Extreme heat fluxes and heat transfer mechanisms during electronics spray and jet impingement cooling with boiling

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Abstract. Microelectronics already needs for heat removal more than 1 kW/cm². To assess the spray cooling capabilities to meet the growing requirements, a review of experimental studies is presented. Both the lack of progress in increasing the limit values of critical heat fluxes over the past 20-30 years and the fact that this technique is considered effective and promising are demonstrated. The "modern" physical picture has been formed at the turn of the 21st century. The review shows that the trend towards increasing the heat transfer coefficients is realized in the same way as in other promising cooling technologies. The paper refers to the studies in which the coolant film thickness was reduced by the authors, as well as those that presented correlations of the three-phase contact line dynamics with the values of the achieved heat flux. A problem is formulated for the required detailed studies of highly dynamic processes in an ultra-thin liquid film at the micro level, aimed at the heat transfer enhancement.

1. Introduction
Now one of the most important problems is power control in microelectronic equipment. Devices may include more than 20 billion transistors with a size of about 7 nm. Therefore, the need to dissipate ultra-high specific heat fluxes has become a reality [1]. Today the strategic goal is to dissipate the specific heat flux of more than 1 kW/cm² and 1 kW/cm³. In promising devices based on silicon carbide or gallium nitride, similar requirements arise. Soon the size of the chip elements will decrease to 6-9 nm, and the specific heat flux will reach 100-300 kW/cm² for the region with the size of 2x2 µm² and 10 kW/cm² for the region with the size of about 1 cm² [2]. These facts reveal the need to reevaluate the values of the critical heat flux (CHF) and heat transfer coefficients (HTC). The review and analysis of experimental studies of spray cooling, as well as analysis and identification of problems that must be solved to expand the spray cooling capabilities are presented.

2. Methods discussed
Schematic of a) spray and, for comparison, b) jet cooling systems are presented in Fig.1. In the first case, the coolant is sprayed by a special device. The formed stream of drops impinges on the hot surface with velocity of about 10-30 m/s. A thin liquid film (1-600 microns) is formed, and boiling, convection and intensive evaporation occurs. A significant number of parameters determine the heat transfer during cooling, and to date, extensive results have been accumulated from the studies of this issue. First of all, they relate to the choice of the coolant and the hot surface parameters. The surface temperature and specific heat flux are determined by an electronic device. Various surface modifications are applied at
the nano- and micro-level in order to intensify heat transfer by boiling. The surface temperature sets the choice of coolant and ambient pressure (boiling point), as well as the possible surface superheating before the onset of a CHF. The thermophysical properties of the liquid and the possibility of its subcooling plays an important role. It is established that the droplets size, their velocity, the specific mass flow rate and the droplets flow density determine the heat transfer for this cooling method. The coolant is sprayed by a special device, which assigns great importance to both the design parameters of the device itself (the nozzles size, the design parameters of the swirlers, turbulators, other items) and the flow characteristics: fluid flow, gas flow (if applicable), and the liquid and gas pressure drops at the nozzle inlets. There are semi-empirical correlations for CHF and HTC depending on a wide set of specified parameters, for example [3].

![Figure 1. Schematic: a) spray and b) jet impingement cooling.](image)

It should be noted that spray devices can perform both under high liquid pressure and use secondary gas for better spraying. Gas allows significantly reducing the required liquid pressure drop, while maintaining or increasing the dispersion of droplets, it allows increasing their speed, thinning the liquid film, and providing a better discharge of the vapor [4]. In addition, a stable droplet size distribution is completely formed at distances of about 8-10 typical nozzle sizes or more. The stream cone providing irrigation of a certain area is formed at about the same distance. So, the choice of the distance from the spray nozzle to the hot surface is also an important aspect. That distance typically is equal to 7-40 mm, but at small cooling devices in electronics, a significant reduction in this distance is required.

In the case of jet impingement cooling (Fig. 1b), a high-pressure subcooled liquid jet impinges on the hot surface. The liquid flows along the surface with a velocity of tens of m/s. It is heated, boils, and is removed from the hot surface. Currently, to enhance heat transfer, the hot surface is structured on nano- and micro-scales in order to intensify boiling, for example, as shown in Fig. 1b. Two factors significantly distinguish this cooling system from the spray cooling system: 1) an entire liquid jet impinges on the hot surface, 2) boiling is realized away from the top point of the jet. Among the design differences, it should be noted that often an increase in heat transfer is achieved by a significant increase in the liquid flow rate along the surface, up to several tens of m/s. This leads to a relatively large required coolant flow rate. In the case of spray cooling, it is recommended to increase the drops velocity while reducing their size. The mass flow rate of the coolant may not increase in this case and may be significantly lower than for jet impingement cooling.

3. Results and discussion
Table 1 presents the maximum values of heat transfer achieved for the four most promising cooling technologies that use boiling and evaporation of the coolant (water). Similar comparisons of different systems were made, for example, in [13]. This paper focuses primarily on the discussion of extreme heat fluxes. It should be noted that for several cooling technologies, the extreme heat fluxes were reached at the beginning of the 21st century or earlier. The Table shows that comparable heat transfer results are achieved for all these methods of cooling, despite that the complex of physical phenomena in these
systems is very different and the realized flow patterns can be also radically different. This may indicate that there are general physical phenomena that may determine the heat transfer, but their role is not sufficiently highlighted and requires some in-depth studies. It should also be noted that the design modifications that allow shifting the extreme value limits were almost the same for all presented methods. Let us look at these issues in more details by the example of spray cooling.

Table.1. Comparison of high heat flux removal technologies (water)

| Cooling technique         | $h$, kW/(m$^2$K) | $q^*$, MW/m$^2$ | Authors                          |
|---------------------------|------------------|-----------------|----------------------------------|
| Spray                     | 83.8             | 9.45            | Chen et al., 2002 [5]            |
| Spray                     | 200              | 8.7             | Yang et al., 1996 [6]            |
| Spray                     | 120              | 20.0            | Cebo-Rudnicka et al., 2016 [7]   |
| Micro-channel             | 132              | 10.16           | Li et al., 2017 [8]              |
| Micro-channel             | 290              | 10.73           | Kalani&Kandlikar, 2015 [9]       |
| Jet impingement           | 280              | 18.20           | Overholt et al., 2005 [10]       |
| Jet impingement           | 414              | 11.1            | Michna et al., 2011 [11]         |
| Shear driven liquid film  | 300              | 12.00           | Kabov et al., 2018 [12]          |

The authors of the present paper have analyzed more than 65 articles on heat transfer during spray cooling, providing experimental data. The review of water spray cooling, Fig.2, shows that for thirty years of research, the limit values of the critical heat flux achieved in most works almost have not changed and usually do not exceed 9.5 MW/m$^2$. There are only two articles [14-15] that claim higher values of critical heat flux (more than 2 and 4.5 times higher). However, this cannot be considered a new trend, since the provided information is not sufficient to reproduce the data, there have been no developments in this direction and the results have not been confirmed by any later publications. The values of heat transfer coefficients increased due to the use of almost the same approaches as in other technologies. Namely: 1) conventional optimization of liquid supply and spray parameters, 2) liquid subcooling, 3) reduction of vapor pressure in the residual atmosphere, 4) joint nano- and micro-texturing of the hot surface. The paper [16] has provided the most significant results for recent years. Note that enhancement of the heat transfer coefficient is a relevant topic for microelectronics due to the requirement for the limit operating temperature, especially at cooling of poorly heat-conducting substances, such as silicon.

The detailed review of the physical phenomena that determine the achieved heat transfer level during spray cooling refers to both more than 74 articles of other authors and some own studies [12-13]. It is generally accepted that the four main physical phenomena are identified as key in this cooling method, [6, 17-19], which distinguishes the spray cooling technology in a special physical case. These are as follows, see Fig.3: 1) intense evaporation from a very thin liquid film, 2) forced convection in the liquid film due to the impingement and coalescence of drops and film that evens out the temperature in liquid film, 3) continuous forced cleaning nucleation sites for vapor bubbles on hot surface that significantly intensify vaporization, and 4) "secondary nucleation" of vapor bubbles at the surface of drops impinging on liquid film or heated surface, which greatly enhances vaporization.

Analysis of these phenomena demonstrates that a significant increase in the thickness of the coolant film deteriorates 1), 3) and 4) physical mechanisms of heat transfer, which will cause a drop in its value by an order of magnitude. Numerous observations indicate the critical nature of the influence of the thickness and surface shape of a thin coolant film on the values of HTC and CHF. For example, it was found that with a film thickness of 1.4 microns and a wall superheating value of 20 degrees, it is possible to dissipate about 10 MW/m$^2$ by evaporation from the water film surface (mechanism 1), [20-21].
Figure 2. Values of heat transfer measured by the authors during 30 years (water).

Figure 3. Schematic of the main physical phenomena at spray cooling heat transfer.

Analysis of the studies demonstrates that the liquid film thickness reduction and an increase of the surface area near the contact line of the surface-liquid-vapour or its length allows radically increasing heat transfer, and, consequently, increasing the extreme values of HTC and CHF. In a small number of studies, the relationship between the dynamics of a contact line and the extreme values of heat transfer is shown quantitatively [22-23]. The authors of these works have developed an original method for monitoring the processes directly on the hot surface, not through a droplets torch and disturbed liquid film, but through a transparent heater. This allows experimentally detecting a correlation between the movement and the length of the three phases contact line with the heat transfer data; at the same time it is identified that there is no correlation between these data and the wetted surface area. However, the generally accepted picture of physical phenomena in the spray cooling technology does not pay due attention to the area near the three-phase contact line.

The current state of research on heat transfer near the contact line is presented in the review [24]. It is found out that the intensity of evaporation near the contact line is more than significant for a number of phenomena and technologies. Direct observation of physical phenomena accompanied by evaporation in this zone was performed in [25]. In [26-27], a new fourth method of effective cooling of electronics was proposed, see Table 1, in which heat dissipation is caused by intensive evaporation of thin liquid film moving in a flat minichannel under the action of a gas flow. Systematic studies of hydrodynamics and heat transfer crisis in stratified flows heated from a 1x1 cm² heat source [12, 28-30] have demonstrated a special role of evaporation in the area of the contact line. About 200 thousand dynamic dry spots per second with a time and spatial scale of about 0.5-5 milliseconds and 100 – 500 microns, respectively, were created in the liquid film.
Conclusions
Spray cooling provides one of the largest CHF and HTC. There is evidence that it is possible to achieve higher extreme heat transfer values (CHF ≥ 12.5 MW/m², HTC ≥ 200 kW/(m²*K)) by forming ultrathin dynamic evaporating coolant films.

It has been established that the key physical phenomena of heat transfer during spray cooling and, in particular, the role of the three-phase dynamic contact line are not fully understood.

Detailed studies of the dynamics of an ultrathin coolant film formed during spray cooling with time registration rates of up to 10⁶ Hz and a high spatial resolution of about 1-10 microns per pixel are required.

It has been found that there are very few published articles in which the distance from the nozzle to the hot surface is less than 7 mm.

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