An experimental investigation of the heat transfer dynamics during evaporation of a single liquid drop on a sapphire substrate

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Abstract. The paper is devoted to an experimental study of the heat transfer dynamics during evaporation of a single liquid drop on a heated horizontal surface, which is a sapphire glass coated with a high heat-resistant black graphite paint. The method employed in research can be used to study the heat and mass transfer processes in the gas-liquid-solid contact line region with maximum heat transfer coefficient. Its particular feature as compared to the previously known methods is the solution of the initial-boundary problem for the heat conductivity equation, which in terms of mathematics is a correct problem. Using the thermography method, the sapphire surface temperature fields after single drop impingement are determined. The data obtained will be used to calculate the heat flux density in the region of the contact line of the drop.

1. Introduction
Evaporation of liquid droplets is discussed in a large number of experimental and numerical studies. However, this phenomenon is still of considerable interest because of its intensive application, importance and complexity. Evaporation of a sessile drop on a horizontal surface is considered as a comprehensive process, in which the Marangoni effect, mass and thermal transfers are observed. Studying and better understanding the drop evaporation can expand the possibilities of control over various fields as electronic cooling [1], cooling systems [2], inkjet printing, coating technologies, combustion engineering, spray drying and biochemical assays, etc. Complete reviews on the questions covering this topic are provided by Yarin [3], Marengo et al. [4], Erbil [5], Ajaev and Kabov [6], Liang and Mudawar [7], Brutin and Starov [8] and etc. Different aspects of the drop interaction with the solid surface are also considered separately and in detail in many publications.

For example, authors in [9-11] proved the key role of the substrate properties in the drop evaporation and studied the influence of its thermal properties on the process of evaporation of sessile drops and the evaporation time. The findings have shown that the evaporation rate of drops is limited by thermal properties of the solid surface. The influence of the thermal properties of the substrate can be explained by the parallel thermal effect of the liquid and solid phases.

The surface-free energy and surface roughness are known to be the crucial key factors of the drop contact angle. Numerous experimentonal studies were carried out to reveal the impact of solid surface properties on the wettability of a sessile drop by using micro- and nanocoated substrates. A large range of wettablility was investigated, from hydrophilic to superhydrophobic situations [12-15]. These research
works demonstrated that the dynamics and kinetics of drop evaporation are absolutely different depending on the solid surface properties since the evaporation rate is directly connected with the contact angle and the triple contact line behavior.

Many scientific works were dedicated to evaporation modes of a sessile drop [16-19]. They found out four behavioral modes of the drop evaporation depending on the wetting properties of the fluid and solid surface: constant contact angle mode, constant contact line mode, mixed mode and stick-slip mode [18]. The first mode was described by the fixed drop contact angle with a decreasing base radius. The second mode was characterized by reducing the contact angle and fixing drop radius. In the third mode evaporation occurred with decreasing both the contact angle and radius. Eventually in the stick-slip mode the contact line fluctuated between pinning and unpinning.

The role of the three-phase gas-liquid-solid contact line of wetting in the sessile drop evaporation process was investigated. However, the thermophysics of the contact line needs further research to deeper understand the drop evaporation. The vicinity of the contact line is a microregion compared with the total drop size, but the wetting physics of the contact line is very important in determining the static and dynamic mechanics and heat and mass transfer of evaporating drops. For liquid evaporation, gas flow is very important, especially, for stagnant liquid layer [20]

Some papers dealt with the flow evaporated at the gas-liquid-solid interface. They demonstrated that the evaporation is more intensive near the contact line [21]. Others focused on the heat transfer in the region of the contact line of the drops impinging and evaporating on a horizontal heated surface [22-25]. The results of studying the heat transfer in the drop placed on the heated surface revealed that the maximum heat flux density appeared in the vicinity of the three-phase contact line of the drop and it was several times higher than the average heat flux density from the entire surface. The highest local heat fluxes near the contact line were observed due to the low thermal resistance from the small film thickness (1 - 3 μm) in the microregion [26]. The relatively small cross size of this region makes direct measurement of the heat flux density in this area impossible [27]. In work [25] the heat flux was determined as a result of the processing of infrared thermography data in the Matlab software environment. In [24] the value of the heat flux density in the contact line region of the drop sited on the thin constantan heated foil was calculated by solving the stationary Cauchy problem for an elliptic equation with using the temperature field measured by an infrared scanner [28].

The current research is intended to investigate the heat transfer dynamics during evaporation of a single liquid drop on a heated thermostabilised sapphire substrate with the help of infrared thermography and numerical calculations.
2. Experimental process
The experimental research essentially includes the evaporation of a liquid drop on a substrate. A schematic diagram illustrating the experimental setup is shown in Fig. 1.

![Schematic diagram of the experimental setup used in the present study.](image)

The sapphire plate (40.07 ± 0.5 × 40.37 ± 0.5 × 6.4 ± 0.5 mm³) is placed in the water aluminum heat exchanger, which is used to heat the substrate and keep constant temperature over the perimeter of the substrate. Temperature is regulated in the range from 20 to 90°C by thermostat LOIP. A programmable syringe pump Cole-Parmer EW-74905-54 is used to generate the desired rate of drop at the needle tip and is made to fall under gravity to reach the required drop impact. The drop is positioned above the heated sapphire glass at a distance of about 10 mm. The precision of volume for injected drop is about ± 0.1 microliters.

Image collection system includes the Titanium 570M infrared camera. Resolution of IR-scanner in experiments is 640×513 pixels, scanning frequency is 50 Hz, and temperature resolution is 0.1 K. Sapphire is transparent in the working optical range of the used IR-camera (3.7 – 4.8 micrometers). After calibration of IR-scanner it can measure temperature of thin foil with resolution of about 0.5 K. Therefore, using the IR-scanner, the temperature distribution on the surface of the sapphire glass can be measured. The transparency of the sapphire glass allows determining the temperature exactly on the surface where the liquid drop is placed, rather than on the opposite side, as in the case with the thin foil in [15, 22-24]. A small gold-plated mirror is mounted below the working section. The infrared radiation from the bottom surface of the substrate reflected from the mirror is recorded by the infrared camera. The surface of the sapphire plate, on which the drop sits, is covered with a high heat-resistant black graphite paint with an emissivity factor close to 1 to improve the response of the IR-camera imaging of the surface. The average thickness of paint, measured by electron-microscopy (JEOL 6700F), is about 8.5 micrometers. The ambient air temperature is measured using the Testo 646 multimeter. Drop impingement experiments are carried out at the ambient temperature of about 26°C.

A super-purified water, obtained with the help of the Milli-Q system is used as a working liquid. The contact angles when wetting the sapphire glass with water are measured by means of DSA100 contact angle measuring system with the accuracy of about 0.1°. The advancing and receding contact angles for water on the sapphire substrate with the graphite paint are about 147.3° and 19.1°, respectively, so the contact angle hysteresis is about 128.2°.
3. Experimental results

As a result of experiments the sapphire surface temperature fields after single drop impingement are obtained using the IR-scanner. Figure 2 shows the spread behavior of the drop of 8.2 microliters over the substrate surface with a pre-impact mean surface temperature of 32.5°C. The heat exchanger is heated with water to the temperature of 80°C.

![Figure 2](image)

**Figure 2.** Single drop impingement over the sapphire substrate surface: sapphire substrate surface temperature after impingement of 8.2 microliters drop and pre-impact mean surface temperature of 32.5°C.

When the drop comes in contact with a heated surface of the sapphire glass, heat transfer occurs cooling the surface. As it may be seen in Figures 3 and 4 the temperature of the substrate surface under the drop initially decreases due to cooling by the drop, and then increases again due to heating and further total evaporation of water. The temperature of the drop increases with time and evaporation across the liquid-gas interface influences the drop spread diameter. At drop impingement, its diameter increases, after that evaporation takes place and the drop diameter decreases.

![Figure 3](image)

**Figure 3.** The graph of the temperature change of the substrate surface under the drop of 8.2 microliters in the central point.
The data obtained with the help of the IR-camera is used to calculate the heat flux density on the surface of the sapphire substrate using heat transfer equation for sapphire plate. The specific feature of using sapphire substrate as compared to the previously known methods is the solution of the initial-boundary problem for the heat conductivity equation, which in terms of mathematics is a correct problem.

The results of this research may be useful to create high efficiency liquid cooling system that allows investigating in detail the region of three phase contact lines with maximum heat transfer coefficient.

Conclusions
The experimental investigation has been carried out to study the heat transfer dynamics during evaporation of a single liquid drop on a heated horizontal sapphire substrate. The work offers ways to investigate the heat and mass transfer in the region of three phase contact line with maximum heat transfer coefficient. The experimental data received by infrared camera, namely, the measured temperature fields on the substrate surface under the drop will be used at the next stages of the study. The research covers the relevant and important practical task of developing the high efficiency cooling system for modern electronics.

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