Spatiotemporal distribution of the temperature field inside the thin heated foil during impacting liquid spray

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Abstract. The spatiotemporal distribution of the temperature inside a constantan foil during impacting spray is resolved experimentally in the present work. The received infrared image sequence will be used to find the local and average heat transfer coefficient of the foil. In the future, the results obtained will be used to calculate the heat flux in the region of the contact line of each drop.

1. Introduction
The thermal management of microelectronics became very important these days due to its miniaturization. Over the past few years, one concludes that the effective solution to this challenge is to use a spray liquid cooling system [1]. Several heat transfer mechanisms are important for drop evaporation, namely, convection [2] and evaporation in the contact line. Previous studies showed an extremely high heat flux of 1,2 kW/cm² with water spray cooling, which is anticipated to be a key in solving thermal management problems of high-power electronic components because of its efficient heat removal. Spray cooling has several benefits as the amount of removed heat and the consumed pumping power compared to other cooling techniques [3]. During spray impact, a large number of the drops are ejected to a hot surface which contributes to removing the heat with drops impact, evaporation, film formation and motion, as well as natural convection. Also, This process is accompanied by forming the contact line areas. The heat transfer coefficient in this area can be extremely high, up to 1 kW/cm² and higher [4].

When forming a spray, several main modes can be distinguished [5]. The shape of the spray that forms depends on the balance of dynamic forces, surface tension, and viscous forces. At a low flow rate of liquid, a drop mode is formed. Initially, the inertial force prevails and a liquid jet is formed. As in the case of a conventional jet, the axial velocities of large droplets prevail, which forces them to move vertically downstream. As the flow rate increases further, the spray shape becomes tulip-shaped. Subsequently, with the dominance of surface tension, this film breaks down into small droplets.

The influence of the initial pressure, the distance between the nozzle and the cooled surface, the angle of inclination of the nozzle, the heat flux on the cooling performance of the spray system are shown in articles [6-8]. It was found that the angle of inclination does not significantly affect the heat transfer process. With an increase in the liquid flow rate, an increase in the critical heat flux is observed [9]. An increase in heat transfer can be achieved by applying microstructures to the heat
transfer surface [10]. The possibility of increasing the critical heat flux due to the application of carbon nanotubes has been shown. One of the important advantages of a spray cooling system is the ability to operate in zero gravity [11]. Due to the dominance of surface tension forces, the liquid layer under weightlessness is significantly larger than under normal acceleration. The presence of this thick layer of liquid decreases heat transfer and, therefore, it is necessary to remove excess liquid from the heat transfer surface for maximum efficiency. Heat and mass transfer enhancement for drop evaporation can be done by microstructures in a wide range of cavities diameters [12].

This experimental work aims at investigating the cooling of hot surfaces by using liquid spray and determining the local characteristics of heat transfer (the local heat fluxes and heat transfer coefficients) in the areas of the contact lines using the thin heated foil method. The method of thin constantan foil is used to determine heat flux in the contact line of falling liquid rivulet in work [13].

2. Experimental setup

The experimental arrangement is shown in Figure 1.

![Figure 1. The schematic representation of the experimental setup](image)

The substrate is made up of a constantan foil (CuNi) with thermal conductivity of 23 W/mK. The dimensions of the substrate are 80×35 mm and the thickness of 25 μm. The foil is connected to the TTi QPX 1200L electrical power supply which is used for heating the foil. The bottom surface of the foil is painted with a layer of high heat resistant black graphite paint to increase the minimum resolvable temperature difference by IR-thermography. The infrared camera measures the temperature of the bottom foil side catching the infrared rays reflected from the metal mirror, that is mounted below the foil. Titanium 570M thermal imager with a resolution of 640×512 pixels is used as an IR-camera. The measurement frequency is kept at 18 Hz in the present work. It can reach up to 115 Hz if imaged at a full resolution. Purified water is used as a working liquid.

The upper surface of the foil is coated by a silicon-based hydrophobic liquid, that changes the wetting properties of the foil. The contact angles when wetting the hydrophobic foil with water are measured using the Kruss DSA-100 contact angle measuring system with an accuracy of about 0.1°. The equilibrium contact angle is about 167 ± 7.5° (Figure 2).
3. Experimental results

Initially, the foil is heated without water droplets. Then, using a spray, water droplets with an average droplet size of 500 micrometers are placed onto the foil. Figure 3 shows thermograms of foil before and with water droplets.

Figure 4 shows the time dependence of the foil temperature. In the beginning, the foil temperature is about 53.4°C, and the ambient temperature is 28.1°C. The thermal power released on the foil in the given case is 4.9 W.

After falling of the liquid droplets on the foil, a rapid drop in the foil temperature was noticeable due to the intense evaporation of the liquid droplets. Then the temperature of the foil increased gradually, which was caused by a decrease in the number of drops on the foil and as a consequence of its cooling ability. After about 70 s, all the drops have already evaporated and the foil temperature has practically stabilized at the initial value.
Figure 4. Variation of the average temperature of the foil with time

4. Conclusions

The experimental results are presented for the impacting water spray on the heated constantan thin foil. The relevance of this work is based on the necessity to create a spray liquid cooling system for modern electronics, as well as for equipment used in other industries. Subsequently, the average and the local heat transfer coefficient and the heat flux density on the surface and at the three-phase contact lines of the droplets will be estimated.

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References
[1] Wang J-X, Guo W, Xiong K, Wang S-N 2020 Progress in Aerospace Sciences 116 100635
[2] Misyura S Ya 2018 Nature Sci Rep 8 11521
[3] Labergue A, Gradeck M, Lemoine F 2015 Int. J. Heat Mass Transfer 81 889-900
[4] Stephan P C, Busse C A 1992 Int. J. Heat Mass Transfer 35 383–391
[5] Chen C, Tang Z., 2020 Science Progress 103 3
[6] Mudawar L, Estes K 1996 ASME J. Heat Transfer 118 672–679.
[7] Wang Y Q, Liu M H, Liu D, Xu K., Chen Y L 2010 Exp. Therm. Fluid Sci. 34 933–942
[8] Visaria M, Mudawar I. 2008 Int. J. Heat Mass Transfer 51 2398–2410
[9] Mudawar I, Estes K 1996 ASME J Heat Transfer 118 672–9
[10] Zhang Z, Jiang P.X., Ouyang X L, Chen J N, Christopher D M 2014 Int. J. Heat Mass Transfer 76 366–375.
[11] Conrad B L, Springmann J C, McGill L A, Shedd T A 2009 AIP 1103 67–72
[12] Misyura S Ya 2019 International Journal of Mechanical Sciences 170 105353
[13] Cheverda V V, Karchevsky A L, Marchuk I V, Kabov O A 2017 Thermophys. Aeromechanics 24 803–806