Experimental Investigation of Transient Thermal Behaviour in Microchannel Pin Fin Heat Sink Under Heat Flux Conditions-A Review Study

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Abstract- **Efficient cooling of compact electronic devices is essential for the effective design of integrated circuits. Among the widely used cooling methods are micro-pin fin heat sinks and microchannel pin fin heat sinks. This research presents a detailed comparison of fluid flow and heat transfer behaviour for both types of heat sinks. A 3D simulation using water as a coolant is carried out under varying heat flux levels (20–110 W/cm²) and Reynolds numbers (150–1000). Different fin shapes, such as square and circular, arranged in staggered configurations, are analyzed. Key performance indicators like the Nusselt number and thermal performance index are employed to assess heat sink effectiveness. The findings reveal that microchannel pin fin heat sinks deliver higher Nusselt numbers and friction factors within the studied Reynolds figure range. The formation of secondary vortices in square-finned channels significantly boosts heat transfer. Among the designs, the micro-pin fin sink stands out for its superior thermal performance, balancing heat dissipation and pressure drop, & making it ideal for use in thermally limited environments.**

Keywords- Microchannel, Pin fin, Heat sink, square pin fin, Circular pin Fin.

I. INTRODUCTION

1. INTRODUCTION:

Pin fin is an extended surface. It is a solid surface within which heat is transferred using conduction and convection. With rapid advancements in power electronics, cooling technique is crucial for managing heat transfer. Electronic components are very sensitive, and the operating temperature is a crucial factor that affects their lifespan. To ensure long term durability, it is important to keep temperature within safe limits. Researchers suggested concept of micro pin fin and microchannel heat sinks for more effective cooling. These heat sinks, produced through micromachining processes, provide several benefits, including high heat transfer and low thermal resistance. They also require minimal space and inventory, making them suitable for efficient heat dissipation. Moreover, sinks can be modified with staggered or inline pin fin configurations, improving performance. They can expel significant amounts of heat from compact spaces, and with an increased pressure drop.

In this investigation, experiments are done on a sink that lacked fins, along with a square pin fin heat sink configured in a staggered layout, and a parallel pin fin sink system to assess the properties of fluid flow and heat rate. The study utilized water with Reynolds figures ranging from 60 to 900 with various heat flux levels. The experiment results indicate that the square pin fin sink with staggered configuration exhibited the most significant improvement in heat transfer. Furthermore, both pin fin heat sinks and diamond pin fin heat sinks in a staggered configuration were analyzed through numerical methods for cases of uniform and non-uniform heat flux. It was noted that heat transfer enhancement was superior for the square pin fin sink when subjected to uniform heat flux.

Heat sinks featuring pin fins are efficient in dissipating heat. They are made up of a base surface along with an array of fins. The configuration of the pin fin array can be staggered or inline, with fluid moving in a perpendicular direction to the axes of the pin fins. In cases of internal flow, the objective is to increase heat transfer while maintaining pressure loss through pin fin array to a minimum. The use of various-shaped micro pin fins in an array to ameliorate heat transfer is a contemporary technology that has gained interest from experimenters over the past ten times. Figure 1 describes the geometry of a micro pin fin sink. In this review study, the configurations of microchannel pin fin heat sinks have been explored in two distinct ways, examining how these micro pin fin heat sinks can manage higher heat fluxes from smaller areas compared to traditional pin fin and microchannel heat sinks. The integrated effect of conduction and convection heat transfer within microchannel pin fin heat sinks is significantly superior, making them a much better option than conventional pin fin heat sinks.

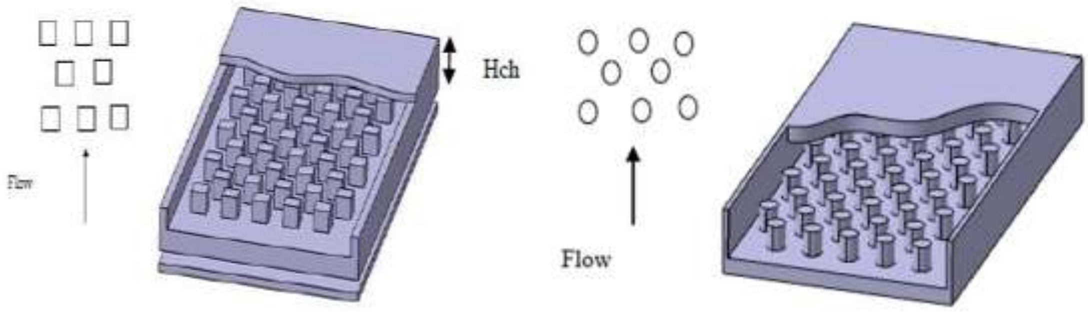

Figure-1 Structure of microchannel rectangular and circular pin fin

1.2. FIN SHAPE:

Pin fins can be distributed into various shapes such as conical, round, square, rectangular, and I-shaped. The arrangement of pin fins differs in models to enhance heat transfer effectiveness. For case, there are plain arrangements, perforated arrangements, and herringbone arrangements. Multitudinous fresh additional arrangements have been developed to give advantages to the system. The geometry of the pin fin greatly influences conduction and inflow patterns, as it can induce varying turbulence. Different pin-fin shapes have been studied within channels, as illustrated in the table, which displays pin-fin biographies employed in systems. On the bases of review, results indicate that the total heat transfer rate of rectangular plate fins surpasses that of cylindrical pin fins when both have identical confines and control parameters. Rectangular fins are 40% more efficient than cylindrical pin fins.

TABLE I. Types of Fins and operations

TYPE OF PIN FINS	OPERATIONS
Circular, Square, Hexagonal, Elliptical, Rounded cube, Flat-ended rectangular	Heat exchangers, Automotive, HVAC
Chamfered/Rounded, Grooved, or slotted	Electronics, CPUs, GPUs, Compact thermal operation systems
aerofoil/elliptic	Aerospace, drones, UAVs
Helical or twisted	High-performance computing, Power Electronics
Hollow or cut-out, Trapezoidal	Space, Drones, Weight-sensitive operations

1.3 FACTORS AFFECTING PERFORMANCE OF HEAT TRANSFER**:**

- The Shape of fin (sampling of fin)
- Geometric parameters (periphery, length, aspect rate)
- Number of fins
- Material of fin
- Cloak clearance
- Nature of fluid inflow
- Position of addict/cracker in forced convection
- Type of flowing fluid
- Face finish of fins

1.4 ADVANTAGES:

- Increased face area
- Compact design
- High heat transfer effectiveness
- Felicity for different coolants
- Cost-effective

1.5 DISADVANTAGES:

- Increased pressure drops
- Complexity in Manufacturing
- Potential for bending

II. LITERATURE SURVEY

2.1 LITERATURE REVIEW**:**

- **Sagar I. Shah (2016)** conducted a comprehensive review on the impact of fin geometry and arrangement on thermal performance in heat exchangers. The study highlighted that geometries such as wavy, triangular, staggered, and rectangular (including lanced and offset) have different effects on heat dissipation. Among various configurations, inline and interrupted pin fin arrangements—such as plain, perforated, and serrated—were found to significantly influence thermal efficiency.

- **Venkatesh Saravanan, Chitra Durga K. Umesh, Doddamani Hithaish, Kanakanahalli Seetharamu (2018)** utilized computational fluid dynamics (CFD) simulations to compare microchannel and micro pin-fin heat sinks. Their study, based on a multi-dimensional model with a constant heat input and varying Reynolds numbers, concluded that micro pin-fin designs demonstrated superior thermal performance compared to traditional microchannel structures.
- **K. Subahan, E. Siva Reddy, R. Meenakshi Reddy (2019)** examined various rhombus-shaped pin fin geometries, employing both forced and natural convection models with multiple material types. Their CFD analysis indicated that rhombus prism fins provided enhanced heat transfer due to their increased surface area.
- **Nhad K. Frhan Al-Abbood, Kamil Abdulhussien Khalaf, Huda Ridha, Mohammed G. Al-Azawy (2022)** investigated the influence of different pin fin shapes—circular, elliptical, and square—and orientations such as inline and staggered. Their results showed that circular fins maintained lower temperatures, while elliptical fins demonstrated superior heat removal capabilities.
- **Abdolvahab Ravanji, Ann Lee, Javad Mohammadpour, Shaokoon Cheng (2023**) developed a novel fin system targeting microchannel and gas turbine cooling applications. The study emphasized the role of material selection, fin height, spacing, and aspect ratio in achieving optimal thermal management.
- **Prabhakar Bhandari, Bhavesh Vyas, Diwakar Padalia, Lalit Ranakoti, Yogesh Kumar Prajapati, Raghubeer Singh Bangari (2024)** evaluated different layouts of micro pin fin sink for liquid-cooled microchannel systems. The study compared uniform-height fins, three-stepped unidirectional fins, and three-stepped bidirectional fins, arranged in both inline and staggered orientations. The findings revealed that inline arrangements demonstrated superior heat transfer enhancement, particularly when the fins were steeply aligned. However, the performance of staggered setups diminished with increasing Reynolds figures below 70. Interestingly, bi-directional fins showed height-based advantages only when arranged inline.
- **Karima ALEM, Djamel SAHEL, Warda BOUDAOUD, Redouane BENZEGUIR (2024)** focused on enhancing the performance of cylindrical pin fin sinks by integrating perforations and ring inserts. Their investigation covered six configurations with Reynolds figures from 8740 to 22060. The optimal design significantly improved heat rate, while also reducing both the volume and mass of the heat sink by 77.5% and 77.65% respectively. This configuration achieved a power enhancement of 41.29% under identical operating conditions, demonstrating its effectiveness in turbulent flow regimes.
- **Jin Yuan, Ningkang Deng, Yongfeng Qu, Liang Du, Wenbo Hu, Zhaoyang Zhang, Hongxing Wanga (2024)** introduced a center-hybrid pin fin microchannel configuration aimed at optimizing thermal regulation. The design incorporated five geometric variations of pin fins. Their findings revealed that simply increasing the length of finned region does not consistently enhance thermal performance, suggesting that geometry plays a more critical role than size alone.
- **Hussain Sallar, Muhammad Irfan, Muhammad Mahabat Khan, Muhammad Wakil Shahzad (2024)** proposed an I-shaped pin arrangement within microchannel structure to improve hydrothermal behaviour. The study examined fins with thicknesses ranging from 0.1 mm to 0.4 mm and heights from 0.75mm to 2 mm. Additionally, fin orientation was varied between 15° and 90°, with the most favourable thermal performance observed at 15-degree angle, yielding a performance index of 1.29.
- **Hanzla Shahid, Abid Hussain, Imran Ali, Hafiz Muhammad Ali, Abu Summama Sadavi Bilal, Muhammad Umar Munir (2024)** developed a hybrid thermal regulation system that incorporates forced convection in pin fin sinks. This configuration utilizes controlled airflow to improve cooling effectiveness, demonstrating that combining passive and active method can enhance overall system efficiency.
- **Mohammad Harris, Hamza Babar, Hongwei Wu (2024)** examined the role of biometric design in optimizing thermal performance. Their study assessed the behaviour of biomorphic pin fins under varying Reynold figures and power input conditions. Among the designs tested, pin fins with filleted edges delivered superior results in terms of Nusselt figures, heat rate and pressure drop minimization.
- **Fatema-Tuj Zohora, Mohammad Rejaul Haque Mostafa Kamal Fahad, Nowroze Farhan Ifraj, Nabil Mohammad Chowdhury (2024)** conducted CFD-based analysis involving innovative fin geometries like infinity loop fins, betel leaf, and spherical cube fins with elliptical and hexagonal perforations. Their findings confirmed that such geometric modifications enhance heat dissipation while simultaneously reducing pressure losses.
- **Amol More1, Sanjeev Kumar, Sandeep Kore (2025)** proposed a novel technique using phase change materials such as paraffin wax in combination with microchannel and round pin fin sinks. This method resulted in a reduction in temperature and thermal resistance in standard arrangements.
- **Dr. Krishna Bharathi Parimi, Dr. Konathala Aravinda Shilpa, L. Jyothi Prasanna, K. Hemalatha, M. Jahnavi (2025)** In this study researchers included hole designs of pin fin with forced convection with specific materials like mild steel, brass. The results revealed that tailoring the cross-sectional area of fins can substantially boost the rate of heat removal. The study emphasized that optimising fin structure is crucial for maximizing both efficiency and performance.
- **Maad. A. Hussein, Ehsan F. Abbas (2025)** In this article fin researchers have studied that the shape of a conical with a circular base pin fin can increase heat performance by stepwise structure of spines that increases heat transfer but by more distancing between thrones the working of refrigerants will be more. In this shape, it is also concluded that higher temperatures can lead to the break of the pin fin in perforated hybrid designs. So, Researchers also included that the design of chillers should be lightweight in applications.

2.2 SUMMARY OF LITERATURE REVIEW:

According to Geometrical and structural optimization**:**

- Geometry Influence: A distinct pattern where heat transfer efficiency increases with the complexity of fin designs: Wavy < Triangular < Staggered Pin < Continuous < Interrupted Rectangular < Inline Pin. In the same vein, the effectiveness of fin types is enhanced from Plain < Perforated < Serrated < Herringbone. Rhombus prism fins outperform rhombus pyramids, owing to their larger surface area.
- Innovative Designs: Among various fin geometries-circular, elliptical, square, and drop-shaped fins, finding that circular fins exhibited the lowest temperatures, while elliptical fins achieved the highest heat transfer rates. Conical stepwise fins, which improved thermal performance but presented structural difficulties at elevated temperatures.
- Hybrid/Bio-Inspired Innovations: Bio-inspired and organic fin designs (for instance, fillet-edged, spherical cube, betel leaf), which enhanced the Nusselt number and minimized pressure drop. Centre-hybrid pin fins in microchannels, noting that longer fin segments do not necessarily lead to better performance.

According to Arrangements & configuration:

- Inline vs. Staggered: Stepped and height-variable pin fins improve performance more effectively in inline configurations than in staggered ones, particularly at Reynolds numbers greater than 70. The geometric arrangement has a significant effect on thermal behaviour, with inline circular fins exhibiting remarkable thermal stability.
- Innovative arrangements: The integration of perforations and ring inserts led to a reduction in volume and mass by more than 77%, while simultaneously increasing power output by over 41%. An I-shaped fin with orientation angles reaching up to 90°, which attained a maximum performance factor of 1.29 at an angle of 15°.

According to Thermal management techniques:

- Convection modes: Micro pin fin heat sinks significantly outperformed those without fins when subjected to forced convection and varying Reynolds numbers (100–900). Larger cross-sections and optimally designed holes enhance the performance of forced convection.
- **Forced air integration: Hanzla Shahid (2024)** showed that using fans or blowers could lower pin fin temperatures by as much as 61%, indicating strong potential for hybrid cooling solutions.
- **Phase change materials:** Incorporating paraffin wax-based phase change materials in microchannel-fin assemblies, resulting in reduced temperatures and thermal resistance.

III. CONCLUSION:

According to the literature reviewed, microchannel pin fin heat sinks exhibit excellent thermal performance under varying heat flux due to their increased surface area and optimized designs. Differences in the shape, height, orientation, and arrangement of pin fins (whether inline or staggered) have a significant impact on heat transfer efficiency and pressure loss. Additionally, hybrid and perforated designs, along with bio-inspired and stepped configurations, enhance heat dissipation further. The combination with forced convection or phase change materials boosts cooling performance, particularly at higher Reynolds numbers. In short, microchannel pin fin heat sinks provide a highly versatile and effective solution for thermal management in compact settings and applications with high heat flux.

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