wettability [25]. In technical devices, formation of crystalline hydrates can lead to formation of crystal plugs and absence of the mixture flow in the channel. Thus, the high-temperature flow of salt solution in minichannels results in formation of an emulsion multiphase flow (water vapor + salt solution + crystal particles). The crystalline film is formed on the wall. This flow is unstable, and the flow is oscillatory in nature [26]. In contrast to single-component liquids, the Marangoni flow is formed in the droplets of salt solution due to the temperature gradient on the droplet surface and due to the concentration gradient, which in turn controls the evaporation rate and affects the dynamics of a bubble microlayer [27].



**Fig. 1.** (a) Principle scheme of setup: 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. (b) Applying droplets on a horizontal heated wall.

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