Modern possibilities of vapour chambers and other intensive cooling techniques. Comparative review

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Abstract. Due to their high reliability, ease of manufacture, passive operation, and efficient heat transfer, vapor chambers (VC) are widely used for temperature management of modern electronic and power devices. This review considers all experimental works on the characterization of the thermal characteristics of VC, in the results of which the threshold in the removal of a specific heat flux of >0.1 kW/cm^2 was overcome. This literature review, when compared with other cooling techniques, showed that they have not shown a noticeable increase in recent decades. Moreover, we should expect a qualitative increase in the capabilities of the VC and the expansion of their use. The principles of operation of modern VCs, often referred to as evaporation chambers, are also conceptually described.

1 Introduction

The development of power and microelectronics, other modern technical devices has led scientists and engineers in many branches of knowledge to new challenges. Thus, temperature management of electronic elements is necessary in all modern devices: computer chips and data centers, microelectronic and data storage devices, mobile devices and communications, microwave devices and radar systems, lasers and the latest optical devices, for example, operating with synchrotron beams, light-emitting diodes and solar energy, in automotive optical devices and power and control modules of hybrid and electric vehicles, in nuclear power of a new generation, lithium-ion batteries and railway transport, in medical technology and aerospace facilities. The localization of heat generation in modern devices has also undergone significant transformations [1].

The miniaturization of electronic devices has led to the emergence of powerful localized heat sources with several micrometers in size, accumulations of local heat sources on a scale of several millimeters, and distribution of heat power over spaces of several square centimeters [2]. In new generation systems, it is necessary to incorporate cooling technologies that provide power semiconductor cooled with specific heat fluxes significantly more than 0.5 kW/cm^2 for hot spots with an area of less than 1 cm^2.

The high specific heat flux created special problems for temperature management. The accumulation of heat in such a small space contributes to a sharp increase in temperature in the absence of effective heat removal. And the performance, reliability and life of electronic components are significantly degraded when the operating temperature exceeds the rated operating temperature [3]. For example, the reliability of a CPU is reduced by 10% for every 2° C above the allowed operating temperature [4]. Increasing the LED junction temperature will reduce LED efficiency and degrade device performance [5, 6]. Operating a lithium-ion battery at temperatures above 50°C will shorten battery life by more than 60% [7, 8].

Efficient elimination of hot spots is becoming an increasingly challenging task in the temperature management of modern devices, given the need to match the thermal strains of dissimilar materials that need to be directly integrated into a semiconductor chip. As devices continue to miniaturize and become more complex, even multi-core application strategies are limited by thermal issues due to the formation of local highly concentrated areas of heat generation or hot spots in areas that experience a lot of activity [9]. These hot spots can easily create heat fluxes of more than 0.3 kW/cm^2 in modern microprocessors [10], disturbing the boundaries of traditional cooling approaches. Specific heat dissipation in other semiconductor devices, such as power electronics, is also constantly increasing, and it is expected that future generations of power converters for electric vehicles will generate heat fluxes up to 1 kW/cm^2 [11].

There are a significant number of cooling techniques that demonstrate this capability. The most modern and rapidly developing of them are: heat pipes and vapour chambers (VC), spray and micro-jet cooling techniques, mini- and micro-channel single phase and two phase cooling techniques, evaporative cooling technique using micro- and nanomembranes, cooling technique due to intensive evaporation of a dynamic shear driven liquid thin film, developed at the Kutateladze Institute of Thermophysics SB RAS by the laboratory of prof. Kabov O.A.

When choosing a cooling technique for the temperature management of a modern integrated device, one should rely not only on the amount of specific heat

dissipation, but also on achieving a much more uniform temperature distribution throughout the device. Modern electronic devices require not exceeding the maximum permissible operating temperature locally, but also temperature uniformity throughout their body. An uneven temperature distribution will result in the formation of hotter zones, which can cause thermal stress and deformation, leading to fatigue failure of the device structure [2]. To exclude the formation of hot spots, a VC was proposed, which is a development of a flat heat pipe [12–15]. This simple approach to hot spot mitigation is to use an intermediate heat spreader with high effective 3D thermal conductivity to convert the localized heat flux into a more uniform distribution one before the heat is removed to the outside. A planar heat spreader can be integrated into a system with relatively low cost and minimal impact on the overall system complexity [16]. VCs are highly efficient heat spreaders, which are based on the almost adiabatic vaporization heat transfer in a sealed cavity to achieve thermal conductivity, often much higher than the thermal conductivity of solid materials [17]. It is established that the effective thermal conductivity of VC is in the range of 20 kW/(m·K) and higher [18]. This value can be significantly improved in ultrathin vapor chambers with a vapor core thickness of less than 200 μm [19]. The heat transfer mechanism is passive and VCs can operate as standalone devices without requiring any external energy sources.

The VC is a two-phase temperature management system. It has the advantages of excellent thermal conductivity, uniform and constant temperature, and the fundamental ability to reverse the direction of heat flow. It eliminates the limitations of conventional heat pipes such as limited contact area, high thermal resistance and spatially non-uniform heat flow. Recent progress in the development of silicon-based VCs has opened up promising opportunities for matched the coordination of thermal expansion coefficients of structural elements, high-performance heat spreaders that can potentially be packaged with semiconductor chips in a variety of novel configurations. The use of silicon as the material of the VC container creates the possibility of metal connection or direct integration of VC with a semiconductor substrate, eliminating unnecessary thermal interfaces between hot spots and the heat dissipation system [20]. Note that VC is preferable to traditional heat pipes for cooling at heat fluxes above 0.05 kW/cm^2, since the heat flux is two- or three-dimensional compared to one-dimensional in heat pipe [21]. The main advantage of a PC is that it can be placed in direct contact with heat generating components in electronics, power electronics, avionics and other heat generating elements, without the additional thermal resistors due to its flat configuration. It should be emphasized that most VCs are insensitive to gravity and will work in any inclination [22].

The present study is focused on a review of published experimental results on the values of the achieved specific heat fluxes dissipated by VC under temperature management, behavior and operation at this maximum value of heat flux, and ways to increase them.

2 Techniques of cooling

In the modern world, a significant number of cooling techniques are used. The following are currently under development:
- cooling by liquid film;
- immersion cooling;
- cooling by pool boiling;
- single-phase mini- and microchannel cooling systems;
- cooling by boiling in mini- and microchannels;
- rivulet cooling in channels and minichannels;
- spray cooling;
- microjet cooling;
- cooling by means of heat pipes and loop heat pipes;
- thermosiphon cooling;
- cooling by means of VC;
- cooling by means of evaporation of a dynamic shear driven thin liquid film [23];
- hybrid cooling through a combination of schemes.

The possibilities and problems of modern techniques of super intensive cooling are considered in [24-26]. The prospects of a number of modern techniques for intensive cooling can be assessed using Table 1. It presents the characteristic values of heat transfer for the most promising techniques using evaporation and boiling of the cooling liquid (using water as an example), experimentally achieved over the past 25 years. In this table, first of all, attention is paid to the discussion of the maximum achieved values of **h** heat transfer coefficients (HTC) and **q"** specific heat fluxes. For each of the cooling techniques, a reference is first given showing typical large values for both heat transfer parameters. Then a link is given, where the largest HTC values are demonstrated. The third is a link with the maximum value of the specific heat flux. The dimensions of the cooled planar region had a scale of about centimeters in both dimensions.

From Table 1 it can be seen that the maximum HTC value 1.80 MW/(m^2·K) was achieved using the membrane cooling technique [37]. The maximum value of the specific heat flux of 6.5 kW/cm^2 has been demonstrated for spray cooling [32], but it has been experimentally established that the membrane cooling technique, according to the article [38], makes it possible to remove heat on a scale of 11 kW /cm^2 by evaporation at 60° C from an separate nanopore.

It should also be noted that in the last 10 years, significant progress has been achieved only where the ideology of heat transfer intensification due to super-intense evaporation in the microregion near the three-phase vapor-liquid-solid line is consciously exploited. An overview of the physical processes occurring in the contact line area is given in [42-44]. This is true for the use of not only water, but also other liquids as a coolant. It is in this context that one can interpret the fact that, for almost all cooling techniques, it has been shown that complex micro texturing of the cooled surface is very effective and can approximately double the HTC value and increase the critical heat flux (CHF) by 30–50%. Modification of the cooled surface at the nano level, especially in the combination of hydrophobic and hydrophilic regions, can further increase the heat transfer by 30-40%.

Table 1. Possibilities of advanced cooling techniques (water).

Cooling technique	h, MW/ (m^2·K)	q", kW/cm^2	Authors
jet impingement	0.280	1.82	Overholt et al. 2005 [27]
jet impingement	0.414	1.11	Michna et al. 2011 [28]
jet impingement	-	4.3	Butterfield & Crockett, 2019 [29]
spray	0.120	2.0	Cebo-Rudnicka 2016 [30]
spray	0.200	0.87	Yang et al. 1996 [31]
spray	-	6.5	Vondran et al. 2012 [32]
minichannel	0.260	1.47	Zhu, 2014 [33]
minichannel	0.630	1.35	Palko & Goodson, 2017 [34]
minichannel	0.134	4.8	Calame, 2009 [35]
shear driven liquid film	0.300	1.2	Kabov et al. 2018 [23]
evaporation from membrane	0.630	1.28	Palco et al. 2017 [36]
evaporation from membrane	1.800	1.7	Alipanah et al. 2020 [37]
evaporation from membrane		11*	Nazari et al. 2018 [38]
boiling in a porous body	-	1,2	Palco et al. 2015 [36]
vapour chamber	-	0.28	Deng et al. 2017 [39]
vapour chamber	0.2	0.38	Ju et al. 2013 [40]
vapour chamber	-	0.58	Hwang et al. 2011 [41]

* in a separate nanopore

Note that boiling in a copper microsized porous body made it possible to remove a heat flux of up to 1.2 kW/cm^2 [36]. Against the background of the values given in Table 1, this result makes one think that evaporation from a porous body currently has a large reserve for intensification in the technical implementation of much larger areas of the microregion. The heat transfer values in Table 1, demonstrated by the VC, show that significant values of HTC can be expected for this cooling technique, but this value is almost never been measured in the experiments. The values of the maximum achieved specific heat fluxes, including critical ones, did not exceed 0.6 kW/cm^2 for VC, which is two times less than the values of the critical heat flux achieved during boiling in a porous body. And yet, VCs are widely researched and used in modern passive cooling technique due to their compactness, flexibility and efficiency.

Let's take a closer look at the VC in comparison with a brief overview of the mini-channel cooling technique. A schematic of one show on Fig. 1. In this case, the liquid under excessive pressure is evenly distributed between the channels. Then, flowing through them, it removes heat from the cooled surface and, at the end, is removed from the system to heat utilization. Both single-phase (without a significant contribution of the evaporative mechanism of heat removal) and two-phase cooling are used. The mini channel single-phase cooling shows rather good results in comparison with the two-phase cooling with a pool boiling: the specific heat flux reaches 1.0 kW/cm^2 by water [45] and 0.3 kW/cm^2 by HFE-7100 [46]. On the other hand the two-phase cooling allows to get a significant advantage over the single-phase in the case of uniform channels filling by a cooling liquid, the presence of an extended three-phase boundary liquid-vapor/gas-(cooled surface), and, no less important, the formation of special channels or artery for vapour removal. Microchannel cooling technique currently does not demonstrate any significant thermal advantages in heat removal in comparison with mini- and macrochannels [26]. However, design considerations, size reduction may be an incentive to use microchannels for cooling. It should be noted the pumps usage needs to move coolant. These devices can be quite energy intensive, besides generating flow instability and instability of the cooling system.

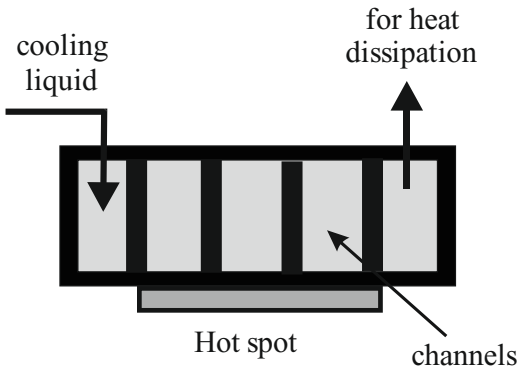

Fig. 1. Schematics of mini-channel cooling technique.

At designing of mini-channel cooling technique the following approaches seem to be the most proven and promising: 1) use of a hybrid cooling technique, i.e., a mini-channel, and elements of another of the above ones, for example, jet or membrane; 2) ensuring uniform distribution of the "subcooled" liquid through the channels of the heat exchanger; 3) the use of short channels; 4) use of arrays of protrusions with high thermal conductivity in the channel; 5) early/"timely" removal of vapour from the channels. By applying of these special techniques, a mini-channel cooling is currently becoming very competitive in the temperature management of modern heat-stressed devices, including miniature ones [26].

We emphasize that only the competent formation of mini-channels for the coolant, the conscious solution of the issues on the hydraulic resistance for channels and the possible problems with vapour removal allow this cooling technique to compete with modern evaporative techniques that exploit the possibilities of super-intense evaporation. However, the channel/mini-channel cooling technique is the most commonly used for cooling heat-stressed devices.

VC is a special type of two-phase flow passive heat dissipation technology widely used, Fig. 2. The VC has a simple structure with very few or no moving parts, and consists of a porous evaporator directly attached to the hot spot, a condenser, a partially filled with coolant capillary structure, also known as a wick, and a sealed adiabatic container. Between the container walls there can be a mesh, columnar or ribbed structure that reinforces the VC body, as well as serving to separate the vapor space and partially drain the condensed liquid to the evaporator. As mentioned above, in most modern

VCs, gravity **g** does not play a significant role, and their characteristics do not depend on the inclination and magnitude of **g**.

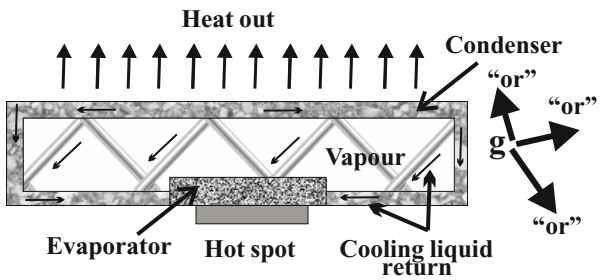

Fig. 2. Schematics of VC cutaway: cooling system principles.

The phase change occurs in the evaporator and on the condenser. In the evaporator, the coolant evaporates and, due to the induced vapor pressure gradient, the vapor passes into contact with the condenser, where it dissipates latent heat and condenses into a liquid. The liquid condensate then returns to the evaporator through the capillary structure due to capillary pressure. Continuous cycling is achieved passively as the condensed liquid is returned to the heat supply section by capillary action in the porous wick material connecting the evaporator and condensation surface. These cycles of mass and energy transfer can continue until the upper limit of heat transfer is reached, i.e. the critical heat flux (CHF) of the VC, or the "dryout" of the evaporator (Dryout limit or condition).

As is known [47], the CHF state represents the upper limit of the heat flux, followed by a sharp increase in the wall temperature or a significant decrease in heat transfer with an increase in the wall temperature during pool boiling. In this case, a vapor layer covers the heated surface, separating it from the cooling liquid. Dryout condition is the termination of constant contact of the coolant with the heat source surface. This follows the gradual depletion of the liquid by evaporation and entrainment of the liquid film. The vapor from the continuous vapor phase covers the heated surface, while discrete liquid droplets may contact the heated surface from time to time.

The VC container material is usually chosen from copper, aluminium, stainless steel, silicon or polymer in case of flexible device cooling. The function of the container is to isolate the cooling fluid from the external environment. The container must be structurally solid, sealed, withstand overpressure, transfer heat efficiently by its walls from the heat source to the evaporator and from the condensation area to the radiator outside. VC must be able to carry out this heat transfer with low thermal resistance.

The overall VC thermal performance as a whole depends on the heat transfer and capillary characteristics of the wick structure, i.e. evaporator, condenser and fluid supply wicks. The capillary pressure created by the wick pores must overcome the cumulative viscous and inertial pressure drops along the vapor and liquid flow paths to maintain operation at any given heat transfer rate. When this condition and several other operational constraints are met, for example by avoiding significant entrainment of liquid into the vapor stream or choking at sonic vapor velocities, an order of magnitude gain in overall effective thermal conductivity over solid heat spreader can be realized. This will ensure that the VC is almost isothermal and has low transverse and longitudinal thermal resistance. The wick structures provide transportation of the cooling fluid within and between different areas of VC. The supply of any areas of the evaporator with liquid is carried out by its overflow inside the porous body of evaporator. The liquid itself comes from both the condenser and other VC surfaces due to the wick structure or gravity.

Reticulated mesh, sintered powder or grooved structure are common wick structures used in VC. A wick design optimized for a specific task is crucial for VC operation with higher heat fluxes [48, 49]. For the manufacture of wicks with different pore sizes of the capillary meniscus, materials such as steel, aluminum, nickel, or copper are mainly used [50]. Ceramic materials are also used, but they are less rigid and require the use of wire mesh for reinforcement. Carbon fibers are of great interest due to their chemical stability, high capillary pressure and thermal conductivity [50].

The VC condenser is responsible for dissipating the heat carried by the vapor phase. There are two main condenser types used in VCs: air-cooled or water-cooled. At the same time, several different approaches can be used to return liquid with minimal hydraulic resistance. In a fully capillary-driven VC, the condenser side is also covered with a porous wick, which brings the liquid back to the evaporator wick and prevents the formation of a bulk liquid film. Since thermal resistance across the wick itself is not as critical, the dimensions of the condenser wick may differ from those of the evaporator wick. More important in this case is that the viscous pressure drop across the wick on the condenser side is minimal compared to the pressure drop across the evaporator wick. This will reduce the contribution to the Dryout limit. A wickless condenser can also be used if the VC is designed in such a way that the coolant is returned to the evaporator by gravity or other forces. However, this may affect the thermal resistance due to the formation of a liquid film with considerable thickness. A particular method of liquid return while maintaining low resistance to condensation is the combination of chemically patterned microstructured surfaces to create superhydrophobic surfaces for liquid return in the form of jumping drops [51-52].

For proper VC operation, all non-condensable gases must be removed from it and impenetrability must be maintained to prevent the formation of a diffusion barrier that prevents vapor transfer between the evaporator and condenser [53-54].

The working fluid in the VC is selected depending on the temperature at which it must operate. In the vast majority of VCs for cooling modern technology, ammonia (213 - 373 K), methanol (283 - 403 K) or ethanol (273 - 403 K), or water (298 - 573 K) is used as a cooling fluid (range of possible operating temperatures). However, helium and nitrogen for cryogenic temperatures (2–4 K), metals such as mercury (523–923 K), sodium (873–1473 K) and even indium (2000–3000 K) were also used as coolant in the VC for extremely high temperatures. Patankar et al. [55]

identified two "quality factors" that are appropriate to use when choosing a cooling fluid, stating that while one prioritizes raising the upper limit of vapor chamber heat dissipation, CHF, the other prioritizes minimizing overall thermal resistance.

The question of the influence of the filling ratio of cooling fluid is important and complex. It has been investigated for both heat pipes and VCs. Consideration of the influence of the filling ratio and the magnitude of heat fluxes on the thermal characteristics of devices can be found, for example, in [56-57].

According to [58], there is a critical value of the height of the VC space. Above the critical value, resistance to condensate flow is predominant. On the contrary, in the case of a limited space height, the pressure drop of the steam flow increases sharply, which greatly increases the thermal resistance of the steam core, which begins to prevail over the total thermal resistance.

3 Results and discussion

A summary of the maximum values of the specific heat flux in VC obtained experimentally for water as cooling liquid over the past 15 years is shown in Fig. 3 in the form of a schedule of publications by years. Works in which this value was higher than or equal to 0.1 kW/cm^2 were taken into account. In total, 25 such publications were discovered in the 21st century. The graph shows that the average value of the specific heat flux was 0.291 kW/cm^2 here. There are only two publications in which the value of the specific heat flux exceeded 0.5 kW/cm^2 [41, 59]. Note that there is no progress or regression in the temporal dynamics of the maximum values of the specific heat flux with such a criterion for selecting scientific papers and patents. Apparently, this reflects the presence of deep problems in understanding the physical mechanisms of boiling and evaporation from a porous body, as well as the complexity of the problem of vapor transfer and its condensation in the constrained conditions of workable VC.

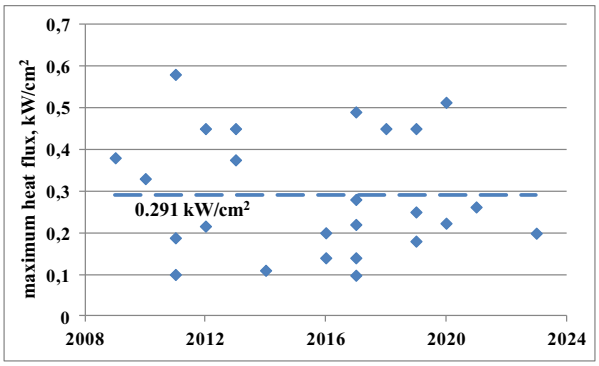

Fig. 3. Experimentally obtained maximum values of the specific heat flux for VC, water.

In the studied articles, interest in ultrathin VC has been revealed. In Fig.4, for the same data that are presented in Fig.3, the VC heights used in the experiments are shown; the dotted line shows the average value of the VC height in this graph. From Fig.4 it can be seen that over the past 15 years there has not been any trend in changing the VC height, provided that the value of the maximum specific heat flux exceeds 0.1 kW/cm^2. The data of the same sample of experimental works are presented in Fig. 5 as a dependence of the specific heat flux on the VC height, the dotted line shows a linear trend for these data. And here, no correlation was found between the height and the specific heat flux value. The absence of trends in Fig. 3-5 shows, first of all, that over the past 15-20 years there has not been a qualitative breakthrough in the technology of utilizing high heat fluxes using VC. The goals of these works differed, but the stability of the presented values in the time of their obtaining confirms the absence of technological growth in the heat removal by VC.

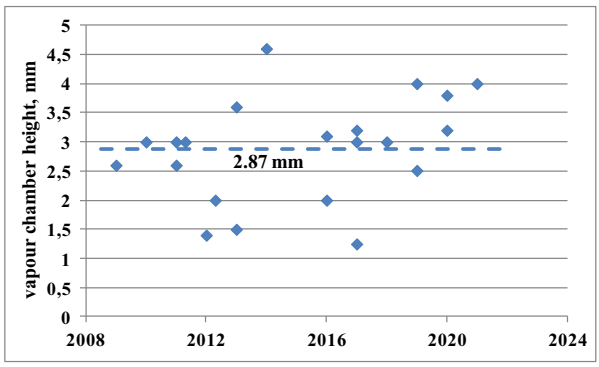

Fig. 4. VC height for the data from Fig. 3.

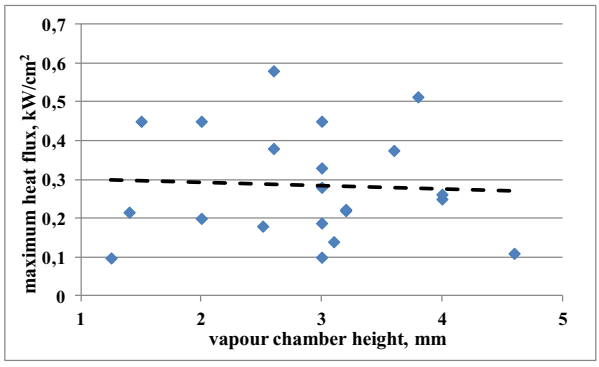

Fig. 5. Experimentally obtained maximum values of the specific heat flux depending on the VC height, the data from Fig. 3-4, (water).

Even though VCs have been around for decades, some technical issues remain to be resolved through future research. There is an opinion, that the limitation of the maximum values of the specific heat flux due to the Dryout limit and the low HTC due to the large total thermal resistance. However, some well-performed parametric studies of VC have shown that performance characteristics such as CHF, HTC, thermal resistance and surface temperature are primarily determined by the capillary characteristics of all VC wick structures. In addition, it has been found that the effective meniscus/pore radius and permeability are the two most important characteristics of a capillary wick. The first is responsible for the capillary pressure, and the second regulates the liquid flow transported through the capillary wick. In this case, the smaller the effective radius of the meniscus, the greater the capillary pressure and, thus, the higher the maximum value of the specific heat flux. And the greater the permeability, the greater

the mass flow of liquid carried inside the capillary wick, which also enhances this effect.

In general, smaller pore size or channel width decreases the effective meniscus radius, i.e. increases capillary pressure but reduces permeability. And larger pore size or channel width increases permeability, i.e. increases fluid volume transfer but reduces effective radius meniscus. Thus, the physical dualism of the wick structure in VC is manifested, and to improve the overall thermal performance, these two parameters must be optimized. Nanostructuring of the microstructure to form a multiscale micro/nano wick structure is also an effective way to increase the reverse flow of the coolant [60-61]. VC with capillary wicks made of sintered metal powder (particles) according to the studied literature provide the best thermal performance of one. This is because smaller and larger pore radii can be simultaneously achieved using small and large metal particles for both a smaller effective meniscus radius and a larger permeability, respectively.

It is necessary to comprehensively introduce into the VC the ideology of heat transfer intensification due to super-intense evaporation in the micro-region near the three-phase vapor-liquid-cooled surface boundary. The formation of the wettability pattern on the surface enhances the evaporation of the drop due to the lengthening of this contact line [24-26, 42, 63-64]. Thus, the integration of the wettability model into the evaporator of a two-phase heat spreader should probably drastically improve the thermal characteristics of VS, as evidenced by the increase in the temperature uniformity of an ultrathin VC using an evaporator with a surface having a wettability pattern [65].

Conclusions

- It is believed that VC is well studied due to their wide practical application and significant technological progress. However, a literature review showed that the last decades have not demonstrated a noticeable increase in the thermophysical parameters of one. Moreover, we should expect a qualitative increase in the capabilities of the VC. This is especially evident in comparison with the capabilities of other modern cooling techniques.
- A natural way for such progress is the intensification of heat transfer due to super-intense evaporation in the micro-region near the three-phase boundary of vapor - liquid - cooled surface. Besides whether or not the stage of vapor condensation in VC is the limiting stage has not been established in the literature of the last 20 years.
- There is some progress in expanding the areas the VC application in temperature management, but there is no progress in the physical rethinking of the VC operating principle and, consequently, ones design.

This work was supported by the Ministry of Science and Higher Education of the Russian Federation within the governmental order for: Kutateladze Institute of Thermophysics SB RAS (project 121031800213-0) and SRF "SKIF" Boreskov Institute of Catalysis (project 123031300092-4).

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