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Optimization of geometric configurations for enhanced thermal performance in microchannel finned plates

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Abstract

This study investigates the thermal performance of microchannel finned plates by comparing various geometric configurations and operating conditions. Twelve models (a to l) were evaluated by varying parameters such as fin height, fin spacing, and channel width, as well as operating factors like inlet velocity and heat flux. The results reveal that increasing the fin height and decreasing the fin spacing enhance heat transfer by expanding the surface area, though at the cost of increased pressure drops and higher pumping power requirements. Variations in channel width impact flow characteristics, with wider channels reducing temperature but potentially lowering convective efficiency. Higher inlet velocities improve convective cooling but increase pressure drops, while elevated heat fluxes lead to steeper temperature gradients. Model k was found to provide an optimal balance between heat transfer efficiency and pressure drop, while Model l's novel fin geometry showed unique temperature distributions warranting further exploration. Temperature contours and volume renders demonstrated air temperature increases across the models, ranging from 4.78 K to 17.36 K, and surface heat flux measurements confirmed the significant influence of fin configuration on thermal performance. The findings offer valuable insights for optimizing the design of microchannel finned plates for enhanced heat transfer and effective thermal management in various applications.

Keywords: Microchannel heat sink; Grey relational optimization; Surface heat flux; Surface Nusselt number; Optimization

1. 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

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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]. 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].

In this thesis work, open microchannel heat sinks with rectangular pin fins heated by its bottom surface with consistent heat flux. The effective dissipation of heat is a crucial challenge in modern electronics and microfluidic systems, where high power densities demand advanced cooling techniques to maintain optimal performance and reliability. Among various cooling solutions, microchannel heat sinks have emerged as a highly effective method due to their high surface area to volume ratio and excellent heat transfer capabilities. This research delves into the computational analysis of an open microchannel heat sink integrated with rectangular pin fins, employing Computational Fluid Dynamics (CFD) to explore its thermal and fluid dynamic behavior. This chapter gives outlines the methodology employed in the computational fluid dynamics (CFD) analysis of a micro channel finned plate used for convection cooling. The analysis was conducted using Ansys Workbench, which provides an integrated platform for pre-processing, solving, and post-processing of fluid flow and heat transfer problems. The detailed steps are described below, including geometry creation, meshing, setup of physical models and boundary conditions, solution process, and post-processing.

2. Computational Fluid Dynamics (CFD) Analysis

The Computational Fluid Dynamics (CFD) analysis process, crucial in engineering research, follows a methodical approach to simulate fluid flow phenomena. This section outlines the structured steps involved in conducting a CFD study, providing a comprehensive framework for understanding the intricacies of such simulations.

- **Problem Formulation:** The initial step involves precisely defining the objectives of the analysis and formulating key questions that guide the study. These questions include determining the appropriate geometry representation, defining operating conditions, selecting spatial dimensions, and deciding on temporal modeling aspects such as steady-state or transient analysis. Additionally, considerations about the nature of the flow (inviscid, laminar, and turbulent) and gas properties are essential for setting up the simulation.
- **Geometry and Flow Domain Modeling:** Modeling begins with CAD software to accurately represent the physical geometry of the object under analysis. This step often requires simplifications to make the analysis computationally feasible. Simultaneously, decisions are made regarding the extent of the computational domain where the flow will be simulated. The geometry and flow domain modeling must align closely with the requirements for subsequent grid generation.
- **Boundary and Initial Conditions:** Defining boundary conditions is critical, as they dictate the physical conditions at the boundaries of the computational domain. These conditions are necessary for initializing the simulation, which typically starts from an initial flow solution and iteratively converges towards a final solution.
- **Grid Generation:** The flow domain is discretized into a structured grid, essential for solving the governing equations numerically. Grid generation involves defining the grid topology and ensuring grid quality metrics meet specified criteria, such as orthogonality near boundaries and appropriate grid spacing to resolve boundary layers adequately.
- **Simulation Strategy:** The simulation strategy is determined based on factors such as the chosen numerical method (space-marching or time-marching), turbulence modeling approach, and algorithmic considerations. These decisions are crucial for achieving accurate and efficient simulation results.
- **Input Parameters and Files:** Input parameters and files are prepared to configure the CFD software according to the simulation strategy. This includes specifying numerical parameters and providing necessary grid and boundary condition files essential for initializing the simulation.
- **Execution of Simulation:** The simulation is executed, utilizing either interactive or batch processing methods, and often leveraging distributed computing resources to manage computational demands effectively.
- **Monitoring and Convergence:** Throughout the simulation process, continuous monitoring is conducted to assess convergence towards a stable solution. This iterative convergence is crucial for ensuring the reliability and accuracy of the results.
- **Post-Processing and Result Interpretation**: Post-processing involves extracting and analyzing relevant flow properties (such as forces and velocities) from the computed flow field. These results are then interpreted to draw meaningful conclusions regarding the studied phenomena.

This systematic approach to CFD analysis forms the backbone of research endeavors aimed at understanding complex fluid dynamics and optimizing engineering designs. By following these structured steps, researchers can effectively simulate and analyze fluid flow scenarios, contributing to advancements in various fields of engineering and technology.

2.1. Geometry Creation

The microchannel finned plate geometry was meticulously created using Ansys Design Modeler, a powerful tool for designing and optimizing complex geometries. This design features a series of parallel fins arranged within a rectangular channel, significantly enhancing heat transfer by increasing the surface area available for thermal interaction. The key dimensions of the fins and channels were meticulously defined based on typical applications in electronic cooling systems, ensuring the design's relevance and efficiency. The geometry was carefully modeled to accurately capture all relevant features, such as fin spacing, height, and thickness, which are crucial for simulating the fluid flow and heat transfer processes. This precise modeling ensures that the simulation results reflect the real-world performance of the microchannel finned plate, providing valuable insights for improving electronic cooling system designs.

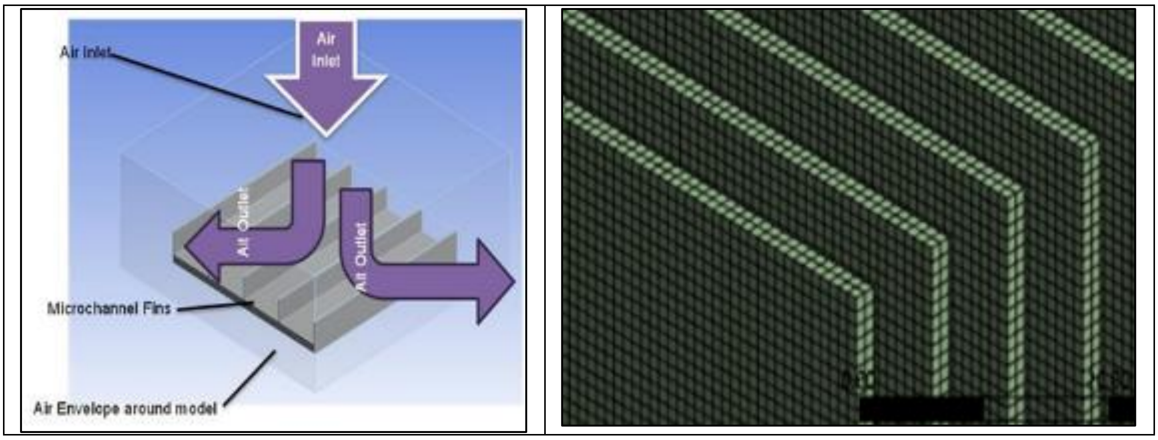


Figure 1 (a) 3-D model of OCMF (b) Meshed Model

Table 1 Configuration of Different models for CFD analysis

Sr. No.	model	Length of the heat sink (L) mm	Width of the heat sink (W) mm	No of fins (N)	Fin height (a) mm	Base height (b) mm	Fin Thickness (d) mm
1	model - a	100	100	10	10	4	1
2	model - b	90	100	10	20	6	1.5
3	model - c	80	80	5	10	8	2
4	model - d	80	80	5	10	4	1
5	model - e	80	80	5	10	6	1.5
6	model - f	80	80	5	10	8	2
7	model - g	90	80	10	30	4	1.5
8	model - h	90	80	10	30	6	2
9	model - i	90	80	10	30	8	1
10	model - j	90	90	15	10	4	1.5
11	model - k	90	90	15	10	6	2
12	model - l	90	90	15	10	8	1

2.2. Properties of Micro Channel Materials

Aluminum is selected as the material for the heat sink due to its excellent thermal conductivity, low density, and cost-effectiveness. These properties make it an ideal choice for applications requiring efficient heat dissipation and lightweight structures. The material characteristics of aluminum used in this study are detailed in Table 4.1. This table includes key properties such as thermal conductivity, specific heat capacity, density, and Young's modulus, which are critical for accurately simulating the thermal and mechanical behavior of the heat sink in computational analysis.

Table 2 Characteristics of aluminium

Property	Value	Unit (Metric)
Density	2.81	g/cm^3
Melting point	629	°C
Boiling point	2470	°C

Latent heat of fusion	4×10^5	J/kg
Thermal conductivity at 20 ºC	204	W/m-K
Modulus of elasticity	69	GPa
Modulus of rigidity	28	GPa

Material properties for the solid and fluid domains were defined based on typical values for aluminum (solid) and water (fluid):

- **Solid Body: Micro channel Fins**
    - Material: Aluminum
    - Thermal conductivity k_{solid}=237 W/mK
- **Fluid Body: Air Envelope around Fins**
    - Material: Air
    - density ρ=1.2041 kg/m3
    - specific heat Cp=1.005 KJ/kgK

3. Results and Discussion

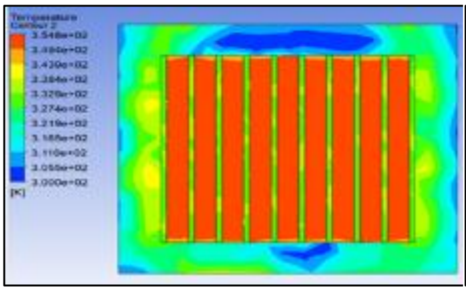
3.1. Temperature Contours 1

It was found that increasing fin height, as shown in Model b, enhances heat transfer by expanding the surface area in contact with the fluid, although it leads to a higher pressure drop. Similarly, decreasing fin spacing, as in Model c, improves convective cooling but requires increased pumping power due to the resultant pressure drop. Variations in channel width also impacted performance, with Model d demonstrating that a wider channel reduces overall temperature but may slow the fluid flow, potentially affecting heat transfer efficiency. Higher inlet velocities (Model f) improved convective heat transfer, though also at the cost of increased pressure drops. The study further highlighted that higher heat fluxes (Model g) create steeper temperature gradients, posing a challenge in managing thermal hotspots. The optimal configuration (Model k) struck a balance between heat transfer and pressure drop, while the novel fin geometry in Model l showed promising results with unique temperature distribution patterns that could be advantageous in specific applications. The models' increases in air temperature, ranging from 4.78 K to 17.36 K, illustrate the significant influence of fin configuration on thermal performance. Additionally, the temperature of the fin tips correlates with fin length, where longer fins tend to have cooler tips due to the larger heat transfer area. These temperature variations, effectively visualized in the provided contours and volume renders, confirm that optimizing fin geometry plays a critical role in achieving efficient heat transfer in microchannel finned plates.

Table 3 Air temperatures for different models at inlet and outlet

SN	model	Temp. of heat source (K)	inlet air temperature (K)	Outlet air temperature (K)	Change in Air Temperature (K)
1	model - a	353	300	309.87941	9.88
2	model - b	353	300	310.63919	10.64
3	model - c	353	300	304.77502	4.78
4	model - d	353	300	316.50031	16.5
5	model - e	353	300	317.35603	17.36
6	model - f	353	300	316.20448	16.2
4	model - g	353	300	310.98878	10.99
8	model - h	353	300	310.63749	10.64
9	model - i	353	300	313.2297	13.23
10	model - j	353	300	314.24158	14.24

11	model - k	353	300	317.35603	17.36
12	model - l	353	300	316.27857	16.28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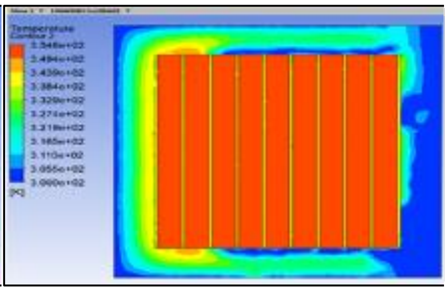
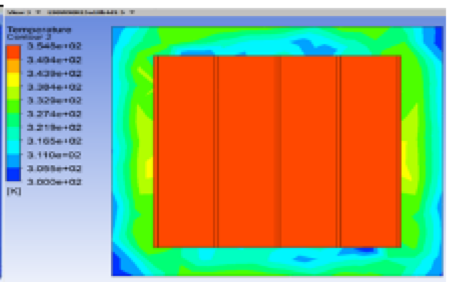
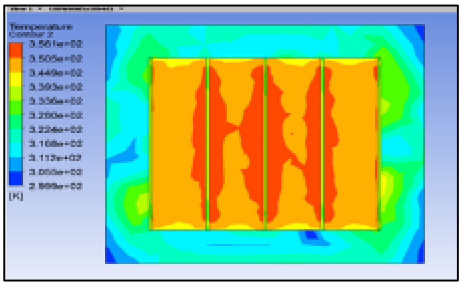
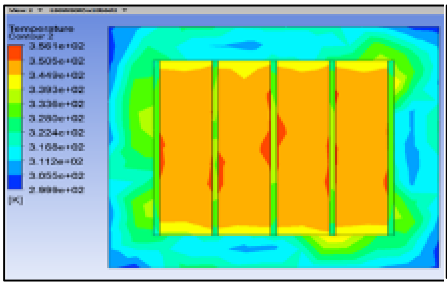

(b) - L90W100N10a20b6d1.5


(c) L80W80N5a10b8d2


(d) - L80W80N5a10b4d1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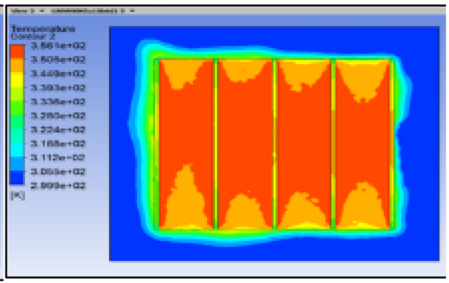
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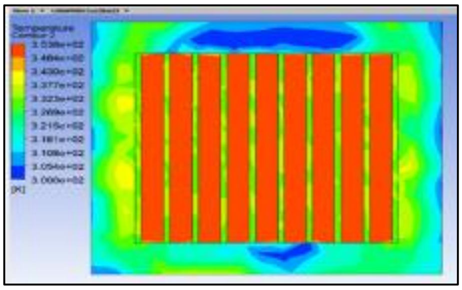
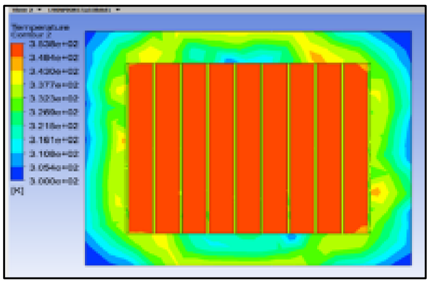
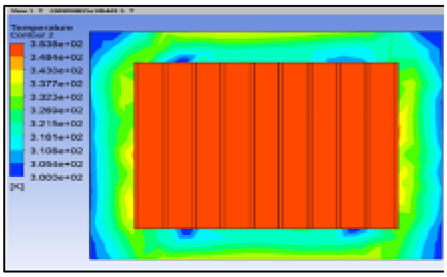

(g) - L90W80N10a30b4d1.5


(h) - L90W80N10a30b6d2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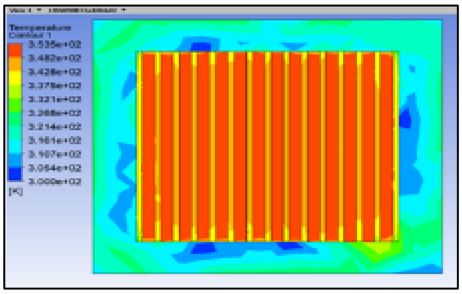
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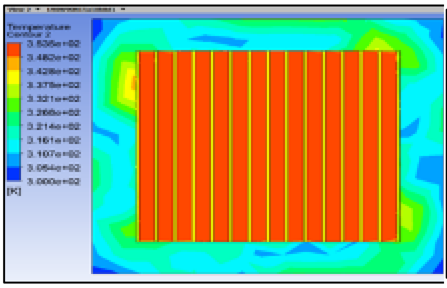

(k) - L90W90N15a10b6d2

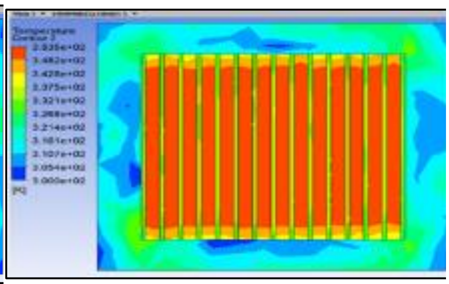
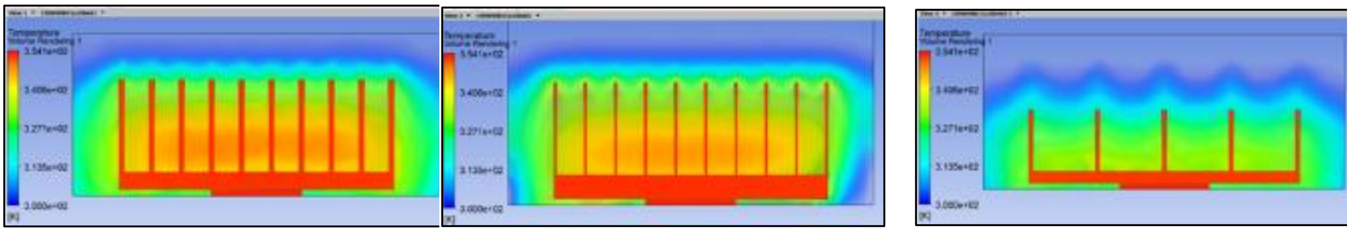

(l) - L90W90N15a10b8d1

Figure 2 Temperature Contours for different models

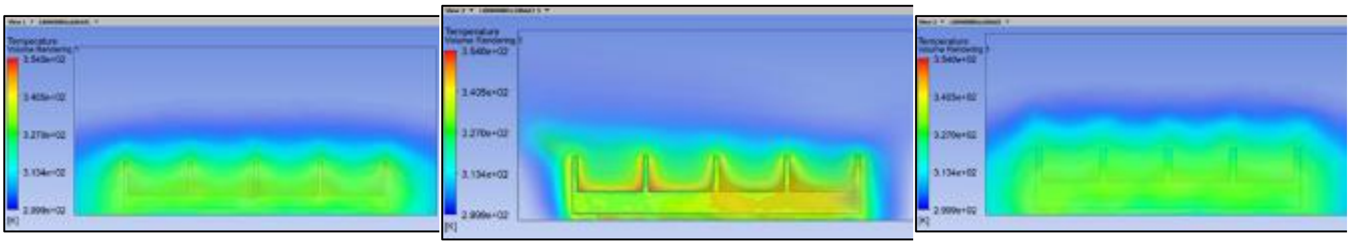
3.2. Volume Rendering of Temperature

Volume rendering is a powerful visualization technique that helps in understanding the 3D temperature distribution within the micro channel finned plate. This section compares the volume renders of the twelve different models (a, b, c, d, e, f, g, h, i, j, k, l) to provide deeper insights into the thermal performance and flow characteristics. The comparison of volume renders provides a comprehensive view of the thermal and fluid flow behavior within the micro channel finned plate. Volume rendering is a powerful visualization technique that helps in understanding the 3D temperature distribution within the micro channel finned plate. This section compares the volume renders of the twelve different models (a, b, c, d, e, f, g, h, i, j, k, l) to provide deeper insights into the thermal performance and flow characteristics. The comparison of volume renders provides a comprehensive view of the thermal and fluid flow behavior within the micro channel finned plate.

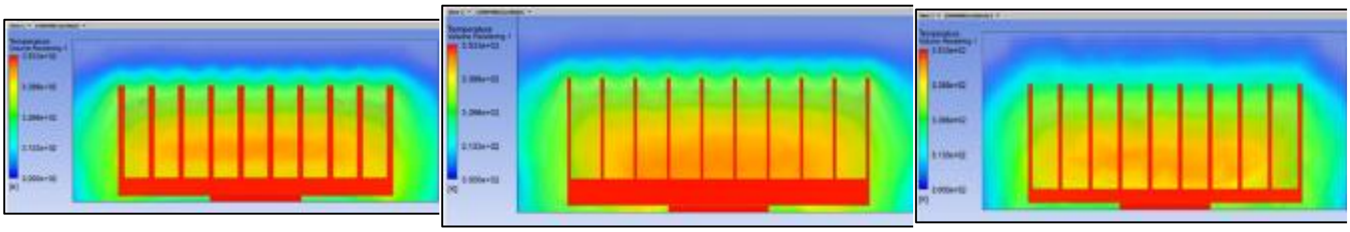
These results show the volume renders to demonstrate the increase in air temperature for the different models and the temperature distribution of fins. Air temperature for model a increased by 9.88 K, model b by 10.64 K, model c by 4.78 K, model d by 16.5 K, model e by 17.36 K, model f by 16.2 K, model g by 10.99 K, model h by 10.64 K, model i by 13.23 K, model j by 14.24 K, model k by 17.36 K, and model l by 16.28 K.



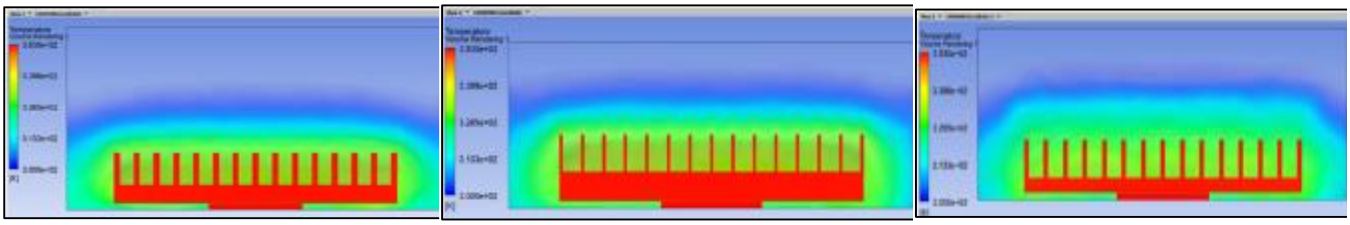
(a) - L100W100N10a10b4d1 (b) - L90W100N10a20b6d1.5 (c) - L80W80N5a10b8d2



(d) - L80W80N5a10b4d1 (e) - L80W80N5a10b6d1.5 (f) - L80W80N5a10b8d2



(g) - L90W80N10a30b4d1.5 (h) - L90W80N10a30b6d2 (i) - L90W80N10a30b8d1



(j) - L90W90N15a10b4d1.5 (k) - L90W90N15a10b6d2 (j) - L90W90N15a10b4d1.5

Figure 3 Volume Rendering of Temperature

The volume render comparisons reinforce the findings from the temperature contours, providing a holistic view of the thermal performance of the micro channel finned plate. The optimized design (Model k) achieves a balance between effective heat transfer and manageable pressure drop, while novel fin geometries (Model l) offer potential for further exploration. By combining temperature contours and volume renders, this study offers a detailed understanding of the thermal and flow characteristics of different micro channel configurations, guiding the design optimization for effective convection cooling. The air temperature increases for the various models were observed as follows: model A showed an increase of 9.88 K, model B 10.64 K, model C 4.78 K, model D 16.5 K, model E 17.36 K, model F 16.2 K, model G 10.99 K, model H 10.64 K, model I 13.23 K, model J 14.24 K, model K 17.36 K, and model L 16.28 K. These temperature increases are effectively illustrated in the temperature contours and volume renders provided in the figures, indicating the thermal impact of different fin configurations. The net heat flux for each model was also analyzed. Model A exhibited a net heat flux of 33.950957 W/m², model B 30.170298 W/m², model C 54.158926 W/m², model D 28.003942 W/m², model E 29.116921 W/m², model F 24.287772 W/m², model G 30.730656 W/m², model H 30.418552 W/m², model I 29.492252 W/m², model J 35.420918 W/m², model K 29.116921 W/m², and model L 20.901338 W/m². These values are illustrated in the contours of wall heat flux, shown in the following table 4.

Table 4 Surface Heat Flux for different models

SN	model	Total Surface Heat Flux [W/m^2]
1	model - a	33.950957
2	model - b	30.170298
3	model - c	54.158926
4	model - d	28.003942
5	model - e	29.116921
6	model - f	24.287772
4	model - g	30.730656
8	model - h	30.418552
9	model - i	29.492252
10	model - j	35.420918
11	model - k	29.116921
12	model - l	20.901338

The data clearly demonstrates that the configuration of fin height, width, base, and number significantly influences the thermal performance of the microchannel fin plate. Certain configurations result in more efficient heat transfer, as evidenced by greater temperature increases in the cooling air and higher net heat flux values. These findings are crucial for optimizing the design of micro channel fin plates for enhanced thermal management

4. Conclusions

The results of this study emphasize the critical impact of fin configuration on the thermal performance of microchannel finned plates. Key conclusions can be drawn from the analysis:

Surface Area vs. Pressure Drop: Expanding the fin surface area, as in Model b, significantly improves heat transfer by increasing the area of contact with the fluid, but it also results in a higher pressure drop. Similarly, reducing fin spacing, as seen in Model c, boosts convective cooling but increases the pumping power required due to the pressure drop.

Channel Width Impact: Variations in channel width, such as in Model d, reduce overall temperature by allowing a larger fluid volume to flow through. However, this can decrease flow velocity, which may negatively impact convective heat transfer efficiency.

Inlet Velocity and Heat Flux: Models with higher inlet velocities (e.g., Model f) enhance convective heat transfer, lowering overall temperatures, though with increased pressure drops. Models exposed to higher heat fluxes (Model g) exhibit steeper temperature gradients, presenting a challenge in controlling thermal hotspots.

Optimal Configuration: Model k demonstrated the best balance between effective heat transfer and manageable pressure drop, making it a potentially optimal design. Furthermore, Model l introduced a novel fin geometry with promising thermal performance and unique temperature distributions, offering potential for further investigation.

Temperature Distribution and Heat Flux: The volume rendering of temperature distribution reinforces these findings. The models showed varied increases in air temperature, with Model e displaying the highest increase (17.36 K), while Model c exhibited the lowest (4.78 K). Surface heat flux measurements further highlighted the influence of fin configuration, with Model c achieving the highest net heat flux (54.16 W/m^2), while Model l had the lowest (20.90 W/m^2).

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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