REVIEW ARTICLE

A Review on Recent Advances in Microchannel Heat Sink Configurations

Ganesan Narendran, Nagarajan Gnanasekaran and Dharmaraj A. Perumal*

Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore-575025, India

ARTICLE HISTORY

Received: November 19, 2017
Revised: July 13, 2018
Accepted: July 19, 2018

DOI:
10.2174/2212797611666180726124047

Abstract: A qualitative observation has been undergone to review the various geometries of a microchannel that has been reported for the last two decades in literature majorly for the application of high power devices. Recent research on microchannel is more focused on numerical and experimental work with various configurations of the heat sink. In this paper, a comparative work on different flow geometries used in the microchannel and their influence on heat transfer and pressure drop is investigated with the brief representation of different working fluids used in microchannel heat sink for the purpose of electronic cooling and their associated performance characteristics with various examined parameters.

Background: The microchannel cooling is an established cooling technique for high power electronic components which effectively enhances the performance of the high power devices.

Objective: This article presents a general overview of microchannels with novel constructional bifurcations structures with related patents. Further, the influential parameter on thermal and flow characteristics with greater depth is also reviewed by authors.

Methods: This review directs by presenting standard and benchmark investigation in the microchannel and different working parameters continued with recent studies. Further, it is addressed with the application of electronic cooling with latest patents using bifurcations and fractal microchannels.

Result: The current situation of 3D cooling requires a robust cooling system to accommodate increased heat flux without compromising the packaging. Moreover, the recently developed patents also evolved with improved thermal load handling under constrained packaging.

Conclusion: The advanced microchannel cooling with an optimized fluid handling system with effective packaging results in a highly effective heat dissipation system.

Keywords: Bifurcations, flow boiling, fractal microchannels, microchannel, nanofluids, porous microchannels.

1. INTRODUCTION

The rapid advancement in the field of consumer electronics has drastically reduced the size of the devices and exponentially increased the computational efficiency. Advances in 3D Transistor further allowed packaging technology to reach the range of less than 22nm. As a result, these miniaturized electronics occupied a vast application; it has redefined our working space and reached a tremendous level where its future growth is highly diversified. Nowadays, it has morphed into flexible electronics, wearable technology, optoelectronics, electronic bio-implants and IoT. However, these devices face bottleneck due to enormous heat dissipation from its increased power in transistors. Moreover, lack of concurrent evolution in cooling technologies let the present cooling systems inadequate to meet the new paradigm of these latest compact electronic devices, which will be a challenging and active field among researchers in coming future. In order to meet the cooling demands of latest high power devices, it is necessary to look for novel and ingenious cooling solutions.

Recently, remarkable works have been reported on microscale heat transfer systems to dissipate heat flux more than 1kW/cm^2 [1, 2]. However, adding parallel type microchannel will not meet the demands of advanced multicore processors [3]. Choi *et al*. [4] reported heat enhancement of heat transfer based on high thermal conductive fluids with highly dispersed nanosize metallic or oxide in the base fluid. Implementing the nanofluid in microscale devices delivered appreciable thermal enhancement for a huge price of pressure drop thereby developing lower performance. Additionally, issue of nanofluids reliability and stability is highly debatable [5, 6]. A substantial amount of studies by Kandlikar [7] and Joshi [8] on microchannels has also put forth a necessity of novel microscale devices for advanced heat dissipation due to integration issues in two-phase flow. Since currently,

*Address correspondence to this author at the Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore-575025, India; Tel: +919159860535; Fax: + 91 08242474058; E-mail: Perumal.iit@gmail.com

we are in the golden age of microfabrication, it further appeals for an innovation in microchannel heat sink design or a hybrid methodology to push the present cooling capability of the microchannel to the next level.

However, it is pertinent to note that the importance of novel technologies in microchannels is not the only hour of demand for high-density electronic components but also to cool data centers, workstation computers, Nozzle cooling for 3D printers, supercapacitors thermal management and cooling of artificial organs. Therefore, the requirement of new sink design to enhance the existing cooling is persuasive by many factors and might provide new insight into many interdisciplinary fields. The above requirements can be approached by methods such as: Designing novel microscale devices for electronic cooling, microscale hybrid cooling devices (involves a combination of two or more cooling technologies), design modifications in existing microchannels etc. The current study will present an extensive review of the above-mentioned methods. In advance of the discussion, it will be beneficial to analyze the significance and challenges involved in implementing a microchannel cooling system and also going through the past work performed in microchannels.

1.1. Trade-Offs in Microchannels

It is evident that the current electronic cooling systems majorly employ heat pipes, fins and a combination of both. The use of the fin and heat pipe based cooling system manages to occupy large volume and appeals a huge setback from the perspective of compactness of the device. For example, a normal heat pipe combined with a fan can dissipate ($300W/m^2K$) energy and at lower magnitude with only fins ($80W/m^2K$) [9]. But these cannot dissipate the latest range - $2000W/cm^2$, due to this, the above devices have limitations for recent electronic components. Using the increased surface area and liquid coolant is one of the better options to move further. The concept of microchannel heat sink was first coined by Tuckerman and Pease [10]. His path-breaking work initiated many other researchers to compare their numerical and experimental work with other microchannel shapes using different fluids in different application domains [11-14]. Bowers and Mudawar [15] performed cooling studies with circular microchannel using R-113 as working fluid and achieved higher heat flux dissipation range of $200W/cm^2$ under low-pressure drop. Garimella *et al*. [16] conducted investigations on trapezoidal microchannel with various aspect ratios. The authors observed that both the change in aspect ratio and sidewall angle of the trapezoidal channel increases the heat transfer. Recinella and Kandlikar conducted experimental studies with manifold microchannel flow boiling and reached a critical heat flux more than $600W/cm^2$ [17]. Singh *et al*. [18] incorporated Al_2O_3 nanofluids in trapezoidal microchannel and reported heat transfer enhancement. Besides the above well-established benefits of the microchannel, it has also its own operational limitations as follows:

1. Due to the increased surface area, friction factor increases in microchannels leading to higher pressure drop and it further intensifies while introducing high viscous fluids.
2. The use of nanofluids or two-phase fluid develops corrosion in the channels and causes a decrement in heat transfer due to fouling effects.
3. The mass flow rate in the channels is not evenly distributed, due to this localized high-temperature zone is developed.
4. Identifying effective manufacturing process for microchannel that provides near zero surface roughness is difficult.
5. If point 4 is reality then the concern about early turbulence effects and higher pressure drop can be solved. But, most importantly the primarily responsible factor that influences heat transfer in the microchannel can be cornered.
6. Robust cooling of multicores which are subjected to the various loading heat flux is quite challenging.

However, most of the studies highlight the effects of heat transfer enhancement; but, very rare attention was paid on accelerated effect on the use of combined microchannel with micropump that leads to reliable commercialization of liquid cooling in compact electronic devices. Upcoming new types of designs must facilitate to solve the fundamental problems on heat transfer characteristics and flow phenomenon in Micro-Meso scale level which eventually bridge the gap to work with an optimized liquid cooling system for a future generation. Thus, the thrust for further research in the cooling of electronic devices is microchannel; therefore, it is worth knowing the designs, techniques and their applications.

2. MICROCHANNEL CONFIGURATION STUDIES

2.1. Structural Based Bifurcation

Increase in heat transfer by recirculation and vortex development by added microstructures and cavities along the flow direction is a method to enhance heat transfer in the microchannel. The studies include providing micro fins in a different orientation, introducing cavities accompanied with ribs and designing Fractal tree for increased flow and heat transfer. Li *et al*. [19] performed numerical studies on microchannels with triangular cavities containing rectangular ribs for Reynolds number (*Re*) ranging from 173 to 635. They investigated the combined effects of cavity and ribs over heat transfer and friction factor. Their investigation includes a method to minimize the entropy generation to enhance the heat transfer. They reported that this type of microchannels develops enhancement due to increased redeveloping flows along the channels. Further, this arrangement intensified the mixing of fluid in the system that contributes to heat transfer with a rated enhancement at $Re = 500$ for a rib of 0.3 and cavity width of 2.24.

Yang *et al*. [20] performed experimental and numerical studies on microchannel with different pin fin shaped like a rhombus, hydrofoil and sine with a top area of $0.0625\ mm^2$ and the entire surface area of $1061119mm^2$. From their numerical simulation, they found that sine type pin fins develop comparatively better results than the remaining at the flow rate of 100 ml/min with a heat flux of $144W/cm^2$. Similarly, the lower pressure drop of 15kPa is obtained by using sine type pin fins for maximum velocity of 4.46m/s.

Ghani *et al*. [21] conducted a numerical investigation on microchannel containing sinusoidal cavity with rectangular ribs for Reynolds number ranging between 100 and 800. The studies were performed by considering the parameters like Nusselt number and friction factor. According to them, the combined output of sinusoidal cavities with rectangular ribs is superior to cavities and ribs of the other designs due to the increased surface area but interestingly with reduced friction factor. The best heat transfer results were found for the Reynolds number of 800.

Tokit *et al*. [22] performed a numerical investigation on interpreted channels with nanofluid as cooling fluid. They have studied Al_2O_3, CuO and SiO_2 nanofluids with a volume fraction range from 1 to 4% under the Reynolds number ranging from 140 to 1034 with a particle diameter of 30 to 60nm. According to them, the augmentation in heat transfer is due to an increase in volume fraction with decreased particle size and maximum enhancement was reported for alumina nanofluid. Chai *et al*. [23] conducted numerical simulation on different types of interpreted ribs in a microchamber. They have showed that with the use of ribs, local heat transfer coefficient can be incremented. They have used rectangular, triangular, diamond and ellipsoidal ribs types in which ellipsoidal design developed a better heat transfer than other types of ribs. The maximum Nusselt number was seen for the *Re* = 75 with an increment of 57% with an increased friction factor of 70% compared to conventional channels.

Chen *et al*. [24] conducted an investigation on entropy generated due to pin fin cylindrical structures. Their study includes developing an optimal system with inlet velocity, heat load and finning material. They found that the generation of entropy increases with increasing aspect ratio of the sink and concluded that by opting reduced fluid velocity with less aspect ratio accompanied with increased material fraction can provide minimum entropy condition. Wong and Lee [25] studied microchannels with triangular ribs in microchambers to develop an optimal design by varying its design parameters. They studied parameters like friction factor, Nusselt number and thermal enhancement factor. They observed that the heat transfer increases with the increase in design parameters like width and height but reduces with increasing length. They registered a highest Nusselt number for Reynolds number of 500 with width, length and height of 100, 400 and 120µm, respectively, up to 56% enhancement with conventional channels.

Abdoli *et al*. [26] conducted numerical studies on pin fin structures for the application of cooling high heat flux in electronic devices. Their investigation on shapes includes circular, hydrofoil, convex and altered hydrofoil with staggered fin arrangement. They have used a hotspot value of $2KW/cm^2$ for an area of $0.25mm^2$ but remaining zones with $1KW/cm^2$. According to them, hydrofoil pin shape found better than the other designs with a reduced pumping power of 30.4% and 3.2% more effective than circular pin fins. They found that the altered hydrofoil fin decreases the maximum temperature by 6.4ºC than circular design.

Shahabeddin *et al*. [27] investigated the effect of nanofluids on micro fins based heat exchangers. According to them, providing lower nanoparticle volume fraction can develop better Coefficient of Performance (COP) with reduced entropy generation. Additionally, under lower Reynolds number, the effect of nanoparticle has negligible effect with increased COP when alumina nanofluid was used as the cooling fluid. The study was performed by providing heat exchanger on both sides of the thermoelectric generator by switching cooling fluid on both hot and cold end. Recently, a cooling system dedicated to micro fins with hydrophilic/hydrophobic surfaces involving under higher heat flux was developed for higher heat flux condition that resulted in better performance [28].

Zhao *et al*. [29] optimized micro pin fin arrangement for the application of electronic cooling with porous media. Here, the investigations were carried out by allowing the porosity values with altered pin fin locations. They have registered an equal importance of the above two parameters for heat transfer enhancement and an optimal porosity of 0.75 with a square rib angle of 30° was recommended. In the case of porous based pin fin cooling under a velocity of 1.44 m/s a maximum Nusselt number of 24 was developed with a pressure drop of 4.6kPa. With the flow velocity of 1.44m/s, Nusselt number increases with increased pressure drop up to 15% for porosity of 0.56.

Vinoth and Senthilkumar [30] performed experimental studies on microchannel with oblique fins, alumina nanofluid along with 0.25% volume fraction. Three different cross-sections were used like square, semicircle and trapezoidal. Here, the study is majorly intended to investigate flow hydrodynamics on these different designs with varied mass flux. Trapezoidal fin develops a 5.878% increased heat transfer with nanofluid as working fluid, this is comparatively higher than other cross-sections. Further selected works on a modified channel based passive heat transfer with the studied domain and its varied parameters are listed in Table **1** [31-40].

2.2. Fractal-Based Bifurcation

Enhancement in heat transfer is extended by creating fractal tree based bifurcations which are a biomimicry of the fluid transport in the leaf of the plant. These fractal channels develop constricted passages along the flow with several branches. This type of channel increases uniformity of the heat sink with increased pressure drop. Lorenzi *et al*. [41] conducted an investigation on the construction of non-uniform X-structures for hotspot application. They performed the analysis by varying length and angle between the pathways. They also observed by using X- shaped blades that generate 56% more heat transfer enhancement than a single pathway. They also investigated I- shaped constructional studies for cooling application by considering thermal resistance.

Hajmohammadi *et al*. [42] performed a numerical investigation of fork type flow patterns for the electronic cooling application. They registered a maximum reduction of 46% in peak temperature by using the fork configurations. According to them, the fork with angles found superior to the other high conductive pathways designs since it consumes only one-third of the material for cooling high thermal zones.

Jimenez *et al*. [43] performed numerical analysis on network-based cooling using a microchannel for electronic application. The investigation was performed for different configurations to find the performances of thermal and hydraulic in accordance with pressure drop and average surface temperature. They observed that T-shaped microchannel was found superior to Y-shaped networks. Also, T-shape increases the development of uniform cooling with reduced thermal resistance.

Table 1. Summary of Microchannel Sink Using Constructional Modifications.

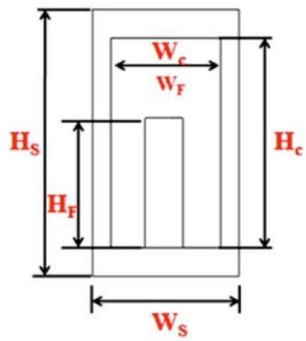
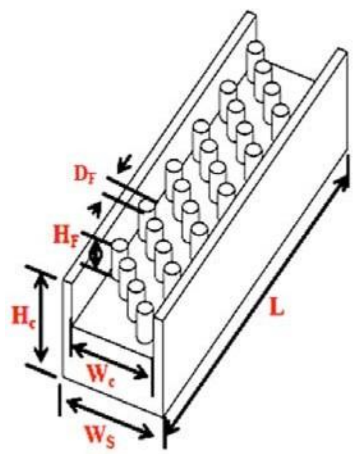
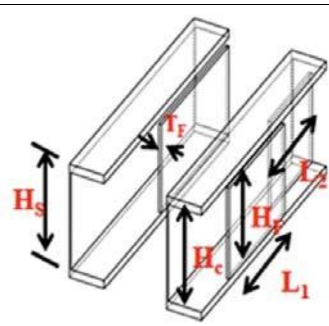
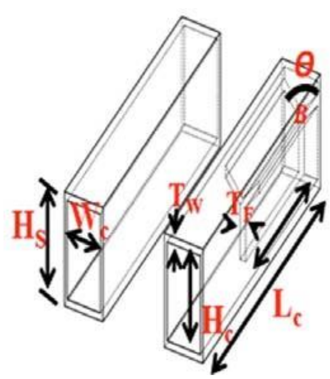
Authors	Construction Specifications	Computational Domain	Remarks
Adewumi *et al.* [31]	H_s = 0.48mm W_c = 0.04mm W_s = 0.06mm H_c = 0.16mm		- They observed that addition of pin fin increases the Global thermal conductance - Diseriable results were ontained for limited three fins with six rows above that the effect of heat transfer is negilible - They found that increase in Beijan number reduces the peak temperature of the microchannel - They concluded that microchannels with few rows having less aspect ratio prvides the best results
Shafeie *et al.* [32]	H_s = 1mm H_c = 90-500µm W_c = 27-35 µm W_s = 10000µm L = 1cm H_f = 330-500µm D_f = 80-100µm		- They observed that the performance of microchannel is enhanced by increasing the height of the fin - Optimal fin height is 300µM which provided better thermal performance - Performance of higher aspect ratio pin fins is better in smaller channels - They reported that for a constant pumping power oblique fin pattern provides better heat removal than staggered fin
Xie *et al.* [33]	W_c = 315µm H_c = 400µm T_F = 15-35µm H_s = 500 µm L_1, L_2 = 5mm-25mm		- They observed that with the increase in bifurcation stages higher pressure drop is developed - Observed that local velocity in the microchannel with bifurcations is higher than smooth channels and it is also a function of the length of plate - Addition of bifurcation increases the thermal enhancement factor by 1.78 times more than normal channels
Li *et al.* [34]	W_c = 315µm H_c = 400µm T_w = 35µm T_f = 35µm H_s = 500µm 8 = 60-180°		- They obtained thermal enhancement by varying angle of *Y* arms and inlet velocity - Result shows that when the angle between *Y* arm increases pressure drop also increases - Addition of the y shaped bifurcations reduced the thermal resistance compared to conventional microchannels - Reported that 0 = 90° provided better performance

Table (1) contd….

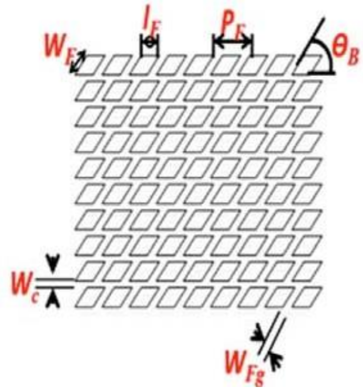
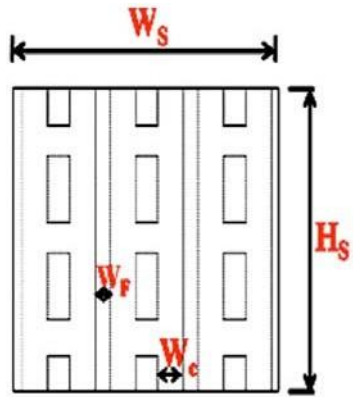
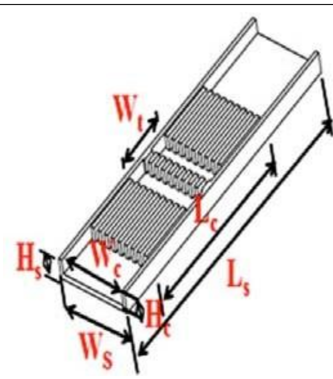
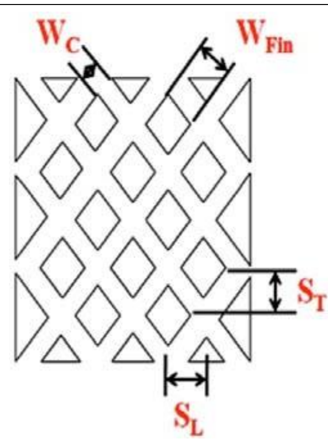
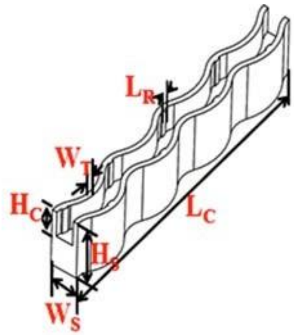
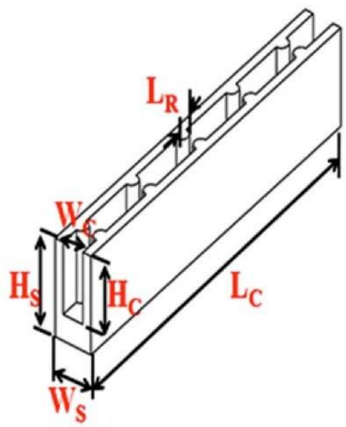
Authors	**Construction Specifications**	**Computational Domain**	**Remarks**
Lee *et al.* [35]	$W_F = 0.485mm$ $W_C = 0.539mm$ $P_F = 1.995mm$ $L_F = 1.331mm$ $W_{Fg} = 0.298mm$ $\theta_B = 27^o$		- Oblique microchannel performance is better than normal microchannels by minimizing the total thermal resistance under increased Reynolds number - By introducing oblique fin in microchannels provides uniform heat removal capacity throughout the sink - Boundary layer thickness is reduced along the flow direction and supports secondary flows with frequent redevelopment - Nusselt number increments 47% more than conventional microchannels - The heat transfer augmentation is better for fin angle 27°
Brinda *et al.* [36]	$W_s = 10mm$ $H_s = 16mm$ $W_c = 280$ µm $W_f = 500$ µm		- Having 3 stage ladder microchannel generates 3.85kPa which is 162% more than conventional channels - Implementing 10 stage ladder substrate temperature is decreased by 7.3°C at *Re* 400 and at *Re* 2000 it goes up to 4.4°C - By extending till 10 links microchannel thermal resistance drops by 20%
Chai *et al.* [37]	$L_c = 10mm$ $W_c = 315µm$ $H_c = 0.2mm$ $H_S = 0.35mm$ $L_S = 20mm$ $W_t = 1.1mm$		- Introduction of the ribs increases the fluid mixing and develops recirculation and vortex generation besides the channel wall - Stagnation zone is developed behind the rectangular rib where the maximum pressure is seen in the microchannel - They suggested that for *Re* < 600 microchannel with rib is beneficial and more than *Re* > 600 ribs with interputted microchannel is better - Further thermal enhancement factor is reduced if Reynolds number is more than 0.1mm of rib length
Liu *et al.* [38]	$W_C = 0.41$-$0.355mm$ $W_{Fin} = 0.445$-$0.559mm$ $S_T = 0.5657mm$ $S_L = 0.5657mm$		- Both heat transfer and friction factor increase with an increase in Reynolds number using staggered square pin fins - Transition of friction factor is observed at *Re* = 300 - They proposed a new correlation for nusselt number as $Re^{0.61}$ - Used 625 square fins in a staggered arrangement

Table (1) contd….

Authors	Construction Specifications	Computational Domain	Remarks
Aliabadi *et al.* [39]	W_s-2mm W_T-0.5mm L_C-50mm H_C-1mm L_R-1.3-5.4mm H_S-5mm		- Here alumina nanofluid is used as the working fluid with 0.1 and 0.4% volume concentration - Implementation of the ribs enhances heat transfer by chaotic advection of working fluid - For the observed *Re* of 100-900 the maximum heat transfer coefficient of 128% with maximum pressure drop of 185% - Oblique positioning of the ribs is the best for wavy microchannel - 0.4% nanofluid developed maximum heat transfer of 19.3% with 15.6% pressure drop
Chai *et al.* [40]	W_s-0.25mm W_c-0.1mm L_C-10mm H_C-0.2mm L_R-0.4mm H_S-0.35mm		- With rib length and its spacing between them develop a decrease in Avg Friction factor but along the length, it increases - By increasing the height of the rib and lowering the ratio of the rib length to its spacing also increases the factor factor - But for the microchannels having offset rib placement has developed lesser friction factor

Farzaneh *et al.* [44] conducted numerical studies with microchannel loops for electronic cooling with lower thermal resistance. They have observed that the increase in branch number in the loop reduces the pressure drop with increased heat transfer. They reported that a maximum temperature of 20% has been achieved with a reduction in pressure drop of maximum 33% for two branched microchannels. Their study also intended to optimize the best channel length to width ratio in the branched networks. Fractal tree based heat transfer device with multilevel branching was developed using high thermal conductive materials by implementing carbon nanotubes with enhanced vortex generation [45].

Peng *et al.* [46] conducted an investigation to enhance heat transfer by bio mimic of plant fluid transport using fractal microchannel bifurcations. They investigated the influence of porous media over heat transfer. They observed that there was no effect on velocity along the direction of the flow. But the implementation of the permissible media allowed developing better uniform temperature with reduced pressure drop.

Chen *et al.* [47] performed numerical analysis on fractal tree microchannel to improve mass transfer and to investigate its effects on temperature and pressure along the channels. Furthermore, they have discussed the importance of the bifurcation angle in terms of the chemical reaction and found that the bifurcation angle is more efficient than serpentine microchannel. They have observed an increased reaction rate by optimally operating the reaction temperature and pressure. They have witnessed negligible effects on bifurcation angle in terms of performance of the system. Xia *et al.* [48] investigated fractal tree based heat transfer for the application of cooling rotating spindles to study its heat transfer and hydrodynamic performance. They have concluded that fractal microchannel develops better uniform temperature distribution with less pressure drop. Moreover, this fractal-based system developed an increased coefficient of performance (COP) than the conventional helical based cooling. At lower Reynolds number of Re = 200 fractal tree system develops a temperature of 380°C but the helical system develops 420°C. As soon as the flow increases, the temperature decreases for both the system.

Liu *et al.* [49] performed an experimental and numerical study with T-Y joint bifurcations with fractal tree type microchannel. They used GaLnSn (Gallium Lanthanide Tin) coolant for heat transfer enhancement. Further, they obtained a temperature difference of 27K for a heat flux range of $10^6 W/m^2$. Also, they reported an optimal bifurcation angle of 60 degrees for better heat transfer. They presented two types of channels one which efficiently develops uniform temperature distribution and other with reduced pressure drop. Peng *et al.* [50] performed experimental studies on vapor based plant vein type bifurcation to enhance the heat dissipation for electronic cooling. Besides this fractal bifurcation, the system also provided with micro fins to replicate tissues (Table **2**) [51-60]. They have performed experiments with both DI and ethanol as working fluids.

Table 2. Summary of Microchannel Using Fractal Bifurcations.

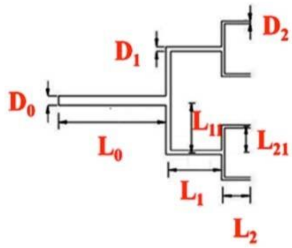
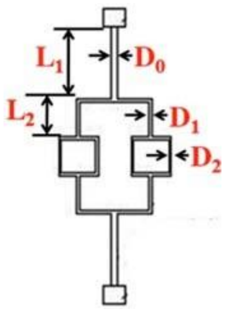
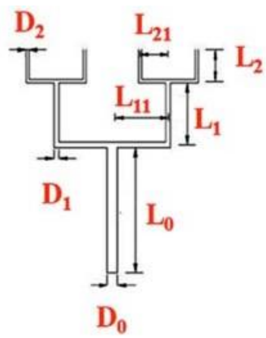
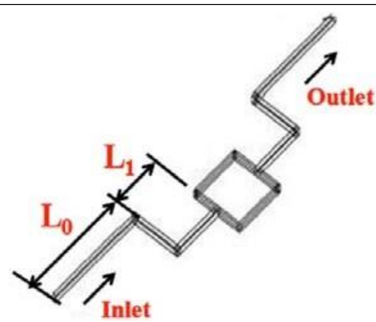
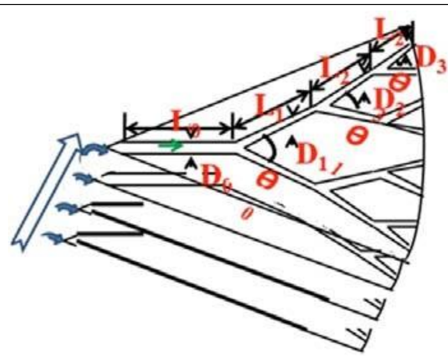
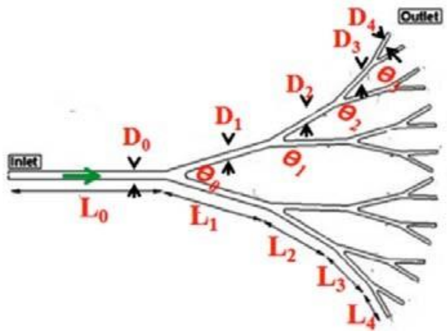
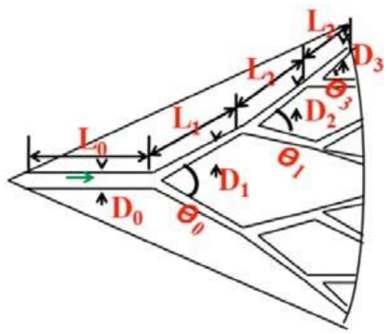
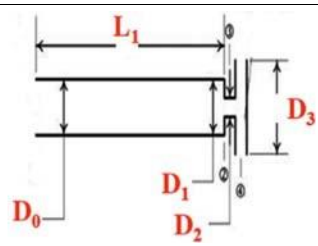
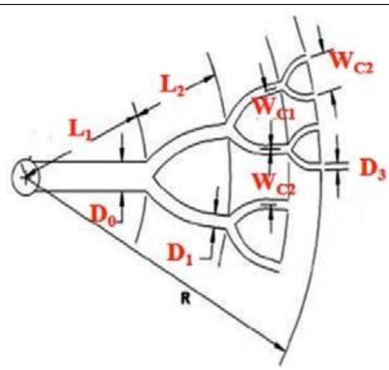
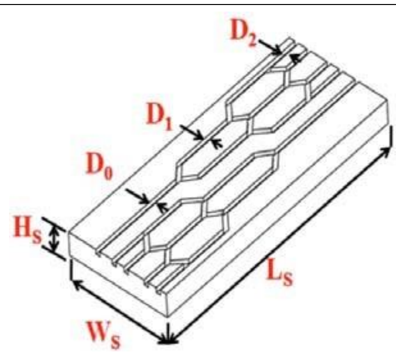
Author	Computational Domains	Remarks
Yu *et al*. [51]		Fractal tree based microchannel enhances heat transfer due to generated vortexes in the channels Increase in pressure drop was observed for implementation of fractal trees Suggestions were made to form semi-circular bends in factral trees to reduce the pressure with increased COP Aspect ratio has major influence in pressure drop development, heat transfer and COP
Zhang *et al*. [52]		Developed subsectional Integrated based method which has a close match with the experimental results Studies proceeded by comparing with conventional method which has higher deviation for friction factor and Nusselt number with increase in Reynolds number
Zhang *et al*. [53]		Fractal-based microchannels are used for thermal studies and compared with straight and serpentine microchannels They observed that aspect ratio and branching levels influence heat transfer and fluid hydrodynamics properties Fractal tree bends with fillets develops reduction in local pressure drop They concluded that the combined effect of lower aspect ratio under high branching levels accompanied with fillets develops desirable results
Zhang *et al*. [54]		Vortex developed in *T* and *L* connections in bifurcation trees where related to the developed recirculation and secondary flow Slower moving fluids are created near the walls of *T* and *L* bends which increases the pressure drop The induced vorticity increased for higher Reynolds number and dropped with fin aspect ratio
Xu *et al*. [55]		Pressure drop in the multi-layer microchannel is lower than a single layer fractal channel with enhanced heat transfer They reported 5 layer fractal tree sink which consumes 0.01-0.1W on the other hand single layer requires 1.45W with re-duced thermal resistance

Table (2) contd….

Author	Computational Domains	Remarks
Ghaedamini *et al*. [56]		Lower pressure drop in the fractal tree is developed for the bifurcation angle of 30° For higher branching, there is no effect in pressure drop in the case of Snelteness 16 and 24 no influence on bifurcation angle is formed The pressure drop by 180° is superior for channels with higher branching levels
Xu *et al*. [57]		Fractal tree generates better heat transfer for pulsating frequency of 10-20Hz They reported that pulsating flow through fractal channels comparatively develops cooling capacity with a reduced peak temperature Increase in pulsating frequency of 30-40Hz heat transfer is increment by 40% Very negilable differences between the pressure drop of steady and pulsating flows were observed
Daniels *et al*. [58]		Fractal microchannels developed pressure drop range from 20 to 90kPa and the maximum was observed for mass flow of 225g/min Observed void fractions range from 0.3 to 0.9 These experimental void formations don't match with the model since model influence more on the dominance of exit quality for increased branching levels
Heymann *et al*. [59]		Effectively implemented optimization methods like gradient-based method and genetic algorithm to minimize the pumping power within the error of 10%-25% at a different heat flux Suggested lower branching on fractal trees for high heat flux systems
Shui *et al*. [60]		They found branching microchannels develops better thermal absorption under increased Reynolds number Experimental and numerical pressure drop predict more than the friction factor correlation and lesser during the turbulent regime. Steam shows as a better-working fluid than air by 17% in thermal performance and 20% less for friction factor Tree branching in better than serpentine type channels with more even cooling

2.3. Double Layer Microchannel

Several methodologies have been implemented to reduce the streamwise temperature rise along the flow length of the microchannel. The best convincing solution was proposed by Vafai and Zhu [61]. The study was conducted with a rectangular microchannel with cooling fluid passed in a counter direction. They observed that by using double layer microchannels streamwise temperature raise was balanced with comparatively reduced pressure drop. The influence of pressure drop in double layer microchannels is determined by allowing a combined double layer mass flow rate to a single layer. It is found that the double layer generated lower pressure drop with an optimal pressure ratio of 2.5-3.0. Similar work on staged microchannel for more than two layers was investigated by Wei and Joshi [62]. They observed the pressure drop to be lower for an increased number of stacks than single. They pointed out that the stacking is efficient only when the sink has high thermal conductivity. They concluded under lower mass flow rate copper is the best suited for stacked microchannels.

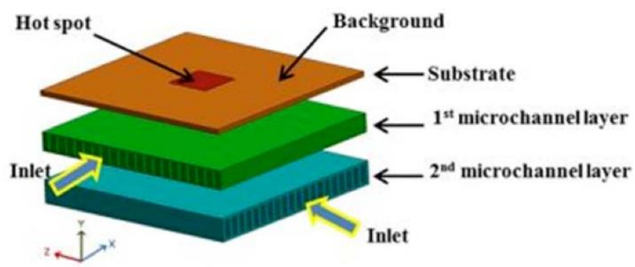


Fig. (1). Hotspot cooling with double layer microchannel.

Abdoli *et al*. [63] considered two layer microchannels for hotspot cooling in electronic chips as shown in Fig. (**1**). The hotspot dimension investigated was about 0.5 x 0.5mm in size. Two heat fluxes of 1500W/cm^2 and 2000W/cm^2 for hotspot were used and a fixed flux of 1000W/cm^2 for remaining portion of the chip. They observed two-layer configuration performed considerably well for heat flux of 1000W/cm^2 but for the hotspot cases, authors suggested using higher thermal conductive fluids and higher conductive heat sinks. They observed a linearly varying stress developed due to thermal gradients which generated a deformation in the range of 50nm.

Koo *et al*. [64] presented a theoretical investigation of integrated cooling in a 3D electronic chip with multiple microchannel layers shown in Fig. (**2**). Their model predicts a decrease in local wall temperature with increased outlet temperature under the use of microchannels at higher thermal

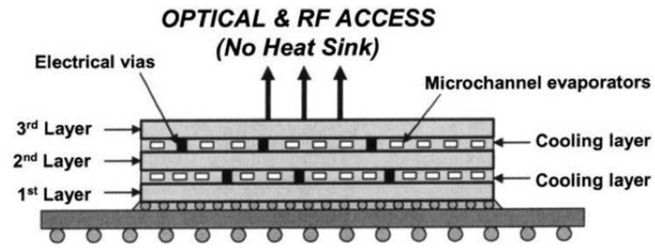


Fig. (2). Integrated microchannel with multiple cooling layers.

loading. Additionally, they suspect whether these predictions are appreciable under 3D chips where loading was varied with location and time; however, observed better uniform temperature in junction and even lower temperature within layers. Local temperature between layers is reduced from 15°C to 1.5°C. A further investigation of interlayer microchannel cooling in 3D circuits was conducted by Kim *et al*. [65]. They reported that using two-phase cooling with R134 and R245 develops better results than single-phase working fluids in the presence of hotspots shown in Fig. (**3**).

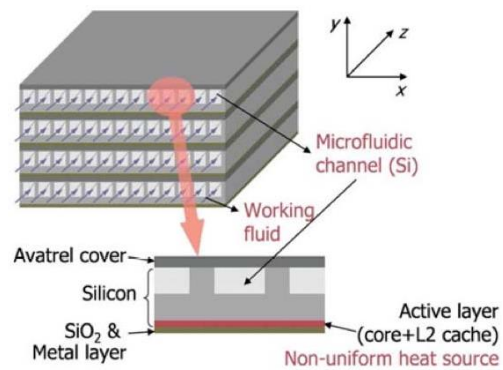


Fig. (3). Integrated microchannel with hotspot.

A numerical study of hotspots cooling using double layer microchannel using rectangular cross section was performed by Ansari and Kim [66] presented in Fig. (**4**). They evaluated the hotspot cooling for two different settings one at the center and next for multiple hotspots distributed evenly. They observed reduced thermal resistance by using a heat sink with the parallel flow for the case of single hot spot, while for multiple hotspots, they suggested heatsink with transverse flow due to lower thermal resistance. Zhai *et al*. [67] performed comparative studies with staggered flow double layer microchannel to counterflow staggered type. Staggered type microchannel used in the study developed a better uniform temperature. It is interesting to see that for the same pumping power staggered model developed very low ther-

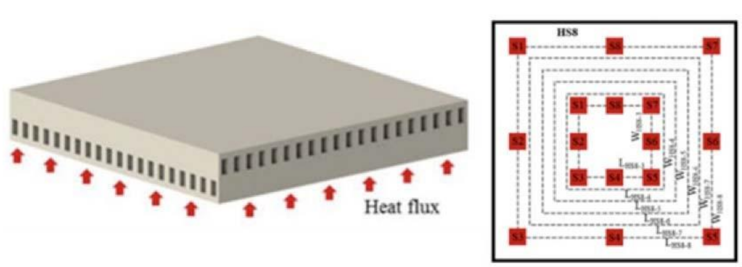


Fig. (4). Double layer microchannel with multiple hotspots.

mal resistance compared to single staggered and counterflow.

Wong and Ang [68] performed numerical studies with double layer microchannel by introducing flow contractions in channels, shown in Fig. (**5**). The study reported that by tapered structures used in double layer counter flow generates better performance than a conventional double layer. Besides, the use of these taper generates high pumping power. They concluded that on considering the combined effect of thermohydraulic performance of the tapered structures is very low compared to conventional double layer. A similar study performed with Al_2O_3-H_2O to find an optimal tapering factor in double layer microchannel is done by Kumar *et al*. [69]. They also observed similar results of lower thermal performance for all the tapers put to study. But the use of nanofluids increased the heat transfer performance and reduced thermal resistance for a volume fraction of 7%. Finally, they concluded that the overall performance of a tapered double layer was not satisfactory even after using nanofluids and they recommended that the tapered microchannels were highly preferred. Arabpour *et al*. [70] conducted an investigation on the effect of double layer using kerosene/MWCNT nanofluid subjected to oscillating heat flux shown in Fig. (**6**). The double channels were studied with three different dimensional lengths (Z) such as 1/3, 2/3, and 3/3. They observed Z of 1/3 satisfied maximum thermal performance criterion on various working conditions and nanofluid volume fractions in a counterflow direction.

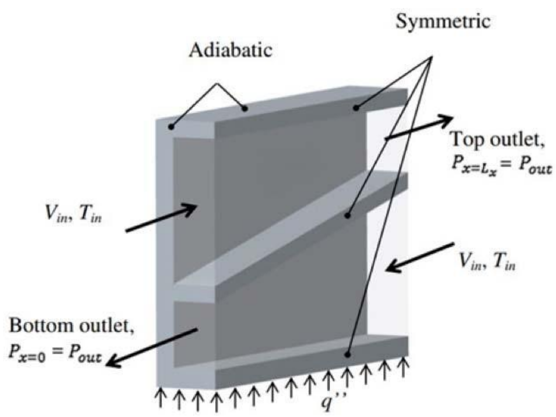


Fig. (5). Double layer microchannels with contractions.

2.4. Effect of Microchannel Shapes

Initially, the performance studies on microchannels were highly concentrated on finding the effective cross-section and working fluid of the microchannel. Various manufacturing methods were carried out to develop different hydraulic diameter and aspect ratio of the microchannel. The convective heat transfer performance of the microchannel is effectively augmented by the use of optimized cross-section with increased thermal conductive fluids. Use of these fluids drastically reduces the response time of the cooling with a low volume of working fluids at a three-fold increase in heat transfer coefficient. This augmentation is attributed to increased Reynolds number, channel structures, volume fraction of nanofluids and surface morphologies. Sadasivam *et al*. [71] investigated forced convection through trapezoidal and hexagonal ducts. The result shows the dependency of aspect ratio and cross section area for various wall angles in heat transfer augmentation. Koo and Kleinstrener [72] used copper oxide nanofluid in a trapezoidal microchannel with water and Ethylene Glycol as base fluid. They observed an increase in heat transfer up to 4% by using higher Prandtl number fluids. Wu and Cheng [73] studied friction factor in a smooth trapezoidal silicon with different aspect ratios. Dharaiya and Kandlikar [74] studied the effect of 2D sinusoidal elements using roughness height and roughness pitch accurately. They established that the wall temperature according to the roughness profile is higher at the bottom of the roughness element. Higher roughness height decreases the heat sink efficiency due to the reduction of the hydraulic diameter and also increases the friction factor. They also modeled a channel with hydraulic diameter 175µm which generates an enhancement of 264.8% with the surface roughness height of 20µm. Jung *et al.* [75] conducted forced convective heat transfer using alumina nanofluid and their convective heat transfer coefficient increased up to 32% compared to pure fluid at a volume fraction of 1.8 without major pressure drop. However, this is contradicting to the experimental observation of Suresh *et al*. [76] where they used circular cross-section with 0.1 volume fraction of alumina nanofluid and more pressure drop is registered than the pure fluid.

Guo *et al*. [77] developed 2D and 3D Gauss surface roughness models which were made to compare with the smooth microchannel; however, 2D roughness model failed to match the real surface roughness. Roughness plays a

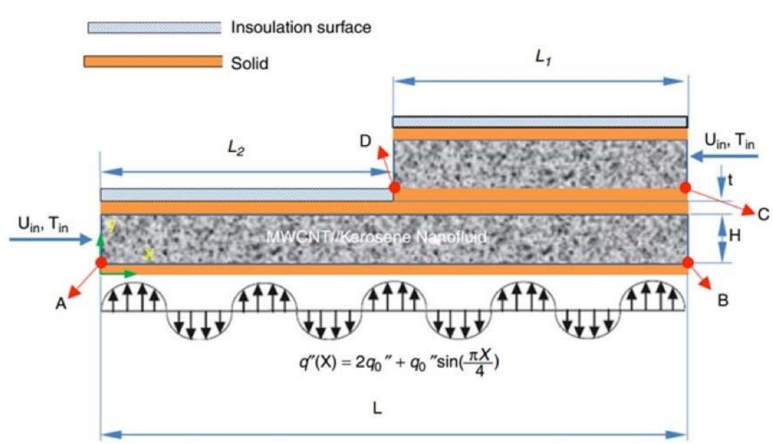


Fig. (6). Double layer microchannel with nonlinear heat flux.

positive role in increasing thermal performance of the heat sink. Numerical investigation of particle interaction due to Brownian motion in trapezoidal channel using copper oxide nanofluid is reported by Fani *et al*. [78]. Travnicek and Vit [79] investigated reversible pulsating jet to enhance heat and mass transfer by 12-40% which is more suitable to increase the collision between the nanoparticles. Glagar *et al.* [80] studied compact heat exchangers with different microchannel shapes. 3D numerical simulations were also done assuming constant temperature or constant heat flux on the pipe walls. The study states that microchannel shape influences the heat transfer effectiveness and pressure drop. They also conclude that best achievement was accomplished with microchannels of diamond and hexagonal shape. Increase in heat transfer with enhanced cooling and flow rate was developed by implementing triangular microchannel, it generated a thermally stable system under higher heat flux situations [81]. From the above-reported studies, microchannels cross sections with higher surface developed better heat transfer performance but with increased pressure drop. Slight effects of surface roughness and microchannel imperfections lead to a huge increase in enhancement of microchannels. Although it is practically impossible to experiment with a microfabricated device without surface abnormalities and additionally it is very difficult to fabricate very complex microchannel systems. But, it is totally possible to predict numerically the difference in enhancements due to surface modifications up to some extent. Furthermore, by efficiently adopting the numerical model for nanofluid we can solve the practical issues like agglomeration and can also predict the cycle time of the microchannel device.

2.5. Numerical Studies on Microchannel

Kalteha *et al.* [82] numerically investigated forced convection of nanofluids in a microchannel using a two-phase method by implementing Finite Volume Method (FVM). They coupled both the phases of copper-water nanofluids to simulate the Eulerian two-fluid model. Cosine weighting function is used to refine the grids of the wall and entrance length of the channel. Line by line method is used in numerical scheme and power law for discretizing the convection and diffusion terms. Mass conservation of the particle and fluid was obtained for pressure correction equation in order to use simple algorithm. They state that the two-phase model provides the uniform distribution of nanoparticles throughout the flow region. They numerically depicted that the nanoparticles inclusion increases the thermal boundary layer significantly. Further analysis registered that increase in volume fraction increases the pressure drop for an increase in Reynolds number. Izadi *et al*. [83] numerically studied the performance of Alumina nanofluids in an annulus. Single phase model has been implemented to study hydrodynamics and thermal characteristics of nanofluids. According to their study, there is no change in dimensionless velocity due to the increase in volume fraction but the temperature distribution is influenced highly by the volume fraction. Single phase model assumes the use of ultra-fine nanoparticles which is in the range less than 50nm. The numerical computation were carried for various Reynolds number (Re = 100-900) and volume fraction (V_f = 0-5%) for a particle diameter of 25nm.

Nimmagadda and venkatasubbaiah [84] discussed the numerical studies on conjugate heat transfer analysis using hybrid nanofluids (Al_2O_3 and Ag/Water). The studies were reported for the effect of various Reynolds number, volume fraction and particle size with water as base fluid. The governing equations were computed by Simplified Marker and Cell (SMAC) procedure with a non-staggered grid using FVM. Further, the interface temperatures between solid and fluid regions for different nanofluids were also analyzed. Results provide 148% increase in heat transfer coefficient for the use of (0.6vol% Al_2O_3 + 2.4vol% Ag) than the pure water. Li and Kleinstreuer [85] presented a numerical investigation with trapezoidal microchannel using CuO/Water nanofluids. The analysis performed for the particle diameter of 28.6nm for the range of 1-4% of volume fractions. The computations were carried out to compare KKL (Koo-Kleinstreuer-Li) model with Brownian- motion model. For the maximum volume fraction of 4%, increase in pressure drop was found to be 15%. Akbarina *et al*. [86] performed an investigation on rectangular microchannel with alumina nanofluid using FVM. The analyses were intended to study on slip and non-slip flows regimes in microchannel. Their result states that the increase in volume fraction does not enhance the Nusselt number, on contrary; the inlet velocity augments the heat transfer. The particle concentration does not have considerable effect in Poiseuille number for examined *Re*.

Tsai and Chein [87] analytically reported the investigation of microchannel heat sinks using copper-CNT/Water. The results were obtained for thermal resistance and performance characteristics of nanofluids. They found that the reduction in conductive thermal resistance and thermal capacity of the sinks by using nanofluids. The analysis was performed by including the porous medium model for nanofluid used in the microchannel and the result suggests that better performance was obtained for optimum porosity and aspect ratio. They used a channel height of 364µm with 88 channels for 4% volume fraction. Abbassi and Aghanajafi [88] investigated conjugate heat transfer in a microchannel heat sink using a combined analytical and numerical approach. The governing equations were based on porous medium model accompanied with Darcy equation. The study involved by assuming the ultrafine copper nanoparticles dispersed in a base fluid. The thermal dispersion model is adopted for heat transfer analysis and it is also integrated with the effect involving interfacial shells between nanoparticles and base fluid. They also investigated the influence of particle concentration, Reynolds number and thermal dispersion coefficient. Work is extended to find the effect of heat transfer in a turbulent region. It also reveals that nanofluid does not influence the temperature distribution of the channel wall.

Zhou *et al.* [89] conducted a numerical study on silicon microchannel within a trapezoidal and triangular cross-section using water as cooling fluid. The governing equations were discretized using FVM. Field synergy principle was discussed on the effect of varying Reynolds number and its influence on channel geometry. From their studies, velocity and temperature gradient are in better synergy when the Reynolds number is less than 100. Their study suggests that trapezoidal geometry provide better heat transfer. Their investigation concluded that the Nusselt number was found to be increasing in fully developed region which is contradictory in the case of conventional ducts. Jang and Choi [90] performed numerical investigation in a microchannel using diamond and copper nanofluids. Their result shows that 1% of diamond nanofluid enhances the performance of 10% than water for the same pumping power of 2.25W. They suggest that the inclusion of nanoparticles reduces the thermal resistance of the heat sink. Bhattacharya *et al.* [91] performed numerical studies on conjugate heat transfer in rectangular cross section using alumina nanofluids in silicon microchannel. Single phase model is used by considering particle as ultrafine with the thermal dispersion model (Table **3**) [92-112]. They have also implemented field synergy principle on forced convective heat transfer. There is 13.6% reduction in thermal resistance by the use of nanofluids due to increase in synergy angle. Simulation also reveals that better synergy level is seen for higher concentration. Decrease in thermal resistance by 7.8% was reported for an increase in Reynolds number from 250 to 500 for a constant volume fraction of 2%.

3. POROUS MICROCHANNEL

Porous media filled in the channel actively increases the surface area with a higher heat transfer coefficient. It also enhances the system by reducing local peak temperature with high uniform temperature distribution. Porous microchannel increases the mixing of the working fluids with an increase in local velocities. Further, the pressure in the system also reduces by optimizing the influential parameters like porosity and permeability. Dehghan *et al*. [113] performed an analytical study on improving the heat transfer in microchannel heat transfer using porous media. They have used Darcy-Brickmann equation and the Two-energy equation for solving fluid flow and heat transfer in a porous medium. Underperformance studies, they have evaluated the parameters like porosity, thermal conductivity, thermal resistance and internal heat generation. According to them, the use of rarefied porous media increases the heat transfer performance. They have also observed that the heat transfer in porous media under a slip condition is higher than that of the no-slip condition. Further, they have investigated for forced convection in porous microchannel using scale analysis (Fig. **7**) [114].

Table 3. Summary of the Microchannels with Various Channel Cross-Sections.

Author	Year	Working Fluid	Channel Details	Nature of Work	Remarks
Leng *et al.* [92]	2015	Water	Rectangular (double)	Numerical	Multi parameter optimization
Azizi *et al.* [93]	2015	Copper nanofluid	Cylinder	Experimental	25nm spherical copper nanoparticles were used
Rostami *et al.* [94]	2015	Water	Rectangular (wavy)	Numerical	Optimization for maximum Nu is done $D_h = f(S, H) = \frac{2S.H}{S+H}$
Haller *et al.* [95]	2009	Water	Rectangular	Experimental and numerical	Due to L and T bends vortices developed due to flow increases the temperature gradient near the walls.
Leelavinothan and Rajan [96]	2014	Water	Rectangular	Numerical	Increased number of inlets augments heat transfer by more boundary layer formations
Yang *et al.* [97]	2014	Copper oxide nanofluid	Trapezoidal	Numerical 3D	Used single phase and two-phase numerical models
Kuppusamy *et al.* [98]	2014	Water	Rectangular L = 180µM H = 25.5µM	Numerical	Thermal performance augments due to the implementation of secondary passage.
Silva *et al.* [99]	2008	Water	D_h = 637µM	Numerical and Experimental	Flow visualization
Lee *et al.* [100]	2012	Water	Rectangular	Numerical	Used synthetic jet
Guzman *et al.* [101]	2013	Air	Rectangular channel with interrupted blocks	Numerical 2D	Heat Transfer is 50% higher for quasi-periodic when compared with periodic and laminar flows
Che *et al.* [102]	2015	Mineral Oil with water droplets	Rectangular	Numerical 3D	Heat transfer study on recirculation in droplets and near the channel walls is discussed
Kwon and Kim [103]	2015	Water	Rectangular (double diameter channel)	Experimental	This designs capillary pressure dominates to reduce the friction developed a pressure drop
Sampaio *et al.* [104]	2015	-	Rectangular W = 100-350, H = 30-40	Experimental	Visualization of plasma layers in blood

Table (3) contd….

Author	Year	Working Fluid	Channel Details	Nature of Work	Remarks
Heck and Papavas-siliou [105]	2013	Water	Rectangular B = 2μM, H = 5μM, W = 2μM	Numerical 3D	Super hydrophobic surfaces are studied
Lin *et al*. [106]	2014	Carbon dioxide	Circular D_h = 1000μM	Experimental	Heat transfer enhancement is observed only at turbulent regime
Rawool *et al*. [107]	2006	-	Square 100 x 100μM	Numerical	Studies were conducted by providing an obstacle on the flow path
Xiong and Chung [108]	2010	Water	Circular D = 50μM L = 100μM	Numerical 3D	Bi-cubic Coons patch is used to construct the micro-tubes with surface roughness
Noorian *et al*. [109]	2014	Liquid Argon	Rectangular Nanochannel Triangular and Cylinder roughness	Numerical 2D	Surface roughness studies using molecular dynamics simulation
Noorian *et al*. [110]	2014	Liquid Argon	Nanochannel 3D Cube 3D Sphere roughness	Numerical 3D	Surface roughness studies using checker molecular dynamics simulation
Chen *et al*. [111]	2010	-	-	Numerical 2D	Channel is constructed using fractal surface roughness
Zhao and Yao [112]	2011	-	Rectangular	Numerical	The transition effects from laminar to turbulent with roughness inclusion in were investigated

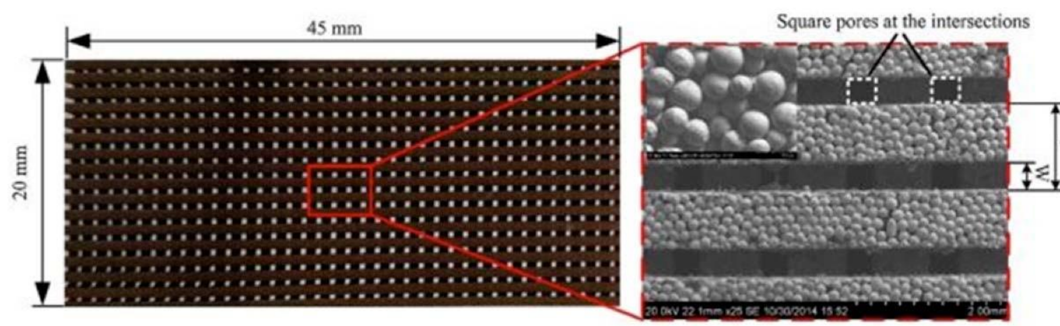


Fig. (7). Sintered porous microchannel, Zhang *et al*. [114].

Torabi and Peterson [115] performed thermodynamic study in microchannel filled with porous media subjected to magnetic field. The study consists of two different conditions where constant temperature was provided at both the top and the bottom walls. Later, the lower wall was provided by constant flux and upper wall with convection boundary condition. They found the influence of magnetic field in the movement of fluid at the porous interface. Higher Nusselt number has been observed by providing a specific number to the temperature coefficient. Additionally, they have performed investigations to develop a model for interface entropy generation in Torabi *et al*. [116]. It has been found that for lower values of temperature jump the overall entropy generation was not affected by the interface generation. By solving these two cases they have come to the conclusion that changing the temperature jump coefficient, total entropy generation can be modified. In such case, total entropy drops on constant temperature boundary condition but in constant flux, entropy generation increases with the temperature jump.

Shena *et al*. [117] performed computational studies on microchannel heat sinks with different porous Y structures. They considered a range of Re from 170 to 554 and its porosity from 0.7 to 0.9. They observed an increase in heat transfer for combined microchannel and porous media. They have developed 44% lesser thermal resistance by having porous Y structures along the flow. These y types develop disturbances along the flow of the fluid. Further, they develop pumping power more than 0.1W. Lu *et al*. [118] developed a new model to reduce pressure drop and thermal resistance at the same time by using microchannels accompanied with wavy type porous fins. By using a new model they observed the thermal resistance to reduce by 16.5% and pressure drop to 39.0% compared to conventional design. Furthermore, it has been observed that with the increment in the amplitude of the wavy channel, pressure drop reduces but thermal resistance is still higher. In short heat transfer is reduced by increasing the amplitude of the wavy channel (Fig. **8**) [119].

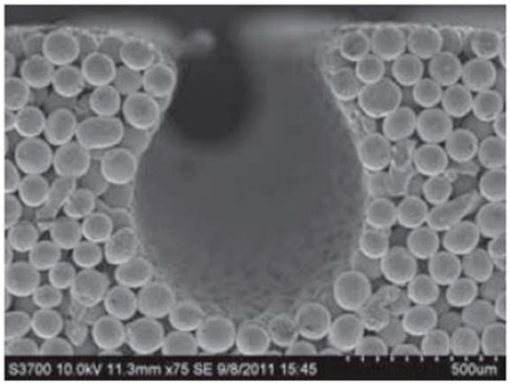


Fig. (8). SEM image of porous reentrant microchannel, Deng *et al*. [119].

Seetharamu *et al*. [120] performed numerical investigations with channel filled porous medium involving variable wall heat flux and temperature condition under non-equilibrium thermal models with internal heat generation. They have performed parametric studies using Biot number (Bi), wall temperature ratio, solid and fluid interface thermal conductivity. They have observed that Bi = 0.5-50 Nusselt number increases with increase in Darcy number. For higher wall heat flux, Nu was observed to decrease with increasing Darcy number and later it becomes constant. The nusselt number was found lesser for the wall with uneven wall temperatures. The nusselt number increases with increasing temperature jump coefficient and decreases for higher internal heat generation. Heydari *et al.* [121] employed truncated ribs with different orientation and attached with triangular microchannel using TiO_2 nanofluid. They observed that by using this model maximum efficiency was obtained for *Re* = 400. Using TiO_2 nanofluid with 4% of volume fraction, Nusselt number achieved was 1.7 times more than the pure fluids. The effect of nanoparticles is less dominant and lower velocity and parallelly the effect of ribs is not desirable. lopez *et al*. [122] performed analytical study over vertical microchannel with porous media using nanofluid. They have used Al_2O_3 nanofluid for their magneto-hydrodynamic studies. Considering nonlinear thermal radiation their result proved that the global entropy generation increases with nanoparticle concentration and Reynolds number. Summary of several other studies is reported in Table **4** [123-136].

4. MICROCHANNEL BOILING

Chen *et al.* [137] conducted an experimental investigation of porous microchannel flow boiling with interconnected nets. They found that under high heat flux situation porous interconnected microchannel performs better than reentrant porous microchannel by overcoming the bubble clogging problem. Also, porous interconnected microchannel develops predominate condensation effects under lower wall superheat conditions with increased mass flux at interconnected microchannel. Nucleate boiling dominates heat transfer mechanism at initial stages of boiling. Zeng *et al.* [138] performed an investigation on the effect of powder size in an interconnected microchannel with porous media. They concluded that the powder sizing of 50-75μm provides better performance due to its balanced permeability and capillary pressure effects. Further, on their pool boiling study, they found that the particle size of the porous microchannel is a highly influential parameter for the estimation of heat transfer coefficient. Additional work on porous boiling is summarized in Table **5** [139-147].

5. EXPERIMENTAL STUDIES

Figure **9** depicts the schematics of the flow line required to conduct the basic experimental investigations using microchannels. The test module consists of parallel microchannel connected with a cartridge heater to provide heat flux. The cartridge heater is controlled by regulated power supply. A peristaltic pump is connected to the microchannel to provide a pulsating flow. The outlet is connected to a secondary heat exchanger to reduce the outlet temperature of the working fluid to the room temperature before it is let to the sump which stores the fluid. The fluid is actively stirred in a low RPM to stabilize the dispersion of the working fluid. The heat sink is connected with the thermocouples to record the necessary change in temperature at the inlet and the outlet of the channel.

Manay and Sain [148] conducted experiments to study the influence of channel height on heat transfer and pressure drop characteristics. TiO_2 with the particle diameter of 25nm dispersed nanofluid was dispersed with volume fraction ranging from 0.25 to 2%. The work was carried out with four different channel heights ranging from 200 to 500μm for a constant flux of 80kW/m^2. Their results provide that increase in channel height increases the pressure drop and reduces the heat transfer rate. However, the TiO_2 nanofluids enhanced heat transfer than pure fluid. Rimbault *et al*. [149] performed an experimental study on copper oxide nanofluid in a microchannel heat sink with a particle diameter of 29nm. Tests were conducted with different volume fractions ranging from 0.24 to 4.5% for both laminar and turbulent regimes. The conditions of isothermal and heated test were analyzed with *Re* = 2500 and *Re* = 5000. Additionally, 70% increase in friction factor is noted for a volume fraction of 4.5%. From the results of suspended fluid, they observed that the transition from laminar to turbulent at *Re* = 1000 was seen similar to that of water. Also, behavior of nanoparticles does not have an impact when we include pumping power to our analysis and this further decreases when volume fraction is increased.

Zhang *et al.* [150] experimented with Alumina nanofluid in a circular microchannel with the diameter of 500μm with the particle volume fraction ranging from 0.25 to 0.77%. Tests were focused to determine the effect of nanoparticles over the Nusselt number and particle concentration. Increase in heat transfer attained for maximum volume fraction with the increment of 10.6%. A correlation was also proposed for the Nusselt number with the experimental results with a deviation of -4% and +5%. Peyghambarzadeh *et al.* [151] performed an experimental investigation on rectangular Cu-Be

Table 4. Summary of Porous Microchannel.

Author	Year	Fluid	Shape	Specifications	Remarks
Hung *et al*. [123]	2013	Water	Rectangular, trapezoidal and sandwich thin rectangular	F = 0.66 Re = 45-1350	Pressure drop is increased by porous medium and lowest is by using sandwich design Thermal performance can be increased by increasing Re
Ting *et al*. [124]	2015	Alumina nanofluid	Rectangular	F = 0.9 Re = 0-200	For high aspect ratio, microchannel with an increase in volume fraction reduced the entropy generation for lower Reynolds Number.
Hatami and Ganji [125]	2014	Copper nanofluid	Rectangular	F = 0-1 Ø = 0-0.06	Nu is increased for higher Aspect ratio due to better nanoparticles interaction with the solid region
Hung *et al*. [126]	2013	Water	Rectangular	F = 0.6 Re = 0-1600	Increased height of outlet region has more possibility of reducing pressure drop in porous microchannel
Ting *et al*. [127]	2014	Alumina nanofluids	Rectangular	F = 0.9 Re = 0-150	At low Reynolds number, nanofluid in porous media creates 12% increase in Heat transfer coefficient
Chuana *et al*. [128]	2015	Water	Rectangular (Porous Fin)	F = 0.6	New fin design drastically reduces the pressure drop by 43-47.9% but an increase in thermal resistance is by order of 4.1-4.9%
Ting *et al*. [129]	2015	Alumina nanofluid	Rectangular	F = 0.95 Re = 0-120	Average heat transfer coefficient is increased by 47% by symmetrical heating with nanofluids
Buonomo *et al*. [130]					
Khadami [131]	2016	-	-	F = 0.9	-
Poormehran *et al*. [132]	2015	Copper nanofluid and Alumina nanofluids	Rectangular	Ø = 0.01-0.04 D_n = 35-50nm	The optimum values of parameters are Ø = 0.01-0.04 A = 800 D_n = 35-50nm F = 45
Hung and Yan [133]	2013	Water	Rectangular	F = 0.55-0.85	76.6% of Enhancement is achieved by increasing the porosity to 0.85
Hung *et al*. [134]	2013	Water	Rectangular	F = 0.6-0.85	Decrease in thermal resistance is noticed with increase in pump power
Hung and Yan [135]	2013	Deionised water	Rectangular (Sandwich)	F = 0.55-0.85	Optimization of the channel parameters is done using inverse method by conjugate gradient method.
Ting *et al*. [136]	2015	Alumina nanofluid	Rectangular L = 0.03m 2H = 480μM Aluminium porous channel	Ø = 2% F = 0.95 D_p = 5nm Re = 0-150	Heat transfer irreversibility is increased when channel is heated asymmetrically but fluid friction is less dominated by thermal asymmetrically effects 2 energy equation model

Table 5. Porous Flow Boiling.

Author	Year	Working Fluid	Specifications	Parameters	Remarks
Deng *et al*. [139]	2015	Deionised water and ethanol	Copper channel D = 0.8mm L = 45mm W = 20mm H = 2mm	Circular D_H = 798μm F = 0.39 d_p = 75-110μM R_a = 2.9μM	Nucleate boiling is possible at very low wall superheats using RPM (reetent porous microchannel)
Pengaan Bai [140]	2014	Copper channel	-	D_p= 80-140μM F= 0.5	Flow boiling stability is improved in porous microchannel than smother microchannel Analysis of flow resistance and convective heat transfer is conducted experimentally

Table (5) contd….

Author	**Year**	**Working Fluid**	**Specifications**	**Parameters**	**Remarks**
Li *et al*. [141]	2015	Porous stainless sheets	-	F = 0.681 Ç = 0.985 S_t = 0.1mm	-
Jaikumar and Kandil-kar [142]	2015	Water Copper channel	Rectangular W_c = 762μM H_c = 40μM W_f = 200μM	D_p = 10-20μM C_t = 100μM	CHF = 128W/cm^2,W_{sh} = 19.5°C Sintered throughout gives 580kW/m^2 °C Heat Transfer Coefficient (HTC) for q = 3000W/m^2 when compared to plane channels
Tang *et al*. [143]	2016	Deionised water Copper (Spherical)	Rectangular P_c = 1.2P/m W_c = 0.40-0.70W/mm	D_p = 50-75μM, 25-50μM and 100-125μM F = 0.38-0.58	Maximum HTC and Wall Temperature (WT) for the particle range of 50-75μM Higher wall superheat is obtained for W_c = 0.40
Jaikumar and Kandil-kar [144]	2015	FC-87	Rectangular W_c = 300-762μM D_c = 200-400μM W_f = 200μM		Increase in CHF is observed for higher width, but not in the case of depth
Deng *et al*. [145]	2015	Water Copper R_c = 350μM, 400μM and 450μM	-	F = 0.39 d_p = 75-110μM	(Flow visualization) Two-phase $D_h = \frac{4A_{c,s}}{P} = \frac{4\left[W_{slot}H_{slot} + r^2\theta/2 + W_{slot}r\cos((2\nu-\theta)/2)\right]/2}{2H_{slot} + W_{slot} + r\theta}$ $\theta = 2\nu - \arcsin(W_{slot}/2r)$ RPM two-phase heat flows are more independent on heat flux and independent to mass flux
Bai *et al*. [146]	2013	Anhydrous ethanol	Rectangular (SS) (copper porous coated) W_c = 400μM H_c = 900μM L_c = 32mm	d_p = 540μM	Experimental, numerical studies -Single and two-phase regions analyzed Flow boiling heat transfer argumentation strictly drops on particle size 55μM is the optimum range
Zhang *et al*. [147]	2016	Deionised water Copper	Rectangular W_c = 0.40mm P_c = 1.2mm H_c = 1.1mm	d_p = 50-75μM F = 0.58	Flow Visualization studies Bubble diameter is bigger in interconnected nets for a complete range of flux than porous inter-connected nets

alloy microchannel with CuO and Al_2O_3nanofluid. The study was performed for a constant heat flux of 19W/cm^2 with the Reynolds number ranging from 500 to 2000. The study performed in a channel dimension of 400μm x 560μm with 17 such channels to analyses heat transfer coefficient, Nusselt number and pressure drop. Maximum enhancement was provided by alumina nanofluid of 49% with 1% volume fraction compared to that of copper oxide of 27% with 0.2% volume fraction. According to them, CuO has better enhancement than alumina; they also registered that increment is not due to volume fraction but due to increased Reynolds number.

Ahmed *et al*. [152] conducted an experimental study on double layered microchannel with triangular and rectangular cross-sections. The experimental series was carried out by suspending alumina and silicon nanoparticles. According to their study, double layered channels provide better performance compared to conventional single layered. Their results showed that triangular double layer provided wall temperature reduction by 27.4% than double rectangular layered and it also provides better uniformity of temperature. The triangular double layer has 16.6% less thermal resistance; moreover, there were no significant changes in pressure drop for both the cross-sections. Xia *et al*. [153] conducted an experimental study on microchannel heat exchangers using oxide nanofluids like alumina and titanium dioxide. The nanofluids were prepared by a two-step process with the volume fraction ranging from 0 to 1%. They used PVP (Poly Vinyl Pyrrolidone) for the stability of particle and also to reduce aggregation. They have used IR imaging to investigate the temperature distribution over heat sink. This reveals that thermal motion of nanoparticles would influence the early breakage of laminar flow and enhance the fluid and channel wall heat transfer.

Anoop *et al*. [154] performed experimental studies on microchannel with the suspensions containing silica nanoparticles for constant wall temperature conditions. Their results showed that an increase in flow rate enhanced heat transfer for both pure fluid and nanofluids. However, comparatively higher enhancement is seen for lower flow rates using nanofluids. They also performed a fouling test on microchannel by performing electron microscope examination due to nanoparticles precipitation. Yang *et al*. [155] performed a numerical and experimental study on different sets of pin fin arrangements. Lowest pressure drop has been ob-

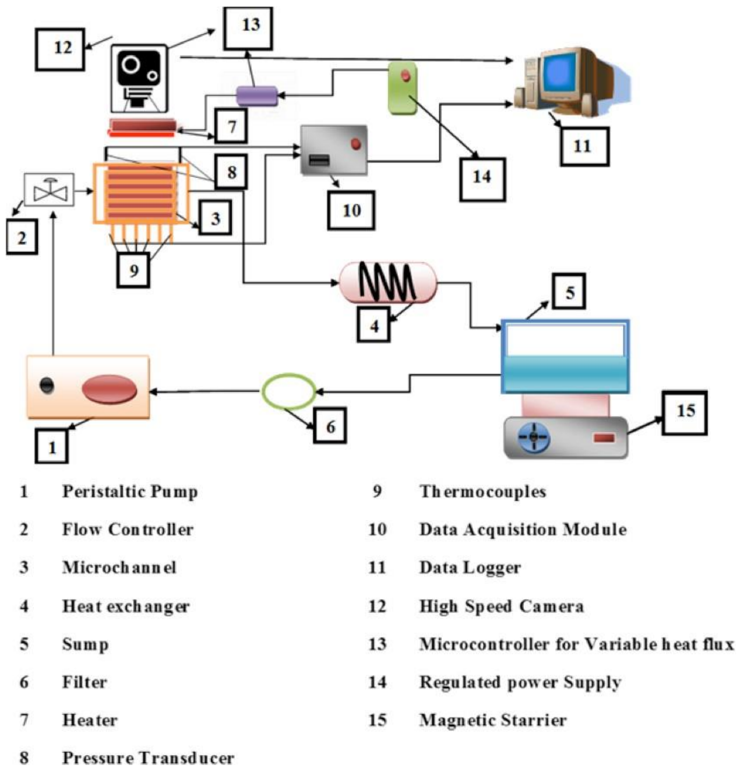


Fig. (9). Schematics of microchannel experimental flow line.

tained for circular pin fins configurations and their results were validated numerically. Several novel works were proposed with a different experimental approach for various applications which are summarized in Table **6** [156-165].

5.1. Electronic Hotspot Cooling

Localized high-temperature regions in processors are referred to as hotspots, these are developed due to high-speed circuits, due to which lower transistor threshold voltage develops a higher source to drain leakage. This leakage current in the transistor is a limiting factor on the development of lower power processors since this generates hotspots. However, the comparatively lower temperature is witnessed by cache zones of microprocessor this produces a non-uniform power and temperature distribution in the processors. Due to this the temperature difference in the processors tries to reach up to 5 to 30K. This hotspot is an acute issue for the latest highly integrated compact devices and has the potential to reduce the effectiveness of the cooling system.

Primarily in literature, the hotspot issue is addressed by using the embedded cooling system, jet impingement, slot nozzles etc. but predominantly it is by implementing microchannels. However flow inside the microchannels are not uniform and highly dependent on the type of flow configuration (e.g. C-Type, Z-Type and I-Type) which give rise to localized high-temperature zones due to fluid maldistribution. Suppose in the case of Parallel I-Type microchannels the mass flow rates in the middle channels is higher than the extreme channel. Due to this outlet temperature of the extreme channels are higher and develops minimal heat transfer near outlet region of the microchannels. Use of parallel microchannels to mitigate hotspot allowed to notice that heat sinks subjected with two different hotspot types one which developed due to flow maldistribution and other formed by the localized heat flux developed by the devices. Additionally, by optimizing the location of hotspots and introducing that nanofluid developed better results than water, but still flow induced hotspot were present in the sink for most of the cases in the literature. In most of the microchannel configurations flow induced hotspot is formed near the outlet region of the heat sink irrespective to the sink design.

An experimental investigation of embedded cooling systems to effectively minimize the hotspots in electronic systems is performed by Sharma *et al.* [166]. They implemented novel concept of slot nozzles with manifold microchannels, they reported that by providing the fluid access directly above the chip will reduce the pressure drop and increase the heat transfer by reducing the thickness of the thermal boundary layer by impinging jets. Sharma *et al.* [167] performed numerical approach on hotspot targeted conjugate heat transfer studies and additional investigation on optimization on the power maps in multicore by providing nonuniform heat flux at different regions ranging from 20W/cm^2 to 300W/cm^2. They used response surface model (RSM) to optimize the system by majorly concentrating to develop an optimal channel structure combined with a better flow rate. By optimizing the system nonuniform temperature distribution got reduced by 54% for a steady heat flux of 300W/cm^2.

Table 6. Novel Experimental Techniques in Microchannel Heat Sinks.

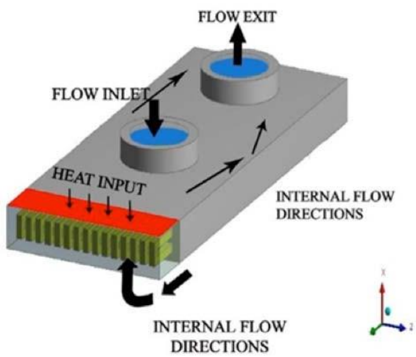
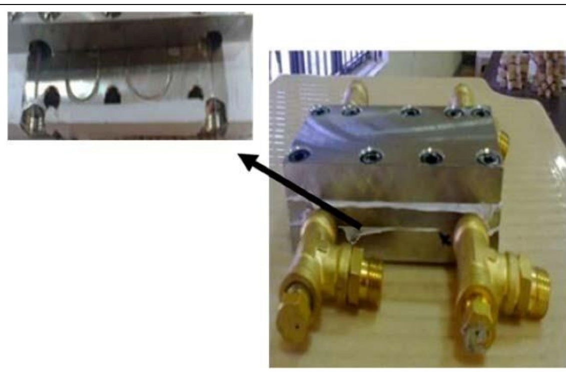
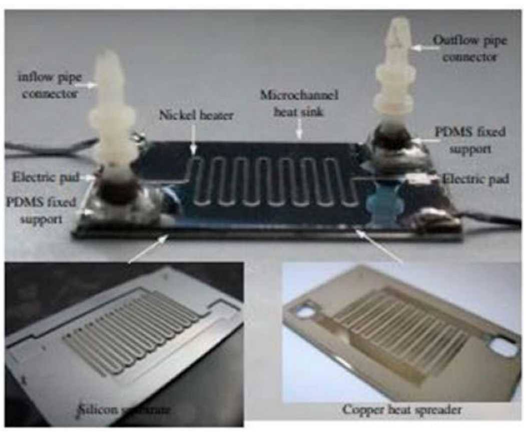
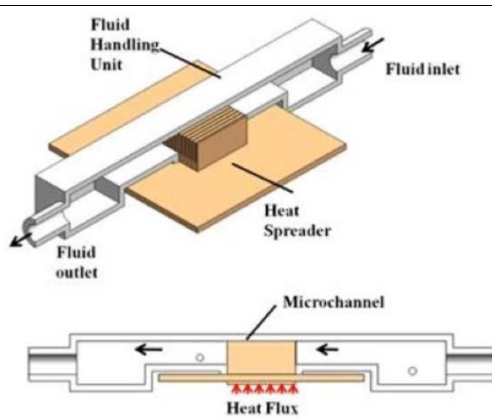
	Microchannel Device	Experimental Description
1		• Beni *et al*. [156] developed special microchannel for high power laser • They used Laser cutting of copper plates and stacked together by soldering
2		• Double layer serpentine based microchannel is developed by Narendran *et al*. [157] • Micromachining is implemented in manufacturing the channels
3		• Wang and Ding [158] demonstrated a novel longitudinal and transverse microchannel as a single unit using a silicon substrate and copper heat spreader using UV- Lithography
4		• Narendran *et al*. [159] demonstrated combined effects of microchannel and heat spreader for electronic cooling application • Electro Discharge Machining is used to manufacture microchannels and Silver soldering is made between copper spreader and channels

Table (6) contd….

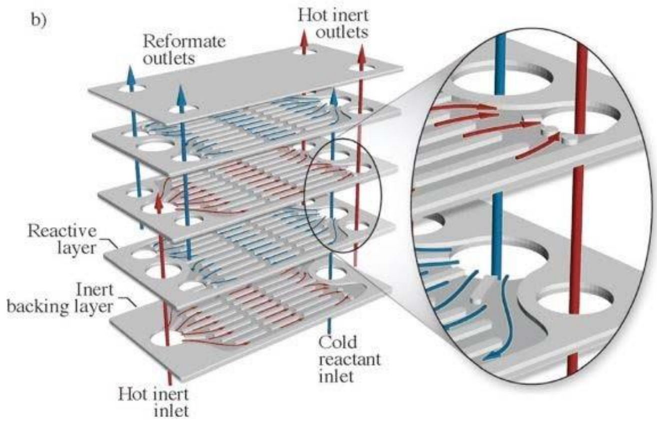
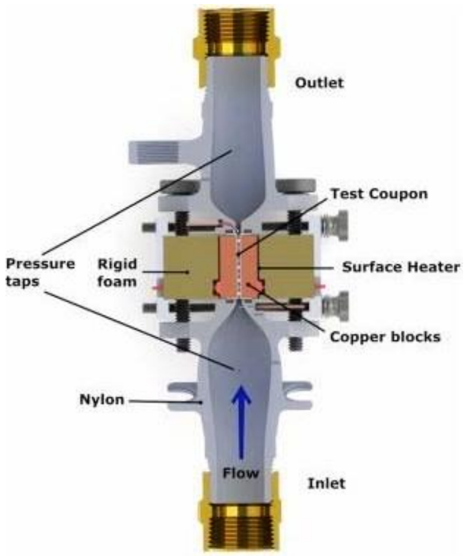
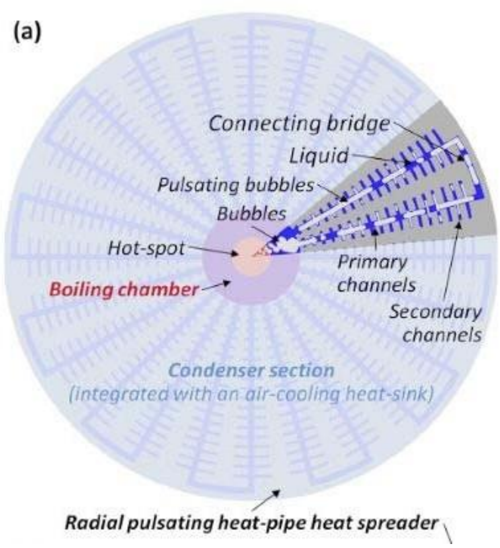
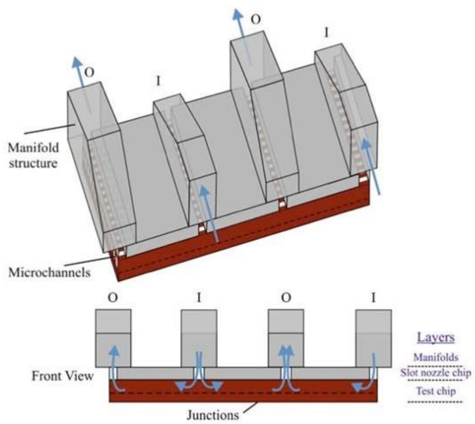
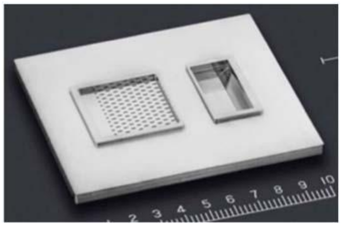
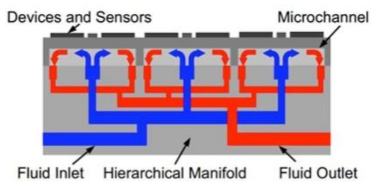
	Microchannel Device	**Experimental Description**
6		• Murphy *et al*. [160] developed novel ceramic based stacked continuous pass microchannel reactor by Green sintering process
7		• Kirsch and Thole [161] developed wavy microchannel using an additive manufacturing process • They used Direct Metal Laser Sintering (DMLS) Technique for printing microchannels
8		• Kelly *et al*. [162] novel pulsating heat pipe based heat spreader which contains fractal microchannels made up of the Brass plate for cooling Hotpots using the two-phase phenomenon

Table (6) contd….

	Microchannel Device	Experimental Description
Hybrid Microscale cooling devices		
9		• Sharma *et al*. [163] developed embedded microchannel heat sink with multiple inlets and outlet slot nozzles to effectively cool hotspots. The test chip is manufactured by photo Lithography technique
10		• Robinson *et al*. [164] developed microchannels combined with hybrid microjet impingement arrays which are manufactured using MICA free-form method
11		• Drummond *et al*. [165] studied Hierarchical based manifold microchannels to reduce conductive and contact resistance in microchannels. They used UV-Lithography to fabricate the microchannel unit

Further, they presented an approach to develop an effective design to implement efficient hot spot cooling. Maganti *et al*. [168] performed an investigation on selecting an optimal parallel microchannel to target hotspots in multicore processors. They have used Intel i7-4770 processor for their study. Additionally, investigation of fluid maldistribution accompanied with induced temperature maldistribution is captured by both numerically and experimentally. Eulerian-Lagrangian models were considered for modeling the nanofluid flow in the system. They concluded that the increase in flow maldistribution concurrently increases the thermal maldistribution.

Drummond *et al*. [169] investigated intra chip hotspot cooling using hierarchical manifold based microchannel cooling. They investigated the hotspot fluxes greater than 2500W/cm^2 and maintained 30°C as the average temperature of the chip with a pressure drop generated up to 75kPa. Inlet and outlet are provided perpendicular to the chip. They established a cooling of 500W/cm^2 with 50kPa of pressure drop. Lorenzini *et al*. [170] investigated embedded microfluidic cooling by implementing micro gaps between pin fin structures for migrating hotspot. They have used pure fluid for cooling by passing them between 200μm gap for a varied hotspot ranging from 250 to 750W/cm^2. They claim that their cooling system effectively maintains the temperature below 65°C with a marginal pressure drop. Their inlet fluid temperature is about 21.5°C. Lee *et al*. [171] conducted an experimental investigation on the obliquely finned microchannel heatsink. Here, they investigated the effectiveness of the oblique fin by varying the fin pitch for cooling hotspot regions. They reported that more than two hotspot condition the performance of the oblique enhanced microchannel developed more uniform temperature in the microchannel.

Han *et al*. [172] performed an experimental investigation on hotspots cooling using diamond heat spreader accompanied with microchannel Gallium nitride (GaN) heat sink. Additionally, numerical investigation was performed using COMSOL software considering temperature dependent material properties. The hotspot was developed by 8 micro heaters with power varying from 10 to 50W. They observed that by providing diamond heat spreader the maximum heater temperature reduces up to 22.9%. Microchannel heat spreaders involving highly conductive materials to spread high heat flux can be implemented with multiple inlets and outlets to generate better heat transfer performance [173]. Additionally, the manifold based microchannel is developed using targeted multiple inlet and outlet ports which is efficient in cooling local high heat flux zones [174].

Okamoto *et al.* [175] conducted an investigation on hotspot cooling on both vertical and horizontal flow to provide a comparison on its efficiency. They concluded that the vertical flow provides better cooling for 3D processors. Analytical study on the flow distribution in parallel microchannels with stepped inlet /outlet manifolds was presented by Solovitz [176]. According to them under lower Reynolds number flow distribution can be maintained to a higher accuracy concurrently hotspots can be controlled under a temperature difference of 2°C. Narayanan *et al.* [177] developed a thin film based evaporating cooling to target hotspots which are implemented by impinging dry air over the capillary assisted porous membrane with a thickness of 15µm. Here they have demonstrated for higher heat flux range more than 600W/cm^{2}where heat transfer coefficient reached up to 0.1MW/m^{2}k.

Green *et al.* [178] developed a hybrid integrated heat sink for managing hotspots on electronic chips. The result presented that the system effectively dissipated hotspot range of 400W/cm^2 with a marginal increase in pumping power. Furthermore, they have established that their proposed methods can extract hotspot near 1kW/cm^2. Experimental investigations on parallel microchannel accompanied with heat spreader for MEMS (Micro-Electro-Mechanical-Devices) cooling was performed by Maganti *et al*. [179]. Their studies investigated different flow configurations with the use of high thermal conductive nanofluid. They employed graphene nanofluid to decrease the hotspots in the parallel microchannel. They observed that the nanofluid provides more uniform cooling than the pure fluids. Numerical investigation of electronic components with micro pin fins subjected to hotspot was reported by Reddy and Dulikravich [180]. They performed multi optimization to determine the optimal working condition by minimizing hotspot temperature and pumping power. Further, they extended by reporting the structural stress experienced by the micro pin fins arrays due to hot spots. Zhang *et al.* [181] investigated transient cooling in an electronic chip with different types of microchannel heat sinks by both experimentally and numerically. According to them straight channels has comparatively higher response timing than U-shaped and serpentine type channels. Additionally, they reported that for increased flow rate reduction in response timing was noticed. Kinkelin *et al.* [182] performed experimental and numerical studies on peak temperature loading under transient chip cooling application by using hybrid heat spreader with combined CNT (Carbon Nano Tubes) and PCM (Phase Change Material). The polymer-based microchannel is implemented in multicore processors with direct contact under the minimal area of cooling which is highly effective for compact electronic components [183]. Furthermore, packaging with stacking multiple devices with insulating surfaces was developed for 3D multicore processors [184].

6. EMERGING SCOPE FOR MICROSCALE COOLING TECHNOLOGY

Due to the robust design of the present compact devices, nowadays, there is more interaction between the hardware devices and surroundings which was beyond reality decades ago. Creditability for this reach in advancement is a combined work of making microfabrication economically liable, developing materials which are compatible to the system and the most important boom is the software which integrated these devices that made it possible to reach us the level of most sophisticated gadgets that we adore today. Now, we are on the verge of transformation tunnel to IoT (Internet of Things) revolution, which is going to empower the human society with smart devices that potentially interact with the environment.

In this new race to the next generation, most of our devices will be wearable, flexible, biocompatible and definitely transparent. Currently, we are in basic research of exploiting the limits, understanding the Multiphysics, marking performance parameters and setting the standards for manufacturing and design. It is worth stating the work of Sitaraman *et al*. [185] who is involved in developing modelling and experimenting with the accelerated test setups for flexible electronics and wearable devices field. Hence, future device predominately flexible and profoundly fabricated by additive manufacturing it better period to initialize work on polymer-based microchannels with enhanced thermal conductivity using nano-additives. It will be resourceful to have a track on works of Heike Glade *et al.* [186] for the insights of polymer-based heat exchangers.

Over the past decades, bioimplants have been evolved to new heights, where sophisticated tailored devices exhibit potential solution for several artificial organs. As a consequence, these devices are developed in such a way that it is multifunctional by involving itself in a biomedical application with self-conditional health monitoring of the device as well as the human body. This opened up new opportunities for numerous biodevices which turned out to be potentially lifesaving. This requires high end device which is integrated with compatibility materials for localized cooling systems. These devices are applied in treatment of Focal Brain Cooling [187] and Cryosurgery to destroy cancer cells using microchannels. Hence, future research for microchannels are highly optimistic and it has the potential to touch our lives through many devices in coming years. It is clear that there will be operational hardship which has to overcome but results will be convincing.

CONCLUSION

Multiple interesting microchannel configurations have been proposed in last decades to fulfill the demands on cooling of the latest electronic devices. This article extends an insight of latest evolution of microchannel studies, accounting from the initial work on microchannel cross section, use of constructional structures in channels, nature-inspired bifurcations, compact microchannels for high-density cooling, enhancement study by using nanofluids, potential of two-phase flow in microchannels, Porous microchannels and so on. Besides lots of novel channels bifurcation numerical studies were reported with best results, only very few have reported experimental results which appeals the practical difficulty and experimental sophistication. For additional trend on bifurcation, design structures performed one may refer passive techniques for heat transfer augmentation in microchannel heat sink reported by Sidik *et al*. [188], Ghani *et al.* [189] and Ghani *et al.* [190].

Even though microchannels in above-mentioned areas exhibited optimistic potential over heat transfer enhancement and compactness, few critical drawbacks still prevail which must be solved to develop a better perspective for microchannel study in future. With the existing microchannel, several works were reported for its capability to reach the heat dissipation rate more than 1kW/cm^2 appear achievable. Moreover, methodological studies to develop compact microchannels with numerous design is also highly established. Additionally, to move forward into the further diversified microscale cooling platforms improvement in certain areas are recommended. The critical analysis of the literature on microchannel heat sink reveals that

1. An ingenious microchannel configuration design to develop better thermal management with reduced pressure drop under economical manufacturing process.
2. Work on combined improvisation of fluid manifold associated with microchannel are very critical in reducing flow maldistribution and its adverse effect of localized high-temperature regions.
3. One of the major drawbacks is the microchannel-based liquid cooling which is not yet commercialized for compact devices in spite of its supremacy but most of the studies were conducted to estimate the performance index of microchannel alone. Also, work on combined performance index by conducting an accelerated study with micropump, flow losses and head losses were not much seen.
4. Similarly, enormous work has been reported on heat transfer and friction factor characteristics of nanofluids using microchannel, but there is very minimal work to study the effect of microchannel heat transfer on nanofluid reliability. This will answer the query “what will be the lifecycle of the nanofluid”.
5. Nowadays, microfabrication is so matured that we have works reported on layered cores integrated with microchannel as a whole processor, then it seems right to investigate the coupled effect of thermal and structural.

CURRENT & FUTURE DEVELOPMENTS

Furthermore, ongoing advancements in microfabrication convince us that microchannel heat sink is an attractive alternative for heat pipes and fins in cooling compact electronic systems. In logical terms, it is only possible when associated practical devices of the microchannels are also taken into consideration as a single unite in the study. On whole single phase cooling using microchannels holds good and still an effective option to dissipate high power systems.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

Authors acknowledge the computing resources utilized in the Department of Mechanical Engineering at NIT Karnataka, Surathkal.

REFERENCES

[1] Zhang R, Hodes M, Nathan L, Wilcoxon R. Water based microchannel and Galinstan based mini channel cooling beyond 1 kW/cm^2 heat flux. IEEE Trans Compon Packag Manuf Technol 2015; 5(6): 762-70.

[2] Faulkner DJ, Shekarriz R. Forced convective boiling in microchannels for KW/cm^2 electronics cooling. *Proceedings of the ASME Summer Heat Transfer Conference*. Las Vegas, USA, July 2003.

[3] Dewan A, Srivastava P. A review of heat transfer enhancement through disruption in a microchannels. J Therm Sci 2015; 3: 201-14.

[4] Choi SUS. Enhancing thermal conductivity of fluids with nanoparticles. In: Siginer DA, Wang HP, Eds. Developments and Applications of Non-Newtonian Flows. ASME. 1995: pp. 99-105.

[5] Das SK, Choi SUS, Patel HE. Heat transfer in nanofluids- A review. Heat Transfer Eng 2006; 27(10): 3-19.

[6] Keblinski P, Eastman JA, Cahill DG. Nanofluids for thermal transport. Mater Today 2005; 8(6): 36-44.

[7] Kandlikar SG. High flux heat removal with microchannels - A roadmap of challenges and opportunities. Heat Transfer Eng 2005; 26(8): 5-14.

[8] Han X, Fedorov A, Joshi Y. Flow boiling in micro gaps for thermal management of high heat flux microsystems. J Electron Packag 2016; 138(4): 040801-6.

[9] Tullius JF, Vajtai R, Bayazitoglu Y. A review of cooling in microchannels. Heat Transfer Eng 2011; 32(8): 527-41.

[10] Tuckerman DB, Pease RFW. High-Performance heat sinking for VLSI. IEEE Electron Device Lett 1981; 5: 126-9.

[11] Malankowska M, Martins CF, Rho HS, Neves LA, Tiggelaar RM, Crespo JG, *et al.* Microfludic devices as gas- Ionic Liquid membrane contactors for CO_2 removal from anesthesia gases. J Memb Sci 2018; 545: 107-15.

[12] Zhai Y, Wang A, Koh D, Schneider P, Oh KW. A robust portable and back flow- free micro mixing device based on both capillary- and vacuum-driven flows. Lab Chip 2018; 18: 279-84.

[13] Hegde SS, Narendran G, Gnanasekaran N, Conjugate heat transfer in a hexagonal microchannels using hybrid nano fluids. *Proceedings of ASME-ICNMM*. Washington, USA, July, 2016.

[14] Santana HS, Tortola DS, Reis EM, Silva JL, Taranto OP. Transesterification reaction of sunflower oil and ethanol for biodiesel synthesis in microchannel reactor: Experimental and simulation studies. Chem Eng J 2016; 302: 752-62.

[15] Bowers MB, Mudawar I. Two-phase electronic cooling using mini-channel and micro-channel heat sinks: Part 1-design criteria and diffusion constraints. J Electron Packag 1994; 116(4): 290-7.

[16] McHale JP, Garimella SV. Heat transfer in trapezoidal microchannels of various aspect ratios. Int J Heat Mass Transf 2010; 53: 365-75.

[17] Recinella. R, Kandlikar SG. Enhanced flow boiling using radial open microchannels with manifold and offset strip fins. J Heat Transf 2018; 140: 021502-9.

[18] Singh PK, Harikrishna PV, Sundararajan T, Das SK. Experimental and numerical investigation into the hydrodynamics of Nano fluids in microchannels. Exp Therm Fluid Sci 2012; 42: 174-86.

[19] Li YF, Xia GD, Ma DD, Jia YT, Wang J. Characteristics of laminar flow and heat transfer in microchannel heatsink with triangular cavities and rectangular ribs. Int J Heat Mass Transf 2016; 98: 17-28.

[20] Yang D, Jin Z, Wang Y, Ding G, Wang G. Heat removal capacity of laminar coolant flow in a micro channel heat sink with different pin fins. Int J Heat Mass Transf 2017; 113: 366-72.

[21] Ghania IA, Kamaruzaman N, Sidik NAC. Heat transfer augmentation in a microchannel heat sink with sinusoidal cavities and rectangular ribs. Int J Heat Mass Transf 2017; 108: 1969-81.

[22] Tokit EM , Mohammed HA, Yusoff MZ. Thermal performance of optimized interrupted microchannel heat sink (IMCHS) using nanofluids. Int Commun Heat Mass Transf 2012; 39: 1595-604.

[23] Chai L, Xia GD, Wang HS. Laminar flow and heat transfer characteristics of interrupted microchannel heat sink with ribs in the transverse micro chambers. Int J Therm Sci 2016; 110: 1-11.

[24] Chen L, Yang A, Xie Z, Sun F. Constructal entropy generation rate minimization for cylindrical pin fin heat sinks. Int J Therm Sci 2017; 111: 168-74.

[25] Wong KC, Lee JH. Investigation of thermal performance of microchannel heat sink with triangular ribs in the transverse micro chambers. Int Commun Heat Mass Transf 2015; 65: 103-10.

[26] Abdoli A, Jimenez G, Dulikravich GS. Thermo-fluid analysis of micro pin-fin array cooling configurations for high heat fluxes with a hot spot. Int J Therm Sci 2015; 90: 290-7.

[27] Mohammadian SK, Zhang Y. Analysis of nanofluid effects on thermoelectric cooling by micro-pin-fin heat exchangers. Appl Therm Eng 2014; 70: 282-90.

[28] Maghaddam, S., Fazeli, S.A. Hierarchical hydrophilic/hydrophobic micro/nanostructures for pushing the limits of critical heat flux. US20160295742 (**2016**).

[29] Zhao J, Huang S, Gong L, Huang Z. Numerical study and optimizing on micro square pin-fin heat sink for electronic cooling. Appl Therm Eng 2016; 93: 1347-59.

[30] Vinotha R, Kumar S. Channel cross section effect on heat transfer performance of oblique finned microchannel heat sink. Int Commun Heat Mass Transf 2017; 87: 270-6.

[31] Adewumi OO, Ochende TB, Meyer JB. Constructal design of combined microchannel and micro pin fins for electronic cooling. Int J Heat Mass Transf 2013; 66: 315-23.

[32] Shafeie H, Abouali O, Jafarpur K, Ahmadi G. Numerical study of heat transfer performance of single-phase heatsinks with micro pin-fin structures. Appl Therm Eng 2013; 58: 68-76.

[33] Xie G, Zhang F, Sundén B, Zhang W. Constructal design and thermal analysis of microchannel heat sinks with multistage bifurcations in single-phase liquid flow. Appl Therm Eng 2014; 62: 791-802.

[34] Li Y, Zhang F, Sunden B, Xie G. Laminar thermal performance of microchannel heat sinks with constructal vertical Y-shaped bifurcation plates. Appl Therm Eng 2014; 73: 185-95.

[35] Lee YJ, Lee PS, Chou SK. Enhanced thermal transport in microchannel using oblique fins. J Heat Transf 2012; 134(10): 101901.

[36] Brinda R, Daniel RJ, Sumangala K. Ladder shape micro channels employed high performance micro cooling system for ULSI. Int J Heat Mass Transf 2012; 55: 3400-11.

[37] Chai L, Xia G, Zhou M, Li J, Jingzhi Q. Optimum thermal design of interrupted microchannel heat sink with rectangular ribs in the transverse micro chambers. Appl Therm Eng 2013; 51: 880-9.

[38] Liu M , Liu D, Xu S, Chen Y. Experimental study on liquid flow and heat transfer in micro square pin fin heat sink. Int J Heat Mass Transf 2011; 54: 5602-11.

[39] Aliabadia MK, Hassanib SM, Mazloumib SH. Enhancement of laminar forced convection cooling in wavy heat sink with rectangular ribs and Al_2O_3/water nanofluids. Exp Therm Fluid Sci 2017; 89: 199-210.

[40] Chai L, Xia GD, Wang HS. Parametric study on thermal and hydraulic characteristics of laminar flow in microchannel heat sink with fan-shaped ribs on sidewalls - Part 2: Pressure drop. Int J Heat Mass Transf 2016; 97: 1081-90.

[41] Lorenzini G, Biserni C, Rocha LAO. Constructal design of non-uniform X-shaped conductive pathways for cooling. Int J Therm Sci 2013; 71: 140-7.

[42] Hajmohammadi MR, Abianeh VA, Moezzinajafabadi M, Daneshi M. Fork-shaped highly conductive pathways for maximum cooling in a heat generating piece. Appl Therm Eng 2013; 61: 228-35.

[43] Jimenez CAR, Guerrero AH, Cervantes JG, Gutierrez DL, Valle CUG. CFD study of constructal microchannel networks for liquid-cooling of electronic devices. Appl Therm Eng 2016; 95: 374-81.

[44] Farzaneh M, Salimpour MR, Tavakoli MR. Design of bifurcating microchannels with/without loops for cooling of square-shaped electronic components. Appl Therm Eng 2016; 108: 581-95.

[45] Alexander, P. Fractal heat transfer device. US20120285660 (**2012**).

[46] Peng Y, Liu W, Chen W, Wang N. A conceptual structure for heat transfer imitating the transporting principle of plant leaf. Int J Heat Mass Transf 2014; 71: 79-90.

[47] Chen Y, Yao F, Huang X. Mass transfer and reaction in methanol steam reforming reactor with fractal tree-like microchannel network. Int J Heat Mass Transf 2015; 87: 279-83.

[48] Xia C, Fu J, Lai J, Yao X, Chen Z. Conjugate heat transfer in fractal tree-like channels network heat sink for high-speed motorized spindle cooling. Appl Therm Eng 2015; 90: 1032-42.

[49] Liu HL, An XK, Wang CS. Heat transfer performance of T-Y type micro-channel heat sink with liquid GaInSn coolant. Int J Therm Sci 2017; 120: 203-19.

[50] Peng YI, Liu W, Liu B, Liu J, Huang K, Wanga L, *et al*. The performance of the novel vapor chamber based on the leaf vein system. Int J Heat Mass Transf 2015; 86: 656-66.

[51] Yu XF, Zhang CP, Teng JT, Huang SY, Jin SP, Lian YF, *et al*. A study on the hydraulic and thermal characteristics in fractal tree-like microchannels by numerical and experimental methods. Int J Heat Mass Transf 2012; 55: 7499-507.

[52] Zhang CP, Lian YF, Yu XF, Liu W, Teng JT, Xua TT, *et al*. Numerical and experimental studies on laminar hydrodynamic and thermal characteristics in fractal-like microchannel networks. Part A: Comparisons of two numerical analysis methods on friction factor and Nusselt number. Int J Heat Mass Transf 2013; 66: 930-8.

[53] Zhang CP, Lian YF, Yu XF, Liu W, Teng JT, Xua TT, *et al*. Numerical and experimental studies on laminar hydrodynamic and thermal characteristics in fractal-like microchannel networks. Part B: Investigations on the performances of pressure drop and heat transfer. Int J Heat Mass Transf2013; 66: 939-47.

[54] Zhang CP, Lian YF, Hsu CH, Teng JT, Liu S, Chang YJ, *et al*. Investigations of thermal and flow behavior of bifurcations and bends in fractal-like microchannel networks: Secondary flow and recirculation flow. Int J Heat Mass Transf 2015; 85: 723-31.

[55] Xu S, Li Y, Hu X, Yang L. Characteristics of heat transfer and fluid flow in a fractal multilayer silicon microchannel. Int Commun Heat Mass Transf 2016; 71: 86-95.

[56] Ghaedamini H, Salimpour MR, Mujumdar AS. The effect of svelteness on the bifurcation angles role in pressure drop and flow uniformity of tree-shaped microchannels. Appl Therm Eng 2011; 31: 708-16.

[57] Xu S, Wanga W, Fang K, Wong CN. Heat transfer performance of a fractal silicon microchannel heat sink subjected to pulsation flow. Int J Heat Mass Transf 2015; 81: 33-40.

[58] Brian JD, Liburdy JA, Pence DV. Experimental studies of adiabatic flow boiling in fractal-like branching microchannels. Exp Therm Fluid Sci 2011; 35: 1-10.

[59] Heymann D, Pence D, Narayanan V. Optimization of fractal-like branching microchannel heatsinks for single-phase flows. Int Therm Sci2010; 49: 1383-93.

[60] Shui L, Huang B, Dong K, Zhang C. Investigation of heat transfer and flow characteristics in fractal tree-like microchannel with steam cooling. *ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition*. Charlotte, NC, USA, June, 2017.

[61] Vafai K, Zhu L. Analysis of two-layered micro-channel heat sink concept in electronic cooling. Int J Heat Mass Transf 1999; 42: 2287-97.

[62] Wei X, Joshi Y. Stacked microchannel heat sinks for liquid cooling of microchannel components. J Electron Packag 2004; 126: 60-6.

[63] Abdoli A, Dulikravich GS, Vasquez G, Rastkar S. Thermo-fluid stress-deformation anlysis of two-layer microchannel for cooling chips with hot spots. J Electron Packag 2015; 137: 031003-8.

[64] Koo MJ, Im S, Joang L, Goodson KE. Integrated microchannel cooling for three-dimensional electronic circuit architectures. J Heat Transf 2005; 127: 49-58.

[65] Kim YJ, Joshi YK, Fedorov AG, Lee YJ, Lim SK. Thermal characterization of interlayer microfluidic cooling of three-dimensional integrated circuits with non-uniform heat flux. J Heat Transf 2010; 132: 041009-9.

[66] Ansari D, Kim KY. Hotspot analysis of double-layer microchannel heat sinks. Heat Transfer Eng 2018: 1-18. DOI: 10.1080/01457632.2018.1460918.

[67] Zhai Y, Xia G, Li Z, Wang HA. Noval arrangement of staggered flow in double-layered microchannel heat sinks for microelectronic cooling. Int Commun Heat Mass Transf 2016; 79: 98-104.

[68] Wong KC, Ang ML. Thermal hydraulic performance of a double-layer microchannel heat sink with channel contraction. Int Commun Heat Mass Transf 2017; 81: 269-75.

[69] Kumar A, Nath S, Bhanja D. Effect of nanofluid on thermos hydraulic performance of double layer tapered microchannel heat sink used for electronic chip cooling. Numer Heat Tr A Appl 2018; 73: 429-45.

[70] Arabpour A, Karimipour A, Toghraie D, Akbari OA. Investigation into the effects of slip boundary condition on nanofluid flow in a double-layer microchannel. J Therm Anal Calorim 2018; 131: 2975-91.
[71] Sadasivam R, Manglik RM, Jog MA. Fully developed forced convection through trapezoidal and hexagonal ducts. Int J Heat Mass Transf 1999; 42: 4321-31.
[72] Koo J, Kleinstreuer C, Laminar nanofluid flow in micro heat-sinks. Int J Heat Mass Transf 2005; 48: 2652-61.
[73] Wu HY, Cheng P. Friction factors in smooth trapezoidal silicon microchannels with different aspect ratios. Int J Heat Mass Transf 2003; 46: 2519-25.
[74] Dharaiya VV, Kandlikar SG. A numerical study on effects of 2D structured sinusoidal elements on fluid flow and heat transfer at microscale. Int J Heat Mass Transf 2013; 57: 190-201.
[75] Jung JY, Oh HS, Kwak HY. Forced convective heat transfer of nano fluids in microchannels. Int J Heat Mass Transf 2009; 52: 466-72.
[76] Suresh S, Venkitaraj KP, Selvakumar P, Chandrasekar M. Effect of Al_2O_3 - Cu/water hybrid nanofluid in heat transfer. Exp Therm Fluid Sci 2012; 38: 54-60.
[77] Guo L, Xu H, Gong L. Influence of wall roughness models on fluid flow and heat transfer in microchannels. Appl Therm Eng 2015; 84: 399-408.
[78] Fani B, Kalteh M, Abbassi A. Investigating the effect of Brownian motion and viscous dissipation on the nanofluid heat transfer in a trapezoidal microchannel heat sink. Adv Powder Technol 2015; 26: 83-90.
[79] Travnicek Z, Vit T. Impingement heat/mass transfer to hybrid synthetic jets and other reversible pulsating jets. Int J Heat Mass Transf 2015; 85: 473-87.
[80] Glazar V, Frankovic B, Trp A. Experimental and numerical study of the compact heat exchanger with different microchannel shapes. Int J Refrig 2015; 51: 144-53.
[81] Dickey, J.T., Lam, T.T. High density Electronic cooling triangular shaped microchannel device. US7523780 (**2009**).
[82] Kalteha M, Abbassi A, Avval MS, Harting J. Eulerian-Eulerian two-phase numerical simulation of nanofluid laminar forced convection in a microchannel. Int J Heat Fluid Flow 2011; 32: 107-16.
[83] Izadi M, Behzadmehr A, Vahida DJ. Numerical study of developing laminar forced convection of a nanofluid in an annulus. Int J Therm Sci 2009; 48: 2119-29.
[84] Nimmagadda R, Venkatasubbaiah K. Conjugate heat transfer analysis of micro-channel using novel hybrid nanofluid (Al_2O_3+ Ag/Water). Eur J Mech B-Fluid 2015; 52: 19-27.
[85] Li J, Kleinstreuer C. Thermal performance of nanofluid flow in microchannel. Int J Heat Fluid Flow 2008; 29: 1221-32.
[86] Akbarinia A, Abdolzadeh M, Laur R. Critical investigation of heat transfer enhancement using nanofluids in microchannels with slip and non-slip flow regimes. Appl Therm Eng 2011; 31: 556-65.
[87] Tsai TH, Chein R. Performance analysis of nanofluid-cooled microchannel heat sinks. Int J Heat Fluid Flow 2007; 24: 1013-26.
[88] Abbassi H, Aghanajafi C. Evaluation of heat transfer augmentation in a nanofluid-cooled microchannel heat sink. J Fusion Energ 2006; 25: 187-96.
[89] Zhuo L, Quan TW, Ling HY. A numerical study of laminar convective heat transfer in microchannel with non-circular cross-section. Int J Therm Sci 2006; 45: 1140-8.
[90] Jang SP, Choi SUS. Cooling performance of a microchannel heat sink with nanofluids. Appl Therm Eng 2006; 26: 2457-63.
[91] Bhattacharya P, Samantha AN, Chakraborty S. Numerical study of conjugate heat transfer in rectangular microchannel heat sink with Al_2O_3/H_2O nanofluid. Heat Mass Transf 2009; 45: 1323-33.
[92] Leng C, Wang XD, Wang TH, Yan YM. Multi-parameter optimization of flow and heat transfer for a novel double-layered microchannel heat sink. Int J Heat Mass Transf 2015; 84: 359-69.
[93] Azizi Z, Alamdari A, Malayeri MR. Convective heat transfer of Cu-water nanofluid in a cylindrical microchannel heat sink. Energy Convers Manag 2015; 101: 515-24.
[94] Rostami J, Abbassi A, Avval MS. Optimization of conjugate heat transfer in wavy walls microchannels. Appl Therm Eng 2015; 82: 318-28.
[95] Haller D, Woias P, Kockmann N. Simulation and experimental investigation of pressure loss and heat transfer in microchannel networks containing bends and T-junctions. Int J Heat Mass Transf 2009; 52: 2678-89.
[96] Vinodhan VL, Rajan KS. Computational analysis of new microchannel heat sink configurations. Energy Convers Manag 2014; 86: 595-604.
[97] Yang YT, Tsai KT, Wang YH, Lin SH. Numerical study of microchannel heat sink performance using nanofluids. Int Commun Heat Mass Transf 2014; 57: 27-35.
[98] Kuppusamy NR, Saidur NNN, Ghazali R, Mohammed HA. Numerical study of thermal enhancement in micro channel heat sink with secondary flow. Int J Heat Mass Transf 2014; 78: 216-23.
[99] Silva GA, Leal N, Semiao V. Micro-PIV and CFD characterization of flows in a microchannel: Velocity profiles, surface roughness and Poiseuille numbers. Int J Heat Fluid Flow 2008; 29: 1211-20.
[100] Lee A, Timchenko V, Yeoha GH, Reizes JA. Three-dimensional modelling of fluid flow and heat transfer in micro-channels with synthetic jet. Int J Heat Mass Transf 2012; 55: 198-213.
[101] Guzmán AM, Beizab MP, Diaz AJ, Fischer PF, Ramos JC. Flow and heat transfer characteristics in micro and mini communicating pressure driven channel flows by numerical simulations. Int J Heat Mass Transf 2013; 58: 568-77.
[102] Che Z, Wonga TN, Nguyen NT, Yang C. Three dimensional features of convective heat transfer in droplet-based microchannel heat sinks. Int J Heat Mass Transf 2015; 86: 455-64.
[103] Kwon GH, Kim SJ. Experimental investigation on the thermal performance of a micro pulsating heat pipe with a dual-diameter channel. Int J Heat Mass Transf 2015; 89: 817-28.
[104] Sampaio D, Lopes D, Semiao V. Horse and dog blood flows in PDMS rectangular microchannels: Experimental characterization of the plasma layer under different flow Conditions. Exp Therm Fluid Sci 2015; 68: 205-15.
[105] Heck ML, Papavassiliou DV. Effects of hydrophobicity-inducing roughness on micro-flows. Chem Eng Comm 2013; 200: 919-34.
[106] Lin TY, Chen CW, Yang CY, Kandlikar SG. An Experimental investigation on friction characteristics and heat transfer of air and CO_2 flow in microtubes with structured surface roughness. Heat Transfer Eng 2014; 35: 150-8.
[107] Rawool AS, Mitra SK, Kandlikar SG. Numerical simulation of flow through microchannels with designed roughness. Microfluid Nanofluid 2006; 2: 215-21.
[108] Xiong R, Chung JN. Investigation of laminar flow in microtubes with random rough surfaces. Microfluid Nanofluid 2010; 8: 11-20.
[109] Noorian H, Toghraie D, Azimian AR. The effects of surface roughness geometry of flow undergoing Poiseuille flow by molecular dynamics simulation. Heat Mass Transf 2014; 50(1): 95-104.
[110] Noorian H, Toghraie D, Azimian AR. Molecular dynamics simulation of Poiseuille flow in a rough nano channel with checker surface roughness geometry. Heat Mass Transf 2014; 50: 105-13.
[111] Chen Y, Fu P, Zhang C, Shi M. Numerical simulation of laminar heat transfer in microchannels with rough surfaces characterized by fractal Cantor structures. Int J Heat Fluid Flow 2010; 31: 622-9.
[112] Zhou G, Yao SC. Effect of surface roughness on laminar liquid flow in micro-channels. Appl Therm Eng 2011; 31: 228-34.
[113] Dehghan M, Valipour MS, Saedodin S. Microchannels enhanced by porous materials: Heat transfer enhancement or pressure drop increment. Energy Convers Manag 2016; 110: 22-32.
[114] Zhang S, Sun Y, Yuan W, Tang Y, Tang H, Tang K. Effects of heat flux, mass flux and channel width on Flow boiling performance of porous interconnected microchannel nets. Exp Therm Fluid Sci 2018; 90: 310-8.
[115] Torabi M, Peterson GP. Effects of velocity slip and temperature jump on the heat transfer and entropy generation in micro porous channels under magnetic field. Int J Heat Mass Transf 2016; 102: 585-95.
[116] Torabi M, Zhang Z, Peterson GP. Interface entropy generation in micro porous channels with velocity slip and temperature jump. Appl Therm Eng 2017; 111: 684-93.
[117] Shena B, Yan H, Sunden B, Xue H, Xie G. Forced convection and heat transfer of water-cooled microchannel heatsinks with various structured metal foams. Int J Heat Mass Transf 2017; 113: 1043-53.
[118] Lu G, Zhao J, Lin L, Wang XD, Yan WM. A new scheme for reducing pressure drop and thermal resistance simultaneously in microchannel heat sinks with wavy porous fins. Int J Heat Mass Transf 2017; 111: 1071-8.
[119] Deng D, Tang Y, Shao H, Zeng J, Zhou W, Liang D. Effect of structural parameter on flow boiling performance of reentrant porous microchannels. J Microelectron Microeng 2014; 24: 065025.

[120] Seetharamu KN, Leela V, Kotloni N. Numerical investigation of heat transfer in a micro-porous-channel under variable wall heat flux and variable wall temperature boundary conditions using local thermal non-equilibrium model with internal heat generation. Int J Heat Mass Transf 2017; 112: 201-15.

[121] Heydari M, Toghraie D, Akbari OA. The effect of semi-attached and offset mid-truncated ribs and Water/TiO_2 nanofluid on flow and heat transfer properties in a triangular microchannel. Therm Sci Eng Prog 2017; 2: 140-50.

[122] Lopez A, Ibanez G, Pantoja J, Moreira J, Lastres O. Entropy generation analysis of MHD nanofluid flow in a porous vertical microchannel with nonlinear thermal radiation, slip flow and convective-radiative boundary conditions. Int J Heat Mass Transf 2017; 107: 982-94.

[123] Hung TC, Huang YX, Yan WM. Thermal performance analysis of porous-microchannel heat sinks with different configuration designs. Int J Heat Mass Transf 2013; 66: 235-43.

[124] Ting TW, Hung YM, Guo N. Entropy generation of viscous dissipative nanofluid flow in thermal non-equilibrium porous media embedded in microchannels. Int J Heat Mass Transf 2015; 81: 862-77.

[125] Hatamia M, Ganji DD. Thermal and flow analysis of Microchannel Heat Sink (MCHS) cooled by Cu-water nanofluid using porous media approach and least square method. Energy Convers Manag 2014; 78: 347-58.

[126] Hung TH, Huang YX, Yan YM. Thermal performance of porous microchannel heat sink: Effects of enlarging channel outlet. Int Commun Heat Mass Transf 2013; 48: 86-92.

[127] Ting TW, Hung YM, Guo N. Viscous dissipative forced convection in thermal non-equilibrium nanofluid-saturated porous media embedded in microchannels. Int Commun Heat Mass Transf 2014; 57: 309-18.

[128] Chuana L, Wanga XD, Wang TH, Yan WM. Fluid flow and heat transfer in microchannel heat sink based on porous fin design concept. Int Commun Heat Mass Transf 2015; 65: 52-7.

[129] Ting TW, Hung YM, Guo N. Viscous dissipative nanofluid convection in asymmetrically heated porous microchannels with solid-phase heat generation. Int Commun Heat Mass Transf 2015; 68: 236-47.

[130] Buonomo B ,Manca O, Lauriat G. Forced convection in microchannels filled with porous media in local thermal non-equilibrium conditions. Int J Therm Sci 2014; 77: 206-22.

[131] Khademi M. Effect of thermal radiation on temperature differential in microchannels filled with parallel porous media. Int J Therm Sci 2016; 99: 228-37.

[132] Pourmehrana O, Gorjia MR, Hatamib M, Sahebic SAR, Domairry G. Numerical optimization of microchannel heatsink (MCHS) performance cooled by KKL based nanofluids in saturated porous medium. J Taiwan Inst Chem E 2015; 55: 49-68.

[133] Hung TC, Yan YM. Thermal performance enhancement of microchannel heat sinks with sintered porous media. Numer Heat Tr A Appl 2013; 63: 666-86.

[134] Hung TC, Huang YX, Sheu TS and Yan YM. Numerical optimization of the thermal performance of a porous microchannel heat sink. Numer Heat Tr A Appl 2014; 65: 419-34.

[135] Hung TC, Yan YM. Optimization of design parameters for a sandwich-distribution porous-microchannel heat sink. Numer Heat Tr A Appl 2014; 66: 229-51.

[136] Ting TW, Hung YM, Guo N. Entropy generation of viscous dissipative nanofluid convection in asymmetrically heated porous microchannels with solid-phase heat generation. Energy Convers Manag 2015; 105: 731-45.

[137] Chen J, Zhang S, Tang Y, Chen H, Yuan W, Zeng J. Effect of operational parameters on flow boiling heat transfer performance for porous interconnected microchannel nets. Appl Therm Eng 2017; 121: 443-53.

[138] Zeng J, Chen C, Tang Y, Wang X, Zhang L, Zhang S, *et al*. Effect of powder size on capillary and two-phase heat transfer performance for porous interconnected microchannel nets as enhanced wick for two-phase heat transfer devices. Appl Therm Eng 2016; 104: 668-77.

[139] Deng D, Chen R, Tang Y, Lu L, Zeng T, Wan W. A comparative study of flow boiling performance in reentrant copper microchannels and reentrant porous microchannels with multi-scale rough surface. Int J Multiphase Flow 2015; 72: 275-87.

[140] Bai PF, Yi ZC, Tang B, Zhou GF. Solid-phase sintering process and forced convective heat transfer performance of porous-structured micro-channels. Trans Nonferrous Met Soc China 2014; 24: 900-06.

[141] Li Z, Haramura Y, Tang D, Guo C. Analysis on the heat transfer characteristics of a micro-channel type porous-sheets stirling regenerator. Int J Therm Sci 2015; 94: 37-49.

[142] Jaikumar A, Kandlikar SG. Enhanced pool boiling heat transfer mechanisms for selectively sintered open microchannels. Int J Heat Mass Transf 2015; 88: 652-61.

[143] Tang Y, Zeng J, Zhang S, Chen C, Chen J. Effect of structural parameters on pool boiling heat transfer for porous interconnected microchannel nets. Int J Heat Mass Transf 2016; 93: 906-17.

[144] Jaikumar A, Kandlikar SG. Enhanced pool boiling for electronics cooling using porous fin tops on open microchannels with FC-87. Appl Therm Eng 2015; 91: 426-33.

[145] Deng D, Chen R, He H, FengJ, Tang Y, Zhou W. Effects of heat flux, mass flux and channel size on flow boiling performance of reentrant porous microchannels. Exp Therm Fluid Sci 2015; 64: 13-22.

[146] Bai P, Tang T, Tang B. Enhanced flow boiling in parallel microchannels with metallic porous coating. Appl Therm Eng 2013; 58: 291-7.

[147] Zhang S, Tang Y, Zeng J, Yuan W, Chen J, Chen C. Pool boiling heat transfer enhancement by porous interconnected microchannel nets at different liquid subcooling. Appl Therm Eng 2016; 93: 1135-44.

[148] Manay E, Sahin B. Heat transfer and pressure drop of nanofluids in a microchannel heat sink. Heat Transfer Eng 2017; 38(5): 510-22.

[149] Rimbault B, Nguyen CT, Galanis N. Experimental investigation of CuO-water nanofluid flow and heat transfer inside a microchannel heat sink. Int J Therm Sci 2014; 84: 275-92.

[150] Zhang H, Shao S, Xu H, Tian CQ. Heat transfer and flow features of Al_2O_3 water nanofluids flowing through a circular microchannel Experimental results and correlations. Appl Therm Eng 2013; 61: 86-92.

[151] Peyghambarzadeh SM, Hashemabadi SH, Chabi AR, Salim M. Performance of water based CuO and Al_2O_3 nanofluids in a Cu–Be alloy heat sink with rectangular microchannels. Energy Convers Manag 2014; 86: 28-38

[152] Ahmed HE, Ahmed MI, Seder IMF, Salman BH. Experimental investigation for sequential triangular double-layered microchannel heat sink with nanofluids. Int Commun Heat Mass Transf 2016; 77: 104-15.

[153] Xia GD, Liu R, Wang J, Du M. The characteristics of convective heat transfer in microchannel heat sinks using Al_2O_3 and TiO_2 nanofluids. Int Commun Heat Mass Transf 2016; 76: 256-64.

[154] Anoop K, Sadr R, Yu J, Kang S, Jeon S, Banerjee D. Experimental study of forced convective heat transfer of nanofluids in a microchannel. Int Commun Heat Mass Transf 2012; 39: 1325-30.

[155] Yang A, Chen L, Xie Z, Feng H, Sun F. Constructal heat transfer rate maximization for cylindrical pin-fin heat sinks. Appl Therm Eng 2016; 108: 427-35.

[156] Beni SB, Bahrami A, Salimpour RM. Design of novel geometries for microchannel heat sinks used for cooling diode lasers. Int J Heat Mass Transf 2017; 112: 689-98.

[157] Narendran G, Ramachandran K, Kumar N. An inline sensing of coolant temperature inside a micro-channel for application in ultra-dense packed high power electronics. Optik 2016; 127: 871-5.

[158] Wang Y, Ding GF. Experimental Investigation of heat transfer performance for a novel microchannel heat sink. J Micromech Microeng 2008; 18: 035021.

[159] Narendran G, Gnanasekaran N, Arumuga Perumal D. Flow induced hotspot migration studies with heat spreader integrated microchannels using reduced graphene oxide nanofluid. *Proceedings of International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems*. Toulouse, France, April, 2018.

[160] Murphy DM, Manerbino A, Parker M, Blasi J, Kee RJ, Sullivan NP. Methane stem reforming in a novel ceramic microchannel reactor. Int J Hydrogen Energ 2013; 38: 9741-50.

[161] Kirsch KL, Thole KA. Experimental investigation of numerically optimized wavy microchannels created through additive manufacturing. J Turbomach 2018; 140: 021002-11.

[162] Kelly B, Hayashi Y, Kim YJ. Novel radial pulsating heat-pipe for high-flux thermal spreading. Int J Heat Mass Transf 2018; 121: 97-106.

[163] Sharma CS, Schlottig G, Brunschwiler T, Tiwari MK, Michel B, Poulikakos DA. Novel method of energy efficient hotspot-targeted embedded liquid cooling for electronics: An experimental study. Int J Heat Mass Transf 2015; 88: 684-94.

[164] Robinson AJ, Kempers R, Colenbrander J, Bushnell N, Chen RA. Single phase hybrid micro heat sink using impinging micro-Jet arrays and microchannels. Appl Therm Eng 2018; 136: 408-18.

[165] Drummond KP, Back D, Sinanis MD, Janes DB, Peroulis D, Weibel JA, *et al*. Hierarchical manifold microchannel heat sink array for high- heat-flux two- phase cooling of electronics. Int J Heat Mass Transf 2018; 117: 319-30.

[166] Sharma CS, Tiwari MK, Zimmermann S, GerdSchlottig TB, Michel B, Poulikakos D. Energy efficient hotspot-targeted embedded liquid cooling of electronics. Appl Energ 2015; 138: 414-22.

[167] Sharma CS, Tiwari MK, Poulikakos D. A simplified approach to hotspot alleviation in microprocessors. Appl Therm Eng 2016; 93: 1314-23.

[168] Maganti LS, Purbarundhar D, Sunderrajan T, Das SK, *et al*. Selecting optimal parallel microchannel configuration for active hot spot migration of multicore microprocessor in real time. J Heat Transf 2017; 139(10): 102401.

[169] Drummond KP, Weibel JA, Garimella SV, Back D, Janes DB, Sinanis MD, *et al*. Evaporative intrachip hotspot cooling with a hierarchical manifold microchannel heat sink array. *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*. Las Vegas, NV, USA, May-June, 2016.

[170] Lorenzini D, Joshi YK, Woodruff GW. CFD study of flow boiling in silicon microgaps with staggered pin fins for the 3D-stacking of ICS. *Proceedings of IEEE ITHERM Conference*. Las Vegas, USA, June, 2016.

[171] Lee YL, Singh PK, Lee PS. Fluid flow and heat transfer investigations on enhanced microchannel heat sink using oblique fins with parametric study. Int J Heat Mass Transf 2015; 81: 325-36.

[172] Han Y, Lau BL, Tang G, Zhang X. Thermal management of hotspots using diamond heat spreader on si micro cooler for gan devices. IEEE Trans Compon Packag Manuf Technol 2015; 5: 12.

[173] Upadhya, G., Herms, R., Zhou, P., Goodson, K., Hom, J. Optimal spreader system device and method for fluid cooled micro-scaled heat exchange. US7806168 (**2010**).

[174] Stevanovic, L.D., Solovitz, S.A. Heat sink with microchannel cooling for power devices. US7353859 (**2004**).

[175] Okamoto Y, Ryoson H, Fujimoto K, Honjo K, OhbaT, Mita Y. Hotspot liquid microfluidic cooling: Comparing the efficiency between horizontal flow and vertical flow. J Phys Conf Ser 2016; 773: 012066 1.

[176] Solovitz SA, Mainka J. Manifold Design for micro-channel cooling with uniform flow distribution. J Fluids Eng 2011; 133: 051103.

[177] Narayanan S, Fedorov AG, Joshi YK. On-chip thermal management of hotspots using a perspiration nano patch. J Micromech Microeng 2010; 20: 075010.

[178] Green C, Fedorov AG, Joshi YK. Fluid-to-fluid spot-to-spreader (F2/S2) hybrid heat sink for integrated chip-level and hot spot-level thermal management. J Electron Packag 2009; 131: 025002.

[179] Maganti LS, Dhar P, Sundararajan T, Das SK. Heat spreader with parallel microchannel configurations employing nanofluids for near-active cooling of MEMS. Int J Heat Mass Transf 2017; 111: 570-81.

[180] Reddy SR, Dulikravich GS. Multi-objective optimization of micro pin-fin arrays for cooling of high heat flux electronics. *Proceedings of the ASME 2015 International Mechanical Engineering Congress and Exposition*. November, Houston, USA, 2015.

[181] Zhang J, Zhang T, Prakash S, Yogesh J. Experimental and numerical study of transient electronic chip cooling by liquid flow in microchannel heat sinks. Numer Heat Tr A Appl 2014; 65: 627-43.

[182] Kinkelin C, Lips S, Soupremanien U, Remondière V, Dijon J, Poche HL, *et al*. Theoretical and experimental study of a thermal damper based on a CNT/PCM composite structure for transient electronic cooling. Energy Convers Manag 2017; 142: 257-71.

[183] Kulah, H., Aziz, K., Okutucu, T.O. CMOS Compatible microchannel heat sink for electronic cooling and its fabrication. US20130105135 (**2010**).

[184] Arnab, C. Methods of forming configurable microchannels in package structures. US20140167296 (**2014**).

[185] Sitaraman S, Wang S, Cantreras T, Wang J, Fan M, Sang Y, *et al*. A highly- miniaturized system integration approach for an IOT contact-less power module. *2017 IEEE 67th Electronic Components and Technology Conference (ECTC)*. Orlando, FL, USA, May-June, 2017.

[186] Glade H, Moses D, Orth T. Polymer composite heat exchangers. Springer; 2018.

[187] Inoue T, Fujii M, Kida H, Yamakawa T, Maruta Y, Tokiwa T, *et al*. Epidural focal brain cooling abolishes neocortical seizures in cat and non-human primates. Neurosci Res 2017; 122:35-44.

[188] Sidik NAC, Muhamad MNA, Japar WMAA, Rasid ZA. An overview of passive techniques for heat transfer augmentation in microchannel heat sink. Inte Commun Heat Mass Transf 2017; 88: 74-83.

[189] Ghani IA, Sidik NAC, Mamat R, Najafi G, Ken TL, Asako Y, *et al*. Heat transfer enhancement in microchannel heat sink using hybrid technique of ribs and secondary channels Int J Heat Mass Transf 2017; 114: 640-55.

[190] Ghani IA, Sidik AAC, Kamaruzzaman N, Yahya WJ, Mahian O. The effect of manifold zone parameters on hydrothermal performance of micro-channel Heatsink: A review. Int J Heat Mass Transf 2017; 109: 1143-61.