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The influence of key factors on the heat and mass transfer of a sessile droplet

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ABSTRACT

Heat transfer, temperature and velocity fields of droplets of water and aqueous salt solutions have been studied. The initial concentration of salt solutions $C_{01} = 30\%$ in accordance with advanced technological applications. It is shown that the heat flux q for a water droplet is several times higher than for salt solutions. During the droplet evaporation, this difference increases, since q for aqueous salt solutions is many times reduced. While maintaining the wall temperature under the drop quasi-constant ($T_w = 83$ °C), the heat transfer coefficient α (for the time $t < 150$ s) for a drop of water 1.5–2 times exceeds α for the salt solution, and is 7 times higher for water than for the salt solution at $t = 280$ s. Using PIV measurements the liquid velocity fields have been obtained; and for the first time it has been shown that only for very small times and at high ΔT, the important role is played by thermo-gravitational convection in the droplet (the Rayleigh number Ra). But already for $t > 10$ s, the thermal and solutal Marangoni flows have a greater influence on the flow in a drop of the salt solution.

1. Introduction

The evaporation of drops of liquids, suspensions, emulsions and solutions is widely used in modern technologies: ice production [1], spray cooling [2], inkjet printing, DNA macromolecules, microelectronics [3], sol-gel-technology [4], and power engineering. The efficiency of evaporation of small droplets for microprocessor cooling is considered in [3]. Gas droplet flows are used in power engineering [5,6]. The use of drops is widely used in modern energy technologies for environmental purposes. Adding water droplets to a gas-coal flow can significantly reduce the emission concentration [5]. The cooling rate of the heat exchanger depends on the geometric parameters (the influence of the drop contact angle and the diameter). At high wall superheating, several different evaporation modes are realized for the drops of aqueous salt solution [7].

Modern technologies widely use nanocoatings and droplet evaporation when droplets evaporate on nanosurfaces. There is a noticeable decrease in heat transfer when water evaporates over a porous film, formed from carbon nanotubes [8]. A sharp decrease in the heat transfer of graphite tubes [9] can lead to an emergency in nuclear power plants utilizing these nanotubes. When droplet stretches on the heated wall, wettability plays an important role [10–14]. The effect of wettability on crystallization and droplet evaporation was considered in [15].

The flow of vapor and fine droplets is formed when burning methane hydrate, which leads to a decrease in the combustion temperature of the fuel [16,17].

In recent years, there have been works that show the importance of taking into account the influence of free convection on the droplet evaporation rate [18,19]. When large droplets evaporate on a wall heated to high temperatures, the degree n in the evaporation law $j \sim (R)^n$ (R is the droplet radius) changes markedly [18,19]. In this case, $n > 1$, which causes a multiple increase in j. Modern technologies for visualizing velocity and temperature fields (Interferometric Particle Imaging (IPI) [20,21], Particle Tracking Velocimetry (PTV) [22,23], Particle Image Velocimetry (PIV) [24], Stereo PIV [25,26], Shadow Photography (SP) [27], Planar Laser Induced Fluorescence (PLIF) [28]) allow deeper understanding the effect of free convection in the drop on evaporation rate and heat transfer. In the recent years, these optical technologies have demonstrated great opportunities of their applications for research of droplets, sprays, micro-channel, heterogeneous flows, two-phase (vapor-liquid) flows, films, and boundary layers.

Experimental investigation of the behavior of drops of solutions during heating is much more complicated than that of single component liquids, as the physical and chemical properties of solutions change in the process of evaporation. Reliable experimental data are necessary to improve the accuracy of simulation of heat and mass transfer and evaporation of solutions. Simulation of absorption and evaporation rate of aqueous salt solutions are considered in [29–31]. An experimental assessment of a hydrophobic membrane-based

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desorber/condenser with aqueous salt solution of LiBr for absorption apparatuses was presented in [32]. Prediction of heat transfer conditions in lubricant emulsions was considered in [33]. Thermodynamic properties of salt solutions were considered in [34–36].

As mentioned above, much attention has been recently paid to studies on the effect of free convection on the droplet evaporation. These works [18,19] note the important role of free convection in the gas phase. However, another important question remains unanswered yet. What is the effect of convection in the liquid on the heat transfer of the sessile droplet, when there are significant temperature gradients inside the droplet and on its surface? To date, most experiments on velocity field measurements inside a sessile drop relate to quasi-isothermal conditions or low wall temperatures ($T_w < 60\,^{\circ}\mathrm{C}$).

Theoretical simulation of the Marangoni flow in the absence of wall heating was performed in [37,38]. There are scarce measurement data on the velocity field in the sessile droplet, located on the high temperature wall, obtained by Particle Image Velocity (PIV). In addition, often the experimental works miss a complete set of data on: heat transfer coefficient α, evaporation rate j, temperature and velocity on the surface and inside the droplet. Combining all these parameters given in different articles is complicated due to different experimental conditions. Therefore, experiments often contradict each other, and it is also difficult to improve the accuracy of simulation due to the lack of experimental data.

In this paper, the simultaneous measurements of parameters α, j, temperature and velocity are realized for a sessile drop on a high-temperature wall, using the thermal imaging measurements and Particle Image Velocity.

2. Experimental methods

2.1. Experimental methods for determining the evaporation rate and heat transfer coefficient

The experimental research was carried out on a horizontal metallic wall (Fig. 1(a)) at air temperature of 21 °C and air pressure of 1 bar.

External air humidity was 40%. The initial temperature of the liquid droplet was 21 °C (before placing the droplet on the heated wall). The droplets were located on a heated brass wall of the cylindrical working section. The droplets were formed by a dispenser (Fig. 1(b)) with maximal relative volume error of 0.5%. The separation of water from the dispenser occurred without the droplet fall, i.e., the dispenser was near the wall surface. Immediately after the drop placement on the wall the dispenser was removed. The experimental setup (Fig. 1(a)) consisted of the following main parts: 1 - brass working section; 2 - scales; 3 - thermocouples; 4 - heater; 5 - thermal imager; 6 – drop. The wall temperature under the drop T_w (Fig. 1(b)) was kept constant automatically ($T_w = \mathrm{const}$) with the accuracy within 0.5 °C. Drop surface temperature T_s (Fig. 1(b)) was determined by the thermal imager (NEC-San Instruments, 640 × 512 pixels, resolution is 10 μm) (5) (Fig. 1(a)). The measurement error of the infrared camera was within 1 °C. The experimental setup with a drop was placed on the precision balance (2). As a result of water evaporation, the mass of the drop decreased. The change in the drop mass was registered by scales. The evaporation rate of the drop (j) was determined as $j = \Delta m/\Delta t$ (m is the liquid mass and t is the time). The maximum error of j was 13–15%. Initial static contact angle of the drop θ_0 was equal to 87–90° for $T_w = 53\,^{\circ}\mathrm{C}$ and $\theta_0 = 81–85^{\circ}$ for $T_w = 83\,^{\circ}\mathrm{C}$. Photographic measurements of θ_0 and area F of the droplet bottom have shown good reproducibility in repeated experiments. The average values of the droplet diameter d_0, θ_0 and area F were determined by the data of 4 experiments. Discrepancy of a droplet diameter did not exceed 6%. The relative error of static contact angle was below 5%. In all experiments, there was an attached drop contact line for most of the evaporation time ($R = R_0 = \mathrm{const}$).

2.2. Experimental measurement methods PIV

To illuminate water droplets in the experiments we used a dual Nd:YAG laser Quantel EverGreen 70 [28] (Fig. 2). The parameters of laser radiation in the performed experiments were: wavelength of 532 nm, repetition rate of 4 Hz, and pulse energy of 70 mJ. Cylindrical lenses with an opening angle of 22° were used to form a laser sheet.

For the purposes of the laser sheet positioning, an optical mirror was used. To record the drop images the camera ImperX IGV-B2020M was used: image resolution of 2048 × 2048 pix, shooting frequency of 4 fps, and bit width of 8 bit. A macro lens Nikon 200 mm f/4 AF-D Macro was applied. The Actual Flow software with PIV Kit software package was applied for data processing and construction of temperature fields of drops. As a heating surface the PL-01 automated heating plate was used (the operating temperature range of the heating surface is 40–400 °C, the temperature setting accuracy is ± 1 °C, and the heating surface material is duralumin with nanoceramic coating). Brass substrate (thickness of 4 mm and diameter of 50 mm) was placed on the heated surface. To determine the substrate temperature it was expedient to use a low-inertia platinum-rhodium thermocouple (junction diameter of 0.05 mm, inertia of 0.1 s, and accuracy of ± 1 °C) mounted on the surface of the substrate by means of thermal paste. For forming the drop and placing it on the substrate it was necessary to use an electronic

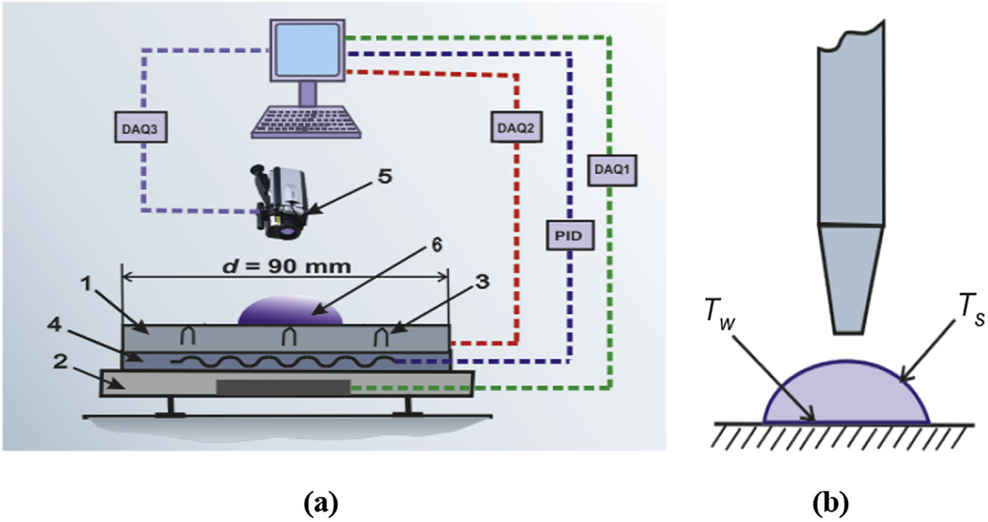

Fig. 1. (a) Experimental setup: 1 - brass working section; 2 - scales; 3 - thermocouples; 4 - heater; 5 - thermal imager; 6 – drop; (b) Drop placement using a dispenser.