Maximum heat fluxes and features of heat transfer mechanisms with boiling during jet impingement cooling of electronics

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Abstract. The needs of microelectronics for heat removal are growing and have already exceeded the value of 1 kW/cm². To assess the ability of jet impingement cooling to meet the growing requirements, a review of experimental studies was conducted. The review demonstrated both the lack of progress in increasing critical heat flux value over the past 30 years, and the fact that this technique is still considered effective and promising. The review showed that the movement to intensify heat transfer is in the same direction as in other promising cooling technologies. It is noted that the most productive heat transfer occurs in the region of the thinnest liquid film spreading from a free impingement liquid jet. New fundamental studies are discussed that note the significance of heat transfer values in a very thin liquid film, and this is important for the development of cooling technologies. Problems are formulated for the required detailed studies of highly dynamic processes in the boiling region of an ultrafine liquid film at the micro level, aimed at intensifying heat transfer.

1. Introduction
Reducing the standard size of microelectronic elements down to 7 nm has led to an increase in the density of their packaging in modern devices. The heat flux density released by individual elements also increased, which predetermined the need to dissipate ultra-high specific heat fluxes [1]. The task of dissipating specific heat fluxes of more than 1 kW/cm² and 1 kW/cm³ on scales of the order of 1 cm² has become a reality. In the scientific publications it is reported that in the developed promising devices made of silicon carbide or gallium nitride, where the size of the chip elements will decrease to 6-9 nm, the following problems appear: specific heat fluxes will reach 100-300 kW/cm² for local areas of 2x2 mm² and 10 kW cm² for areas of the scale of about 1 cm², [2]. This work is devoted to the review and analysis of experimental studies of jet impingement cooling of microelectronics and highly integrated systems, analysis and identification of problems that must be solved to expand the capabilities of the system. The maximum of the values of specific heat fluxes and heat transfer coefficients (HTC) were estimated in comparison with other popular cooling methods, such as spray cooling.
2. Methods of cooling

Figure 1 shows the schematic of a) jet impingement and, for comparison, spray cooling systems, b). To cool miniature devices with a liquid jet, three device implementation schemes are most often used: 1) using a free jet, 2) a submerged jet, and 3) a confined by the device surfaces jet. These schemes have their own hydrodynamic features, but there are also things common to these schemes. For miniature devices, a jet with a characteristic velocity of 10 m/s is used. The jet is directed either normal to the surface or at an angle within 45°. Most often, the jet is subcooled in relation to the saturation temperature, which determines that boiling occurs away from the axis of the jet, regardless of its inclination to the surface. Forced convection plays an important role in the steam removal in the boiling area, but the mode and intensity of boiling are not the same in the direction measured from the axis of the jet, which creates a temperature inhomogeneity of the hot surface. A significant number of parameters determine the heat transfer during such cooling. It should be noted that the technical design of the jet impingement cooling scheme fundamentally affects the laws of heat and mass transfer. Therefore, despite the accumulated extensive data on the experimental and numerical description of the characteristics and the capability of jet impingement cooling, it is currently not possible to create a general model of the cooling process and systematize experimental data in a single way, which is also noted in [3]. It is possible to generalize the results either for a free impingement jet with forced convective heat transfer without boiling, or for characterization of the maximum specific heat fluxes of a narrow class of devices both by the scheme of design (especially for arrays of jets) and by their characteristic sizes. For example, one can note a significant difference in heat transfer by micro- and macro-jets, [4].

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

In addition to the schematic design and its geometric parameters, a number of general significant parameters that determine the results of cooling can be distinguished. First of all, it is the choice of the coolant and the parameters of the cooled surface. As a cooling liquid one may consider: water, ethylene glycol, R-11, R-13, R-134a, FC-72, FC-77, FC-87, PF-5052, HFE-7100, kerosene, various nanofluids, as well as a liquid eutectic alloy of gallium and indium, liquid nitrogen or helium. The operating surface temperature and specific heat flux are determined by the design of the electronic device. Various surface modifications are applied at the nano- and micro- levels in order to intensify heat transfer during boiling. The working temperature of the hot surface sets the choice of liquid and pressure in the gas phase (boiling point), the possibility to superheat the surface before the boiling crisis. An important role is played by the thermophysical properties of the liquid, the possibility of its subcooled before reaching the hot surface. The liquid jet is accelerated and formed by a special device, and here both the geometric parameters of the device itself (the size, location and nozzles design) and the flow characteristics (liquid flow rate, liquid pressure at the device inlet and nozzle) are extremely important. This, mentioned above, set of parameters has been thoroughly investigated by various authors. The literature presents empirical dependences for critical heat fluxes depending on a wide set of specified parameters for various circuit implementations, for example, in [5, 6].
In the technique of jet impingement cooling of miniature devices, the use of a large array of jets (up to two thousand) produced by micro nozzles is widely used, for example [7,8-9]. This significantly reduces the spatial inhomogeneity of cooling and the requirements for pumping equipment. However, the use of multi-nozzles or their arrays creates complex conditions for jet interaction, especially for the two-phase case. Designing and optimizing such devices is still a non-trivial task. Typical distances from the nozzle to the cooled surface range from 2.5 to 15 nozzle diameters, and in the case of micro devices – up to 3.5 diameters. That with the typical size of a micro nozzle of 0.3 mm will be a distance of 1 mm scale.

In the case of spray cooling (figure 1b) a special device is used to spray the coolant. The formed stream of drops with velocities on the order of 10-30 m/s bombards the hot surface. A thin liquid film (1-600 microns) is formed, intense evaporation, boiling, and forced convection occurs. It is important to note that the steady state droplet jet is completely formed at distances of about or more than 8-10 typical nozzle sizes. At the same distance, the shape of the torch is formed, which provides irrigation of a certain area, so choosing the distance from the spray nozzle to the hot surface in this cooling technique is not a trivial task. Typical distances from the nozzle to the hot surface in the case of spray cooling are 7-40 mm, but when cooling miniature electronic devices, a significant reduction in this distance is required for design reasons. There are three factors that characterize significant differences of spray cooling from the jet impingement cooling: 1) a liquid drop jet is fed to the film surface, which significantly intensifies forced convection, 2) boiling is realized over the entire irrigation surface, 3) it is shown that micro- droplets bouncing off when a thin superheated liquid film is bombarded can be places where vapor micro-bubbles appear, as a place of "secondary" nucleation that significantly intensify heat transfer. Among the optimization differences, it should be noted that in the case of spray cooling to intensify heat transfer, it is recommended to increase the speed of drops while reducing their size. The liquid flow rate may not increase and may be significantly lower than for jet impingement cooling [10].

3. Results and discussion
The characteristic heat transfer values experimentally achieved over the past 25 years for the four most promising microelectronic cooling methods using evaporation and boiling of the coolant (water) are presented in the table 1. Some comparisons of these systems have been made also, for example, in [10,11]. In this table, first of all, attention is paid to the discussion of the maximum achieved values of specific heat fluxes and HTC. For each of the cooling methods, the first article is characteristic, which demonstrates typical large values for both heat transfer parameters. Then the article is presented, where the largest value of HTC is demonstrated. The third paper is one with the maximum value of the specific heat flux. It should be noted that for many cooling methods, the maximum values were reached at the very beginning of the 21st century or earlier. The table 1 shows that for all cooling methods, comparable heat transfer values are typically achieved. And this is despite the fact that the complex of significant physical phenomena in these methods is very different, and the realized flow patterns can be also radically different. And some important phenomena like [12] can be very important only for very thin liquid films. The maximum values of heat transfer characteristics for all methods were achieved by taking special actions. And these actions were aimed at enhancement of steam generation.

| Cooling method | \( h \), kW/(m²·K) | \( q^* \), MW/m² | Authors |
|----------------|------------------|----------------|---------|
| Jet impingement | 280              | 18,20          | Overholt et al., 2005 [7] |
| Jet impingement | 414              | 11,1           | Michna et al., 2011[13] |
| Jet impingement | -                | 43             | Butterfield&Crockett, 2019 [14] |
| Spray           | 120              | 20,0           | Cebo-rudnicka 2016 [15] |
| Spray           | 200              | 8,7            | Yang et al., 1996 [16] |
Let's look at these questions in more detail for the case of jet impingement cooling. The authors of this article analyzed more than 80 experimental works devoted to the study of heat transfer during jet impingement cooling of miniature devices. An overview of the maximum values presented in these articles over twenty years of research on cooling by the water is shown in figure 2.

The chart demonstrates several unexpected trends. First, there is no significant increase in the maximum values of heat transfer in the modern history. The similar fact was previously noted in [10, 22] for a wider range of cooling methods on the scale of the last 40 years. The following facts should be noted: 1) the maximum values of heat transfer were demonstrated in the second third of the 20th century for a free impingement jet with a water flow rate of more than $10^{-3}$ m$^3$/s, which of course is a very significant value for micro devices; 2) in practice, when considering the miniature devices cooling, due to the technical features, it is very rare to realize not only theoretically possible critical heat fluxes, but also the conditions for reaching the maximum HTC values; 3) the desire to create micro devices that are applicable in the modern technology leads to the appearance of requirements that complicate flow by spatial confine of the jet and make it difficult to remove steam.

In a small number of articles, some really outstanding heat transfer values are demonstrated. All values of the maximum heat flux with a scale value of 20 MW/m$^2$ or more were obtained for the free impingement jet. The most recent work [14], which obtained values of more than 43 MW/m$^2$, was also distinguished by the fact that a hybrid hot surface with different wettability was created, and the attention was directed on the presence of super hydrophobic areas. Works [7, 23], which demonstrated very high achieved HTC values, used arrays of micro-jets with characteristic nozzle diameters less than 0.3 mm. In addition, special efforts were taken to remove steam.

It should be noted that in most of the works, almost the same methods were used to enhance the heat transfer as in other cooling methods: 1) the traditional method of the parameters optimizing of liquid injection and steam removal; 2) subcooling of the liquid of impingement jet (traditionally an effective method); 3) reducing the vapor pressure in the atmosphere where the hot surface is located and degassing of the coolant; 4) joint nano - and micro - texturing of the hot surfaces; 5) the use of nanofluids. It is shown that microtexturing of the hot surfaces is also very effective, capable of doubling HTC, and slightly raising the maximum heat flux, [24]. Modification of the cooled surface at the nanoscale, especially in a combination of hydrophobic and hydrophilic areas, can increase the heat transfer coefficient.
transfer values by 30-40%, [14]. The use of nanofluids due to the intensification of boiling on the hot surface can lead to an increase of about 100% in the HTC value, may double the maximum heat flux, and may shift the boiling curves to smaller superheat by 10-20°C, [25].

A detailed review of the physical phenomenon that determine the achieved level of heat transfer during jet impingement cooling was carried out for a total of more than 90 works. It was found that in general, jet impingement cooling requires higher coolant flow rates than mini-/micro-channel and spray cooling, but the pressure drop during the liquid injection will be relatively small. The highest values that characterize heat transfer should be expected for a free impingement jet. A unified picture of the physical phenomenon can be formed only for some regions of a single free impingement jet, and analogies are used for nucleate boiling, which turns into transition boiling. However, with a submerged and, especially, with a confined impingement jet, these analogies usually not applicable, since steam bubbles strongly affect both the dynamics of the entire process and the flow being realized. Recently, it has been experimentally proved that nucleate boiling is the dominant mechanism in heat transfer [26], that is, during boiling, near-surface jet flux and the heat transfer coefficient are dictated mainly by the growth and exit of bubbles. In the case of a confined impingement jet, the near-surface flux can quickly turn into a two-phase flow in the channel. A clear understanding of this configuration of "confined flow" is essential for the design of the cooling module. The use of multi-nozzles or their arrays creates complex interaction conditions, especially at the two-phase case, which, most often, cannot be described in detail.

A large methodological and experimental research of the group of Prof. S.V. Garimella, see, for example [27-30], on the development of high spatial and temporal resolution techniques for studying the temperature profiles of the cooled surface and the dynamic boiling pattern in the vapor-liquid layer of a confined impingement jet has been carried out in recent years. The group made extensive use of the development of classical methods for capturing the temperature profiles of a thin film heater irrigated by an impingement jet, combined with high-resolution visualization of boiling processes. New methods of two-dimensional stereo photography and three-dimensional tomography of the boiling process have been developed. The work of this group has provided an important and new knowledge on the heat and mass transfer process. Some aspects are shown in figure 3.

Figure 3. Schematic of changes in the boiling phenomenon of a confined impingement circular jet with an increase in the specific heat flux from the hot device.

The figure shows the development of the boiling phenomenon of a confined impingement circular jet as the specific heat flux from the cooled device increases, which is marked with arrows. The intensification of nucleate boiling (left drawings from bottom to top) leads to the formation of a zone in near-surface jet flux in which steam bubbles occupy a large volume of space, causing the formation of a return circulation flow. With a further increase in the heat flux (right drawings from top to bottom), a steam cavity is formed near the nozzle, which confined the jet more and more. In this way,
this confined impingement jet becomes similar in all respects to a free impingement jet out flowing into the vapor space. Thus, a rational approach for intensifying heat transfer should be considered the deliberate creation of conditions for the free impingement jet implementation, even in limited device spaces. This can be done not only using the space geometry, but also using the flux and pressure characteristics of the unit array, forming ultrafine liquid microfilms.

It is known that, in a free impingement jet there is a zone with maximum heat transfer, which is realized in the thinnest liquid film that breaks on a heated surface. Often, this highly productive heat transfer zone can be described as a liquid zone near the three-phase vapor-liquid-solid line. The current state of research on heat transfer near this contact line is presented in the review [31]. It is shown that the intensity of evaporation near this line is more than significant for a number of processes [32, 33]. Direct observation of microlevel phenomenon accompanied by evaporation in this liquid zone was performed in [34-37]. In [21], the special role of evaporation in the contact line area is shown. About 200,000 dynamic dry spots have been formed in the liquid film per second with time and spatial scales of about 0.5-5 milliseconds and 100 – 500 microns, respectively. We may assume that by controlling the formation of these zones at the device design stages and its operation, it is possible to significantly increase the heat transfer intensity, and, apparently, to overcome the period of 40 years of stagnation of the maximum values of heat transfer in this field of science and technology.

4. Conclusion
- with jet impingement cooling, some of the largest values of specific heat fluxes and heat transfer coefficients can be realized. One of the steps to implement this is to technically create an array of non-interacting free impingement jets, thereby forming large areas of ultrafine liquid films of evaporating coolant;
- detailed studies of the boiling phenomenon under confined conditions, which is formed during impingement jet cooling, which is close in essence to free impingement jet cooling, are required;
- it is necessary to resolve the issue of intensive steam removal from an inlet space;
- detailed studies of the dynamics of an ultra-fine coolant film formed during impingement jet cooling, with time registration rates up to 10^6 Hz and a high spatial resolution of the order of 1-10 microns per pixel, are required.

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