Al-Qadisiyah Journal for Engineering Sciences 17 (2024) 239–249

Contents lists available at http://qu.edu.iq

Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: https://qjes.qu.edu.iq

Heat transfer augmentation by using different techniques in small scale channels: A review study

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ARTICLE INFO

Article history:
Received 08 July 2023
Received in revised form 27 September 2023
Accepted 10 March 2024

Keywords:
Heat sinks
Heat transfer
Forced convection
Enhancement
Channel curvature

ABSTRACT

This paper highlights the most significant recent developments in the scientific study of Heat sinks: thermal management components made of materials with sufficient thermal conductivity qualities. Due to the increase in operating power, speed, and the general reduction in system size, the issues of heat removal and temperature management have an increasing importance in these studies. Changing the geometry of extended surfaces, the material from which they were made, the working fluid that ran over them, and/or the dimensions of the channel, are some of the ways in which studies have been conducted. This review addresses the main recent findings in forced convection heat transfer that happens at laminar flow inside small-scale diameter channels. Recent studies indicate a remarkable enhancement through the change of Re, D, and internal geometry of the channel. The configuration of flow passages has also adopted a different passive technique to enhance thermal fluid flow.

1. Introduction

As a result of developments in the electronics sector, microscale heat transfer devices were created, providing a high heat transfer coefficient in a small size. The working temperature of electronic components may exceed the desired temperature level, which increases the circuit failure rate of the equipment in the absence of sufficient heat removal. Therefore, advanced electronic equipment with small size and high heat generation requires efficient and compact cooling devices to provide reliable system operation.

2. Flow formation

Mohammed and Abood [1] studied how formation flow affects hydrothermal performance and base temperature homogeneity in the serpentine small channel heat sink. The flow formation was altered to use the straight channel model (A) and the wavy channel model (B), and the location of the inlet and outlet was altered by placing the entry in the middle of the heat sink and utilizing water as the working fluid. A 3D ANSYS Fluent program is utilized to get the findings numerically. Additionally, the results show that flow arrangement has a significant impact on temperature and pressure drop distribution. Although the pressure drop and temperature homogeneity are improved by the model with straight tubes. All of the novel models being studied also outperform traditional models in terms of overall performance factor (OPF). In models (A) and (B), respectively, the average OPF is (1.43) and (1.26). Additionally, model (A) is superior to model (B) by 11.89% as a result of the effective OPF and the consistent base temperature.

Liu and Yu [2] performed research to enhance the flow distribution and heat transfer performance in micro-channels, and nonuniform mini baffles were suggested for usage in the heat sinks. Using the FVM and the CFD package FLUENT, the fluid and thermal performances of four MCHSs with and without baffles are computationally examined. The numerical comparisons demonstrate that the nonuniform barriers can be used to enhance the flow maldistribution of heat sinks, leading to greater temperature distribution uniformity. Additionally, it is discovered that adding nonuniform baffles

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https://doi.org/10.30772/qjes.2023.141640.1005

can reduce the total thermal resistance of MCHSs by 9.9–13.1% while maintaining the same operational parameters and geometrical dimensions. These benefits of the non-uniform mini-baffle heat sinks are advantageous for their use in thermoelectric coolers. Singh et al. [3] investigated the MCHS's secondary interconnecting channels, which are responsible for the fluid flow and heat transported away characteristics. Software and hardware on electrical equipment could be harmed by overheating. MCHS that are water-cooled is a successful and fundamental cooling technique for electronic devices. In this study, 3 separate mini-channels with variously constructed secondary channels interconnecting them were employed to analyze the problem mathematically. The computational model was solved using FVM methodology in ANSYS Fluent Solver. In every aspect of the MCHS system, water is used as a coolant, and the streamflow is laminar and single-phase. The mathematical results show that the minimum base plate temperature (BPT) of the MCHS is seen at a 10° secondary channel angle; as a result, this is the angle at which the electronic device performs at its peak. Zhu et al. [4] investigated the impact of channel geometry utilizing CFD to comprehend the parameters of fluid flow and heat transmission in microchannel heat sinks having rectangular furrows in the sidewalls and variously shaped ribs in the central core flow. The rectangular, elliptic, forward triangular, and diamond rib shapes are among the four that are taken into consideration. The total performance of these devices was investigated and evaluated in detail in terms of Nu, apparent friction factor, and thermal enhancement efficiency to completely comprehend the structure and operation of microchannel heat sinks. To choose the best channel structure, the augmentation mechanism of heat transfer and fluid flow was discussed. The goal was to enhance heat transmission while lowering flow resistance and pressure drop by optimizing the channel for microchannel heat sinks. The outcomes showed that the combination of grooves and ribs can significantly boost overall performance. The benefits of ribs, which improve flow disturbance and improve heat transfer, and of grooves, which expand flow area and lower pressure drop, may both be fully utilized in this combination. The total performance is significantly influenced by the size and form of the ribs. At Re< 500, the overall performance achieved with rectangular ribs is the best however, at Re> 500, elliptic ribs achieve a better performance, and at Reynolds numbers beyond 700, diamond ribs achieve an even worse performance. With a relative rib width of 0.25, a minimum rib-groove spacing of 0.1 mm, and a Re= 500, the rectangular grooved channel with rectangular ribs produces the optimum overall performance. Bi et al. [5] employed the field synergy principle in a computational study of the heat transfer associated with convective cooling in mini-channels with dimples, cylindrical furrows, and low fins. To investigate the mechanisms of the improved heat transfer in the upgraded surfaces, the analyzed synergy angle distribution was. The entire performance of the improved surfaces is investigated using the parameter PEC as the evaluation coefficient. The findings indicate that the dimpled surface offers the best performance for enhancing heat transmission. The performance review plot of increased heat transfer approaches is used to determine the most advantageous dimple object shapes. The geometry size effects of dimples are examined throughout a Re range of 2700-6100.

Ho et al. [6] investigated the effects of nano-encapsulated PCM particles and Al_2O_3 nanoparticles on improving heat transfer in the mini-channel heat sink. A three-dimensional computational technique is utilized to model the forced convection heat dispersion of water-based suspensions of nano-encapsulated PCM particles and Al2O3 particles in the mini-channel heat sink. The energy equation and a homogeneous mixture formulation using the pseudo-vorticity-velocity formulation are used to assess the cooling properties. Evaluated at different concentrations of Al2O3 and nano-encapsulated PCM particles, flow Reynolds numbers, and heat fluxes are several critical system parameters, including the friction factor, the thermal resistance, the figure of merit, and the average heat transfer coefficient ratio. The numerical findings demonstrate that by injecting the nano-encapsulated PCM suspension at concentrations of 2% and 10%, respectively, the highest thermal resistance decrease of 1.2% and 6.9% may be obtained. For the instance of an Al2O3 nanoparticle suspension in water, the heat transfer coefficient ratios are greater than one for all heat flow and Re values. Al2O3 nanoparticle use offers superior cooling performance in comparison to nano-encapsulated PCM particles. Al2O3 particles have a considerably stronger positive impact than nano-encapsulated PCM particles because of this. Muhammad et al. [7] provided a numerical study of Galinstan's forced convective heat transfer through a mini-channel heat sink subjected to a steady heat flux. This study contributes to the cutting-edge and effective cooling method that uses liquid metal as the working fluid. The effect of the shape of the heat sink and the inlet velocity on the pressure drop, pumping power, and maximum heat flow has been thoroughly parametrically analyzed. The size and inflow velocity of the heat sink is adjusted. Additionally, a comparison of the calculated values and the analytical correlations is made, and any discrepancies are discussed. Furthermore, the flow and heat transfer capabilities of water, nanofluid, and liquid metal for mini-channel heat sink cooling are investigated, which logically demonstrates the benefit of employing liquid metal as a coolant. By combining three-dimensional fluid flow simulations with a multi-objective optimization technique, Nemati et al. [8] provided the ideal shape for a water-cooled mini-channel heat sink. Thirteen coordinate points were utilized to define the design of a mini channel along its length, and the multi-objective genetic algorithm (MOGA) was employed to determine the best outcome. Both the total heat transfer resistance and the pumping power were lowest at the optimum location. Later, LINMAP was suggested as a method for selecting the best non-inferior point among the options. By increasing pumping power by just 10%, it was demonstrated that the LINMAP system could reduce thermal resistance to 87% of that of a straight channel. The outcome was contrasted with a completely wavy channel. It was demonstrated that even if the thermal resistance value in a wavy channel was better, accessing a thermal resistance required a very high pumping power. To increase flow distribution and heat transfer performance, Kumar and Singh [9] suggest a microchannel heat sink with a newly modified inlet/outlet configuration with various flow inlet angles, such as (θ=90°, 105°, and 120°). With the assistance of ANSYS-Fluent, this suggested mini-channel heat sink has undergone numerical analysis. Aluminum is used as the heat sink material, and water is used as the working fluid. There are 28 parallel small channels in total, each with a 1.5 mm hydraulic diameter. The suggested inlet/outlet arrangement with θ=105° has the least amount of flow maldistribution and results in more effective and uniform cooling of the heat sink. It is discovered that flow distribution differs with this flow inlet angle. The non-uniformity of the flow is increased by further increases in the flow inlet angle. The value of the highest base temperature was also minimum for this design, and the thermal performance was also determined to be greatest for θ= 105°. The concept is that the small channel heat sink's performance can be enhanced if the coolant enters the distributor header with a flow intake angle of 105 degrees and exits from the center of the collector header. Sarowar et al. [10] evaluates the thermal and hydraulic performance of a small channel heat sink using four various gallium alloys (EGaInSn, GaIn, GaSn, and EGaIn) as the working fluid and five various substrate materials (aluminum nitride, hafnium diboride, beryllium oxide, zirconium diboride, and titanium diboride,). Additionally discusses the impact of various rectangular channel shape factors on the heat sink's overall performance. The 3D numerical model examines the heat sink's thermal and hydraulic performance. The findings are verified using data from published sources and theoretical relationships. Aluminum nitride (AlN) heat sinks have been discovered to function better than any other base material. GaIn was determined to be the best coolant material after investigation.

Tikadar et al. [11] describes a computational 3D analysis of the fluid flow and heat transfer efficiency of a parallel and counter flow mini-channel heat sink where pass flow among parallel channels was achieved by interconnectors. The analyzed mini-channel had an aspect ratio of 0.33 and a hydraulic diameter of 750 m, respectively. In this investigation, water was used as the coolant, and the flow was laminar with Re ranging from 150 to 1044. The flow was in the single-phase regime. The bottom surface of the heat sink received a 20 W/cm2 continuous heat flux. The performance of the mini-channel heat sink at 5 distinct interconnector widths was investigated to determine the impact of cross-flow on the overall thermo-hydraulic performance. To assess the overall effectiveness of the interconnected mini-channel heat sink, the non-dimensional pressure, temperature, velocity, friction factor, total Nu, and thermal resistance were computed. By computing the performance evaluation criteria (PEC), the interconnected mini channel's performance was compared to that of the traditional mini channel. The findings demonstrate that the counter-flow mini-channel heat sink is substantially more affected by the interconnector than the parallel flow mini-channel is. In comparison to the traditional parallel flow mini-channel, Nu for the counter-flow mini-channel heat sink was increased by a highest of 36% at Re = 1044, while the friction factor was reduced by a highest of 31.13% at Re = 150. The counter flow mini-PEC channel's increased to 1.33, and its value exhibits an upward trend when Re rises Channel geometry. Alfellag et al. [12] used a conjugate heat transfer model to computationally examine the impact of a tilted slotted plate-fin mini-channel heat sink with triangular pins on fluid flow and laminar convection heat transmission. A parametric analysis of the structural pattern of the slots and pins was done in order to improve the heat sink's hydro-thermal performance. The investigation was carried out by altering the height of the tilted slot, its angle, and the placement of the pin in relation to the slot's leading edge. Between 100 and 1600 were assigned to the Reynolds number. In compared to the straightforward mini-heat sink, the CFD findings demonstrated that the full height slot with a 55o angle of inclination improved the Nu and the hydrothermal performance factor (JF) up to 1.5 and 1.43, respectively. Additionally, the heat sink's Nu and JF factors were higher than those of the straight tube by approximately 1.84 and 1.54, respectively.

Datta et al. [13] has conducted a numerical inquiry to evaluate the effectiveness of a design innovation for a rectangular microchannel heat sink by utilizing the ideas of thermal performance (TP) optimization and entropy generation (EG) optimization. The canal is designed as a series of modifying units with trapezoidal cavities (TRC) on opposing side walls and ribs proportionately placed between each of them. Going to follow validation against a reflective experimental and computational analysis, a three-dimensional laminar-flow conjugate heat-transfer study was performed between Re= 140 and 600 based on SIMPLEC algorithm for the flow as well as conduction thru the bounding walls and the inner ribs. Convection is clearly more dominant at higher Re, according to a comparison between the predictions of models with constant fluid properties and those with genuine fluctuations with temperature. The bulk fluid temperature has increased at a moderate rate, while the temperature of the substrate has increased even more slowly, thanks to copper's significantly better thermal conductivity than silicon's. Four different rib structures—rectangular (RR), backward triangular (BTR), forward triangular (FTR), and diamond—have been taken into consideration (DR). The forecasts against Re showed the greatest EG with backward triangular rib combination (TRC-BTR) and the optimum TP with diamond rib combination (TRC-DR). This work makes a significant contribution by proving that maximizing of TP is equal to reduction of EG when pumping power is constrained. Hung et al. [14] looked mathematically at how expanding the channel outlet affected the flow of heat through a porous microchannel heat sink (MCHS). The effects of the magnification ratios for the canal exit width and height on the thermal and hydraulic showings of a porous MCHS were highlighted. Raising the width or height enlargement ratio lowers the pressure drop across an MCHS, according to the simulation results. With an expanded channel outlet, thermal resistance is decreased while the averaged Nu, heat transfer efficiency, and temperature control effectiveness are all improved. The hydraulic and thermal behavior of porous MCHSs can thus be improved by raising the width or height magnification ratio of the channel exit. If a pumping power is insufficient to compensate for the pressure loss, the thermal resistance of a porous MCHS may not always be less than that of an MCHS without a porous medium for specific width or height enlargement ratios. Sadoon et al. [15] conducted a numerical analysis to improve the mini-channel heartsink's coefficient of heat transmission. Utilizing pure water and hybrid nanofluids as a coolant, the new form of a mini-channel (converge-diverge) was presented and compared with the rectangular (straight) canal. In mathematical analysis, the 3D fluid and heat flow problem in a small channel was resolved by modeling using the COMSOL Multiphysics tool. The FEM is the foundation of a CFD module in COMSOL Multiphysics, and the governing partial differential equations are solved using a Galerkin strategy. Studying the channel arrangement's base temperature, Nu, friction factor, and thermal resistance while using Re ranges of 200–1000 and concentration volume variations of 0%–0.075%. At the bottom, the minicanal heat sink is subjected to a steady heat flux of 180 KW/m2. The numerical findings demonstrate that the hydrothermal behavior of the heat sink can be improved by nanofluid and (converge-diverge) mini-channel, and that (Ag-H2O) nanofluid exhibits superior heat transfer performance than Fe3O4 nanofluid as improvement in Nu reached 43.27% at volume concentration 0.075%. In order to successfully improve the thermal-hydraulic performance in the mini-channel heat sink, Xiao et al. [16] developed a new technique for creating the optimum flow field. The selected mini-channel heat sink had a substrate dimension of 30 mm by 30 mm and a Re of 100 to 1100. Three sets of longitudinal swirls flow were the distinguishing feature of the improved flow pattern after conjugate heat transfer improvement using the exergy destruction reduction principle. Then, it was suggested to use angled parallelepiped ribs to achieve the ideal flow profile in the mini-channel heat sink. Through the examination of temperature distributions, velocity distributions, and heat convection strength, the method for the augmentation of heat transfer was discovered. Additionally, the exergy destruction reduction principle was confirmed while the overall thermal resistance was lowered. Thus, the Nu/Nu0, f/f0, efficiency evaluation criterion (EEC), and overall performance criterion (R3) fluctuation ranges were 1.35-5.92, 1.27-8.75, 0.68-1.12, and 1.31-4.22, respectively. The highest mean heat flux was 3.2 106 W/m2 at a 60 K temperature differential between the fluid and the substrate. The suggested values for the set variables pitch ratio (PR) and width ratio (WR) are 1 and 0.2, respectively. The shape of mini-channel heat sinks will benefit from this study. Moradikazerouni, et al. [17] studied the impact of the air's 3D flow on the efficiency of heat sinks with tiny channels that may be configured in five various ways (e.g., rectangular, hexagonal, triangular circular, and straight slot). The Nu, pressure loss, heat transfer coefficient, and necessary pumping power were all studied with flow rate Re and air inlet temperature. According to the data, the triangular shape offers the best thermal performance among the 5 channel layouts for cooling a particular micro-channel heat sink. Therefore, the straight slot arrangement is advised in terms of manufacturing costs. The impact of the production material was then taken into account about the thermal conductivity of aluminum, alumina (92%), stainless steel, silver, copper, and cobalt. In the last stage, it was determined if the coolant flow rate between 60 and 120 CFM could void body failure by studying the impact of air flow rate on thermal stress and geometrical distortion. The findings of this investigation may be useful in designing supercomputer cooling systems. Leng et al. [18] provided an optimal design for a double-layered microchannel heat sink (DL-MCHS) with terminated top channels. A 3D solid -emulsion conjugate heat transfer model was used to quantitatively analyze the benefits of the design. Comparing the improved performance of the design to the original DL-MCHS was a good way to show this. The findings show that there is an ideal truncation location for the top channel, where the coolant temperature is roughly equal to that of the bottom channel, to obtain the greatest DL-MCHS performance. The trade-off between the top coolant's cooling and heating effects leads to the best truncation location. The effectiveness of the suggested design was then examined with each model variable, namely overall pumping power (Ω), channel number (N), bottom channel length (Lx), and channel-to-pitch width ratio (β). It is discovered that the top coolant's cooling and heating effects are both improved for the original DL-MCHS with greater Lx compared to the design with shorter Lx. In this situation, a top channel with a properly truncated design can greatly lessen the top coolant heating effect without sacrificing the cooling effect. Thus, when employed in a DL-MCHS with greater Lx, the benefits of the truncated idea are more readily apparent. For the same purpose, the truncated shape is strongly advised for a specific design with higher N, shorter β, or smaller Ω to improve the DL-MCHS performance. Xia et al. [19] combined the multi-objective evolutionary algorithm (MOEA) with CFD to analyze several factors that affect the performance of the microchannel to determine the ideal structure size of an MCHS with arc-shaped grooves and ribs by the actual demand. The proportional groove height, rib height, and rib width are design parameters, and the two primary goals are to reduce overall thermal resistance and pumping power at steady volume flow rates. A CFD analysis of the two-goal functions' impacts from the design parameters comes first. As a result of the analysis, the proof is provided the two functions are affected differently by each design parameter. Plots of the Pareto front created by MOEA show how competitively the two-goal functions are related. The relative rib height is shown to have the greatest effect on the two objective functions according to a Pareto sensitivity analysis.

To obtain an optimum design that enhances the thermal and hydraulic performance of traditional microchannels, Ghahremannezhad, and Vafai [20] provided a comprehensive analysis using porous substrates in microchannel heat sinks (MCHS). This paper analyzes the three-dimensional designs of MCHS with various solid and porous fin thicknesses. To assess different performance factors for various MCHSs, a parametric improvement of the thickness of the solid and porous fin has been conducted. The outcomes are compared to those of conventional heat sinks and show that, for each combination of MCHS geometry parameters, an improved porous design exists that can enhance both thermal and hydraulic performance simultaneously, or at least do so while maintaining the other at a level comparable to that of a conventional heat sink. Several Reynolds numbers and pumping powers are explored for this enhancement. The optimization technique has been used with porous MCHSs that have different heat sink materials and porosities. In every instance, the superior impact of the improved porous design has been seen. Wong, and Lee [21] performed a numerical analysis to forecast the thermal and hydraulic performances of the MCHS using various triangular rib design variables in the transverse microchamber. The triangular rib's parametric elements of width, length, and height are investigated to determine the best design. The features and flow structure of the interrupted MCHS are analyzed in depth. The average Nu, friction factor, and thermal improvement factor non - dimensional ratios are assessed. It has been discovered that the rate of heat transfer increases with rib breadth and height but decreases with rib length. The triangular rib's impacts on boundary layer interruption and rebuilding are examined. The triangular rib's ideal structural properties are width, length, and height =100 µm x120 µm x400 µm, for around Re of 500, delivering 43% improvement compared to non-interrupted rectangular MCHS at equal pumping power. A maximum improvement of 56% in comparison to non-interrupted MCHS is shown by the average Nu ratio data. Lin et al. [22] presented a better wavy microchannel heat sink design with varying amplitude or wavelength along the flow direction. Under steady pumping power, the new design's thermal resistance R and highest bottom wall temperature difference ΔTb,max are compared to those for the regular and the original wavy designs. The findings demonstrate that if the wavelength of wavy units is reduced or increased, the effectiveness of the new design is greatly improved with smaller R and lower ΔTb,max. When the absolute magnitude of the amplitude difference ΔA or wavelength difference Δλ between two adjacent wavy units rises, the amplification becomes much more visibly noticeable. By simultaneously raising Δλ and ΔA 's absolute levels, the performance can be enhanced even more. Furthermore, the decreases in R and ΔTb,max for the new model are shown to be more substantial for the heat sink with a lower channel aspect ratio as compared to the linear and the original wavy microchannel heat sink. The curved walls' ability to create vortices in the canal cross sections, which encourage coolant mixing and improve convective heat transfer among coolant and canal wall surfaces, is thought to be the reason of the improved heat transfer working fluid.

Shamsi et al. [23] performed numerical research on computational fluid dynamics and non-Newtonian fluid laminar flow. The non-Newtonian fluid is made up of water and 0.5 weight percent carboxymethyl cellulose (CMC). In this calculation, solid aluminum oxide nanoparticles with sizes of 25, 45, and 100 nm have been injected to the non-Newtonian fluid in volume concentration ranging from 0 to 2 percent. The alleged microchannel has a rectangular shape and two-dimensional coordinates. The cooling nanofluid's dynamic viscosity has been predicted using the power law. The Re range of (5-300) is used to simulate the field of analytical solution. On the bottom walls of the shape being examined, a continuous heat flux of 10,000 W/m2 is applied. Additionally, the impact of triangular ribs having attacks at 30, 45, and 60 degrees is investigated in terms of flow characteristics and heat transfer from fluid flow. The findings demonstrate that increased heat transfer is caused by using nanoparticles having smaller particle sizes and increasing the volume percentage of nanoparticles. The triangular rib shape with a 30° angle of attack has the highest Nu and the lowest pressure losses through the microchannel of all the tested shapes. Additionally, a decrease in length of the rib a rise in the angle of attack, and a quick touch between both the fluid and the ribs all prevent the fluid from transferring heat to areas farther away from the wall (tip of the rib). Wang et al. [24] considerably enhanced the performance of a particular porous-ribs microchannel heat sink presented previously by the use of a 3D fluid-solid conjugated model together with a multi-objective and multi-parameter genetic algorithm optimization technique. Under conditions with a constant volumetric flow rate, the ideal design and operation characteristics are reached. According to the Pareto-optimal front, the MCHS can achieve a lower thermal resistance of 0.06306 K/W with 0.38317 W of pumping power and a lower pumping power of 0.00171

W with 0.37755 K/W of thermal resistance. The optimum determines the ideal thermal resistance (0.09348 K/W) and pumping power (0.02888 W). It demonstrates that when compared to the original design, not only the cooling performance is dramatically increased by 14.06%, and the pumping power is significantly decreased by 16.40%. The fundamental physics of how multi-parameter affects effectiveness is also examined. The outcomes show that achieving an excellent result is the outcome of a suitable mediation of both the pumping power of the top canal and the cooling effectiveness of the bottom canal. The suggested design requirements to achieve the effectiveness of choice are based on this process.

Shi et al. [25] optimized the shape of a microchannel heat sink with a secondary flow channel using many objectives. The goal of improvement is to reduce the heat sink's thermal resistance and pumping power while maintaining a constant water mass flow rate. The proportion of the width of the second channel to the width of microchannel α, the proportion of half pitch of the secondary channel to the width of microchannel β, and the tangent amount of secondary channel angle γ are among the design factors. To find the Pareto-optimal solutions, K-means clustering analysis was used to quantitatively investigate the impact of a single key design element on the objective functions. The findings demonstrate that the design variable α has a significant impact on both heat resistance and pump power. As α rises from 1 to 2, the thermal resistance rises by 17.2% while the pump power falls by 13.7%. Objective functions are less impacted by the design parameter β. The pump power and heat resistance both rise by 6.9% and 17.1%, respectively, in the examined range. 5 cluster spots of Pareto optimum solutions form a useful trade-off point. In a practical design, the required heat resistance or the supplied pump power to propel the fluid can be used to choose the construction characteristics from 5 cluster points. By optimizing the construction characteristics, the efficiency of the microchannel heat sink with a secondary flow channel is greatly increased. Under the mass flow rate range examined in this study, the improved microchannel with a secondary flow channel may lower its thermal resistance and pumping power by a maximum of 28.7% and 22.9%, respectively, compared to the traditional flat channel. Shi, and Dong [26] proposed an entropy generation rate that takes into account flow friction, heat transfer, and the clearance between pin fin end and the shroud panel for a flow in a microchannel with dispersed pin fin arrays. For all scenarios under examination, the entropy generation rate resulting from heat transfer is orders of magnitude greater than that caused by flow friction, which is nonetheless significant given its scaling impact on the pumping power usage. The influence of tip clearance was observed to be greater pronounced for the pin fin structure with a large aspect ratio (height to diameter) when conductive nature competed with convective. When this ratio decreases, the influence of the clearance gap, which is supported by a greater aspect ratio, predominates over the variance of entropy formation via heat transfer and flow friction. In order to find the best possible combination of all the effect elements under examination, the entropy reduction method is used. Multiobjective Optimization Genetic Algorithm is used to obtain the Pareto frontier and its accompanying solution sets. The pin fin density zone with decreased pin fin density is where the trade-off between the convective and conductive impacts is recognized, and this is where the solution sets obtained for the situation with high aspect-ratio pin fins fall. The solution sets for situations with smaller aspect ratios, further, are in theory located towards the upper bounds and are influenced by the convective nature.

Micro/Mini-channel Heat Sinks, Jajja et al. [27] performed research utilizing mini channel heat sinks with water as a liquid to evaluate the systematic impact of basin shape on the temperature of a microprocessor. The tests were performed on a flat plate heat sink and five distinct heat sinks with fin spacings different (0.2 _1.5 mm). A hot copper block with water acting as a coolant was used to imitate microprocessor heat. The minimum documented base temperature of 44 C utilizing a nanofluid with a commercial heat sink in the open literature was obtained at a heater output of 325 W by employing a heat sink with 0.2 mm fin spacing, which was nearly 9% lower. Reduced fin spacing and higher volumetric flow rates of water passing through heat sinks were shown to lower their base temperature and thermal resistance. The greatest thermal resistance for the flat plate heat sink was 0.216 K/W, but it could be as low as 0.03 K/W when utilizing a heat sink with 0.2 mm fin spacing. For a flat plate, and heat sinks with 0.2 mm fin spacing, the total heat transfer coefficient was determined to be 1297 W/m2 K and 2156 W/m2 K, respectively. The latter exhibited an improvement of about two times over the former. A double-layer mini-channel heat sink with interlocking layers that can achieve counterflow—where the flow direction in the next channel is the opposite—is what Lim and Lee [28] suggest. The experimental investigation of the heat sink's single-phase flow cooling capacity yielded the test data. By disconnecting the variation in the single channel heat transfer coefficient amplified by the counterflow channel impact, the heat transfer properties of the heat sink are examined. A significantly low value of 104 K-m2/W order for the thermal resistance, which represents the suggested heat sink's overall cooling performance, illustrates the new heat sink's benefit in heat transfer performance. By analyzing the heat transfer coefficient achieved from the suggested heat sink with the prediction utilizing the prior correlation for unidirectional single-phase flow heat transfer coefficient, the favorable effect of counterflow is confirmed. The observed heat transfer coefficients are substantially bigger than the values that various historical correlations have suggested. At low flow rates, when the temperature gradient rises more noticeably with flow direction, the gap between the calculated values and the projected value is substantially bigger. It may be deduced from this that counterflow reduction of temperature gradient leads to an extra enhancement in heat transfer that is unpredicted in the earlier unidirectional flow correlations. To forecast the heat transfer coefficient impacted by the counterflow, a novel correlation is suggested. The investigation is the first to experimentally use a counterflow heat sink, proving its clear advantage over traditional heatsinks in terms of better cooling performance. Additionally, the study is significant because it offers a performance prediction model that can be applied to the design of counterflow heat sinks for actual use. Kumar et al. [29] studied the thermal-hydraulic behavior of a composite dispersed hybrid nanofluid using an experimental microchannel heat sink. A hybrid nanofluid with a 0.01% volume concentration was created by synthesizing rGO-ZnO nanocomposite particles and dispersing them in water. It is thoroughly investigated how various Re, volumetric flow rates, heat fluxes, and channel aspect ratios affect pressure drop, heat transfer, and their respective performance parameters. At a flow rate of 0.5 lpm, a reduction in the channel aspect ratio from 5 to 2.5 (hydraulic diameter from 1.33 to 1.11 mm) improves the convective heat transfer coefficient by 47.2%. With an increase in heat flux from 33.33 W/cm2 to 66.67 W/cm2, the heat transfer coefficient dramatically rises by roughly 17.41%. Through the entire range of Re, the impact of heat flow on the friction factor is negligible. All channel aspect ratios and heat fluxes exhibit a decreasing-increasing-decreasing pattern with flow rate for performance evaluation criteria. At every combination of heat flux and channel aspect ratio, an ideal flow rate has been found for the figure of merit. The figure of merit can achieve a maximum of 1.39 with a heat flux of 66.67 W/cm2 and a channel aspect ratio of 3.75 (corresponding to a hydraulic diameter of 1.26 mm).

Mohammadi et al. [30] investigated the use of a nanofluid-based mini-channel heat sink to cool an electronic chipset (EC). The impacts of altering heat flux, nanofluid mass percent, and coolant flow rate were investigated, respectively, within the ranges of (6000:10000 W/m2), (0:1%), and (100:300 ml/min). Several significant characteristics were looked into, including transient EC temperature, energy efficiency, and thermal resistance. Experimental results showed that the maximum EC temperature was achieved to be 48.6 °C with an applied heat flux of 6000 W/m2 and a flow rate of 100 ml/min. This temperature dropped by 1.3 and 2.3 degrees Celsius when the coolant flow rate was increased to 150 and 200 ml/min, respectively. The findings showed that at flow rates of 100 (200 ml/min), the thermal efficiency of the liquid-based module employing pure water, SiC/water 0.5 and 1% wt. became 33.8 (50.7%), 37.9 (55.5%), and 40.4 (58.1%), respectively. In the situations of 6000, 8000, and 10,000 W/m2, respectively, the average thermal resistance reduction was found to be 14.81, 19.64, and 21.21% employing water-based heat sinks with flow rates of 200 ml/min compared to 100 ml/min. Ho et al. [31] conducted an experimental study on the cooling properties of water-based nano-phase change material emulsions in mini-channel heat sinks. Pure water and n-eicosane nanoparticles are regarded as the base fluid and phase change material. The volumetric flow rate varied from 60 cm3 /min to 600 cm3/ min, three different values of the heat flux applied on the bottom wall of the heat sinks included qh′ ′ = 3.2, 3.95, and 4.78 W/cm2, and the mass fraction of n-eicosane nanoparticles ranged from ω pcm = 0%–10%. These parameters were used to study the fluid flow and convection heat transfer on the friction factor, wall temperature, efficiency of heat transmission, Nu, coefficient of performance, figure of merit, and thermal resistances, the effects of these characteristics are examined. It is determined that employing n-eicosane nanoparticles with higher values of mass fraction is more appropriate to lower the wall temperature for the small rate of volumetric flow and the heat fluxes of 3.2, 3.95, and 4.78 W/cm2. For most amounts of Re and small values of heat flow, the quantity of the convective heat transfer effectiveness is greater than one. At a Re= 1381, a heat flux of 4.78 W/cm2, and a mass fraction of 2%, the highest figure of merit index of 1.098 may be obtained. As the mass fraction of n-eicosane particles increases, the figure of merit index decreases. With an increase in the mass fraction of n-eicosane particles from 2% to 10% for the heat flux of 3.20 W/cm2, the figure of merit index is reduced by around 44%. Lower thermal resistances than in the event of pure water are obtained by using n-eicosane nanoparticles at a concentration of 2%. As the heat flux increases, there is a decreasing trend in the variance between the thermal resistances for different n-eicosane nanoparticle mass fractions. Halelfadl et al. [32] concentrate on the analytical improvement of an aqueous nanofluid based on carbon nanotubes used as a coolant in a rectangular microchannel heat sink. In this study, a weight concentration of 0.01% of particles was utilized. Empirical research is done to determine the density, thermal conductivity, and rheological behavior of the nanofluid to assess the thermal resistance and pumping power in the microchannel under laminar flow. Using a systematic thermal resistance model as a methodology and the elitist non-dominated sorting genetic algorithm (NSGA2), an approach to improvement was used. On the thermal resistance and the pumping power, the impacts of temperature, canal aspect ratio, canal wall ratio, and the usage of aqueous carbon nanotube-based nanofluid are explored. The improved results demonstrated that the utilization of the nanofluid as a working fluid can considerably improve the thermal performance of the working fluid at high temperatures and decrease the overall thermal resistance. The influence of fluid flow fractionation on the hydrothermal performance characteristics of the serpentine microchannel heat sink (SMCHS) has been investigated by Jaffal et al. [33] using both computational and experimental methods. The perpendicular and diagonal innovative designs, which are connected to the locations where the fluid flow is broken up in the SMCHS, are examined. Both of the new designs have two exits and two entrances. Each entrance's flow is split into two branches. The numerical simulations in this work are performed using the 3D CFD ANSYSIS-Fluent tool. To verify the accuracy of the numerical emulations and to compare the performance empirically, the three designs one conventional and the other two novels were produced and tested. Analysis reveals that, when compared to the standard SMCHS, the flow fragmentation significantly enhances the SMCHS properties. Additionally, the results show that as compared to the traditional design, the fragmentation disperser's improved heat transmission, as measured by the Nusselt number, rises by 13% while the pressure drop decreases by almost 180%. The perpendicular fragmentation design of the new SMCHS is determined to be marginally superior to the diagonal fragmentation design. Khalifa and Jaffal [34] performed computational and experimental analyses of the thermal and hydraulic performances of cylindrical mini-channel heat sinks (CMCHSs) depending on the constructal theory and the entrance principle. It was suggested that helical and wavy channels will improve the heat transfer of CMCHSs compared to a typical channel layout. Using the finite volume method in three dimensions, a numerical simulation was carried out. Five degrees of freedom (DOFs) were introduced, studied, and discussed to demonstrate the geometrical effects on the performance of CMCHSs when the laminar flow of water < 500. This work was done based on constructal theory. The design's DOFs were pitch ratio (1.5, 1.8, 2.1, 2.4, and 2.7), wave amplitude ratio (0.032, 0.048, 0.062, 0.080, and 0.095) solid void fraction (80%, 85%, and 90%), channel configuration (helical, wavy and straight), and channel aspect ratio (0.467-4). The experimental investigation evaluated the computational simulation by examining the effects of factors on the thermal performance of CMCHSs that had been manufactured with the ideal channel dimensions predicted by the numerical simulation. The entrance dissipation thermal resistance and minimum entrance dissipation rate (EDR) were determined through performance analysis using the entrance principle in addition to the energy analysis of the performance of CMCHSs. The numerically predicted findings verified that DOFs have a big effect on CMCHS performance. 90% and 0.46, are the optimum solid void fraction and channel aspect ratio. Nusselt number and friction factor ratios rise for the proposed CMCHSs with helical and wavy channels as pitch and amplitude ratios rise. Due to their high-performance factor, 2.1 and 0.08 are the optimum pitch and amplitude ratios. The analysis of the channel configurations revealed that the three channels' overall EDR values only slightly differ from one another. The best result was also found in the helical channel with the lowest overall EDR, according to a comparison of the best thermo-hydraulic performance of CMCHSs between helical and wavy channels. Ghasemi et al. [35] describes the experimental thermal and hydraulic performances of heat sinks for cooling electronic components with different channel diameters. A heat sink made of aluminum with dimensions of 60, 60, and 16 mm overall. Four circular Mini channels and three distinct hydraulic channel diameter values (D = 4, 6, and 8 mm) make up the heat sink's design. A constant base heat flux is used to warm the Mini channel heat sink. Additionally, the problem is numerically simulated using the FVM The mathematical results are in excellent agreement with the experimental data, as shown by a comparison of the numerical and experimental results. The circular-shaped Mini channel heat sink's capabilities for heat transfer and pressure drop are impacted by variations in channel diameter. Imran et al. [36] conducted research into the geometric optimization of a 3D SMCHS. There were four suggested SMCHS configurations. Then, these designs underwent numerical simulation and experimental testing. In a 3D mini-channel heat sink with several channel configurations, single-phase forced convection for water-cooling laminar flow is modeled using the finite volume approach of mathematical fluid dynamics. To examine the impact of heat load and water mass flow rate on the thermal and hydraulic performances of the SMCHS, experiments were carried out. Experimental findings and numerical findings are in good agreement. Results show that using serpentines with 2 inlets and 2 outlets increases the performance of the proposed device more than using serpentines with just one inlet and one outlet.

Kumar [37] utilized FVM to perform a numerical study of fluid flow and heat transfer in a trapezoidal microchannel for the Reynolds numbers from 96 to 720. To find the ideal heat flux distribution over the microchannels, 3D simulations were run at constant heat flux and various pressure drop circumstances. Additionally, researchers looked at the additional effects of grooves made within the microchannel that were rectangular and semicircular in shape. Pressure drop is calculated for a wide range of Re and determined to be comparable, which serves as proof for the accuracy of numerical modeling of the trapezoidal and rectangular microchannel. From simulations for both microchannels, the Nu, performance parameters, and heat transfer were computed. When compared to a rectangular microchannel, it was shown that the heat transfer in a trapezoidal microchannel dramatically enhanced by 12%. With an improvement in Re and channel disturbances brought on by the existence of furrows on the channel walls, it was discovered that the average Nu was of great value. Additionally, the trapezoidal microchannel's improved impacts on groove size and number were methodically examined. Abdulqadur et al. [38] suggested a brand-new channel design to improve the efficiency of a cylindrical mini-channel heat sink (CMCHS) with the least amount of pressure loss. The channel was designed as a straight-wavy hybrid channel, changing from straight to wavy at the entrance to the CMCHS. For the purpose of analyzing the fluid flow and heat transmission of the CMCHS, 3-dimensional CFD was used. On the CMCHS water with a Re of under 500, simulation was performed. Various geometric characteristics were used to optimize CMCHS performance on the basis of the entropy generation minimization technique. The parameters comprised the wave amplitude ratios of the second and third parts of the channel, as well as the entrance channel length ratio. To evaluate the simulation model, a test rig was created to evaluate CMCHSs under a variety of operational situations. The best dimensions derived from the numerical simulations were used to build two models of CMCHS with straight and hybrid straight-wavy channels. According to the findings, under the identical operating conditions, the straight-wavy channel of the CMCHS performs better overall than the straight channel. In terms of lowering the highest surface temperature along the CMCHS channel length, the straight-wavy channel outperforms the traditional straight channel. When using a straight-wavy channel instead of a straight tube, the CMCHS temperature homogeneity is improved.

Tikadar et al. [39] intends to create a revolutionary water-cooled interconnected counter flow mini-channel sink to improve thermal-hydraulic performance by breaking and re-developing the boundary layers (ICMCHS). The flow domain was divided into three regions by two interconnectors (ICs) that were placed transversely between two counter flow mini-channels (CMCs) (zone 1–3). The nearby CMCs' pressure differences were used to create secondary flow through the ICs, which disrupted the thermal and hydraulic boundary layers. The current numerical studies were conducted for various cases (cases 1-9) by differing ICs width from 1 mm to 1.5 mm and ICs position from 4 mm to 9 mm in order to examine the impact of the ICs position and width on the thermal-hydraulic properties of the counter flow mini-channel heat sink (CMCHS). In contrast to the recently proposed ICMCHS, the base case was decided to be a similar conventional CMCHS. For CMCHS, also experiments were conducted to validate the quantitative results, and accurate result between measured data and the corresponding simulation result was discovered. A highest Performance Evaluation Criterion (PEC) value of 1.22 was attained at the smallest regarded Re (Re = 150) for the longest zone 1 and 3 and the narrowest ICs (case 7), while a peak PEC value of 1.42 was recorded at the greatest Re (Re = 1044) for the middle zone 1 and 3 and the widest ICs (case 6). In order to compare the findings to the smooth examples, Chamanroy and Khoshvaght-Aliabadi [40] evaluated the performance of straight and wavy miniature heat sinks (SMHS and WMHS, respectively) when straight and wavy pin-fins were present. Findings demonstrate the existence of significant velocity and temperature fields differences, which vary depending on the channel and pin-fin shapes, between the improved cases and the smooth cases. Additionally, it is discovered that SMHSs and WMHSs with pin-fins always have larger heat transfer coefficients and pressure drops than those without pin-fins. The augmented cases exhibit 0.05 to 2.3 times higher heat transfer coefficients and 2.6 to 13.6 times higher pressure drops than the smooth cases at the examined Re range (i.e. 100 to 1000). The WMHS with wavy pin-fins with an adverse spin has the greatest values reported. With the same pumping power, it is demonstrated that all improved cases remove more heat than smooth instances do. The SMHS with straight pin-fins and the WMHS with wavy pin-fins, both of which have the same spin, perform better than other configurations when compared overall utilizing ratio of heat transfer rate to pumping power.

Liu et al. [41] developed A unique sort of microchannel heat sink made from copper that is porous like a lotus and has long cylindrical pores oriented in one direction. The impact of the pore structure, involving porosity, pore diameter, and open porosity, on its performance of heat transfer may be anticipated by using the straight fin model to the lotus-type porous copper. The structural element window of lotus-type porous copper that satisfies the heat dissipation need can be determined provided an accessible pump pressure. Pore structure can be optimized by strengthening the process control, and when the sample length along the pore growth direction is 16 mm, 80% of the pores in optimized lotus-type porous copper samples are open. It was evaluated how well modified lotus-type porous copper heat sinks transferred heat. A heat transfer coefficient of 7.86 (W/cm2.K) could be attained at a pressure drop of 100 kPa.

3. Forced convection

Tsai and Chein [42] developed a straightforward model based on energy balance to forecast microchannel heat sink performance. Impacts from both hydrodynamic and thermal development are also included. Comparisons with experimental results demonstrate that this model accurately predicts thermal resistance. To perform structural improvement on the microchannel heat sink, the model is further expanded. When compared to those generated from three-dimensional simulations, the outcomes from the straightforward model show good consistency. Mat Tokit et al. [43] examined only one interrupted microchannel heat sink's thermal efficiency. The study examined the generalizability of Brownian motion velocity in the 168 to 1200 Reynolds number and 0.01 to 0.04 Al_2O_3 nanofluid volume fraction ranges. In two-phase simulations of a nanofluid solution, three alternative Brownian motion velocities have been simulated to describe the nanoparticle velocity. the anticipated Nusselt number is used to analyze the heat transfer improvement. The average Nu is expected to improve from 57.64% to 57.97% when the Re rises from 200 to 1200. Conduction predominated the heat transfer process as the nanofluid volume fraction increased from 0.01 to 0.04, this caused the Nusselt number to increase from 3.90% to 5.13%. Yang et al. [44] presented a mathematical simulation of a trapezoidal MCHS with three-dimensional incompressible steady, turbulent and laminar fluid flow utilizing a CuO/water nanofluid as a cooling fluid. Using the FVM, Navier-Stokes equations with conjugate energy equations are partitioned. CuO/water nanofluid forced convection assumptions made by single-phase and two-phase models (mixed model) using CFD are evaluated. The variables examined include the volumetric flow rate (10, 15 and 20 mL/min) and the particle volume fraction (0.204, 0.256, 0.294, and 0.4%). The two-phase model is more accurate than the single-phase model when the thermal resistance anticipated by the single-phase and two-phase models is compared with the corresponding test findings. In a laminar flow, nanofluids have lower thermal resistance than water, which increases as the rate of volumetric flow and particle volume fraction both rises. Also, the pressure loss of both pure water-cooled and nanofluid-cooled MCHS is examined. The pressure loss for nanofluid-cooled MCHS in the laminar flow condition somewhat rises.

Investigated is how the length of the Y-shaped bifurcation and the angles of the arms affect overall effectiveness. To select the ideal Y-shaped plate length, three models are first compared against the matching rectangular flat microchannel. The impact of arm angles on five distinct Y-shaped plate designs is further examined based on the optimum thermal performance for a particular length. The associated temperature field, flow field, and pressure loss parameters are provided through the computations. It is discovered that MHSs with internal Y-shaped bifurcations have significantly superior thermal performance than the conventional rectangular microchannel. Better thermal performance is achieved by using the tallest internal Y-shaped bifurcation microchannel. Otherwise, the internal Y-shaped bifurcation microchannel performs better thermally when the arm angle is greater.

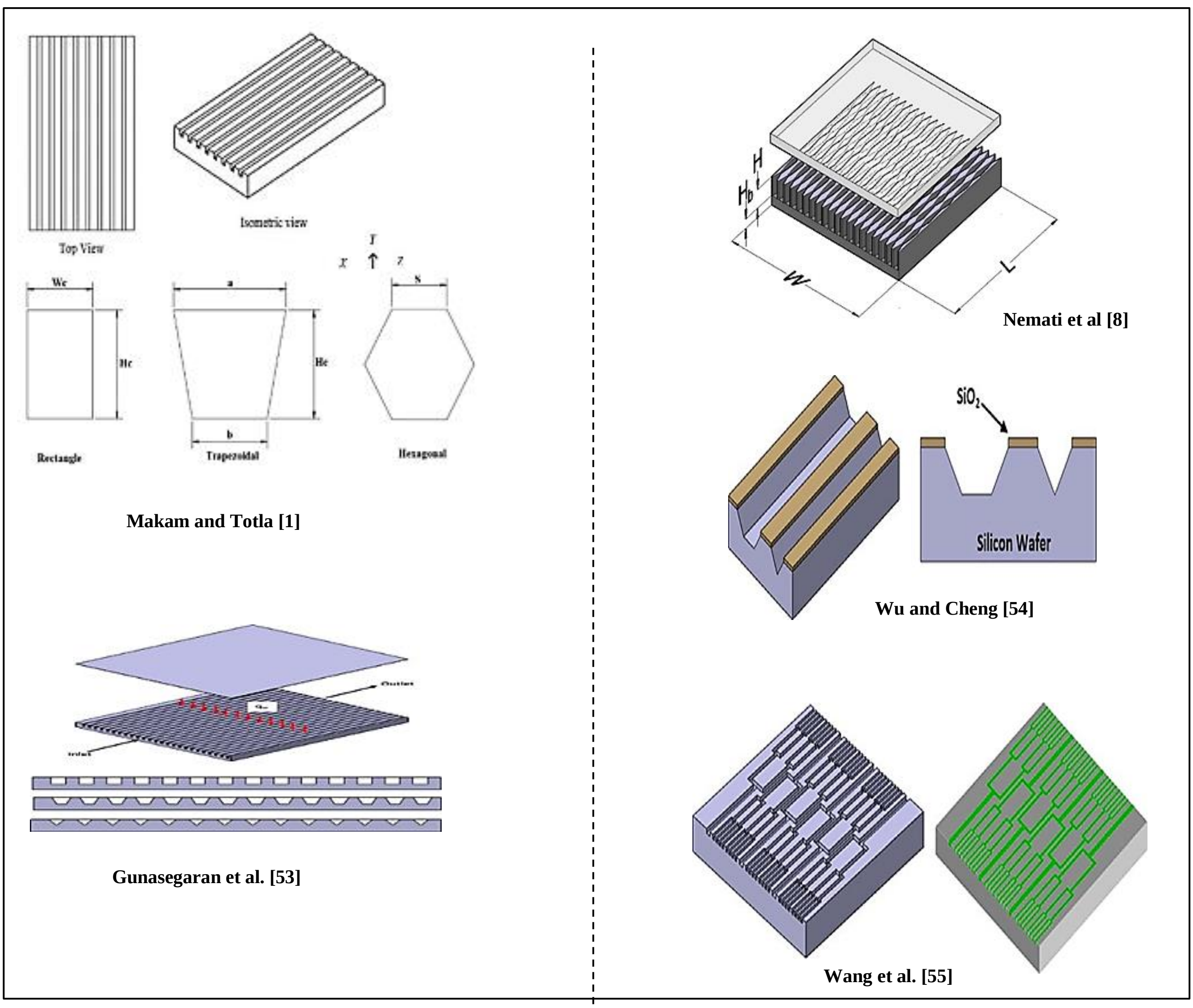

Figure 1. Most common micro/ mini channel heat sink shapes

Xie et al. [45] explored the thermal and fluid flow properties of internal vertical Y-shaped bifurcation plates that are incorporated with MHS.

Dewan, and Srivastava [46] provided a thorough overview of the improvement of heat transport through microchannels. In order to evaluate the pressure losses, friction, and heat transfer properties caused by various flow conditions, roughness structure, and passive surface modifications, latest developments in experimental and computational simulations of single-phase liquid cooled microchannel have been presented. It has been discovered that flow disruption strategies improve heat transmission with fewer negative pressure drop side effects. The study concludes with recommendations for additional studies in this field. Xu et al. [48] conducted a numerical analysis of the flow and heat transmission properties in microchannels with dimples. Dimple depth, aspect ratio, and dimple spacing were three geometric properties of a dimpled channel that were independently evaluated at Re=500. To mimic a high-power device, a constant heat flux of 1 W/mm2 was established at the center region just at bottom of a microchannel heat sink. Dimpled surfaces lowered localized flow resistance and enhanced the thermal efficiency of micro-channel heat sinks when compared to straight channels. The ideal dimpled case has 3.2 K less temperature, 15% more Nu, and 2% fewer pressure losses than the flat channel case. The experimental investigation that Anbumeenakshi et al. [49] conducted looks into how a microchannel heat sink cools when a nanofluid and non - uniform heating are coupled. The microchannel heat sink taken into consideration in study includes 30 rectangular channels that are equally spaced apart and have a hydraulic diameter of 0.727 mm. The experimental investigation makes use of three different heaters with the same dimensions. By turning on every two of the three heaters simultaneously, an uneven heating situation is produced. Working fluids include pure water and nanofluids of Al2O3/water with volume concentrations of 0.1% and 0.25%. According to the findings, an Al2O3/water nanofluid with a volume concentration of 0.25% has a lower peak surface temperature and mean surface temperature than an Al2O3/water nanofluid with such a volume fraction of 0.1% when water is heated uniformly or unevenly. The location of the heater significantly affects the highest temperature of heat sink for the a given heat input and heat transfer fluid. Once the heaters are positioned upstream of the flow, the microchannel heat sink's peak surface temperature is at its minimum. The measurements of the thermal efficiency of nanofluids support their usage in microchannel heat sinks for the thermal control of temperature-sensitive cooling systems. Manay and Sahin [50] conducted research to establish the upper bounds of the volume fraction of particles for the heat transfer efficiency of TiO2-water nanofluids within microchannels. Using pure water as the base fluid, TiO2 metallic nanoparticles were added in five various volumetric ratios (0.25%_ 2.0%) to create nanofluids. The empirical analysis was done to determine the impacts of the Re (100-750) and particle volume percentage on the features of heat transfer and pressure loss at microchannel height (200 m). Although the heat transfer rate was higher than that of pure water, injecting metallic oxide particles in nanoscale diameters into the base fluid did not significantly raise the friction coefficient. Furthermore, it was shown that up to 2.0 vol.%, a water-TiO2 nanofluid boosted heat transfer; however, after 2.0 vol.%, heat transfer reduced. Also, the thermal resistance was measured, and it was discovered that decreasing the thermal resistance by introducing nanoparticles with an average diameter lower than 25 nm into the base liquid. Sidik et al. [51] went into great detail about the usage of passive cooling techniques in microchannel heat sinks. Been presented the impacts of a few key variables just on the rate of heat transfer inside a microchannel heat sink, including the fluid additives, surface roughness, kind of channel, and Reynolds number. Eventually, based on the information gathered, findings and significant summaries were supplied.

4. Conclusions

Raising the heat-flux removal levels for the thermal management of electronic devices or chips is becoming more and more necessary. The strategies that improve heat transfer are summarized in this research, including channel form, dimple surfaces, pin fins, ribs, chambers, groove patterns, and more. Additionally, a discussion aboutthe combined impacts of these geometrical arrangements on heat transfer enhancement is provided. The use of flow interruption techniques was found to have the ability to improve heat transfer, all while minimizing the negative effects of increasing pressure drop. To fully explore the potential of flow disruption techniques while considering viable fabrication methods for mass production, the geometrical arrangements of the approaches must be optimized. Recirculation, eddying, and flow separation occurring behind the surface alterations also require numerical methods with appropriate algorithm and experimental validation. An additional topic that calls for exploration is the computational and experimental validation of porous microchannel heat sinks with various geometrical configurations. Reliability and affordability are the two most important considerations to take into account in the future for industrial applications of high heat flux removal technology.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] Mohammed, H.M. and B.H. Abood, Influences the channel path on hydro-thermal performance in the serpentine mini-channel heat sink. Journal of Engineering and Sustainable Development (JEASD), 2022. 26(3). https://doi.org/10.31272/ jeasd.26.3.5

[2] Liu, X. and J. Yu, Numerical study on performances of mini-channel heat sinks with non-uniform inlets. Applied Thermal Engineering,2016.93:p.856-864. https://doi.org/10.1016/j.applthermaleng.2015.09.032

[3] Singh, V., H.C. Das, and P. Nemalipuri. Numerical analysis of heat transfer and fluid flow in mini-channel heat sink with interconnecting channels. in Advances in Mechanical Engineering: Select Proceedings of ICRIDME 2018. 2020. Springer. https://doi.org/10.1007/978-981-15-0124-1_88

[4] Zhu, Q., et al., Characteristics of heat transfer and fluid flow in microchannel heat sinks with rectangular grooves and different shaped ribs. Alexandria Engineering Journal, 2020. 59(6): p. 4593-4609. https://doi.org/10.1016/j.aej.2020.08.014

[5] Bi, C.T., G. H. Tao, W. Q., Heat transfer enhancement in mini-channel heat sinks with dimples and cylindrical grooves. Applied Thermal Engineering, 2013. 55(1): p. 121-132. https://doi.org/10.1016/j.applthermaleng.2013.03.007

[6] Ho, C.J.G., Yu-Wei Yang, Tien-Fu Rashidi, Saman Yan, Wei-Mon, Numerical study on forced convection of water-based suspensions of nanoencapsulated PCM particles/Al2O3 nanoparticles in a mini-channel heat sink. International Journal of Heat and Mass Transfer, 2020. 157: p. 119965. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119965

[7] Muhammad, A.S., Deepak Wu, Jian, Numerical investigation of laminar flow and heat transfer in a liquid metal cooled mini-channel heat sink. International Journal of Heat and Mass Transfer, 2020. 150: p. 119265. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119265

[8] Nemati, H., M.A. Moghimi, and J.P. Meyer, Shape optimisation of wavy mini-channel heat sink. International Communications in Heat and Mass Transfer, 2021. 122: p. 105172. https://doi.org/10.1016/j.icheatmasstransfer.2021.105172

[9] Kumar, S. and P.K.J.I.J.o.T.S. Singh, Effects of flow inlet angle on flow maldistribution and thermal performance of water cooled mini-channel heat sink. 2019. 138: p. 504-511. https://doi.org/10.1016/j.ijthermalsci.2019.01.014

[10] Sarowar, M.T.J.C.I., Numerical analysis of a liquid metal cooled mini channel heat sink with five different ceramic substrates. 2021. 47(1): p. 214-225. https://doi.org/10.1016/j.ceramint.2020.08.124

[11] Tikadar, A.O., Saad K. Paul, Titan C. Salman, Azzam S. Morshed, A. K. M. M. Khan, Jamil A., Parametric study on thermal and hydraulic characteristics of inter-connected parallel and counter flow mini-channel heat sink. Applied Thermal Engineering, 2019. 153: p. 15-28. https://doi.org/10.1016/j.applthermaleng.2019.02.007

[12] Alfellag, M.A., H.E. Ahmed, and A.S. Kherbeet, Numerical simulation of hydrothermal performance of minichannel heat sink using inclined slotted plate-fins and triangular pins. Applied Thermal Engineering, 2020. 164: p. 114509. https://doi.org/10.1016/j.applthermaleng.2019.114509

[13] Datta, A.S., Vivek Sanyal, Dipankar Das, Pritam, A conjugate heat transfer analysis of performance for rectangular microchannel with trapezoidal cavities and ribs. International Journal of Thermal Sciences, 2019. 138: p. 425-446. https://doi.org/10.1016/j.ijthermalsci.2018.12.020

[14] Hung, T.-C., et al., Thermal performance of porous microchannel heat sink: Effects of enlarging channel outlet. 2013. 48: p. 86-92. https://doi.org/10.1016/j.icheatmasstransfer.2013.08.001

[15] Saadoon, Z.H.A., Farooq H. Sheikholeslami, M., Numerical investigation of heat transfer enhancement using (Fe3O4 and Ag-H2O) nanofluids in (converge-diverge) mini-channel heat sinks. Materials Today: Proceedings, 2021. https://doi.org/10.1016/j.matpr.2021.07.091

[16] Xiao, H., Z. Liu, and W.J.A.T.E. Liu, Conjugate heat transfer enhancement in the mini-channel heat sink by realizing the optimized flow pattern. 2021. 182: p. 116131. https://doi.org/10.1016/j.applthermaleng.2020.116131

[17] Moradikazerouni, A.A., Masoud Alsarraf, Jalal Mahian, Omid Wongwises, Somchai Tran, Minh-Duc, Comparison of the effect of five different entrance channel shapes of a micro-channel heat sink in forced convection with application to cooling a supercomputer circuit board. Applied Thermal Engineering, 2019. 150: p. 1078-1089. https://doi.org/10.1016/j.applthermaleng.2019.01.051

[18] Leng, C.W., Xiao-Dong Wang, Tian-Hu, An improved design of double-layered microchannel heat sink with truncated top channels. Applied Thermal Engineering, 2015. 79: p. 54-62. https://doi.org/10.1016/j.applthermaleng.2015.01.015

[19] Xia, G.D.J., Y. T Li, Y. F. Ma, D. D. Cai, B., Numerical simulation and multiobjective optimization of a microchannel heat sink with arc-shaped grooves and ribs. Numerical Heat Transfer, Part A: Applications, 2016. 70(9): p. 1041-1055. https://doi.org/10.1080/10407782.2016.1230394

[20] Ghahremannezhad, A., K.J.I.J.o.H. Vafai, and M. Transfer, Thermal and hydraulic performance enhancement of microchannel heat sinks utilizing porous substrates. 2018. 122: p. 1313-1326. https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.024

[21] Wong, K.-C., J.-H.J.I.c.i.h. Lee, and m. transfer, Investigation of thermal performance of microchannel heat sink with triangular ribs in the transverse microchambers. 2015. 65: p. 103-110. https://doi.org/10.1016/j.icheatmasstransfer.2015.04.011

[22] Lin, L.Z., Jun Lu, Gui Wang, Xiao-Dong Yan, Wei-Mon, Heat transfer enhancement in microchannel heat sink by wavy channel with changing wavelength/amplitude. International Journal of Thermal Sciences, 2017. 118: p. 423-434. https://doi.org/10.1016/j.ijthermalsci.2017.05.013

[23] Shamsi, M.R.A., Omid Ali Marzban, Ali and D.M. Toghraie, Ramin, Increasing heat transfer of non-Newtonian nanofluid in rectangular microchannel with triangular ribs. Physica E: Low-dimensional Systems and Nanostructures, 2017. 93: p. https://doi.org/10.1016/j.physe.2017.06.015

[24] Wang, T.-H.W., Hao-Chi Meng, Jing-Hui Yan, Wei-Mon, Optimization of a double-layered microchannel heat sink with semi-porous-ribs by multi-objective genetic algorithm. International Journal of Heat and Mass Transfer, 2020. 149: p. 119217. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119217

[25] Shi, X.L., Shan Mu, Yingjie Yin, Bangtao, Geometry parameters optimization for a microchannel heat sink with secondary flow channel. International Communications in Heat and Mass Transfer, 2019. 104: p. 89-100. https://doi.org/10.1016/j.icheatmasstransfer.2019.03.009

[26] Shi, Z., T.J.E.C. Dong, and Management, Entropy generation and optimization of laminar convective heat transfer and fluid flow in a microchannel with staggered arrays of pin fin structure with tip clearance. 2015. 94: p. 493-504. https://doi.org/10.1016/j.enconman.2015.02.009

[27] Jajja, S.A.A., Wajahat Ali, Hafiz Muhammad Ali, Aysha Maryam, Water cooled minichannel heat sinks for microprocessor cooling: Effect of fin spacing. Applied Thermal Engineering, 2014. 64(1): p. 76-82. https://doi.org/10.1016/j.applthermaleng.2013.12.007

[28] Lim, K., J.J.E.C. Lee, and Management, Experimental study on single-phase convective heat transfer of interlocking double-layer counterflow mini-channel heat sink. 2021. 243: p. 114415. https://doi.org/10.1016/j.enconman.2021.114415

[29] Kumar, V., J. Sarkar, and W.-M.J.I.J.o.T.S. Yan, Thermal-hydraulic behavior of lotus like structured rGO-ZnO composite dispersed hybrid nanofluid in mini channel heat sink. 2021. 164: p. 106886. https://doi.org/10.1016/j.ijthermalsci.2021.106886

[30] Mohammadi, M.T., Amin Passandideh-Fard, Mohammad Sardarabadi, Mohammad, Electronic chipset thermal management using a nanofluid-based mini-channel heat sink: An experimental study. International Communications in Heat and Mass Transfer, 2020. 118: p. 104836. https://doi.org/10.1016/j.icheatmasstransfer.2020.104836

[31] Ho, C.J., et al., Cooling performance of mini-channel heat sink with water-based nano-PCM emulsion-An experimental study. International Journal of Thermal Sciences, 2021. 164: p. 106903. https://doi.org/10.1016/j.ijthermalsci.2021.106903

[32] Halelfadl, S.A., Ahmed Mohammed Mohd-Ghazali, Normah Maré, Thierry Estellé, Patrice Ahmad, Robiah, Optimization of thermal performances and pressure drop of rectangular microchannel heat sink using aqueous carbon nanotubes based nanofluid. Applied Thermal Engineering, 2014. 62(2): p. 492-499. https://doi.org/10.1016/j.applthermaleng.2013.08.005

[33] Jaffal, H.M.F., Basim Hussain, Ammar A. Hasan, Ala, Effect of the fluid flow fragmentation on the hydrothermal performance enhancement of a serpentine mini-channel heat sink. Case Studies in Thermal Engineering, 2021. 24: p. 100866. https://doi.org/10.1016/j.csite.2021.100866

[34] Khalifa, M.A. and H.M.J.A.T.E. Jaffal, Effects of channel configuration on hydrothermal performance of the cylindrical mini-channel heat sinks. 2019. 148: p. 1107-1130. https://doi.org/10.1016/j.applthermaleng.2018.11.101

[35] Ghasemi, S.E., A.A. Ranjbar, and M.J. Hosseini, Experimental and numerical investigation of circular minichannel heat sinks with various hydraulic diameter for electronic cooling application. Microelectronics Reliability, 2017. 73: p. 97-105. https://doi.org/10.1016/j.microrel.2017.04.028

[36] Imran, A.A., et al., Numerical and experimental investigation of heat transfer in liquid cooling serpentine mini-channel heat sink with different new configuration models. 2018. 6: p. 128-139. https://doi.org/10.1016/j.tsep.2018.03.011

[37] Kumar, P.J.I.J.o.T.S., Numerical investigation of fluid flow and heat transfer in trapezoidal microchannel with groove structure. 2019. 136: p. 33-43. https://doi.org/10.1016/j.ijthermalsci.2018.10.006

[38] Abdulqadur, A.A., H.M. Jaffal, and D.S.J.I.J.o.T.S. Khudhur, Performance optimiation of a cylindrical mini-channel heat sink using hybrid straight–wavy channel. 2019. 146: p. 106111. https://doi.org/10.1016/j.ijthermalsci.2019.106111

[39] Tikadar, A.P., Titan C. Oudah, Saad K. Abdulrazzaq, Nabeel M. Salman, Azzam S. Khan, Jamil A., enhancing thermal-hydraulic performance of counter flow mini-channel heat sinks utilizing secondary flow: Numerical study with experimental validation. International Communications in Heat and Mass Transfer, 2020. 111: p. 104447. https://doi.org/10.1016/j.icheatmasstransfer.2019.104447

[40] Chamanroy, Z. and M. Khoshvaght-Aliabadi, Analysis of straight and wavy miniature heat sinks equipped with straight and wavy pin-fins. International Journal of Thermal Sciences, 2019. 146: p. 106071. https://doi.org/10.1016/j.ijthermalsci.2019.106071

[41] Liu, X., et al., Effect of pore structure on heat transfer performance of lotus-type porous copper heat sink. International Journal of Heat and Mass Transfer, 2019. 144: p. 118641.

https://doi.org/10.1016/j.ijheatmasstransfer.2019.118641

[42] Tsai, T.-H. and R. Chein, Simple model for predicting microchannel heat sink performance and optimization. Heat and Mass Transfer, 2012. 48(5): p. 789-798. https://doi.org/10.1007/s00231-011-0933-2

[43] Mat Tokit, E., M.Z. Yusoff, and H.A. Mohammed, Generality of Brownian motion velocity of two-phase approach in interrupted microchannel heat sink. International Communications in Heat and Mass Transfer, 2013. 49: p. 128-135. https://doi.org/10.1016/j.icheatmasstransfer.2013.10.005

[44] Yang, Y.-T.T., Kuo-Teng Wang, Yi-Hsien Lin, Shih-Han, Numerical study of microchannel heat sink performance using nanofluids. International Communications in Heat and Mass Transfer, 2014. 57: p. 27-35. https://doi.org/10.1016/j.icheatmasstransfer.2014.07.006

[45] Xie, G., H. Shen, and C.-C. Wang, Parametric study on thermal performance of microchannel heat sinks with internal vertical Y-shaped bifurcations. International Journal of Heat and Mass Transfer, 2015. 90: p. 948-958. https://doi.org/10.1016/j.ijheatmasstransfer.2015.07.034

[46] Dewan, A. and P. Srivastava, A review of heat transfer enhancement through flow disruption in a microchannel. Journal of Thermal Science, 2015. 24: p. 203-214. https://doi.org/10.1007/s11630-015-0775-1

[47] Shi, Z. and T. Dong, Entropy generation and optimization of laminar convective heat transfer and fluid flow in a microchannel with staggered arrays of pin fin structure with tip clearance. Energy Conversion and Management, 2015. 94: p. 493-504. https://doi.org/10.1016/j.enconman.2015.02.009

[48] Xu, M.L., Hui Gong, Liangn Chai, John C. Duan, Xinyue, Parametric numerical study of the flow and heat transfer in microchannel with dimples. International Communications in Heat and Mass Transfer, 2016. 76: p. 348-357. https://doi.org/10.1016/j.icheatmasstransfer.2016.06.002

[49] Anbumeenakshi, C.T., M. R., On the effectiveness of a nanofluid cooled microchannel heat sink under non-uniform heating condition. Applied Thermal Engineering, 2017. 113: p. 1437-1443. https://doi.org/10.1016/j.applthermaleng.2016.11.144

[50] Manay, E. and B. Sahin, Heat Transfer and Pressure Drop of Nanofluids in a Microchannel Heat Sink. Heat Transfer Engineering, 2017. 38(5): p. 510-522. https://doi.org/10.1080/10407782.2016.1195162

[51] Sidik, N.A.C., et al., An overview of passive techniques for heat transfer augmentation in microchannel heat sink. International Communications in Heat and Mass Transfer, 2017. 88: p. 74-83. https://doi.org/10.1016/j.icheatmasstransfer.2017.08.009

[52] Makam, J.S. and N.B. Totla, Heat Transfer Characteristics of Water Cooled Minichannel Heat Sink Using Different Fluid Flow Geometries. IOP Conference Series: Materials Science and Engineering, 2020. 998(1): p. 012018. DOI 10.1088/1757-899X/998/1/012018

[53] Gunnasegaran, P., et al., The effect of geometrical parameters on heat transfer characteristics of microchannels heat sink with different shapes. International Communications in Heat and Mass Transfer, 2010. 37(8): p. 1078-1086. https://doi.org/10.1016/j.icheatmasstransfer.2010.06.014

[54] Wu, H.Y. and P. Cheng, Friction factors in smooth trapezoidal silicon microchannels with different aspect ratios. International Journal of Heat and Mass Transfer, 2003. 46(14): p. 2519-2525. https://doi.org/10.1016/S0017-9310(03)00106-6

[55] Wang, X.-Q., A.S. Mujumdar, and C. Yap, Thermal characteristics of tree-shaped microchannel nets for cooling of a rectangular heat sink. International Journal of Thermal Sciences, 2006. 45(11): p. 1103-1112. https://doi.org/10.1016/j.ijthermalsci.2006.01.010