Convection in an evaporating drop of aqueous solution at a high concentration of microscopic particles

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Abstract. This article presents the performed experimental studies on the effect of the concentration of microparticles on free convection in a water drop located on a heated smooth and textured wall surface. It is shown that at a high concentration of particles, their aggregation and deposition take place on the wall and on the free surface of droplet. As a result, the average convection velocity in the droplet decreases significantly. Suppression of convection is important to consider when simulating heat transfer and droplet evaporation. The results obtained are important for technologies that use colloidal solutions (drops, films).

1. Introduction
To intensify heat and mass transfer, liquids with microscopic particles are used, and laser texturing of metal surfaces is also widely used. Evaporation of fine droplets and liquid films on hot surfaces, as well as the use of sprays, allows achieving high heat fluxes [1–4]. To cool modern microprocessors, it is necessary to use intensive cooling methods with high heat transfer coefficients. Local overheating of the heat exchanger wall may lead to a crisis of heat transfer (to a decrease in heat transfer tens of times) [5, 6]. The features of evaporation and heat transfer of multicomponent liquids are considered in [7].

Evaporation of drops and a film of water on the surface of a layer of methane hydrate powder lead to a decrease in the flame temperature and to unstable combustion [8–10]. For correct modeling of combustion, it is necessary to determine the concentration of water vapor in the combustion zone, as well as the heat loss due to ice melting and water evaporation. The evaporation of finely dispersed water droplets in a multicomponent fuel can reduce the concentration of harmful emissions [11, 12]. One of the most effective ways to intensify heat transfer during evaporation of droplets and films is the use of structured surfaces. Various methods of creating textures are widely used: mechanical action on the material; chemical and electrochemical metal etching; deposition and adhesion of particles from a multicomponent colloidal solution; plasma spraying; laser texturing and 3D printing. Laser texturing allows creating materials with different functional properties: superhydrophilic and superhydrophobic materials [13]; surfaces with resistance to corrosion [14], bio-formation and pollution [15, 16], materials with high wear resistance [17, 18], as well as surfaces with anti-icing [19]. The physical mechanisms for creating textures from a laser are considered in [20–22].

Over time, superhydrophilic surfaces can become hydrophobic [23]. Corrosive action on the material leads to a decrease in the contact angle of the droplet [24]. The kinetics of crystallization and evaporation of a droplet depend on the wall wettability and are controlled by textures [25]. Due to droplet evaporation, a surface Marangoni flow arises [26, 27]. At an elevated temperature of the wall...
or external gas, it is necessary to take into account free convection in the droplet [28-30]. Semi-empirical methods for taking the effect of convection into account are considered in [31, 32]. Nonisothermal evaporation of salt solution droplets is considered in [33]. The effect of Marangoni convection on droplet evaporation is considered in [34, 35]. The features of using optical methods for visualizing the velocity field are given in [36–38].

An analysis of the existing literature has shown that today there is an insufficient amount of experimental data on the effect of wall textures and microparticles in a liquid on free convection in a droplet.

2. Experimental data on the effect of the textured wall and particle concentration on the evaporation of a water droplet

The scheme of droplet heating and evaporation is shown in Figure 1a. Degassed distillate was used in all experiments. The drop evaporates on the horizontal surface of the wall. The backing is made of an aluminum-magnesium alloy. The droplet evaporates at a constant wall temperature of 65–67 °C. Smooth (polished) (Figure 1b) and textured surfaces (Figure 1c) of the substrate are used. The structured wall is obtained using laser action. SiO₂ particles with a diameter of 1-5 µm and a concentration of (10⁸, 5 · 10⁹) / ml (0.01%, 5% of the water mass) are added to the water. Before the experiments, the mass of the powder of SiO₂ particles was measured using the gravimetric method. Then the powder was mixed in water using a magnetic stirrer. The resulting powder is not deposited on the bottom wall for an hour. The experiment time was less than 2 minutes. Thus, the deposition of the powder did not affect the experimental results. The wall temperature under the drop is measured with a thermocouple. The instantaneous velocity field in the horizontal section of the droplet (at a distance of 0.4-0.5 mm from the wall surface) is visualized using the non-contact optical method, the Particle Tracking Velocimetry (PTV).

![Figure 1](image)

**Figure 1** (a) Scheme of the drop on the surface of the heated substrate (q is the heat flux, \( J_{ev} \) is the water vapour flux): 1 - a drop of aqueous solution; 2 - a substrate made of an aluminum-magnesium alloy; 3 - thermocouple; 4 - heated copper cylinder; (b) smooth wall surface (photo width 100 µm); (c) the surface of the wall after laser texturing.

Figure 2 shows the experimental data on the change in the average velocity in the drop \( V \). The velocity is measured using the PTV method. A 500-fold increase in particle concentration results in significant velocity suppression for both smooth and textured walls. Video filming using an optical microscope shows that at a high concentration of particles, aggregation and partial deposition of
aggregates occurs on the wall surface and on the free surface of the liquid. Experimental data for points 5 (water without SiO$_2$ particles) correspond to data for points 1 within the experimental error.

![Figure 2](image)

**Figure 2** Convection velocity in a droplet (1, 3, 5 – smooth wall, 2, 4 – textured surface); mass concentration of SiO$_2$ particles: 1, 2 – 0.01%, 3, 4 – 5%, 5 – 0%.

As a result of this effect of particles, the Marangoni convection decreases. The scheme of partial suppression of the Marangoni flow is shown in Figure 3. The aggregation of particles and their deposition on the surface of the substrate also leads to a weakening of the near-wall motion of the liquid. The effect of reduced convection due to particles has features in common with previous studies in [29].

![Figure 3](image)

**Figure 3** Scheme of free convection in a liquid droplet in the presence of particle aggregation and aggregate deposition.

![Figure 4](image)

**Figure 4** Peclet number $Pe$ in a drop (1, 3, 5 – smooth wall; 2, 4 – textured surface); mass concentration of SiO$_2$ particles: 1, 2 – 0.01%, 3, 4 – 5%, 5 – 0%.
The excess of free convection over the conductive transfer is characterized by the Peclet number \( Pe \) \((Pe = \frac{Vh}{a}\) where \( V \) is the average velocity in a liquid droplet, \( h \) is the droplet height, and \( a \) is the thermal diffusivity of the liquid). Figure 4 shows the experimental curves of change in the \( Pe \) number with time during droplet evaporation. The effect of free convection is tens of times greater than the conductive heat transfer inside droplet. A high concentration of particles leads to a noticeable decrease in \( Pe \) values.

Thus, when simulating droplet evaporation, it is necessary to take into account the effect of free convection on heat transfer inside the liquid. At a high concentration of particles, a significant suppression of the average convection velocity inside droplet is realized for both smooth and textured walls.

**Acknowledgments**

This work was carried out at the Kutateladze Institute of Thermophysics SB RAS and financially supported by the Russian Science Foundation (project number 21-19-00732).

**References**

[1] Chakraborty S, Rosen M A and MacDonald B D 2017 *Appl. Therm. Eng.* **125** 104
[2] Rose J W 1998 *Chem. Eng. Res. Des* **15** 143
[3] Nebuchinov A S, Lozhkin Y A, Bilsky A V and Markovich D M 2017 *Exp. Therm. Fluid Sci.* **80** 139
[4] Lebedev V P, Lemanov V V, Misyura S Ya and Terekhov V I 1995 *Int. J. Heat Mass Transfer* **38** 2117
[5] Nakoryakov V E, Misyura S Y, Elistratov S L 2013 *J. Eng. Thermophysics*. **22** 1
[6] Misyura S Y 2016 *Exp. Therm. Fluid Sci.* **70** 389
[7] Tonini S and Cossali G E 2015 *Int. J. Therm. Sci.* **89** 245
[8] Misyura S Y 2020 *Appl. Energy* **270** 115042
[9] Misyura S Y 2019 *Energy* **181** 589
[10] Misyura S Y 2020 *Energy* **206** 118120
[11] Misyura S Y, Manakov A Y, Morozov V S, Nyashina G S, Gaidukova O S, Skiba S S, Volkov R S and Voytkov I S 2020 *Entropy* **22** 710
[12] Wu R, Liang S, Pan A, Yuan Z, Tang Y, Tan X, Guan D and Yu Y 2012 *Appl. Surf. Sci.* **258** 5933
[13] Ta V D, Dunn A, Wasley T J, Li J, Kay R W, Stringer J, Smith P J, Esenturk E, Connaughton C and Shephard J D 2016 *Appl. Surf. Sci.* **365** 153
[14] Sun K, Yang H, Xue W, He A, Zhu D, Liu W and Adayemi K, Cao Y 2018 *Appl. Surf. Sci.* **436** 263
[15] Chebolu A, Laha B, Ghosh M and Nagahanumaiah 2013 *Micro Nano Letters* **8** 280
[16] Min T 2012 *Design and fabrication of super-hydrophobic surfaces by laser micro/nano-processing: PhD thesis* (Tang Min, Singapore) 142
[17] Emelyanenko A M, Shagieva F M, Domantovsky A G and Boinovich L B 2015 *Appl. Surf. Sci.* **332** 513
[18] Römer G, del Cerro D A, Sipkema R C J, Groenendijk M N W, Huis in ‘t Veld A J 2009 *Ultra short pulse laser generated surface textures for anti-ice applications in aviation*, Proceedings of the 28th International Congress on Applications of Lasers & Electro-Optics (Laser Institute of America, Orlando) 30
[19] Libenson M N 1996 *Zhurnal fizika* 103
[20] Libenson M N, Shandybina G D and Shakhmin A L 2000 *Tech. Phys.* **45** 1219
[21] Lee D J and Jeong S H 2004 *Appl. Phys. A* **79** 1341
[22] Kuznetsov G V, Feoktistov D V, Orlova E G, Batishcheva K and Ilenok S S 2019 *Appl. Surf. Sci.* **469** 974
[24] Misyura S Y 2021 Colloids Surf. A Physicochem. Eng. Asp. 610 125735
[25] Misyura S Y 2021 Int. J. Therm. Sci. 159 106602
[26] Hu H and Larson R G 2005 Langmuir 21 3972
[27] Hu H and Larson R G 2006 J. Phys. Chem. B. 110 7090
[28] Misyura S Y, Volkov R S and Filatova A S 2018 Colloids Surf. A Physicochem. Eng. Asp. 559 275
[29] Misyura S Y, Kuznetsov G V, Volkov R S, Lezhnin S I and Morozov V S 2020 Powder Technol. 362 341
[30] Misyura S Y 2020 Appl. Therm. Eng. 165 114536
[31] Kelly-Zion P L, Pursell C J, Vaidya S and Batra J 2011 Colloids Surf. A Physicochem. Eng. Asp. 381 31
[32] Carle F, Semenov S, Medale M and Brutin D 2016 Int. J. Therm. Sci. 101 35
[33] Misyura S Y 2020 Int. Commun. Heat Mass Transfer 117 104727
[34] Girard F, Antoni M and Sefiane K 2008 Langmuir 24 9207
[35] Kuznetsov G V, Misyura S Y, Volkov R S and Morozov V S 2019 Colloids Surf. A Physicochem. Eng. Asp. 572 37
[36] Kreizer M, Ratner D and Liberzon A 2010 Exp. Fluids 48 105
[37] Westerweel J 1997 Meas. Sci. Technol. 8 1379
[38] Volkov R S and Strizhak P A 2017 Appl. Therm. Eng. 127 141