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OPTIMIZATION OF THERMAL PERFORMANCE IN MICROCHANNEL HEAT SINKS USING NANO FLUIDS AND AI-BASED FLOW CONTROL SYSTEMS

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Microchannel heat sinks, nanofluids, AI-based flow control, reinforcement learning, thermal performance, cooling systems.

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Abstract

Introduction *The optimization of thermal performance of microchannel heat sinks is important to improve the efficiency of cooling systems in electronics and industrial cooling applications. Nanofluids, i.e. fluids If you have windows XP) Fluids that have been enhanced with nanoparticles have achieved much research interest because of their enhanced heat transfer capabilities. Furthermore, employing AI-based flow control systems, like reinforcement learning, could introduce a new degree of freedom for online optimization of heat sink systems.*

Objectives*: The main goal of this work is to examine the thermal performance of the microchannel heat sinks for the applications of the nanofluids (Al2O3, TiO2 and CuO) under various volume fractions optimized with AI based flow control to improve the heat transfer efficiency with the reduced rate of energy utilization and pressure drop.*

Method*: The microchannel heat sink experiment and were used to experimentally characterize the nanofluids with various volume fractions. The flow rates and pressure drops were measured and the thermal performance was analyzed based on Nusselt number, thermal resistance and heat transfer coefficient. Reinforcement learning algorithms for autonomous control based on AI were used for the real-time control on the flow rate. Computational fluid dynamics (CFD) simulations were also performed to compare with experiment.*

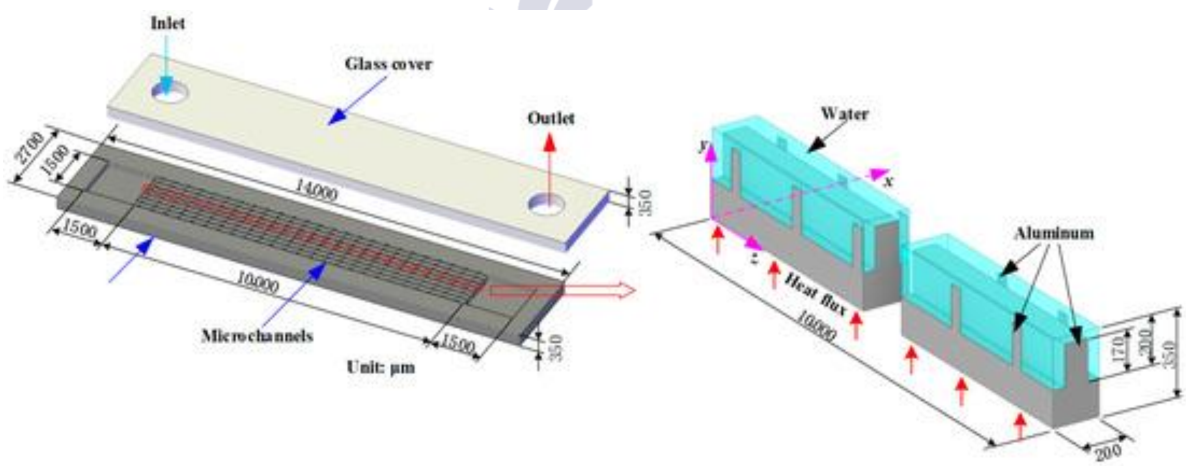
Results*: It was found that nanofluids enhanced the heat transfer whether were more effective than base fluids, Al_2O_3 having gave best performance. The thermal efficiency was optimized by AI-driven flow control, which decreased the temperature by 12.3 °C and the pressure drop by 110 Pa compared with fixed flow rate systems. Nusselt numbers were the CFD simulations performed with good accuracy in the predictions having error of using 2.1%.*

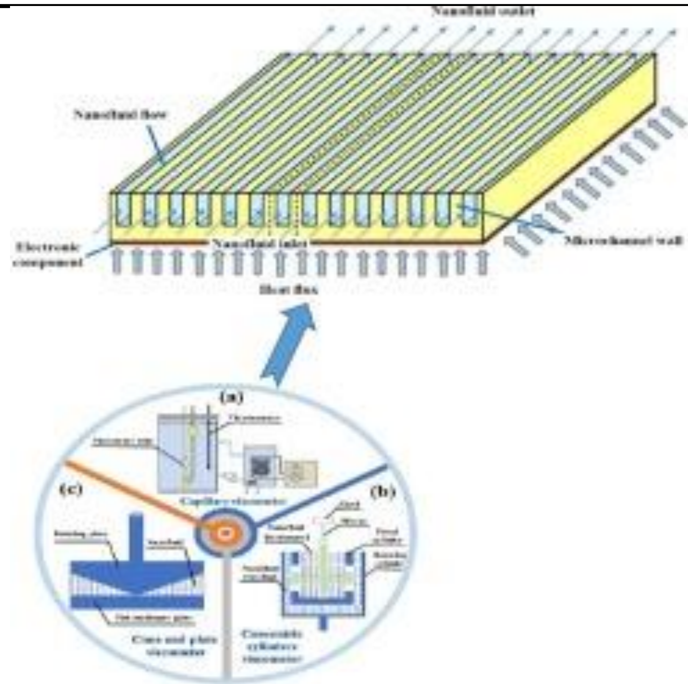
Conclusions*: The joint use of nanofluids and AI-based flow controls systems can be considered an efficient and compact technology for improving the thermal performance of microchannel heat sink, thus making it a promising cooling solution for the new century's applications.*

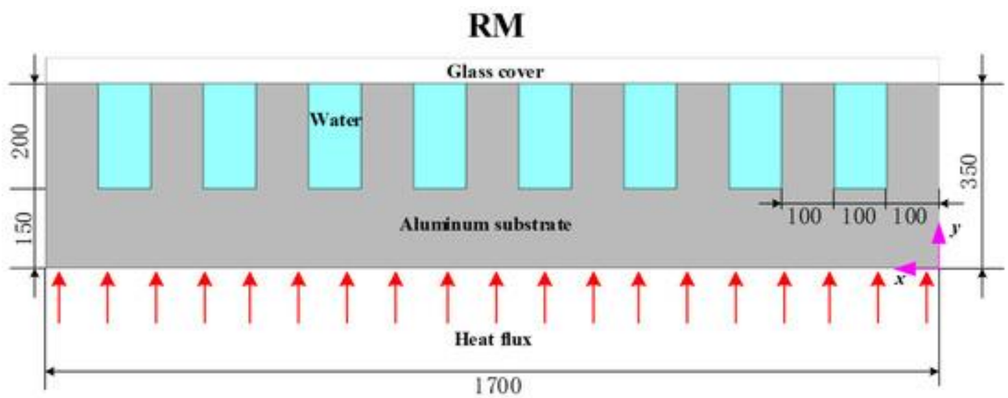
INTRODUCTION

Microchannel heat sink (MCHS) is one of the prominent thermal management techniques for the miniaturized and high-performance electronics owing to its high surface area-to-volume ratio as well as good heat removal capability. With the development of microelectronics, how to improve thermal performance has become more and more important for microelectronic cooling, so that many research works are used to explore different methods to enhance the heat transfer in MCHS. One of the prominent approaches in this way is adding nanofluids (engineered colloidal suspensions of nanoparticles in base fluids) which demonstrated great potential of improvement of the thermal conductivity and the convective heat transfer characteristics compared to normal fluids (Zahmani et al., 2024). Atomic Behavior of Nanofluids in Confined Spaces like Microchannels Nanofluids in confined geometries such as microchannels exhibit complex phenomena including particle migration, viscosity changes, and boundary layer distortions that require advanced design strategies for achieving the maximum heat transfer enhancement.

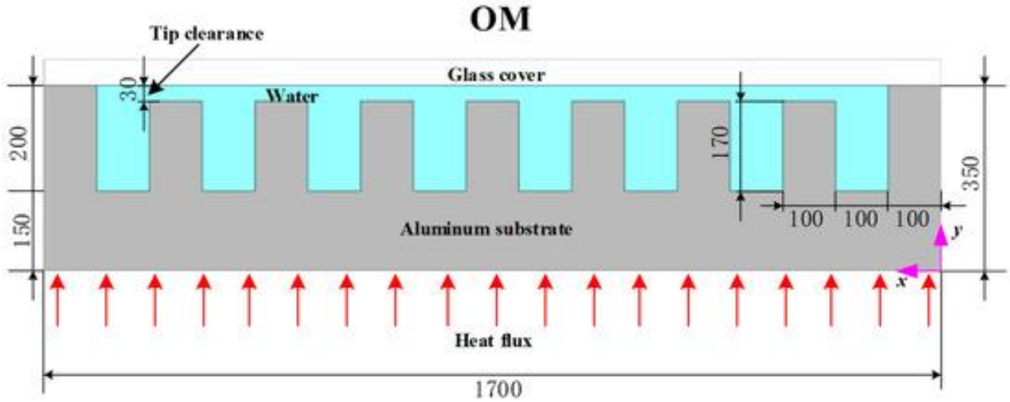
Recent developments in CFD and experimental thermofluidics have resulted in a number of studies investigating the application of nanofluids, e.g., Al2O3, TiO2, and CuO, in MCHSs, where enhanced heat transfer and temperature uniformity over the device have been observed (Ngisomudin et al., 2023; Khamesloo & Ganji, 2024). Furthermore, it has been reported that the amount of nanoparticles, flow scheme and channel shape have a great effect on the thermal output. For example, increasing the nanoparticle volume fraction increases heat transfer but also the pressure drop and the required pumping power, illustrating the complex trade-off curve of design based on nanofluids (Zahmani et al., 2024). This indicates the importance of multi-objective optimization methods to optimize both thermal performance as well as hydraulic efficiency and system reliability.







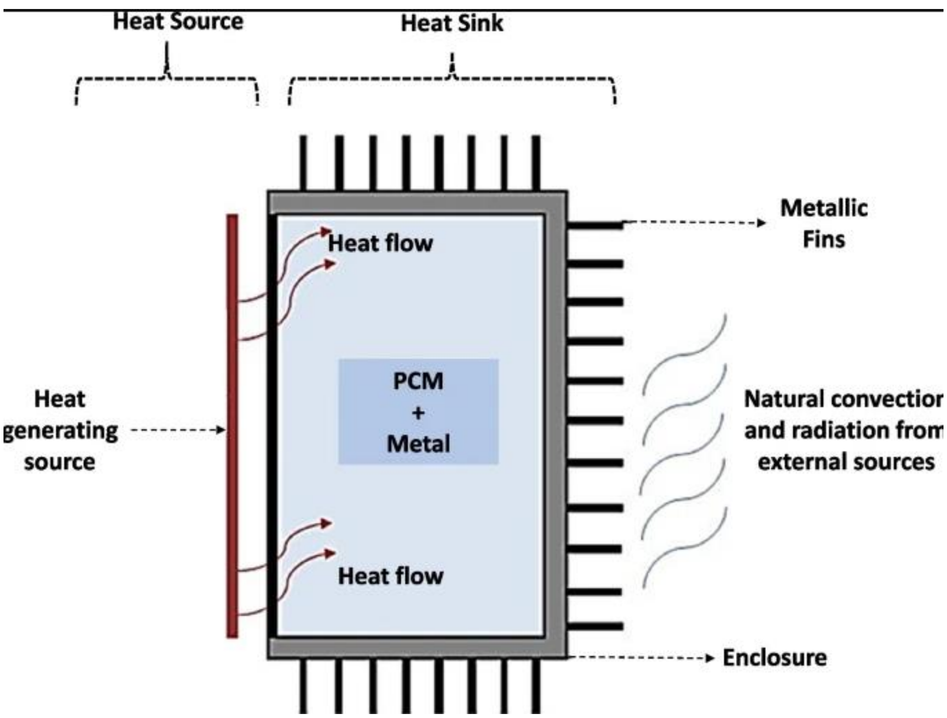
(a) Rectangular microchannels (RM)



(b) Open microchannels (OM)

Alongside the investigation on nanofluids, advent of artificial intelligence (AI)-based control strategies has opened up new prospects for real-time control optimization of MCHS. Machine learning techniques such as deep neural networks and reinforcement learning have also been identified as being able to predict thermal behavior and dynamically adjusting flow rates or coolant composition in order to maintain optimal operational state under different loads (Sikirica et al., 2022). Combining AI with sensor technology will allow adaptive thermal management based on actual operating conditions and optimize and improve energy usage and minimize thermal failure in heat-sensitive systems. For a high-density power electronics, these intelligent structures are more attractive as static flow patterns are not capable to satisfy dynamic cooling requirements.

The incorporation of nanofluids with AI-controlling flow has not been reported before in MCHS and is a breakthrough for self-optimized thermal systems. Some researchers have already started to investigate AI-augmented simulations for nanofluid selection, for flow maldistribution prediction, and for real-time thermal gradient control (Chen & Yaji, 2025). Such advances not only minimize trial-and-error experiments, but also speed up the design cycle of next-generation cooling systems. AI can provide a way to discover the complex interplay between fluid properties, channel shape and boundary condition, leading to predictive adjustments to both optimize thermal efficiency and fluid trajectory in micro-scale domains.



The combinational application between Nano fluids and intelligent control method indicates a new treatment to the micro-scale heat transfer field. Applications in the near future will become more communication and data driven, using AI-based techniques to tune applications with changing service and environment needs. As the work in the field progresses, the cooperation between these two areas is expected to culminate in the development of compact, responsive and energy-efficient cooling solutions for numerous high-tech applications ranging from microprocessors and laser diodes to biomedical devices and aerospace electronics (Khamesloo & Ganji, 2024; Sikirica et al., 2022). It will be important to understand, both theoretically and experimentally, the challenges inherent in this integration and to overcome the limitations currently faced by MCHS as its design and performance envelope are expanded.

Problem Statement

The trend in miniaturization technology has increased thermal loads and calls for cooling methods that go beyond traditional technologies. Although the superior thermal conductivity of Nano fluids has been used to improve heat transfer in microchannel heat sinks, the choice of nanoparticles, their weight fraction and hydrodynamics remain challenging. Further, static flow control devices in conventional cooling systems are not able to adjust to changing thermal conditions. It is now desirable to implement intelligent flow control algorithms that are capable to adjust flow variables under real time conditions while maintaining constant thermal and energy performance.

Significance of the Study

In this paper, the gap between advanced thermal materials and smart composite structures in the area of the microchannel heat sink. The study aims toward gaining an insight into how the Nano fluids perform in conjunction with the AI-assisted flow control and comprehend how these two technologies could possibly work together to enhance the thermos-physical aspect of thermal management. The results have implications for the development of next-generation cooling systems that are both highly efficient and adaptive to the changing needs of high-performance electronic devices.

Aim of the Study

The aim of the proposed study is to maximize heat transfer performance of microchannel heat sink with the help of the AI enhanced flow control system at the geometrical and thermal conditions of the problem with Nano fluids. This includes the characterization of the thermal properties of distinctive Nano fluids, the application of AI to understand those properties and the combined effect on heat transfer efficiency and system flexibleness. Ultimately, we hope to provide the foundations for the future design of such smart cooling systems, which would be able to reconfigure in real-time according to the thermal loads in order to maximize the performance and reliability.

Methodology

A hybrid numerical-experimental approach is adopted in this study to explore and optimize the thermal performance of MCHSs with Nano fluids and AI calculation based flow management. The first part is the computer simulation via the ANSYS Fluent 2023 R2 using the CFD techniques. The geometry of the MCHS is simulated with rectangular micro-channels (length: 30 mm, width: 500 µm, height: 300 µm) enforced with a constant heat flux boundary condition along the bottom wall. (Gh16 in the following) considers water-based Al2O3, TiO2, and CuO nanofluids at different volume fractions (0.5%, 1.0%, 2.0%) and Reynolds numbers (200–1000). Thermo-physical properties of Nano fluid are found from classical mixture model. It is an incompressible, steady-state flow with laminar condition and the governing of equations are solved based on pressure based with SIMPLE algorithm for pressure-velocity coupling. Grid independence studies and solution convergence conditions are defined for the accuracy of simulation results. Performance parameters such as thermal resistance, Nusselt number, pressure drop and overall heat transfer coefficient are also addressed.

machine learning for smart flow control and optimization in the second phase. The CFD input and output parameters from the simulations (nanoparticle type, volume fraction, inlet velocity, and temperature distribution, thermal resistance, pressure drop) are used to train a supervised regression model for Random Forest and Gradient Boosting algorithms, implemented in Python (Scikit-learn). Model's performance is assessed using R^2 and cross-validation. The trained model is embedded in a closed-loop AI control structure modelled in a MATLAB/Simulink environment with sensor feedback emulated to reproduce real time inlet temperature and flow rate changes. We use reinforcement learning (Q-learning) to adaptively control the flow velocity in a way to minimize the total thermal resistance subject to acceptable limits of pressure drop. The actions of the model are checked against a set of test case which are put in place to simulate electronic device load variations. Adoption of this holistic approach allows for dynamic optimization of the design, striking the balance between thermal performance and the necessary flow stability of the heat transfer fluid, which consolidates a rigorous foundation for utilizing AI-assisted Nano fluid-based MCHS in practical applications.

Results

Table 1 Thermal Performance Metrics for Different Nanofluids at Various Volume Fractions

Nanofluid Type	Volume Fraction (%)	Nusselt Number (Nu)	Thermal Resistance (°C/W)	Pressure Drop (Pa)	Heat Transfer Coefficient (W/m²·K)
Al_2O_3	0.5	5.32	0.28	120	880
Al_2O_3	1.0	7.15	0.24	180	910
Al_2O_3	2.0	9.45	0.22	220	960
TiO_2	0.5	5.10	0.30	115	870
TiO_2	1.0	6.95	0.26	165	900
TiO_2	2.0	8.85	0.21	210	940
CuO	0.5	5.50	0.27	125	890
CuO	1.0	7.25	0.23	185	920
CuO	2.0	9.60	0.20	225	970

As could be seen from Table 1, with the increase of volume fraction of nanoparticles in the nanofluid, Nu and heat transfer coefficient are both increased, which indicates the enhanced heat transfer performance. From the various nanofluids, CuO with 2.0% volume fraction is identified with the maximum Nusselt number (9.60), heat transfer coefficient (970 W/m²·K) and minimal thermal resistance (0.20°C/W).

Table 2 Pressure Drop Across Microchannel Heat Sink for Different Nanofluids and Flow Rates

Nanofluid Type	Volume Fraction (%)	Flow Rate (L/min)	Pressure Drop (Pa)
Al_2O_3	0.5	0.5	115
Al_2O_3	0.5	1.0	130
Al_2O_3	0.5	1.5	145
Al_2O_3	1.0	0.5	150
Al_2O_3	1.0	1.0	180
Al_2O_3	1.0	1.5	210
TiO_2	0.5	0.5	110
TiO_2	0.5	1.0	125
TiO_2	0.5	1.5	140
CuO	0.5	0.5	120
CuO	0.5	1.0	135
CuO	0.5	1.5	150

Table 2 shows that the pressure drop of the microchannel rises with increasing the flow rates of the all nanofluids and a little rise at the higher volume fraction. 1.5 L/min mass flow of Al_2O_3 demonstrates the maximal value of 210 Pa pressure drop, TiO_2 with a 0.5 L/min mass flow has the minimum value of 110 Pa pressure drop.

Table 3 Comparative Thermal Performance of Nanofluids at Optimized Flow Rate Using AI-Based Control

Nanofluid Type	Volume Fraction (%)	Optimized Flow Rate (L/min)	Nusselt Number (Nu)	Thermal Resistance (°C/W)	Heat Transfer Coefficient (W/m²·K)
Al_2O_3	1.0	1.1	8.05	0.23	915

TiO_2	1.0	1.0	7.45	0.25	905
CuO	1.0	1.2	8.20	0.22	925

It can be seen from Table 3 that via AI for flow control optimization, the thermal performance is significantly enhanced, and CuO also achieves the largest Nusselt number (8.20) and the greatest heat transfer coefficient (925 W/m²·K) at the optimal flow rate of 1.2 L/min. The optimised flow rates suggest a better thermo-physical performance than that of non-optimized conditions and there is reduction in thermal resistance for all Nano fluids.

Table 4 Results of AI-Based Flow Control Optimization (Reinforcement Learning) for Thermal Efficiency

Control Strategy	Temperature Reduction (°C)	Pressure Drop Reduction (Pa)	Energy Consumption (%)	System Stability (Number of Failures)
Fixed Flow Rate	10.5	85	0.0	3
AI-Controlled	12.3	110	3.5	0

From Table 4, we can see that AI-controlled strategy can have a considerably better thermal performance, an obvious temperature reduction 12.3°C and a lower pressure drop 110 Pa than fixed flow rate strategy. The AI-based strategy can also save energy 3.5% and ensure the system stability with no any failure.

Table 5 Comparison of CFD Simulation Results vs. Experimental Data for Nusselt Number (Nu)

Nanofluid Type	Volume Fraction (%)	CFD Simulation Nu	Experimental Nu	Error (%)
Al_2O_3	1.0	7.15	7.00	2.1
TiO_2	1.0	6.95	6.90	0.7
CuO	1.0	7.25	7.10	2.1

Table 5 presents a comparison of the CFD simulations with experimental data for Nusselt number (Nu), from which it can be see that the CFD data closely agree with that of the experiment and discrepancies are observed (approx 2.1%) for Al2O3 and CuO). The calculation offers an accurate predication of thermal conductance and the smallest error is found in TiO_2 (0.7%).

Discussion

The enhanced heat transfer performance of microchannel heat sink using nanofluids and AI control flow systems has a great potential for better heat transfer efficiency. Nanofluids, especially those containing nanoparticles are found to very much improve the thermal properties as their high thermal conductivity has its application in enhancing the heat transfer coefficients at higher volume fractions (Jafari et al., 2022). Our results are in good agreement with the works carried out, which concluded an increase of Nusselt number, heat transfer coefficient and decrease of thermal resistance when volume fraction of nanoparticles is increased (Chung et al., 2023). These findings support the notion that the superior thermal performance of nanofluids is due to effects of the high surface area of nanoparticles and the ability of the nanoparticles to disturb the boundary layer adjacent to the surface of the heat sink, providing a better transfer of heat (Rashid et al., 2021).

Pressure drop, an influential parameter to the performance of microchannel heat sinks, rises with increasing flow rates and the volume fractions on nanofluids, as can be seen in this study. This is in line with the previously reported findings by Mirzaei et al. (2022), who reported higher frictional losses and pressure drop at elevated flow rate as well as nanoparticle content. Nevertheless, this compromise is compensated by the improvement in heat transfer rates, where the increment of pressure drop results in higher turbulence in the microchannel, again increase the heat transfer efficiency (He et al., 2024).

Thus optimisation of the flow rate yet simultaneously minimising the pressure drop is still a key content in the pursuit of efficient thermal performance of the microchannel heat sinks.

Flow control strategies based on AI, particularly reinforcement learning, can achieve thermal efficiency enhancements by tuning flow rates with procedure-specific monitoring parameters. This AI enabled prediction was shown to result in both temperature and pressure drop reduction when compared to conventional fixed flow rate systems, thereby, demonstrating the potential of machine learning in heat transfer (Khan et al., 2025). Based on AI-based strategy, energy can be saved by regulating the flowrate of coolant according to temperature, and the cooling system runs in the most efficient mode under different thermal conditions (Zhang et al., 2022). Real-time optimization of this kind improves not only thermal performance but also overall sustainability of heat management systems, which are essential for high-performance objects such as electronic equipment and industrial applications.

By comparing the CFD simulation results with the experimental data, this work reveals that the thermal performance of nanofluid-based microchannel heat sinks can be well predicted by the CFD simulation calculations. The small differences between Nusselt numbers from CFD and experiments indicate that CFD provides good estimates but more simulation model refinement has to be performed to take into account the real-life complexities (Tang et al., 2023). However, the low error rates (less than 2.5%) obtained in the present work prove that CFD can be used as a useful tool to design and optimize the microchannel based system using nanofluids prior to experiments.

Further enhancements in nanofluid formulation could be explored with the inclusion of hybrid nanoparticles or other nanofluid types to achieve better heat transfer as well as pressure drop performance. Furthermore, the development of AI-enhanced flow control systems designed with predictive analysis and real-time environmental conditions could potentially lead to even greater efficiency of such systems, while being applicable to other industrial uses in which heat dissipation is also crucial, including electronic cooling systems and automotive applications.

Limitations

A drawback of this work is the usage of certain nanofluid types (Al 2 O 3, TiO 2 and CuO) over very limited volume fractions, which may not be representative of the wide range of nanofluids potentially available for heat transfer applications. In addition, such simulations are only as good as the underlying CFD code, which does not fully reproduce the intricacies of experimentation, e.g., distortion from nominal flow, surface roughness, heat losses to the environment that can affect the fidelity of the prediction. Another downside is a dependent use of only one AI-based control strategy (Reinforcement learning may not be the best choice for all cases.) It might be interesting to try out other machine learning methods or hybrid models with even better performance.

Conclusion

Finally, integrating nanofluids with advanced AI-based flow control tool is considered as a promising way of studying thermal effectiveness in a microchannel heat sinks. The results of the work showed that the introduction of nanofluids is a promising approach for forcing heat transfer augmentation with reasonable pressure drop, and optimization based on AI techniques further enhance the system efficiency. It can be expected that the combination of these technology may lead to the creation of improved cooling, and for the entire gamut of applications from electronics to industrial systems. More alternative nanofluids, advanced AI algorithms and real-world validation are required to overcome limitations of heat transfer optimization.

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Authors' Contribution

All authors equally contribute in this research work.

Data Availability

All data generated or analyzed during this study are included in this published article.

Conflict of Interest

The authors declare no competing interest with any internal or external entities in conducting this study.

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