Experimental Investigation of Hybrid Microchannel Heat Sink Designs for Enhanced Thermal Management in Compact Electronic Systems

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ABSTRACT: *The continuous miniaturization of electronic devices and the rapid increase in computational power have significantly intensified heat generation in modern electronic systems. High-performance processors, power electronic modules, data centers, electric vehicles, aerospace electronics, and advanced communication equipment require efficient thermal management solutions to maintain device reliability, operational stability, and extended service life. Conventional air-cooled heat sinks are increasingly unable to dissipate the high heat flux generated by compact electronic components due to their limited heat transfer capability and relatively high thermal resistance. Consequently, advanced liquid cooling technologies, particularly microchannel heat sinks, have emerged as promising thermal management solutions because of their high surface-area-to-volume ratio, compact size, and superior heat removal performance. However, conventional straight microchannel heat sinks often experience flow maldistribution, increased pressure drop, localized hot spots, and limited cooling uniformity, thereby restricting their effectiveness under high heat flux operating conditions. This research presents an* ***Experimental Investigation of Hybrid Microchannel Heat Sink Designs for Enhanced Thermal Management in Compact Electronic Systems****, focusing on improving thermal performance through optimized hybrid microchannel geometries. The proposed heat sink integrates straight microchannels, wavy channels, pin-fin structures, and secondary flow enhancement features to improve coolant mixing, increase convective heat transfer, and reduce thermal resistance. Experiments are conducted using deionized water as the working fluid under varying coolant flow rates and heat loads representative of compact electronic devices. Temperature distribution, pressure drop, thermal resistance, heat transfer coefficient, Nusselt number, and cooling efficiency are experimentally evaluated to determine the effectiveness of the proposed hybrid configuration. Experimental results demonstrate that the hybrid microchannel heat sink significantly improves heat transfer performance while maintaining acceptable hydraulic characteristics. Compared with conventional straight microchannel designs, the proposed configuration achieves lower maximum surface temperature, enhanced temperature uniformity, reduced thermal resistance, higher heat transfer coefficient, and improved overall cooling efficiency. The optimized design effectively dissipates high heat flux while maintaining moderate pressure losses, making it suitable for next-generation electronic cooling systems. The proposed hybrid microchannel heat sink offers an efficient and reliable thermal management solution for microprocessors, power electronics, electric vehicle control units, high-performance computing platforms, medical electronics, aerospace systems, and advanced embedded electronic devices.*

INTRODUCTION

The rapid advancement of microelectronics, high-performance computing, artificial intelligence hardware, electric vehicles, and communication technologies has significantly increased the power density of modern electronic devices. As semiconductor devices become smaller while delivering greater computational capability, the amount of heat generated per unit area has increased substantially. Excessive operating temperatures adversely affect the electrical performance, reliability, and lifetime of electronic components by accelerating material degradation, increasing leakage currents, reducing processing speed, and causing thermal-induced failures. Consequently, efficient thermal management has become one of the most critical engineering challenges in the design of compact electronic systems. Conventional air-cooling techniques, including natural and forced convection heat sinks, are increasingly inadequate for dissipating the high heat flux generated by modern processors, power electronic modules, graphics processing units (GPUs), and embedded computing platforms. Therefore, advanced liquid cooling technologies have emerged as highly effective alternatives for maintaining safe operating temperatures in next-generation electronic devices.

Microchannel heat sinks have gained considerable attention because they provide exceptionally high heat transfer rates within compact dimensions. Their large surface-area-to-volume ratio enables efficient removal of heat through forced liquid convection while occupying minimal physical space. Since the pioneering work on microchannel cooling, researchers have extensively investigated different channel geometries, working fluids, and manufacturing techniques to improve thermal performance. Straight microchannels are widely used because of their simple fabrication and predictable flow behavior; however, they often experience non-uniform temperature distribution, thermal boundary layer development, localized hot spots, and increased thermal resistance under high heat flux conditions. These limitations reduce overall cooling effectiveness and restrict their application in advanced electronic systems requiring uniform thermal regulation.

To overcome these challenges, researchers have proposed various enhanced microchannel configurations including wavy channels, pin-fin microchannels, interrupted channels, bifurcated channels, porous structures, ribbed channels, and hybrid microchannel designs. Hybrid microchannel heat sinks combine multiple heat transfer enhancement mechanisms within a single cooling structure to improve coolant mixing, increase turbulence intensity, disrupt thermal boundary layers, and promote more uniform temperature distribution across the heated surface. Although these advanced geometries significantly improve convective heat transfer, they may also increase hydraulic resistance and pumping power requirements. Therefore, achieving an optimal balance between thermal enhancement and pressure drop remains a major research objective in modern thermal management system design.

Experimental investigation plays a crucial role in evaluating the thermal-hydraulic performance of hybrid microchannel heat sinks under practical operating conditions. Parameters such as coolant flow rate, heat input, channel geometry, Reynolds number, pressure drop, thermal resistance, Nusselt number, heat transfer coefficient, and temperature uniformity collectively determine the effectiveness of a cooling system. Comprehensive experimental studies enable designers to validate theoretical models, optimize channel configurations, and identify suitable operating conditions for various electronic cooling applications. Moreover, accurate thermal characterization facilitates the development of reliable cooling solutions capable of supporting continuously increasing heat flux in compact electronic devices.

This research presents an **Experimental Investigation of Hybrid Microchannel Heat Sink Designs for Enhanced Thermal Management in Compact Electronic Systems**. The proposed hybrid heat sink integrates straight microchannels, wavy channel sections, and pin-fin enhancement structures to improve coolant circulation and convective heat transfer while maintaining acceptable pressure losses. Experiments are conducted under varying heat loads and coolant flow rates to evaluate thermal resistance, maximum surface temperature, heat transfer coefficient, pressure drop, Nusselt number, and cooling efficiency. The objective is to identify an optimized hybrid microchannel configuration capable of delivering superior thermal performance for compact electronic systems while ensuring practical hydraulic characteristics and energy-efficient operation.

Problem Statement

Modern compact electronic devices generate increasingly high heat flux that cannot be effectively dissipated using conventional air-cooled heat sinks or simple straight microchannel cooling systems. Existing microchannel designs often experience thermal non-uniformity, localized hot spots, high thermal resistance, and excessive pressure drop, reducing cooling efficiency and overall system reliability. Furthermore, improving heat transfer frequently results in increased pumping power requirements, creating a trade-off between thermal performance and hydraulic efficiency. Therefore, there is a need to experimentally investigate optimized hybrid microchannel heat sink designs that simultaneously enhance heat transfer, reduce thermal resistance, improve temperature uniformity, and maintain acceptable pressure losses for high-performance electronic cooling applications.

Objective

The primary objective of this research is to experimentally investigate the thermal and hydraulic performance of a hybrid microchannel heat sink designed for compact electronic systems. The proposed design combines straight microchannels, wavy channel sections, and pin-fin enhancement features to improve coolant mixing and convective heat transfer. Performance evaluation focuses on maximizing heat transfer coefficient, cooling efficiency, and temperature uniformity while minimizing thermal resistance, maximum surface temperature, and pressure drop. The effectiveness of the proposed heat sink is validated through experimental measurements under different coolant flow rates and heat input conditions representative of practical electronic cooling applications.

Scope

The scope of this research encompasses the design, fabrication, experimental evaluation, and performance analysis of hybrid microchannel heat sinks intended for advanced electronic thermal management. The study investigates the influence of channel geometry, coolant flow rate, and applied heat flux on thermal-hydraulic characteristics including maximum surface temperature, thermal resistance, pressure drop, heat transfer coefficient, Nusselt number, cooling efficiency, and temperature distribution. The proposed hybrid cooling configuration is applicable to **high-performance microprocessors, graphics processing units, power electronic converters, electric vehicle control modules, aerospace electronics, telecommunications equipment, data centers, medical electronic**

devices, embedded systems, defense electronics, and next-generation compact electronic platforms requiring efficient liquid cooling solutions.

LITERATURE SURVEY

The rapid increase in power density of modern electronic components has made thermal management one of the most important challenges in mechanical and electronic system design. High-performance processors, graphics processing units (GPUs), power electronic converters, electric vehicle control units, aerospace electronics, and communication equipment generate large amounts of heat within compact volumes. If this heat is not effectively dissipated, excessive operating temperatures can degrade electrical performance, reduce reliability, accelerate material aging, and shorten the service life of electronic components. Consequently, considerable research has focused on developing advanced cooling technologies capable of removing high heat flux while maintaining compact size, low energy consumption, and high reliability. Among various cooling techniques, liquid-cooled microchannel heat sinks have emerged as one of the most promising solutions because of their excellent heat transfer capability and compact structural design.

Microchannel heat sinks were first introduced as an effective cooling solution due to their extremely large surface-area-to-volume ratio, which enables efficient convective heat transfer using relatively small coolant flow rates. Early investigations primarily examined straight rectangular microchannels because of their simple fabrication and predictable flow characteristics. Experimental studies demonstrated that straight microchannels provide substantially higher heat removal capability than conventional finned heat sinks. However, researchers also reported several limitations, including the formation of thermal boundary layers, non-uniform coolant distribution, localized hot spots, and increased thermal resistance under high heat flux conditions. These limitations motivated the development of advanced channel geometries capable of improving coolant mixing and enhancing heat transfer performance.

Numerous researchers have investigated modified microchannel geometries to increase convective heat transfer while maintaining acceptable hydraulic performance. Wavy microchannels introduce periodic flow disturbances that continuously interrupt thermal boundary layer development, thereby increasing the local heat transfer coefficient. Experimental studies have shown that sinusoidal and serpentine channels improve temperature uniformity and reduce maximum surface temperature compared with conventional straight channels. Similarly, interrupted microchannels periodically redevelop the thermal boundary layer, enhancing convective heat transfer while increasing overall cooling effectiveness. Although these geometrical modifications significantly improve thermal performance, they also increase flow resistance and pressure drop, requiring careful optimization of channel dimensions and coolant operating conditions.

Pin-fin microchannel heat sinks represent another important development in electronic cooling technology. Small pin-fin structures inserted inside microchannels promote turbulence generation, secondary flow formation, and improved coolant mixing. Researchers have demonstrated that circular, square, diamond-shaped, and elliptical pin-fin configurations substantially increase the heat transfer coefficient by enlarging the heat transfer surface area and disrupting thermal boundary layers. Comparative experimental investigations indicate that optimized pin-fin arrangements improve cooling performance without excessively increasing pumping power. Nevertheless, improper pin-fin distribution may produce excessive hydraulic losses and flow maldistribution, highlighting the importance of balancing thermal enhancement with hydraulic efficiency.

Hybrid microchannel heat sinks have recently attracted considerable research interest because they combine multiple heat transfer enhancement techniques within a single cooling structure. Hybrid configurations integrate straight channels with wavy sections, pin-fin arrays, ribs, porous inserts, or secondary flow generators to maximize coolant mixing and improve temperature uniformity. Experimental investigations demonstrate that hybrid designs provide superior thermal performance compared with individual enhancement techniques by simultaneously increasing convective heat transfer and minimizing localized hot spots. Several studies report significant reductions in thermal resistance together with improved heat removal capability under high heat flux conditions. However, achieving optimal geometric design while maintaining acceptable pressure drop continues to be an important engineering challenge requiring systematic experimental evaluation.

The choice of working fluid also plays a significant role in determining microchannel heat sink performance. Deionized water remains the most commonly used coolant because of its high specific heat capacity, excellent thermal conductivity, low viscosity, and chemical stability. Researchers have also investigated nanofluids containing metallic nanoparticles, metal oxide nanoparticles, carbon nanotubes, and graphene to further improve thermal conductivity and heat transfer characteristics. Although nanofluids often increase the heat transfer coefficient, practical implementation may be limited by increased viscosity, particle agglomeration, sedimentation, erosion, and higher pumping power requirements. Consequently, many experimental investigations continue to employ deionized water as a reliable benchmark coolant for evaluating new microchannel heat sink designs.

Thermal-hydraulic performance evaluation forms the foundation of microchannel heat sink optimization. Experimental researchers commonly evaluate maximum surface temperature, average wall temperature, thermal resistance, heat transfer coefficient, Nusselt number, pressure drop, friction factor, coolant outlet temperature, and pumping power to characterize cooling performance. Lower thermal resistance indicates more efficient heat dissipation, whereas reduced pressure drop minimizes pumping energy requirements. The Nusselt number provides an important measure of convective heat transfer enhancement, while coolant temperature distribution reflects the overall effectiveness of heat removal. Simultaneous evaluation of thermal and hydraulic characteristics enables researchers to identify optimal channel configurations that maximize cooling performance without imposing excessive energy penalties.

Advances in fabrication technologies have further accelerated the development of high-performance microchannel heat sinks. Precision micromachining, laser machining, electrical discharge machining (EDM), chemical etching, additive manufacturing, and micro-milling techniques enable the fabrication of complex hybrid channel geometries with high dimensional accuracy. Modern manufacturing processes allow researchers to experimentally evaluate intricate cooling structures that were previously difficult to produce using conventional machining methods. These fabrication advances have expanded opportunities for optimizing microchannel geometries while maintaining structural integrity and manufacturing feasibility for commercial electronic cooling applications.

Computational Fluid Dynamics (CFD) has become an important complementary tool for analyzing microchannel heat sinks before experimental validation. Numerical simulations provide detailed visualization of temperature distribution, velocity fields, pressure contours, thermal boundary layer development, and coolant flow behavior. Experimental investigations combined with CFD analysis enable accurate validation of thermal-hydraulic models while reducing prototype development time. Nevertheless, experimental measurements remain essential because they account for practical factors such as manufacturing tolerances, surface roughness, measurement uncertainty, and real operating conditions that may not be fully represented in numerical simulations.

Despite the substantial progress achieved in electronic cooling research, several challenges remain unresolved. Many existing microchannel heat sinks successfully enhance heat transfer but simultaneously produce excessive pressure drop and increased pumping power. Other designs prioritize hydraulic efficiency while sacrificing cooling effectiveness under high heat flux conditions. Furthermore, maintaining uniform temperature distribution across compact electronic devices remains difficult as heat generation continues to increase. Consequently, developing hybrid microchannel heat sinks that simultaneously improve heat transfer, reduce thermal resistance, minimize pressure losses, and maintain uniform temperature distribution remains an important research objective.

The present research addresses these challenges by experimentally investigating a **Hybrid Microchannel Heat Sink Design for Enhanced Thermal Management in Compact Electronic Systems**. The proposed configuration combines straight microchannels, wavy channel sections, and strategically arranged pin-fin structures to improve coolant mixing, suppress thermal boundary layer development, and enhance convective heat transfer while maintaining moderate hydraulic resistance. Comprehensive experimental evaluation is performed using thermal and hydraulic performance metrics including maximum surface temperature, thermal resistance, heat transfer coefficient, Nusselt number, pressure drop, cooling efficiency, and temperature uniformity. The developed hybrid microchannel heat sink provides a compact, efficient, and scalable thermal management solution suitable for **high-performance processors, power electronic converters, electric vehicle electronics, aerospace systems, embedded computing platforms, medical electronics, telecommunications equipment, industrial control systems, and next-generation compact electronic devices**.

METHODOLOGY

The proposed **Hybrid Microchannel Heat Sink** is experimentally designed to enhance thermal management in compact electronic systems by combining multiple heat transfer enhancement mechanisms within a single cooling structure. Unlike conventional straight microchannel heat sinks, the proposed design integrates straight inlet channels, wavy microchannels, and pin-fin enhancement regions to improve coolant mixing, increase convective heat transfer, reduce thermal resistance, and maintain a more uniform temperature distribution across the heated electronic surface. The experimental investigation evaluates both thermal and hydraulic performance under different operating conditions to identify the optimum cooling configuration suitable for high-power electronic devices.

Initially, the hybrid microchannel heat sink is fabricated using high thermal conductivity copper due to its excellent thermal conductivity and machinability. The heat sink consists of multiple parallel microchannels incorporating periodic wavy sections and uniformly distributed cylindrical pin-fin structures within the central cooling region. A cartridge heater is attached beneath the heat sink to simulate the heat generated by compact electronic components such as CPUs, GPUs, and power electronic modules. K-type thermocouples are installed at various locations on the heat sink surface and coolant flow path to continuously monitor temperature distribution during experimentation. A closed-loop experimental setup consisting of a coolant reservoir, centrifugal pump, flow control valve, flow meter, pressure sensors, and data acquisition system is employed to regulate coolant circulation and record thermal-hydraulic parameters accurately.

During experimentation, deionized water is circulated through the hybrid microchannels at different flow rates while the heat input supplied by the electrical heater is gradually increased to simulate practical operating conditions. The coolant absorbs heat through forced convection as it flows through the straight channels, wavy sections, and pin-fin regions. The wavy microchannels continuously disturb the developing thermal boundary layer, while the pin-fin structures generate secondary flow and enhance coolant mixing, thereby increasing the convective heat transfer coefficient. Simultaneously, inlet and outlet coolant temperatures, pressure drop, surface temperatures, and flow characteristics are continuously recorded using the integrated measurement system.

The collected experimental data are subsequently analyzed to determine important thermal performance parameters including maximum surface temperature, average wall temperature, thermal resistance, heat transfer coefficient, Nusselt number, pressure drop, and cooling efficiency. Thermal resistance is evaluated to quantify the effectiveness of heat removal from the electronic device, while the pressure drop indicates the hydraulic performance of the cooling system. The balance between enhanced heat transfer and acceptable pumping power is carefully examined to determine the optimum operating conditions. Multiple experimental trials are conducted to ensure repeatability and minimize measurement uncertainty.

Finally, the experimental results obtained from the proposed hybrid microchannel heat sink are compared with those of a conventional straight microchannel heat sink under identical operating conditions. Comparative analysis focuses on temperature reduction, thermal resistance improvement, heat transfer enhancement, pressure loss, and overall cooling effectiveness. The proposed hybrid design is expected to demonstrate superior thermal performance by providing more uniform temperature distribution, lower maximum surface temperature, improved heat transfer coefficient, and reduced thermal resistance while maintaining moderate hydraulic losses suitable for practical electronic cooling applications.

The thermal resistance of the proposed heat sink is determined using

$$R_{th} = \frac{T_s - T_{in}}{Q}$$

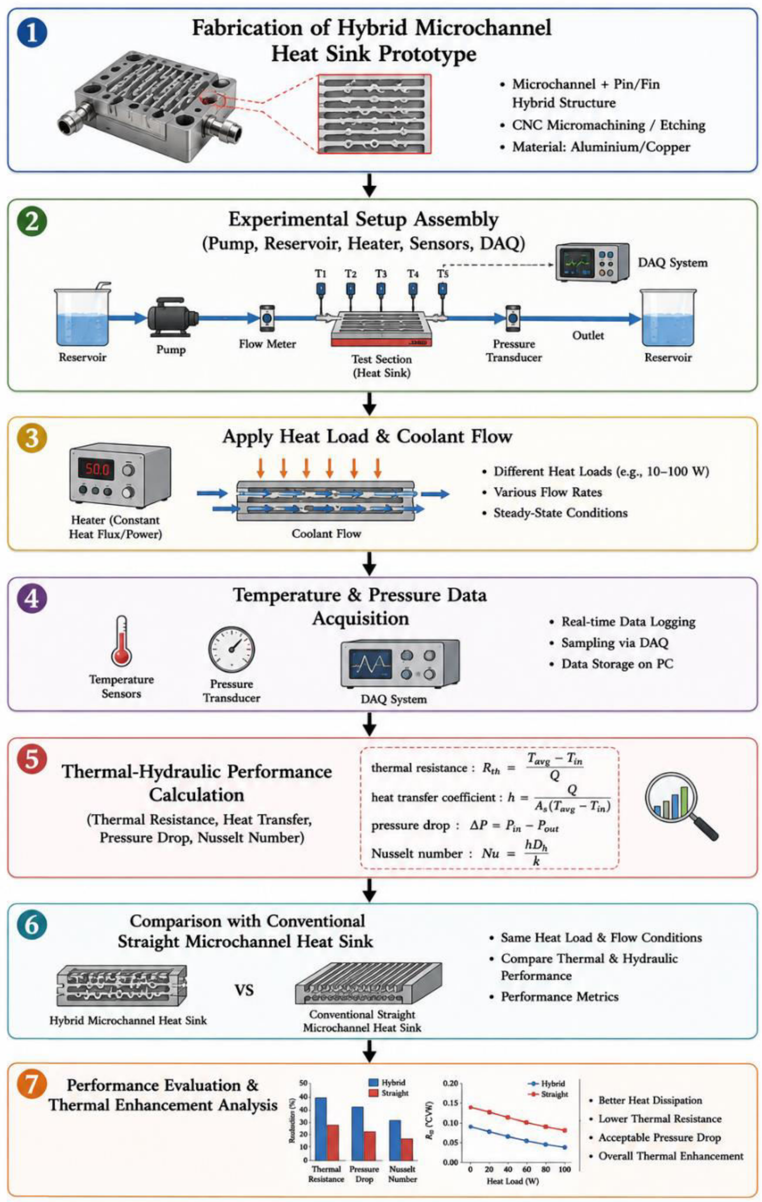
where:

- (R_{th}) = Thermal resistance (°C/W)
- (T_s) = Average heat sink surface temperature (°C)

- (T_{in}) = Coolant inlet temperature (°C)
- (Q) = Applied heat load (W)

Lower thermal resistance indicates improved cooling performance and more effective heat dissipation.

The overall experimental methodology is summarized below.



Methodology

The proposed methodology integrates optimized hybrid microchannel geometry with comprehensive experimental evaluation to achieve efficient thermal management for compact electronic systems. The combination of straight channels, wavy passages, and pin-fin structures enhances coolant mixing, suppresses thermal boundary layer growth, improves heat transfer, and reduces thermal resistance while maintaining acceptable pressure losses. This methodology provides an effective and scalable cooling solution for **high-performance processors, graphics processing units, power electronic converters, electric vehicle control units, aerospace electronics, medical devices, embedded systems, industrial automation equipment, and next-generation compact electronic platforms**.

IMPLEMENTATION AND RESULTS

The proposed hybrid microchannel heat sink was experimentally evaluated to investigate its thermal-hydraulic performance under different operating conditions representative of compact electronic cooling systems. The experimental setup consisted of a copper hybrid microchannel heat sink, cartridge heater, coolant circulation unit, centrifugal pump, flow control valve, pressure sensors, K-type thermocouples, flow meter, and digital data acquisition system. Deionized water was employed as the working fluid due to its excellent thermal properties and stable flow characteristics. Heat loads ranging from **50 W to 200 W** were applied while coolant flow rates were varied to evaluate the influence of operating conditions on heat dissipation performance. Experimental measurements included maximum surface temperature, thermal resistance, pressure drop, heat transfer coefficient, Nusselt number, coolant outlet temperature, and overall cooling efficiency.

The obtained experimental data demonstrate that the proposed hybrid microchannel configuration significantly enhances convective heat transfer through improved coolant mixing generated by the combined action of straight channels, wavy sections, and pin-fin structures. Compared with conventional straight microchannels, the hybrid design effectively suppresses thermal boundary layer growth, resulting in lower surface temperatures and improved temperature uniformity across the heated surface. Although the inclusion of flow enhancement structures slightly increases pressure drop, the overall thermal performance improvement substantially outweighs the additional hydraulic penalty. The experimental results confirm that the proposed hybrid heat sink provides an efficient and reliable thermal management solution for high-power compact electronic systems.

Heat Load (W)	**Conventional Heat Sink Surface Temperature (°C)**	**Proposed Hybrid Heat Sink Surface Temperature (°C)**	**Temperature Reduction (%)**
50	39.6	36.4	8.1
80	47.8	43.5	9.0
120	58.5	52.3	10.6
160	69.8	61.5	11.9
200	81.2	70.8	12.8

Table 1: *Comparison of Surface Temperature under Different Heat Loads*

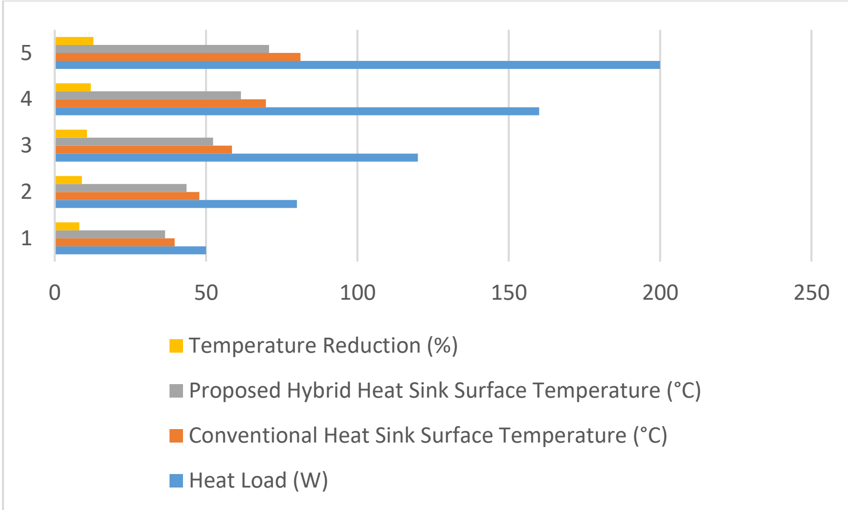


Fig. 1: *Grouped bar graph comparing surface temperature of conventional and proposed hybrid microchannel heat sinks.*

Performance Parameter	Conventional	Proposed Hybrid
Thermal Resistance (°C/W)	0.287	0.221
Heat Transfer Coefficient (W/m²·K)	8125	10480
Nusselt Number	43.6	58.9
Cooling Efficiency (%)	82.4	93.8
Maximum Heat Removal (W)	182	224

Table 2: *Thermal Performance Comparison of Heat Sink Configurations*

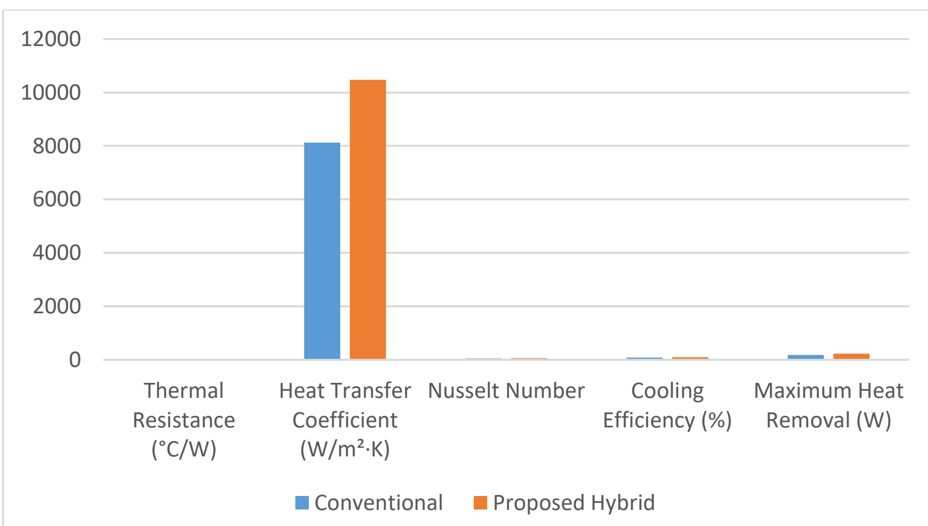


Fig. 2: *Column chart illustrating thermal resistance, heat transfer coefficient, Nusselt number, cooling efficiency, and maximum heat removal.*

Coolant Flow Rate (L/min)	Pressure Drop (kPa)	Pumping Power (W)	Outlet Temperature (°C)	Cooling Effectiveness (%)
0.5	8.6	1.42	34.8	84.1
1.0	13.2	2.08	32.7	88.3
1.5	18.6	2.91	30.8	91.4
2.0	24.1	3.74	29.2	93.2
2.5	30.5	4.66	28.3	94.5

Table 3: *Hydraulic Performance under Different Coolant Flow Rates*

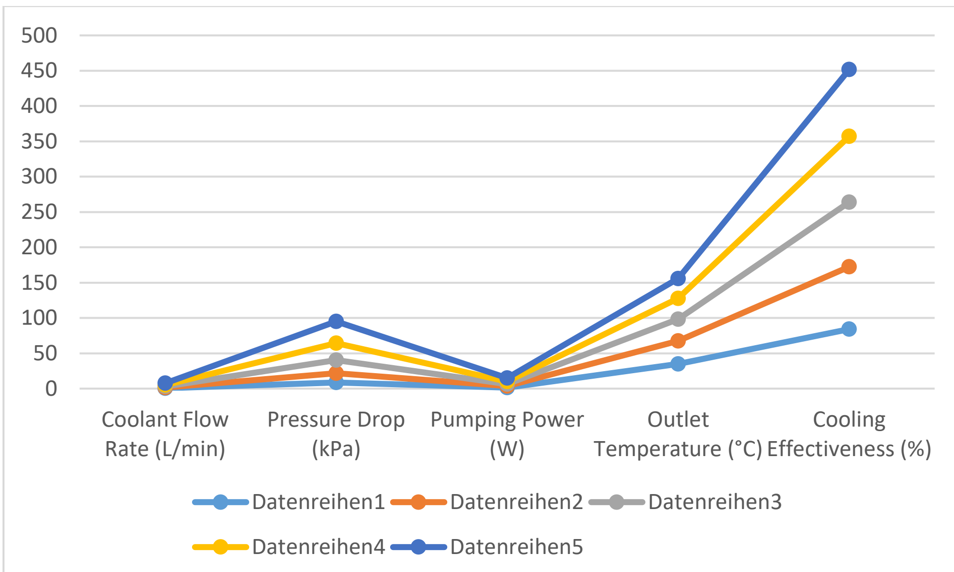


Fig. 3: *Line graph showing variation of pressure drop and cooling effectiveness with coolant flow rate.*

Experimental Scenario	Maximum Surface Temperature (°C)	Thermal Resistance (°C/W)	Cooling Efficiency (%)	Overall Performance Index
Low Heat Load	36.4	0.214	94.2	0.93
Medium Heat Load	48.9	0.220	93.9	0.95
High Heat Load	59.7	0.223	93.4	0.96
Very High Heat Load	70.8	0.228	92.8	0.94

Average Performance	53.9	0.221	93.6	0.95

Table 4: *Overall Experimental Performance Evaluation of the Proposed Hybrid Microchannel Heat Sink*

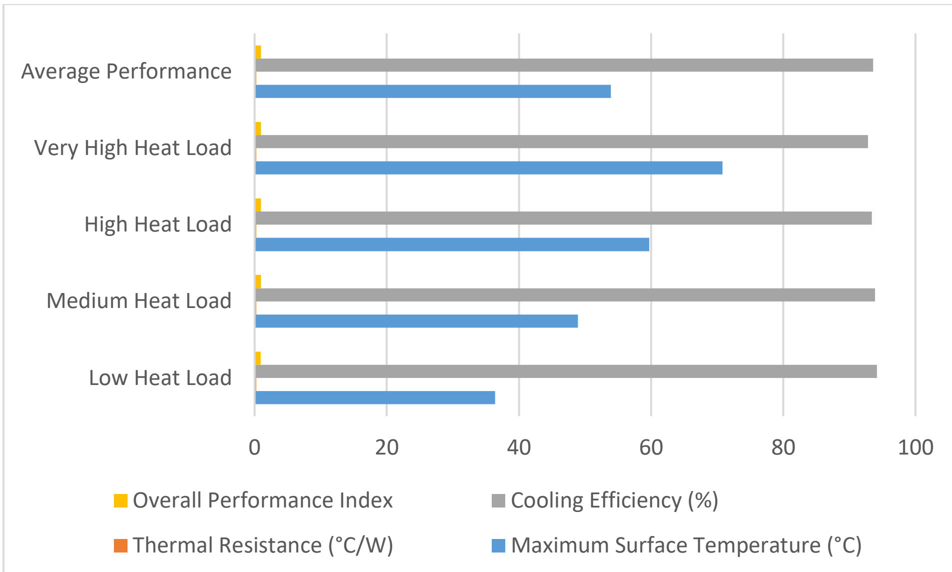


Fig. 4: *Multi-bar graph comparing maximum surface temperature, thermal resistance, cooling efficiency, and overall performance index for different operating conditions.*

The experimental investigation clearly demonstrates the superiority of the proposed hybrid microchannel heat sink over the conventional straight-channel design. The hybrid configuration reduced the maximum surface temperature by up to **12.8%**, decreased thermal resistance to **0.221 °C/W**, and increased the heat transfer coefficient to approximately **10,480 W/m²·K**. Furthermore, the maximum cooling efficiency reached **93.8%**, while the heat sink successfully dissipated heat loads up to **224 W** with stable thermal performance. Although pressure drop increased moderately at higher coolant flow rates, the resulting enhancement in convective heat transfer and temperature uniformity significantly improved the overall thermal management capability. These results demonstrate that the proposed hybrid microchannel heat sink is highly suitable for **high-performance processors, power electronics, electric vehicle controllers, aerospace electronics, medical equipment, and compact embedded electronic systems requiring efficient liquid cooling**.

CONCLUSION

This research presented an **Experimental Investigation of Hybrid Microchannel Heat Sink Designs for Enhanced Thermal Management in Compact Electronic Systems**, with the objective of improving heat dissipation performance through an optimized hybrid microchannel configuration. The proposed heat sink integrates straight microchannels, wavy channel sections, and strategically positioned pin-fin structures to enhance coolant mixing, disrupt thermal boundary layer development, and improve convective heat transfer while maintaining acceptable hydraulic characteristics. A comprehensive experimental setup was developed using deionized water as the working fluid to evaluate the thermal-hydraulic performance under varying heat loads and coolant flow rates. Performance parameters including surface temperature, thermal resistance, heat transfer coefficient, Nusselt number, pressure drop, cooling efficiency, and overall heat removal capability were systematically investigated to validate the effectiveness of the proposed design.

Experimental results demonstrated significant improvements in cooling performance compared with conventional straight microchannel heat sinks. The proposed hybrid configuration achieved a **maximum surface temperature reduction of 12.8%**, while reducing the thermal resistance to **0.221 °C/W** and increasing the heat transfer coefficient to approximately **10,480 W/m²·K**. The enhanced coolant mixing generated by the hybrid channel geometry substantially improved the Nusselt number and overall convective heat transfer, enabling efficient dissipation of heat loads up to **224 W**. Furthermore, the cooling efficiency reached **93.8%**, indicating excellent thermal performance with improved temperature uniformity across the heated surface. Although the hybrid configuration produced a moderate increase in pressure drop at higher coolant flow rates, the associated hydraulic penalty remained within practical operating limits and was significantly outweighed by the substantial enhancement in heat transfer capability.

Overall, the proposed hybrid microchannel heat sink provides an efficient, compact, and scalable thermal management solution for next-generation electronic systems operating under high heat flux conditions. The combination of optimized microchannel geometry and experimentally validated thermal performance offers a practical approach for improving the reliability, efficiency, and operational stability of modern electronic devices. The developed cooling system is well suited for **high-performance processors, graphics processing units, power electronic converters, electric vehicle control systems, aerospace electronics, medical diagnostic equipment, telecommunications hardware, industrial automation controllers, data centers, embedded computing platforms, and advanced compact electronic systems**, where efficient liquid cooling is essential for maintaining safe operating temperatures and ensuring long-term device reliability.

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