The study of spray impact on the heated sapphire plate

T G Gigola¹,³, V V Cheverda¹,²
¹Kutateladze Institute of Thermophysics SB RAS, 630090, Lavrentyev Avenue 1, Novosibirsk, Russia
²Novosibirsk State University, 630090, Pirogov Avenue 1, Novosibirsk, Russia
³Novosibirsk State Technical University, 630073, K. Marx Ave., 20, Novosibirsk, Russia

E-mail: t.evans2010@yandex.kz

Abstract. The process of the liquid spray impact on the heated surface is studied experimentally using the IR-transparent sapphire plate method. The spatiotemporal distribution of the temperature field on the sapphire substrate surface during impacting spray is received. The obtained experimental data are an important step in a study of the local characteristics of heat transfer in the areas of the contact lines during liquid spray impact on the heated surface. Further, the local heat fluxes and heat transfer coefficients will be determined by solving the problem of thermal conductivity in the sapphire substrate.

1. Introduction

Drop impacts on solid surfaces are a key process of a wide range of phenomena that are present in technical applications, such as ink-jet printing, internal combustion engines [1], spray painting and coating, crop spraying, and spray cooling of hot surfaces [2-3] (for example, turbine blades, semiconductor chips, electronic devices, etc.). In referring to the latter point, creating a highly efficient and compact cooling system is one of the most advanced practical tasks to date. The local heat flux in separate areas of the chip with a size of about one mm can exceed the average heat flux density on the chip by more than an order of magnitude and reach the value of 1 kW/cm² and higher. Traditional air-cooling techniques have become inefficient due to the exponential increase in the amount of heat generated per unit area, as well as the poor thermophysical properties of air [4]. The spray liquid cooling system is assumed to be capable of tackling the challenges and removing high and nonuniform heat fluxes due to its design features.

Spray cooling is a method where a liquid is pressurized before being atomized into droplets through a special nozzle, then rapidly rejected to a hot surface, which removes heat with droplet impact, drop motion, and evaporation, film and bubble formation, and environmental convection [5]. Thus, despite more than 100 years of research, the process of drops impact, coalescence, and evaporation still continue to attract the attention of researchers. There are many investigations and reviews which deal with drop impacts and dynamics on thin liquid layers and dry surfaces [6-8]. A large number of studies were also carried out on the investigation of the evaporation modes of a single sessile drop. The effect of the substrate thermophysical properties on the evaporation rate was proved in works [9,10]. The heat transfer in an evaporating drop on a horizontal heated surface and the effect of the surface temperature and ambient air temperature on the evaporation is investigated in [11,12].

The heated surface is only partially covered with a macroscopic liquid layer at the time of using the spray cooling system. Such flow pattern is described by the presence of three-phase contact lines.
characterized by extremely high heat fluxes. The liquid flow evaporated at the solid-liquid-gas interface is the subject of several experimental research works. In work [13] the evaporation flux profile along the interface of an evaporating sessile drop and its effect on the fluid dynamics inside the drop were studied. It was shown that the evaporation was more intense near the triple line. The authors of [14], using the method of the thin foil and data of IR-thermography revealed that the maximum heat flux density takes place in the region of the drop contact line and exceeds the average heat flux density on the entire surface of the foil by a factor of 5. The paper [15] presented a new investigation method of the heat and mass transfer processes in the solid-liquid-gas contact line area, which is called IR transparent sapphire plate. As a result, the local heat flux distribution at drop evaporation on the sapphire surface with two local highs near the contact line regions was measured.

In summary, many investigations focus on understanding the heat and mass transfer phenomena of drop evaporation of a single drop but the practical applications involve a great deal of the drops on the same substrate. The present research is aimed to study the process of the liquid spray impact on the heated surface, namely, the spatiotemporal distribution of the temperature field on the surface during impacting spray.

2. Experimental setup

The experimental investigation is carried out using the IR-transparent sapphire plate method. This technique has several advantages over the thin foil method when studying the heat transfer processes that are described more precisely by authors in [15].

The sapphire substrate is placed in a controlled water aluminum heat exchanger, which enables it to keep constant temperature over the perimeter of the substrate (Figure 1). The heat exchanger, which is used for thermal stabilization of the substrate, is connected to the LOIP thermostat, in which the water can be heated to 90°C. The sapphire glass top side is provided with a layer of a high heat-resistant black graphite paint, that is non-transparent for IR-rays. The average thickness of this paint is defined by electron microscopy (JEOL 6700F) and is about 8,5 µm.

![Figure 1. Schematic diagram of the experimental setup.](image)

The water drops are deposited on the sapphire substrate using a spray when the sapphire plate temperature becomes equilibrium after heating. Obviously, there was no air movement inside the room and the natural convection did not disturb the temperature distribution on the sapphire substrate. The lower side of the heat exchanger was equipped with an infrared transparent sapphire window to allow
measuring the temperature at the surface with drops using the infrared camera (Titanium 570M, 640 × 512 pixels, temperature resolution is 0.1 K, maximum scanning frequency is 115 Hz). The infrared camera caught the infrared rays from the underside of the sapphire substrate reflected from the metal mirror, which was installed below the heat exchanger.

A Kruss-shape analyzer was employed to measure the drop contact angle on the coated sapphire substrate. The advancing angle was equal to 149.3° and the receding angle was equal to 19.1°.

3. Experimental results

The set of experiments on the spray impact on the heated sapphire substrate was carried out. The sapphire surface temperature fields during spray impacting are obtained using the IR scanner.

Figure 2 shows the behavior of the tiny droplets over the sapphire substrate surface when the heat exchanger is heated with water to the temperature of 70°C.

![Figure 2](image)

**Figure 2.** Snapshots of the spray impact process until its total disappearance, taken by the infrared video camera.

The sapphire surface temperature before spray impact is 65.7°C, and the ambient temperature is 27°C. At the first moment, the temperature under the droplets decreases but then the droplets are heated to the substrate temperature and completely evaporated. Further, there is a gradual increase in the temperature of the sapphire surface up to the initial temperature. Figure 4 presents the time dependence of the sapphire substrate temperature.

![Figure 3](image)

**Figure 3.** The average temperature change of the sapphire substrate surface under the impact of spraying
4. Conclusions
The experimental part of the study on the heat transfer and evaporation of liquid droplets on the sapphire substrate is accomplished. A new method of IR-transparent sapphire plate is used to receive some preliminary experimental results. As compared to the other methods, the proposed technique allows solving the problem related to the heat conductivity equation, which is a correct problem and is characterized by a more simple solution process. This mathematical procedure will be used to study the heat and mass transfer processes in the solid-liquid-gas contact line areas. The local heat fluxes and heat transfer coefficients will be determined employing the obtained spatiotemporal distributions of the temperature field on the sapphire substrate surface during the impact of the liquid spray.

5. Acknowledgments
The experimental study is performed with the financial support by the grant from the Ministry of Science and Education No. 075-15-2021-988.

References
[1] Murko V I, Fedyaev V I, Karpenok V I, Zasypkin I M, Senchurova Y A, Riesterer A 2015 Thermal Science 19 1 243-251
[2] Bar-Cohen A, Arik M and Ohad M M 2006 Proceedings of the IEEE 94 8 1549-1570
[3] Chen Z, Xiea Q, Chen G, Yua Y, Zhaoa Z 2019 Thermal Science 22 1 359-370
[4] Salman A S, Abdulrazzaq N M, Tikadar A, Oudah S K, Khan J A 2021 Applied Thermal Engineering 183 115824
[5] Xu H, Wang J, Li B, Yu K, Tian J, Wang D, Zhang W 2021 Applied Thermal Engineering 189 1 116757
[6] Yarin A L 2006 Annu. Rev. Fluid Mech. 38 159–92
[7] Zaitsev D V, Kirichenko D P, Ajaev V S and Kabov O A 2017 Physical Review Letters 119 094503
[8] Marchuk I, Karchevsky A, Surtaev A, Kabov O 2015 Intern. J. of Aerospace Engng. Art. 2015 391036
[9] David S, Sefiane K and Tadrist L 2007 Colloids and Surfaces A 298 1-2 108-114
[10] Dunn G, Wilson S K, Duffy B R, David S, Sefiane K 2009 Journal of Fluid Mechanics 623 329-351
[11] Cheverda V V, Karchevsky A L, Marchuk I V and Kabov O A 2017 Thermophysics and Aeromechanics 24 5 803–6
[12] Xia Y, Gao X and Li R 2020 Applied Thermal Engineering 180 115819
[13] Widjaja E, Harris M 2008 Computers and Chemical Engineering 32 10 2169-2178
[14] Cheverda V V, Karchevsky A L, Marchuk I V, and Kabov O A 2017 Thermophysics and Aeromechanics 24 5
[15] Karchevsky A L, Cheverda V V, Marchuk I V, Gigola T G, Sulyaeva V S, Kabov O A 2021 Microgravity Science and Technology 33 53