

EVAPORATION RATE OF AQUEOUS SALT SOLUTIONS DROPLETS

Konstantin O. Ponomarev¹, Dmitry V. Feoktistov^{1,}, and Igor V. Marchuk²*

¹ Tomsk Polytechnic University, 634050, Tomsk, Russia

² Kutateladze Institute of Thermophysics, 630090, Novosibirsk, Russia

Abstract. The evaporation of aqueous salt solution droplets from metal surfaces has been studied experimentally. The volumetric evaporation rate is found to decrease in time for any initial droplet volume due to an increase in salt concentration and the efforts of system to take a state of thermodynamic equilibrium. Crystalline hydrate film was being formed during desorption of CaCl₂ 10%, LiCl 10%, LiBr 30% salts. When NaCl 10% salt solution evaporated, there was no film. The average evaporation rate of NaCl salt is higher than for other salts. The lowest values of the average evaporation rate were found for LiBr 30% salt solution.

1 Introduction

Nowadays evaporation of thin liquid films, rivulets or droplets on a solid is very urgent problem for all scientific community. Spreading of a droplet over a heated surface is a complex problem, and to solve it, it is necessary to take into account many factors. Theoretical and experimental results about the mechanisms describing such processes [1-21] are not enough. For this reason, there are some difficulties of modelling the spreading and evaporation of droplets on the surfaces of heat exchange systems, which are used in all industrial processes of petrochemical processing.

The agreement about modernization of the Russian refining complex up to 2020 was signed between eleven large oil and gas companies and Russian Government in July 2011. As a result, all fuels produced on factories must comply with the Euro-5 standard, and oil conversation ratio must be increased from 72 to 85 % or more. These plans can be effectively implemented through using of absorption lithium bromide refrigerating machines and heat pumps in various technological processes.

In addition to water, different aqueous solutions, for example, lithium bromide (LiBr), are used as working liquids (absorbent) in heat pumps, thermotransformers and absorption refrigerating machines. Thin films, jets, and droplets of salt solutions, are formed on the walls of the heat exchange equipment. To date, there is not enough experimental data on the evaporation of salt solution droplets of LiBr, CaCl₂, LiCl и NaCl under the crystalline formation to simulate effective absorption heat pumps. So the purpose of this work is to determine experimentally the effect of the composition and the volume of aqueous salt solution droplets on their evaporation rate.

* Corresponding author: fdv@tpu.ru

2 Experimental technique

Research was conducted using the experimental setup including shadow system. For implementation of this system, the high speed video camera and source of parallel light were used. The principle of operation of the setup is described in detail in [16].

A disk-shaped substrate (54 mm in diameter, 4 mm in thick) used in the experiments was made of aluminium. It is heated up by the Peltier element. Temperature under the substrate was kept constant 80°C. Geometric characteristics, such as, contact angle, height and diameter of a droplet were obtained after processing the shadow images in Drop Shape Analysis software.

The experimental setup was isolated from external influences (convection, radiation) by transparent box 11 made of 3 mm thick polymer glass. It ensures constancy of heat and mass transfer conditions.

We used the following working liquids: 10 % NaCl, 10 % CaCl₂, 10% LiCl, 30 % LiBr. The liquid volume was varied in the following range: 10, 20, 30, 40, 50, 60 μL.

The volumetric evaporation rate was calculated as follows:

$$Es = \Delta V / \Delta t, \mu L / sec, \quad (1)$$

where $\Delta V = (V_{i+1} - V_i)$ is the change of volume of aqueous solution, μL; $\Delta t = (t_{i+1} - t_i)$ is the period of time when the volume changed, sec.

3 Results and discussion

Figure 1 presents time dependences of the evaporation rate of aqueous salt solution droplets.

The initial values (Fig. 1) correspond to the time when a droplet was placed on the substrate, final values – to the crystallization when the shape of a droplet was distorted by crystalline hydrates. It did not allow to use optical methods of processing.

During evaporation of aqueous salt solution droplets it is found that the evaporation rate decreases with time for any initial droplet volume. There is one molecule of water for one molecule of salt in solutions of LiBr, LiCl at 80 °C temperature and atmospheric pressure. But in CaCl₂ solution there are two molecules of water for one molecule of salt. It causes the intensive decrease in the evaporation rate of CaCl₂ with time compared to the lithium salts. In the case of NaCl salt at 80 °C crystals of pure salt are formed (without crystalline or crystalline hydrates are unstable and transit quickly in pure crystals of NaCl). In contrast to the above-mentioned salts, for aqueous salt solution of NaCl the evaporation rate in the initial period of time decreases, then the curve has a quasi-linear nature. It is connected with the early crystallization.

The evaporation rate decreases in time because of an increase in salt concentration and due to the efforts of system to take a state of thermodynamic equilibrium, i.e. the difference between the equilibrium concentration at the droplet interface and the average volumetric concentration decreases with time. Changing of the droplet volume occurs only due to desorption of water from the solution. In this case, mass of salt in the droplet remains constant as there is no boiling crisis, which can lead to droplet detachment with periodic discharge of salt with water.

In comparison with single-component liquids, in solutions during desorption the third phase (solid state) forms. It is known that with increasing initial concentration of salt solution there is a significant decrease in the intensity of desorption. This law is determined by decrease in the saturated water vapour pressure above the surface at the solution/gas

interface. Probably, it is caused by intensive change in the evaporation rate of LiBr 30 % droplets and the lowest values of their rates in comparison with other salts.

Evaporation along the edges of the droplet is more intensive so compensation capillary flow occurs inside the droplet, which transfers a dispersed phase from central part of the droplet to the three-phase contact line. As a result, crystal growth does not start from the centre, but from the periphery of the droplet. In this case, the movement of crystallization is always directed from the periphery to the centre. It is connected to the fact that the thickness of the solution along droplet perimeter is minimal and, consequently, the local heat flow from the heated surface to the droplet along perimeter is larger than in the centre. This leads to a more intense evaporation of the solution, its super saturation and solid phase extraction. Regions located in the droplet periphery stretch central part causing radial flow, with that the ratio of components in inside part of the droplet varies. The lack of solution near the droplet top is compensated by an upward flow in the centre. What is more, the temperature of the flow is higher than at the surface. The surface tension continues to decrease, and circulation enhances in this manner. It continues to decrease the surface tension and enhances circulation. Concentration heterogeneity of the aqueous solution leads to non-uniform evaporation of droplet; the central part of the droplet flattens and becomes thinner.

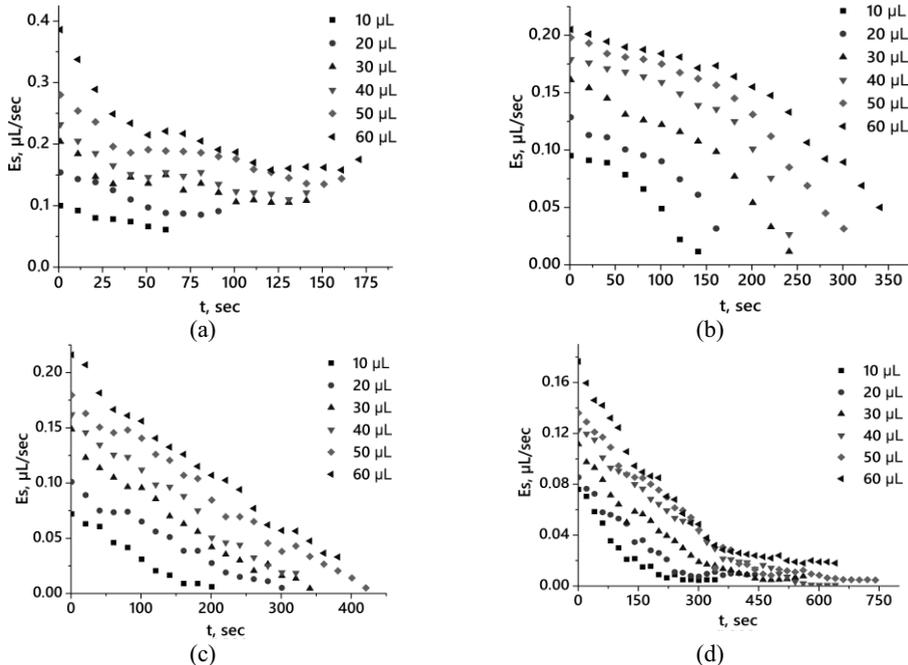


Fig. 1. Time dependences of the evaporation rate of droplet on the aluminium substrate heated up to 80 °C at different droplet volumes: (a) NaCl 10 %; (b) CaCl₂ 10 %; (c) LiCl 10 %; (d) LiBr 30 %.

Crystals formed at the edges of the droplet create a film, which moving to the centre, completely covers its entire surface. After forming a solid surface of the crystal or crystalline hydrates film, desorption process continues. Water diffuses, or penetrates the crystalline film, and then evaporates, but this process is very slow. The dimensions of formed crystals depend on the conditions of crystallization process, which can be divided into two stages: formation of crystal nuclei and their growth due to a substance in solution. For the formation of finely crystalline sediments it is required that the first stage (formation of crystal nuclei) occurred quickly. Many nuclei of crystallization form small crystals because a little substance is deposited on their surfaces. The transition from slow to rapid

crystallization is accompanied by changes in the morphology of structures. The emergence of new well-ordered crystalline structures is advantageous from an energy point of view, since it allows to increase vapour desorption flow and significantly reduce total time of droplet evaporation.

4 Conclusion

After conducting the experimental studies of aqueous salt solution droplets evaporation on metal surface, it is found that the volumetric evaporation rate decreases in time for any initial droplet volume due to an increase in salt concentration and the efforts of system to take a state of thermodynamic equilibrium. During desorption of CaCl₂ 10%, LiCl 10 %, LiBr 30% salts thin film was being formed, and after that it moved from the periphery to the droplet centre and covered its entire surface. During evaporation of NaCl 10 % salt solution, there was no film.

The reported study was supported by RFBR, research project No. 16-38-50221 mol_nr.

References

1. V. Nakoryakov, S. Misyura, S. Elistratov, *Int. J. Heat Mass Transfer*, **55**, 6609 (2012)
2. E. Gatapova, A. Semenov, D. Zaitsev, O. Kabov, *Colloids and Surf., A*, **441**, 776 (2008)
3. A. Sivkov, Y. Shanenkova, A. Saigash, I. Shanenkov, *Surf. Coat. Technol.*, **292**, 63 (2016)
4. V. Nakoryakov, S. Misyura, *J. Eng. Thermophys.*, **25**, 24 (2016)
5. V. Nakoryakov, S. Misyura, S. Elistratov, *Thermal Sci.*, **16**, 997 (2012)
6. D. Zaitsev, D. Rodionov, O. Kabov, *Tech. Phys. Lett.*, **35**, 680 (2009)
7. D. Zaitsev, D. Kirichenko, O. Kabov, *Tech. Phys. Lett.*, **41**, 551 (2015)
8. G. Kuznetsov, A. Zakharevich, N. Bel'kov, *Chem. Petr. Eng.*, **50**, 424 (2014)
9. V. Maksimov, T. Nagornova, I. Shestakov, *EPJ Web of Conf.*, **82**, 01048 (2015)
10. D. Glushkov, J. Legros, P. Strizhak, A. Zakharevich, *Fuel*, **175**, 105 (2016)
11. D. Glushkov, G. Kuznetsov, P. Strizhak, R. Volkov, *Therm. Sci.*, **20**, 131 (2016)
12. O. Vysokomornaya, G. Kuznetsov, P. Strizhak, *Russian Journal of Physical Chemistry B*, **5**, 668 (2011)
13. E. Orlova, G. Kuznetsov, D. Feoktistov, *EPJ Web of Conf.*, **76**, 01039 (2014)
14. R. Volkov, G. Kuznetsov, P. Strizhak, *Int. J. Therm. Sci.*, **88**, 193 (2015)
15. G. Kuznetsov, G. Mamontov, G. Taratushkina, *Combust., Explos. Shock Waves*, **40**, 70 (2004)
16. K. Batischeva, E. Orlova, D. Feoktistov, *MATEC Web of Conf.*, **19**, 01001 (2014)
17. E. Orlova, D. Feoktistov, G. Kuznetsov, *EPJ Web of Conf.*, **82**, 01053 (2015)
18. G. Kuznetsov, D. Feoktistov, E. Orlova, *J. Eng. Phys. Thermophys.*, **89**, 317 (2016)
19. D. Feoktistov, E. Orlova, A. Islamova, *MATEC Web of Conf.*, **23**, 01054 (2015)
20. K. Ponomarev, E. Orlova, D. Feoktistov, *EPJ Web of Conf.*, **110**, 01060 (2016)
21. G. Kuznetsov, D. Feoktistov, E. Orlova, K. Batischeva, *Colloid J.*, **78**, 335 (2016)