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A Comprehensive Review on Computational Fluid Dynamics Analysis and Optimization of Open Micro-Channel Heat Sinks with Pin Fins

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Abstract: The increasing demand for efficient thermal management in microelectronics has driven significant advancements in heat sink designs. Among various cooling technologies, open micro-channel heat sinks (OMCHS) with pin fins have emerged as a promising solution due to their ability to enhance heat transfer performance while maintaining compact dimensions. This paper presents a comprehensive review of the use of Computational Fluid Dynamics (CFD) in analyzing the thermal and fluid flow behavior of OMCHS with pin fins. The review focuses on key findings from recent studies, comparing different pin fin geometries, materials, and micro-channel configurations. Emphasis is placed on the accuracy and computational efficiency of CFD models, the influence of boundary conditions, and the optimization of design parameters for maximizing heat transfer while minimizing pressure drop. The insights gained from these analyses offer valuable guidelines for the design and optimization of next-generation heat sinks in high-performance electronic devices. Finally, the review highlights the challenges and future directions for improving CFD simulations in predicting real-world heat sink performance.
Keywords: Microchannel heat sink, Grey relational optimization, Surface heat flux, Surface Nusselt number, optimization

I. INTRODUCTION

Electronic devices generate significant heat during operation. This heat needs efficient management to prevent overheating and ensure reliable performance. Micro-channel heat sinks (MCHS) with pin fins are a promising technology for thermal management due to their high surface area and efficient heat transfer capabilities. The movement toward smaller, more durable electronics has completely changed how consumers interact with technology in today's fast-paced market. Daily demand for miniaturization is rising across a wide range of devices, from laptops and cellphones to automotive and medical equipment [1][2][3]. In today's rapidly evolving industry, the trend towards smaller and more durable electronic products is significantly changing how consumers interact with technology. This shift is evident in various sectors, including smartphones, laptops, automotive systems, and medical devices. The demand for miniaturization is increasing as consumers seek more compact, robust, and efficient devices that offer enhanced functionality and convenience. This drive for smaller, more resilient technology is reshaping the design and manufacturing processes across multiple industries [4]. While technological advancements open up numerous opportunities, they also bring certain challenges. The significant miniaturization of energy systems and electronic devices requires the precise arrangement of complex components within a limited space. This compact design leads to higher densities of electronic components, which in turn generate substantial heat flow and create hot spots. Effective heat management becomes crucial to maintain the performance and longevity of modern electrical equipment. Without adequate cooling, these devices can overheat, leading to reduced efficiency, potential failures, and shorter lifespans. The need for internal cooling systems in miniaturized devices is paramount. These cooling systems must be highly efficient and capable of dissipating heat effectively in a confined space. Engineers and designers are constantly innovating to develop advanced cooling solutions, such as microchannel heat sinks, heat pipes, and phase-change materials. These technologies help manage the thermal load and ensure the reliable operation of electronic devices [5]. Microchannel heat sinks (MCHSs) have demonstrated significant potential for addressing these thermal management challenges. Researchers' attention has been drawn to microchannel heat sinks (MCHSs), a type of liquid-cooling heat sink that has replaced standard air-cooling heat sinks by exhibiting desirable performance in addition to compact design [6][7]. Over time, extensive research has been conducted to enhance the hydrothermal performance of microchannel heat sinks (MCHS) by implementing various innovative strategies. These strategies include, Modulating the Pin-Fin Arrangements, Altering Fin Shapes, Adjusting Fin Spacing and Fin Tip Clearance. Through these diverse approaches, researchers aim to optimize the design and operation of MCHS, ultimately achieving greater efficiency in thermal management for applications ranging from electronics cooling to industrial processes[8].

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Technological developments bring about endless opportunities, but they also have drawbacks. An optimal arrangement of complex components within a limited space is essential for the aggressive miniaturization of energy systems and electronic devices [8][9][10]. This frequently raises the component's operating temperature and results in a notable increase in heat fluxes produced per unit volume [11]. Elevated temperatures have been linked to shorter lifespans, decreased efficiency, and a higher chance of component malfunction. Therefore, in order to ensure the consistent and reliable operation of these devices, it is imperative to evacuate the surplus heat effectively. The pursuit of developing a sophisticated cooling technique to address thermal management issues in electronic equipment has become increasingly consequential for engineers [12]. Microchannel heat sinks (MCHSs) have emerged as a highly effective solution for managing thermal imbalances and enhancing the performance of miniature systems. Their design and functionality offer significant advantages over traditional cooling methods, especially in applications where space is limited and efficient heat dissipation is critical [13]. Electronic devices generate significant heat during operation. This heat needs efficient management to prevent overheating and ensure reliable performance. Micro-channel heat sinks (MCHS) with pin fins are a promising technology for thermal management due to their high surface area and efficient heat transfer capabilities [14]. In today's quickly changing market, the transition to smaller and more durable electronic items has altered how customers interact with technology. Whether it's smartphones, computers, automotive systems, or medical gadgets, the desire for downsizing is always expanding [15]. While technological advancements create numerous opportunities, they also come with certain challenges. The growing downsizing of energy systems and electronic gadgets involves the careful grouping of complicated components inside a limited space[16].

The functionality of contemporary electrical equipment depends on efficient heat management. Internal cooling systems are required because to the rapid heat flow and hot spots caused by the high-density integration of electronic components [4]. These advanced cooling devices are designed to efficiently manage heat in compact electronic systems where space and cooling efficiency are critical [17]. Microchannel heat sinks represent a significant advancement over traditional air-cooling heat sinks. Unlike their air-cooled counterparts, which rely on air flow to dissipate heat, MCHSs utilize liquid cooling. This shift from air to liquid cooling is driven by the superior thermal conductivity of liquids, which allows MCHSs to achieve more effective heat removal in a smaller footprint. Researchers have increasingly focused on MCHSs due to their ability to handle high thermal loads while maintaining a compact and lightweight design.

This makes them particularly suitable for applications in modern electronics, where devices are becoming more powerful and densely packed. Their small size and efficient heat transfer capabilities make them ideal for use in environments with limited space, such as in high-performance computing systems, aerospace applications, and compact consumer electronics. Traditionally, experienced technicians chose parameters by trial and error, which was time and money intensive for each new welded product to match the specified requirements of the welded joint. Several researchers have used single-quality characteristic analyses to overcome these difficulties.

The single-objective approach consists entirely of simplifications of the genuine situation. Open micro-channel heat sink with pin fins processes the heat sink's length, breadth, number of fins, fin height, base height, and fin thickness to maximize heat transmission.

All of these process factors have the potential to alter the quality and attributes of the weld. It is difficult to discover the ideal design of open micro-channel heat sink with pin Fins process parameters by employing single objective optimization approaches such as ANOVA [18], response surface optimization [19], Taguchi method [10], thus the total heat transfer rate is represented by many quality characteristics. To improve welding characteristics under ideal process circumstances, it is necessary to investigate the multi-objective optimization strategy. Then, using grey relational analysis (GRA), a correlation between the process's quality attributes in these situations is established. [20][21].

II. HEAT DISSIPATION USING THE MICRO HEAT SINK

A device with a large active surface area that can effectively absorb and transmit heat generated is called a micro heat sink. Its usefulness in efficiently eliminating excessive heat flux in electronic equipment has garnered attention. MPF heat exchangers are one of the most promising approaches among the current extended surface-based heat sinks that have emerged in recent years [22]. Numerous studies have attempted to enhance the hydro-thermal performance of MPFs by the use of different phase change materials and hybrid coolants, as well as through optimization of the pin-fin geometry, fin spacing, fin tip clearance, porosity, and arrangement [23][24]. The following section discusses a few of the most important studies.

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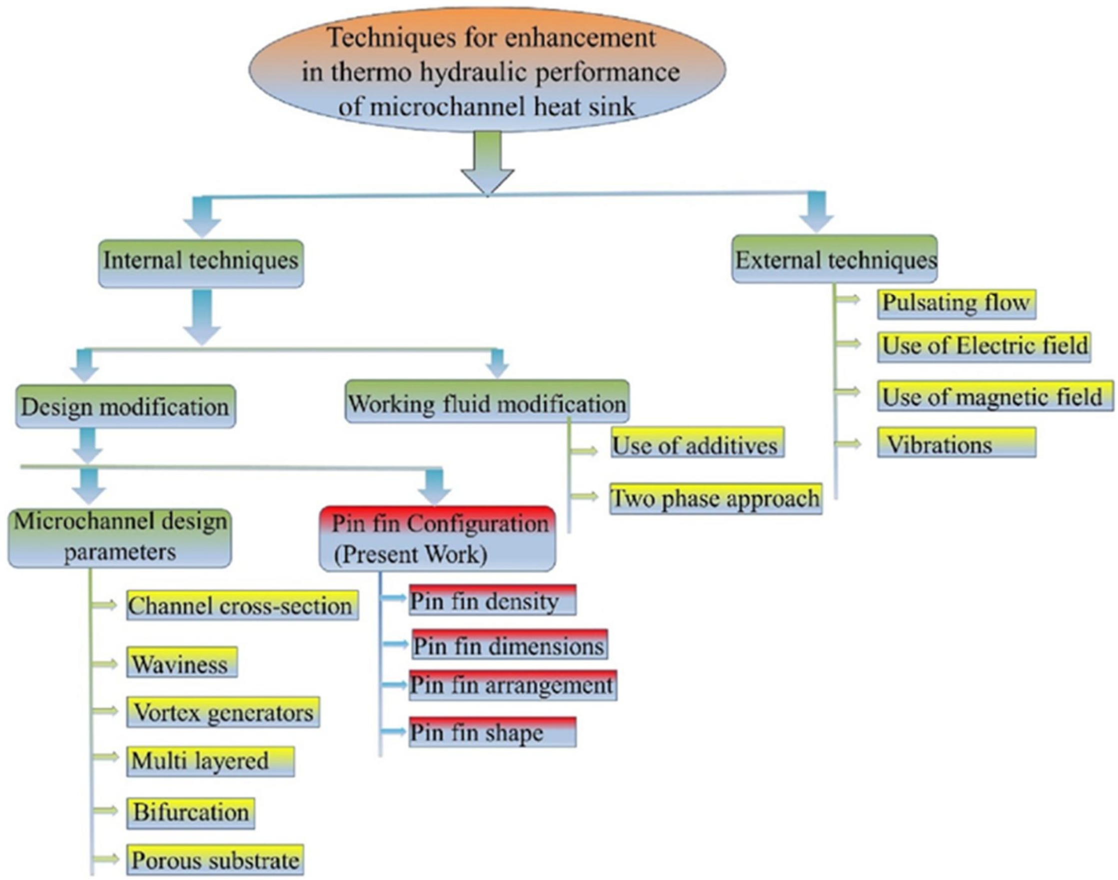

Figure 1 Leading methods for improving thermo-hydraulic performance in MCHS [13]

III. GEOMETRY AND COOLANTS MODIFICATIONS

The several methods for improving heat transmission for micro pin fin heat sinks-such as altering their configuration, form, and coolant choice-are covered in this section.

A. Shapes and Arrangements of the Micro Pin fin Heat Sink

Dhakulkar et al. [25] conducted a numerical investigation on the air-cooled, triangular-shaped MPF heat sink while taking into account intake turbulence, as part of a series of research on the heat transfer improvement of MPF heat sinks. They discussed how the fin dimension affected heat sink effectiveness. Using de-ionized water as a working fluid, Gohane et al. [26] conducted an experimental and computational investigation of the hydro-thermal performance characteristics of the elliptical-shaped MPF heat sink. They discovered that the MPF's porosity and aspect ratio had a significant influence on the performance measures. Using a piezoelectric fan, Bhandari et al. [13] conducted an experimental investigation to enhance the thermal performance of staggered organized MPF. They found that the inclusion of the piezoelectric fan considerably improves the MPF heat sink's thermal performance at higher Re, although the vibrations cause an extra pressure loss. Using a computational approach, Bndu et al. [27] examined several staggered configurations of cylindrical MPF in the low Reynolds number region ($20 \leq Re \leq 160$). A novel cooling method using both active and passive parts in the MPF heat sink was presented by Yeom et al. By adding high-frequency piezoelectric translational agitators with airflow below the range of Re (1,000–10,000), it improves heat transmission. Microfluidic systems are becoming more and more common in industries including biotechnology, electronics, and sensing because to advancements in microfabrication. These systems depend on microchannels, which makes the phenomenon of convective transport in microchannels essential. Data on pressure drop and heat transfer for turbulent and laminar flows in microchannels are presented in recent works. The first microchannel heat sinks were proposed by Tuckerman and Pease [28], who demonstrated that conventional devices had lower heat transfer coefficients in turbulent flow compared to laminar flow.

Their research showed that improving heat transport at the microscale by lowering channel height prompted additional studies that validated and expanded upon their results. An experimental research into the single-phase forced convective heat transfer capabilities of water/methanol traveling through rectangular micro-channels with five various sizes.(0.6 × 0.7 mm² to (0.2 × 0.7 mm²) was carried out by Wang and Peng [29]. Their discoveries provide important information and new perspectives on forced-flow convection behavior in microchannels. Peng and Peterson [30] conducted an experimental investigation on single-phase forced convective heat transfer in microchannels featuring different geometric designs and hydraulic diameters ranging from 0.133 to 0.367 mm. They discovered that geometry includes an enormous effect on fluid flow and heat transfer, with turbulent flow resistance being lower than conventional predictions and laminar heat transfer dependent on aspect ratio. Fedorov and Viskanta [31] created a 3D model having same shape as Kawano et al.'s [32] tests to examine conjugate heat transmission into a microchannel heat sink. Their analysis showed that, except for the area close to the intake, where there were noticeable temperature gradients, the normal channel surface temperature was almost constant through out the flow path. They concluded that while thermal qualities rely on temperature, changing them in numerical models is difficult because of the close relationship between temperature and velocity. Qu and Mudawar [31] used deionized water as the coolant in experimental and numerical investigations of pressure drop and heat transfer for single-phase laminar flow in 231 µm by 713 µm channels. 100 and 200 W/cm³ of heat flow were measured in relation to the planform area of the heat sink. The use of traditional Navier-Stokes equations for microchannels was validated by their results, which demonstrated good agreement between observations and numerical predictions. Near the bottom wall channel intake, higher values of the Nusselt number and heat flux were noted. Qu and Mudawar [33] employed techniques similar to those of Fedorov and Viskanta [34] and Kawano et al. [35] to conduct a three-dimensional numerical analysis of fluid flow and heat transfer in a rectangular microchannel heat sink. They discovered that the length of the developing flow region is influenced by the Reynolds number. The heated base surface close to the channel exit was usually where the maximum temperature was found, and both the solid and fluid regions' temperature rise along the flow direction could be roughly described as linear. Using water as the working fluid, Mishan et al. [36] conducted an experimental investigation on heat transmission and fluid flow in a rectangular microchannel. Their findings shown that water flows through microchannels may be explained by traditional theory, which takes entry effects into account. Additionally, they created an innovative method for determining the channel's fluid temperature distribution.

B. Micro pin Fin with Different Working Fluids

Because coolants have better transfer coefficients than air cooling, using them to lower the temperature of electrical equipment has grown increasingly attractive. It is possible to use liquid coolants in single- and multi-phase systems. Numerous researchers have studied the micro heat sink with various working fluids and discovered the impact on the pressure drop across the heat sink and the rates of heat transfer. Bhandari and Prajapati [37] conducted several studies on the hydro-thermal characteristics of micro-pin fin arrays for circular and square pin fins with diameters (30–150 µm) and height (200 µm) considering a single-phase de-ionized (DI) water and a two-phase R245fa coolant. Zeng et al.[38] used nano-fluids made of titania (TiO_2), alumina (Al_2O_3), and silica (SiO_2) to cool the quad-core CPU microchip. Highly conductive thermal paste was employed to reduce thermal resistance between the interface of the block and the heat spreader of a processor. Better thermal performance, cost-effectiveness, and lack of chemical and corrosion effects are only a few of the criteria that should be taken into account when choosing a nano-fluid for computer cooling. Kosar et al. [39] numerically investigated the effects of six various nano-fluids in a triangle-shaped microchannel heat sink for the laminar regime. The heat transfer coefficient improvements for diamond and Al_2O_3 nano-fluids were the highest and lowest, respectively. For SiO_2 nano-fluid, the pressure loss was greatest; for Ag nano-fluid, it was lowest. Diamond and Ag nano-fluids were linked to the lowest heat resistance and wall shear stress, respectively. Qidwai et al. [40], [41], [42] investigated the influence of fin height on the heat transfer properties of rectangular fin heat sinks utilizing TiO_2 nano-fluid as a coolant. Because there is more surface area with increasing fin height, there is a tendency for surface roughness to increase, which speeds up heat transfer. As the convective heat transfer coefficient improves, the thermal resistance also does as well because it is inversely connected to this parameter. They reported 1.15 °C reduction in the heat sink’s base temperature for a 0.2% CuO nano-fluid compared to water and showed the impact of pin fin arrangements on heat sink performance by employing nano-fluid as a coolant in a heat sink under a laminar flow regime. The influence of flow rate on the heat transfer parameters and the pressure drop requirement of the micro heat sink. Conventionally, a heat sink with high-pressure air is still preferable to control the temperature of the electronic components due to its being lightweight, less expensive, and more reliable. When designing an effective heat sink, consideration should be given to factors including a simpler structure, a high heat transfer rate, and a low-pressure drop. The cooling techniques that employ liquid as the medium can dissipate more heat in less space. However, liquid cooling techniques have intricate designs, are more expensive, and require continuous maintenance and monitoring.

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Whereas air-cooling has certain advantages, as it does not require pipe fittings, it also requires less maintenance, and there is no chance of fluid leakage. Therefore, several studies focused on the air- cooling of electronic components over the past few decades [26][43].

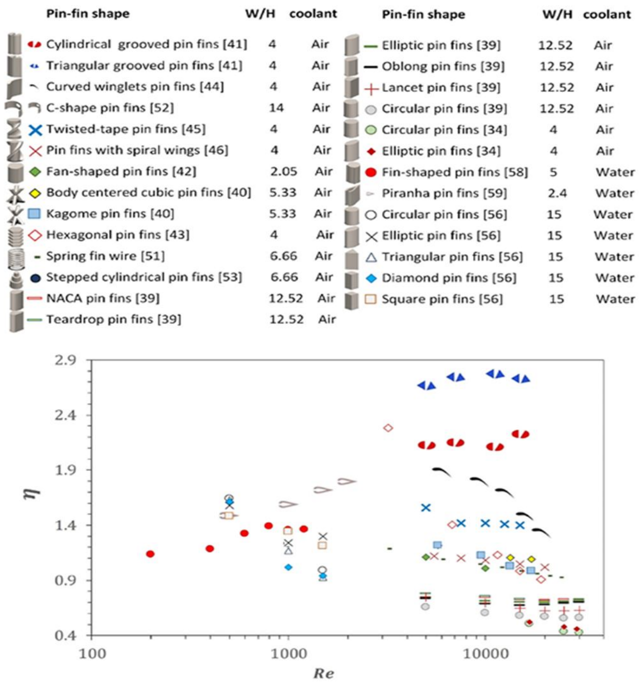

Figure 2 Comparing the characteristics of thermohydraulic performance on different roughened surfaces.

IV. OPTIMIZATION OF HEAT SINK’S DESIGN VARIABLES

The goal of heat sink optimization is to maximize its efficiency for applications involving the improvement of heat transmission. The heat sink may be optimized using a variety of design elements, including height, breadth, form, and inflow velocity. The Nusselt number and pressure drop of a heat sink are the most important performance indicators. A perfect balance between these variables can result in the best design for a given use case. In this part, a few research has optimization studies are covered.

A. *Using Parametric Analysis through Experiments and Simulations*

Saha et al. [44] conducted a CFD-based parametric research to investigate the impacts of pitch, aspect ratio, and channel height on the thermal performance of a rectangular MPF heat sink at Reynolds numbers (Re) ranging from 180 to 600. Increasing pin pitch and channel height leads to better thermal performance. According to John et al.'s [45] CFD-based parametric investigations, the inter-fin distance, fin aspect ratio, and hydraulic diameter value are the main determinants of the figure of merit, which is the product of the inverse of the pumping power and thermal resistance. Similar to this, Lee et al. 74 conducted an experimental parametric analysis on oblique micro fins and proposed that high heat transfer rates are obtained from smaller fin pitches and oblique angles. An important understanding of the heat sink system design was gained with the aid of these parametric studies.

B. *Using the Dedicated Optimization Techniques*

Zhu et al. [46] obtained the design parameters for a thermoelectric cooler heat sink by combining an entropy generation-based optimization approach with a numerical solver. The geometrical parameters of a water-cooled microchannel heat sink with dimples and pin-fins were found by Li et al. [47] using a pattern search optimization technique, and they were able to achieve a roughly 10% improvement in thermal performance. Chong et al. [48] optimized the channel width, depth, and intake flow velocity of microchannel heat sinks with single-layer counter-flow (SLCF) and double-layer counter-flow (DLCF) using a direct search technique. In order to maximize the channel design parameters—such as height, width, and aspect ratio for the least amount of heat resistance at a constant pumping power, Jeevan et al. [49] used a genetic algorithm (GA) and box optimization approach. Yaji et al. [50] looked into level set-based topology optimization to enhance a heat sink's capacity for heat transmission. In their study, the thermal performance of the optimal design is evaluated based on the number of meshes or optimization rounds.

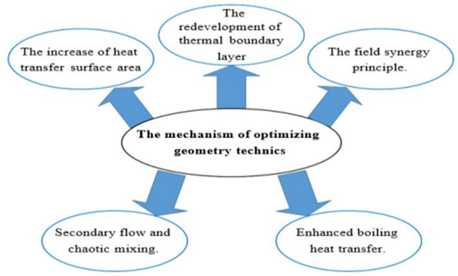

Figure 3 various mechanism for optimization of Micro channel heat sink with pin fins [51]

Table 1 Summary of Micro channel Cooling Operations and Variable Solutions

Ref.	Emphasis	Micro Channel variables			Fluid Type with Additive		Output variables
		Shape	Size	Material	Fluid Type	Additive Type	
Nomura & Kumano, [52]	Studied the flow and heat transfer characteristics of the oil and water emulsion	circulated	0.27 and 0.80 mm	SUS430	water	Silicone oil and Span85	apparent viscosity, Nusselt number, temperature distribution
S. Lee et al., n.d. [53]	For laminar flow, how the entrance length is effected by microchannel geometry is studied	Rectangular shaped micro-channel	aspect ratio ~2.65 and the hydraulic diameter 380µm	Transparent acrylic.	Deionized water	---	velocity profiles, entrance length
J.-T. Liu et al., [54]	Study the effects of viscosity and thermal conductivity variations	---	100 µm single channel	--	Water	---	Reynolds number, heat flux
Ansari et al., [55]	Optimization and Comparative Study on heat sink with microchannels having Rectangular-Fins and Oblique- fins	Oblique- and Rectangular	single periodic channel,	---	Deionized ultra filtered water	---	Velocity and temperature
Cheng et al., [56]	Thermal-hydraulic performance of a tapered microchannel	Tapered microchannel	19.4 mm insert OD, Block 20 mm	SS Insert and copper block	distilled water	---	Nusselt number, pressure drop, Heat Flow
P.-S. Lee & Garimella et al., [57]	Studied Heat exchange in rectangular shaped microchannel and studied flow of thermally developed fluid	Rectangular	200 µm and 120 mm, Varying Aspect ratio	---	Water	---	Nusselt number
(D. Liu & Garimella et al., [58]	Investigation Of Liquid Flow In Microchannels	Cylindrical	244 to 974 □m	---	deionized water	---	Flow Visualization
Gunnasegaran et al., [59]	Studied Heat exchange with respect to the geometrical parameters of microchannel	rectangular, trapezoidal, and triangular	Varying Size	aluminum substrate	Water	---	Distribution of Temperature, Heat exchange coefficient, drop in pressure
Jung & Kwak, et al., [60]	Analysis of heat exchange and fluid flow characteristics in rectangular shaped microchannels	rectangular cross section	20 x 30 mm	double-polished- prime silicon wafer	Deionized water	---	Nusselt number
Husain & Kwang-Yong Kim et al., [61]	Shape Optimization of Micro-Channel	rectangular	10 x 10 mm	---	Water	--	Temperature distribution
Kohl et al., [62]	Internal pressure was measured in microchannel experimentally for flow in microchannel	rectangular cross- sectional area	diameters ranging from 25 to 100 µm	silicon chips	Water with air	--	Pressure and temperature
H. Li & Olsen, et al., [63]	Studied turbulent flow and transitional flow in context with Aspect Ratio	Rectangular	Range of Aspect ratio was considered from 0.97 to 5.69	silicon wafer	deionized water	---	velocity profiles, Reynolds numbers

Raghuraman et al.,[64]	Studied Thermal performance and variation in performance due to Aspect Ratio	Rectangular	36.75 width, 31 mm length	Copper	Water	---	heat exchange coefficient, thermal variation, flow friction and drop in pressure
Peng et al., [65]	Frictional Flow Characteristics Of Water Flowing	Rectangular	0.133-0.367 mm	stainless steel	Water	---	flow friction
Peng & Peterson, et al., [66]	Effect of thermo fluid and geometrical parameters on convective heat transfer of liquids	Rectangular	45 x 18 mm	---	water and methanol	---	Transition and laminar heat transfer
P.-S. Lee & Garimella, et al,. [67]	determine the heat transfer characteristics and cooling performance	Rectangular	18 mm wide and 125 mm long,	steel plates	Water	--	Heat Flux, Reynolds number, heat transfer or liquid flow mode` Transition
Peng & Peterson, [30]	Heat exchange through Convection and flow friction in microchannel structures for water as coolant	Rectangular	0.1 -0.4 mm	stainless steel plate substrate	Water	--	Heat transfer and flow characteristics
Steinke & Kandlikar, [68]	Friction factors in Single-phase liquid flow in microchannels	--	Diameter range of 8 < Dh < 990 µm	--	Water	--	Pressure drop measurements
H. Wu & Cheng, [69]	experimental study of heat transfer through convection	Rectangular channel	--	Silicon	deionized water	--	Heat transfer through convection and drop in pressure
Peiyi & Little, et al,. [70]	friction factors for the flow of gases	Rectangular channel	Width of 130 to 200 microns, depth 30 to 60 microns	silicon substrates	deionized water	--	Friction factor

V. CONCLUSIONS

Studies have investigated the performance of micro-channel heat sinks with pin fins. Research has shown that parameters like fin geometry such as fin height, diameter, spatial arrangement significantly affect heat transfer. Other studies also revealed that increasing fin height and decreasing fin spacing generally enhance heat transfer but also increase pressure drop. Higher airflow velocities improve heat transfer but also lead to higher pumping power requirements. Therefore, modeling the interaction between solid and fluid domains provides a more accurate prediction of heat transfer performance. To get a larger heat flow, researchers have also employed several hybrid coolants, such as dielectric fluid and nanofluid. However, because of its lower cost, lighter weight, easier upkeep, straightforward design, and higher durability, the air-cooled heat sink is still chosen over the one that uses liquid coolants. According to the literature, air-cooled rectangular-shaped MCHSs are an effective choice for electronic device cooling. In general, rectangular MCHS are utilized as 62.5% of the researches for car applications. Figure 4 displays a thorough design review based on previous research

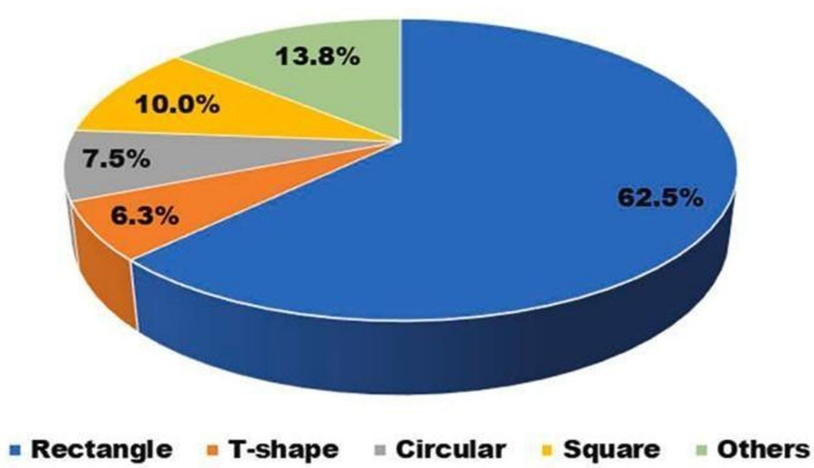

Figure 4 Different design implementation used by researchers

It is also anticipated that the shape and number of the perforations could play an important role in augmenting the thermal performance of these devices. Therefore, this work also investigates the hydrodynamic and thermal characteristics of the proposed heat sink with different shapes and numbers of perforations over a wide range of airflow velocities suited for electronic cooling applications. Furthermore, their thermal performance is also investigated for varying perforation diameter and location. However, it is not computationally viable to simulate a large number of cases with different perforation diameters and locations to obtain a configuration that simultaneously yields the best thermal performance and the optimal pressure over a wide range temperature distribution. Therefore, a multi-objective optimization technique like the standard deviation objective weighting method and the GRA- based Taguchi method in conjunction with the numerical solver is applied in the present thesis to handle this problem of perforated MCHSs) with the constraints on the size of perforation diameter and location considering the manufacturing limitations.

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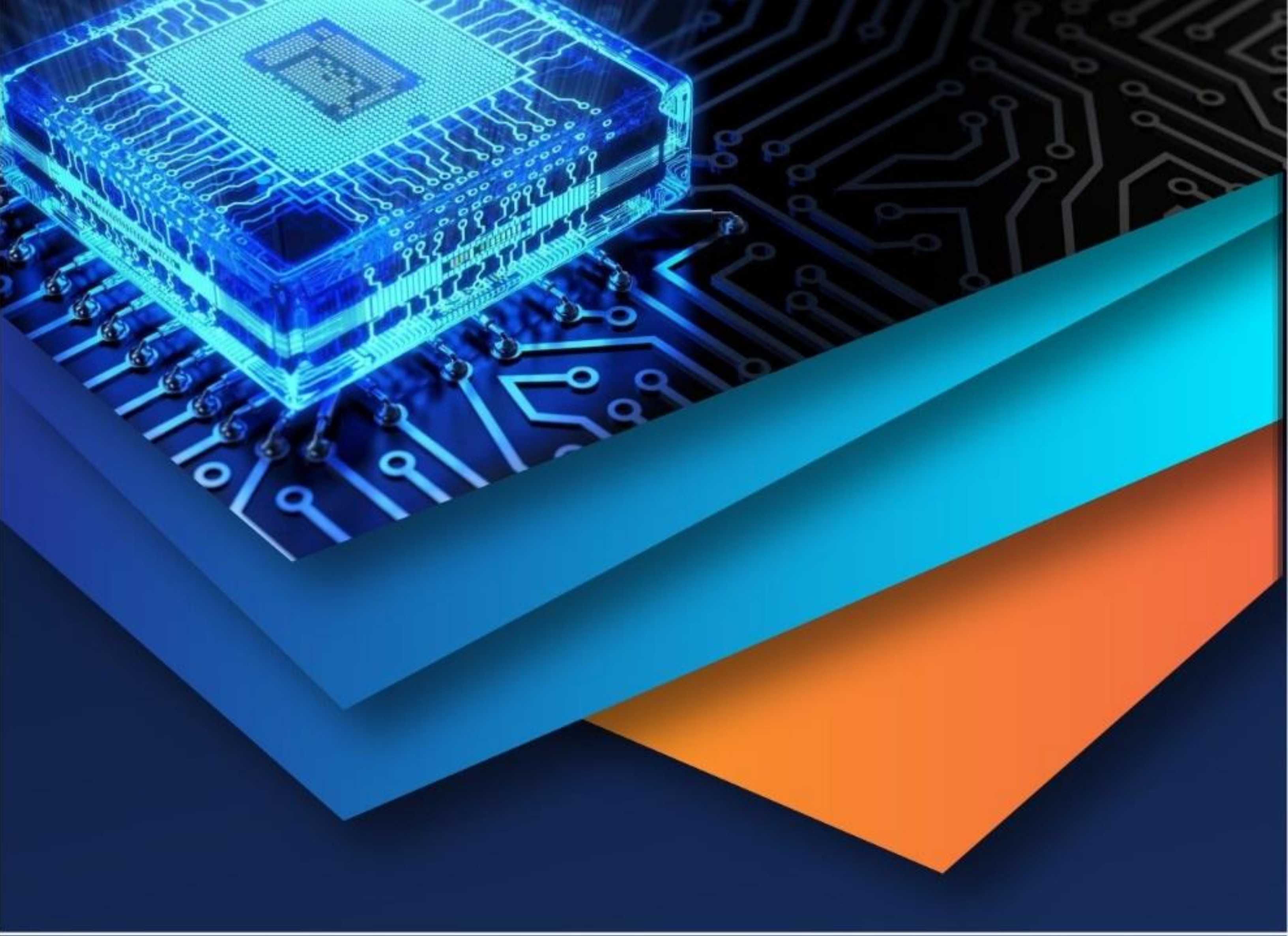

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