Free convection in a drop at liquid evaporation

S Y Misyura and V S Morozov
Kutateladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences, 1. Lavrentiev Ave., Novosibirsk, 630090, Russia
E-mail: misura@itp.nsc.ru

Abstract. This paper is devoted to the study of convection inside a droplet and its effect on heat transfer. A drop of water and a water-salt solution of the LiBr salt was located on a horizontal cylindrical surface of copper. The surface temperature was 53 °C. The novelty of the work is that the influence of free convection in gas and liquid is investigated experimentally. The analysis of experimental data has shown that in the initial period of water drop evaporation, the predominant role in the heat exchange is played by the thermal Marangoni convection.

1. Introduction
The processes of evaporation of droplets of solutions have found wide application in power devices and modern chemical technologies. Evaporation of sessile water droplets was studied in [1-5]. Gas-droplet flows are widely used in technical apparatuses [6-8]. Spray cooling leads to uneven cooling of the wall when droplets of different sizes fall onto the wall. The cooling rate of the heat exchanger depends on the geometric parameters of the drop [9]. A flow of vapor and fine droplets are formed when burning methane hydrate, which leads to a decrease in the combustion temperature of the fuel [10-15]. At high heat fluxes, it is important to take into account the droplet size and thermophysical properties of a liquid and a solid wall [9]. In the first seconds of dropping the drop on the wall, the velocity and temperature fields in the liquid change rapidly, since the coefficient of heat transfer changes rapidly. A drop falling on the wall with different diameters can evaporate both in the bubble boiling mode and in the boiling crisis mode with a tenfold drop in the heat transfer coefficient [16-18]. The rate of evaporation is affected both by convection and by external turbulence [9, 19-24]. The behavior of salt solution differs significantly from pure water [25-32]. When the boiling of a liquid gas, a multicomponent mixture is formed (vapor-liquid droplets-crystal hydrates) [33, 34]. At high-temperature non-stationary evaporation, the time dependence of salt concentration, evaporation temperature and diffusion coefficient is formed. The structured wall leads to an intensification of heat transfer [19, 20]. When evaporation of a drop on a high-temperature wall, an important role is played by free convection in the gaseous phase [20]. At the present time, there is very little experimental data on the effect of convection inside a droplet on heat exchange during liquid evaporation. The purpose of this work is an experimental study of convection inside a drop and its effect on heat transfer. The experiments used non-contact methods: Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) to visualize the instantaneous temperature and velocity fields inside the drop. The thermal fields of the free surface of the drop were measured using a thermal imager. These optical methods make it possible to reveal more deeply the effect of free convection on the rate of evaporation.
2. Experimental data
The experiments were carried out on a horizontal heated copper wall (figure 1) in an air atmosphere with its parameters: pressure 1 atm, humidity 40%, temperature 21 °C. The diameter of the working surface was 40 mm. The wall temperature was kept constant in automatic mode to within 1 °C and equal to 53 °C. The initial concentration of the mass solution of the LiBr salt was 30% and was determined by standard densitometers. The thermal field of layer surface (T_s) was measured by the thermal imager (NEC-San Instruments, 640 x 512 pixels, the resolution is 10 μm). The surface temperature of the heated wall was determined by thermocouples located near the wall with a relative error within 1%. The droplets of water and aqueous solution of LiBr salt were formed by the dispenser Finnpipette Novus with the maximal relative volume error of 0.5%. The separation of the droplet from the dispenser occurred without the droplet fall, i.e., the dispenser was near the wall and it was located normally to the metallic surface. The droplet radius was R_0 = 4 mm. The initial drop height was h = 2mm. Immediately after applying the drop, the dispenser was removed. In experiments, a double Nd: YAG Quantel EverGreen 70 laser was used to obtain instantaneous velocity fields [35]. Measurements were carried out with the following parameters of laser radiation: wavelength – 532 nm, repetition rate – 4 Hz, and pulse energy – 70 mJ. Cylindrical lenses with an opening angle of 22 ° were used to form a laser sheet. Registration of drops’ images required the camera ImperX IGV-B2020M with features: image resolution – 2048×2048 pix, frequency of shooting – 4 fps, bit width is 8 bit, and macro lens Nikon 200mm f/4 AF-D Macro. For data processing, Actual Flow software was used. All measurements of temperature and velocity in the liquid were carried out in the horizontal cross-section of the droplet at the same distance from the wall.

3. Result and Discussion
Figure 2 (a) shows the drop image obtained using the PLIF method. The temperature distribution in the horizontal section of the drop after 10 s is shown in figure 2 (b). Curve 1 corresponds to water, and
Figure 2. (a) PLIF photo; (b) Temperature profile inside the drop ($T_w = 53 \, ^\circ \text{C}$): 1 – H$_2$O; 2 – H$_2$O/LiBr.

Figure 3. Two-component velocity field of the H$_2$O/LiBr droplet flow ($R_0 = 4 \, \text{mm}$, $T_w = 53 \, ^\circ \text{C}$, $C_0 = 30\%$).

Figure 4. Two-component velocity field of the H$_2$O droplet flow ($R_0 = 4 \, \text{mm}$, $T_w = 53 \, ^\circ \text{C}$).

curve 2 corresponds to an aqueous LiBr salt solution. A peak (a sharp increase) in the temperature profile is observed for a drop of water and for an aqueous solution of the LiBr salt near the axis. The peak for LiBr salt solution is more pronounced than for water. This local increase in temperature is probably related to the intersection area of two counter-rotating vortices inside the drop. More intense circulation creates congestive temperature region between the two vortices.

Figures 3-4 show the change of velocity field inside the droplet ($R_0 = 4 \, \text{mm}$), obtained by the PIV method. In figure 5 shows the experimental curves for the change in the average flow velocity inside the $U_C$ water droplet (curve 1) and the aqueous solution of the LiBr (2) salt. For the entire measurement period, a constant contact radius (CCR) mode was implemented. The maximum fall in convection velocity in the liquid is observed in the first few seconds, after touching the wall by drop.
Thermophysics 2018
IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series 1105 (2018) 012044
doi:10.1088/1742-6596/1105/1/012044

Figure 5. Average velocity in a drop $U_C(R_0 = 4$ mm, $T_w = 53$ °C, $C_0 = 30\%$): 1 - H$_2$O; 2 - LiBr.

This velocity fall is caused by rapid heating of the liquid from the wall and a sharp decrease in the temperature gradient. As a result, the thermal Marangoni is formed, which is directed from the center of the drop to its edge. $Ma_T = (\Delta T/\mu a)(d\sigma/dT)$, where $a$ is the liquid thermal diffusivity, $\Delta T = (T_w - T_s)$, $\sigma$ is the surface tension of a liquid, $\mu$ is viscosity, $h$ is the droplet height. With increasing time ($t > 20$ s), the fall in the velocity inside the droplet is related to several factors: 1) decreasing the height of the drop of water and the salt solution; 2) viscosity increase in salt solution; 3) decrease in the temperature gradient $\Delta T_s = T_w - T_s$, where $T_w$ is the wall temperature, $T_s$ is the temperature of the droplet surface.

The velocity fields in the liquid were obtained using the PIV method. It is shown that thermocapillary convection has an important effect on heat transfer in a drop. The greatest influence of convection is observed in the first 6-8 s after the fall of the drop on the wall.

4. Summary
The non-stationary and non-isothermal evaporation process depends on the convection in the droplet.

The distributions of drop temperature have been obtained using the PLIF method. For a drop of water and for an aqueous salt solution of LiBr near the axis of the drop there is a peak (noticeable change) in the temperature profile. This temperature jump is associated with the intersection of two counter-rotating fluid flows inside the droplet.

The PIV method was used to measure instantaneous velocity fields inside the droplet in a horizontal plane. Measurements made in the first 20 s show that the velocity field is highly inhomogeneous and the flow pattern changes rapidly over time. The average velocity in the liquid in the first 20 s, after placing the drop on the hot wall, falls several times from 0.7 to 0.38-0.4 mm/s.

5. Acknowledgement
This work was supported by grants of Russian Science Foundation (Project № 15-19-10025).

References
[1] Kuznetsov G V et. al. 2016 Thermophysics and Aeromechanics 23 17
[2] Kuznetsov G V et. al. 2018 Int. J. Heat Mass Transfer 126 161
[3] Kuznetsov G V et. al. 2016 J. Engineering Thermophysics 89 317
[4] Misyura S Y 2017 Exp. Therm. Fluid Sci. 84 190
[5] Misyura S Y 2018 Chem. Eng. Research and Design 129 306
[6] Kuznetsov G V et. al. 2016 Int. J. Heat Mass Transfer 96 20
[7] Strizhak P A et. al. 2017 J. Hazardous Materials 338 148
[8] Kuznetsov G V et. al. 2017 Exp. Therm. Fluid Sci. 81 256
[9] Misyura S Y 2018 Int. J. Heat Mass Transfer 116 667
[10] Misyura S Y 2016 Scientific Reports 6 30324
[11] Misyura S Y and Nakoryakov V E 2013 Energy and Fuels 27 7089
[12] Nakoryakov V E et. al. 2013 J. Engineering Thermophysics 22 169
[13] Nakoryakov V E et. al. 2013 J. Engineering Thermophysics 22 87
[14] Misyura S Y and Donskoy I G 2017 Fuel Processing Technology 158 154
[15] Misyura S Y and Donskoy I G 2016 Chemical Engineering Science 148 65
[16] Misyura S Y 2016 Exp. Therm. Fluid Sci. 70 389
[17] Misyura S Y 2016 Exp. Therm. Fluid Sci. 75 43
[18] Avksentyuk B P and Ovchinnikov V V 2017 Thermophysics and Aeromechanics 24 537
[19] Misyura S Y 2017 Appl. Therm. Eng. 113 472
[20] Misyura S Y 2017 Appl. Surf. Sci. 414 188
[21] Lebedev V P et. al. 1993 Fluid Dynamics 28 624
[22] Misyura S Y 2017 Scientific Reports 7 14759
[23] Misyura S Y 2018 Int. J. Therm. Sci. 124 76
[24] Misyura S Y 2017 Chem. Eng. Research and Design 126 153
[25] Nakoryakov V E et.al. 2011 J. Engineering Thermophysics 20 338
[26] Nakoryakov V E and Misyura S Y 2016 J. Engineering Thermophysics 25 24
[27] Misyura S Y 2018 Thermal Science 22 295
[28] Nakoryakov V E et.al. 2012 Int. J. Heat Mass Transfer 55 6514
[29] Nakoryakov V E et.al. 2011 Int. J. Heat Mass Transfer 54 4485
[30] Misyura S Y 2018 Appl. Therm. Eng. 139 203
[31] Misyura S Y 2018 Int. J. Heat Mass Transfer 125 610
[32] Misyura S Y 2018 Crystal Growth and Design 18 1327
[33] Chernov A A et al. 2017 Int. J. Heat Mass Transfer 108 1320
[34] Chernov A A et al. 2017 Scientific Reports 7 40809
[35] Kuznetsov G V et al. 2018 Appl. Therm. Eng. 131 340