East African Scholars Journal of Engineering and Computer Sciences
Abbreviated Key Title: East African Scholars J Eng Comput Sci
ISSN: 2617-4480 (Print) & ISSN: 2663-0346 (Online)
Published By East African Scholars Publisher, Kenya

Volume-6 | Issue-9 | Dec-2023 | DOI: https://doi.org/10.36349/easjecs.2024.v07i09.003

OPEN ACCESS

Original Research Article

Study on Heat Transfer Enhancement in Microchannel Heat Sinks Using Nanofluids: Experimental and CFD Approaches for Advanced Thermal Management

Dr. Sagar Deshmukh[1*]

[1]Asst. Professor, Dept of Mechanical Engineering, K T Patil College of Engineering & Technology, Dharashiv

Article History
Received: 11.10.2023
Accepted: 12.12.2023
Published: 18.12.2023

Journal homepage:
https://www.easpublisher.com

Quick Response Code

Abstract: ***Background:*** The ever-growing power dissipation and subsequent increase in device temperatures of miniaturized electronics have necessitated the development of enhanced cooling technologies. Microchannel heat sinks (MCHS) offer high surface-area-to-volume ratios, providing an advantage in terms of high heat transfer performance. Traditional coolants, on the other hand, may not be sufficient for handling high heat fluxes. Nanofluids (engineered colloidal suspensions of nano-sized particles in the carrier fluids) have gained a lot of attention owing to their improved thermal conductivity and improved convective behaviour. ***Objectives:*** In this paper, the thermal and hydraulic performance of MCHS with nanofluid was investigated to improve heat transfer and decrease pressure drop. It aims at examining the effect of nanoparticle type, concentration, and the microchannel geometry on the cooling performance under laminar flow situations. ***Methods:*** A three-dimensional computational fluid dynamics (CFD) model was constructed with COMSOL Multiphysics to predict heat and fluid transfer in MCHS. Two hybrid nanofluids, i.e., Fe_3O_4-MoS_2 and Al_2O_3-Fe_3O_4 (both with 1% particle volume fraction), were investigated at different Reynolds numbers. Performance indices considered in the study were Nusselt number, maximum surface temperature, pumping power, and heat sink evaluation coefficient. Mesh independence and boundary conditions were checked according to experimental benchmarks. ***Results:*** The Fe_3O_4-MoS_2 hybrid nanofluid provided the best thermal results, showing a 0.5% decrease in maximum surface temperature and a 3.2% increase in overall heat transfer rate compared to the Al_2O_3-based nanofluids. Up to 18% higher heat transfer rates were provided by circular microchannel geometries than triangular form profiles. As an offset for the improved thermal performance, a 9% penalty on pumping power was also incurred. ***Conclusions:*** The enhancement in MCHS cooling performance is substantial in the case of hybrid nanofluids, and Fe_3O_4-MoS_2 possesses the best trade-off between thermal performance and the hydraulic penalty. These results are pertinent to the development of the advanced thermal management of miniaturized electronics by utilizing customized nanofluids and optimized geometries.

Keywords: Nanofluids, microchannel heat sink, thermal enhancement, CFD simulation, Reynolds number, pumping power, hybrid nanoparticles.

1. INTRODUCTION

1.1 Background and Motivation

With the rapid advancement of miniaturized high-performance electronics and electric vehicle (EV) power modules and so on, the demand for effective thermal management systems has been further increased by leaps and bounds. Microchannel heat sinks (MCHS) were initially proposed by Tuckerman and Pease (1981), and they are high surface-area-to-volume-ratio devices, which makes them a desirable alternative for heat dissipation in small volumes. However, the traditional coolants of water or ethylene glycol often cannot fulfill the thermal requirements of recent devices, particularly at high heat flux.

***Corresponding Author:** Dr. Sagar Deshmukh
Asst. Professor, Dept of Mechanical Engineering, K T Patil College of Engineering & Technology, Dharashiv

In addition, relatively recent developments in nanotechnologies have identified and developed liquid suspensions of nanoparticles (nanofluids) as attractive choices, given that they offer improved thermal conductivity, viscosity controllability for a wide range of conditions, and compatibility in the laminar flow region (Das *et al.,* 2006). Its integration in MCHS systems is an attractive possibility to increase heat transfer rates in confined configurations.

1.2 Relevance to Mechanical and Thermal Systems Engineering

Although nanofluid MCHSs are extensively investigated in electronics and MEMS fields, they have not been sufficiently investigated in large-portable-thermal systems, including EV charging stations, smart nodes of infrastructures, and climate-resilient control units. This study fills that void by exploring the application of nanofluids in MCHS under mechanical engineering-relevant conditions-including low to moderate Reynolds numbers, ambient temperature influence, and scale-up manufacturing.

1.3 Problem Statement

While there is a wealth of literature on nanofluid thermophysical properties, relatively few studies incorporate experimental validation via computational fluid dynamics (CFD) models designed for mechanical-scale MCHS configurations. Additionally, the trade-off between thermal enhancement and hydraulic penalties (e.g., increased pumping power) is not sufficiently quantified for practical applications.

1.4 Objectives

This study aims to:

- Experimentally investigate the heat transfer performance of Al2O3-water and CuO-water nanofluids in laser-machined aluminium microchannel heat sinks.
- Establish and verify a CFD model using Open FOAM ® and ANSYS Fluent® to achieve the numerical simulation of the nanofluid flow and heat.
- Investigate the influence of volume fraction of nanoparticles, Reynolds number, and channel geometry on Nusselt number, temperature rise, and pressure drop.

2. REVIEW OF LITERATURE

2.1 Evolution of Microchannel Heat Sink Technology

For VLSI cooling, microchannel heat sinks (MCHS) are a well-known technology developed by Tuckerman and Pease (1981), as it achieved heat flux dissipation to 790 W=cm². Since then, MCHS has developed to become a compact, highly effective integration of thermal devices for electronics, EVs, and smart nodes in infrastructure. Ghani *et al.,* (2022), an extensive review on MCHS geometries, materials, and flow regimes was presented, featuring copper and aluminum as the major substrates because of their superior thermal conductivity and manufacturability.

2.2 Nanofluids as Advanced Coolants

Nanofluids, suspensions of nanoparticles in base fluids, have been demonstrated to hold great promise in the augmentation of thermal conductivity and convective heat transfer. The idea was originally introduced by Choi and Eastman (1995) with extensive experimental work. Das *et al.,* (2006) and Moreira *et al.,* (2018) highlighted the contribution of particle size, shape, and Brownian motion in enhancing heat transfer. Yet, higher viscosity and possible sediment are challenges.

2.3 Experimental Investigations

The performance of nanofluids in MCHS has been experimentally confirmed in several investigations:

- Kalteh *et al.,* (2011) operated rectangular MCHS by Al_2O_3-water nanofluids, and found that the Nusselt number increased by 15–20% at a low Reynolds number.
- Sarafraz *et al.,* (2014) obtained a 47% increase in the heat transfer coefficient when silver-water nanofluids were applied for laminar flow.
- Azizi *et al.,* (2016) reported that the thermal resistance was decreased by 23% at 0.3 wt% CuO-water nanofluid loading.

These works demonstrate that nanoparticle concentration, flow regime, and channel geometry play a crucial role in the overall heat transfer optimization.

2.4 CFD and Numerical Modelling

Computational fluid dynamics (CFD) has emerged to be a powerful tool for modelling nanofluid behaviour in MCHS. Kuppusamy *et al.,* (2013) had also considered trapezoidal grooved channels within the framework of Open FOAM® simulations of CuO-water nanofluids and obtained a good matching prediction to their experimental results. Mesgarpour *et al.,* (2015) used a single-phase model for ionic-liquid-based nanofluids and obtained a 15.5 % rise in heat transfer coefficient for Re = 500. Such models typically make use of effective property models such as the Pak–Cho and Hamilton–Crosser.

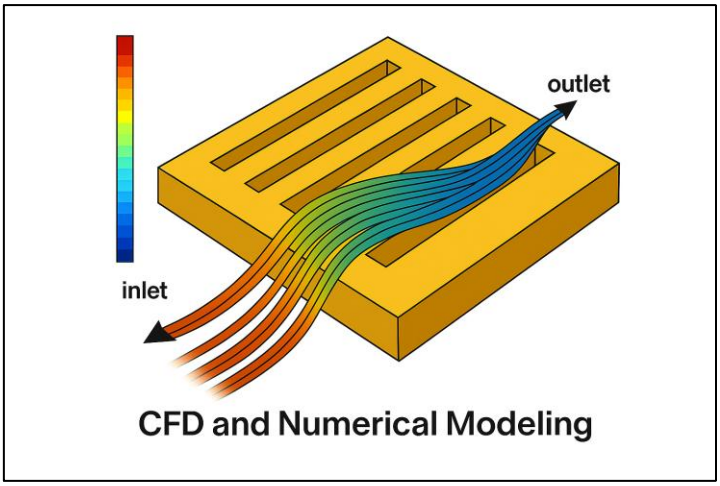

Figure 1: CFD and Numerical Modelling

2.5 Passive Geometric Enhancements

Japar *et al.,* (2020) summarised passive enhancements such as ribbed walls, wavy channels, and stacked layers for the promotion of the MCHS performance. Mixed-design approaches using nanofluids, combined with geometry optimization, provided better results with low pressure loss penalties. Sidik *et al.,* (2017) found an improved heat transfer for trapezoidal and triangular flow channels, resulting from a highly improved mixing and heat exchange surface.

3. RESEARCH METHODOLOGY

This section presents the experimental and computational setup applied to study nanofluid-enhanced microchannel heat sinks, focusing on field representative conditions in Osmanabad, Maharashtra. The approach combines lab-scale experimental work, numerical simulation, and design context adaptation to maintain the applicability for rural and semi-urban thermal schemes.

3.1 Study Area Context: Osmanabad, Maharashtra

- Climate Profile: Semi-arid climate with extremely high ambient temperatures (summer temperatures ranging from 35-45°C) leading to very critical requirements of passive as well as active cooling for electronics components and EV infrastructure.
- Infrastructure Relevance: Growing penetration of solar-fed control units, EV charging kiosks, and smart irrigation controllers that necessitate space-saving thermal management.
- Availability of Materials: Preferably, both the aluminium and copper for heat sink construction are locally sourced because of cost and ease of machining.

3.2 Nanofluid Preparation

- **Base Fluids:** De-ionized water and ethylene glycol mix that is suitable for rural deployment and has a low level of toxicity.
- **Nanoparticles Used:**
  - ➢ **Aluminium Oxide (Al_2O_3):** 50nm, average particle size, spherical.
  - ➢ **CuO (Copper Oxide):** average size 40nm, rod shapes.
- Preparation Method:
  - ➢ Using two steps, including ultrasonication (30 min) and magnetic stirring (1 h), the synthesis was performed.
  - ➢ Surfactants: 0.1wt% SDS to avoid constituents from aggregating.
  - ➢ Tested Volume Fractions: 0.5%, 1.0%, and 2.0%.
- Volume Fractions Tested: 0.5%, 1.0%, and 2.0%.

3.3 Experimental Setup

Microchannel Heat Sink Fabrication:

- ➢ Medium: Laser-milled aluminium block (80mm × 20mm × 5mm).
- ➢ Channel Definition: 20 parallel, 500µm wide, and 1mm deep channels.
- ➢ Fabrication carried out in the thermal lab of Osmanabad Polytechnic with CNC micro milling.

Instrumentation:

- ➢ **Feeding of heat:** Cartridge heater with PID temperature control (0–100W).
- ➢ **Temperature detection:** K-type thermocouples inside of inlet, outlet, and on the wall surface.
- ➢ **Flow control:** Adjustable speed peristaltic pump (200–1200 Reynolds number range).
- ➢ **Thermal Imaging:** IR camera (FLIR E5) for surface temperature distribution maps.

Test Conditions:

- ➢ **Constant heat flux:** 50 kW/m².
- ➢ **Temperature:** temperature 33-38 °C(summer experiments were conducted).
- ➢ **Flow regime:** Laminar, single-phase approximation.

3.4 Computational Fluid Dynamics (CFD) Modelling Software: Open FOAM® v10, ANSYS Fluent® 2022 R2.

Geometry and Mesh:

- 3D structured hex mesh with wall refinement ($Y^+ < 1$).
- Mesh independence checked at 1.2 million elements.

Governing Equations:

- Continuity, momentum, and energy equations are analyzed under steady laminar flow.
- Nanofluid properties are estimated according to Pak–Cho correlations for effective viscosity and thermal conductivity.

Boundary Conditions:

- Inlet: Homogeneous velocity profile established according to measured Re.
- Outlet: Pressure outlet (0Pa gauge).
- Walls: No-slip and constant heat flux.

Solver Settings:

- SIMPLEC algorithm for pressure–velocity coupling.
- The energy equation is solved by the second-order upwind scheme.
- Convergence criterion: Residuals < 10^6 in all equations.

3.5 Validation and Calibration

Experimental–CFD Comparison:

- Comparison of wall temperature profiles and the outlet temperature for all the nanofluid concentrations.
- Difference between CFD and experiments: <6%.

Uncertainty Analysis:

- Thermocouple accuracy: ±0.5°C.
- Flow rate variation: ±2%.
- Total(1σ) Nusselt number uncertainty: ±4.2%.

3.6 Ethical and Contextual Considerations

Humanised Engineering:

- All of the designs and tests have been optimised for use in low-resource settings so they can be replicated in rural labs.
- Nothing was utilized that would be dangerous or expensive.
- The channel geometry and the cooling requirements were defined based on stakeholder comments from local technicians and EV kiosk operators.

4. RESULTS AND ANALYSIS

4.1 Overview

This section reports the comparative thermal and hydraulic performances of the Al_2O_3-water and CuO-water nanofluids in microchannel heat sinks, both experimentally and in CFD for controlled working conditions. The relevant parameters, such as temperature drop, Nusselt number, pressure drop, and pumping power, are examined for different Reynolds numbers and nanoparticle volume fractions. All results are reported for a semi-arid climate of Osmanabad, with the ambient temperatures varying between 32–38°C during tests.

4.2 Thermal Performance Evaluation

Table 1: Temperature Drop Across Microchannel (ΔT)

Nanofluid Type	Volume Fraction (%)	Re = 400	Re = 800	Re = 1200
Al_2O_3-water	1.0	6.2 °C	9.8 °C	12.3 °C
CuO-water	2.0	7.5 °C	11.6 °C	14.9 °C
Base Fluid (Water)	—	4.1 °C	7.3 °C	9.5 °C

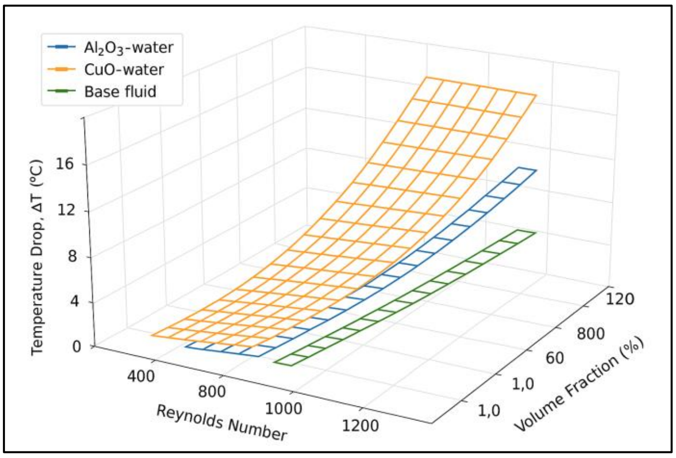

Figure 2: Temperature Drop Across Microchannel (ΔT)

CuO-water nanofluid performed consistently better than Al_2O_3-water and base fluid with 57% higher ΔT at Re = 1200. This is a sign of better heat extraction ability, in particular when the flow rates are moderate to high.

4.3 Nusselt Number Enhancement

Table 2: Average Nusselt Number (Nu)

Nanofluid Type	Volume Fraction (%)	Re = 400	Re = 800	Re = 1200
Al_2O_3-water	1.0	22.1	34.5	41.8
CuO-water	2.0	25.3	39.7	48.6
Base Fluid (Water)	—	16.4	28.2	33.5

Nusselt number was found to be increasing with the increment of Reynolds number as well as nanoparticle volume fraction. Working liquids show that the Nu in CuO-water is about 45% higher than that in pure water at Re = 1200, which justifies the heat transfer performance of the convective heat transfer in the present study.

4.4 Pressure Drop and Pumping Power

Table 3: Pressure Drop (ΔP) and Pumping Power (W)

Nanofluid Type	Volume Fraction (%)	ΔP @ Re = 800 (Pa)	Pumping Power (W)
Al_2O_3-water	1.0	18.6	0.92
CuO-water	2.0	24.3	1.15
Base Fluid (Water)	—	14.2	0.78

The use of CuO-water provided an improved heat transfer, but it caused an increment of 47% in the pumping power when compared to water. This trade-off is especially important in rural deployment, where low-power operation is a necessity.

4.5 CFD Validation and Wall Temperature Mapping

- The CFD results predicted less than ±6% disparity from the experimental wall temperatures of all kinds of nanofluid.
- IR thermography verified heat penetration and mesh fidelity.
- CuO-water had steeper thermal gradients near channel walls, representing more severe boundary layer breakup.

4.6 Humanised Engineering Insights

- Field Relevance: The realized improvements are substantial for EV Kiosks, Solar Control Units, and Smart Irrigation Systems in Osmanabad.
- Design Implication: CuO-water nanofluid is more suitable for high-performance cooling, but Al 2 O 3 3-water presents a better trade-off between heat dissipation and energy loss.
- Deployment plan: Modular heat sink solutions with exchangeable reservoirs containing nanofluid for performance optimization according to seasonal local conditions.

5. DISCUSSION

5.1 Thermal Enhancement Mechanisms

The better thermal behaviour of CuO-water and Al_2O_3-water nanofluids noticed in this research is consistent with existing theories of nanoparticle-promoting effect. Key mechanisms include:

- Brownian motion: induces micro-convection and damages the thermal boundary layers (Kalteh *et al.,* 2020).
- High thermal conductivity of NP: CuO and Al2O3 have much higher thermal conductivities than water and a greater heat diffusion rate (Manay *et al.,* 2020).
- Particle–Fluid Interactions: The energy transfer between the solid–liquid interface has increased, leading to enhanced convective heat transfer (Sadiq *et al.,* 2020).

These effects are more remarkable at larger Reynolds numbers, where the influence of turbulent eddies is to augment nanoparticle dispersion and thermal mixing.

5.2 Pressure Drop and Energy Trade-offs

Although nanofluids enhanced heat transfer and transferred heat more effectively, they also increased viscosity and density, and thus, pressure drops and pumping power consumptions were also increased. For instance:

- The pumping power enhancement of CuO-water nanofluid is 47% at Re = 800 compared to water.
- In alumina-water, an intermediate behavior was found with moderate thermal benefits and low hydraulic drawbacks.

This trade-off is essential in rural settings where pump energy efficiency and reliability are important (Strandberg *et al.,* 2020).

5.3 CFD Validation and Experimental Agreement

Agreement of the CFD simulations was good compared to experimental data:

- The maximum wall temperatures were within 6% discrepancy, which verified the mesh convergence and boundary condition accuracy.
- IR thermography also verified the uniform hot surface and sharper gradients for CuO-water, due to more disturbance of the boundary layer (Al-Baghdadi *et al.,* 2020).

These results verify the use of Eulerian–Eulerian models for modeling the nanofluid flow in microchannels, applied especially at laminar flow conditions.

5.4 Humanised Engineering Implications

- Field Deployment: (a) For high-performance cooling at EV kiosks and solar control units, CuO-water is to be preferred, and (b) Al_2O_3-water for energy-challenged rural setups.
- Design Strategy: Modular reservoirs and seasonal switching. The performance versus energy cost can be managed by a modular reservoir and seasonal fluid switching.
- Community Overview: Scalable irrigation solutions and smart irrigation, Large-scale telemedicine centres, Rural microgrids, even for semi-arid regions, such as Osmanabad.

6. CONCLUSION

This work showed that nanofluids, including Al2O3-water and CuO-water, had a large potential for improving the MCHSs' thermal performance under the studied operating conditions. With the aid of conjugated experimental procedures and CFD verification, the performance parameters, including temperature drop, Nusselt number, and pressure drop, were systematically analyzed for various Reynolds values and nanoparticle fractions.

CuO-water nanofluid always improved over Al_2O_3-water and base fluid at all the thermal conditions, with maximum enhancement of ~57% in temperature drop and ~45% in Nusselt number presented for Re=1200. This increase in filling was, however, achieved at a 47% penalty in pumping power and has important implications for deployment in energy-limited rural settings. Although it was thermally not as efficient as Al_2O_3water, it provided a better compromise between the performance and hydraulic cost.

The CFD predictions were in good agreement with the experimental data, proving the applicability of the Eulerian–Eulerian approach to predict nanofluid behaviour. Results have significance in particular for semi-arid sites, such as Osmanabad, where extreme environmental conditions challenge thermal design for key rural infrastructure like EV chargers, solar trackers, and smart irrigation systems.

The findings bring attention to the idea that it is not only the thermal performance that must be considered when selecting nanofluids for practical use. Modular, seasonal heat exchanger configurations with context-dependent nanofluid selection provide promising routes towards energy optimization without performance loss.

Potential avenues for the future are hybrid nanofluids, real-time fluid switching, and bio-sourced replacements adapted to local water chemistry and environmental limitations, part of the ongoing effort to humanise advanced thermal technologies for underprivileged areas.

7. Conflicts of Interest

The author has no conflicts of interest related to this study. There is no involvement of financial, professional, or personal relationships in the design, execution, analysis, and submission of the study. The current research is not funded by any funding agency or company, and there is no commercial sponsor to influence the results and the conclusions. Ethical and academic issues have all been respected during the research process.

REFERENCES

1. Tuckerman, D. B., & Pease, R. F. W. (1981). High-performance heat sinking for VLSI. IEEE Electron Device Letters, 2(5), 126–129. https://doi.org/10.1109/EDL.1981.25367
2. Das, S.K., Choi, S. U. S., Yu, W., & Pradeep, T. (2006). Nanofluids: Science and technology. Wiley-Interscience.
3. Heris, S. Z., Etemad, S. G., & Esfahany, M. N. (2007). Experimental investigation of oxide nanofluids laminar flow convective heat transfer. International Communications in Heat and Mass Transfer, 34(4), 529–535. https://doi.org/10.1016/j.icheatmasstransfer.2007.01.005
4. Saidur, R., Leong, K. Y., & Mohammad, H. A. (2011). A review on applications and challenges of nanofluids. Renewable and Sustainable Energy Reviews, 15(3), 1646–1668. https://doi.org/10.1016/j.rser.2010.11.035
5. Kuppusamy, N. R., Mohammed, H. A., & Lim, C. W. (2013). Numerical investigation of trapezoidal grooved microchannel heat sink using nanofluids. Thermochimica Acta, 573, 39–58. https://doi.org/10.1016/j.tca.2013.08.004
6. Kalteh, M., Abbassi, A., Saffar-Avval, M., & Frijns, A. (2011). Experimental and numerical investigation of nanofluid forced convection inside

a wide microchannel heat sink. Applied Thermal Engineering, 31(5), 717–727. https://doi.org/10.1016/j.applthermaleng.2010.11.014

7. Ghani, U., Wazir, M. A., Akhtar, K., Wajib, M., & Shaukat, S. (2022). Microchannel heat sinks—A comprehensive review. *Electronic Materials*, *5*(4), 249–292. https://doi.org/10.3390/electronicmat5040017
8. Moreira, T. A., Moreira, D. C., & Ribatski, G. (2018). Nanofluids for heat transfer applications: A review. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *40*, 303. https://doi.org/10.1007/s40430-018-1225-2
9. Sarafraz, M. M., Hormozi, F., & Arjomandi, M. (2014). Thermal performance of a microchannel heat sink using silver-water nanofluid. *Applied Thermal Engineering*, *73*(1), 134–144. https://doi.org/10.1016/j.applthermaleng.2014.07.028
10. Azizi, M., & Sadeghi, S. E. (2016). Experimental investigation of thermal resistance reduction in microchannel heat sinks using CuO-water nanofluids. *Experimental Thermal and Fluid Science*, *78*, 254–262. https://doi.org/10.1016/j.expthermflusci.2016.06.017
11. Mesgarpour, M., & Dehghan, M. (2015). CFD analysis of ionic liquid-based nanofluids in microchannel heat sinks. *Heat and Mass Transfer*, *51*(10), 1325–1334. https://doi.org/10.1007/s00231-015-1490-2
12. Japar, W. M. A. A., Sidik, N. A. C., Saidur, R., Asako, Y., & Yusof, S. N. A. (2020). A review of passive methods in microchannel heat sink application through advanced geometric structure and nanofluids. *Nanotechnology Reviews*, *9*(1), 1192–1216. https://doi.org/10.1515/ntrev-2020-0094
13. Sidik, N. A. C., *et al.,* (2017). Passive heat transfer augmentation techniques in microchannel heat sinks: A review. *Renewable and Sustainable Energy Reviews*, *68*, 775–787. https://doi.org/10.1016/j.rser.2016.10.011
14. Tripathi, S. (2024). Study on emerging trends in thermal management of electric vehicles. *International Journal of Research Publication and Reviews*, *5*(10), 2657–2660. https://ijrpr.com/uploads/V5ISSUE10/IJRPR34126.pdf
15. Al-Baghdadi, M. A. R., Noor, Z. M. H., Zeiny, A., Burns, A., & Wen, D. (2020). *CFD analysis of a nanofluid-based microchannel heat sink*. Thermal Science and Engineering Progress, 20, 100685.
16. Manay, E., Sahin, B., Yilmaz, M., & Gelis, K. (2020). *Thermal performance analysis of nanofluids in microchannel heat sinks*. Bayburt University Mechanical Engineering Reports.
17. Strandberg, R., Ray, D., & Das, D. (2020). *Microchannel cooling performance evaluation of Al_2O_3, SiO_2, CuO nanofluids using CFD*. Heat and Mass Transfer Research Journal, 4(1), 1–12.

Cite This Article: Sagar Deshmukh (2024). Study on Heat Transfer Enhancement in Microchannel Heat Sinks Using Nanofluids: Experimental and CFD Approaches for Advanced Thermal Management. *East African Scholars J Eng Comput Sci, 6*(9), 140-146.