High temperature nonisothermal desorption in a water–salt droplet

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ABSTRACT

Experimental data on dynamics of nucleate boiling in the droplets of LiBr water solution were obtained. Time dependences for a change in bubble geometry were determined and characteristic desorption regimes were distinguished. The rate of bubble growth decreases with a rise in salt concentration and boiling stops completely at high concentration of LiBr. An increase in salt concentration in a liquid layer of the bubble bottom leads to a considerable decrease in the rate of desorption, and the rate of bubble diameter increase decreases significantly, and a dry spot is not formed. The growth features of the crystalline-hydrate film depend on the rate of crystallization. Thermal measurements were carried out by means of thermal imager lenses with ten-fold magnification. The video and thermal recording allowed us to distinguish the self-organized crystalline-hydrate structures at high crystallization rates: rod-like, dendrite, and dome-shaped ones. Complex morphology of these structures promotes an increase in the rate of water desorption from the surface of crystalline-hydrate film.

1. Introduction

Droplet evaporation is used in practice for cooling power plants and widely observed in nature, biology and medicine. For small droplets put on a heated wall at low heat fluxes the area of the droplet bottom stays constant during the most period of evaporation. In this case there is a fixed contact line, and only droplet shape and contact angle change with time. Evaporation of droplets of liquids without nucleate boiling were studied in Refs. [1–10]. For the mentioned conditions it is possible to calculate exactly a change of droplet geometry in time and the rate of its evaporation. For the small droplet sizes (diameter of 1–3 mm), slight wall superheating and contamination of liquids convection in liquid and gas as well as the Marangoni flow are usually neglected. However, Hu & Larson [11] showed that the Marangoni flow occurs even at low temperatures (up to 25 °C), when there are very low evaporation rate and Marangoni number $Ma = $ -233-840. Low concentration of surfactants or contamination weakens dramatically the Marangoni flow. Girard et al. [12] demonstrated that the Marangoni effect can be neglected for the droplets with diameter of 1–2 mm and at liquid temperature of 30–50 °C. At these temperatures, evaporation is relatively slow and the temperature difference between the wall and liquid upper interface does not exceed 1 °C. Nakoryakov et al. [13] revealed that the picture of evaporation at the wall temperature above 100 °C changes significantly, when wall superheating is 10–20 °C and the diameter of droplet basis is more than 10 mm. In this case, near the contact line of the droplet there is a significant gradient of evaporation rate and, consequently, a marked temperature gradient. This causes a stronger Marangoni flow and convective flow in the droplet. At high heat fluxes and nucleation of bubbles the boundary conditions (the area of droplet bottom, evaporation rate, and surface temperature of the droplet) change in time. Droplet equilibrium is broken and we have to deal with a sliding contact line. Experimental studies Xu & Luo [14] using the fluorescent nanoparticles have shown that near the contact line (at a distance of about 10–20 μm) there is the point of a change in rate direction caused by the Marangoni force. Moreover, Ristenpart et al. [15] claimed that the direction depends on the contact angle and ratio of thermal conductivity coefficients of the wall material to liquid. We can emphasize another important demonstration of the Marangoni force. At droplet evaporation, instability and hydrothermal waves can be generated. The nature of such instabilities, as was shown by Karapetsas et al. [16], is associated with thermocapillary Marangoni stresses.

Dynamics of droplet evaporation depends on the contact angle [11,15,17–19] that decreases with time. At low evaporation rates, the diffusion-limited models are commonly used. Recently Stauber et al. [18] showed that the lifetime of an evaporating droplet

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depends on the mode in which it evaporates and, in particular, that the lifetime of a droplet evaporating in a stick-slide (SS) mode can exceed that of droplets with the same initial volume and contact angle evaporating in either the constant contact radius mode (CR) or the constant contact angle (CA) mode. Nakoryakov et al. [13] demonstrated that in the presence of intense nucleate boiling in the droplet, the wetting diameter, even for distilled water, firstly increases more than twice and then, both the diameter and contact angle continuously decrease. At the same time, four evaporation regimes are implemented. Dynamics of a thin layer of liquid (optionally, a microlayer) near the contact line (for brevity, the near-wall liquid layer of a bubble) was studied theoretically in papers [20–22]. At times of about 100 ms and more, the maximal thickness of the bubble near-wall layer can reach 0.001–0.01 mm [23,24]. Singularity-free description of the moving contact lines is suggested in the paper of Rednikov & Colinet [21]. The macroscopic hydrodynamic approach avoided attracting the microscopic effect (slip, disjoining pressure, precursor film). It is shown that the Kelvin effect plays a key role for the very small contact angles. Thermal and hydrodynamic singularities in the vicinity of the triple contact line are considered in the paper of Nikolayev [22]. It is shown that it is important to consider not only the slip, but also the Marangoni stress. In the microvicinity of the contact line, despite the low temperature difference between the wall and liquid layer interface, a huge heat flux of about $6 \cdot 10^3 - 1 \cdot 10^4$ W/cm^2 is generated, even for relatively large times of 100 ms. This results in the large temperature gradients in a solid wall or liquid near-wall layer. During a bubble growth on the heated wall, a thin near-wall liquid layer can be formed [20,25]. The factors contributing to formation of a microlayer: high wall superheating, high saturation temperature, and low environmental pressure. At high rates of the bubble growth, its dynamics is determined by microlayer evaporation, and this is well confirmed by simulation and experiment by Cooper & Lloyd [20]. A drop of the wall temperature under the bubble microlayers can be 10–20 °C, and this causes a high longitudinal temperature gradient in the wall and microlayer. In the paper of Jawurek [25], the optical engineering was used for experimental study of geometry of the near-wall microlayer of the growing bubble on the superheated wall. With the growth of the radius of the bubble base, the lengths of microlayer and dry spot in the center of the base increased firstly, and then decreased to zero. With time, the microlayer evaporated completely and only a dry spot was under the bubble on the wall. When changing the radius of the bubble base from 3 to 5.5 mm (an increase less than in 2 times), the thickness of microlayer increased approximately by the factor of 3: from 0.15 to 0.5 μm. The bubble separated from the wall at times of about 40 ms. According to experimental data and analytical estimates by Moore & Mesler [26], substantial intensification of heat transfer at nucleate boiling is primarily caused not by convection and turbulent mixing, but evaporation of a thin near-wall layer at the bubble base. These various factors are interrelated and influence each other; the correct description of boiling on the superheated wall is impossible without consideration of evaporation of the near-wall liquid layer. Temperature fluctuations in the wall under the growing bubble at pool boiling were measured in the paper of Moore & Mesler [26]. The temperature drop reaches 20–30 °C only in 2 ms. Complete evaporation of the microlayer occurs during the time less than 10 ms. It should be noted that such a decrease in the wall temperature was accompanied by a sharp increase in the heat flux. The high heat flux was consistent with low temperature differences across the near-wall liquid microlayer and extremely low thicknesses of this layer (about 0.1 μm). It is not surprising that such rapid wall cooling produces strong temperature fluctuations near the wall surface and affects the behavior of adjacent active nucleation

sites that leads to the nonlinear chaotic behavior of the entire system [27,28].

At nucleate boiling, it is important to know the number of active nucleation sites and their spatial and temporal distribution. Kenning et al. [29] demonstrated that theoretical modeling of pool boiling gives a significant overstatement of the number of active nucleation sites and the rate of vapor production compared with experiment. The nonlinear random interaction of bubbles at pool boiling relates to the following effects: 1) hydrodynamic; 2) thermal; and 3) coalescence (vertical, declining, horizontal). The regime map at nucleate boiling in a droplet differs significantly from pool boiling. The hydrodynamic effect is mainly implemented through bubbles bursting and their merging in the horizontal direction. Misyura [30] has established that the number of active sites and bubbles in the droplet volume decrease with time because of a decrease in the droplet diameter. At boiling, it is important to take into account the difference between the liquid temperature and saturation temperature, i.e., the implemented regime is superheating or subcooling. Usually, at pool boiling the temperature of the flow core is close to saturation temperature, which is fundamentally different from the temperature of droplet boiling. Most frequently at droplet boiling on the superheated surface the regime of subcooled liquid occurs in the air atmosphere. The effect of subcooling is considered in papers [31,32]. In the paper of Kenning at al. [33] demonstrated experiments and modeling of a vapor bubble growth in a capillary tube at initially uniform superheat. The thickness of the liquid films round confined bubbles and changes in saturation temperature due to the changes in pressure generated by bubble motion were investigated. A high degree of subcooling at pool boiling can lead to collapse of bubbles due to vapor condensation on the surface of bubbles. Avksentyuk & Ovchinnikov [34,35] explored explosive nucleate boiling at very high wall superheating and third heat transfer crisis at subcooling.

In papers [37–41] it is revealed that the behavior of salt solutions and suspension differs absolutely from the behavior of one-component liquids. Zhang & Evans [37] demonstrated that due to liquid circulation and deposition of particles, both the ordered and disordered residue layer is formed in suspension droplets. Moreover, the rate of evaporation and deposition effect the orientation and morphology of microstructure ensembles. Nakoryakov et al. [36] revealed that for solutions of salts thermodynamic equilibrium and evaporation rate varies with time, and a new phase is formed: crystalline hydrates. In the paper of Nakoryakov et al. [41] it is claimed that when surfactant is added into water solution of LiBr, the intensive Marangoni flow is formed on the liquid layer surface, causing solution circulation inside the layer. As a result, the profiles of temperature and concentration as well as absorption rate are changed significantly. At evaporation of water solutions of salts only water evaporates (desorbs), the salt stays in solution. At desorption even at low heat fluxes and low wall temperatures the rate of desorption decreases continuously with time. Lower [42] investigated the phase equilibrium for water–salt solutions at "liquid–vapor" interface is determined by concentration of dissolved substances together with pressure and temperature. In the paper of Nakoryakov et al. [36] claimed that formation of a crystalline-hydrate film on the droplet surface causes the necessity of solution to the problem of heat and mass transfer not only in liquid and vapor phases, but transfer in the solid crystalline-hydrate film should be taken into account.

Desorption of water solution of Li–Br is used in desorbers of lithium-bromide thermotransformers. Both in absorbers and desorbers of heat engines the liquid film can be broken and dry spots, jets and droplets can be formed there. One of the methods to increase the efficiency of heat pump is increase of wall overheating, and this in turn allows desorption reduction in time and increase in