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A Comprehensive Review on the Core Thermal Management Improvement Concepts in Power Electronics

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ABSTRACT A heat sink is a specific type of heat exchanger integrated with heat generating devices – mostly electronics – for the sake of thermal management. In the design procedure of heat sinks, several considerations such as manufacturing cost, reliability, thermal and hydraulic performance have to be included. In the past few decades, the prevailing trend of electronics design miniaturization has led to high-power-density systems necessitating high performance cooling concepts. This paper intends to provide a comprehensive review on various employed heat transfer enhancement techniques in cooling procedures of electronics thermal management devices, with a focus on core ideas. The main motivation is to give a rapid overview on the key concepts in different high-performance cooling designs along with a quantitative comparison between the different concepts all in one reference which is missing in literature. For this, the key idea of each design is firstly categorized, and then a detailed description is provided for each case. The discussed categories consist of concepts based on channel cooling in various scales, phase transition, jet impingement, spray cooling and hybrid design. At the end, quantitative comparison is illustrated for thermal and hydraulic performance of a selection of the reviewed references covering all these different categories. Based on this comparison, an overview on thermo-hydraulic performance of the presented categories is provided, and recommendations for future studies are given based on this and the detailed review of references.

INDEX TERMS Coolant, convection, heat transfer, impingement, phase transition, thermal management.

I. INTRODUCTION

In order to achieve reliable and highly-efficient operation for power electronics, especially for those cases with high requirements on compactness following the ongoing miniaturization trend, it is necessary to provide thermal management solutions capable of dealing with high-power-densities. Thermal management is a crucial topic in a variety of applications including electronics, solar collectors and furnace engineering [1]. Specifically, in electronic devices, in order to avoid damage caused by formation of local hot spots on the one hand, the maximum temperature within the device is desired to be kept in a restricted range [2]. On the other hand, in order to achieve the desired reliability, smooth cooling with uniform temperature distribution has to be achieved. This explains why efficient cooling mechanisms have become an important topic of numerous research activities with the growing trend of developing high-power-density electronic devices with compact design. For this, various thermal management techniques have been developed. As illustrated in FIGURE 1 along with corresponding references, the major methods in this reference list, that form the main categories in this paper, are channel cooling-based thermal management designs in various scales including mini-channel and

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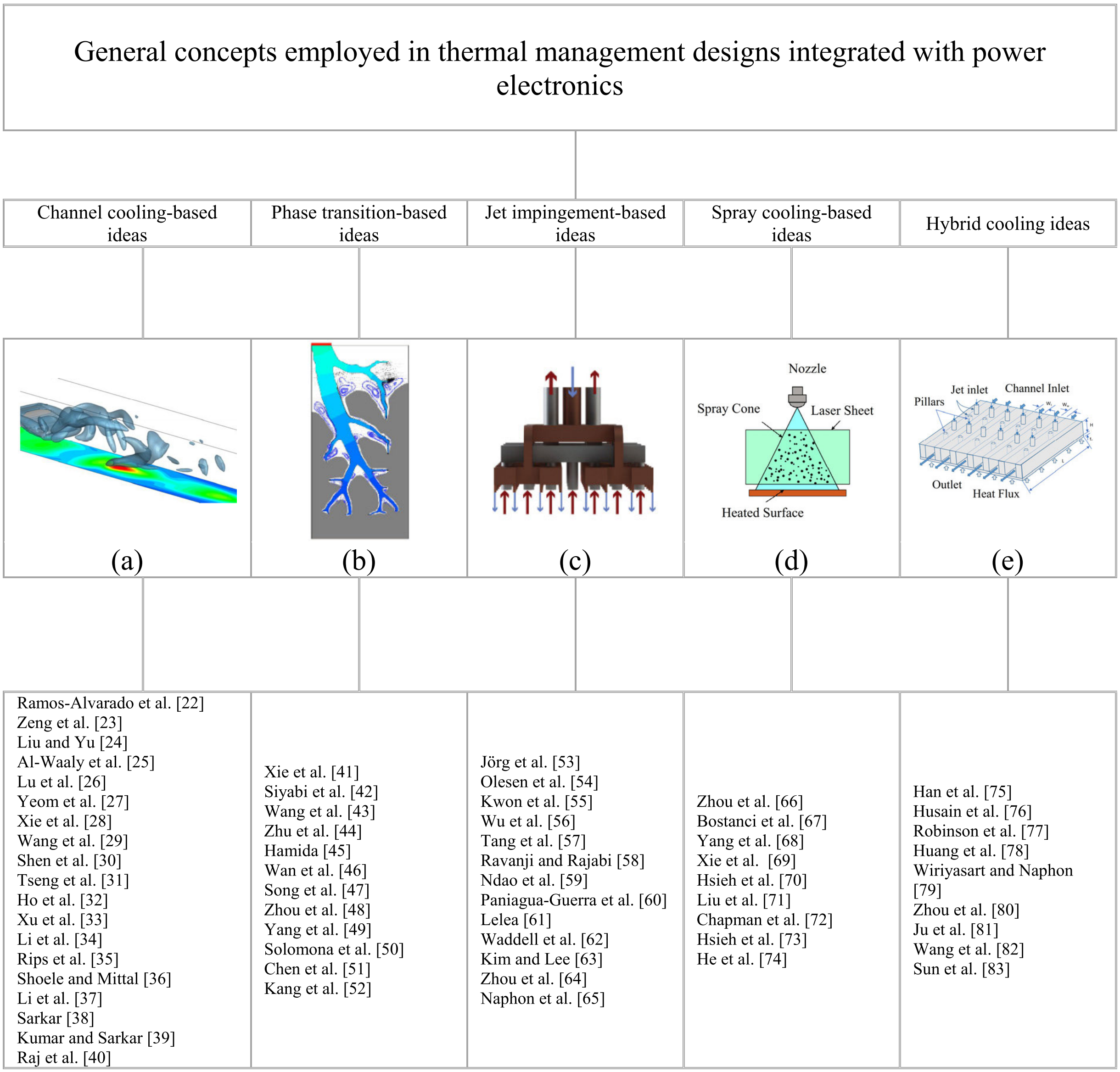

General concepts employed in thermal management designs integrated with power electronics

Channel cooling-based ideas	Phase transition-based ideas	Jet impingement-based ideas	Spray cooling-based ideas	Hybrid cooling ideas
(a)	(b)	(c)	(d)	(e)
Ramos-Alvarado et al. [22] Zeng et al. [23] Liu and Yu [24] Al-Waaly et al. [25] Lu et al. [26] Yeom et al. [27] Xie et al. [28] Wang et al. [29] Shen et al. [30] Tseng et al. [31] Ho et al. [32] Xu et al. [33] Li et al. [34] Rips et al. [35] Shoele and Mittal [36] Li et al. [37] Sarkar [38] Kumar and Sarkar [39] Raj et al. [40]	Xie et al. [41] Siyabi et al. [42] Wang et al. [43] Zhu et al. [44] Hamida [45] Wan et al. [46] Song et al. [47] Zhou et al. [48] Yang et al. [49] Solomona et al. [50] Chen et al. [51] Kang et al. [52]	Jörg et al. [53] Olesen et al. [54] Kwon et al. [55] Wu et al. [56] Tang et al. [57] Ravanji and Rajabi [58] Ndao et al. [59] Paniagua-Guerra et al. [60] Lelea [61] Waddell et al. [62] Kim and Lee [63] Zhou et al. [64] Naphon et al. [65]	Zhou et al. [66] Bostanci et al. [67] Yang et al. [68] Xie et al. [69] Hsieh et al. [70] Liu et al. [71] Chapman et al. [72] Hsieh et al. [73] He et al. [74]	Han et al. [75] Husain et al. [76] Robinson et al. [77] Huang et al. [78] Wiriyasart and Naphon [79] Zhou et al. [80] Ju et al. [81] Wang et al. [82] Sun et al. [83]

FIGURE 1. Classification of the reviewed research categories (a: reprinted with permission from [35], b: reprinted with permission from [41], c: reprinted with permission from [60], d: reprinted with permission from [84], e: reprinted with permission from [76]).

microchannel, phase transition-based cooling techniques, jet impingement and spray cooling designs along with hybrid designs benefitting from combination of these methods.

A wide variety of general cooling concepts is available in literature, and they are different from the viewpoint of cooling capacity, involved mechanisms and improvement potential. A primary method for electronics cooling is to attach highly-conductive extended surfaces called fins with various structures to the heat dissipating part [3]. Heat is conducted through the solid layers to the extended surfaces, and natural convection releases heat to the ambient. Obviously, thermal interface materials play a key role in such designs [4], and an area increase is the core idea. However, the advances in electronics have necessitated higher cooling capacities making this method incompatible with a majority of more recent designs [5].

In order to achieve higher cooling performance, forced convection-based air cooling concepts have emerged. Fan induced air cooling, benefiting from the forced convection mechanism, was proposed as another thermal management solution in electronics industry. Further improvement of the heat transfer coefficient in this method for instance by higher air flow velocities is accompanied by higher noise and requires high power. Ultimately, it is the low heat capacity of air which impedes the usage of forced convection-based air cooling concepts in high-power-density applications [6].

Another major thermal management method is liquid cooling. The designs in this category show higher cooling capacity making them suitable for being integrated with compact electronics and high power densities [7]. Liquid cooling methods can be categorized by various concepts including direct and indirect approaches. The wide application of liquid cooling has been emerged in different design concepts including cold plates, jet impingement-based designs and immersion cooling [8], [9]. Each of the above-mentioned methods has attracted growing attention in the past few years. In cold plate designs, channel cooling in various scales from micro to mini-channel is used. The microchannel topic has been the center of attention according to its desirable features for miniaturization. In fact, in spite of low flow rate and small hydraulic diameter in microchannels which lead to laminar flow regime, effectively a high heat transfer can be achieved by allowing many small channels in parallel, inducing a large solid-fluid interface. In addition, it benefits from design flexibilities such as diameter reduction for increasing heat transfer coefficient which is in accordance with compact design scope that has made this method attractive to thermal management designers [10]. However, the increased pressure drop can lead to restriction of further miniaturization [11]. This is why tuning the parameters in microchannel-based designs has formed a great proportion of research items in this field [12].

The other method of liquid cooling in the subcategory of direct methods is immersion cooling. This concept benefits from the desirable feature of having the fluid close to the heat source, for instance the electronic chip [9]. In this method, natural convection and two-phase flow are involved; however, an important restriction of this method - i.e. the requirement of liquid compatible with the device - led to restrictions of its application in thermal management devices.

Liquid jet impingement has been shown to be an efficient cooling technology by achieving thin thermal boundary layers and desirably high heat transfer coefficients, which make the concept suitable for compact designs [13]. However, the more complicated design and manufacturing procedure of this type of cooling devices compared to channel cooling designs led to intense competition between these two methods.

Another efficient thermal management method is spray cooling which works by breaking the coolant into droplets and impinging them to the hot surface. The role of the thermal boundary layer acting as a thermally insulating layer in channel cooling and impingement cooling designs is minimized in this method, so it is known as an efficient concept widening its application in high capacity cooling and general compact designs [14]. However, there are important parameters restricting performance of spray-based thermal management designs, and the most important one is the high pressure drop required in the nozzle to produce spray droplets [15].

In another category of cooling devices, phase transition is utilized. Phase change material (PCM) and heat pipe-based designs can be placed in this group. The main advantage of heat sinks utilizing PCM lies in the significantly higher heat absorbed in latent form compared to sensible heat absorption designs [16]. However, low thermal conductivity of conventional materials used as PCM led to a restriction of this approach, and also a great attention is attracted to the enhancement of effective thermal conductivity in these systems [17] and [18]. On the other hand, heat pipes, which can be placed in different categories from indirect liquid cooling to phase transition cooling designs, benefit from liquid-vapour phase change mechanism. In fact, a heat pipe is partially filled by liquid, and its inner wall called wick acts as capillary pump. Heat is absorbed by the working fluid in the evaporator side leading to fluid evaporation. Following this, the vapour goes to the condenser side due to a pressure gradient and is condensed there. The wick structure transports the fluid back to the evaporator. As a result, benefitting from this mechanism, the effective thermal conductivity of a heat pipe reaches several tens of thousands of Watt per meter Kelvin, which makes it an attractive technology for thermal management purposes [19], [20].

With the growing trend towards high-power-density electronics applications on the one hand, and performance restrictions of conventional thermal management solutions on the other hand, the use of high performance heat transfer enhancement concepts in this field has become more critical in the past few years [21]. Since heat sink design for being integrated with electronic devices is becoming more compact and needs to be capable of dealing with high-power-density thermal management applications, it seems necessary to provide a review on novel ideas on heat transfer enhancement methods used in such systems in one review paper. By doing this, it is intended to collect inspiring ideas in one reference to facilitate the design procedure for future studies.

The main motivation of this review paper goes back to the fact that the reviews available in literature in the field of thermal management are restricted to a specific topic, such as phase transition cooling [1] and [85], channel cooling ideas [86], nanoparticle dispersion [87] and jet impingement cooling [88]. However, in this paper, the focus is on core heat transfer improvement ideas used in various designs with different heat transfer mechanisms from phase transition, natural to forced convention and different working fluids ranging from air, liquid, refrigerants, nanofluids, and phase change materials with different physics from single phase convection to multiphase. These are grouped in a comprehensive classification ranging from channel cooling-based heat sinks, impingement designs, spray cooling, phase transition cooling to hybrid cooling systems used for thermal management of power electronics (see FIGURE 1). Moreover, a quantitative comparison is made between all these different ideas at the end in order to provide the thermal management designers with the opportunity of rapid scan of the core ideas used in different papers and a quantitative comparison of the cooling capacities. Note that all of the reviewed references may not necessarily be integrated with power electronics; however, their key concepts are reviewed here as the representative inspiring ideas that can be potentially utilized in future cooling designs integrated with power electronics. Besides, it is noteworthy that for each thermal management idea, there may be several papers, but at least one representative paper is brought to compare with other different concepts in order to provide the thermal management society with a guideline.

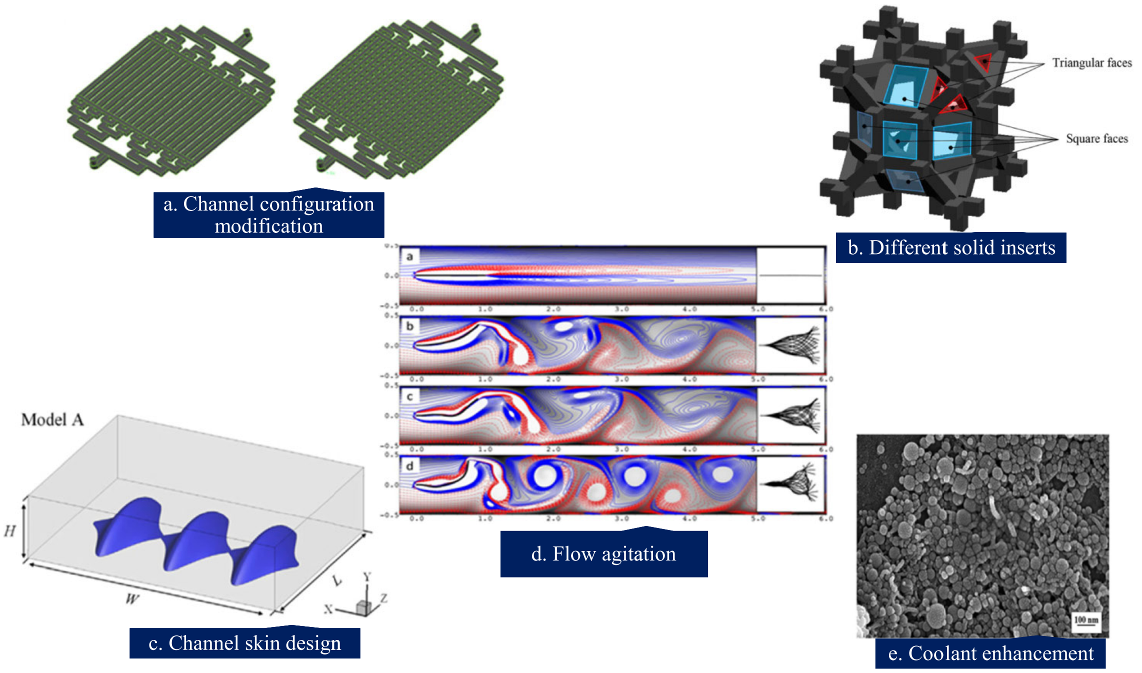


FIGURE 2. Graphical review of papers containing high performance ideas for heat transfer enhancement in channel cooling-based heat sinks: (a) reprinted with permission from [22]; (b) reprinted with permission from [32]; (c) reprinted with permission from[34]; (d) reprinted with permission from [36]; and (e) reprinted with permission from [39].

This work should enable to have a quick scan on the previous works and also to inspire from high performance ideas as a starting point to come up with new exclusive thermal management ideas. For each category in the proposed classification, an introductory description, a table and a schematic of ideas are provided in the next sections. Finally, a quantitative analysis is done to provide fair comparison between the various reviewed methods from thermo-hydraulic performance point of view. Moreover, at the end of this paper, the gaps that can be potentially filled later are listed in the conclusions.

II. HIGH PERFORMANCE IDEAS IMPLEMENTED IN CHANNEL COOLING – BASED HEAT SINK DESIGNS

A. INTRODUCTION TO CHANNEL COOLING

Channel and mini/micro channel cooling-based thermal management designs are reviewed in this section. According to the advances in manufacturing methods, channel cooling in all scales has attracted considerable attention as thermal management solution [89]. In contrast, there are still undeniable challenges involved in channel cooling, including pressure drop/pumping power penalty and restricted heat transfer due to the formation of a boundary layer, and non-uniform cooling due to undesirable temperature rise in the coolant. To tackle these issues, several ideas have been implemented in order to reduce the thermal boundary layer and to achieve uniform cooling at minimal pressure loss. In FIGURE 2, a schematic of some channel cooling designs is provided. As illustrated in this figure, the facilitated manufacturability made channel configuration ideas one of the most widely-investigated methods in this class. In addition, inserting different solid bodies such as pin fin, lattice structures and various types of vortex generators form another main concept for heat transfer enhancement in this category. Similarly, flow agitation by simple structures such as reeds is a simple and efficient method, used to cause strong vortices in the flow to disturb boundary layer and enhance heat transfer. Another part of studies in this context is skin design such as nature-inspired shark skin structure as illustrated in the mentioned figure. Finally, enhancing thermal performance of a heat sink by improving the coolant is the other field reviewed here. In addition to single phase channel cooling, another possibility is to use a boiling fluid as a coolant with higher cooling capacity compared to its single-phase counterpart due to utilization of latent heat of vaporisation in the heat transfer process. Besides, uniform temperature distribution should be in principle easier achieved in flow boiling heat transfer since it occurs at the fluid saturation temperature. However, there are restricting challenges associated with this approach. Flow instabilities such as flow reversal causing strong severe pressure drop fluctuations and wall temperature instabilities are the examples. Accordingly, benefitting from positive aspects of multiphase channel cooling along with tackling the challenges has become a hot topic in this field [90]. The characteristic parameters in this category of thermal management designs include flow rate, Reynolds number (Re), Prandtl number (Pr), Strouhal number (St), hydraulic diameter (D_h) and geometrical parameters associated with each case. Besides, the response functions considered in the design procedure are the approximated total thermal resistance (R_{th}), thermal efficiency index (η_i), thermal performance factor (η), heat transfer coefficient in terms of Nusselt number (Nu) or convective coefficient (h), and hydraulic loss in terms of pressure drop (ΔP), friction factor (f), and pumping power ($P.P$). In addition, the junction temperature (the highest operating temperature of the active region within a semiconductor device), peak temperature, maximum temperature difference and critical heat flux (in two phase cooling) are also used to describe thermal performance. The equations describing the abovementioned parameters are as follows [27]:

- $D_h = \frac{4A}{p}$, where A and p represent flow cross section and wetted perimeter respectively.
- $Re = \frac{\rho UD}{\mu}$, where ρ, U, D and μ represent fluid density, flow characteristic velocity, characteristic length and dynamic viscosity, respectively,
- $Pr = \frac{c_p\mu}{k}$, where c_p, μ and k are specific heat, dynamic viscosity and thermal conductivity respectively.
- $St = \frac{\nu L}{U}$, ν is vortex shedding frequency, L is characteristic length and U is flow velocity
- $R_{th} = \frac{T_h - T_c}{P_t}$, where P_t, T_h and T_c are total heat load generated by the device, hot spot temperature and inflow bulk temperature, respectively. Note that there is another version of total thermal resistance where P_t represents the input heat flux on the heating surface (W/m^2). In this case, thermal resistance unit is Km^2/W instead of K/W.
- $h = \frac{q}{T_w - T_b}$, where q, T_w and T_b are heat flux, channel wall temperature, and average coolant bulk temperature respectively.
- $Nu = \frac{hD}{k}$, where *h, D* and k represent convective coefficient, characteristic length, and fluid thermal conductivity, respectively.
- $P.P = Q\Delta P$, where Q and ΔP are volumetric flow rate and pressure drop, respectively.
- $f = \frac{2\Delta P}{\rho u^2}.\frac{D_h}{L}$, where u and L refer to average flow velocity and length of the channel, respectively. Besides, ΔP, D_h and ρ are flow pressure drop, hydraulic diameter of flow passage and fluid density, respectively.
- $\eta_i = \frac{Nu}{f^{1/3}}$, where *Nu and f* are Nusselt number and friction factor, respectively.
- $\eta = \frac{(Nu/Nu_p)}{(f/f_p)}$ or $\eta = \frac{(Nu/Nu_p)}{(f/f_p)^{1/3}}$, where *Nu and f* are Nusselt number and friction factor, respectively. Note that in this equation, the subscript p refers to plain channel in the absence of thermal enhancement. It is noteworthy that the two presented forms of thermal enhancement factor (η) show the same concept of considering both thermal and hydraulic performance; however, in the second version, less emphasis is placed on hydraulic loss.

The detailed review of channel cooling thermal management concepts is presented in TABLE 1. the reviewed concepts include channel configuration modification, conductive insert immersion, obstruction introduction, flow vibration, use of structured surface, and coolant property enhancement. As discussed in this table, in the channel cooling concepts, the applied approaches are mainly targeting on disturbing boundary layer for the sake of thermal mixing enhancement in terms of temperature uniformity, heat transfer coefficient improvement and junction temperature decrease at minimized hydraulic cost in terms of pressure drop or pumping power. In the majority of the reviewed references, the enhancement methods lead to a rise of pressure drop. However, there are ideas with negligible pressure drop increase, and there is even an idea reducing pressure drop, which is the channel skin design. Finally, two-phase channel cooling which normally achieves higher thermal performance compared to single phase shows promising opportunities for further improvements.

III. HIGH PERFORMANCE IDEAS IMPLEMENTED IN PHASE TRANSITION – BASED HEAT SINK DESIGNS

A. INTRODUCTION TO PHASE TRANSITION COOLING

Solid-liquid and liquid-gas phase changes are the most widely-used phase transition-based designs in power electronics thermal management. For this, two main approaches are the utilization of phase change materials (PCM) and heat pipe assisted heat sinks. Thermal management by utilizing PCMs has been considered as a promising technique due to numerous desirable features including high heat storage density as a consequence of high latent heat of fusion for common PCMs, and being able to withstand a large number of cycles at relatively constant melting temperature. However, the main drawback of PCM-based thermal management is the low thermal conductivity of PCM materials. The other phase transition-based group of devices which benefit from the high effective thermal conductivity of heat pipes face some challenges in terms of heat transfer performance from heat pipe to device and regarding design compactness, which should be also complemented by innovative ideas. The main idea of heat pipe was proposed by Grover *et al.* [91]. Cotter [92] developed a basic theory that has been used since then as a basis for heat pipe design. Heat pipes make use of a liquid-gaseous phase change of a working fluid to transport heat from an evaporator to a condenser. Since the phase change takes place at a constant temperature, the device is capable of transferring heat for long distances with small temperature gradients. This makes them act as a "thermal superconductor" and an efficient alternative for thermal management of high-power-density electronic components. However, conventional heat pipes suffer from restrictions in thermal performance that are tried to be eradicated by the ideas discussed in this section. According to the mentioned plus and minus points for the abovementioned phase transition-based heat sink designs, heat transfer enhancement has become a hot topic in this field. In this section, the related innovative ideas employed to enhance these systems are reviewed. An overview is provided in FIGURE 3.

The characteristic parameters in PCM based thermal management devices are phase change time, operation time of electronic devices without exceeding critical temperature, melting fraction, heat source temperature, solid insert efficiency, input power, and the stored energy. On the other hand, filling ratio is one important parameter in heat pipe assisted devices, and it is defined as the ratio of working

TABLE 1. High performance heat transfer enhancement ideas utilized in channel cooling heat sink designs.

Method	Core idea	Main heat transfer mechanism	coolant	Nature of study	Major result	Quantitative results	Ref
Channel configuration modification	Achieving uniform flow distribution in multi-channel liquid cooled heat sink and as a result, uniform temperature distribution on the heated surface.	Laminar forced convection	De-ionized water	Numerical	The proposed novel channel configuration achieved uniform temperature distribution in the heat sink with minimized thermal resistance. Besides, pressure drop and pumping power are minimised due to the symmetrical flow distribution.	With P.P= 3×10^{-3}W as pumping power and an input heat flux of 41.5 kW/m^2, the thermal resistance and maximum temperature difference on the heating surface of the most desirable flow distributor configuration was one third of those obtained by conventional serpentine channel configuration.	[22]
Channel configuration topology optimization	Topology optimization is used to find the desired distribution and shape of solid structures inserted into the fluid in a mini-channel heat sink to achieve maximized thermal performance and minimized pressure drop by causing strong flow mixing effect, continuous boundary layer disruption and local high velocity areas.	Laminar forced convection	Air	Experimental and numerical	According to the enhanced flow mixing effect, local high velocity regions and continuous boundary layer disturbance, the topology optimized heat sink is able to achieve lower junction temperatures at the same pumping power in comparison with a common straight channel design.	The topology optimized heat sink proved to be capable of achieving 54.9% reduction in required pumping power while maintaining heat sink temperature at 44.5°C and heating power of 40W.	[23]
Channel inlet flow modification	Improve the flow maldistribution by utilizing non-uniform baffle array at the inlet of mini-channel heat sink cooling channels.	Laminar forced convection	Water	Numerical	The adopted method indicated good performance in achieving desired temperature distribution uniformity and low total thermal resistance. However, increased pressure drop is reported as a result of embedding non-uniform baffles at the inlet of channels.	The obtained results indicated that this method leads to uniform flow distribution causing reduction in total thermal resistance by 9.9 to 13.1%.	[24]
Using subchannels adjacent to hot spot area	Minimization of hot spot and non-uniform heat flux by increasing the heat extraction potential of the channel and dividing it into subchannels in hot spot areas.	Laminar forced convection	Water	Experimental and numerical	Uniformity of temperature distribution and reduced total thermal resistance are achieved. In addition, the maximum temperature is also reduced. However, these are obtained at the expense of increased pressure drop due to the flow recirculation at the inlet of the sub-channels and also due to the increased velocity in the sub-channels as a result of a reduction in channel cross section.	A 20% reduction in thermal resistance at 11% rise in pumping power was obtained.	[25]
Levelled channel branching	In order to achieve uniform cooling performance in liquid cooled heat sinks for chip thermal management, Y-shaped channel branching by constructal theory with 1-4 levels was proposed.	Natural and forced convection/ unspecified flow regime	Water	Numerical	Desirably uniform temperature distribution was achieved and peak temperature was reduced considerably by the proposed branched design. The advantage of this method is nearly negligible pressure loss by each level of branching.	The obtained results revealed that a significant decrease in peak temperature (28.8%) and average temperature (13.5%) of the liquid cooling-based heat sink was obtained at a negligible pressure drop increase (0.04 kPa by each branching level).	[26]
Micro-pin fin roughened wall	Copper micro pin fins are fabricated on the channel surface to achieve heat transfer enhancement as a result of flow mixing on the rear side of pins.	Laminar and turbulent forced convection	Air	Experimental	In the adopted micro sized pin fin array, the desirable fluid dynamics effect got stronger with the increase of pin diameter. Besides, it was reported that at fixed pin height and pitch-to-diameter-ratio but variable number of pins, with the decay in micro pin fin diameter, the pressure-drop increased as a result of increased friction area.	Promising heat transfer coefficient enhancement (maximum 79% over plain surface) was reported for the micro pin fin assisted heat sink design as a result of desirable flow mixing around the micro pin fins.	[27]

TABLE 1. ***(Continued).*** **High performance heat transfer enhancement ideas utilized in channel cooling heat sink designs.**

Method	Core idea	Main heat transfer mechanism	coolant	Nature of study	Major result	Quantitative results	Ref
Array of flow obstructions	Enforce the flow in micro channel heat sinks to split as a result of making the flow encounter an array of obstacles. This is done to avoid formation of fully developed boundary layer flow.	Laminar forced convection	Water	Numerical	The overall thermal performance considering both heat transfer and pressure drop effects showed desirable enhancement over the case in the absence of these obstacles.	Thermal performance factor (η) for the best case was reported to be approximately 1.6, which strongly justifies the implemented enhancement method by considering both thermal and hydraulic aspects.	[28]
Novel louvered microchannel heat sink controlling flow pulsation for the sake of heat transfer enhancement	The main idea was to utilize flow pulsation in microchannel in the presence of louver-like structures with specified geometrical parameters including pitch ratio in order to control and enhance thermal performance of cooling channel.	Laminar forced convection	Water	Numerical	The obtained results illustrate improved mixing between core and near wall flows as a result of contraction-expansion induced and controlled by the proposed louver structure. Consequently, the convective coefficient in the proposed structure was reported to be superior to ribbed and baffled microchannels at the same range of pressure loss.	The quantitative comparison between the proposed louvered design and conventional ribbed and baffled microchannels proved a maximum Nu ratio (averaged Nu divided by Nu number for fully developed laminar flow in parallel plates) of 6.16 in the range of friction factor ratios less than 50 (averaged friction factor divided by friction factor for fully developed laminar flow in parallel plates).	[29]
Insertion of structured metal foam	Y-shaped a structured copper foam was immersed in microchannel heat sink in order to benefit from both foam effect and enhanced mixing effect as a result of bifurcated Y shape.	Laminar forced convection	Water	Numerical	The microchannel with Y-shaped foam showed desirable thermal enhancement as a result of flow mixing. Porosity of metal foam showed insignificant effect on thermal performance and large effect on pressure drop.	In more details, the thermal resistance of microchannel heat sink in the presence of combined metal foam indicated 44% reduction compared to the case in the absence of metal foam at the same Reynolds number.	[30]
Insertion of additively manufactured porous structure	Inserting uniform and non-uniform additively-manufactured porous structures in working fluid in order to guide the flow toward heated surface and enhance heat transfer.	Forced convection-unspecified regime	Water	Experimental	Decrease in thermal resistance at reasonable pumping power is reported. The non-uniform porous structure showed better thermal performance and considerably lower pressure drop compared to the uniform structure.	In details, 26% and 67% reduction in thermal resistance were observed compared to homogeneous porous structure and chevron-type corrugation channel at 1W pumping power, respectively.	[31]
Insertion of additive manufactured lattice structure	The core idea was to immerse a new class of lattice structure with uniformly arranged lattice unit cells benefitting from high packing density with its orderly ligament arrangement in cooling channel to enhance conduction paths along with forced convection thermal and hydraulic performance.	Laminar forced convection	Water	Experimental and numerical	The thermal efficiency index containing both thermal and hydraulic performance at the same time showed superior performance of the printed lattice structure over aluminium foam and pin fin-based heat sinks. This was mainly attributed to the enhancement of effective thermal conductivity	The highest Nu of 906 with up to 5.5 times greater effective thermal conductivity compared to aluminium foam was obtained as a result of inserting the proposed lattice structure in coolant. Comparison in Re range of around 1700 to 5800 led to 2.8 to 3 times greater thermal efficiency index for lattice structure over pin fin based heat sink.	[32]
Channel skin modification by dimple structure	Dimpled structure with different geometrical parameters including aspect ratio, depth and spacing is used to modify microchannel skin in order to improve heat transfer.	Forced convection-laminar regime	Water	Numerical	Dimpled channel surface causes swirling flows and transverse convection which can be considered as the main reason of heat transfer enhancement. Besides, pressure drop is reported to decrease compared to smooth channel as a result of trapped flow in dimples where main channel flow is in contact with forward moving trapped flow which leads to reduced velocity gradient and pressure drop compared to smooth channels with flow in contact with solid surface.	Comparison between the proposed optimum dimpled channel with a flat channel case illustrated 3.2 K decrease in temperature, 15% increase in Nu number and 2% decrease in pressure loss.	[33]
Channel skin modification by shark skin bionic structure	Shark skin – inspired surface structure is adopted to reduce friction loss by reduction of shear	Forced convection-laminar regime	Water	Numerical	The proposed skin modifications push the main flow towards the side walls, and the sequential	The range of thermal performance factor was obtained between 1.1 to 3.1 which illustrated the	[34]

TABLE 1. ***(Continued).*** **High performance heat transfer enhancement ideas utilized in channel cooling heat sink designs.**

Method	Core idea	Main heat transfer mechanism	coolant	Nature of study	Major result	Quantitative results	Ref
	stress as a result of modifying velocity distribution/fluctuation. Besides, this structure can enhance thermal performance through the secondary flows by guiding a part of main flow to side walls, enhancing the secondary flow in channel.				contraction-expansion area of split passage enhance the fluid exchange. Besides, thermal performance and temperature uniformity as a result of secondary flows caused by the proposed structure are reported to be strongly dependent upon Reynolds number.	justification of channel skin design from thermo-hydraulic performance viewpoint.	
Flow-induced vibrations by self-actuated fluttering reed	The core idea was inspired from wind-instruments where the flow induced vibration of a "reed" generates sound. In fact, in this design, the reed installed in a channel subjected to heat from side walls in order to generate vortex structures. These vortices are formed and jetting of coolant toward hot walls takes place. As a result, temperature gradient and heat transfer are enhanced.	Forced convection-laminar regime	Air	Numerical	As a result of using self-actuated fluttering reed in the channel, efficient flow mix caused considerable enhancement in heat transfer at low pressure drop penalty. The low pressure loss is attributed to the fact that the "unused" high core flow momentum is extracted to generate reed fluctuations causing a better mixing of core/near wall flows.	In comparison with plain channel, the obtained results showed 30% higher heat transfer at constant flow rate. Besides, by considering both thermal and hydraulic performance aspects, the thermal performance factor was enhanced by 11%.	[35]
Flow-induced vibrations by reed-parametric study of system properties	The main idea was to find the suitable properties of flexible reed (inertia and bending stiffness) in convective heat transfer in channel flow subjected to heat flux in the presence of flow induced oscillating reed.	Forced convection-laminar regime	Air	Numerical	Thermal performance of the channel cooling system was more sensitive to the reed inertia rather than bending stiffness. Therefore, if mass properties of the reed are adjusted to achieve the proposed optimum mass ratio, operating in near maximum thermal performance would be fulfilled. Besides, thermal performance enhancement by vibrating reed is more dependent upon the large modulations created in the boundary layer as a result of interaction between the wake induced by the reed and channel walls. In contrast, the large circular vortices occupying a great part of the channel do not contribute so much to thermal performance enhancement	Quantitatively speaking, for a reed inertia of 1 as optimum point, a maximum thermal enhancement factor of 1.23 was obtained for the investigated range of parameters.	[36]
Bio-inspired self-agitator	Self-agitator inspired by blades of grass vibrating in the wind is proposed as the solution to achieve heat transfer enhancement. In fact, self-sustained vibration introduces strong vortices disturbing thermal boundary layer. For further enhancement, it is tried to match the frequency of structural motion to that of the dominant flow mode to cause resonance and enhanced fluid mixing.	Forced convection-laminar regime	Air	Experimental and numerical	As a result of resonance in flow mixing caused by self-agitator, considerable heat transfer improvement is achieved without additional pumping power requirement.	The experimental results revealed up to 200% enhancement in the heat transfer coefficient in comparison to the plain channel at the same Re number. At the same pumping power, this enhancement was reported as 120%.	[37]
Heat transfer fluid improvement by utilizing	Supercritical CO2 is used as the coolant in micro-channel heat sink for power electronics cooling.	Forced convection-laminar regime	Supercritical CO2	Numerical	The supercritical CO2 leads to better performance compared to conventional coolants such as water for	Maximum 30% thermal resistance reduction as a result of utilizing	[38]

TABLE 1. ***(Continued).*** **High performance heat transfer enhancement ideas utilized in channel cooling heat sink designs.**

Method	Core idea	Main heat transfer mechanism	coolant	Nature of study	Major result	Quantitative results	Ref
Supercritical CO2					certain range of inlet temperature. In fact, the use of supercritical CO2 as coolant for power electronic cooling at lower ambient temperature is recommended.	supercritical CO2 as coolant was reported.	
Heat transfer fluid improvement by utilizing hybrid nanofluid	Hybrid nanofluid was used with total volume fraction of 0.01% containing Al2O3 and multi-walled Carbon nanotube (MWCNT) with various mixing ratios in order to improve thermophysical properties of working fluid in minichannel heat sink to benefit from positive aspects of both Al2O3 nanoparticles (low cost, high accessibility, chemical firmness and desired heat transfer capability by considering pumping power) and MWCNT (high thermal conductivity and very high surface area).	Forced convection-laminar regime	Water Al2O3+MWCNT nanoparticles	Experimental	All hybrid nanofluids are superior to base fluid (with overall thermal performance factor above one) from thermal performance point of view by considering pressure loss effects. More importantly, the proposed hybrid nanofluid showed considerable heat transfer coefficient enhancement compared to available hybrid nanofluids. The thermal performance enhancement was mainly attributed to thermal conductivity enhancement and various slip mechanisms along with the effects of nano-fin and nano-porosity.	The hybrid nanofluid with Al2O3 plus MWCNT with a mixing ratio of 6:4 was reported as the best mixture from hydrothermal characteristics perspective. For this mixture, the maximum achieved heat transfer coefficient at the investigated flow rate was reported to be approximately 4200 W/(m2K). This was achieved at approximately 0.225 kPa pressure loss.	[39]
Stepped microchannel used to tackle the hydrothermal challenges in two phase channel cooling	The core idea was to use a stepped microchannel (narrow V-shaped at the bottom and wider converging channel on top) to compromise between the accelerating and frictional pressure drop to mitigate the fluctuations of pressure drop and wall temperature in order to reduce flow boiling instability.	Unspecified	Deionized water	Experimental	The obtained results showed that the combination of a narrow V channel at the bottom and wider converging channel at the top eradicated the hydrodynamic instability caused by upstream compressible volume by providing a larger area for flow passage in form of wider channel. Besides, heat transfer coefficient was observed to enhance due to increased surface area and better bubble removal capability for the proposed stepped design.	Quantitative results indicated up to 98% increase in heat transfer coefficient and 77% reduction in pressure drop as compared to conventional rectangular cross section microchannels.	[40]

fluid volume to the total volume of the miniature-loop heat pipe. In addition, condenser/evaporator temperature and their temperature difference along with evaporation, condensation and total thermal resistance form the other important parameters in heat pipe-assisted thermal management devices. These thermal resistance values are calculated as follows [48]:

- $R_{th_e} = \frac{T_e - T_a}{P_h}, R_{th_c} = \frac{T_a - T_c}{P_h} \quad and\ R_{th_t} = R_{th_e} + R_{th_c},$

Where $P_h, T_a, T_e\ and\ T_c$ are heat load and temperature at adiabatic section, evaporator and condenser, respectively.

Finally, the heat transferred by the heat pipe for calculation of heat transfer capacity by $Q_{transferred} \big/ Q_{input}$ is the other characteristic parameter.

The reviewed phase transition based thermal management concepts are provided in detail in TABLE 2. In the PCM based concepts, the conducted review shows that the main challenge is to deal with the weak thermal conductivity of phase change materials. This explains why a majority of works in this field are focused on the use of conductive inserts or other methods in order to improve the functionality of PCM based designs in minimizing and stabilizing maximum temperature of the target system. The heat pipe assisted thermal management devices reviewed in this article benefit from various ideas from modification of evaporator and condenser to modification of wick in order to enhance the thermal performance of heat pipes in terms of quick response, minimized thermal resistance and reliable operation.

IV. HIGH PERFORMANCE IDEAS IMPLEMENTED IN JET IMPINGEMENT – BASED HEAT SINK DESIGNS

A. INTRODUCTION TO JET IMPINGEMENT COOLING

The jet impingement technique has attracted the attention of thermal management designers in the past decade due to desirable features including higher local thermal absorption, potential of achieving more temperature uniformity, and suitability for hot-spot-targeted cooling design. However, impingement-based cooling designs suffer from

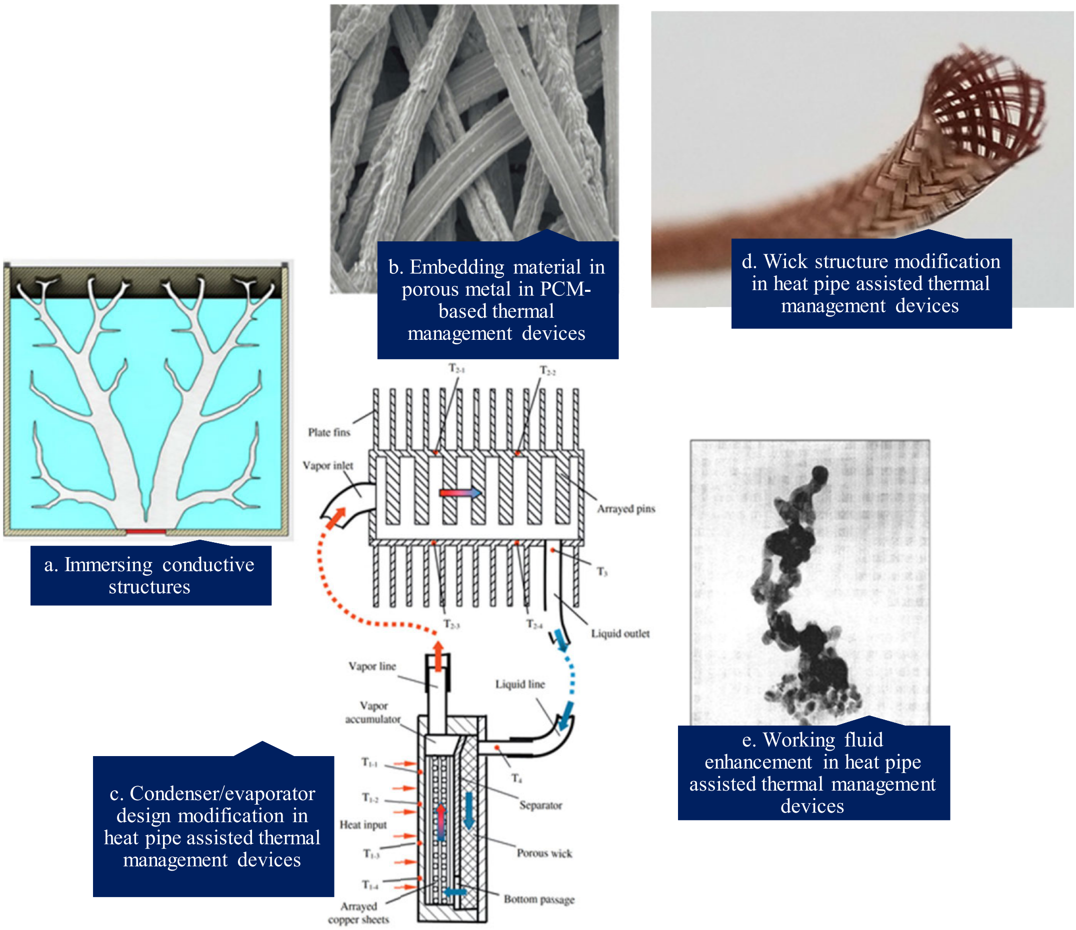


FIGURE 3. **Graphical review of papers containing high performance ideas for heat transfer enhancement in phase transition-based heat sinks: (a) reprinted with permission from [41]); (b) reprinted with permission from [43]; (c) reprinted with permission from [46]; (d) reprinted with permission from [48]; and (e) reprinted with permission from [52].**

various restrictions. Interferences between adjacent jets or interactions due to collision of surface flows, large size/weight of fluid delivery system, and the required pumping apparatus can be named as a few. In this section, the recent research items containing novel ideas for improving impingement-based heat sink designs for being integrated with power electronics are reviewed. The different enhancement techniques are mainly categorized in six groups including impingement configurations, immersed jet array, impinged area design, impingement manifold design, utilization of multiphase impingement cooling and additively manufactured impingement nozzles (see FIGURE 4).

The important parameters and response functions used for performance evaluation and design of impingement-based systems are jet dimensions, jet-to-wall distance, critical heat flux (two phase impingement cooling), surface superheat defined as the surface and saturation temperature difference (two phase cooling), steady state temperature, outlet temperature, maximum – minimum temperature difference, heat flux, coolant flow rate, Reynolds number, heat transfer coefficient (*Nu* and *h*), pressure drop, and pumping power. Besides, pressure coefficient in the following form is also used as another response function in this section among the reviewed references [57]:

$C_p = \frac{2(P_x - P_{atm})}{\rho u^2}$, where P_x, P_{atm}, ρ *and* u represent local static pressure on target surface, atmosphere pressure, coolant density and impingement velocity. Meanwhile, another performance evaluation criterion used in this field is overall performance as a balance between thermal and hydraulic considerations in the form of the area under the curve of thermal resistance as a function of pumping power [60].

A wide variety of methods are used as impingement design modifications in impingement based cooling concepts as reviewed in TABLE 3. The major ideas are those using various jet configurations for strong and uniform cooling performance, surface modification and coolant properties enhancement. The review shows that in general, jet impingement based cooling with potentially high number of cooling units is an efficient thermal management solution with a potentially low pressure drop. Meanwhile, the reviewed articles in this table also show that the manufacturing challenges of fluid delivery system for such designs are being tackled

TABLE 2. High performance heat transfer enhancement ideas utilized in phase transition-based heat sink designs.

Method	Core idea	Phase change process	coolant	Nature of study	Major result	Quantitative results	Ref
Immersing novel conductive structures in PCM-based heat sinks	The main idea was to immerse a novel branched conductive structure into low-conductivity PCM contained heat sink in order to improve heat transfer by optimizing the orientation/configuration of heat diffusion assisting branches and to minimize the volume fraction of the immersed body. Furthermore, it was the goal to maximize operation time for the cooling-targeted electronic device without violating critical temperature.	Solid-liquid	PCM (RT35)	Numerical	The proposed conductive structure showed high potential in enhancing heat sink performance in terms of critical temperature and inserted material minimization. Besides, the role of natural convection heat transfer mechanism on melting of PCM, which is the heat absorbing stage in the PCM-based heat sink was reported to be beneficial and crucial in the design procedure. However, it was illustrated that the increase of the metal volume fraction weakens the natural convection motion and restricts convective flow; therefore, minimization of the total solid mass by optimization of conductive structure was reported to be crucial.	The obtained results revealed that the safe operation time is increased from 61.6 s to 1339.7 s as a result of increasing metal volume fraction from 20% to 27.6% when considering 45 °C as critical temperature to define the safe operation. Besides, this efficiency of highly conductive solid insert in increasing safe operation time was observed to be more pronounced at low critical temperatures, which proves the opportunity of optimizing solid structure inserted in PCM based heat sinks for low critical temperature applications.	[41]
Using multiple PCMs in PCM-based heat sink	The core idea was to use multiple PCMs with different properties and melting temperatures to control the response of PCM-based heat sinks. For this, the effects of PCM arrangement, melting temperature and heat source intensity were examined.	Solid-liquid	PCM (RT47, RT50, RT52, RT 55 and RT58)	Experimental	The obtained results revealed that the arrangement of combined multiple PCM systems can significantly increase thermal regulation period and reduce the maximum temperature.	The obtained quantitative results illustrate that the two-PCM technique, with combination of RT50–RT55, causes 110 min and 130 min rise in safe operation time in comparison with the system containing just RT50 and RT55, respectively. Besides, this PCM combination of 2.0 W input power led to heat sink temperature reduction by 10.3 °C and 6.1°C compared to RT50 and RT55, respectively.	[42]
Filling PCM-based heat sink with porous metal fiber	The main idea was to embed PCM in a new porous metal matrix made of copper fibers with ample antler microstructures on the surface fabricated by cutting by multitooth tool in order to enhance heat dissipation in low-conductivity phase change material. The idea was to enhance heat dissipation due to the high thermal conductivity and large specific area of the insert.	Solid-liquid	PCM (RT55)	Experimental	The obtained results for a PCM-based heat sink in the presence of novel porous metal fibers subjected to a LED as heat source indicated significant heat transfer enhancement and decrease in heat source temperature. More interestingly, heat transfer enhancement was observed to be more pronounced under larger heat flux. This heat transfer enhancement is mainly attributed to high thermal conductivity and large specific area of the matrix.	With a critical temperature of 65 °C, both time averaged thermal resistance and safe operation time of PCM-based heat sink are increased as a result of using porous metal fiber in PCM. Under 8.54 W input power, this increase is from approximately 700 s (for Paraffin) to more than 1000 s (for PCM in the presence of metal fiber). In the same comparison, time averaged thermal resistance is reduced from 7.018 to 6.854 °C/W.	[43]
PCM with partially filled copper foam	The core idea was to use partially filled copper foam in low conductivity phase change material in order to benefit from effective thermal conductivity enhancement of PCM in the presence of foam at optimum weight/cost.	Solid-liquid	PCM (RT40)	Experimental	As a result of investigation of filling height ratio on thermal response of a PCM-based heat sink, performance enhancement was observed to be saturated when approaching the full-filling case. Consequently, it was concluded that partially filling strategy shows a promising behaviour for such systems benefitting from foam structure to achieve enhancement in effective thermal conductivity in the composite phase change material at minimized cost and weight.	It was observed that safe operation time was reduced by 25% from the full-filling case for the 15 ppi copper foam. Accordingly, partial filling of 2/3 was recommended for a balanced relation between the heat transfer enhancement gain and cost/weight penalty.	[44]

TABLE 2. ***(Continued.)*** **High performance heat transfer enhancement ideas utilized in phase transition-based heat sink designs.**

Method	Core idea	Phase change process	coolant	Nature of study	Major result	Quantitative results	Ref
PCM-based heat sink in the presence of fins with alternate air-PCM cavities	The core idea was simultaneous use of passive fin natural convection cooling and transient thermal management by PCM to enhance overall thermal management performance. This was done by investigation of different cases including a finned heat sink filled with PCM, partially filled with PCM in alternate pattern, and without PCM.	Solid-liquid	PCM (RT42)	Numerical	Different arrays of heat sinks including one with fin and without PCM, one filled with PCM and the one with alternate cavities air-PCM were investigated, and the results revealed that from the viewpoint of delaying the peak temperature and preserving temperature in low range for a long time, the alternate cavities air-PCM shows better performance compared to the other two cases.	The best case was reported in the presence of ten fins and five PCM cavities as a result of better switch between passive natural convection cooling by increased number of fins and transient thermal management by PCM cavities. This decreased junction temperature by 21%.	[45]
Miniature loop heat pipe-assisted heat sink with modified evaporator/condenser design	The main idea was to modify the design of the condenser and evaporator for the sake of heat transfer enhancement. For this, arrayed copper sheets are welded on a boiling chamber substrate in parallel to provide regular passages for vapour flow and to increase the heat transfer area. Besides, on condenser side, the heat dissipation capacity intensification is achieved by machining numerous arrayed pins on the upper wall of the condenser so that the vapour condensation area is increased, and the condensed vapour is able to flow along the pins to the bottom of the condenser quickly to reduce the heat transfer resistance.	Liquid-vapour	Absolute ethyl alcohol	Experimental	The obtained results revealed that optimal condenser structure led to efficient thermal management performance, reliable startup and continuous operation under variable power, and achieved quick dynamic response to abrupt change in heat load.	The obtained results indicated that the proposed miniature loop heat pipe is capable of keeping the object temperature below 100°C when subjected to 200W heat load.	[46]
Novel flat evaporator structure in heat pipe assisted thermal management device	The core idea was to utilize a ribbed plate for improvement of a large square flat evaporator in order to deal with the challenge of the large active zone caused by large flat structures of the heat pipes.	Liquid-vapour	R245fa	Experimental	As a result of utilizing a strengthened ribbed plate structure in evaporator, the large squared flat evaporator achieved normal and reliable operation, desirable temperature uniformity and high overall thermal performance.	The proposed design was reported to preserve the advantages of the flat structure, including temperature uniformity, where the difference between the monitoring points was less than 0.5 °C.	[47]
Designing ultrathin flattened heat pipe utilizing biporous spiral woven mesh wick	The main idea was to propose a hybrid biporous spiral woven mesh wick structure in the presence of large and small internal pores to achieve an ultrathin heat pipe suitable for high-power-density thermal management. The proposed hybrid structure for the wick enables benefiting from low flow resistance due to large pores and strong capillary forces due to the presence of small pores.	Liquid-vapour	Deionized water	Experimental	The hybrid biporous spiral woven mesh wick was reported to be successful in achieving enhanced thermal performance and high heat removal capacity with relatively low production costs.	It was reported that the optimal biporous wick had 22% fewer copper wires compared to mono-porous wick. Besides, 24 W was reported as the maximum heat transport capacity of the ultrathin flattened heat pipe.	[48]
Use of novel oxidized braided wires wick structure in ultra-thin heat pipe	The main idea was to propose oxidized composite wires wick structures for thermal performance enhancement of ultrathin flattened heat pipes so that the surface roughness of braided wires was increased as a result of oxidization, and as a result, the capillary force was increased leading to heat transfer improvement.	Liquid-vapour	Deionized water	Experimental	The obtained results proved that surface oxidization induced high roughness for the braided wires achieved stronger heat transfer for all types of braided wires. Besides, the core wire with a larger diameter provided low resistance for the returning flow, and the smaller exterior structure achieved larger capillary pressure at the liquid-vapour interface compared to the core structure.	In details, heat transfer capacity of more than 15 W was reported for oxidized mono and composite braided wire under horizontal operation. Besides, comparison between heat transfer capacity for mono and composite designs showed over 32.5% superiority of the composite design. Finally, the optimal filling loading ratio which was reported as a pivotal parameter achieved thermal resistance as low as 0.12 K/W with heat transfer capacity of 20 W.	[49]

TABLE 2. ***(Continued.)*** **High performance heat transfer enhancement ideas utilized in phase transition-based heat sink designs.**

Method	Core idea	Phase change process	coolant	Nature of study	Major result	Quantitative results	Ref
Bio wick material as wick structure in compact loop heat pipes	The core idea was to use a natural bio-carbon-based wick structure with high water-absorbing capacity to enhance loop heat pipe thermal performance at minimized cost. Besides, the biomaterial-based wick structure benefits from high availability, environmental friendliness, light weight and low cost features.	Liquid-vapour	Deionized water	Experimental	The obtained measurement results revealed reduction in thermal resistance and temperature difference between the evaporator and condenser. This was attributed to a combined capillary force produced by different sizes of pores enhancing wetting and capillary pumping of the working fluid. Besides, this advantage was accompanied by cost effectiveness, light weight, high capillarity and being environmentally friendly compared to metal-based wick structures.	Reduction in total thermal resistance (0.75 to 0.17 °C/W) was observed as a result of utilizing charcoal in compact loop heat pipe. Besides, evaporator temperature was reported to be kept in the range of 65 to 95 °C under input power ranging from 50 to 250 W. Accordingly, the heat pipe performance was reported to be suitable for electronic applications with junction temperature level lower than 100 °C.	[50]
Use of surface functional wicks in ultra-thin flat plate heat pipe assisted thermal management device	The core idea was to use surface functional wicks. The wick in this study benefits from orthogonal microgrooves. Besides, the groove surfaces were covered by grain-like microstructures. This is done to promote hydrophilicity for the sake of intensifying capillary performance of the wick.	Liquid-vapour	acetone	Experimental	The proposed novel ultrathin flat plate heat pipe, in the presence of surface functional wick structure to enhance capillary performance, proved to achieve rapid thermal response, favourable thermal performance at stable and minimized thermal resistance in the entire test range.	Quantitatively speaking, the proposed ultra-thin Aluminium flat plate heat pipe achieved a thermal resistance as low as 0.156 °C/W under 140 W input power due to the desired capillary performance of the surface-functional wicks.	[51]
Working fluid enhancement in heat pipe assisted thermal management device	Dispersion of highly conductive nanoparticles in the working fluid was the core idea of this work in order to benefit from thermal conductivity enhancement induced by the nanofluid. This was used to flatten the transverse temperature gradient of the fluid and to reduce the boiling limit because of the increasing effective liquid conductance in heat pipes. This is expected to lead to a decline in the heat pipe's thermal resistance.	Liquid-vapour	Deionized water with Silver nanoparticles	Experimental	The temperature distribution results for the heat pipe in the presence of nanofluid indicated considerable decline in thermal resistance in comparison with heat pipe with deionized water; and thermal resistance was reported to be decreased with the increase in nanoparticles volume fraction and diameter.	The maximum thermal resistance reduction of 80% and 50% over distilled water was obtained for nanoparticle sizes of 35nm and 10nm, respectively.	[52]

by the new trends in manufacturing technologies especially additive manufacturing which may facilitate novel impingement designs.

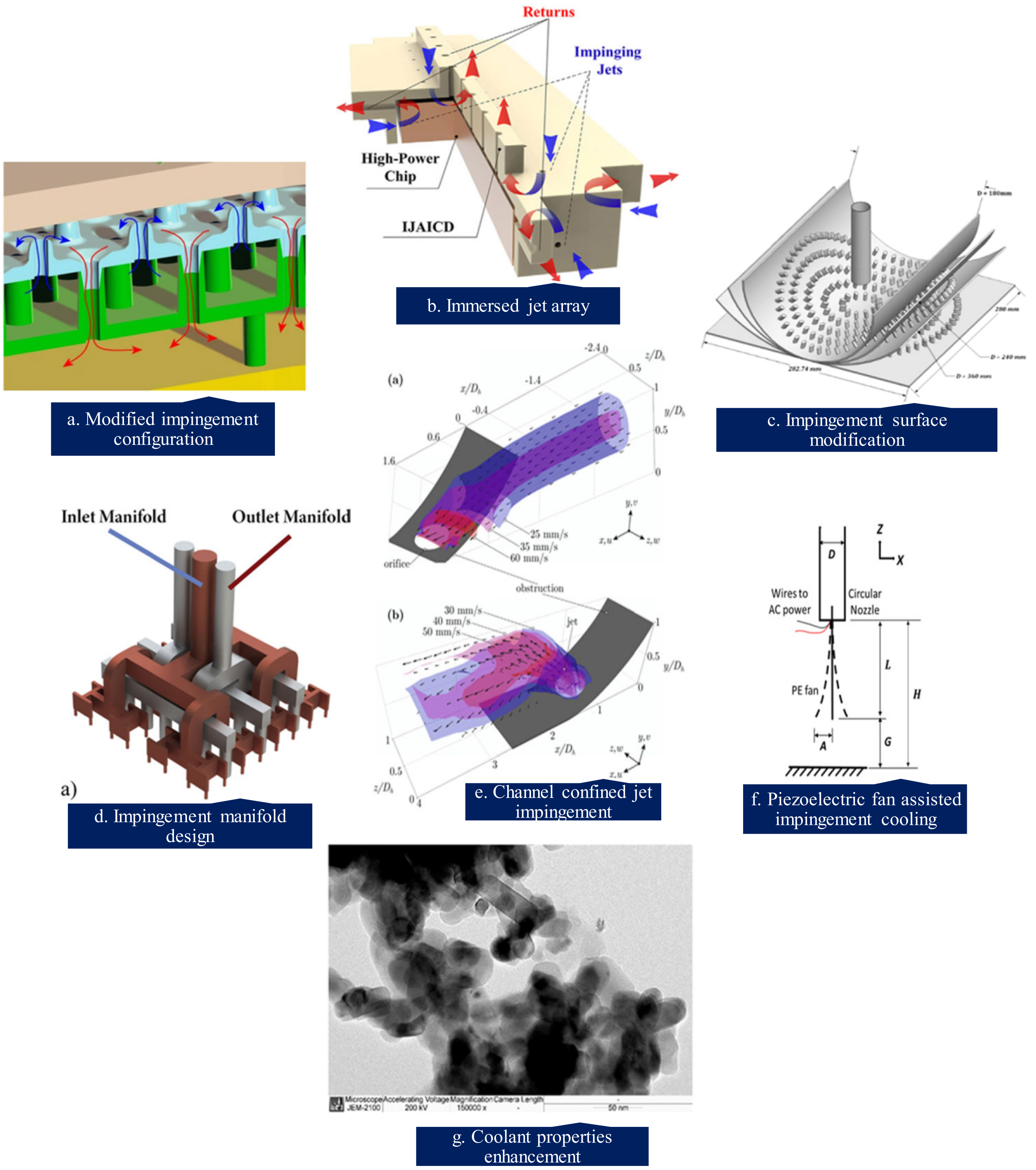
V. HIGH PERFORMANCE IDEAS IMPLEMENTED IN SPRAY COOLING – BASED HEAT SINK DESIGNS

A. INTRODUCTION TO SPRAY COOLING

Spray cooling is recognized as higher cooling capacity method compared to natural/forced convection cooling methods discussed earlier [84]. In this method, a liquid coolant is emitted from a pressurized nozzle and breaks up into droplets impinging the hot target surface. As a result of this impingement, droplets are turned into a thin liquid film which flows radially along the surface. Obviously, compared to the normal/tangential flow impingement-induced heat sink designs where coolant generates a thermally insulating liquid boundary layer and experiences undesirable temperature rise, in spray cooling the hot surface permanently receives fresh coolant droplets, leading to high cooling performance. In a relatively different spray cooling mechanism entitled electrospray cooling, electric potential is applied between liquid and target surface to produce the spray for evaporation heat removal. This technology benefits from several advantages over conventional spray cooling including lower required power to generate the spray compared to mechanical spray systems with high friction losses, and avoidance of droplet deceleration by drag force. This is achieved by droplet acceleration by an electrostatic force, leading to droplets impinging on the surface with higher velocities.

Investigation of spray cooling is categorized by approaches on the spray and droplet level. The former examines spray cooling performance from flow behaviour, surface conditions, fluid properties, nozzle array and similar viewpoints. However, in the droplet level analysis, the impact of droplet flow (single droplet or droplet burst) on the film flow (dry surface, stationary film, and flowing film) is analysed. Obviously, in the spray level examination approach, deep understanding of detailed heat transfer mechanisms (convection between hot surface and film flow, nucleate boiling on the hot surface, conduction in film flow, and interfacial evaporation from liquid film to surroundings) is missing unlike the droplet level [15]. The categories of enhancement ideas exploited in this field are illustrated in FIGURE 5 and a detailed description is provided in TABLE 4.

The important parameters and response functions in spray cooling devices can be named as follows: critical heat flux



a. Modified impingement configuration

b. Immersed jet array

c. Impingement surface modification

d. Impingement manifold design

e. Channel confined jet impingement

f. Piezoelectric fan assisted impingement cooling

g. Coolant properties enhancement

FIGURE 4. **Graphical review of papers containing high performance ideas for heat transfer enhancement in jet impingement-based heat sinks: (a) reprinted with permission from [54]; (b) reprinted with permission from [56]; (c) reprinted with permission from [58]; (d) reprinted with permission from [60]; (e) reprinted with permission from [62]; (f) reprinted with permission from [64]; (g) reprinted with permission from [65].**

(the peak average heat flux that is met once nucleation sites cover the heated surface completely), surface temperature and its non-uniformity, junction temperature, surface superheat as the difference between surface-temperature and saturation-temperature, heat transfer coefficient, averaged surface temperature, and thermal resistance. Besides, the difference between inlet pressure and back pressure of the spray nozzle is used for hydraulic cost description is some references. Finally, spray angle, droplet diameter, droplet velocity, and volume fraction along with surface tension can be named as the other important parameters in this class. In addition, a dimensionless number used in this category is known as Bond (Bo) number to evaluate the contribution of the capillary effect, which physically reflects the ratio of the gravitational force to the capillary force as $Bo = R\big/\sqrt{\gamma}\big/(\rho_l - \rho_V)\,g$, where R, γ, ρ_l, ρ_V, and g represent the radii of microcavities, the surface tension of coolant, the density of liquid coolant, the density of coolant gas and the gravitational constant, respectively.

TABLE 3. High performance heat transfer enhancement ideas utilized in jet impingement heat sink designs.

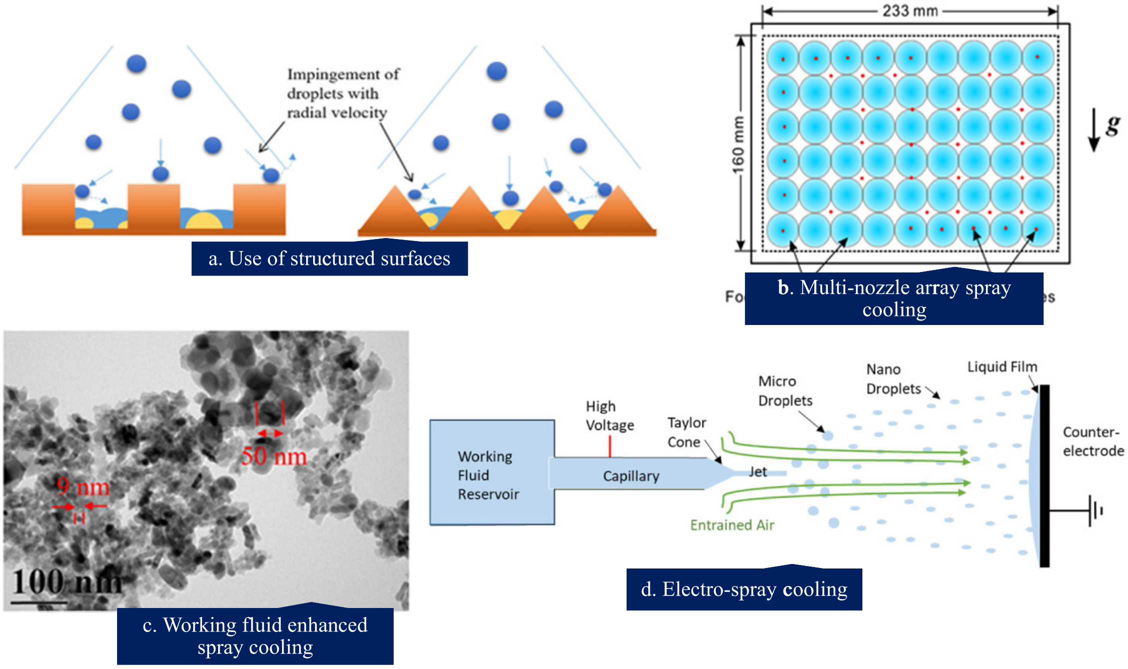
Method	Core idea	Heat transfer mechanism	coolant	Nature of study	Major result	Quantitative results	Ref
Direct liquid jet impingement	The main concept is focused on direct cooling by utilizing micro-water jets for hot spot removal and thermal resistance minimization.	Laminar and turbulent forced convection	Water	Experimental and numerical	The obtained results indicated great potential of direct micro jet liquid cooling with minimized flow travel path and compact designs. Besides, the design shows promising opportunity to reduce the coolant flow rate due to the achieved high heat transfer coefficients.	From compactness perspective, heat transfer coefficients up to 12000 W/(m^2K) were achieved in 10.8 cm^2assembly space in the case without electrical insulation. In the other case with electrical insulation, 6000 W/(m2K) was achieved at 30 ml/min as flow rate and 3 mW as pumping power.	[53]
Normal liquid jet impingement	The core idea was to impinge the coolant perpendicularly to the hot surface and to get rid of the coolant instantly before it accumulates large temperature gradients along large portions of the target device. For achieving this, an array of nozzles guides the coolant to the target surface. On the other hand, a corresponding number of outlet nozzles guides the coolant away before the coolant travels large distances on the hot surface.	Forced convection/unspecified flow regime	Ethylene - Glycol/water	Numerical	The idea led to simple, potentially low cost due to simplicity, low pressure loss and high thermal performance design. Besides, due to the use of high number of cooling cells, uniform cooling was the other achievement. The obtained results showed considerable enhancement in thermal performance of the proposed design compared to pin fin heat sink.	The obtained thermal performance examinations showed maximum heat transfer coefficients higher than 10000 (W/m2K) for the proposed design and 30-40% superiority over conventional pin-fin based heat sink under the same conditions.	[54]
Additively manufactured nozzles for jet impingement	Additively manufactured polymer jet coolers were used to impinge air flow onto heat source. The main advantage of additive manufacturing for producing nozzles was reported for compact designs by consolidating flow delivery system, distributer and nozzle. Besides, it was facilitated to produce complex and lightweight cooling designs for high-power-density systems.	Forced convection/unspecified flow regime	Air	Experimental and numerical	The obtained results showed cooling performance comparable with common materials and manufacturing methods but with greater manufacturing flexibility and compactness opportunity.	Heat flux dissipation of 58.4 W/cm2, cooling rate of 6.6 °C/s, and convective coefficient up to 17000 W/(m2·K)) were achieved with the mentioned manufacturing flexibility and compactness.	[55]
Direct impingement immersed jet cooling	In this liquid cooling design, the chip was immersed in the coolant, and the coolant impinges all surfaces of the chip. In order to prevent the interference between neighbouring jets, distributed array of outlets were designed.	Forced convection/unspecified flow regime	Deionized-water	Experimental and numerical	The proposed immersed jet impingement was reported as a suitable design for high-power-density applications mainly due to the fact that it was able to use all of the heat dissipating area of the chip.	Results indicated an average temperature of 78.7 °C for the high-power chip with input heat flux of 1.6×10^6 W/m^2 in the presence of 2000 ml/min as maximum flow rate and 41377 W/$m^2\cdot$K as maximum achieved heat transfer coefficient.	[56]
Impingement area design-cone shaped surface	The impingement region was modified for the sake of thermal performance enhancement. For this, a conical protuberance was used in impingement area instead of flat plate.	Turbulent forced convection	Water	Numerical	The heat transfer coefficient was enhanced in the case where conical protuberance was present in the impingement area compared to a flat impingement region. In fact, when there is a conical structure, two stagnation regions were formed. The first one was observed in the apex where the jet meets the surface for the first time, and the second one was in the conical edge region where an inclined jet (secondary jet) was formed. In this secondary jet area, a horseshoe vortex was generated and led to desirable flow mixing and heat transfer improvement.	Maximum increase of 13.6% in thermal performance for the modified surface over flat plate was reported at Re=23,000 and a cone angle of 60°	[57]

TABLE 3. ***(Continued.)*** **High performance heat transfer enhancement ideas utilized in jet impingement heat sink designs.**

Method	Core idea	Heat transfer mechanism	coolant	Nature of study	Major result	Quantitative results	Ref
Impingement on concave surface covered with pin fins	The core idea was to combine two main ideas including a concave target surface and surface design in order to intensify the effect of jet impingement in the cooling performance. In fact, the concave target surface with different curvatures was subjected to heat flux in the presence of a circular pattern of elliptical pin fins.	Turbulent forced convection	Air	Experimental and numerical	It was revealed that the presence of pin fins can significantly improve cooling performance. This was attributed to two main reasons. The first was the formation of horseshoe vortices at the leading edge of pins, and the second one was attributed to the elliptical profile of the pins. This was reported to minimize the effect of dead area due to the strong recirculation in the downstream of the pins. Besides, the efficiency of pin fins in heat transfer enhancement was reported to be more pronounced at higher relative curvature of the concave target surface.	The quantitative results illustrated 51, 53 and 59% increase in averaged Nu number for Re numbers 23000, 35000 and 55000, respectively, in the presence of a pin finned concave surface at constant curvature as the target of jet impingement cooling.	[58]
Micro structured target surfaces in two phase impingement cooling	The main idea was to enhance two phase impingement cooling performance by enhanced surfaces with circular, hydrofoil, and square micro pin fins with area increase and nucleate boiling enhancement.	Single phase convection and two phase boiling	R134a	Experimental	Flow boiling jet impingement on micro pin fins displayed large heat transfer coefficients. Moreover, a smoother transition from single-phase to two-phase boiling was achieved which led to the suppression of temperature overshoots and boiling hysteresis observed in the case of smooth surfaces.	Quantitative results indicated heat transfer coefficients up to 15×10^4W/m2 K at a relatively low velocity of 2.2 m/s in the presence of the large (D = 125 lm) circular micro pin fins.	[59]
Fractal manifold for microjet liquid cooling	A fractal manifold design with high number of nozzles was used to provide impingement cooling with desired thermal performance while achieving a compromise with pressure loss and pumping power by adjusting the manifold parameters.	Laminar forced convection	Water	Numerical	The manifold design showed desirable flexibility in achieving balance between heat transfer and hydraulic performance by adjusting the manifold parameters, especially the number of nozzles. In fact, thermal resistance reduction and pressure loss minimization were achieved by higher number of nozzles due to uniform cooling performance.	Up to 35% thermal resistance reduction at maximum pressure drop of approximately 0.14 kPa was obtained for a fractal flow pattern with 64 channels.	[60]
Impingement pattern modification in microtube heat sink-tangential injection	The core idea was to use tangential injection in order to benefit from swirl-flow induced high mixing in addition to impingement features in order to improve heat transfer in channel-based cooling heat sink designs.	Forced convection/laminar flow regime	Water	Numerical	Results indicated a decrease in peak temperature and achievement of uniform cooling as a result of swirl-flow enhanced mixing by utilizing tangential impingement. Besides, this swirl mixing was reported to cause efficient mixing at desirably high flow rates.	According to the obtained results, at 0.003 W pumping power, the maximum temperature is reduced by adopting the jet impingement microtube compared to conventional heat sinks (T = 311.13 K vs. T = 324.14 K). Moreover, a temperature difference of 7.8 K and 19.2 K along the heated surface was reported for the impingement design and classic microtube, respectively.	[61]
Channel confined jet by orifice plate obstruction	The main idea was to provide a low profile jet impingement inside a channel to achieve compact and hot-spot-targeted cooling at low Reynolds numbers by immersing curved orifice in the channel to cause the desired inclined and confined impingement in the cooling channel.	Laminar forced convection	Water	Experimental	Successful impingement caused by the unconventional obstruction led to considerable enhancement in the convective coefficient which proves the high potential of immersing such obstructions in channel cooling to cause impingement in compact designs.	The results showed desirable inclined jet impingement toward the hot spot which led to a maximum 495% enhancement in average convective coefficient at Re=498.	[62]

TABLE 3. ***(Continued.)*** **High performance heat transfer enhancement ideas utilized in jet impingement heat sink designs.**

Method	Core idea	Heat transfer mechanism	coolant	Nature of study	Major result	Quantitative results	Ref
Carbon dioxide dry-ice assisted jet impingement cooling	Carbon dioxide jet flow is utilized in impingement-based cooling. When CO2 passes through jet nozzle, it goes through a rapid temperature and pressure drop, which leads to dry CO2 ice particles formation (Joule-Thomson effect). This effect was used to enhance heat transfer by utilizing the concept of solid-gas two phase impingement cooling. In addition to carbon dioxide, Nitrogen was used as single-phase impingement cooling to provide a comparison in order to clarify the role of two-phase impingement cooling.	Forced convection/unspecified flow regime	CO2 and N2	Experimental	As a result of utilizing the idea of CO2 dry ice assisted impingement cooling, heat transfer enhancement was reported due to two main reasons. The first was reported as reduction in coolant bulk temperature as a result of dry ice particle formation. The second reason was considered as the sublimation effect between hot surface and dry-ice particles.	At around Re= 45000, the CO2 solid-gas two-phase jet caused 8.1°C lower stagnation temperature than that of single-phase N2 jet which was mainly attributed to coolant bulk temperature reduction and sublimation heat transfer between dry ice particles and hot surface.	[63]
Jet impingement cooling enhanced by piezoelectric fan	In order to increase the turbulent kinetic energy in the circular jet in impingement-based cooling design, an active method using a piezoelectric fan was applied. The fan was driven at its resonance frequency where it oscillates with maximized amplitude.	Turbulent forced convection	Air	Experimental	The measurement results illustrated an improved heat transfer coefficient and also a widened cooling region for the case in the presence of a fan actuator compared to a circular jet without actuator. This was mainly attributed to intensified turbulent kinetic energy by the fan oscillations.	Based on the obtained results, 10-20% enhancement of averaged heat transfer coefficient was observed for Re numbers in the range of 10000-18000.	[64]



a. Use of structured surfaces
b. Multi-nozzle array spray cooling
c. Working fluid enhanced spray cooling
d. Electro-spray cooling

FIGURE 5. **Graphical review of papers containing high performance ideas for heat transfer enhancement in spray cooling-based thermal management designs: (a) reprinted with permission from [66]; (b) reprinted with permission from [69]; (c) reprinted with permission from [70], (d) reprinted with permission from [72].**

Aside from all of the plus points in thermal performance of spray cooling-based thermal management devices, there are undeniable challenges restricting overall performance of these systems including significant pumping power required to provide large pressure drops for the nozzles to produce the desired fine spray. Clearly, thermal performance enhancement methods are required to deal with the challenges to enhance the overall performance of such systems and reduce

TABLE 4. High performance heat transfer enhancement ideas utilized in spray cooling thermal management designs.

Method	Core idea	Droplet or spray level	coolant	Nature of study	Major result	Quantitative results	Ref
Surface modification induced heat transfer enhancement in spray cooling thermal management device	Pyramid/square macrostructures and nanopores were used as surface modification to enhance heat transfer in spray-based cooling. It was expected that macrostructures improve heat transfer by increasing the wetted area.	Spray level	R410A	Experimental	The pyramid surface structure led to better heat transfer performance although it had smaller wetted area compared to square structure. Therefore, shape of surface modification was found to be an important parameter. Besides, it was observed that due to the increase in the number of nucleation sites and wettability, the nanoporous surface structure led to enhanced heat transfer. Moreover, it was observed that in the nanoporous case heat flux experienced a decrease and then increase with pore size, which is mainly attributed to a transition between an evaporation-limited to a viscosity-limited regime.	The major quantitative results illustrated enhanced thermal performance for the case with rough pyramid fins compared to the case of a flat surface. In fact, the achieved critical heat flux and heat transfer coefficient were $3.3\times 10^6\ W/m^2$ and $3\times 10^5\ W/m^2K$. These are reported to be 1.6 and 5 times greater than those obtained by the smooth flat surface.	[66]
Multi-scale surface structure for heat transfer enhancement in spray cooling device	Multi-scale surface structures including microscale indentations and protrusions along with macroscale pin fins with different shapes are used to enhance heat transfer in a spray cooling device by considering different scales.	Spray level	ammonia	Experimental	Compared to a smooth surface, the structured surface achieved a significant increase in heat transfer coefficient which is mainly related to surface area augmentation and stronger role of boiling through surface nucleation in addition to free-surface evaporation and secondary nucleation.	The quantitative results showed 7.72×10^5 W/(m^2°C) at $5\times 10^6\ W/m^2$ input flux which corresponds to 161% increase in heat transfer coefficient by multiscale structured surfaces over the reference surface.	[67]
Structured microcavity surfaces used for heat transfer enhancement tool in spray cooling device	The core idea was the utilization of a structured surface benefitting from microcavities in order to increase the capillary effect and nucleate boiling mechanism as a result.	Spray level	ammonia	Experimental	The use of microcavities on the surface in spray cooling led to improved heat transfer and temperature uniformity. More importantly, the extent of heat transfer enhancement was observed to be dependent upon the predominant heat transfer mechanism in each case. In fact, thermal performance enhancement in the case of low surface superheats where single-phase convection is the main mechanism was insignificant. While considerable enhancement was observed for the case of high surface superheats where nucleate boiling is the predominant heat transfer mechanism.	The obtained results showed a maximum heat transfer coefficient of 148245 W/(m^{2}K) at a heat flux of 4.51×10^6 W/m^2 for a microcavity surface. This was attributed to the enhanced capillary effect. On the other hand, from temperature uniformity point of view, temperature distribution with deviation below 1.5°C was reported when subjected to 4.2×10^6 W/m^2 input flux.	[68]
Multi-nozzle spray cooling array as thermal management solution for being integrated with high power-large area source	The main idea was to use multi-nozzle spray cooling in order to enable the use of closed-loop spray cooling systems that naturally require large volume in the drainage region in order to efficiently remove the excessive liquid and the produced vapour during spray cooling. So a large volume system is proposed with the purpose of maximization of vaporization of sprayed coolant to avoid accumulation of liquid. And obviously, the multi-nozzle array spray cooling can be parallelized to deal large areas.	Spray level	R134a	Experimental	The obtained results indicated that the proposed multi-nozzle spray cooling device provides high heat transfer coefficients at high liquid usage fraction before the incidence of critical heat flux. Besides, it was reported that heat transfer coefficient and temperature uniformity are strongly dependent upon nozzle flow rate and pressure drop. Moreover, it was reported that from the viewpoint of nozzle array geometrical parameters, the distance of a location relative to the outlets add a more pronounced effect on the local surface temperature compared to spray-to-spray interactions.	The obtained measurement results indicated heat transfer coefficients as high as 2.81×10^4 W/(m^{2}K) but at high nozzle pressure drop (0.42 MPa).	[69]
Working fluid enhancement in spray cooling based thermal management device by utilizing nanofluid	Seven different types of nanofluids in the presence of nanoparticles or carbon nanotubes are used instead of conventional coolants in order to inspect heat transfer enhancement in spray cooling from the viewpoint of coolant improvement.	Spray level	Deionized water and Ag, Al, Al2O3, Fe3O4, SiO2, TiO2 nanoparticles and multi-walled carbon nanotubes	Experimental	They reported significant improvement in the average heat transfer coefficient and the critical heat flux as a result of utilizing nanofluids compared to base fluid spray cooling. This improvement was observed for both nucleate boiling and critical heat flux for all nanofluids.	The obtained results indicated considerable increase over distilled water for averaged heat transfer coefficient and critical heat flux by 1.7 and 1.84 times, respectively, if nanoparticles volume fraction increases from 0.04% to 0.1. Besides, Al2O3 showed superior performance at volume fraction of 0.1 vol% up to 3.75×10^6 W/m^2. This was attributed to the small size of nanoparticles and surface tension.	[70]

TABLE 4. ***(Continued.)*** **High performance heat transfer enhancement ideas utilized in spray cooling thermal management designs.**

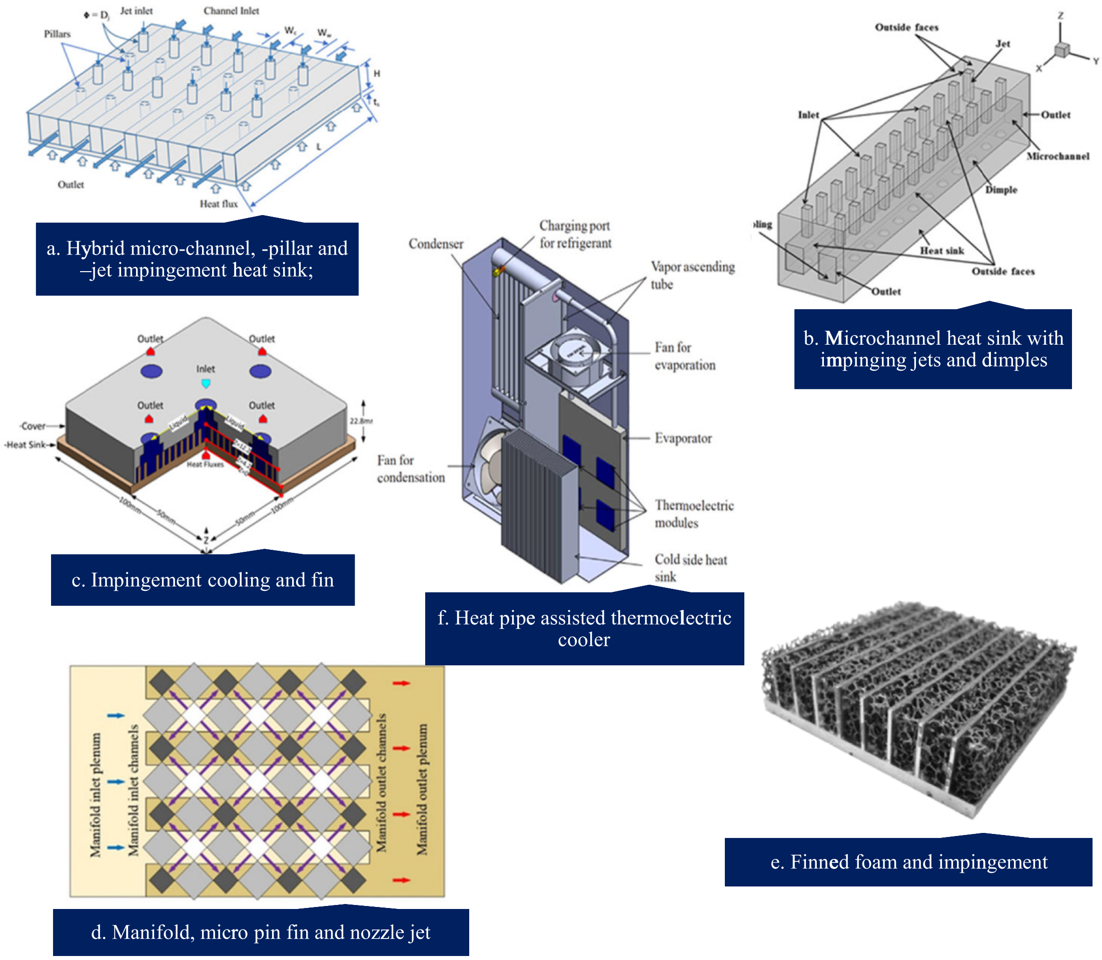
Method	Core idea	Droplet or spray level	coolant	Nature of study	Major result	Quantitative results	Ref
Working fluid enhancement in spray cooling based thermal management device by utilizing low-alcohol additives	The main idea was to add different types of alcohol to the base fluid in spray cooling device and observe the response in droplet level analysis.	Droplet level	Water and ethanol/n-propanol/iso-propanol	Experimental	They reported that with the addition of even small amounts of all proposed alcohols to water, faster evaporation and higher bubble growth rate were observed. Besides, it was indicated that surface tension and contact angle were decreased as a result of adding alcohol to water; and consequently, the heat transfer rate was enhanced because of improved wettability.	The obtained results showed a heat transfer coefficient of 2.02×10^4 W/(m^{2}K) under an input heat flux of 1.0×10^6 W/m^2 in the presence of 4% volume fraction ethanol in water. This was equivalent to approximately 36.5% enhancement in comparison with pure water.	[71]
Electrospray phase change cooling with entrained air streaming	The core idea was to use a high momentum electrospray jet with entrained air flow to impinge high velocity droplets to the target surface and to benefit from enhanced mass transfer for evaporation by making use of surrounding air entrainment.	Spray level	Methanol	Experimental and numerical	It was observed that the jet was successful in thinning the films and reducing conduction resistance in the film in addition to minimizing mass transfer resistance by surrounding air entrainment by spray jet. This caused high evaporation rates and heat removal leading to enhanced heat transfer and low surface temperatures.	Under the maximum heat load, 245 W/cm^2 was dissipated at 99.5°C as average surface temperature.	[72]
Microspray-based thermal management device for cooling of LED	The core idea was to use a piezo-electric micropump in order to propose a high performance microspray cooling based thermal management device	Droplet level	Deionized water	Experimental	The performance of the proposed system in the non-boiling regime was analysed, and the results revealed that the proposed microspray cooling system using piezo-electric micropumping led to minimized thermal resistance and a high average heat transfer coefficient.	The obtained results illustrated 9375 W/(m^2°C) as maximum average heat transfer coefficient and 2 °C/W as minimum thermal resistance for a single spray.	[73]
Spray cooling in the presence of dual synthetic jet actuator and piezoelectric atomizer	The main idea was to minimize the weaknesses of spray cooling designs such as narrow impacting area by utilizing dual synthetic jet and piezoelectric atomizer with high capability of flow manipulation. A piezoelectric synthetic jet actuator was used as a flow control for increased cooling efficiency and rapid response. This can be achieved due to several effects including increase of droplet velocity, control of impact area, and change of the uniformity of droplets.	Droplet level	Water	Experimental and numerical	By having the opportunity of flow manipulation, spray angle and impingement area are under control. A uniform and wider distribution of droplets on the surface led to heat transfer enhancement as a consequence of rising evaporation efficiency of the liquid film.	The proposed spray cooling with dual synthetic jet actuator integrated with a piezoelectric atomizer indicated enhanced cooling capability from 44 °C in conventional spray cooling to 36 °C. Besides, from the viewpoint of temperature uniformity, it achieved 18 °C deviation compared to 32 °C. Finally, direct impacting range is reported to be increased from (−30 mm, 25 mm) to (−60 mm, 57 mm).	[74]

total cost in terms of pumping power. For this, several methods are used. TABLE 4 contains the core concepts and major results of spray cooling designs for thermal management. This technology is generally known for its high cooling performance due to the mentioned features which have made it suitable for high power density applications. As illustrated in this table, the major design modifications in this category are the use of structured surfaces, nozzle array modifications and coolant property enhancements. However, the motivation for adopting such approaches in spray cooling is different from the single phase cooling designs since these modifications can also alter wettability and nucleation sites in addition to a surface area increase for the sake of thermal transport enhancement. The review shows that spray cooling is an attractive technology for high performance cooling, but still there are crucial challenges to be addressed for ensuring reliable operation.

VI. HIGH PERFORMANCE IDEAS IMPLEMENTED IN HYBRID HEAT SINK DESIGNS

A. INTRODUCTION TO HYBRID COOLING DESIGNS

In this section, the designs benefiting from two or more heat transfer improvement techniques known as hybrid designs are reviewed. The research items in this section utilize combinations and synergies of jet impingement, solid insert, mini-microchannel array, surface modifications, phase transition and thermoelectric coolers (see FIGURE 6 and TABLE 5). The characteristic parameters in the reviewed hybrid designs are jet dimensions, jet-to-wall distance (for impingement contained designs), volume fraction of nanoparticles (for nanofluid contained systems), thermoelectric cold and hot side temperatures, fin dimensions, flow rate, Reynolds number, heat transfer coefficients, pressure drop and pumping power, hot spot temperature, maximum temperature rise (difference between maximum and



a. Hybrid micro-channel, -pillar and –jet impingement heat sink;

b. Microchannel heat sink with impinging jets and dimples

c. Impingement cooling and fin

f. Heat pipe assisted thermoelectric cooler

e. Finned foam and impingement

d. Manifold, micro pin fin and nozzle jet

FIGURE 6. **Graphical review of papers containing high performance ideas for heat transfer enhancement in hybrid designs: (a) reprinted with permission from [75]; (b) reprinted with permission from [78]; (c) reprinted with permission from [79]; (d) reprinted with permission from [81]; (e) reprinted with permission from [82]; (f) reprinted with permission from [83].**

minimum substrate temperature). Besides, overall performance is defined as $(h/\Delta P)$ and thermal conductance is defined as $(q/(\bar{T}_s - T_{inflow}))$ where q, $\bar{T}_s$ and T_{inflow} are input heat flux, averaged surface temperature and coolant inflow temperature respectively.

The hybrid thermal management ideas along with the key ideas and major results are discussed in detail in TABLE 5. The table contains the designs combining at least two concepts among jet impingement, fin insertion, microchannel, structured surface, thermally enhanced coolant, foam insertion, phase transition and thermoelectric cooler. The review of the hybrid designs indicates that in the majority of the proposed designs, the combination of ideas leads to a higher thermal performance in comparison with either of the individual ideas. However, in some designs, this combination is shown to require further considerations in order to avoid side effects caused by the interactions between different individual concepts.

VII. QUANTITATIVE COMPARISON BETWEEN THE THERMAL MANAGEMENT CATEGORIES

In order to provide a fair comparison between the cooling performance of the reviewed ideas in this paper including channel cooling, spray cooling, impingement cooling, hybrid designs and phase transition based designs, the effective thermal conductance is adopted as the quantitative criterion as follows [77]:

- $\alpha_{eff} = \frac{q}{\Delta T}[Wm^{-2}K^{-1}]$, Where q and ΔT represent heat flux and temperature difference.

In channel cooling, impingement and hybrid cooling, the temperature difference between inflow and hot spot is used. In spray cooling, it is calculated as the difference between surface temperature and saturation temperature. Finally, in heat pipe thermal management devices as the candidate of phase transition-based cooling, it is defined as the temperature difference between evaporator and condenser. The comparison is provided in FIGURE 7. The diameter of the circles in this figure is proportional to the required pumping power except for the phase transition-based cases (No. 11 and 12), where no pumping power is required.

As illustrated this figure, the operating range of channel cooling and impingement cooling ideas shows the possibility of achieving desired performance with comparably low pumping power. However, the effective thermal performance is lower for these cases compared to other categories

TABLE 5. High performance heat transfer enhancement ideas utilized in hybrid heat sink designs.

Method	Core idea	Heat transfer mechanism	coolant	Nature of study	Major result	Quantitative results	Ref
Hybrid design-micro-jet slot array, micro-pin fin array and drainage micro-trenches	The hybrid heat sink design consisted of three main layers including pin fin, jet slot-drainage trenches and inlet/outlet channels. By this combination, firstly, the coolant impinges the heated wall. Then this spent flow extracts heat from pin fin. Finally, heat is delivered to outside when heated coolant flows through nearby trenches.	Forced convection/unspecified flow regime	Water	Numerical	As a result of combining the cooling techniques to form multi-layer hybrid design, the design achieved high heat removal efficiency at low flow rate and pumping energy.	The thermal resistance of 1.3×10^{-3} m^2°C/W is obtained at a flow rate of 0.5 l/min and 0.8 kPa pressure loss, and this resistance can be further reduced by 40% by increasing the flow rate to 1 l/min which leads to 2.4 kPa pressure drop. Besides, desirably uniform cooling performance was also fulfilled by the design. In fact, the surface temperature variation rate at the bottom heating area which is the ratio between the maximum temperature difference and the spatially averaged temperature is <3% at a flow rate of 0.5 l/min.	[75]
Hybrid heat sink containing microchannel, pillar and jet impingement	This hybrid design consists of micro-jet impingement and cylindrical micro-pillars on the target surface located at the middle of a micro-channel. Flow from nozzles impinge the hot surface. Besides, the channel flow guides this wall jet flow toward the outlet. When this flow reaches pillars, it is disturbed and flow vortices enhancing heat transfer are formed.	Laminar forced convection	Water	Numerical	For the hybrid design, high thermal performance enhancement was observed. However, it was found that the interaction of different individual cooling concepts has to be considered as a design priority in hybrid approach. In fact, on the one hand, introducing channel flow in the jet impingement cooling design increases the overall flow rate. Consequently, it reduces liquid caloric thermal resistance. On the other hand, the channel flow suppresses thermal performance and increases thermal resistance by its sweeping effect which reduces the stagnation effect of jet impingement and thickens the wall jet.	As a result of this combination, a high heat transfer coefficient of more than 1.5×10^3 W/(m^2K) was obtained by the proposed hybrid design. The pumping power in the order of 0.0008W was obtained at Re=200 for a mass flow of 8.63×10^{-5} kg/s.	[76]
Hybrid heat sink design with integrating micro-jet, microchannel and fin array	Additive manufacturing is used to design a complex high performance heat sink benefiting from positive features of microjets and microchannels that can achieve higher performance compared to either of the individual methods. The design is called 'FINJET' since the jet nozzles also serve as hollow fins. In fact, fluid is forced through the center of each fin in order to direct jet impingement on top of the heat source. Then the flow is passed from the jets into a microchannel system. Due to the beneficial features of microchannels, especially the high surface-to-volume-ratio along with high fin efficiency, good thermal performance was expected.	Laminar forced convection	Water	Experimental and numerical	The combination proved that the hybrid design benefits from features of microjets and microchannels. It achieved higher performance compared to either of the individual methods in terms of thermal conductance and pressure drop cost which makes it suitable to be integrated with high performance applications.	They reported a heat transfer coefficient of 296×10^3 W/(m^2K) at 160 kPa pressure loss and 0.5 l/min flow rate.	[77]

TABLE 5. ***(Continued.)*** **High performance heat transfer enhancement ideas utilized in hybrid heat sink designs.**

Method	**Core idea**	**Heat transfer mechanism**	**coolant**	**Nature of study**	**Major result**	**Quantitative results**	**Ref**
Hybrid heat sink combining jet impingement, microchannels and dimpled surface modification	The core idea is to benefit from desirable flow and heat transfer behaviour of impingement (compared to parallel flow) along with microchannel arrays in the presence of dimpled surfaces. Especially convex dimples are able to break the pre-existing boundary layer and cause turbulence without forming considerable dead area that hinders heat transport. Besides, the other motivation is the reduced flow resistance at high flow rates in the case of using convex dimple structure which is achieved since dimples function as stream guidance.	Laminar forced convection	Water	Numerical	Major results prove that as a result of combining impinging jets instead of parallel flow with microchannels in the presence of convex dimples, desirable boundary layer disturbance and heat transfer enhancement is achieved at reduced pressure drop. Besides, comparison between concave, convex and mixed dimples illustrates superior thermal performance of the convex type.	In details, heat transfer coefficients up to 3.75× 10^4 W/(m^2K) at a mass flow rate of 30 g/s and approximately 80 kPa as pressure drop were reported.	[78]
Hybrid heat sink with impingement, nanofluid and fin	The main idea was to combine liquid jet impingement and different fin configurations, and also to improve thermal performance of coolant by dispersing solid nanoparticles in water.	Turbulent forced convection	Water and water-TiO_2 nanofluid	Experimental and numerical	The combination of the mentioned elements led to desirable performance and minimized thermal resistance for high heat flux applications. However, implementation of different fin configurations illustrated some important considerations including scrubbing effect of flow in contact with different fin geometries that have to be taken into account in designing such cases benefitting from jet impingement with fin inserts.	The quantitative results showed thermal resistance of approximately 0.03 ℃/W at Re=26800 with a cooling area of 40mm×40mm subjected to 150W input power.	[79]
Hybrid cold plate design-slot jet and minichannel	Slot jet and minichannel are combined to form a hybrid cold plate. A manifold channel flow is used to achieve flow and heat transfer uniformity as the main purpose. For this, the manifold system distributes coolant into different power modules. Besides, this manifold separates the heat sink into segments to avoid the coolant flow travelling long path and experiencing undesirable temperature increase.	Laminar forced convection	Water/Ethylene Glycol	Numerical	As a result of combining slot jet with channel flow, uniform thermal performance with at reasonable pressure drop was achieved which was mainly attributed to the mentioned flow division.	Maximum to minimum base temperature difference of approximately 3 K at a heat transfer coefficient of 3.4× 10^4 W/(m^2K) and a pressure loss of 9.36 kPa was reported.	[80]
Hybrid heat sink design-manifold, nozzle jet and micro pin fin	The main idea was to utilize a novel flow distribution structure in the heat sink which is inspired by the chessboard. In fact, each inlet nozzle is surrounded by four outlet nozzles and vice versa. The combination of manifold inlet/outlet channels above nozzles, and using a micro pin fin structure underneath, leads to desirable flow distribution and disturbance, and as a result, desired heat transfer performance.	Laminar forced convection	Water	Numerical	As a result of combining manifold channel, nozzle jet and micro-pin fin ideas, desirable flow distribution and thermal performance are fulfilled. In fact, the temperature nonuniformity of the heating surface is reported to be low. The novel heat sink proved to be able to take advantage of both uniform flow distribution and ultra-high heat flux cooling.	The obtained results showed total thermal resistance of 9.37×10^{-6} m^2K/W and temperature non-uniformity of 2.33 K under input heat flux of 7×10^6 W/m^2 at 4.928 kPa pressure drop.	[81]

TABLE 5. ***(Continued.)*** **High performance heat transfer enhancement ideas utilized in hybrid heat sink designs.**

Method	Core idea	Heat transfer mechanism	coolant	Nature of study	Major result	Quantitative results	Ref
Hybrid heat sink design-reinforced copper foam with inserted fins subjected to flow impingement	The combined use of slot jet impingement, fin and foam element in heat sink was proposed for an efficient hybrid design. The core idea was to benefit from positive features of coolant impingement (strong flow mixing and thin boundary layer), foam insertion (large heat exchange area) and overcoming the restriction of heat conductivity in the foamed design by reinforcing it with plate fins.	Forced convection/ unspecified flow regime	Air	Experimental	Thermal performance enhancement of finned foam was fulfilled due to the large heat exchange area but at high flow resistance. Therefore, it was recommended to use such structures in compact thermal management designs where pumping power is not the main design consideration.	In fact, in this study, finned foam heat sinks showed 10–20 times greater pressure loss compared to finned heat sinks. Therefore, this combination was recommended for compact heat exchanger designs where pumping power is not so crucial.	[82]
Hybrid thermal management design-heat pipe assisted thermoelectric cooler	The core idea was to use a compact thermoelectric based cooling design by removing its thermal restrictions due to high thermal resistance on its hot side by attaching a gravity assisted heat pipe on this side.	Forced convection/ unspecified flow regime	Air	Experimental and numerical	The results revealed that the integration of a gravity assisted heat pipe was able to improve the cooling capacity of a thermoelectric cooler and at the same time preserving its desirable thermal and vibration-free operation features. On the one hand, an airflow rate increase at condenser side led to enhanced cooling performance. But this enhancement was reported to be restricted to high ambient air temperature. On the other hand, the cooling capacity was increased by air flow rate increase on evaporator side, but again it was restricted by the thermoelectric cold side temperature.	The measurements illustrated a significant increase in cooling capacity (64.8%) as a result of using a gravity assisted heat pipe.	[83]

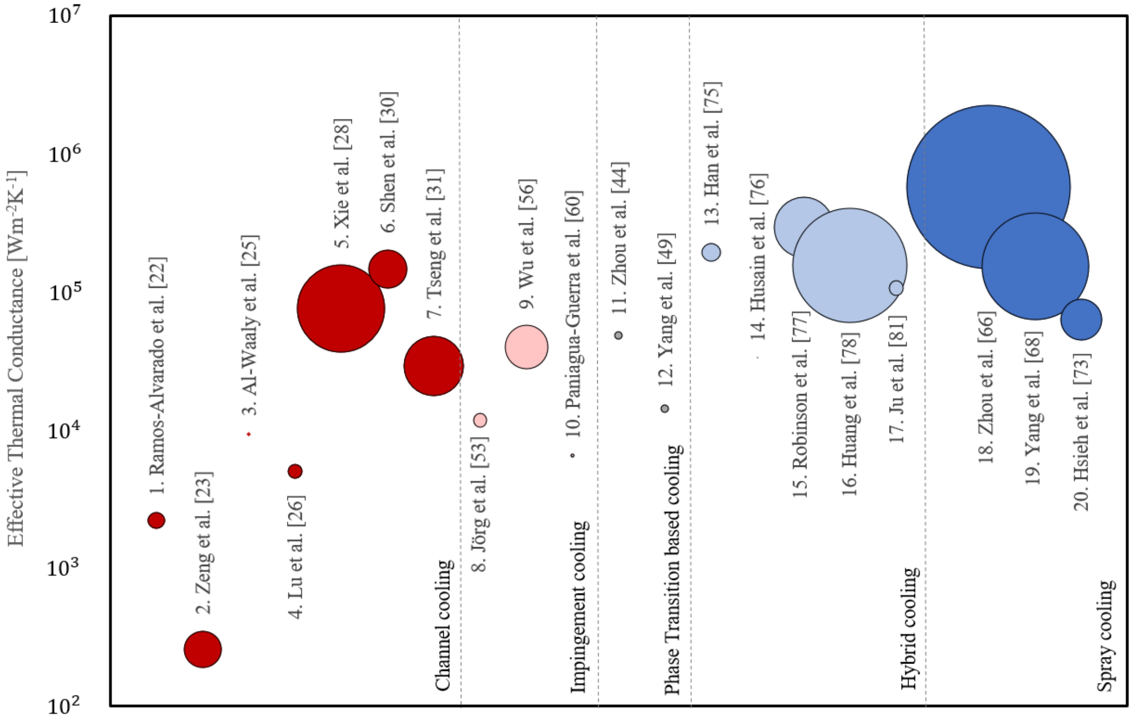


FIGURE 7. Effective thermal conductance versus pumping power for the papers reviewed in the categories provided in FIGURE 1 (diameters are proportional to pumping power (W) except for No. 11 and 12).

especially spray cooling. This can be mainly attributed to the nature of single-phase channel cooling and impingement cooling benefitting only from sensible heat absorption unlike the spray cooling or two-phase channel cooling designs.

Another reason is that the majority of channel cooling ideas available in literature are based on the laminar flow regime, and only a minority of research items has provided analysis on turbulence enhanced designs to benefit from increased momentum/energy exchange due to turbulence nature. On the other hand, the impressive effective thermal performance of spray cooling ideas is normally accompanied by high pumping power. In fact, it is known that in spray cooling cases, the crucial challenge is to keep the system working safely and reliably under high pressure differences in the order of MPa between the inlet pressure and back pressure for a long time. In addition, it is inferred that a combination of different cooling ideas and wise layout of hybrid designs can fulfil high thermal performance at affordable pumping power as achieved in case No. 13 and 15. Finally, the impingement and phase transition-based concepts indicate an overall thermal performance of the same order but at different power demands. Therefore, choosing among these methods should be based on the specific priorities of the target system.

VIII. CONCLUSION AND RECOMMENDATIONS

A review on high performance concepts used for improving heat transfer mechanisms involved in power electronics thermal management was provided in this paper. The main motivation was to give a comprehensive overview on the available thermal management ideas and potentially inspiring new ones and combinations of them. For this, a categorization covering the commonly-used heat sink designs was presented. In the categories, channel cooling in various scales, impingement cooling, phase transition-based designs, spray cooling and hybrid designs were presented. Following this, a detailed description of the core of each idea was provided. Finally, a quantitative comparison was given for a representative sample of the reviewed concepts from the viewpoint of thermal and hydraulic overall performance.

Based on the conducted study, the following items are proposed as future research recommendations.

- Turbulence-enhanced channel cooling forms a tiny minority of designs in this category. However, the upcoming manufacturing technologies enabling complicated structures for novel mixing devices, and allowing a balance between enhanced thermal performance and increased hydraulic loss are promising opportunities for adopting this approach.
- The employed heat transfer enhancement methods in spray cooling such as surface modification indicate considerable heat transfer enhancement and a great potential for power electronics thermal management, but there are still crucial challenges such as safe and reliable operation under high pressure difference between the high and low pressure sides of the nozzles. Meanwhile, in spite of the high cooling capacity at the maximum power operation point, keeping the hot spot temperature stable at real transient working conditions has to be considered in spray analysis. More works on miniaturization attempts, for instance driven by piezo actuation-based pumping, are needed in order to enable ultra-compact designs also with spray cooling concepts.
- In heat pipe-assisted cooling devices, the effective thermal conductivity and thermal performance are desirably high. But still some ideas seem to have crucial shortcomings that necessitate further studies. For instance, ultra-thin flattened heat pipes indicate impressive thermal performance, but there are still drawbacks such as decreased thermal performance under miniaturization constraints which necessitate a decrease of thickness. More research is to be done by reconsidering the inner structure of this type of heat pipes to address such serious issues while preserving the positive thermal aspects.
- Impingement cooling with low pressure drop and hot-spot targeted cooling ability was shown to be promising for achieving compact designs by adopting approaches such as channel–confined jets. However, the generation of the impingement jets in such configurations by common methods such as orifice plate obstructions can be costly from the hydraulic performance viewpoint. Fulfilling compactness at minimized hydraulic loss is recommended as a topic of further study.
- According to the illustrated high potential of hybrid designs in achieving high thermal performance at acceptable hydraulic loss, it seems promising to find an optimum combination of the individual cooling concepts by considering the synergies between individual methods.

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REFERENCES

[1] Z. Ling, Z. Zhang, G. Shi, X. Fang, L. Wang, X. Gao, Y. Fang, T. Xu, S. Wang, and X. Liu, ''Review on thermal management systems using phase change materials for electronic components, Li-ion batteries and photovoltaic modules,'' *Renew. Sustain. Energy Rev.*, vol. 31, pp. 427–438, Mar. 2014, doi: 10.1016/j.rser.2013.12.017.

[2] F. P. McCluskey, T. Podlesak, and R. Grzybowski, *High Temperature Electronics*. Boca Raton, FL, USA: CRC Press, 2018.

[3] M. J. Huang, P. C. Eames, B. Norton, and N. J. Hewitt, ''Natural convection in an internally finned phase change material heat sink for the thermal management of photovoltaics,'' *Sol. Energy Mater. Sol. Cells*, vol. 95, no. 7, pp. 1598–1603, Jul. 2011, doi: 10.1016/j.solmat.2011.01.008.

[4] J. Hansson, C. Zanden, L. Ye, and J. Liu, "Review of current progress of thermal interface materials for electronics thermal management applications," in *Proc. IEEE 16th Int. Conf. Nanotechnol. (IEEE-NANO)*, Aug. 2016, pp. 371–374, doi: 10.1109/NANO.2016.7751383.

[5] S. Pua, K. Ong, K. Lai, and M. Naghavi, "Natural and forced convection heat transfer coefficients of various finned heat sinks for miniature electronic systems," *Proc. Inst. Mech. Eng., A, J. Power Energy*, vol. 233, no. 2, pp. 249–261, Mar. 2019, doi: 10.1177/0957650918784420.

[6] E. Ozturk and I. Tari, "Forced air cooling of CPUs with heat sinks: A numerical study," *IEEE Trans. Compon. Packag. Technol.*, vol. 31, no. 3, pp. 650–660, Sep. 2008, doi: 10.1109/TCAPT.2008.2001840.

[7] E. Baker, "Liquid cooling of microelectronic devices by free and forced convection," *Microelectron. Rel.*, vol. 11, no. 2, pp. 213–222, 1972, doi: 10.1016/0026-2714(72)90704-4.

[8] D. Chen, J. Jiang, G.-H. Kim, C. Yang, and A. Pesaran, "Comparison of different cooling methods for lithium ion battery cells," *Appl. Thermal Eng.*, vol. 94, pp. 846–854, Feb. 2016, doi: 10.1016/j.applthermaleng.2015.10.015.

[9] M. Arik and A. Bar-Cohen, "Immersion cooling of high heat flux microelectronics with dielectric liquids," in *Proc. 4th Int. Symp. Adv. Packag. Mater. Process., Properties Interfaces*, 1998, pp. 229–247, doi: 10.1109/ISAPM.1998.664464.

[10] T. L. Bergman, F. P. Incropera, D. P. DeWitt, and A. S. Lavine, *Fundamentals of Heat and Mass Transfer*. Hoboken, NJ, USA: Wiley, 2011.

[11] W. Duangthongsuk and S. Wongwises, "An experimental investigation on the heat transfer and pressure drop characteristics of nanofluid flowing in microchannel heat sink with multiple zigzag flow channel structures," *Exp. Thermal Fluid Sci.*, vol. 87, pp. 30–39, Oct. 2017.

[12] N. H. Naqiuddin, L. H. Saw, M. C. Yew, F. Yusof, T. C. Ng, and M. K. Yew, "Overview of micro-channel design for high heat flux application," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 901–914, Feb. 2018, doi: 10.1016/j.rser.2017.09.110.

[13] P. Naphon and S. Wongwises, "Investigation on the jet liquid impingement heat transfer for the central processing unit of personal computers," *Int. Commun. Heat Mass Transf.*, vol. 37, no. 7, pp. 822–826, Aug. 2010, doi: 10.1016/j.icheatmasstransfer.2010.05.004.

[14] P. Smakulski and S. Pietrowicz, "A review of the capabilities of high heat flux removal by porous materials, microchannels and spray cooling techniques," *Appl. Thermal Eng.*, vol. 104, pp. 636–646, Jul. 2016, doi: 10.1016/j.applthermaleng.2016.05.096.

[15] X. Gao and R. Li, "Spray impingement cooling: The state of the art," in *Advanced Cooling Technologies and Applications*. London, U.K.: IntechOpen, 2018.

[16] M. I. Hasan and H. L. Tbena, "Using of phase change materials to enhance the thermal performance of micro channel heat sink," *Eng. Sci. Technol., Int. J.*, vol. 21, no. 3, pp. 517–526, Jun. 2018, doi: 10.1016/j.jestch.2018.03.017.

[17] A. N. Desai, A. Gunjal, and V. K. Singh, "Numerical investigations of fin efficacy for phase change material (PCM) based thermal control module," *Int. J. Heat Mass Transf.*, vol. 147, Feb. 2020, Art. no. 118855, doi: 10.1016/j.ijheatmasstransfer.2019.118855.

[18] X.-H. Yang, S.-C. Tan, Y.-J. Ding, L. Wang, J. Liu, and Y.-X. Zhou, "Experimental and numerical investigation of low melting point metal based PCM heat sink with internal fins," *Int. Commun. Heat Mass Transf.*, vol. 87, pp. 118–124, Oct. 2017, doi: 10.1016/j.icheatmasstransfer.2017.07.001.

[19] A. A. El-Nasr and S. M. El-Haggar, "Effective thermal conductivity of heat pipes," *Heat Mass Transf.*, vol. 32, nos. 1–2, pp. 97–101, Nov. 1996, doi: 10.1007/s002310050097.

[20] C. J. Lasance and R. E. Simons, "Advances in high-performance cooling for electronics," *Electron. Cooling*, vol. 11, no. 4, pp. 22–39, 2005.

[21] S. M. S. Murshed and C. A. N. de Castro, "A critical review of traditional and emerging techniques and fluids for electronics cooling," *Renew. Sustain. Energy Rev.*, vol. 78, pp. 821–833, Oct. 2017.

[22] B. Ramos-Alvarado, P. Li, H. Liu, and A. Hernandez-Guerrero, "CFD study of liquid-cooled heat sinks with microchannel flow field configurations for electronics, fuel cells, and concentrated solar cells," *Appl. Thermal Eng.*, vol. 31, nos. 14–15, pp. 2494–2507, Oct. 2011, doi: 10.1016/j.applthermaleng.2011.04.015.

[23] S. Zeng, B. Kanargi, and P. S. Lee, "Experimental and numerical investigation of a mini channel forced air heat sink designed by topology optimization," *Int. J. Heat Mass Transf.*, vol. 121, pp. 663–679, Jun. 2018, doi: 10.1016/j.ijheatmasstransfer.2018.01.039.

[24] X. Liu and J. Yu, "Numerical study on performances of mini-channel heat sinks with non-uniform inlets," *Appl. Thermal Eng.*, vol. 93, pp. 856–864, Jan. 2016, doi: 10.1016/j.applthermaleng.2015.09.032.

[25] A. A. Y. Al-Waaly, M. C. Paul, and P. Dobson, "Liquid cooling of non-uniform heat flux of a chip circuit by subchannels," *Appl. Thermal Eng.*, vol. 115, pp. 558–574, Mar. 2017, doi: 10.1016/j.applthermaleng.2016.12.061.

[26] Z. Lu, K. Zhang, J. Liu, and F. Li, "Effect of branching level on the performance of constructal theory based Y-shaped liquid cooling heat sink," *Appl. Thermal Eng.*, vol. 168, Mar. 2020, Art. no. 114824.

[27] T. Yeom, T. Simon, T. Zhang, M. Zhang, M. North, and T. Cui, "Enhanced heat transfer of heat sink channels with micro pin fin roughened walls," *Int. J. Heat Mass Transf.*, vol. 92, pp. 617–627, Jan. 2016, doi: 10.1016/j.ijheatmasstransfer.2015.09.014.

[28] G. Xie, Y. Li, F. Zhang, and B. Sundén, "Analysis of microchannel heat sinks with rectangular-shaped flow obstructions," *Numer. Heat Transf., A, Appl.*, vol. 69, no. 4, pp. 335–351, Feb. 2016, doi: 10.1080/10407782.2015.1080580.

[29] C.-S. Wang, T.-C. Wei, P.-Y. Shen, and T.-M. Liou, "Lattice Boltzmann study of flow pulsation on heat transfer augmentation in a louvered microchannel heat sink," *Int. J. Heat Mass Transf.*, vol. 148, Feb. 2020, Art. no. 119139, doi: 10.1016/j.ijheatmasstransfer.2019.119139.

[30] B. Shen, H. Yan, B. Sunden, H. Xue, and G. Xie, "Forced convection and heat transfer of water-cooled microchannel heat sinks with various structured metal foams," *Int. J. Heat Mass Transf.*, vol. 113, pp. 1043–1053, Oct. 2017, doi: 10.1016/j.ijheatmasstransfer.2017.06.004.

[31] P.-H. Tseng, K.-T. Tsai, A.-L. Chen, and C.-C. Wang, "Performance of novel liquid-cooled porous heat sink via 3-D laser additive manufacturing," *Int. J. Heat Mass Transf.*, vol. 137, pp. 558–564, Jul. 2019, doi: 10.1016/j.ijheatmasstransfer.2019.03.116.

[32] J. Y. Ho, K. C. Leong, and T. N. Wong, "Experimental and numerical investigation of forced convection heat transfer in porous lattice structures produced by selective laser melting," *Int. J. Thermal Sci.*, vol. 137, pp. 276–287, Mar. 2019, doi: 10.1016/j.ijthermalsci.2018.11.022.

[33] M. Xu, H. Lu, L. Gong, J. C. Chai, and X. Duan, "Parametric numerical study of the flow and heat transfer in microchannel with dimples," *Int. Commun. Heat Mass Transf.*, vol. 76, pp. 348–357, Aug. 2016, doi: 10.1016/j.icheatmasstransfer.2016.06.002.

[34] P. Li, D. Guo, and X. Huang, "Heat transfer enhancement, entropy generation and temperature uniformity analyses of shark-skin bionic modified microchannel heat sink," *Int. J. Heat Mass Transf.*, vol. 146, Jan. 2020, Art. no. 118846, doi: 10.1016/j.ijheatmasstransfer.2019.118846.

[35] A. Rips, K. Shoele, A. Glezer, and R. Mittal, "Efficient electronic cooling via flow-induced vibrations," in *Proc. 33rd Thermal Meas., Modeling Manage. Symp. (SEMI-THERM)*, 2017, pp. 36–39.

[36] K. Shoele and R. Mittal, "Computational study of flow-induced vibration of a reed in a channel and effect on convective heat transfer," *Phys. Fluids*, vol. 26, no. 12, pp. 1–25, 2014, doi: 10.1063/1.4903793.

[37] Z. Li, X. Xu, K. Li, Y. Chen, Z. Ke, S. Wang, H.-H. Chen, G. Huang, C.-L. Chen, and C.-H. Chen, "Bio-inspired self-agitator for convective heat transfer enhancement," *Appl. Phys. Lett.*, vol. 113, no. 11, Sep. 2018, Art. no. 113703.

[38] J. Sarkar, "Improving thermal performance of micro-channel electronic heat sink using supercritical CO_2 as coolant," *Thermal Sci.*, vol. 23, no. 1, pp. 243–253, 2019.

[39] V. Kumar and J. Sarkar, "Experimental hydrothermal behavior of hybrid nanofluid for various particle ratios and comparison with other fluids in minichannel heat sink," *Int. Commun. Heat Mass Transf.*, vol. 110, Jan. 2020, Art. no. 104397, doi: 10.1016/j.icheatmasstransfer.2019.104397.

[40] S. Raj, A. Shukla, M. Pathak, and M. K. Khan, "A novel stepped microchannel for performance enhancement in flow boiling," *Int. J. Heat Mass Transf.*, vol. 144, Dec. 2019, Art. no. 118611, doi: 10.1016/j.ijheatmasstransfer.2019.118611.

[41] J. Xie, K. F. Choo, J. Xiang, and H. M. Lee, "Characterization of natural convection in a PCM-based heat sink with novel conductive structures," *Int. Commun. Heat Mass Transf.*, vol. 108, Nov. 2019, Art. no. 104306, doi: 10.1016/j.icheatmasstransfer.2019.104306.

[42] I. Al Siyabi, S. Khanna, T. Mallick, and S. Sundaram, "Multiple phase change material (PCM) configuration for PCM-based heat sinks—An experimental study," *Energies*, vol. 11, no. 7, p. 1629, Jun. 2018.

[43] H. Wang, F. Wang, Z. Li, Y. Tang, B. Yu, and W. Yuan, "Experimental investigation on the thermal performance of a heat sink filled with porous metal fiber sintered felt/paraffin composite phase change material," *Appl. Energy*, vol. 176, pp. 221–232, Aug. 2016, doi: 10.1016/j.apenergy.2016.05.050.

[44] Z.-Q. Zhu, Y.-K. Huang, N. Hu, Y. Zeng, and L.-W. Fan, "Transient performance of a PCM-based heat sink with a partially filled metal foam: Effects of the filling height ratio," *Appl. Thermal Eng.*, vol. 128, pp. 966–972, Jan. 2018, doi: 10.1016/j.applthermaleng.2017.09.047.

[45] S. B. Salah and M. B. B. Hamida, "Alternate PCM with air cavities in LED heat sink for transient thermal management," *Int. J. Numer. Methods Heat Fluid Flow*, vol. 29, no. 11, pp. 4377–4393, Nov. 2019.

[46] Z.-P. Wan, X.-W. Wang, and Y. Tang, "Condenser design optimization and operation characteristics of a novel miniature loop heat pipe," *Energy Convers. Manage.*, vol. 64, pp. 35–42, Dec. 2012, doi: 10.1016/j.enconman.2012.06.004.

[47] S. He, J. Zhao, Z.-C. Liu, W. Tian, J.-G. Yang, and W. Liu, "Experimental investigation of loop heat pipe with a large squared evaporator for cooling electronics," *Appl. Thermal Eng.*, vol. 144, pp. 383–391, Nov. 2018, doi: 10.1016/j.applthermaleng.2018.08.075.

[48] W. Zhou, Y. Li, Z. Chen, L. Deng, and Y. Gan, "A novel ultra-thin flattened heat pipe with biporous spiral woven mesh wick for cooling electronic devices," *Energy Convers. Manage.*, vol. 180, pp. 769–783, Jan. 2019.

[49] K.-S. Yang, C.-W. Tu, W.-H. Zhang, C.-T. Yeh, and C.-C. Wang, "A novel oxidized composite braided wires wick structure applicable for ultra-thin flattened heat pipes," *Int. Commun. Heat Mass Transf.*, vol. 88, pp. 84–90, Nov. 2017, doi: 10.1016/j.icheatmasstransfer.2017.08.014.

[50] A. B. Solomon, A. K. Mahto, R. C. Joy, A. A. Rajan, D. A. Jayprakash, A. Dixit, and A. Sahay, "Application of bio-wick in compact loop heat pipe," *Appl. Thermal Eng.*, vol. 169, Mar. 2020, Art. no. 114927, doi: 10.1016/j.applthermaleng.2020.114927.

[51] G. Chen, Y. Tang, Z. Wan, G. Zhong, H. Tang, and J. Zeng, "Heat transfer characteristic of an ultra-thin flat plate heat pipe with surface-functional wicks for cooling electronics," *Int. Commun. Heat Mass Transf.*, vol. 100, pp. 12–19, Jan. 2019, doi: 10.1016/j.icheatmasstransfer.2018.10.011.

[52] S.-W. Kang, W.-C. Wei, S.-H. Tsai, and S.-Y. Yang, "Experimental investigation of silver nano-fluid on heat pipe thermal performance," *Appl. Thermal Eng.*, vol. 26, nos. 17–18, pp. 2377–2382, Dec. 2006, doi: 10.1016/j.applthermaleng.2006.02.020.

[53] J. Jörg, S. Taraborrelli, G. Sarriegui, R. W. De Doncker, R. Kneer, and W. Rohlfs, "Direct single impinging jet cooling of a MOSFET power electronic module," *IEEE Trans. Power Electron.*, vol. 33, no. 5, pp. 4224–4237, May 2018.

[54] K. Olesen, R. Bredtmann, and R. Eisele, "Shower power: New cooling concept for automotive applications," in *Proc. Automot. Power Electron.*, Jun. 2006, pp. 1–9.

[55] B. Kwon, T. Foulkes, T. Yang, N. Miljkovic, and W. P. King, "Air jet impingement cooling of electronic devices using additively manufactured nozzles," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 10, no. 2, pp. 220–229, Feb. 2020.

[56] R. Wu, Y. Fan, T. Hong, H. Zou, R. Hu, and X. Luo, "An immersed jet array impingement cooling device with distributed returns for direct body liquid cooling of high power electronics," *Appl. Thermal Eng.*, vol. 162, Nov. 2019, Art. no. 114259, doi: 10.1016/j.applthermaleng.2019.114259.

[57] Z. Tang, H. Li, F. Zhang, X. Min, and J. Cheng, "Numerical study of liquid jet impingement flow and heat transfer of a cone heat sink," *Int. J. Numer. Methods Heat Fluid Flow*, vol. 29, no. 11, pp. 4074–4092, Nov. 2019.

[58] A. Ravanji and M. R. Zargarabadi, "Effects of elliptical pin-fins on heat transfer characteristics of a single impinging jet on a concave surface," *Int. J. Heat Mass Transf.*, vol. 152, May 2020, Art. no. 119532, doi: 10.1016/j.ijheatmasstransfer.2020.119532.

[59] S. Ndao, Y. Peles, and M. K. Jensen, "Experimental investigation of flow boiling heat transfer of jet impingement on smooth and micro structured surfaces," *Int. J. Heat Mass Transf.*, vol. 55, nos. 19–20, pp. 5093–5101, Sep. 2012, doi: 10.1016/j.ijheatmasstransfer.2012.05.009.

[60] L. E. Paniagua-Guerra, S. Sehgal, C. U. Gonzalez-Valle, and B. Ramos-Alvarado, "Fractal channel manifolds for microjet liquid-cooled heat sinks," *Int. J. Heat Mass Transf.*, vol. 138, pp. 257–266, Aug. 2019, doi: 10.1016/j.ijheatmasstransfer.2019.04.039.

[61] D. Lelea, "The microtube heat sink with tangential impingement jet and variable fluid properties," *Heat Mass Transf.*, vol. 45, no. 9, pp. 1215–1222, Jul. 2009.

[62] A. M. Waddell, J. Punch, J. Stafford, and N. Jeffers, "The characterization of a low-profile channel–confined jet for targeted hot-spot cooling in microfluidic applications," *Int. J. Heat Mass Transf.*, vol. 101, pp. 620–628, Oct. 2016, doi: 10.1016/j.ijheatmasstransfer.2016.04.108.

[63] D. Kim and J. Lee, "Experimental investigation of CO_2 dry-ice assisted jet impingement cooling," *Appl. Thermal Eng.*, vol. 107, pp. 927–935, Aug. 2016, doi: 10.1016/j.applthermaleng.2016.07.054.

[64] W. Zhou, L. Yuan, X. Wen, Y. Liu, and D. Peng, "Enhanced impingement cooling of a circular jet using a piezoelectric fan," *Appl. Thermal Eng.*, vol. 160, Sep. 2019, Art. no. 114067.

[65] P. Naphon, L. Nakharintr, and S. Wiriyasart, "Continuous nanofluids jet impingement heat transfer and flow in a micro-channel heat sink," *Int. J. Heat Mass Transf.*, vol. 126, pp. 924–932, Nov. 2018, doi: 10.1016/j.ijheatmasstransfer.2018.05.101.

[66] Z.-F. Zhou, Y.-K. Lin, H.-L. Tang, Y. Fang, B. Chen, and Y.-C. Wang, "Heat transfer enhancement due to surface modification in the close-loop R410A flash evaporation spray cooling," *Int. J. Heat Mass Transf.*, vol. 139, pp. 1047–1055, Aug. 2019, doi: 10.1016/j.ijheatmasstransfer.2019.05.063.

[67] H. Bostanci, D. P. Rini, J. P. Kizito, V. Singh, S. Seal, and L. C. Chow, "High heat flux spray cooling with ammonia: Investigation of enhanced surfaces for HTC," *Int. J. Heat Mass Transf.*, vol. 75, pp. 718–725, Aug. 2014, doi: 10.1016/j.ijheatmasstransfer.2014.04.019.

[68] B. H. Yang, H. Wang, X. Zhu, Q. Liao, Y. D. Ding, and R. Chen, "Heat transfer enhancement of spray cooling with ammonia by microcavity surfaces," *Appl. Thermal Eng.*, vol. 50, no. 1, pp. 245–250, Jan. 2013, doi: 10.1016/j.applthermaleng.2012.06.029.

[69] J. L. Xie, Y. B. Tan, T. N. Wong, F. Duan, K. C. Toh, K. F. Choo, P. K. Chan, and Y. S. Chua, "Multi-nozzle array spray cooling for large area high power devices in a closed loop system," *Int. J. Heat Mass Transf.*, vol. 78, pp. 1177–1186, Nov. 2014, doi: 10.1016/j.ijheatmasstransfer.2014.07.067.

[70] S.-S. Hsieh, H.-H. Liu, and Y.-F. Yeh, "Nanofluids spray heat transfer enhancement," *Int. J. Heat Mass Transf.*, vol. 94, pp. 104–118, Mar. 2016, doi: 10.1016/j.ijheatmasstransfer.2015.11.061.

[71] H. Liu, C. Cai, M. Jia, J. Gao, H. Yin, and H. Chen, "Experimental investigation on spray cooling with low-alcohol additives," *Appl. Thermal Eng.*, vol. 146, pp. 921–930, Jan. 2019, doi: 10.1016/j.applthermaleng.2018.10.054.

[72] J. D. Chapman, P. A. Kottke, and A. G. Fedorov, "Enhanced thin film evaporation via impinging electrospray liquid jets with entrained air streaming," *Int. J. Heat Mass Transf.*, vol. 131, pp. 85–95, Mar. 2019, doi: 10.1016/j.ijheatmasstransfer.2018.11.049.

[73] S.-S. Hsieh, Y.-F. Hsu, and M.-L. Wang, "A microspray-based cooling system for high powered LEDs," *Energy Convers. Manage.*, vol. 78, pp. 338–346, Feb. 2014, doi: 10.1016/j.enconman.2013.10.066.

[74] W. He, Z. Luo, X. Deng, and Z. Xia, "A novel spray cooling device based on a dual synthetic jet actuator integrated with a piezoelectric atomizer," *Heat Mass Transf.*, vol. 56, pp. 1–13, Dec. 2019.

[75] Y. Han, G. Tang, B. L. Lau, and X. Zhang, "Hybrid micro-fluid heat sink for high power dissipation of liquid-cooled data centre," in *Proc. IEEE 19th Electron. Packag. Technol. Conf. (EPTC)*, Dec. 2017, pp. 1–4.

[76] A. Husain, M. Ariz, N. Z. H. Al-Rawahi, and M. Z. Ansari, "Thermal performance analysis of a hybrid micro-channel, -pillar and -jet impingement heat sink," *Appl. Thermal Eng.*, vol. 102, pp. 989–1000, Jun. 2016, doi: 10.1016/j.applthermaleng.2016.03.048.

[77] A. J. Robinson, W. Tan, R. Kempers, J. Colenbrander, N. Bushnell, and R. Chen, "A new hybrid heat sink with impinging micro-jet arrays and microchannels fabricated using high volume additive manufacturing," in *Proc. 33rd Thermal Meas., Modeling Manage. Symp. (SEMI-THERM)*, 2017, pp. 179–186.

[78] X. Huang, W. Yang, T. Ming, W. Shen, and X. Yu, "Heat transfer enhancement on a microchannel heat sink with impinging jets and dimples," *Int. J. Heat Mass Transf.*, vol. 112, pp. 113–124, Sep. 2017, doi: 10.1016/j.ijheatmasstransfer.2017.04.078.

[79] S. Wiriyasart and P. Naphon, "Liquid impingement cooling of cold plate heat sink with different fin configurations: High heat flux applications," *Int. J. Heat Mass Transf.*, vol. 140, pp. 281–292, Sep. 2019, doi: 10.1016/j.ijheatmasstransfer.2019.06.020.

[80] F. Zhou, E. M. Dede, and S. N. Joshi, "A novel design of hybrid slot jet and mini-channel cold plate for electronics cooling," in *Proc. 31st Thermal Meas., Modeling Manage. Symp. (SEMI-THERM)*, 2015, pp. 60–67.

[81] X. Ju, C. Xu, Y. Zhou, Z. Liao, and Y. Yang, "Numerical investigation of a novel manifold micro-pin-fin heat sink combining chessboard nozzle-jet concept for ultra-high heat flux removal," *Int. J. Heat Mass Transf.*, vol. 126, pp. 1206–1218, Nov. 2018, doi: 10.1016/j.ijheatmasstransfer.2018.06.059.

[82] J. Wang, H. Kong, Y. Xu, and J. Wu, "Experimental investigation of heat transfer and flow characteristics in finned copper foam heat sinks subjected to jet impingement cooling," *Appl. Energy*, vol. 241, pp. 433–443, May 2019, doi: 10.1016/j.apenergy.2019.03.040.

[83] X. Sun, L. Ling, S. Liao, Y. Chu, S. Fan, and Y. Mo, "A thermoelectric cooler coupled with a gravity-assisted heat pipe: An analysis from heat pipe perspective," *Energy Convers. Manage.*, vol. 155, pp. 230–242, Jan. 2018.

[84] J. L. Xie, Z. W. Gan, T. N. Wong, F. Duan, S. C. M. Yu, and Y. H. Wu, "Thermal effects on a pressure swirl nozzle in spray cooling," *Int. J. Heat Mass Transf.*, vol. 73, pp. 130–140, Jun. 2014, doi: 10.1016/j.ijheatmasstransfer.2014.01.077.

[85] X. Chen, H. Ye, X. Fan, T. Ren, and G. Zhang, "A review of small heat pipes for electronics," *Appl. Thermal Eng.*, vol. 96, pp. 1–17, Mar. 2016, doi: 10.1016/j.applthermaleng.2015.11.048.

[86] A. Mohammed Adham, N. Mohd-Ghazali, and R. Ahmad, "Thermal and hydrodynamic analysis of microchannel heat sinks: A review," *Renew. Sustain. Energy Rev.*, vol. 21, pp. 614–622, May 2013, doi: 10.1016/j.rser.2013.01.022.

[87] Z. Guo, "A review on heat transfer enhancement with nanofluids," *J. Enhanced Heat Transf.*, vol. 27, no. 1, pp. 1–70, 2020.

[88] G. Krishan, K. C. Aw, and R. N. Sharma, "Synthetic jet impingement heat transfer enhancement—A review," *Appl. Thermal Eng.*, vol. 149, pp. 1305–1323, Feb. 2019.

[89] S. Ashman and S. G. Kandlikar, "A review of manufacturing processes for microchannel heat exchanger fabrication," in *Proc. ASME 4th Int. Conf. Nanochannels, Microchannels, Minichannels, A B*, Jan. 2006, pp. 855–860.

[90] M. Law, P.-S. Lee, and K. Balasubramanian, "Experimental investigation of flow boiling heat transfer in novel oblique-finned microchannels," *Int. J. Heat Mass Transf.*, vol. 76, pp. 419–431, Sep. 2014, doi: 10.1016/j.ijheatmasstransfer.2014.04.045.

[91] G. M. Grover, T. P. Cotter, and G. F. Erickson, "Structures of very high thermal conductance," *J. Appl. Phys.*, vol. 35, no. 6, pp. 1990–1991, Jun. 1964.

[92] T. P. Cotter, *Theory of Heat Pipes*. Berkeley, CA, USA: Los Alamos Sci. Lab., Univ. California, Berkeley, 1965.

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