

Nanofluid-Enhanced Biomimetic Liquid-Cooled Heat Sinks for Efficient Thermal Management Applications

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ABSTRACT

The escalating demand for compact, high-performance electronic devices, driven by the rapid advancement of artificial intelligence, electric vehicles, and data-intensive technologies, has imposed significant thermal management challenges. Traditional air-cooled and straight-channel liquid cooling systems are increasingly inadequate in addressing the high heat fluxes generated by these technologies, particularly when operating under space, energy, and sustainability constraints. This thesis addresses the urgent need for efficient, scalable, and adaptive cooling solutions through the experimental development and evaluation of novel biomimetic liquid-cooled heat sink designs integrated with nanofluid technology.

This research adopts an interdisciplinary approach, combining thermofluids, materials science, and biomimetic design. It introduces a new concept in heat sink design inspired by the fluid dynamics of aquatic organisms such as tuna and the black ghost knifefish, novel heat sink designs were conceived to optimise flow dynamics, reduce pressure loss, and maximise heat transfer. These designs depart from traditional linear geometries, encouraging researchers to view nature as a blueprint for rethinking engineering solutions. The bioinspired hybrid pin-fin geometries were designed, fabricated, and optimised under varying operating conditions. The final optimised Staggered Arranged Airfoil Integrated Split Corrugated Curvilinear Pin-Fin (SAISCCPF) configuration create secondary flow paths, enhance mixing, and promote turbulence, thereby improving heat transfer performance while providing alternative passages in case of channel blockage.

A series of quantitative, experimental investigations were carried out to examine the hydrothermal performance of different heat sink configurations under varying Reynolds numbers and heating powers. The study began with straight-channel and inline pin-fin configurations, then advanced to staggered and split-fin biomimetic designs. Using a custom-built test facility, the experiments evaluated key performance parameters including Nusselt number, pressure drop, wall temperature, thermal resistance, and temperature distribution. The experimental methodology was rigorously validated, and data was collected across a broad range of flow rates and thermal loads to ensure robustness and repeatability.

Parallel to the heat sink design investigations, this work also involved the formulation and testing of mono, binary, and tri-hybrid nanofluids. These nanofluids were based on carefully selected nanoparticles include metallic (silver, Ag), ceramic (aluminium nitride, AlN; silicon carbide, SiC; beryllium oxide, BeO), and carbon-based (multi-walled carbon nanotubes, MWCNTs) materials, each chosen for their unique combination of thermophysical properties, particle morphology, cost, and chemical compatibility with water. The nanofluids were prepared using a two-step method involving ultrasonication and surfactant-assisted dispersion to ensure long-term colloidal stability and avoid agglomeration, a critical factor for maintaining consistent thermal and hydraulic performance.

The research was structured into two phases. In the first phase, mono and hybrid nanofluids based on Ag, BeO, and SiC were synthesised and tested. Among these, Ag-based nanofluids delivered the highest

thermal conductivity improvement of approximately 6.95%, while BeO offered minimal viscosity increase, and SiC provided a cost-effective compromise. Hybrid nanofluids such as Ag–SiC (60:40) achieved conductivity gains up to 7.43% with balanced hydraulic performance. A subsequent study focused on nanofluids containing MWCNTs, Ag, and AlN. While MWCNTs exhibited superior heat transfer capability, they suffered from stability issues. Tri-hybrid nanofluid MWCNTs/Ag/AlN, particularly the formulations 20:40:40 and 20:60:20, demonstrated an optimal combination of high thermal conductivity, suspension stability, and manageable viscosity, emerging as the most promising formulation. Phase II involved experimental thermal-hydraulic evaluation of the nanofluids developed in Phase I, applied across novel biomimetic heat sink designs. The phase began by testing a conventional straight-channel heat sink with a hydrophobic-coated surface using water. While the hydrophobic treatment moderately reduce pressure drop, limitations remained in improving heat transfer. This was followed by a comparative study with the newly designed Airfoil Integrated Corrugated Curvilinear Pin-Fin (AICCPF) configuration. The results showed an approximately 103% improvement in Nusselt number, while the pressure drop also increased by around 37.5% compared to the straight-channel design.

These enhanced biomimetic configurations were then evaluated using Ag, BeO, and SiC nanofluids and their hybrids. Ag-based fluids once again demonstrated the best thermal performance, while BeO continued to show minimal flow resistance. Among hybrids, Ag–SiC mixtures sustained high Nusselt number enhancements with manageable pressure drop penalties, especially under the SAICCPF geometry.

In the final stage, the optimised heat sinks were tested using MWCNTs, Ag, and AlN nanofluids including mono, binary, and tri-hybrid formulations. The SAISCCPF configuration, coupled with the (20:60:20) tri-hybrid nanofluid, achieved the best overall performance with a Nusselt number enhancement of around 17% at 325 W. While the pressure drop increased modestly to approximately 475 Pa, this was justified by the substantial thermal gains and enhanced flow distribution. The design's multi-path structure and local swirl generation proved effective in maintaining particle suspension, reducing agglomeration, and maximising convective performance across all tested fluids and conditions.

This thesis contributes a foundational understanding of hybrid nanofluid behaviour in complex geometrical domains and provides robust experimental data to support future designs. Future research is encouraged to explore long-duration cyclic stability of these nanofluids under operational loads, adaptation of these concepts to dynamic cooling systems (e.g., thermosyphons, phase change materials (PCM), pulsating heat pipes), and full-scale prototyping in data centres, EV batteries, or power electronics environments.

Keywords: Heat Sink, Nanofluid, Thermal Management, Liquid Cooling, Thermofluids, Pressure Drop, Nusselt Number

List of Publication

The following is a comprehensive list of research outputs produced during the course of my PhD at the University of Hertfordshire. These works reflect the breadth of investigation undertaken across nanofluid development, biomimetic heat sink design, thermal–hydraulic performance analysis, and experimental validation. The research has contributed to a range of high-impact journals and international conferences, demonstrating both the scientific rigour and practical relevance of the investigations undertaken.

Journal Articles

- **Babar, H.**, Wu, H., Eltaweel, M., Zhang, W., (2025), Performance Evaluation of Nanofluid-Enhanced Biomimetic Liquid-Cooled Heat Sinks for Efficient Thermal Management Applications, *International Journal of Heat and Mass Transfer*, 127498. DOI: 10.1016/j.ijheatmasstransfer.2025.127498
- **Babar, H.**, Wu, H., Zhang, W., Asim, M., (2025), Synergistic approach to colloidal stability and thermophysical optimisation of multi-walled carbon nanotubes, aluminium nitride, and silver-based hybrid nanofluids, *Powder Technology*, 121348. DOI: 10.1016/j.powtec.2025.121348
- **Babar, H.**, Wu, H., Zhang, W., (2025), Experimental assessment of advanced biomimetic heat sink designs using hybrid nanofluids containing multi-walled carbon nanotubes, silver, and aluminium nitride, *Status: To be Submitted*.
- Harris, M., **Babar, H.**, & Wu, H. (2025). Assessing thermohydraulic performance in novel micro pin-fin heat sinks: A synergistic experimental, agile manufacturing, and machine learning approach. *International Journal of Heat and Mass Transfer*, 239, 126581. DOI: 10.1016/j.ijheatmasstransfer.2024.126581
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- **Babar, H.**, Wu, H., Zhang, W., Shah, T. R., McCluskey, D., & Zhou, C. (2024). The promise of nanofluids: A bibliometric journey through advanced heat transfer fluids in heat exchanger tubes. *Advances in Colloid and Interface Science*, 325, 103112. DOI: 10.1016/j.cis.2024.103112
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- **Babar, H.**, Wu, H., Ali, H.M., Shah, T.R., Zhang, W., (2022). Staggered oriented airfoil shaped pin-fin heat sink: Investigating the efficacy of novel water based ferric oxide-silica hybrid nanofluid. *International Journal of Heat and Mass Transfer*, 194, 123085. DOI: 10.1016/j.ijheatmasstransfer.2022.123085
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Conference Paper

- **Babar, H.**, Wu, H., Zhang, W., (2024), Investigating surfactant effects on stability and thermal properties of silicon carbide nanofluids, *Proceedings of the 10th International Symposium on Heat Transfer ISHT-10 July 7-10, 2020, Beijing, China.*
- **Babar, H.**, Wu, H., Zhang, W., (2025), Biomimetic liquid-cooled heat sink for efficient thermal management applications, *4th Journal of Thermal Analysis and Calorimetry Conference & 10th V4 (Joint Czech Hungarian-Polish-Slovak) Thermoanalytical Conference, 24–27 June, 2025, Budapest, Hungary.*
- Eltaweel, M., Heggy, A., **Babar, H.**, Abdel-Rehim, A.A, (2025), Optimization of nanofluid concentration and flow rate in evacuated tube solar collectors using anova: energy and exergy analysis, *4th Journal of Thermal Analysis and Calorimetry Conference & 10th V4 (Joint Czech Hungarian-Polish-Slovak) Thermoanalytical Conference, 24–27 June, 2025, Budapest, Hungary.*
- **Babar, H.**, Wu, H., Zhang, W., (2025), Bio-inspired flow channeling in liquid-cooled hybrid pin-fin heat sinks for compact cooling systems, *11th Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, 15–18 August, 2025, Beijing, China.*

Declaration of Authorship

I declare that this thesis, submitted to the University of Hertfordshire for the degree of Doctor of Philosophy, is my own work and has not been submitted for any other degree or professional qualification.

The work presented in this thesis includes material that has been published by the author, as outlined in the comprehensive list of publications provided. In addition to the published work, the author is currently preparing further articles based on this research, which will be submitted for publication in due course.

Where the work of others has been used or referenced, it has been clearly acknowledged and appropriately cited. Collaborative research and contributions from co-authors in published or submitted work are duly credited, and my individual contribution to these works is fully detailed in the relevant sections of the thesis.

I confirm that this work complies with the University's policies on academic integrity and ethical standards.

Signed: Hamza Babar

Name: Hamza Babar

Date: 04/07/2025

Reader's Guide and Statement

The author has made every effort to ensure that the research presented in this thesis is comprehensive, clearly articulated, and supported by in-depth discussion, methodological rigour, and critical analysis. This body of work reflects several years of sustained investigation into advanced thermal management systems and nanofluid applications. It is the author's sincere hope that the findings, frameworks, and concepts explored herein will not only support ongoing research but also stimulate innovative thinking and new lines of inquiry within and beyond this domain.

To maintain consistency and continuity across the document, certain foundational concepts and methodological explanations are intentionally revisited at relevant points throughout the chapters. This repetition has been thoughtfully employed to aid understanding and allow each chapter to stand on its own. Given the multidisciplinary nature of the thesis, which is composed of several interrelated but distinct studies, the structure is designed so that readers interested in a specific section or application area can engage with that content directly, without needing to read the entire thesis linearly. Where appropriate, cross-references have been provided to guide readers to foundational discussions or related methodologies.

Researchers and investigators aiming to reproduce the experimental results or adopt the proposed designs are encouraged to follow the described procedures as closely as possible. The experimental setups, preparation methods, operating conditions, and analysis techniques have all been documented in detail to facilitate repeatability and transparency. It is recommended to adhere to the same methodology to ensure consistency and comparability in outcomes.

Readers from all backgrounds students, academics, industrial practitioners, or technology enthusiasts are warmly invited to explore the presented research, reflect on its implications, and engage in dialogue. The author welcomes inquiries, collaboration opportunities, and interdisciplinary knowledge exchange that contribute meaningfully to the scientific, educational, or societal advancement.

Preface

The motivation for this work stemmed from the growing demand for efficient and sustainable cooling solutions across a range of industries from data centres and microprocessors to electric vehicles and renewable energy systems. As modern devices become more powerful and compact, the burden on thermal management systems continues to intensify. This thesis contributes to this evolving field through a combination of comprehensive experimental studies, rigorous data analysis, and interdisciplinary design approaches. The research also brings together concepts from thermofluids, materials science, and biomimicry, presenting integrated solutions that have been developed and validated through carefully designed test campaigns.

The journey that led to this thesis began with a simple yet powerful observation: nature, through millions of years of evolution, has already solved many of the engineering challenges we face today. Among the most fascinating of these are the efficient flow mechanisms found in fast-swimming aquatic species such as the tuna fish and the black ghost knifefish. This study embraces that perspective, translating biological movement and flow dynamics into engineered geometries for liquid-cooled heat sinks.

What sets this work apart is the way it reframes the conventional understanding of fluid dynamics within thermal systems. Inspired by the internal and external flow dynamics of fast-swimming aquatic organisms such as the tuna fish and black ghost knifefish, the heat sink geometries introduced here translate natural flow mechanisms into practical engineering designs. These configurations rooted in the way these creatures channel fluid through and around their streamlined bodies have demonstrated significant improvements in heat transfer, flow distribution, and pressure regulation.

This study arrives at a crucial time, as artificial intelligence, edge computing, and compact high-performance electronics continue to demand more efficient thermal management in smaller form factors. By integrating biomimetic geometry with nanofluid-enhanced cooling techniques, the research proposes a new direction for designing scalable and high-efficiency thermal systems.

Beyond technical performance, the value of this study lies in its ability to encourage researchers to look at nature with a different lens, not just as a source of inspiration but as a source of solutions. The designs explored here may seem unconventional at first glance, but they challenge the status quo and expand the creative boundaries of what thermal management systems can be.

It is the author's hope that this thesis not only contributes to the academic discourse but also sparks new ideas, collaborative endeavours, and innovations across engineering disciplines. The future of thermal systems lies in interdisciplinary thinking, and this work is a step in that direction.

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This acknowledgement is dedicated not only to those who directly contributed to the completion of this thesis but also to those who raised me, nurtured my values, and have been unwavering in their support throughout my life—my parents, teachers, mentors, and friends.

I come from Harappa, a small city in Pakistan, where educational opportunities and resources are limited. Despite these constraints, my parents devoted themselves wholeheartedly to ensuring I received the best possible education. First and foremost, I would like to express my deepest gratitude to my father, Mr. Zaheer Babar, and my Mother, whose unconditional love and sacrifices are the foundation of my achievements. Although my mother is not formally educated and may not fully understand what a PhD entails, her support has been more powerful than any degree or title in the world.

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My educational path began in my hometown schools, where I was fortunate to be taught by inspiring teachers like Mr. Ghulam Sarwar Ansari, who instilled in us not just knowledge but values. I am grateful to Mr Gul Muhammad, Hafiz Manzoor Ahmed, Mr Mazhar Fareed, and many others who guided us with wisdom and kindness. I extend special appreciation to Dr Abubaker and Dr Hafiz Muhammad Ali, who not only supervised me during my undergraduate and master's studies but also served as lifelong mentors.

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Nomenclature

Abbreviations

<i>AFM</i>	<i>Atomic Force Microscopy</i>
<i>AI</i>	<i>Artificial Intelligence</i>
<i>AICCPF</i>	<i>Airfoil Integrated Corrugated Curvilinear Pin-Fin</i>
<i>ANOVA</i>	<i>Analysis of Variance</i>
<i>CF</i>	<i>Circulating Fluid</i>
<i>CFD</i>	<i>Computational Fluid Dynamics</i>
<i>CPU</i>	<i>Central Processing Unit</i>
<i>CS</i>	<i>Conventional Surface</i>
<i>CTAB</i>	<i>Cetyltrimethylammonium Bromide</i>
<i>DLS</i>	<i>Dynamic Light Scattering</i>
<i>DSC</i>	<i>Differential Scanning Calorimetry</i>
<i>DW</i>	<i>Distilled Water</i>
<i>EDX</i>	<i>Energy Dispersive X-ray Spectroscopy</i>
<i>EV</i>	<i>Electric Vehicle</i>
<i>GA</i>	<i>Gum Arabic</i>
<i>GO</i>	<i>Graphene Oxide</i>
<i>HPC</i>	<i>High-Performance Computing</i>
<i>HS</i>	<i>Hydrophobic Surface</i>
<i>IACPF</i>	<i>Inline Arranged Airfoil Integrated Curvilinear Pin-Fin</i>
<i>ICP</i>	<i>Inductively Coupled Plasma</i>
<i>IR</i>	<i>Infrared</i>
<i>JCPDS</i>	<i>Joint Committee on Powder Diffraction Standards</i>
<i>LMTD</i>	<i>Logarithmic Mean Temperature Difference</i>
<i>LVGs</i>	<i>Longitudinal Vortex Generators</i>
<i>MAE</i>	<i>Mean Absolute Error</i>
<i>MCHS</i>	<i>Microchannel Heat Sink</i>
<i>MD</i>	<i>Molecular Dynamics</i>
<i>MWCNT</i>	<i>Multi-Walled Carbon Nanotube</i>
<i>NACA</i>	<i>National Advisory Committee for Aeronautics</i>
<i>NIST</i>	<i>National Institute of Standards and Technology</i>
<i>Nu</i>	<i>Nusselt Number</i>
<i>PD</i>	<i>Pressure Drop</i>
<i>PEC</i>	<i>Performance Evaluation Criterion</i>

<i>PER</i>	<i>Performance Enhancement Ratio</i>
<i>PG</i>	<i>Propylene Glycol</i>
<i>PIV</i>	<i>Particle Image Velocimetry</i>
<i>PP</i>	<i>Pumping Power</i>
<i>PRESS</i>	<i>Predicted Residual Error Sum of Squares</i>
<i>PVT</i>	<i>Photovoltaic-Thermal</i>
<i>Re</i>	<i>Reynolds Number</i>
<i>SAICCPF</i>	<i>Staggered Airfoil Integrated Corrugated Curvilinear Pin-Fin</i>
<i>SAISCCPF</i>	<i>Staggered Airfoil Integrated Split Corrugated Curvilinear Pin-Fin</i>
<i>SDBS</i>	<i>Sodium Dodecylbenzene Sulfonate</i>
<i>SDS</i>	<i>Sodium Dodecyl Sulfate</i>
<i>SEM</i>	<i>Scanning Electron Microscopy</i>
<i>TDP</i>	<i>Thermal Design Power</i>
<i>TEM</i>	<i>Transmission Electron Microscopy</i>
<i>TGA</i>	<i>Thermogravimetric Analysis</i>
<i>TPS</i>	<i>Transient Plane Source technique</i>
<i>UV</i>	<i>Ultraviolet</i>
<i>WOS</i>	<i>Without surfactant</i>
<i>XRD</i>	<i>X-ray Diffraction</i>

Chemical Formulas

<i>Ag</i>	<i>Silver</i>
<i>AlN</i>	<i>Aluminium Nitride</i>
<i>Al₂O₃</i>	<i>Aluminium Oxide</i>
<i>BeO</i>	<i>Beryllium Oxide</i>
<i>CNT</i>	<i>Carbon Nanotube</i>
<i>CuO</i>	<i>Copper Oxide</i>
<i>Fe₂O₃</i>	<i>Ferric Oxide</i>
<i>GO</i>	<i>Graphene Oxide</i>
<i>MgO</i>	<i>Magnesium Oxide</i>
<i>MWCNT</i>	<i>Multi-Walled Carbon Nanotube</i>
<i>SiC</i>	<i>Silicon Carbide</i>
<i>SiO₂</i>	<i>Silicon Dioxide</i>
<i>TiO₂</i>	<i>Titanium Dioxide</i>
<i>ZnO</i>	<i>Zinc Oxide</i>

<i>Symbols</i>	
$A_{fin,top}$	<i>Top surface area of the fin (m²)</i>
A_{seff}	<i>Effective convection area (m²)</i>
A_{avg}	<i>Average cross-sectional area (m²)</i>
A_w	<i>Wall surface area (m²)</i>
C_p	<i>Specific heat capacity of the fluid (J/kg·K)</i>
d_h	<i>Hydraulic diameter (m)</i>
f	<i>Darcy friction factor</i>
H	<i>Height (m)</i>
k_c	<i>Thermal conductivity of coolant (W/m·K)</i>
k_s	<i>Thermal conductivity of solid (heat sink) material (W/m·K)</i>
L	<i>Length (m)</i>
$L_{a,fin}$	<i>Active length of airfoil fin (m)</i>
L_s, W_s	<i>Length and width of heat sink base (m)</i>
$\dot{m}$	<i>Mass flow rate (kg/s)</i>
M	<i>Molecular Weight</i>
N	<i>Avogadro's Number</i>
Nu	<i>Nusselt number</i>
P_f	<i>Effective fin perimeter (m)</i>
PP	<i>Pumping power (W)</i>
q	<i>Volumetric flow rate (m³/s)</i>
$\dot{Q}$	<i>Heat transfer rate (m³/s)</i>
Re	<i>Reynolds number</i>
R_{th}	<i>Thermal resistance (K/W)</i>
S_{sec}	<i>Wetted perimeter/side surface area of flow section (m²)</i>
T_{inlet}	<i>Fluid inlet temperature (°C or K)</i>
T_{outlet}	<i>Fluid outlet temperature (°C or K)</i>
T_{mean}	<i>Mean bulk temperature of the fluid (°C or K)</i>
T_w	<i>Wall temperature (°C or K)</i>
T_b	<i>Base temperature of the heat sink (°C or K)</i>
v	<i>Average fluid velocity (m/s)</i>
V_{sec}	<i>Volume of flow section (m³)</i>
ΔP	<i>Pressure drop (Pa)</i>
l_x	<i>Distance from base to channel wall (m)</i>
$LMTD$	<i>Log mean temperature difference (°C or K)</i>

<i>Greek Letter</i>	
ρ	<i>Density [kg/m³]</i>
μ	<i>Dynamic viscosity (Pa · s)</i>
λ	<i>Wavelength of the X-rays</i>
θ	<i>Bragg angle</i>
<i>Subscripts</i>	
<i>b</i>	<i>Base</i>
<i>bf</i>	<i>Base fluid</i>
<i>c</i>	<i>Coolant</i>
<i>hnf</i>	<i>Hybrid nanofluid</i>
<i>I</i>	<i>Inlet</i>
<i>m</i>	<i>Mean</i>
<i>nf</i>	<i>Nanofluid</i>
<i>np</i>	<i>Nanoparticle</i>
<i>o</i>	<i>Outlet</i>
<i>p</i>	<i>Particle</i>
<i>s</i>	<i>Heat sink</i>
<i>w</i>	<i>Wall</i>

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CHAPTER 1

1 Introduction

1.1 Motivation

Technological advancements continue to demand increasingly compact and high-performance electronic devices, which present major challenges in thermal management. Designing an efficient heat sink within the spatial constraints of modern systems is a daunting task. Industries such as electronics, automotive, energy, robotics, medical, and manufacturing all involve devices that generate considerable heat during operation. Inefficient heat dissipation can not only degrade performance but also cause permanent damage in severe cases.

The miniaturisation trend in electronics, combined with higher power densities and intensified computing tasks (e.g., artificial intelligence, blockchain processing, and edge computing), has exponentially increased heat generation per unit area. A recent study revealed that thermal management alone accounts for approximately 33% of the total electricity consumed in global data centres [1]. In the European Union alone, data centres consumed between 45–65 TWh of electricity in 2022, equivalent to 1.8–2.6% of the total regional electricity use, and this figure is expected to increase with the proliferation of digital services and artificial intelligence workloads [2].

Thermal stress is widely recognised as a major contributor to the degradation of electronic components. It is estimated that for every 2 °C increase in temperature beyond the safe temperature threshold, the reliability of silicon-based semiconductor devices can decline by approximately 10%, significantly shortening their operational lifespan and increasing the risk of premature failure. In fact, temperature rise is the major cause of electronic components failure which accounts for 55% compared to the other factors like vibration, humidity, and dust, each of which accounts for 20%, 19%, and 6%, respectively [3], as shown in Fig. 1.1.

Recent industrial trends further highlight the urgency and industrial relevance of improving thermal management technologies. According to Omdia's 2024 analysis report, the global data centre cooling market reached \$7.7 billion in 2023, reflecting a 26% year-over-year growth [4]. This surge is largely attributed to the proliferation of AI applications and the consequent need for efficient thermal solutions. Within this growth, the liquid cooling segment alone is nearing a \$1 billion valuation, emphasising its critical role in next-generation data infrastructure.

One of the most prominent technological trends identified in the report is the 65% year-over-year increase in adoption of Rear Door Heat Exchangers (RDHx) in combination with single-phase (1-P) direct-to-chip liquid cooling. These systems not only offer improved thermal regulation but also enable heat reuse, contributing directly to sustainability and energy efficiency goals. The accelerated

deployment of these technologies illustrates a fundamental shift in how industries approach thermal management not just as a means of maintaining device reliability, but as a strategic tool to reduce environmental impact and operational energy costs.

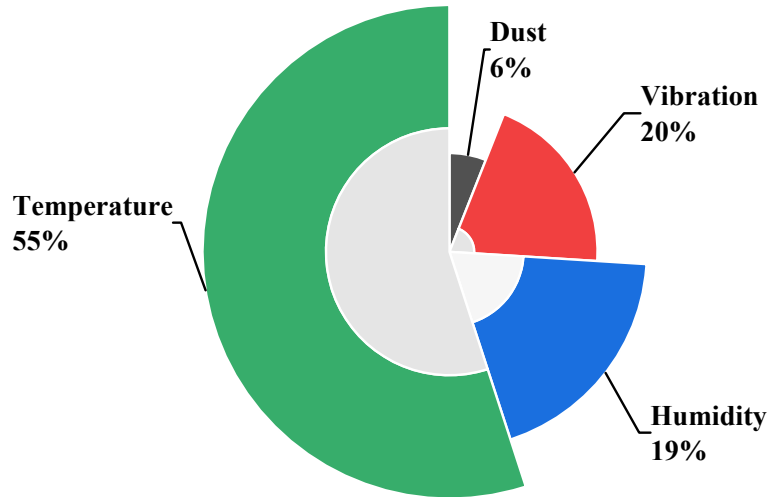


Figure 1.1. Factors account majorly for electronic component failure.

1.1.1 Limitations of Conventional Cooling Approaches

Traditionally, air-cooling systems have been the mainstream choice for thermal regulation due to their simplicity and low cost. However, air-based systems are increasingly incapable of meeting the demands of today's high-power, high-density electronic environments. Their inherently low heat transfer coefficient restricts heat removal efficiency, especially when dealing with compact, confined geometries. A real-world example that highlights the inadequacy of conventional air-based cooling solutions is the discontinuation of the Boxed Intel® Xeon® E-2274G processor. According to Intel's Product Change Notification (PCN #117255-00), the processor was withdrawn from the market in 2019 due to the failure of the included stock cooling fan (DHA-A heatsink, PN# E97378-003) to meet thermal performance requirements. The heat sink's inability to dissipate heat effectively under load conditions led to thermal throttling and potential reliability concerns. Intel consequently replaced the boxed version with a tray processor alternative and advised customers to source custom cooling solutions. This case underscores the limitations of mass-produced, generic air-cooling systems in meeting the demands of high-performance computing environments.

In contrast, liquid cooling, particularly single-phase cooling techniques, offers significantly improved performance due to the superior heat capacity and thermal conductivity of liquids. These systems have proven effective in handling high heat fluxes and ensuring uniform temperature distribution [5,6]. Notably, according to the Data Centre Frontier Liquid Cooling Technology Transition Report, a staggering 93% of surveyed organizations are now engaging with direct-to-chip liquid cooling either through pilot programs or full-scale deployment while only 7% report no current adoption plans [7].

This statistic underscores a significant transformation within the data centre industry, driven by the need to handle growing processor power densities, optimise energy use, and maintain system reliability under high computational loads.

Most of the studies conducted on heat sinks have focused on reducing the core temperature improving heat transfer. However, it is also crucial to keep the pressure drop to a minimum, resulting in a low pumping power requirement. Along with the rate of heat transfer, the pressure drop is also a significant factor that needs to be considered to develop an optimum design of the heat sink. Nowadays various geometrical configurations of heat sinks have been examined [8]. It was revealed that with a considerable improvement in heat transfer pressure drop elevated significantly as the fins resist fluid flow. Thus, a slight increase in heat transfer at the expense of excessive pumping power is undesirable. A well-designed heat sink must optimise both parameters to achieve sustainable and practical thermal management.

1.1.2 Emergence of Nanofluids and Biomimetic Designs

To overcome these challenges, researchers are increasingly exploring the use of nanofluids—engineered suspensions of nanoparticles in conventional base fluids. These nanofluids demonstrate significantly enhanced thermophysical properties, including improved thermal conductivity, specific heat, and viscosity. As a result, they enable better convective heat transfer, particularly in microchannel and compact heat exchanger applications.

In addition to fluid enhancement, biomimetic heat sink designs are gaining traction due to their ability to replicate the efficiency of natural systems. For instance, the branched structures in leaves, vascular networks in animals, and gill formations in aquatic organisms exhibit highly efficient heat and mass transfer characteristics. These bio-inspired geometries are being translated into engineered systems to improve fluid distribution, reduce pressure losses, and maximise heat exchange surface areas.

The combination of nanofluids and biomimetic geometries represents a cutting-edge approach to thermal management. Such hybrid systems have the potential to deliver high thermal performance at low energy cost, making them ideal candidates for applications in data centres, electric vehicles, wearable electronics, and space-limited military systems.

1.1.3 Socio-Technical and Environmental Relevance

The demand for efficient thermal management systems extends far beyond traditional electronics and IT infrastructure. In recent years, the scope of this challenge has grown to encompass a broad array of high-impact sectors, each of which plays a vital role in global energy consumption, environmental sustainability, and socio-economic transformation.

According to the International Energy Agency (IEA), global electricity consumption by data centres reached between 240–340 TWh in 2022, representing a substantial share of the world's electricity

demand and contributing significantly to greenhouse gas emissions depending on the energy mix of the source grid [9]. This figure is expected to grow further due to the proliferation of data-intensive services such as cloud computing, streaming platforms, artificial intelligence (AI), and blockchain technologies. In particular, AI-driven workloads have been shown to increase data centre energy intensity due to the need for high-performance GPUs and inference engines that operate continuously and require advanced thermal regulation. As such, even incremental improvements in thermal management technologies within data centres can result in measurable reductions in electricity use and emissions.

In parallel, the automotive industry particularly the electric vehicle (EV) sector has emerged as another critical domain where effective thermal management has become indispensable. As reported by the IEA, the global stock of EVs surpassed 10 million units in 2022, a significant leap from just 3 million in 2019, marking a compound annual growth rate (CAGR) of over 45% in a short period [10]. This rapid adoption has brought heightened attention to thermal regulation in EV battery packs, inverters, motors, and onboard chargers. Poor thermal control in EVs can lead to accelerated battery degradation, reduced charging efficiency, and safety hazards such as thermal runaway. Consequently, vehicle manufacturers are increasingly investing in advanced liquid-cooled systems and phase-change materials to manage heat loads across different driving conditions.

Furthermore, modern EV architectures specifically those designed for fast charging and long-range travel generate high heat fluxes comparable to data centre processors. The development of compact, energy-efficient, and scalable thermal solutions for EVs is thus essential not only for ensuring performance and user safety but also for enabling mass-market adoption. In this context, nanofluid-enhanced liquid cooling and biomimetic channel designs have begun attracting attention due to their ability to provide superior heat transfer capabilities with minimal pumping power.

Beyond the confines of the automotive and ICT sectors, other energy-intensive applications such as aerospace, industrial automation, power electronics, and renewable energy systems (e.g., concentrated solar and wind power converters) also demand robust and lightweight thermal management solutions. In aerospace, for instance, weight constraints and exposure to extreme temperatures necessitate the use of highly efficient and compact heat sinks. Similarly, wind and solar inverters are subject to frequent thermal cycling and harsh environmental conditions, which can compromise performance if heat is not effectively dissipated.

Improving thermal management efficiency directly supports international climate goals, such as those outlined in the EU Green Deal, which aims to make Europe the first climate-neutral continent by 2050 through enhanced energy efficiency, reduced greenhouse gas emissions, and clean industrial innovation [11]. Enhancing the performance of cooling systems in sectors like data centres, electric vehicles, and industrial electronics contributes to this objective by lowering electricity demand and minimizing waste heat. Similarly, under the Paris Agreement, countries are committed to limiting global temperature rise to well below 2 °C above pre-industrial levels, with efforts to constrain it to 1.5 °C [12]. Reducing energy consumption in thermal management directly decreases fossil fuel dependency and carbon

emissions, thus supporting signatory nations in achieving their nationally determined contributions (NDCs). Regarding this, the United Kingdom has committed to a legally binding target of achieving net-zero emissions by 2050, under the revised Climate Change Act [13]. The UK government emphasises the need for decarbonization across digital infrastructure, transport, and manufacturing. With the continued growth of energy-intensive sectors such as data processing and electric mobility, advanced thermal management technologies are vital to reduce peak electricity loads and enhance system efficiency.

Moreover, from a policy standpoint, improving the efficiency of cooling systems contributes to several of the United Nations Sustainable Development Goals (SDGs). It aligns with SDG 7 (Affordable and Clean Energy) by reducing the energy intensity of industrial systems, SDG 9 (Industry, Innovation, and Infrastructure) by promoting resilient and sustainable infrastructure, and SDG 13 (Climate Action) by mitigating the emissions footprint of high-energy sectors.

In summary, the development of high-performance, low-energy thermal management systems is not merely a technical optimisation problem, but a strategic imperative that intersects with climate policy, economic growth, urban planning, and sustainable mobility. By integrating nanofluid technology with biomimetic design principles, this research aims to contribute to scalable and environmentally responsible solutions that support the ongoing transition toward a digital, electrified, and low-carbon global economy.

1.2 Study Plan

The current study was undertaken to address the growing challenges associated with the effective and scalable cooling solutions capable of dissipating significant amounts of heat, particularly from compact and high-performance electronic devices. To this end, the research systematically investigated the hydrothermal performance of biomimetic heat sinks integrated with various advanced nanofluids. The entire project was guided by a phased, methodical plan that evolved based on findings, resource availability, and technical feasibility.

The first phase of the study involved a comprehensive and critical literature review of state-of-the-art cooling technologies. The intention was not only to identify research gaps but also to contribute to the academic community through a scholarly review article that synthesised global advancements in the field of compact thermal management systems. This review served as a foundational basis for the subsequent experimental work.

Following the literature review, the design and fabrication of innovative biomimetic heat sinks were carried out using CAD tools such as SolidWorks. Drawing inspiration from the fluidic architecture of aquatic respiration systems where water not only flows around the body but also passes through internal channels, entering via the mouth, facilitating gas exchange, and exiting through opercular flap openings, multiple heat sink configurations were designed. These bio-inspired geometries were aimed at enhancing fluid interaction, promoting effective heat dissipation, and minimising flow resistance within

compact cooling domains. The streamlined body shapes of efficient swimmers such as tuna and the black ghost knifefish further informed the design strategy, aiming to replicate their low-drag characteristics in engineered flow pathways. Finally, these designs were manufactured in collaboration with technical staff and tested for dimensional accuracy and robustness.

A custom experimental test rig was developed to evaluate the cooling performance and hydraulic behaviour of the fabricated heat sinks under a range of thermal loads. The setup was designed with flexibility in mind, allowing the testing of heat sinks of various sizes and geometries suitable for different applications. It also allows testing under varying flow rates and heating powers, thereby enabling comprehensive performance analysis under diverse operating conditions. After careful calibration, a series of extensive experimental trials were conducted to determine key performance indicators such as the heat transfer coefficient, Nusselt number, thermal resistance, and pressure drop for different nanofluid types and heat sink configuration. To ensure the reliability and accuracy of the experimental data, the test rig was validated using three complementary approaches. First, computational fluid dynamics (CFD) simulations were performed on a straight-channel heat sink, and the simulation results were compared against the experimental measurements under varying flow rates and heating powers. Second, the experimentally obtained Nusselt number values were compared with theoretical predictions using well-established empirical correlations from the literature. Finally, a comparison was made between the present results and previously published experimental data to confirm consistency and accuracy. This multi-level validation process reinforced the credibility of the test rig, and the experimental outcomes derived from it.

In parallel with the hardware development, nanofluids were synthesised using a well-established two-step method. Multiple categories of nanofluids were prepared, including mono, hybrid, and tri-hybrid formulations. Characterization of nanoparticles was undertaken using advanced tools such as X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and zeta potential analysis to assess dispersion quality and detect agglomeration. The stability of the synthesised nanofluids was monitored over time, with particular attention paid to the effects of surfactants and nanoparticle loading on the pH levels of the formulations. Thermophysical properties such as thermal conductivity, density, and viscosity were experimentally measured using a thermal property analyser, a density meter, and a viscometer, respectively. These measurements were conducted across a range of temperatures and particle concentrations. Based on the acquired data, statistical models were developed to characterise and predict the behaviour of these properties as functions of temperature, nanoparticle concentration, and, in the case of hybrid samples, the mixing ratio of constituent nanoparticles.

Additionally, a novel investigation into the impact of hydrophobic surface coatings was conducted using 303 graphene nanocoating. This coating had not previously been tested in this context and was applied to evaluate its influence on wettability, pressure drop, and potential bubble entrapment issues within the microchannels.

Throughout the project, data reduction, analysis, and interpretation were continuously performed. The findings were consolidated to compare the performance of various coolants and heat sink designs. These insights not only informed conclusions within this thesis but also formed the basis of several peer-reviewed publications and conference presentations. Figure 1.2 illustrates the overall research workflow, detailing the sequential progression from the initial literature review and procurement of materials, through the design, synthesis, and experimental validation phases, culminating in data analysis, publication, and the final thesis compilation.

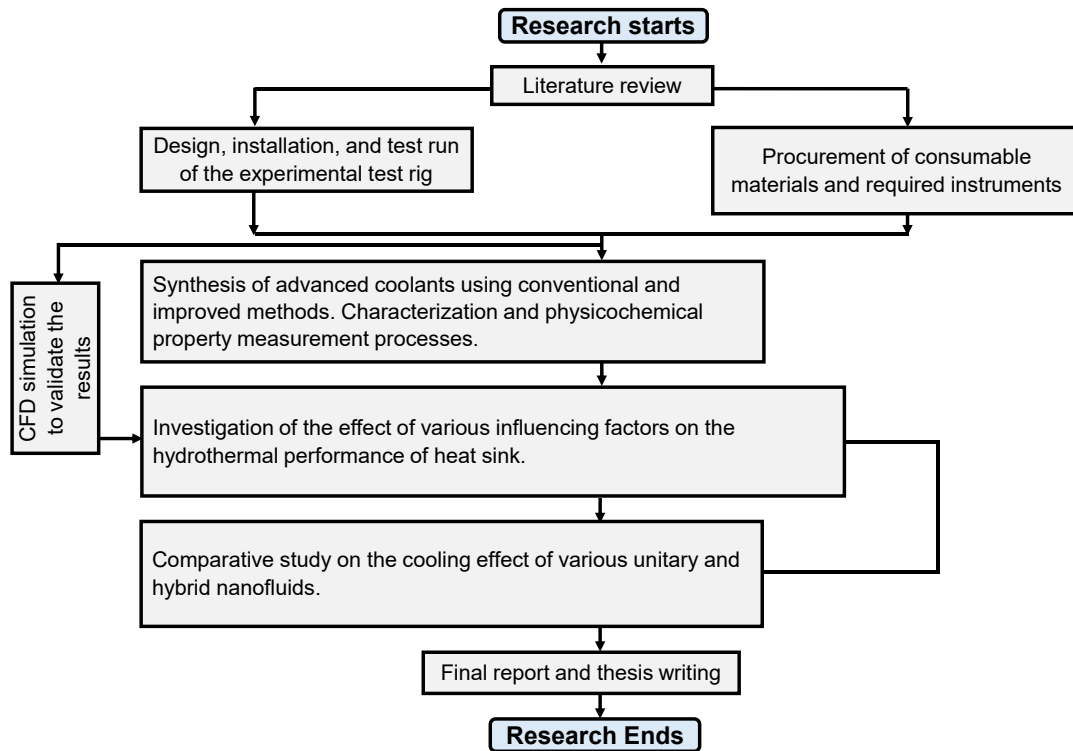


Figure 1.2. Structured layout of the experimental and analytical study plan outlining the sequential phases and key components of the research methodology.

1.2.1 Overview of Experimental Strategy

Following the comprehensive literature review, the fabrication of experimental test rig, and the selection of suitable nanoparticles for nanofluid synthesis, the experimental phase of this research was systematically planned and executed in a series of interrelated studies. Each study was designed to incrementally contribute to a deeper understanding of nanofluid behaviour, heat sink performance, and the interplay between coolant properties and geometry. The experimental campaign was divided into six major investigations, as detailed below, however, a schematic overview of these experimental stages is presented in Fig. 1.3.

- The initial study focused on investigating the thermophysical behaviour of mono and hybrid nanofluids formulated using silver (Ag), beryllium oxide (BeO), and silicon carbide (SiC) nanoparticles. These fluids were studied over a temperature range of 15–45 °C to evaluate their

thermal conductivity, density, and viscosity. Hybrid nanofluids were prepared in varying volumetric ratios of 20:80, 40:60, 60:40, and 80:20 to assess the influence of composition on thermal performance. Additionally, the role of different surfactants in enhancing colloidal stability and thermal characteristics was examined. Particle morphology and structure were characterised using SEM, TEM, and XRD, while suspension stability was analysed via Malvern Zetasizer measurements.

- The second study extended the investigation to hybrid and tri-hybrid nanofluids composed of multi-walled carbon nanotubes (MWCNTs), silver (Ag), and aluminium nitride (AlN). This phase aimed to explore the impact of volumetric ratios and surfactant type on colloidal stability, thermal performance, and cost-effectiveness. Various formulations were prepared using ratios of 80:20, 60:40, 40:60, and 20:80 for hybrid mixtures, and 20/20/60, 20/40/40, and 20/60/20 for tri-hybrid combinations. Thermophysical properties were measured across the temperature range of 20–45 °C. Surfactants including sodium dodecyl sulfate (SDS), cetyltrimethylammonium bromide (CTAB), gum arabic (GA), and sodium dodecyl benzene sulfonate (SDBS) were evaluated for their effectiveness in maintaining suspension stability. Among these, SDBS consistently demonstrated superior performance in sustaining particle dispersion and preserving thermal enhancement over time.
- The third study served a dual purpose: validating the experimental test rig and assessing the performance of a baseline straight-channel heat sink. The test rig was validated through comparison with classical Nusselt number models and recent experimental data from the literature, as well as by benchmarking against CFD simulations of the same configuration.
- In the fourth phase, two innovative biomimetic heat sink designs were experimentally evaluated: the Inline Arranged Airfoil-Integrated Curvilinear Pin-Fin Heat Sink (Configuration 1) and the Inline Arranged Airfoil-Integrated Corrugated Curvilinear Pin-Fin Heat Sink (Configuration 2). These geometries were tested to compare their hydrothermal performance under similar boundary conditions. The nanofluids synthesised in Study 1 were utilised to assess the impact of coolant type on Nusselt number enhancement and pressure drop characteristics in both configurations.
- The fifth study focused on the influence of pin-fin arrangement on the heat sink's thermal-hydraulic performance. Two variants were considered: the inline-arranged Configuration 2 and the staggered-arranged Airfoil-Integrated Corrugated Curvilinear Pin-Fin Heat Sink (Configuration 3). The effect of distributing fins in an inline versus staggered manner was systematically investigated to understand changes in flow mixing, pressure drop, and heat transfer enhancement.
- The final study compared Configuration 3 with a further modified geometry: the Staggered Arranged Airfoil-Integrated Split Corrugated Curvilinear Pin-Fin Heat Sink (Configuration 4). This design introduced discontinuities (splits) within the pin-fins to induce localised mixing and secondary flows. The resulting improvement in fluid mixing was expected to augment convective

heat transfer. In this phase, the hybrid and tri-hybrid nanofluids developed in Study 2 were employed to assess their potential in enhancing the thermal performance of the modified heat sink geometry.

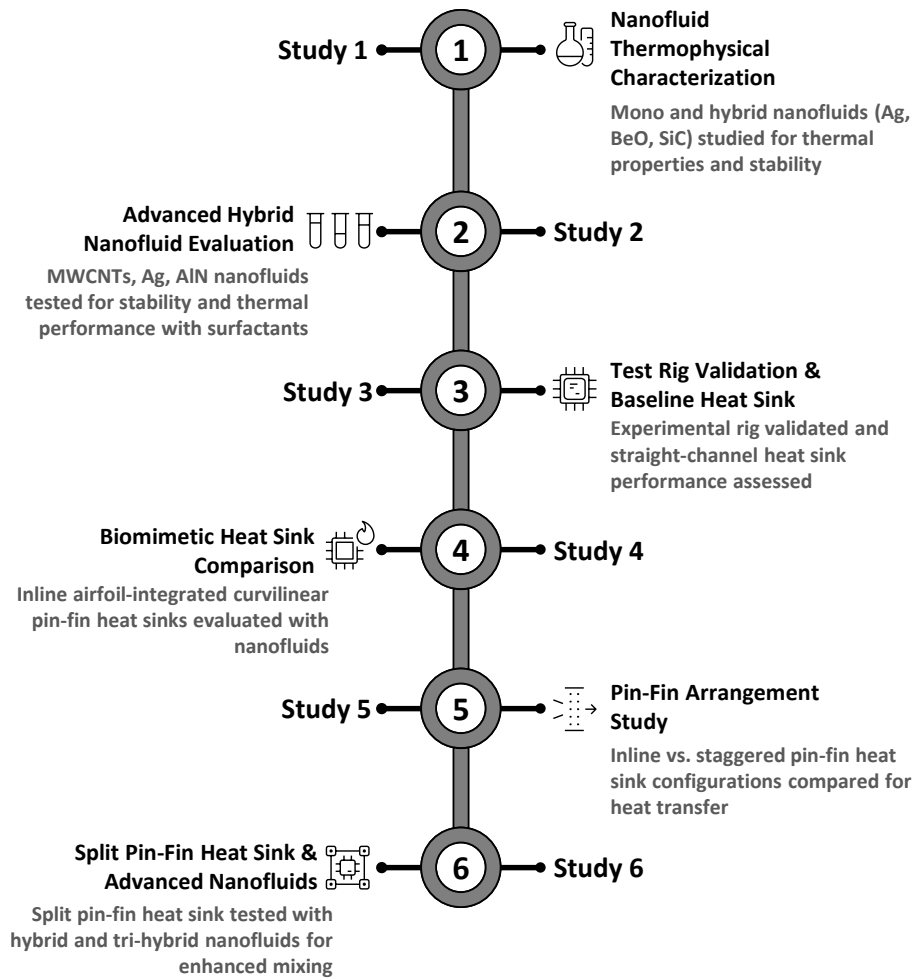


Figure 1.3. Schematic illustration of the sequential experimental stages.

1.3 Aims and Objectives

This study aims to develop and evaluate advanced heat sink configurations for electronic cooling applications, with a focus on achieving minimal flow resistance while ensuring effective thermal management. To fulfil this aim, novel biomimetic heat sink geometries were designed and assessed, with further performance enhancement achieved through the integration of unitary and hybrid nanofluids. These nanofluids were synthesised and characterised to evaluate their thermophysical properties across varying conditions.

The specific objectives of this research were as follows:

- Design and construct a versatile experimental test rig capable of evaluating the hydrothermal performance of various heat sink configurations.
- Prepare and characterise the thermophysical properties of nanofluids as a function of temperature and nanoparticle concentration.

- Analyse the influence of key operational parameters including flow rate, particle concentration, and heat flux on the cooling performance of the proposed system.
- Enhance heat transfer by increasing the effective surface area of the heat sink and utilising high-performance thermal fluids (nanofluids).
- Develop an efficient, environmentally friendly, and cost-effective solution for the thermal management of high heat-generating electronic components.

The key outcomes of this work contribute valuable insights into the design of next-generation heat sinks and present practical implications for their deployment in advanced electronics cooling systems and other relevant thermal management applications. By lowering flow resistance and improving heat removal, the proposed designs reduce the energy needed for pumping and allow compact cooling systems to perform better. This means processors, GPUs, and other high heat-generating components can operate more reliably, handle higher workloads, and maintain safe temperatures without requiring larger or more complex cooling hardware.

1.4 Research Gap

An optimised heat sink must achieve an effective balance between enhancing heat transfer and controlling hydraulic losses. Although numerous studies have investigated ways to improve thermal performance, such as increasing surface area, modifying fin geometries, or employing advanced working fluids, the majority of these works tend to prioritise heat-transfer enhancement as the primary performance indicator. While hydraulic performance is indeed reported in many heat exchanger studies, it is often treated as a secondary metric or expressed only through pressure-drop correlations, without a deeper examination of how geometric modifications influence the combined thermo-hydraulic performance. The designs that appear to perform well from a thermal point of view may impose significantly higher flow resistance, which can limit their suitability for compact electronic cooling systems where pumping power is restricted and reliability is important. The skewed focus may lead to misleading conclusions in real-world applications where increased flow resistance can significantly compromise system-level energy efficiency and operational reliability.

Moreover, the optimisation of heat sinks is particularly critical in compact systems where space is constrained and thermal loads are substantial. Such scenarios are not limited to data centres and computing platforms but extend to high-density power electronics in electric vehicles (EVs), aerospace avionics, telecommunication base stations, and medical diagnostic equipment. In these domains, devices operate under strict thermal budgets and spatial limitations, necessitating cooling solutions that are not only thermally effective but also compact, cost-efficient, and environmentally sustainable.

This creates a fundamental research gap, especially in the development of compact cooling solutions where both thermal and fluidic performance must be simultaneously optimised. The present study addresses this gap by proposing and investigating a series of novel biomimetic heat sink designs inspired by the respiratory system of fish. The fish inhales water continuously through its mouth,

exchanges the essential volume of gases through grills, and then leaves through orifices available on both sides of the throat. The water not only moves around the outer body of the fish but also flows inside out. It was observed that the fish body structure offers small resistance while moving in water. An airfoil shaped pin-fin is integrated and replaced with the interior of the fish. It is like a fin bordered by various shaped fins or the hybrid pin-fin. Four different shaped pin-fins have been designed for this study aims to find the optimum geometry. The geometrical configuration and positioning of the fins have been varied.

The configurations named inline arranged airfoil integrated curvilinear pin-fin heat sink, inline arranged airfoil integrated corrugated curvilinear pin-fin heat sink, staggered arranged airfoil integrated corrugated curvilinear pin-fin heat sink, and staggered arranged airfoil integrated split corrugated curvilinear pin-fin heat sink. Each configuration was experimentally analysed under varying flow rates and heating powers, utilising a range of advanced nanofluids. These specially shaped geometries are anticipated to deliver enhanced thermal performance while maintaining a manageable increase in pressure drop, offering a balanced trade-off critical for practical applications.

To the best of the authors' knowledge, these specific heat sink configurations featuring airfoil-inspired pin-fins integrated in novel spatial arrangements and their underlying biomimetic design philosophy have not been previously reported in the literature. This integrated approach establishes a new paradigm in the development of compact, high-performance thermal management solutions. By drawing from natural flow-optimised systems and adapting them to engineered geometries, the study provides a fresh perspective on how biologically inspired designs can be harnessed to address the dual challenges of heat transfer enhancement and hydraulic efficiency in constrained domains.

The fabricated experimental setup was intentionally designed to be modular and adaptable, enabling the testing of heat sinks of various shapes and dimensions. This flexibility allows the system to be utilised beyond the scope of electronics cooling, for instance, in thermal management applications in electric vehicles, aerospace systems, battery thermal regulation, power electronics, and renewable energy technologies. While the focus of the current investigation is on the cooling of high-performance electronic components, the methodological framework and experimental platform developed here can be readily extended to other fields where compact and efficient thermal solutions are required.

In this study, the thermal management of electronic components was selected as the primary application domain. To align the experimental work with real-world operational conditions, the heat sink designs were tailored to match the physical footprint of Intel® Xeon® processors, specifically the Silver, Gold, and Platinum series. These processors are widely used in demanding computational environments such as multimedia rendering, engineering simulations, big data analytics, and internet-based database servers.

A detailed study has been carried out in this regard, revealing that Xeon processors generate heat outputs ranging from 50 W to 300 W. Figure 1.4 presents a graphical comparison of the base temperatures and Thermal Design Power (TDP) values of these processors (see Appendix A for more details) [14].

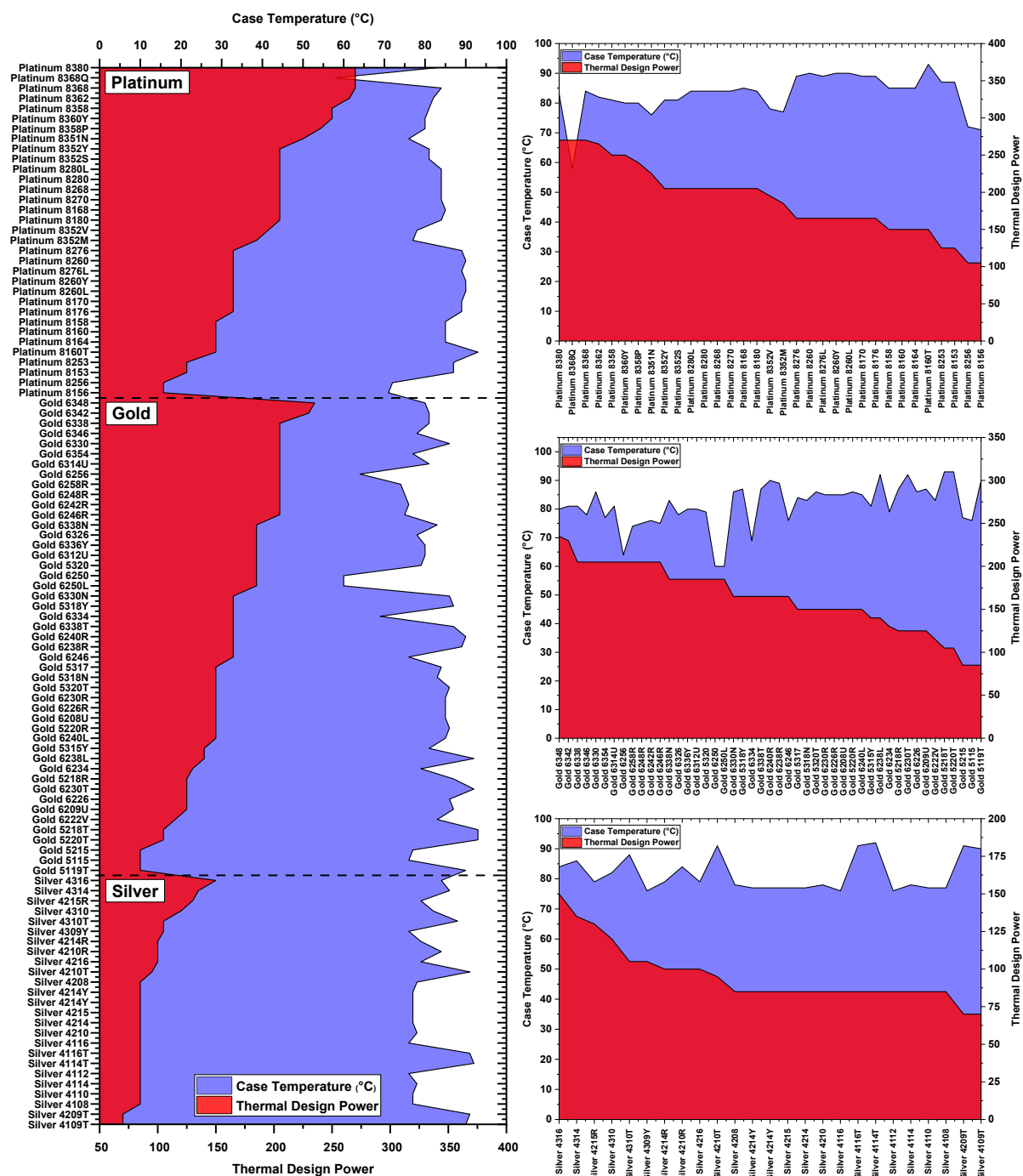


Figure 1.4. Comparison of base temperatures and thermal design power (TDP) ratings for various Intel® Xeon® processor models, illustrating the thermal management demands associated with each class.

The red-shaded area, scaled on the right axis, represents the TDP, which indicates the maximum amount of heat that the processor is designed to dissipate under peak load. The blue-shaded area represents the case temperature, scaled on the left axis, which shows the maximum allowable temperature before performance throttling occurs. Beyond this temperature threshold, even a slight increase can significantly impact the processor's efficiency and stability. The Platinum series exhibits the highest

power consumption and temperature thresholds, followed by the Gold series, and finally, the Silver series, which has the lowest thermal and power demands. This comparison highlights the varying thermal characteristics and power requirements across different Xeon processor tiers.

Designing a compact and efficient cooling solution for such high-performance chips poses significant challenges, especially given the need to maintain operating temperatures below 85 °C. To manage such high heat fluxes within tight spatial constraints, the use of advanced thermal coolants becomes essential. In this study, different nanoparticles were evaluated based on thermal conductivity, density, particle size, and economic feasibility. Selected nanoparticles were used to formulate novel hybrid nanofluids, which were then subjected to a detailed characterisation.

The study includes an in-depth analysis of the thermal conductivity and viscosity of these fluids at various temperatures, particle concentrations, and mixing ratios. By integrating these advanced fluids with the proposed pin-fin geometries, the research addresses both thermal and hydraulic aspects of heat sink performance contributing a comprehensive solution for the thermal management of electronic components.

1.5 Research Questions

The growing demand for high-performance, compact, and energy-efficient cooling solutions ranging from electronic processors to electric vehicle (EV) battery packs necessitates the development of novel heat sink designs and advanced thermal fluids. While several studies have explored ways to enhance heat transfer using extended surfaces or high-conductivity nanofluids, there remains a fundamental need to balance thermal enhancement with hydraulic efficiency. This research aims to address these issues through the development of biomimetic heat sink configurations integrated with nanofluids.

Based on the identified research gaps, the following key questions were formulated to guide the investigation:

- What are the emerging challenges in thermal management for compact, high-performance systems, and how can advanced cooling technologies address them?
 - This question explores the growing thermal bottlenecks in modern electronics, AI, EVs, and data centres, and considers how integrated approaches combining advanced geometries and nanofluid-based liquid cooling can provide scalable, efficient, and future-ready solutions.
- What are the key limitations of existing cooling technologies, and what potential do nanofluids and biomimetic heat sink geometries offer in overcoming them?
 - This question evaluates the shortcomings of conventional air and liquid cooling approaches and considers how nature-inspired designs and enhanced working fluids can provide superior thermal performance and design flexibility.
- How can a reliable experimental platform be developed to evaluate the hydrothermal performance of nanofluid-enhanced biomimetic heat sinks under varied flow and thermal loads?

- This question addresses the need for a flexible and accurate testing setup capable of simulating real-world conditions, enabling systematic comparison of heat sink configurations and coolant types.
- How do various nanoparticles and their hybrid combinations influence the thermophysical properties of nanofluids across a range of temperatures and concentrations?
 - This question aims to understand how the composition of mono, hybrid, and tri-hybrid nanofluids affects their thermal conductivity, viscosity, density, and overall suitability for use in heat sinks.
- What are the optimal volumetric mixing ratios and surfactants that ensure maximum thermal enhancement and colloidal stability of the nanofluids?
 - The goal is to identify stable nanofluid formulations that deliver enhanced heat transfer without significant settling or agglomeration over time.
- How do different nanoparticle combinations and mixing ratios affect the stability, performance, and economic viability of nanofluids when used in engineered cooling systems?
 - This addresses the trade-offs between enhanced performance and practical implementation costs.
- How does temperature variation influence the thermophysical properties such as viscosity, thermal conductivity, and density of mono and hybrid nanofluids?
 - This question investigates how temperature-dependent behaviour of nanofluids impacts their heat transfer efficiency and flow characteristics, which are critical for dynamic thermal management scenarios.
- How does the proposed configuration compare to conventional straight-channel configurations in terms of thermal and hydraulic performance under identical conditions, and what role do different nanofluid formulations play in enhancing its effectiveness?
 - This question assesses the relative advantages of the developed biomimetic design over baseline configurations, while examining the synergistic effect of various nanofluid compositions on performance enhancement.
- Is it possible to develop a generalisable design strategy for compact cooling solutions that can be adapted to other high heat-flux applications beyond electronics, such as EV battery packs or renewable energy inverters?
 - This broadens the scope of the study and evaluates its potential for wider industrial relevance.
- How do various geometrical configurations affect the balance between Nusselt number enhancement and pressure loss?
 - This question investigates the effect of biomimetic design features such as inline vs staggered arrangements and split fins on the thermal and hydraulic characteristics of the system.

- To what extent does the integration of nanofluids improve the performance of the designed heat sinks compared to water as the base fluid?
 - Here, the focus is on quantifying the benefits of advanced nanofluids in terms of Nusselt number, thermal resistance, and flow resistance.
- Can the proposed biomimetic heat sinks maintain efficient cooling under varying thermal loads (50–300 W) typically encountered in high-performance electronic processors like Intel® Xeon®?
 - This question links experimental performance data to real-world applications, testing whether the proposed solutions are practically viable for modern electronic cooling demands.
- How can thermal and hydraulic performance be simultaneously optimised to deliver a compact, efficient, and environmentally sustainable cooling solution?
 - The final question aims to define a balanced metric or design framework that captures both aspects of thermal performance and pumping power, offering guidelines for next-generation heat sink development.

These research questions form the backbone of the experimental investigations presented in this thesis and ensure that both scientific innovation and real-world relevance are addressed in the pursuit of advanced thermal management solutions.

1.6 Knowledge contribution

This research introduces several key contributions that advance current understanding and practical capabilities in the field of thermal management, particularly in the design of biomimetic heat sinks and the synthesis of cost-effective nanofluids. The work addresses critical limitations in existing literature, offers practical innovations for industry, and provides a foundation for future interdisciplinary exploration. The main contributions are outlined below:

Novel Biomimetic Heat Sink Designs Inspired by Aquatic Flow Mechanics

The study introduces, for the first time, a set of airfoil-integrated pin-fin heat sink configurations that draw inspiration from the inside-out flow mechanism in aquatic organisms. Unlike traditional biomimicry efforts that focus only on surface drag minimisation, this work considers both external and internal flow through structures mimicking how water enters the mouth of a fish, passes through the gills, and exits laterally. This concept opens a new perspective for researchers and engineers, potentially influencing not just thermal management solutions, but also aerodynamic and fluid-transport applications such as unmanned aerial vehicles (UAV's), future air mobility concepts (e.g. air cars), marine propulsion systems, and other low-resistance compact devices.

Scalable and Real-World-Applicable Experimental Platform

A modular experimental test rig was developed to allow flexible testing of heat sinks across varying dimensions, flow rates, and thermal loads. This rig supports the evaluation of designs not only for computing systems (as demonstrated using Intel® Xeon® processors) but also for power electronics in

electric vehicles, renewable energy inverters, and aerospace subsystems. By replicating real-world thermal conditions, this work directly links lab-scale innovation with industrial deployment potential.

Comprehensive Bibliometric Study of Nanofluid Research

A detailed bibliometric and co-citation analysis was conducted to identify the most influential authors, countries, and journals in the field of nanofluids in heat exchangers. This analysis is a valuable resource for new researchers entering the field, helping them locate high-impact sources, research hotspots, and collaboration opportunities. It also informs funding agencies and policymakers on emerging leaders and research trends across different geographical regions.

Development and Characterisation of Cost-Effective Hybrid Nanofluids

This study offers an in-depth synthesis and experimental evaluation of mono, binary hybrid, and tri-hybrid nanofluids using combinations such as Ag/BeO, Ag/SiC, and MWCNT/Ag/AlN. These nanofluids were selected and optimised based on thermal conductivity, viscosity, cost, and long-term stability. Among the key observations was the formation of unique chain-like agglomerates in silicon carbide (SiC)-based fluids, which contributed to anisotropic thermal pathways and enhanced heat transfer under certain flow regimes. Statistical models were developed to predict thermophysical properties based on temperature, concentration, and mixing ratios, providing valuable datasets and predictive tools for future nanofluid researchers and thermal system designers.

Bridging Academic Design with Industrial Reality

The heat sinks were tailored to the size and power requirements of Intel® Xeon® processors (50–300 W) widely used in computing, graphics processing, and large-scale data environments. The experimental design and resulting data provide insight into how advanced cooling strategies can be applied in industrial settings where traditional air-cooled systems may soon become obsolete due to higher heat flux demands.

Global and Industrial Relevance

The outcomes of this research hold wide-ranging significance across academic, industrial, and geographical contexts, contributing to the development of next-generation thermal management solutions.

United Kingdom and Europe: This work supports the transition to energy-efficient technologies aligned with the UK's Net Zero Strategy and the EU Green Deal. The results are directly relevant to the electrification of transport, miniaturisation of power electronics, and the expansion of high-performance data centres in the region.

United States: The increasing thermal demands of AI servers, military electronics, and cloud computing infrastructure in the US have made advanced liquid-cooling technologies essential. The integrated thermal-hydraulic design approach presented here offers solutions that align with Department of Energy priorities and industry trends toward sustainable cooling.

Asia: Countries such as China, India, Japan, and South Korea are leading global manufacturing hubs for electronics, EV batteries, and renewable energy systems. This research supports Asia's strong investment in high-density packaging and thermal system miniaturisation. Additionally, the cost-effective nanofluids developed in this study address the growing need for scalable and affordable thermal solutions in both emerging and advanced economies.

Global Industry 4.0 Applications: The combination of biomimetic design, smart nanofluids, and experimentally validated compact systems makes this research highly relevant to Industry 4.0 enabling smarter, smaller, and more efficient cooling technologies for next-generation automation, robotics, and connected devices.

1.7 Limitations

While this research provides novel insights into biomimetic heat sink design and nanofluid-enhanced cooling strategies, certain limitations are acknowledged that may influence the generalisability and scope of the findings. These limitations offer direction for future improvements and investigations.

Restricted Geometrical Scope

Although four novel biomimetic heat sink configurations were designed and analysed, the study was limited to a specific range of geometries inspired by aquatic respiration. Further exploration of alternative bio-inspired or topology-optimised structures could yield additional improvements in thermal and hydraulic performance.

Operating Range Constraints

Experiments were conducted within a specific range of flow rates and thermal loads. While this ensures application relevance, the extrapolation of results to significantly different operational regimes (e.g. high-temperature industrial reactors) should be approached with caution.

Single-Phase Flow Assumption

The study considered only single-phase liquid cooling. Two-phase phenomena such as boiling or condensation, which are prevalent in high heat flux applications, were not investigated. These could introduce new challenges related to flow stability, pressure drop, and surface interactions.

Nanofluid Stability over Extended Durations

Although surfactants and formulation techniques were applied to improve nanofluid stability, the study primarily focused on short- to medium-term stability under laboratory conditions. Long-term performance under cyclic loading or prolonged operational use in real systems was not assessed.

Limited Economic and Environmental Assessment

While cost-effective nanoparticles were considered during nanofluid selection, a comprehensive life-cycle cost or environmental impact analysis (e.g. recyclability, toxicity, energy footprint of nanoparticle synthesis) was not within the scope of this thesis.

CFD Modelling Limited to Straight Channel Geometry

The computational fluid dynamics (CFD) simulations conducted for validation purposes were based on simplified straight-channel heat sink models. The complex biomimetic geometries were not fully simulated due to computational limitations, which may limit direct numerical insight into flow interactions.

1.8 Structure

This thesis is structured into ten chapters, each designed to build upon the previous one to form a cohesive narrative, starting from the foundational background to the experimental work and concluding with key insights and future directions. The structure reflects a logical progression of the research activities undertaken and the knowledge developed throughout the study. The overall structure and flow of this thesis are visually summarised in Fig. 1.5, which highlights the logical progression of the research from foundational background through experimental investigations to concluding remarks and future directions.

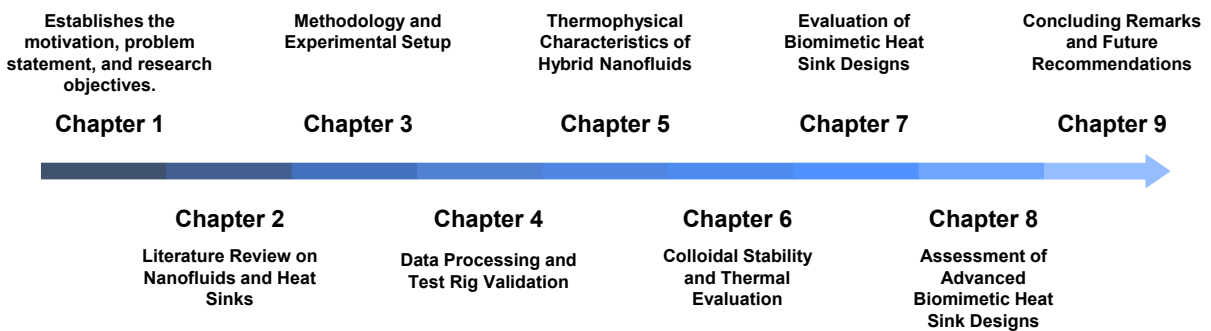


Figure 1.5. Schematic illustration of the thesis structure.

Chapter 1: Introduction

This chapter outlines the background and motivation for the research, highlighting the growing demand for advanced thermal management systems in high heat flux applications. It identifies the limitations of conventional cooling techniques and establishes the rationale for investigating nanofluid-enhanced biomimetic heat sink designs. The chapter further details the research aims, objectives, novelty, and scope, providing a clear direction for the subsequent chapters.

Chapter 2: Literature Review

A comprehensive review of existing literature is presented in this chapter, encompassing the evolution of nanofluids, thermophysical modelling, stability challenges, surfactant effects, and hybrid nanofluid development. Additionally, this chapter reviews recent trends in heat sink geometries—particularly biomimetic designs—and critically evaluates both numerical and experimental studies related to nanofluid-based thermal systems.

Chapter 3: Methodology and Experimental Setup

This chapter elaborates on the design, fabrication, and experimental preparation methods for heat sinks and nanofluids. It includes the selection criteria for nanoparticles (MWCNTs, Ag, AlN, SiC, BeO), nanofluid formulation strategies, and thermal characterisation techniques. The development of inline and staggered airfoil-based pin-fin heat sink geometries is discussed, along with the implementation of both conventional and advanced designs.

Chapter 4: Data Processing and Test Rig Validation

The procedures for experimental data acquisition, instrumentation, and validation are detailed here. The chapter explains the calibration of sensors and validation of the test rig using standard fluids, followed by a description of the performance parameters used—such as Nusselt number, thermal resistance, pressure drop, and Log Mean Temperature Difference (LMTD). Computational simulations using ANSYS Fluent are also introduced to complement the experimental findings.

Chapter 5: Thermophysical Characteristics of Silver, Beryllium Oxide, and Silicon Carbide in Hybrid Nanofluid Formulations

This chapter investigates the thermal conductivity, viscosity, and stability of mono and binary nanofluids based on Ag, BeO, and SiC. The effects of surfactants and preparation techniques are critically examined. This work was published in the Journal of Molecular Liquids, underscoring its scientific significance.

Chapter 6: Colloidal Stability and Thermal Evaluation of MWCNTs, Ag, and AlN-Based Hybrid and Tri-Hybrid Nanofluids

Extending the study of Chapter 5, this chapter explores the performance of more complex nanofluid formulations, focusing on tri-hybrid systems involving MWCNTs, Ag, and AlN. Detailed evaluations of different mixing ratios, stability profiles, and thermophysical properties are provided. The performance trade-offs between conductivity, cost, and stability are analysed, offering practical guidance for fluid selection in real-world applications.

Chapter 7: Experimental Evaluation of Inline Airfoil-Integrated Biomimetic Heat Sink Designs Using Nanofluids

This chapter presents the hydrothermal performance of two inline-configured biomimetic heat sinks—Inline Arranged Airfoil Curvilinear Pin-Fin (IACPF) and Inline Arranged Corrugated Curvilinear Pin-Fin (AICCPF)—cooled with selected nanofluids. The chapter demonstrates how geometry optimisation can significantly influence flow dynamics, thermal resistance, and temperature uniformity.

Chapter 8: Experimental Assessment of Advanced Biomimetic Heat Sink Designs Using Hybrid Nanofluids

Divided into two phases, this chapter first compares the performance of the staggered AICCPF (SAICCPF) configuration against its inline counterpart. The second phase introduces and evaluates a novel split-pin design—Staggered Arranged Airfoil Integrated Split Corrugated Curvilinear Pin-Fin

(SAISCCPF). The nanofluids studied in Chapter 6 are applied to these geometries, and results are analysed for thermal and hydraulic performance. The role of staggered fin layout and alternative flow paths in improving heat transfer and managing bubble entrapment is emphasised.

Chapter 9: Concluding Remarks and Future Recommendations

The final chapter concludes the thesis by summarising the key findings, contributions, and significance of the research. It also outlines potential directions for future studies, offering recommendations for both academic investigation and practical implementation.

CHAPTER 2

2 Literature Review

Efficient thermal management is a critical challenge in numerous engineering applications where rising heat fluxes threaten system performance, reliability, and longevity. While electronic cooling has been a primary driver of innovation in heat sink technologies—especially in data centres, high-performance computing, and consumer electronics—the need for compact, high-efficiency cooling extends well beyond this sector. Modern advancements in electric vehicles (EVs), aerospace systems, renewable energy conversion, telecommunications infrastructure, and medical diagnostics are increasingly reliant on densely packed power components operating at elevated thermal loads. These sectors demand next-generation cooling strategies that are not only thermally effective but also compact, adaptable, and energy-efficient.

Traditional air-cooled systems, although still prevalent due to their simplicity and cost-effectiveness, are fast approaching their functional limits, especially in applications involving transient or high steady-state heat loads. Liquid-cooled and phase-change systems offer improved performance, but their implementation is often hindered by design complexity, pressure drop concerns, and material compatibility issues. As thermal boundaries continue to shrink and sustainability goals become more pressing, there is an urgent need to revisit fundamental cooling design philosophies with emphasis on integrated, low-resistance solutions that are scalable and multifunctional.

As we venture into the future, the advancement of artificial intelligence (AI) continues to drive an increased demand for more efficient and sophisticated cooling systems in data centres and AI hardware infrastructure. Among various liquid cooling methods, the implementation of liquid-cooled heat sinks has gained significant attention. Liquid cooling emerges as a highly auspicious technique for effectively dissipating heat generated by electronic devices, owing to its commendable attributes such as a significantly elevated thermal conductivity and unparalleled prowess in facilitating heat transfer.

Literature reports numerous cooling techniques like metallic foams, phase change materials (PCM), PCM in combination of metallic foam or heat sink, heat pipes, air circulating fans, and heat sink with extended surfaces, etc. for the thermal management of electronic devices [15]. There is no doubt that these techniques provide respectable results but have failed to provide acceptable results for high heat generating devices. To transfer excessive heat and keep devices within a safe temperature threshold, researchers are shifting towards hybrid and smart cooling techniques.

In the past few decades, nanofluids attracted the attention of young scholars and investigators as an advanced coolant due to their enhanced heat transfer characteristics. Literature reported the employment of different types of base fluids and nanoparticles to augment the rate of heat transfer. For high heat generating systems such as microprocessors to effectively transfer the excessive amount of heat micro

channel heat sinks with nanofluids (fluids having a suspension of nanosized metallic or non-metallic particles) as a working fluid found to be the most efficient technique due to fewer requirements of coolant and large surface area to volume ratio [16].

2.1 Nanofluids as Advanced Coolants

Nobody can dispute the fact that as the industrial sector expands, there is a growing demand for small and lightweight devices with improved capabilities. It is a fact that, achieving sustainable growth requires prioritizing the efficient production, conversion, and consumption of energy. Heat transfer devices are the essential part of almost all devices that consume or generate energy used in various industrial and commercial sectors. Researchers are focused on making these devices more compact while also exploring advanced thermal coolants with enhanced thermal characteristics that can transfer heat more effectively like ionic liquids, nanofluids, superfluid helium, graphene-based coolants, phase change material, etc. Nanoparticles suspended fluids are one of the promising candidates grabbing the attention of researchers because of their improved thermal properties. Nanofluids are mixtures of base fluid with metallic or non-metallic nano sized particles typically having a size less than 100 nm in at least one dimension. The uniformly suspended particles enable them to exhibit improved thermal properties, which can lead to more efficient heat transfer in the heat exchanger.

The concept of nanofluids was first proposed by Choi [17] in the mid-1990s, the study suggested that suspending nanoparticles in a base fluid could enhance heat transfer properties. Later on, Choi and Eastman [18] suspended various metallic particles in different fluids and found that each study resulted in an improvement in performance. It was found that nanofluids had significantly higher thermal conductivity than the base fluid, stimulating interest in their potential applications. The early research in the field of nanofluids focused on developing methods for synthesizing stable nanoparticle suspensions and characterizing their thermal and rheological properties. In this effort, Zhu et al. [19] introduced the chemical method for preparing the ethylene glycol (EG) based copper nanofluid while Choi and Eastman [18] proposed the vapour deposition technique to prepare the nanofluid in one step inside a chamber. A substantial amount of research has been carried out since the early 2000s on the synthesis, characterization, and application of nanofluids. The focus was to understand the mechanisms behind the enhanced properties of nanofluids and develop methods to optimise their performance for specific applications. Xuan and Roetzel [20] proposed the correlations to predict the heat transfer coefficient (HTC) of nanofluids treating the fluid as a single phase and multiphase solid-liquid. In 2004, Eastman et al. [21] compiled a comprehensive study on the thermal characteristics of nanofluids summarizing the numerous heat transfer mechanisms. The authors came to the conclusion that more investigation would be required in the upcoming years to fully comprehend the transfer of heat at the atomic level. The study shed a light on the impact of several factors, such as particle size, surface morphology, agglomeration, and fluid temperature, on the thermal transport capacity of nanofluids. On the basis of a considerable number of studies, it was concluded that the particle size, surface treatment,

and temperature significantly affected the thermal characteristics, while the formation of particles clusters is undesirable.

Researchers also explored various types of materials and started investigating the impact of parameters like shape, size, concentration, etc. on their thermal and rheological properties. Over the next decade, the study of nanofluids continued to gain even more attention, particularly in applications such as heat exchangers, energy storage, thermal management of electronics, and biomedical equipment. Researchers focused their efforts on exploring the potential of nanofluids in these areas, recognizing their promising prospects and the impact they could have on enhancing performance and efficiency [22,23].

After 2010, the focus of the investigation starts shifting gradually towards more practical applications, such as developing nanofluid-based compact heat transfer devices, enhancing heat transfer in solar thermal systems, and improving the efficiency of power generation and industrial processes [24]. This transition has paved the way for innovations in nanofluid technology, with companies worldwide actively engaging in the development and deployment of these advanced fluids to address pressing challenges in various industries. A Korean company named Zalman introduced nanofluids as a cooling agent in two of their products, the Reserator 3 Max and Reserator 3 Max Dual. These coolers use a proprietary “nano-coolant” formulation designed to improve heat absorption and enhance thermal conductivity within the loop compared to conventional liquid coolants. Both products were launched as part of Zalman’s high-performance PC cooling line and have been available commercially to consumers worldwide. Their release represents one of the early commercial implementations of nanofluid technology in mainstream electronics cooling. FlexeGRAPH has introduced “Go Chiller”, a graphene-enhanced nanofluid specifically designed for high-performance cooling applications, including data centres and advanced computing systems [25]. By incorporating graphene nanoparticles, the coolant exhibits substantially higher thermal conductivity compared to conventional fluids, enabling faster heat dissipation and reduced thermal resistance within liquid-cooling loops. The company reports that these enhancements can improve overall cooling efficiency and system stability, particularly in environments where heat fluxes continue to rise due to increasing processor densities. This emerging commercial product demonstrates that nanofluids are advancing beyond laboratory research and are beginning to gain traction in real-world thermal management applications. There is another company named Ice Dragon Cooling supplying nanofluids to several industrial sectors for use in diverse applications. Hydromx, a USA-based company with global reach, specialises in commercialising nanofluids for heating and cooling applications. Their revolutionary heat transfer nanofluid, powered by Nano-Thermo™ technology, accelerates heat transfer through suspended nano-particles [26]. This results in significant energy savings and cost efficiency for clients. In this effort, Synano is working to bring this nanofluid innovation to market to meet the considerable cooling challenges faced in data centres and other electronics thermal management applications. Synano claims they are developing nanofluids that have a thermal conductivity value more than 20% higher than the base fluid, without a substantial

increase in viscosity. Their nanofluids technology seeks to maintain the favourable flow properties of the base fluid while significantly boosting its heat transfer capabilities [27]. An Italian company TCT Nanotech has developed a nanofluid product called HTF Compact that contains copper oxide nanoparticles suspended in a fluid with corrosion inhibitors. Characterised by nanoparticles measuring 3-7 nanometers, this nanofluid is specifically crafted to enhance the efficiency of HVAC/R systems when introduced into established closed water loops such as chilled water or hot water loops. Notably, this nanofluid presents an opportunity to reduce or eliminate the need for antifreeze glycols, substances that typically hinder heat transfer, resulting in a further enhancement of overall efficiency. A demonstration of the fluid took place at a Pfizer research facility in New York, where it was integrated into the glycol-based heat recovery loop, chilled water loop, and hot water loop. Remarkably, at a 5% mix ratio with the existing fluid, the nanofluid showcased a notable improvement in heating/cooling efficiency, leading to reported electricity savings of 14.1% and fuel savings of 7.8%, as reported by the vendor. Werner Finley, a company functioned in India, has developed a nanofluid named Nanofluid-99, asserting that their heat-transferring fluid can contribute to a minimum electricity savings of 20%. Beyond its potential for energy conservation, this nanofluid offers the additional benefits of being corrosion-resistant and providing protection against freezing. Collectively, these companies represent a global movement towards harnessing the potential of nanofluids, demonstrating their efficacy in optimising thermal processes and heralding a new era in heating and cooling system efficiency.

In recent years, nanofluids have also been found to be very effective in other applications, such as antimicrobial activity [28], improved lubrication [29], and desalination [30]. However, some challenges have prevented their widespread commercial adoption. One major issue is nanoparticle aggregation and sedimentation over time, which compromises stability [31]. Market uncertainties, unclear health implications, high production costs, and potential environmental impacts contribute to the hesitancy of companies to invest in nanofluid production. Additionally, the high maintenance expenses and corrosion issues of nanofluid-based systems, coupled with uncertainties in thermophysical properties and complex system performance predictions, further complicate widespread adoption [32].

Luo et al. [33] prepared oil-based SiC nanofluids with a wide concentration ranged 0.1–10.3 vol% using the two-step method for immersion cooling applications in data centres. The thermal conductivity exhibited a maximum enhancement of 25.5% for 10.3 vol% nanofluids at 30 °C, while the specific heat capacity decreased by up to 22.5% compared to the base mineral oil. Additionally, viscosity showed a moderate increase, with a maximum increment of 35% for the 10.3 vol% nanofluids. Through numerical simulations and experiments, they identified the optimal nanofluid concentrations for different Reynolds numbers. At low Reynolds numbers (≤ 1000), nanofluids with 0.3 and 0.5 vol% concentration showed better heat transfer performance, with a maximum enhancement of 11.4% for the 0.3 vol% nanofluids at $Re = 250$. At higher Reynolds numbers (> 1000), nanofluids with 3.7 vol% concentration performed better, achieving a maximum enhancement of 11.7% at $Re = 500$, due to their enhanced thermal conductivity. They stated that lower concentrations are preferable for applications where the

fluid rate is lower, or the Reynolds number is under 1000. Sheikholeslami and Khalili [34] explored the solar photovoltaic-thermal (PVT) system using eco-friendly graphene nanoplatelets (graphene nanoplatelets (GNP) nanofluid to enhance heat transfer. They employed an eight-lobed tube with copper fins and tested GNP at 0.025% and 0.1% weight fractions. The system achieved maximum exergy and thermal efficiencies of 15.32% and 55.22% respectively, using 0.1% GNP at a Reynolds number of 1611. The GNP nanofluid improved cooling, boosting electrical efficiency by 5.8%, and increased CO₂ reduction by 7.1 tons compared to water, highlighting its environmental benefits. In another study, Sheikholeslami et al. [35] investigated the PVT system featuring a cylindrical reflector, a thermoelectric generator (TEG) made from Cu₂SnS₃ (CTS), and a MgO-water nanofluid spectral filter. The nanofluid improved cooling, enhancing system performance by 36.3%. The combined system doubled CO₂ reduction compared to conventional PV systems, showing strong energy efficiency and environmental benefits. These studies demonstrated that incorporating nanofluids into various systems can significantly reduce carbon dioxide emissions. This reduction is achieved by enhancing the overall performance and efficiency of these systems. By optimising the performance of systems such as cooling and heating mechanisms, nanofluids contribute to a greener, more sustainable approach to energy consumption. Adam et al. [36] investigated the optical properties and colloid stability of SiO₂-water nanofluids for hybrid thermal/photovoltaic applications at elevated temperatures. Different nanoparticle volume fractions were synthesised, ranging from 0.0011% to 0.0367%, and factors such as sonication temperature, nanoparticle concentration, exposure temperature, and exposure time were examined. Their findings exhibited that reducing the temperature during sonication while preparing the fluid improved stability, with 30°C yielding the best results. The absorbance of the nanofluids decreased with increasing exposure temperatures from 25°C to 90°C, with higher temperatures resulting in increased agglomeration. Their study also assessed the energy performance of a concentrating photovoltaic/thermal (CPVT) system using the NFs as optical filters instead of water. Despite some stability challenges at elevated temperatures, the SiO₂-H₂O HNFs showed promise for enhancing the efficiency of CPVT devices, providing valuable insights into the temperature-dependent behaviour of nanofluids for solar energy applications.

Regarding the current state of the art in processor cooling, nanofluids have progressed from early-stage laboratory research to pilot-scale and early commercial adoption. Their documented benefits include enhanced thermal conductivity, increased convective heat-transfer coefficients, and reduced junction temperatures, enabling more efficient operation of high-power processors. Despite extensive research efforts since 2000, stability remains a significant hurdle to the commercialization of nanofluids, posing alarming and persistent challenges for investigators. However, it's essential to note that stability is not the sole barrier; other issues further impede the widespread adoption of nanofluids in various applications.

Heat transfer in heat exchangers using nanofluids has become an area of active research due to the potential benefits offered by these fluids. The suspension of nanometer-sized particles in working fluid

could potentially act as a "heat bridge" between the coolant and the heat exchanger surface, supporting more effective heat transmission. Another way that nanofluids can enhance heat exchanger performance is by increasing the convective HTC. The fluid can experience turbulent flow because of the nanoscale particles, resulting in an increase in heat transfer from the fluid to the heat exchanger surface. At the nanoscale, the particles introduce additional complexity to the fluid dynamics. As they move through the fluid, these nanoparticles disrupt the normal flow patterns, creating localised turbulence. This turbulence, in turn, intensifies the mixing and interaction between the fluid and the heat exchanger surface [37,38]. Moreover, the turbulent flow induced by nanoscale particles helps in breaking down thermal boundary layers that may develop on the heat exchanger surface. This breakdown further improves the overall heat transfer efficiency by preventing the formation of stagnant fluid layers that could impede the transfer of thermal energy. While nanofluids can significantly improve heat transfer rates, it is important to note the trade-off with pumping power. Optimising this balance is essential for practical and energy-efficient applications.

According to the stats of the Scopus database, there has been a growing interest regarding the utilization of nanofluids in heat exchangers. A considerable number of studies have been undertaken to delve into the potential advantages and limitations of nanofluids in greater depth, approaching the subject from various perspectives. These investigations intend to gain a comprehensive understanding of nanofluids and their suitability for enhancing heat exchanger performance. In this regard, significant progress has been made in this field, encompassing a deeper understanding of the mechanisms responsible for enhanced heat transfer, the formulation of new nanofluids, optimisation of flow parameters, utilization of advanced manufacturing techniques, and efforts towards scale-up and commercialization. The presented study aims to provide critical insights into the current state of knowledge about the use of nanofluids in heat exchangers and identify areas for further study. Notable, a comprehensive bibliometric analysis has been conducted to discern emerging research trends, identify primary contributors, and pinpoint areas that demand further exploration within this field.

2.1.1 Preparation

Nanofluids exhibit enhanced thermal properties compared to traditional thermal fluids, a distinction attributed to heightened thermal conductivity resulting from the colloidal suspension of metallic particles within the base fluid. The spectrum of nanofluids encompasses simple, ionic, magnetic, hybrid, and organic nanofluids, each contributing unique attributes to the enhancement of thermal performance. The superior thermal characteristics of nanofluids are intricately linked to the properties of nanoparticles employed in their formulation. These nanoparticles play a pivotal role in determining the overall effectiveness of nanofluids. Figure 2.1 illustrates the diverse types of nanoparticles utilised in preparing nanofluids, encapsulating a range of materials that contribute to the improved thermal properties. In the continuous exploration of this field, significant strides have been made in understanding and harnessing the full potential of nanofluids. Researchers have delved into novel

synthesis techniques, optimising nanoparticle properties and exploring innovative applications. Advanced studies have focused on tailoring nanofluid compositions to specific thermal requirements, paving the way for customised solutions in diverse industrial and technological domains [39,40]. Moreover, ongoing research endeavours aim to unravel the intricate interplay between nanoparticle characteristics and their influence on nanofluid performance. This deeper understanding opens avenues for the precision engineering of nanofluids, allowing for the creation of tailored thermal solutions that address specific challenges in heat transfer and thermal management.

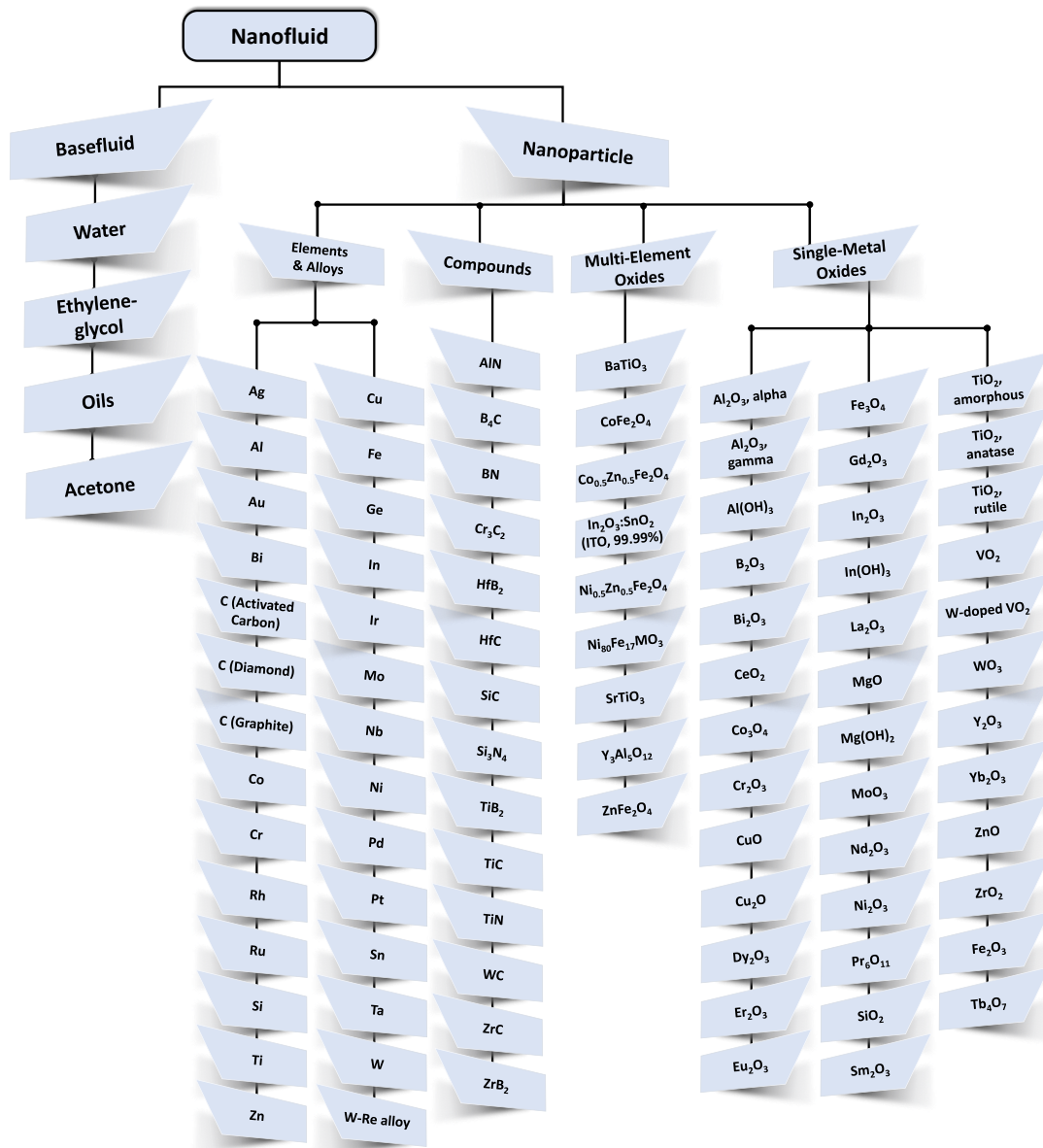


Figure 2.1. Nanoparticles used in nanofluids' preparation.

The preparation of nanofluids is achieved by two different methods named single-step and two-step methods. These methods are categorized based on the number of stages involved in the preparation process. Figure 2.2 provides a graphical illustration of these two techniques used for nanofluid

preparation. In the single-step method, the nanoparticle synthesis and nanofluid production are carried out simultaneously using the hotwire method. In the two-step synthesis approach, the generation of nanoparticles involves initial processes employing diverse mechanical methods for nano-powder production. Subsequently, the nanofluid is prepared through the implementation of suspension creation techniques. This methodical two-step procedure allows for the precise control and customization of both the nanoparticle and fluid phases, thereby enhancing the overall versatility and applicability of the synthesised materials.

A single-step approach involves the production of particles and nanofluid in a single step, rather than requiring multiple steps or different processing stages. In this method, the nanoparticles are produced in a chamber under extreme pressure and heat, and the resulting suspension is subsequently cooled to produce the nanofluid. The two-step process, which requires the separate production and dispersion of nanoparticles, is more popular since it can provide a more stable solution but is also more expensive [41,42]. For small-scale manufacturing, the one-step technique is favoured; however, the two-step method is preferred for industrial or bulk production of nanofluids.

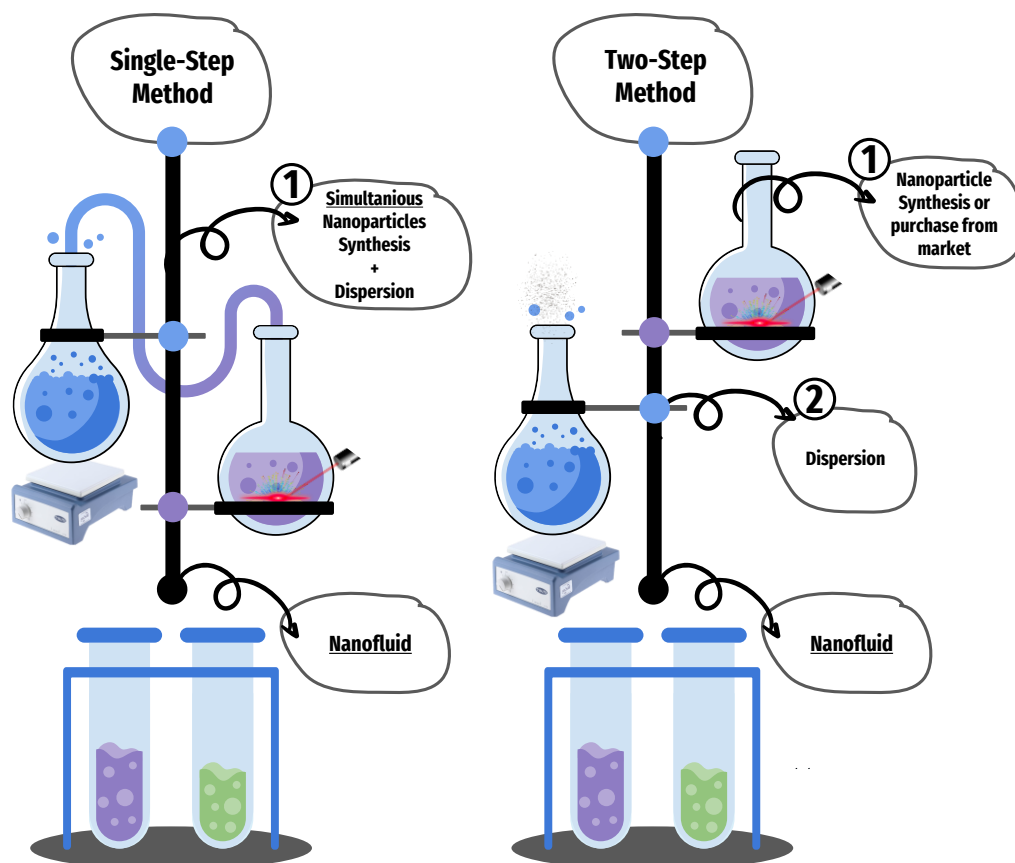


Figure 2.2. Illustration of Nanofluid Preparation Methods (a) Single-step approach and (b) Two-step approach.

A number of research articles compiled by different investigators have stated that the two-step method among several is the most effective one for nanofluid preparation. This technique involves two steps;

first step deals with the nanoparticles synthesis while these synthesised nanoparticles are dispersed in base fluid in the second step. To ensure the proper mixing and avoid the agglomeration of the particles in base fluid the solution is further treated with the help of a magnetic stirrer, ultrasonicator, and homogenizer. Some kinds of surfactants have also been used to enhance the stability period [43,44]. Shoghl et al. [45] performed magnetic stirring for 1 h and ultrasonic vibration for 4 h to prepare the stabilized nanofluid of MgO. The study of Ali et al. [46] on the thermal performance of car radiator using MgO nanofluid employed a two-step method for nanofluid preparation. It was observed that the stability of the fluid increased by making it more acidic or decreasing the pH value. For this purpose, they used HCL and noted that after adding HCL to the MgO solution, it turned transparent, and no sedimentation was found even after 7 days. Mahbubul et al. [47] studied the effect of ultrasonication time on the stability of titania nanofluid. Positive impact of ultrasonication was observed on the suspension of particles in base fluid. In addition, it was revealed that re-agglomeration of particles begins after performing the sonication process for more than 150 min.

Ghadimi and Metselaar [48] observed that surfactant supplementation while performing the ultrasonication process exhibited improved thermal properties. Zouli et al. [49] followed the two-step method for preparing the Fe_2O_3 -water nanofluid. The samples were homogenized for 45 minutes using an IKA homogenizer (T25) and sonicated for 30 minutes to ensure the proper mixing. Four different samples with the particle concentration of (0.01 vol.%, 0.02 vol.%, 0.05 vol.%, and 0.09 vol.%) were prepared and investigated the variation of thermal conductivity with particle concentration and temperature. It was observed that the thermal conductivity increased with temperature and volume fraction of the particles. Kumar and Sonawane [50] also observed an enhancement in thermal conductivity with increasing temperature and particle concentration. Ferric oxide nanoparticles were dispersed in water and ethylene glycol base fluids to prepare the samples with different particle concentrations (0.01-0.08 vol.%). Then, the ultrasonication process was performed for 50 minutes to homogenize the solution. Phuoc and Massoudi [51] prepared the samples of Fe_2O_3 -water having a particle diameter of 20 to 40 nm and concentration in the range of (0.01-0.04% by volume) to observe the variation in viscosity. To disperse the particles in water, magnetic stirring and ultrasonication was carried out for half an hour. Parsian and Akbari [52] adopted the two-step method to prepare the ethylene-glycol based hybrid nanofluids of copper and alumina. The samples were prepared with various concentrations ranging (0.125-2.0 vol.%) considering a particle mixing ratio of 50:50. To break the clusters and make the suspension more homogeneous the sonication process was carried out for 7h. The solution prepared adopting this method was found to be stabilized for 3 days. For the preparation of MWCNT- Al_2O_3 (15:85)/oil hybrid nanofluid, Asadi et al. [53] used two-step approach. To obtain a stable solution, magnetic stirring was performed for 2 hours prior to 1 hour of sonication.

Despite extensive research into preparation techniques, several challenges remain that limit the wider adoption of nanofluids in practical applications. These include difficulties in maintaining long-term stability, the influence of preparation parameters on thermophysical properties, and the economic trade-

offs involved in large-scale synthesis. Furthermore, a comparative standardisation of preparation protocols such as stirring duration, sonication intensity, surfactant type and concentration remains elusive, which complicates benchmarking and reproducibility across studies. To address these concerns, this study not only adopts a systematic two-step method but also investigates the effects of surfactant selection, ultrasonication, and fluid ageing. The knowledge derived from these experiments supports the ongoing pursuit of scalable, high-performance coolants for use in diverse engineering systems ranging from electronics to electric vehicles and renewable energy technologies.

2.1.2 Mechanism of Heat Transfer in Nanofluids

Heat transfer in nanofluids refers to the process by which thermal energy is transferred within a suspension of nanoparticles in a base fluid. These nanoscale suspensions exhibit unique thermophysical properties that can significantly impact heat transfer mechanisms. The addition of nanoparticles to the base fluid alters its thermophysical properties. Some of the important characteristics of nanoparticles that play a decisive role in the overall performance of the nanofluids include the particle size, shape, thermal conductivity, and intermolecular attraction/clustering effect.

The thermal conductivity and morphology of nanoparticles within a nanofluid play a pivotal role in shaping the efficiency of convection heat transfer, as the available surface area for thermal transport is intricately tied to these two critical factors. Notably, the rate of heat transfer is significantly influenced by the size and shape of the nanoparticles. Additionally, the formation of clusters, driven by intermolecular attractive forces, contributes to an amplification of heat transfer mechanisms. It is crucial to acknowledge, however, that while this cluster formation enhances heat transfer, it concurrently introduces the potential challenge of nanoparticle sedimentation. Transitioning from the considerations of nanoparticle characteristics, it is essential to explore the broader mechanisms that govern heat transfer within nanofluids. Heat transfer in nanofluids is primarily governed by three mechanisms: conduction, convection, and radiation. Understanding the mechanisms of heat transfer in nanofluids is crucial for various applications, including thermal management in electronics, energy conversion systems, and advanced cooling technologies [54].

- Conduction is the process by which heat is transferred between particles directly. Conduction occurs in nanofluids not just between the nanoparticles but also between the nanoparticles and the surrounding fluid.
- Convection is the transfer of heat by the movement of a fluid. In nanofluids, heat can be transferred by convection when the nanoparticles suspended in the fluid are in motion, either due to natural convection (e.g., due to differences in density caused by temperature gradients) or due to forced convection (e.g. when the fluid is pumped through a system).
- The transport of heat by electromagnetic waves is known as radiation. Radiation can happen in nanofluids between the nanoparticles and the environment.

The heat transfer dynamics exhibit variations between stationary and flowing nanofluids. In the case of stationary nanofluids, the predominant mode of heat transfer revolves around conduction. However, in the context of moving nanofluids, the interplay of conduction, convection, and additional transport phenomena introduces a more intricate and dynamic heat transfer mechanism. The literature describes several mechanisms involved in conduction heat transfer within nanofluids, including nanoparticle Brownian motion, nanoparticle clustering, nano-layering effect, nonlocal effect, thermophoretic effect, ballistic transport, and near-field radiation [55], illustrated in Fig. 2.3.

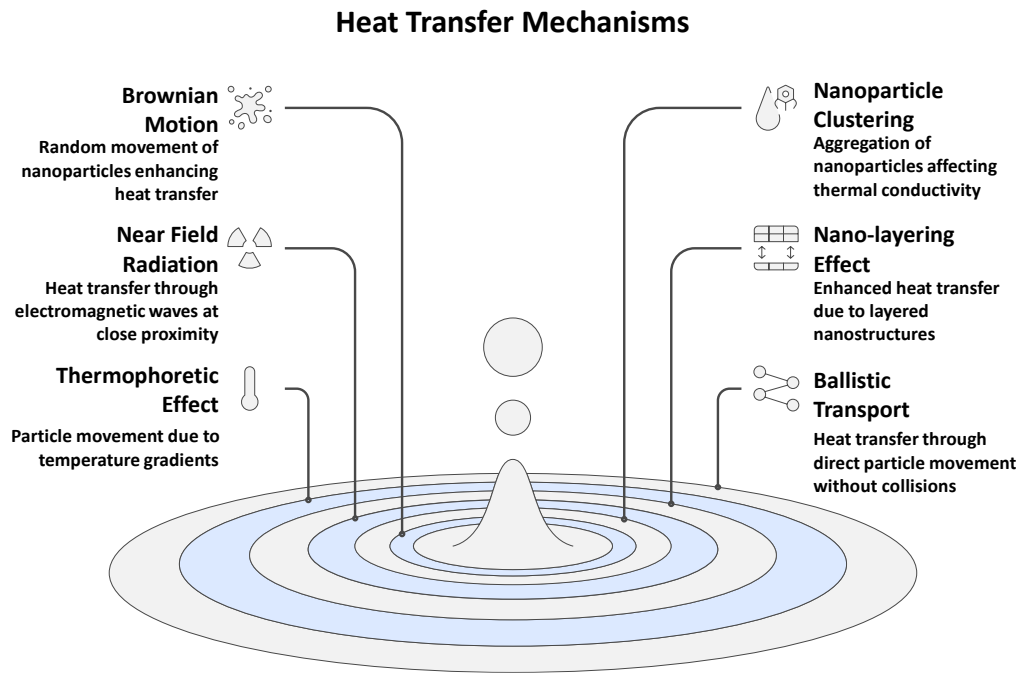


Figure 2.3. Conduction-based Heat Transfer Mechanisms in Nanofluids.

The overall heat transfer coefficient rises as a result of the collisions between the fluid molecules and the randomly moving nanoparticles caused by their thermal motion. This effect, referred to as "enhanced Brownian motion," can improve the nanofluid's overall heat transfer performance.

In addition to enhanced Brownian motion, another mechanism by which nanofluids can enhance heat transfer is through the formation of nanoparticle clusters. When nanoparticles are suspended in a fluid, they may aggregate or cluster together due to various factors such as van der Waals forces, Coulombic forces, or hydration forces. The formation of these clusters can affect the heat transfer properties of the nanofluid. Murshed et al. [56] examined the impact of nanoparticle clustering on the thermal conductivity of aqueous nanofluids containing TiO_2 and Al_2O_3 nanoparticles. According to the findings, the cluster size grows along with nanoparticle concentration, which reduces the augmentation of the thermal conductivity of the nanofluids.

In nanofluids, nano-layering effect is the propensity of nanoparticles to gather at the interface between a fluid and a solid surface, such as the wall of a heat exchanger. The gradual aggregation of nanoparticles at the fluid-solid interface can lead to the formation of a thin layer of nanoparticles on the solid surface,

which can enhance the heat transfer performance of the nanofluid or in some cases it can impact adversely. As time progresses, this layer becomes increasingly thicker, further influencing the heat transfer process.

Thermophoretic effect is a phenomenon that occurs when particles suspended in a fluid are transported by temperature gradients due to a temperature-dependent diffusivity. The thermophoretic effect can lead to the separation or concentration of nanoparticles in certain regions of the fluid. Mehdi Bahiraei [57] studied the impact of thermophoresis on the distribution of nanoparticles in a TiO_2 -water nanofluid flowing through a circular tube. It was found that thermophoresis has a significant effect on the distribution of particles in basefluid, and as the particle size increases, the non-uniformity of the concentration distribution also increases. The results also revealed that thermophoresis increases the concentration distribution's non-uniformity, with the effect being most pronounced at higher mean concentrations. The study conducted by Malvandi et al. [58] on concentric vertical annulus employing Al_2O_3 -water nanofluids observed that the thermophoretic force pushed the particles towards the adiabatic wall, leading to an increase in nanoparticle concentration near the adiabatic wall and a decrease near the heated wall.

The ballistic transport effect and the nonlocal effect are phenomena influenced by the size of nanoparticles. The ballistic transport effect refers to the transport of heat by nanoparticles through the base fluid via ballistic phonon transport, while the nonlocal effect refers to the nonlocal nature of heat transport by nanoparticles due to their small size. These effects can lead to an enhancement in HTC of the nanofluid [59].

In a nanofluid, the nanoparticles can act as "hot spots" that emit near field radiation due to their small size and high surface-to-volume ratio. Near field radiation, sometimes referred to as near field thermal radiation, is the electromagnetic radiation that can be exchanged between two bodies when they are in close proximity. The absorption of this radiation by the base fluid or another nanoparticle can enhance the heat transfer coefficient. Chen et al. [60] investigated the thermal radiation characteristics of nanofluids with nanoparticle aggregation theoretically and experimentally. To conduct the study, titanium dioxide/silver plasmonic nanofluids were prepared in distilled water, and their spectrum transmittance was assessed with different levels of aggregation. According to the findings, nanoparticle aggregation has a substantial impact on the thermal radiation characteristics of nanofluids in the long wavelength band.

A variety of factors such as the size and concentration of the nanoparticles, the kind of base fluid, and the system temperature, determine how much thermal transportation mechanisms affect a nanofluid's ability to transfer heat. In order to exploit nanofluids for heat transfer applications to their maximum potential, it is crucial to properly take into account these parameters.

However, in the moving nanofluids, the cause of heat transfer is the convection heat transfer mechanism. Convection heat transfer, a crucial mechanism in fluid dynamics, is governed by several key factors that significantly impact the efficiency of heat exchange within a fluid medium. These

critical elements include the effective surface area, flow rate, and channel geometry. An increase in surface area increases the heat transfer performance of the system. The increase in surface area can be achieved by increasing nanoparticles size, promoting cluster formation, and increasing the number of nanoparticles, if the size of the nanoparticles is small in magnitude. Flowrate of the nanofluid increases the heat transfer rate due to increasing intermolecular interaction and particle interaction with the channel's surface. Importantly, increasing the flow rate not only leads to a higher thermal transportation rate but also amplifies the turbulence within the fluid. Channel coefficient geometry also plays a critical role in heat transfer augmentation in nanofluids since the surface and geometry of the channel have a direct impact on convective heat transfer.

A variety of mechanisms have been proposed to explain the enhancement of heat transfer in nanofluids, but their relative importance is not equal. The most widely accepted contribution is the increase in effective thermal conductivity arising from the high conductivity of the dispersed nanoparticles and the formation of interfacial nanolayers at the solid–liquid boundary. Recent reviews and modelling studies consistently identify effective thermal conductivity, together with particle aggregation and interfacial layering, as the dominant factors governing the macroscopic behaviour of nanofluids [61].

In contrast, the role of Brownian-motion-induced micro convection and particle-driven mixing is now regarded as much more limited than originally suggested. Molecular dynamics simulations and kinetic-theory-based analyses indicate that the hydrodynamic effects associated with Brownian motion make only a minor contribution to thermal conductivity enhancement, and that the diffusive motion of nanoparticles is often two or more orders of magnitude slower than heat diffusion in the base fluid [62]. Several authors have also argued that some early reports of very large enhancements cannot be fully attributed to Brownian motion or micro mixing alone and may instead reflect measurement artefacts, unstable suspensions, or unaccounted changes in fluid properties [63].

Taking these considerations together, the general consensus is that effective thermal conductivity enhancement is the primary mechanism, followed by more modest contributions from interfacial layering and boundary-layer modification, while Brownian motion effects and particle-induced mixing contribute at a lower order of magnitude. Presenting these mechanisms in a ranked and contextualised manner is essential for understanding how nanofluids may interact with specific channel geometries. It also clarifies that not all reported mechanisms contribute equally, and some may be insignificant depending on the flow regime, temperature range, and particle concentration.

2.2 Thermal Transportation Characteristics of Nanofluids

The distinctive molecular chain behaviour of nanofluids urged the investigators to study this advanced class of coolants as a potential substitute for traditional fluids in heat exchangers, as they have potential applications in various fields. The objective is to attain the highest possible thermal conductivity at the smallest possible concentration of nanoparticles. It notes that conventional fluids such as water and mineral oils have poor thermal characteristics, and that the use of nanoparticles suspended in these

fluids has shown promise in improving thermal properties. The significance of these advancements is further underscored by the comprehensive presentation of key nanofluid characteristics in Fig. 2.4, shedding light on the evolving trends and interests in nanofluid research over time. Figure 2.5 shows the number of publications over time for different properties of nanofluids, based on the Scopus database. The data was obtained by searching with the keyword “nanofluid” and then filtering the results by the property of interest. The publications on thermal conductivity have shown remarkable growth over the years. The numbers have increased significantly, reflecting the importance of understanding and optimising thermal conductivity in nanofluids. This could be attributed to the crucial role thermal conductivity plays in enhancing heat transfer efficiency. Closely followed to thermal conductivity, the number of publications on viscosity has steadily increased, indicating a growing recognition of its importance in the stability and flow characteristics of nanofluids.

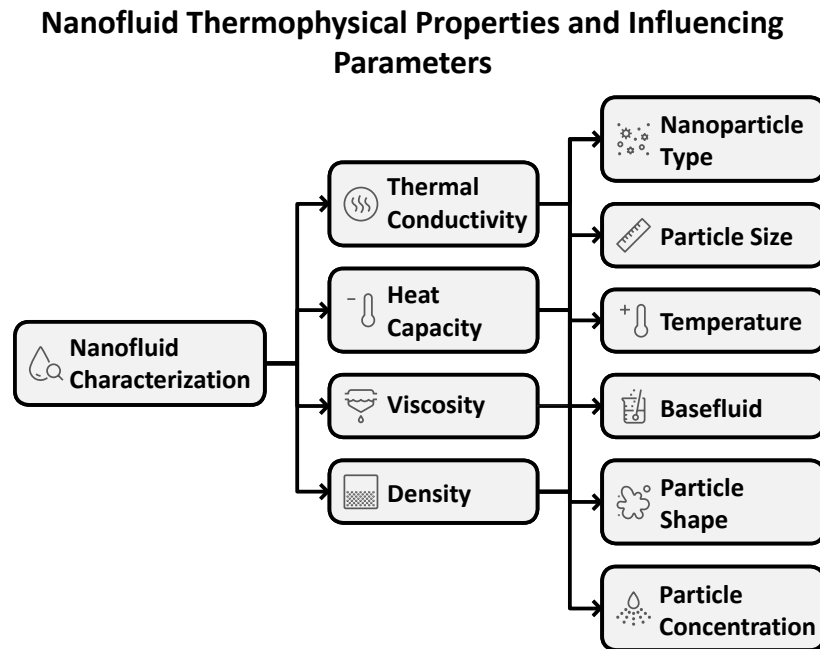


Figure 2.4. Nanofluid characteristics.

The rise in publications may signify efforts to address challenges related to viscosity in practical applications. While density publications have not seen as rapid an increase as thermal conductivity and viscosity, there is a consistent upward trend. The growing interest in density suggests a recognition of its impact on buoyancy and specific heat in nanofluids. Heat capacity, though the least studied property, has witnessed a gradual rise in publications. The increasing attention to heat capacity indicates a growing awareness of its significance in influencing thermal energy storage and heat transfer rates in nanofluids. A comparative analysis across properties reveals that thermal conductivity consistently receives the highest number of publications, followed by viscosity, density, and heat capacity. This order aligns with the perceived importance of these properties in various applications, such as heat transfer and energy conversion.

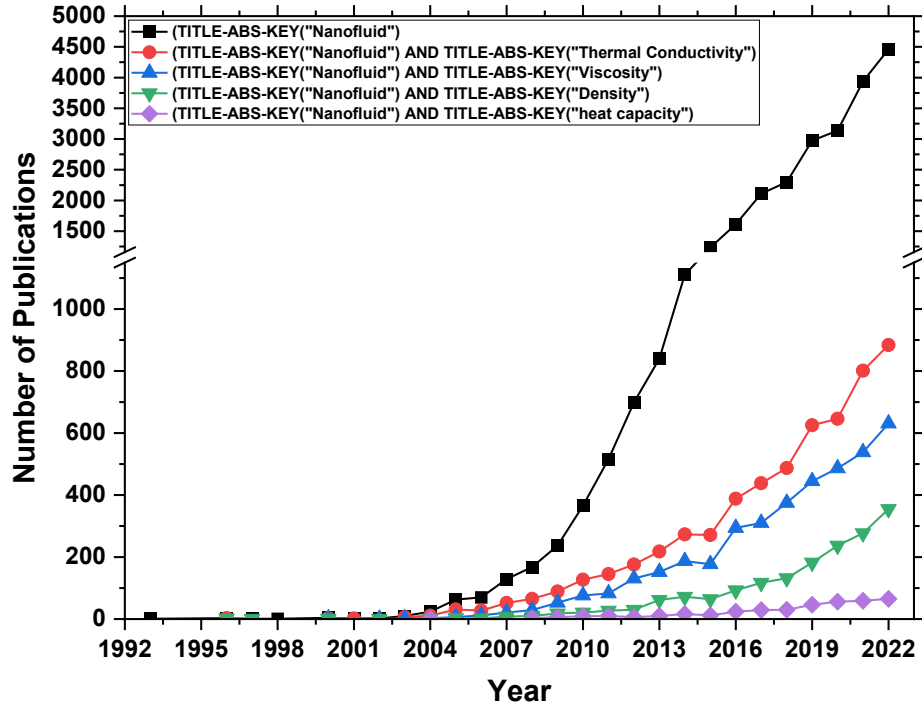


Figure 2.5. Evolution of published studies over time investigating key thermophysical properties of nanofluids (Scopus database).

2.2.1 Thermal Conductivity

Nanofluids, colloidal suspensions of nanoparticles in base fluids, have emerged as a promising frontier in the realm of thermal conductivity enhancement [64]. The manipulation of nanoscale materials within fluids has led to significant improvements in thermal properties, sparking intense research across various scientific disciplines. Due to their small size, nanoparticles experience significant Brownian motion, which leads to enhanced mixing and improved heat transfer characteristics. The motion of nanoparticles creates more interactions between the particles and the fluid molecules, increasing the energy transfer and promoting thermal conductivity. Their viability as advanced heat transfer fluids could revolutionize cooling solutions for microelectronics, lasers, and data centres to manage escalating thermal loads [65]. Additionally, nanofluid-based technologies present opportunities to radically improve the efficiency of industrial heat exchangers and energy systems for significant energy savings and reduced emissions [66].

Several critical parameters exert significant influence on the thermal conductivity of nanofluids, encompassing base fluid properties, nanofluid temperature, fluid flow rate, nanoparticle concentration, Brownian motion of nanoparticles, and nanoparticle size. The choice of base fluid emerges as a pivotal determinant, showcasing a substantial impact on thermal conductivity. Distinct base fluids exhibit varying degrees of thermal conductivity enhancement, attributed to chemical interactions and inherent competence. Timofeeva et al. [67] conducted a study on the thermal conductivity of water-based and ethylene glycol/water-based (50:50) silicon carbide (SiC) nanofluids. The findings revealed that at the

same particle concentrations and sizes, the addition of nanoparticles to ethylene glycol/water resulted in 4-5% higher thermal conductivity enhancements than in water, as illustrated in Fig. 2.6.

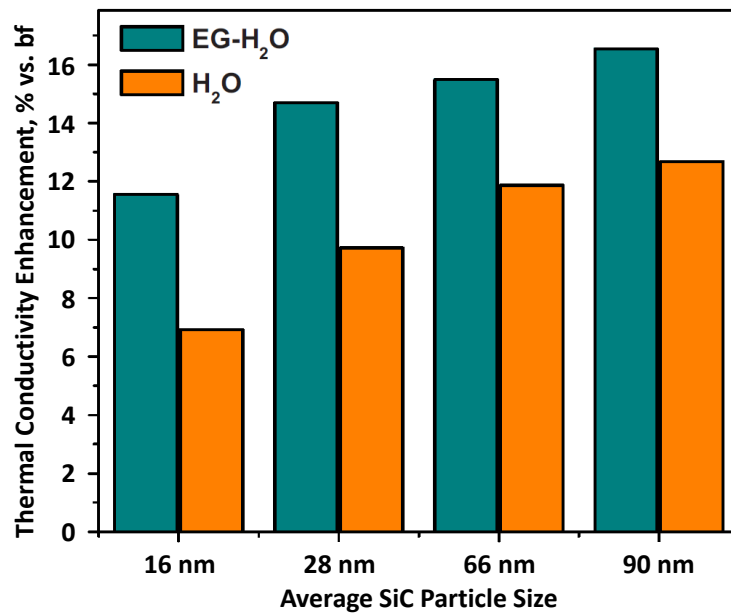


Figure 2.6. Effect of base fluid on thermal conductivity of the nanofluid [67].

In navigating the intricate realm of coolants for various applications, there's a considerable body of research dedicated to the ethylene glycol as a base fluid, despite the fact that water exhibits nearly double the thermal conductivity. Water, a reliable and widespread coolant, undoubtedly carries its thermal weight, but possesses certain limitations, including a low boiling point and a high freezing point. In contrast, ethylene glycol, as a liquid coolant, offers a higher boiling point and a lower freezing point than water, making it a more suitable option for applications requiring a broader temperature range. This makes ethylene glycol better suited for applications needing to operate below water's freezing point or above its boiling point. The high boiling point allows ethylene glycol to remove more heat before turning into a gas, while the low freezing point prevents it from solidifying at low temperatures where water would freeze.

Particles loading is another important parameter that significantly affects the thermal conductivity of the fluid. Increasing the particle loading means more number of nanoparticles, which in turn, enhances the thermal conductivity of the nanofluids. Moreover, as the nanoparticle concentration increases, there is greater molecular interaction, which further contributes to the improvement of thermal conductivity. The effect of concentration on nanofluid thermal conductivity has been presented in Fig. 2.7.

The impact of particle size on nanofluids' thermal conductivity is multifaceted, with conflicting findings. The study conducted by Ambreen and Kim [68] analysed the impact of particle size on the thermal properties of nanofluids. It was found that while the thermal conductivity generally increases with decreasing particle size, the effect is not consistent across all nanofluids. Additionally, the magnitude of the enhancement also depends on the volume fraction and size distribution of the particles.

A large part of the literature reported higher thermal conductivity with smaller particles and others with larger particles.

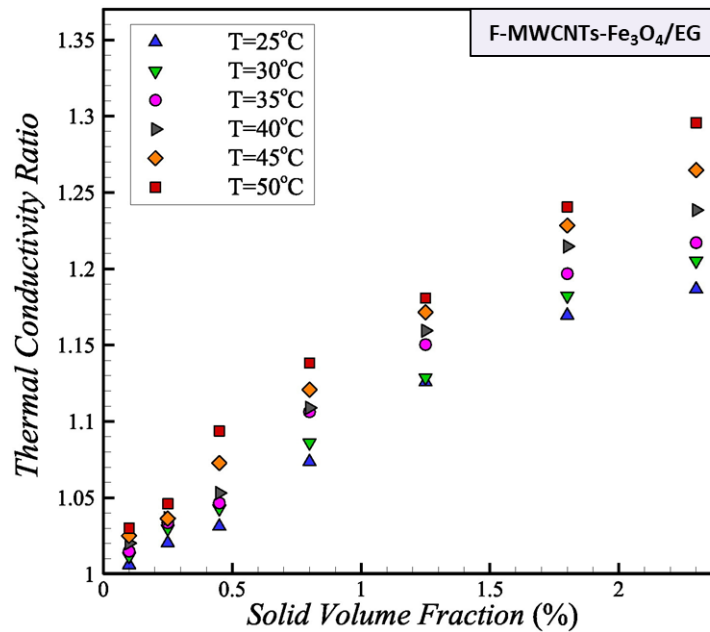


Figure 2.7. Effect of nanoparticle concentration on thermal conductivity of the nanofluid (Harandi et al. [69]).

The cost also needs to be considered while selecting the particles for a particular application. Nanoparticles with sizes smaller than 50nm tend to be relatively more expensive. Therefore, the cost implications should be carefully considered alongside other factors when deciding on the particle size for a given application. In this regard, Alirezaie et al. [70] conducted a study on ethylene glycol based nanofluids consisting various sized nanoparticles of iron (Fe) and magnesium oxide (MgO). The findings indicated that particles with smaller sizes delivered better thermal conductivity values with a penalty of higher production costs, resulting in a lower price-performance ratio. It was concluded that the trade-off between increased thermal conductivity and higher cost must be carefully considered when deciding which particle size to use in different applications. The effect of nanoparticle size on the thermal conductivity of a nanofluid is shown in Fig. 2.8.

The nanofluid has a higher effective thermal conductivity as a result of the increased nanoparticle mobility and interaction brought on by the temperature increase. This trend has been observed in a different type of nanofluids, including those containing metal or oxide nanoparticles suspended in water, oil, or other base fluids. The rate at which the thermal conductivity increases with temperature can depend on a number of factors like the morphological and thermal properties of the particles and thermal and rheological behaviour of fluid. Sundar et al. [71] investigated the influence of temperature on the thermal conductivity of Fe₃O₄/water + EG nanofluid was investigated. The researchers observed that as the temperature of the nanofluid increased, there was a corresponding enhancement in its thermal conductivity. Kole and Day [72] conducted a study on the thermal conductivity of lubricating oil-based

copper oxide (CuO) nanofluid at various fluid temperatures. Their results indicated a significant augmentation of 10% and 12% in thermal conductivity at temperatures of 30 °C and 80 °C, respectively, specifically for a nanofluid with a volume fraction of 2.5%.

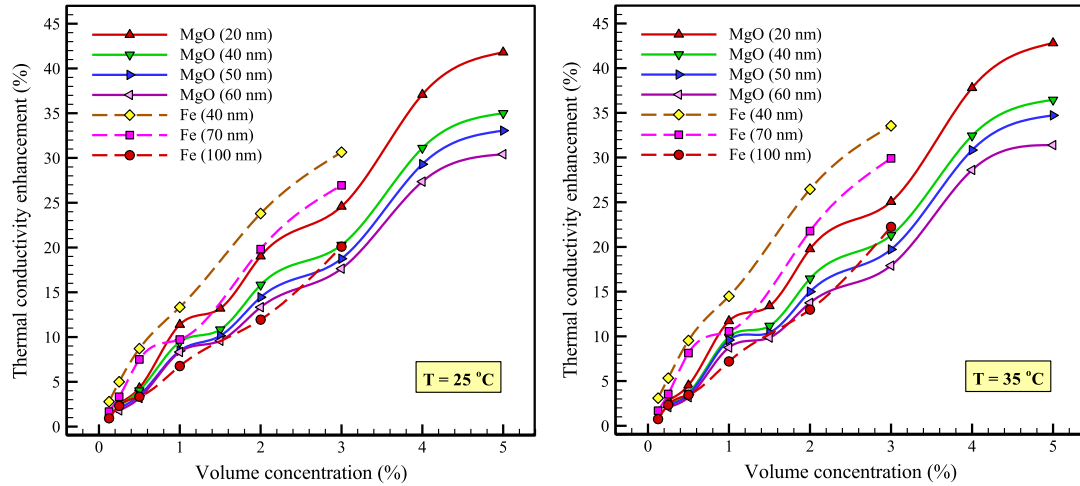


Figure 2.8. Effect of nanoparticle size on thermal conductivity of nanofluid [70].

The thermal conductivity of certain nanofluids can exhibit a maximum value at a specific temperature, beyond which it starts to decline, a phenomenon referred to as thermal conductivity saturation. This behaviour is commonly attributed to nanoparticle aggregation at elevated temperatures, leading to a reduction in their effectiveness as thermal conductors.

The shape of nanoparticles also has a significant effect on thermophysical characteristics. Various nanoparticle shapes, such as spherical, triangular, rod-like, plate-like, and others, exhibit distinct thermal and transport properties [73], as shown in Fig. 2.9. Tailoring the nanoparticle shape can provide opportunities for optimising nanofluid performance in various applications, including cooling systems, energy storage, and heat exchangers.

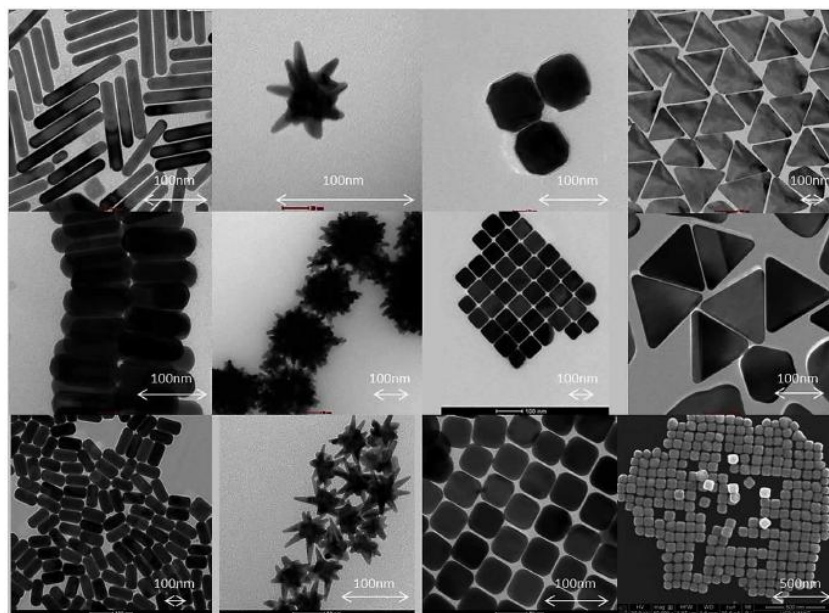


Figure 2.9. Shapes of nanoparticles and shape factor value [73].

Nine et al. [74] investigated the thermal conductivity of Al_2O_3 -MWCNT hybrid nanofluid prepared with different weight concentrations ranging from 1% to 6%. The findings showed that compared to those with spherical nanoparticles, nanofluids with cylindrical nanoparticles showed a larger improvement in thermal conductivity. Spherical nanoparticles are commonly used in many nanofluid applications due to their favourable thermophysical properties. Timofeeva et al. [75] explored the influence of particle shape on the thermophysical properties of alumina nanofluids. The samples were prepared in an equal percentage of water and EG suspending alumina nanoparticles with different shapes, including bricks, platelets, blades, cylindrical, and plates-like structures, Fig. 2.10. The thermal conductivity measurements of the nanofluids revealed that particle shape significantly affects the enhancement in thermal conductivity. The results showed that nanofluids containing blades-shaped nanoparticles exhibited the highest thermal conductivity enhancement compared to the others. The findings from this study highlight the importance of considering particle shape when selecting nanofluids for thermal systems.

Importantly, it has been observed in various studies that the observed thermal conductivity values from experimental studies have exhibited discrepancies when compared to the predicted values derived from conventional theoretical models [76–78]. The divergence between experimental and theoretical predictions underscores the complexity of thermal transport phenomena, urging researchers to reassess existing models and explore additional factors that may influence heat transfer. The realization that conventional theoretical frameworks may not fully capture the intricacies of the thermal behaviour in certain conditions has spurred a reevaluation of the governing principles. Researchers are scrutinizing factors such as nanoscale effects, interfacial interactions, and the impact of particle size distribution, recognizing that these intricacies may play pivotal roles in influencing thermal conductivity.

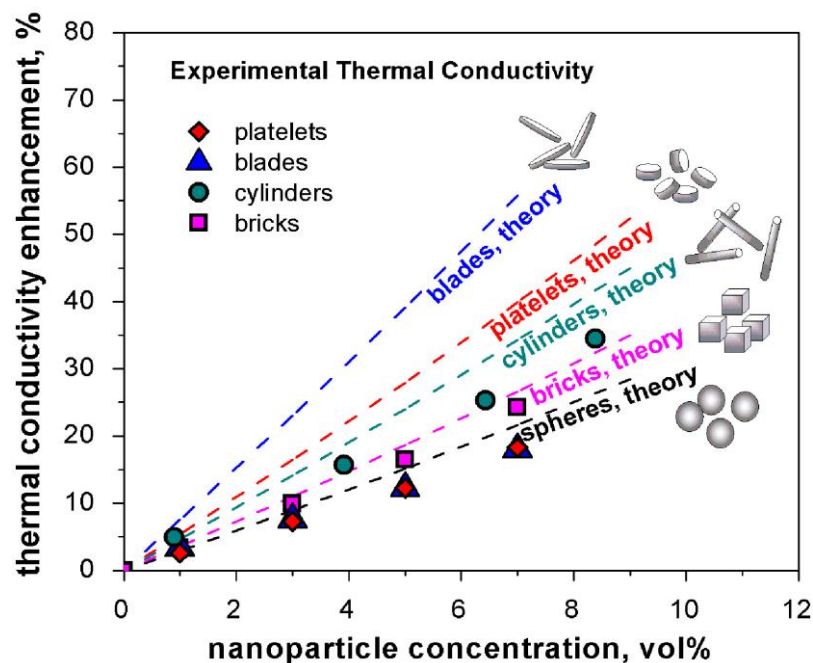


Figure 2.10. Nanoparticle shape effect on thermal conductivity of nanofluids [75].

The comprehensive body of literature pertaining to various nanofluid types underscores a notable lack of uniformity in outcomes. This inconsistency is evident not only across distinct nanofluid categories but also within the same nanofluid composition. Establishing reliable and consistent values for thermal conductivity becomes a formidable task in light of these variations.

Numerous factors contribute to this disparity, including diverse preparation techniques, stability of nanofluids, particle characteristics, properties of the base fluid, uncertainties in equipment, and the presence of measurement errors. Surfactants, pH levels, and Brownian motion introduce other variables that impact the results. These multifaceted influences collectively underscore the complexity inherent in obtaining accurate and consistent thermal conductivity data for nanofluids. Proposed models based on Brownian motion, liquid layering, ballistic phonon transport, and nanoparticle clustering aim to explain experimental observations but a unified theory remains elusive. As nanofluids bridge across disciplines of colloid science, materials engineering, physics, and nanotechnology, developing a universal model for thermal conductivity prediction remains an open quest in the field.

2.2.2 Viscosity of Nanofluids

Viscosity plays a crucial role in the flow characteristics of fluids, which is a measure of a fluid's resistance to flow. It significantly impacts various aspects such as pumping power, pressure drop in laminar flow, and convective heat transfer. The practical utilization of nanofluids in thermal management systems relies on striking a balance between their high thermal conductivity and the low viscosity associated with factors such as nanoparticle type, loading, shape, size, and fluid temperature. The rheology of nanofluids is essential in understanding their flow behaviour and its impact on pressure drop in flow systems like heat exchangers [79]. Accurately determining the rheological behaviour involves examining the relationship between shear rate and shear stress, that is viscosity. Newtonian fluids demonstrate a direct and consistent correlation between shear stress and shear rate, exhibiting a constant apparent viscosity. In contrast, for non-Newtonian fluids shear stress and shear rate did not correlate linearly.

Studies on nanofluid viscosity reveal that these fluids can exhibit both Newtonian and non-Newtonian flow behaviour depending on various factors and conditions. Factors such as base fluid properties, nanoparticle concentration, temperature, shear stress, shear rate, as well as the type and size of nanoparticles, influence the rheological characteristics. These factors influenced the viscosity significantly.

- Size and shape of the nanoparticles: Smaller and more spherical nanoparticles tend to have a lower effect on the viscosity of the nanofluid compared to larger and more irregularly shaped nanoparticles.
- Concentration of the nanoparticles: As the concentration of nanoparticles increases, the viscosity of the nanofluid generally increases.

- Type of base fluid: Different types of base fluids can have different viscosities and can affect the overall viscosity of the nanofluid.
- Surface properties of the nanoparticles: The surface properties of the nanoparticles, such as their surface charge and surface roughness, can affect the way they interact with the base fluid and thus affect the viscosity of the nanofluid.
- Temperature: The viscosity of a nanofluid generally decreases with increasing temperature.
- Shear rate: The viscosity of a nanofluid can also be affected by the shear rate, or the rate at which the fluid is deformed due to an applied force. The viscosity of nanofluid tends to decrease with an increase in shear rate.
- Preparation method: The viscosity of nanofluids is not solely dictated by their composition but is also significantly influenced by the methods employed during the preparation process. Various preparation techniques such as laser ablation, vapour deposition, mechanical stirring, submerged arc method, and ultrasonication play a crucial role in shaping the rheological properties of nanofluids, thereby adding an additional layer of complexity to the understanding of their viscosity behaviour.

Li et al. [80] were among the pioneers in exploring the transport properties of nanofluids. Their investigation revealed that viscosity was influenced not only by volume concentration but also by the size of nanoparticles. The surge in research on convective heat transfer involving nanofluids prompted numerous studies focusing on viscosity. In the early stages, Pozhar [81] made theoretical and simulation efforts to predict the viscosity of nanofluids. Timofeeva et al. [75] studied the impact of nanoparticle shape on the viscosity of ethylene glycol/water based alumina nanofluids. It was observed that the rheological behaviour was significantly influenced by the shape and aspect ratio of the nanoparticles. Specifically, higher viscosity was observed for agglomerated and elongated particles at the same volume fraction, attributed to structural constraints on transitional and rotational Brownian motions. The study recommended the use of spherical particles or spheroids with lower aspect ratios. Additionally, the research demonstrated a notable 31% reduction in the viscosity of alumina nanofluids by adjusting the pH of the nanofluid suspension, attributed to the alteration of surface charge on nanoparticles, influencing particle-particle interactions and agglomeration dynamics. Jeong et al. [82] investigated the viscosity of ZnO nanofluids containing different nanoparticle shapes, including nearly rectangular and spherical particles, at various volumetric concentrations. They found that the viscosity significantly increased with increasing particle concentration, from 5.3% to 68.6% for the nearly rectangular particles and 5.9% to 59.0% for the spherical particles as the concentration varied from 0.5 vol% to 5.0 vol.%. Notably, the viscosity of the nanofluid with the nearly rectangular shape particles was higher by 7.7% compared to the nanofluid with the spherical particles. To validate their findings, the experimental viscosity data was compared with predictions from multiple models. The Batchelor [83] and Brinkman [84] models were observed to underestimate the results, while the Timofeeva model

tended to over-predict. In contrast, the Chen model [85], which considers particle aggregation, demonstrated favourable agreement with mean deviations falling within the range of 1.7-2.2%.

Zhou et al. [86] conducted a comprehensive experimental analysis of the viscosity of several common surfactant solutions under varying conditions. They found that the non-ionic surfactant PVP showed a rapid increase in viscosity at low concentrations, with the zero-shear viscosity at 4 wt% being about twice that of water. In contrast, the viscosity of the ionic surfactants SDS and SDBS did not increase substantially except at higher concentrations where larger micelles formed. The viscosity of all surfactant solutions decreased markedly with increasing temperature, especially for PVP where it dropped by 50% from 20°C to 50°C. At higher temperatures, the viscosity of PVP approached closer to that of the ionic surfactants and water. It was concluded that using PVP surfactant at higher temperatures results in more stable nanoparticle suspensions while also yielding lower fluid viscosity.

Li et al. [87] investigated the viscosity of Cu-H₂O nanofluids, comparing formulations prepared with and without the dispersant SDBS. Their findings underscored temperature and SDBS concentration as pivotal factors influencing nanofluid viscosity. In contrast, the impact of Cu nanoparticle mass fraction was observed to be less prominent within the explored experimental range. Specifically, the apparent viscosity exhibited a decrease with rising temperature and a slight increase with higher SDBS dispersant concentrations. Moreover, viscosity remained largely unchanged with varying Cu mass fractions from 0.04% to 0.16%. At higher nanoparticle loadings beyond this range, viscosity would be expected to increase more substantially.

Mahbubul et al. [88] noted a significant decrease in the viscosity of alumina-water nanofluid as the temperature increased from 10°C to 50°C. This phenomenon was attributed to the weakening of interparticle adhesion forces at elevated temperatures. Additionally, the researchers observed a reduction in nanofluid viscosity with longer ultrasonication duration during the preparation process. The decrease was particularly rapid during the initial hour of ultrasonication, slowing down with extended ultrasonication periods. Interestingly, at lower temperatures, a longer ultrasonication time was required to achieve the minimum viscosity level compared to higher temperatures. These viscosity reductions over ultrasonication duration were linked to improved nanoparticle dispersion and the breakdown of agglomerates, leading to a decrease in flow resistance.

Tiwari et al. [89] studied the impact of different surfactants, sonication times, and temperatures on the viscosity of hybrid nanofluids made of CeO₂ and MWCNT nanoparticles dispersed in various base fluids like water, silicone oil, ethylene glycol, and Therminol VP-I. The findings revealed a nuanced impact of different surfactants, sonication times, and temperatures on nanofluid viscosity. It was noted that viscosity initially decreased with increasing sonication time, reaching an optimal duration that varied for each base fluid, followed by a gradual increase thereafter. Furthermore, viscosity exhibited a linear increase with higher nanoparticle concentrations but underwent a significant decrease as temperatures rose from 55°C to 80°C. Among the tested base fluids, the nanofluid formulated with deionised water demonstrated the least viscosity enhancement. The study also developed a correlation to predict the viscosity of the CeO₂-MWCNT/water hybrid nanofluid, considering temperature and

nanoparticle concentration. The optimised nanofluid, composed of CeO₂-MWCNT in deionised water with the Benzalkonium chloride (BAC) surfactant, demonstrated long-term stability and minimal viscosity enhancement, making it suitable for heat transfer applications. He et al. [90] found that the TiO₂ nanofluids exhibited shear thinning behaviour, with the shear viscosity decreasing rapidly with increasing shear rate until reaching around 100 s⁻¹, above which the viscosity approached a constant value. The constant viscosity was found to increase with both increasing particle concentration and increasing particle size. At a given particle size, the increase of viscosity with concentration was highly non-linear, deviating significantly from the Einstein equation prediction for dilute suspensions. This indicates strong particle interactions in the nanofluids. Compared to particle size, particle concentration had a more significant effect on viscosity. The reasons for the non-linear concentration dependence were unclear, but the authors hypothesised that different nanofluid structures at varying concentrations could play a role. The authors recommend directing readers to recent comprehensive review studies that specifically delve into the intricate aspects of nanofluid viscosity [91–95]. These reviews offer an in-depth exploration and analysis of the latest findings and advancements in the field, providing valuable insights into the complex behaviour of nanofluids. Engaging with these studies is highly recommended for those seeking a thorough understanding of the current state of research on nanofluid viscosity.

The measurement of viscosity can be done through two approaches: experimental measurement and the use of classical or empirical models. Experimentally it is measured using the viscometers or rheometers which have been extensively reported in various studies [96–98]. Alternately, there are several models that have been developed to predict the viscosity of nanofluids there is currently no universally accepted model available that can precisely estimate the viscosity of nanofluids. Researchers commonly used the classical or empirical models based on their experimental data [99]. These models need to be verified as their accuracy can vary depending on the specific conditions of the nanofluid and the assumptions made in the model. The Einstein model [100], a seminal and pioneering approach, stands out as a classic in the field and holds the distinction of being extensively cited and modified. Despite its widespread use, the applicability of the Einstein model is constrained to low concentrations, specifically below 2 vol%. This limitation arises from the model's foundation on the assumption of hard-sphere particles, neglecting particle interactions. The expression for the Einstein model is given by Eq. (2.1).

$$\mu_{nf} = (1 + 2.5\phi_{np})\mu_{bf} \quad (2.1)$$

here, μ_{nf} represents the viscosity predicted by the Einstein model, μ_{bf} is the viscosity of the base fluid, and ϕ denotes the volume fraction of particles. It's crucial to note that the model's accuracy diminishes at higher concentrations due to its inherent simplifications. Consequently, advancements and modifications have been made to address these limitations and enhance the model's applicability in a broader range of concentration regimes.

Following Einstein's pioneering work, subsequent researchers have endeavoured to refine and extend the model through various amendments. One notable enhancement was put forth by Brinkman in 1952

[84], expanding the applicability of the Einstein model to slightly higher volume fractions, up to 4%. Brinkman's modification is expressed through Eq. (2.2).

$$\mu_{nf} = \frac{\mu_{bf}}{(1 - \varphi_{np})^{2.5}} \quad (2.2)$$

Taking into account the Brownian motion within an isotropic suspension of rigid spherical particles and recognizing the impact of particle interactions, Batchelor in 1967 [83] proposed a model that goes beyond the simplifications of earlier formulations, Eq. (2.3).

$$\mu_{nf} = (1 + 2.5\varphi_{np} + 6.5\varphi_{np}^2)\mu_{bf} \quad (2.3)$$

In addition to the aforementioned correlations, several models have been proposed that diverge from the approach of enhancing the Einstein model. These alternative models employ different methodologies or take into account additional influencing factors [101–103]. Each model brings its unique strengths and applicability, addressing specific challenges or phenomena. The emergence of nanofluids has led to the development of numerous empirical models also, often represented as simple mathematical correlations derived from fitting experimental data. A current trend gaining significant attention involves utilizing artificial intelligence such as artificial neural networks for constructing models that predict various properties. In light of these advancements, the authors propose an integration of the latest tools to formulate a comprehensive model capable of accommodating diverse nanofluids. The development of such a general model is envisioned as a substantial contribution to the field, offering a valuable tool for predicting viscosity across a broad spectrum of nanofluid compositions and applications. This pursuit aligns with the evolving methodologies in nanofluid research, paving the way for enhanced predictive capabilities and insights.

2.2.3 Density

The density of nanofluids plays a significant role in influencing various heat-transferring properties, including the pumping power, frictional factor, Reynolds number, and stability. It is considered one of the most crucial thermophysical properties in this regard. The density of a nanofluid depends on the density of the base fluid and the concentration and size of the suspended nanoparticles. The model developed by Pak and Cho [104] is most commonly employed to estimate the value of density, Eq. (2.4). This model considered the effect of particle concentration, density, and the density of basefluid. The model has been employed in numerous investigations and found to be effective at predicting values within acceptable error bounds.

$$\rho_{nf} = \varphi_{np}\rho_{np} + (1 - \varphi_{np})\rho_{bf} \quad (2.4)$$

Vajjha et al. [105] conducted a study to investigate the density of different nanofluids, including alumina (Al_2O_3), zinc oxide (ZnO), and antimony-tin oxide ($\text{Sb}_2\text{O}_3\text{:SnO}_2$) in a water:EG (60:40) base fluid. They

looked at how temperature change affected the density of prepared samples using an Anton Paar digital density meter with a temperature control bath. The outcomes demonstrated good agreement with the Pak and Cho model. In a study conducted by Ganeshkumar et al. [106], the impact of adding MWCNT in a W/EG basefluid on density was investigated by adopting the flask method and the results were compared with the Pak and Cho model. The results indicated that the nanofluid density increased proportionally with MWCNT concentration, and the results showed good agreement with the conventional mixture model at lower concentrations. However, as the concentration increased, particularly at 1.5 wt%, the model noticeably overpredicted the density values, revealing its limitations in accurately capturing the behaviour of nanofluids at higher loadings. This deviation was attributed to complex interactions such as fluid entrapment within nanotube cavities and non-ideal dispersion effects, which are not accounted for in the simple theoretical formulation. These findings emphasize the need for refined models at elevated concentrations and also demonstrate the potential of using high-density nanofluids to enhance thermal inertia in compact heat sink designs, improving their performance under dynamic thermal loads.

The density of nanofluids typically increases with rising nanoparticle concentration; however, the extent of this effect depends on the specific type of nanoparticles and the base fluid used. Interestingly, nanofluids can exhibit anomalous density behaviour, where the addition of nanoparticles may either raise or lower the overall density compared to the base fluid alone. This unique characteristic creates opportunities across various applications: in thermal management and cooling systems, higher-density nanofluids can enhance heat transfer efficiency, while in buoyancy-sensitive industries, lower-density nanofluids can improve system performance. As such, understanding and predicting nanofluid density behaviour remains an active and critical area of research with significant implications for future technological innovations.

Abbasi et al. [107] conducted molecular dynamics simulations to investigate how particle shape and the type of base fluid impact the density of nanofluids, taking into consideration the formation of an interfacial nanolayer around nanoparticles. Their findings revealed that liquid argon formed a thicker nanolayer around silver nanoparticles (1.3 nm) compared to water (0.9 nm), attributing this difference to stronger silver-argon interactions and increased fluctuation freedom of argon atoms. Analysis of various nanoparticle shapes indicated that planar particles exhibited the highest nanolayer density due to their expansive surface area, while nanorods with higher aspect ratios also contributed to increased nanolayer density. Furthermore, the density of nanofluids containing planar and spherical nanoparticles was observed to decrease with an increase in particle diameter. Utilizing an innovative ternary mixture model that accounted for the nanolayer led to significantly improved predictions of nanofluid density compared to traditional binary models, particularly for non-spherical particles. These results offer valuable insights into how the choice of base fluid and the design of nanoparticle shapes can be leveraged to fine-tune nanofluid density through interfacial effects. Karimi and Yousefi [108] devised a sophisticated hybrid model that integrates a back-propagation neural network (BPN) with a genetic

algorithm (GA) to predict the density of four distinct nanofluids. This prediction is contingent on variables such as temperature, nanoparticle volume fraction, base fluid density, and the density ratio between the base fluid and nanoparticles. The model underwent training using experimental density data derived from nanofluids containing ZnO, Al₂O₃, Sb₂O₅/SnO₂, and CuO nanoparticles suspended in water/ethylene glycol mixtures within the temperature range of 273-323K, with volume fractions reaching up to 10%. During testing, the hybrid model exhibited remarkable accuracy, showcasing an impressive mean absolute relative error of merely 0.13% and a correlation coefficient of 0.999 when compared to experimental values. Comparative assessments against radial base function neural network and Pak-Cho models underscored the superiority of the BPN-GA approach, yielding error reductions of 64% and 95%, respectively. This substantiated the higher precision of the BPN-GA model across all studied nanofluids. The researchers concluded that this hybrid model reliably predicts nanofluid density, effectively capturing the impact of temperature fluctuations and nanoparticle loading.

It is worth noting that there is limited data available in the literature regarding the measurement of nanofluid density, particularly for base fluids containing ethylene glycol/water. Measuring the density of nanofluids poses challenges due to the influence of nanoparticles on the fluid's viscosity, which can hinder the accuracy of traditional measurement methods like hydrometers and pycnometers that rely on viscosity, while also affecting surface tension and other physical properties. Additionally, precise control of temperature and pressure is crucial when measuring nanofluid density, considering their potential influence, while the accuracy of density models could also be influenced by nanoparticle size, shape, concentration, base fluid type, and temperature. Nevertheless, to undertake a thorough examination and analysis of the most recent discoveries and progressions in the field, offering valuable perspectives on the influence of diverse factors on the density of nanofluids, the authors seek to bring the readers' attention to the recent review studies that specifically concentrate on the density of nanofluids [109–111].

2.2.4 Heat capacity

The specific heat (C_p) is also a significant property that greatly influences the heat transfer rate of nanofluids. The heat capacity of a nanofluid can be determined through calorimetry techniques, such as differential scanning calorimetry (DSC), by measuring the heat required to increase the nanofluid's temperature by a specific amount. Two specific heat models have been used most commonly in studies to determine the C_p of nanofluids. The first model, proposed by Pak and Cho [104], is based on the volume concentration of nanoparticles, developed considering the formula for liquid-particle mixtures, Eq. (2.5). The second model, presented by Xuan and Roetzel [20], incorporates a heat equilibrium mechanism developed sometime after the first one, represented with Eq. (2.6). The widely used model of Xuan and Roetzel [20] considers both the heat capacity of individual particles and the heat capacity of particles in the fluid and has been found to be generally accurate for a wide range of nanofluids. Zhou and Ni [112] examined the specific heat of alumina-aqua nanofluid as a function of particle volume

concentration using a DSC. Their experimental findings demonstrated a satisfactory agreement with the predicted values obtained from the Xuan model. However, like other models, these models have their limitations and may not consistently deliver precise predictions for all nanofluids. It is crucial to diligently validate the model using experimental data to ensure accuracy and to recognize any potential limitations or uncertainties that may arise. The interaction between nanoparticles and the base fluid plays a crucial role in determining the impact of nanoparticles on the heat capacity of nanofluids, as strong attraction results in effective dispersion and a larger influence, while nanoparticle aggregation or settling leads to a diminished effect on heat capacity.

$$C_{p,nf} = \varphi_{np}C_{p,np} + (1 - \varphi_{np})C_{p,bf} \quad (2.5)$$

$$C_{p,nf} = \left(\frac{\varphi_{np}\rho_{np}C_{p,np} + (1 - \varphi_{np})\rho_{bf}C_{p,bf}}{\rho_{nf}} \right) \quad (2.6)$$

As anticipated the factors, such as the base fluid, the type and size of the nanoparticles, morphology, and concentration of the nanoparticles have a notable effect on the heat capacity of nanofluid. The impact of nanoscale particles on the heat capacity of nanofluids remains inconclusive, with some studies indicating enhancement, reduction, or no change, posing challenges in accurately predicting and designing systems utilizing these fluids. The study conducted by Yarmand et al. [113] on ethylene glycol based activated carbon-graphene nanofluid observed an enhancement in heat capacity with temperature and particle concentration. Robertis et al. [114] employed the modulated temperature differential scanning calorimetry (MTDSC) technique to determine the specific heat of nanofluids. The obtained results demonstrated a strong agreement between the measured specific heat values and the tabulated values of the individual components of the nanofluid (copper and ethylene glycol). Interestingly, the inclusion of copper nanoparticles in the base fluid was found to influence the crystallization and melting processes, resulting in a reduction of the specific heat values of the nanofluids across the entire temperature range investigated. However, the collaborative efforts of different researchers in publishing review studies on the specific heat of nanofluids provide valuable resources for readers seeking a thorough understanding of this particular property [115–118].

2.3 Stability and Use of Surfactants

The stability of nanofluids plays a critical role in determining their long-term effectiveness and reliability in thermal management systems. Without adequate stability, nanoparticles tend to agglomerate and sediment over time, which can lead to inconsistent thermophysical properties, clogging in microchannels, increased pressure drop, and ultimately, performance degradation. Thus, stabilisation strategies both chemical and physical are of paramount importance in nanofluid research and application.

2.3.1 Mechanisms of Instability

Nanofluid instability arises from factors like van der Waals attractions between particles, gravitational settling due to density differences between nanoparticles and the base fluid, and interactions with ions or contaminants in the solution. Temperature fluctuations can further exacerbate instability by altering viscosity and particle motion, potentially accelerating agglomeration or phase separation. These effects are particularly problematic in recirculating cooling systems or long-term industrial applications where consistent performance is essential.

2.3.2 Role of Surfactants in Enhancing Stability

Surfactants, also known as dispersants or surface-active agents, are commonly employed to mitigate instability issues. They function by adsorbing onto the surface of nanoparticles, providing steric or electrostatic repulsion that inhibits particle aggregation. The type and concentration of surfactant significantly influence both the short and long-term stability of nanofluids, as well as their thermal and rheological behaviour.

Common surfactants include:

- **Anionic:** Sodium dodecyl sulfate (SDS), Sodium dodecylbenzene sulfonate (SDBS)
- **Cationic:** Cetyltrimethylammonium bromide (CTAB)
- **Non-ionic:** Triton X-100, Tween-80
- **Natural polymers:** Gum arabic (GA)

Khairul et al. [119] investigated the effects of SDBS surfactant and particle concentration on several important properties of alumina-water and copper oxide-water nanofluids, including stability, viscosity, pH, and thermal conductivity. It was observed that increasing the concentration of nanoparticles could lead to an elevation in the pH levels of both nanofluids. This intriguing change is likely attributed to interactions occurring between the surface of nanoparticles and water molecules. Furthermore, the addition of SDBS surfactant had a similar effect, further pushing the pH towards the alkaline side. Their results revealed that an optimal surfactant concentration exists for each nanofluid formulation that maximises zeta potential magnitude, indicating stability. The optimised surfactant concentration also lowered viscosity and enhanced thermal conductivity. Ma et al. [120] examined the impact of various surfactants, i.e. Polyvinylpyrrolidone (PVP), CTAB, and SDS on the stability and thermophysical properties of hybrid nanofluids of alumina (Al_2O_3), titania (TiO_2), and copper oxide (CuO). According to the results, the non-ionic surfactant PVP was found to be the most effective in retaining stability even at low concentrations. Interestingly, the viscosity values were found to remain close to water at lower PVP concentrations but increased significantly at higher concentrations due to excess surfactant molecules. Significant enhancements in thermal conductivity, with improvements of 12% for Al_2O_3 - CuO and 14% for Al_2O_3 - TiO_2 nanofluids, were achieved at 0.005 wt% and 0.01 wt% PVP

concentrations, respectively. The results demonstrated the importance of surfactants in achieving stable nanofluids and improving their overall thermal characteristics.

Kanti et al. [121] examined the thermophysical properties and stability of water-based graphene oxide (GO) and alumina and their hybrid nanofluids for solar energy applications. They used sol-gel and Hummer's methods for nanoparticle synthesis and assessed stability with different surfactants, finding PVP best for GO and SDBS for Al_2O_3 and hybrids. All the nanofluids demonstrated good stability even after 30 days. Ghadimi et al. [48] conducted a study to assess how the introduction of surfactants and the application of ultrasonication influence the stability and thermal characteristics of nanofluids consisting of titanium dioxide and water. The non-ionic surfactant SDS was found to reduce nanoparticle aggregation compared to preparations without surfactant, but only when coupled with ultrasonication. Ultrasonic horn processing for 15 mins and ultrasonic bath processing for 3 hours both broke down agglomerations into smaller sizes. Analysis of absorbance measurements unveiled that nanofluids with SDS and ultrasonication had improved stability and dispersion compared to simple mixing. It is important to note that the viscosity of these nanofluids also exhibited an increase, likely attributed to the additional interactions between the nanoparticles, a phenomenon induced by the SDS surfactant and the ultrasonication process.

2.3.3 Influence on Thermophysical Properties

While surfactants improve stability, their presence can also influence key thermophysical properties. Depending on the surfactant used and its concentration, thermal conductivity may be slightly reduced due to the interfacial resistance introduced by the surfactant layer. On the other hand, surfactants often increase viscosity, especially at higher concentrations, which can lead to higher pumping power requirements. Therefore, the selection of an appropriate surfactant must balance stability enhancement with minimal negative impact on flow and heat transfer characteristics.

2.3.4 Concentration Optimisation and Zeta Potential

The optimal concentration of surfactant varies with particle type, shape, and size, as well as the base fluid. Excessive surfactant use can lead to micelle formation, foaming, and undesired rheological changes. The zeta potential measurement is a commonly used indicator of colloidal stability; values above ± 30 mV generally indicate a well-dispersed suspension. In this study, zeta potential analysis confirmed that the selected formulations achieved this threshold, particularly in cases where surfactants were carefully tailored to match the surface chemistry of the nanoparticles.

2.3.5 Hybrid Nanofluids and Multi-Particle Challenges

For hybrid and tri-hybrid nanofluids, stabilisation becomes more complex due to the varying surface energies and interactions of the constituent nanoparticles. In such systems, surfactants must be selected

not only for their individual effectiveness but also for their compatibility with mixed-particle interfaces. The study demonstrated that effective dispersion could be achieved using a combination of surfactant strategies, including pre-sonication and sequential mixing, followed by immediate application to avoid sedimentation.

The incorporation of surfactants is essential for achieving stable, high-performance nanofluids suitable for practical thermal systems. The selection must consider compatibility, concentration, and long-term behaviour, especially in multi-particle systems. While surfactants introduce certain trade-offs, their role in enabling sustained nanoparticle dispersion makes them indispensable in advanced heat transfer applications. Future research may explore bio-based or smart surfactants that offer adaptive stability with reduced environmental impact.

2.4 Hybrid and Tri-Hybrid Nanofluids

Hybrid and tri-hybrid nanofluids have emerged as advanced alternatives to conventional mono nanofluids for enhancing heat transfer in thermal systems. By combining two or more types of nanoparticles in a single base fluid, these formulations aim to leverage the unique thermal, morphological, and chemical properties of each constituent particle, thereby achieving improved thermophysical performance, enhanced stability, and cost-efficiency. This approach is particularly valuable in engineering applications that demand high heat dissipation, compact design, and operational reliability under varying thermal loads.

In 2007, Jana et al. [78] made a pioneering contribution to the field of nanofluid research by introducing hybrid nanofluids. Hybrid nanofluids are a groundbreaking innovation, as they comprise two different types of nanoparticles. These nanoparticles may belong to the same family in some cases, but more often, they come from distinct families. For instance, one type may be from the oxide family, which provides superior stability but lower thermal conductivity, while the other type is from the metallic family, offering superior thermal characteristics but lacking in stability. This characteristic allows hybrid nanofluids to harness the synergistic effects between these materials, resulting in significantly improved physical properties compared to traditional nanofluids. This approach has opened up exciting possibilities for enhancing various aspects of nanofluid performance. Hybrid nanofluids offer a versatile solution as they can be tailored to meet specific application requirements [122,123]. The ability to combine different nanoparticles allows for the optimisation of thermal properties while considering cost constraints. This adaptability makes hybrid nanofluids applicable across various industries and technological domains.

2.4.1 Rationale for Hybridisation

Mono nanofluids, consisting of a single nanoparticle dispersed in a base fluid, have been extensively studied and shown to improve thermal conductivity relative to pure fluids. However, the performance

of mono nanofluids can be limited by factors such as particle agglomeration, sedimentation, and suboptimal thermal conductivity at low concentrations. Hybrid nanofluids address these limitations by introducing a secondary (or tertiary) nanoparticle that may enhance dispersion, modify fluid rheology, or provide synergistic improvements in thermal conductivity, specific heat, and viscosity.

The combination of metallic (e.g. Ag, Cu), metal oxide (e.g. Al_2O_3 , BeO), and ceramic (e.g. SiC, AlN) nanoparticles can yield significant gains in thermal transport due to improved phonon and electron conduction pathways. Additionally, the variation in surface energy and interparticle forces among the different types of nanoparticles contributes to improved suspension stability by disrupting uniform aggregation and reducing the tendency for particle agglomeration.

2.4.2 Recent Advances and Performance Trends

The field of nanofluid research has witnessed significant evolution, transitioning from mono nanofluids toward more complex hybrid and tri-hybrid formulations. This progression is driven by the growing need for highly efficient, stable, and application-tailored thermal fluids capable of meeting the demands of miniaturised systems, high heat flux electronics, and multifunctional heat exchangers. Recent advances focus not only on enhancing thermal conductivity but also on maintaining or improving stability, flow behaviour, and economic feasibility under practical operating conditions. Guan et al. [124] explored the enhancement of thermal conductivity in hybrid nanofluids through molecular dynamics simulations, specifically focusing on Cu-Ag nanoparticles suspended in liquid argon (Ar). Their results showed that the Cu-Ag 50%/Ar hybrid nanofluid outperforms unitary nanofluids, with a remarkable 69.7% increase in thermal conductivity compared to pure liquid Ar. Analyses revealed that Ar atoms at the nanoparticle surface engage in dynamic equilibrium, influencing density, diffusion, and ultimately thermal conductivity. Their study also highlighted the potential of hybrid nanofluids for optimising heat transfer by fine-tuning nanoparticle material combinations and ratios to enhance the nanolayer structure and dynamics.

Contreras et al. [125] investigated the thermohydraulic characteristics of graphene and silver nanofluids as automotive coolants. The nanofluids were formulated by dispersing nanoparticles within a mixture of water and ethylene glycol in a 50:50 ratio. To evaluate practical performance, heat transfer experiments were carried out within an automotive radiator test configuration. The results revealed that, in comparison to the base fluid, thermal conductivity of nanofluids exhibited enhancements ranging from 1.3% to 9.2% for silver and 2.4% to 9.2% for graphene. The viscosity was found to be increased by 10.8% for silver in comparison to the base fluid, however, a noticeable decrease was observed as the temperature rose. Additionally, the findings demonstrated that silver nanofluids illustrated a notable maximum heat transfer enhancement of 4.7%, suggesting their potential to enhance the performance of automotive cooling systems. However, it was observed that graphene nanofluids yielded varying outcomes, indicating limited benefits in this particular application. Sharma et al. [126] investigated the thermophysical properties of polydisperse SiO_2 nanoparticles dispersed in an aqueous glycerol mixture.

The nanofluids were formulated with different sizes of nanoparticles (15, 50, and 100 nm) in a glycerol-water mixture at concentrations of 0.5 vol% and 1.0 vol%. The results demonstrated a clear trend of increasing thermal conductivity with rising temperature for both the base liquid and the nanofluids. At 0.5 vol% and 60°C, SiO₂ concentration, the thermal conductivity exhibited an increase of 11.1% relative to the base liquid while the addition of nanoparticles led to a 32% rise in viscosity.

Tri-hybrid nanofluids represent the latest generation of nanofluids, incorporating three different types of nanoparticles to exploit multiple enhancement mechanisms. These systems allow greater flexibility in tuning fluid properties and are particularly useful in multi-objective optimisation scenarios where thermal performance, viscosity, and cost must be simultaneously balanced. Formulations such as MWCNT–Ag–AlN have shown remarkable results in terms of thermal conductivity enhancement, with manageable increases in viscosity. However, the complexity of multi-particle systems introduces new challenges in dispersion stability, particle interaction, and formulation repeatability.

2.4.3 Thermophysical Behaviour and Trade-offs

The thermophysical properties of hybrid and tri-hybrid nanofluids are highly dependent on the volumetric ratios of the constituent particles, particle size and shape, base fluid properties, and the method of preparation. Generally, an increase in particle concentration improves thermal conductivity but also raises viscosity, which can negatively affect pumping power. Therefore, achieving an optimal balance between enhanced heat transfer and acceptable flow resistance is essential for practical applications.

In the present study, various volumetric ratios such as 20:80, 40:60, 60:40, and 80:20 were employed for binary hybrids, while tri-hybrids were tested at combinations like 20/20/60, 20/40/40, and 20/60/20. The experiments revealed that specific combinations could provide stable suspensions with enhanced thermal performance without significantly increasing viscosity, particularly when aided by appropriate surfactants (e.g. SDBS) and dispersion techniques (e.g. probe sonication).

Interestingly, in the case of SiC containing nanofluids, unique aggregate formations in the form of “chains” were observed, indicating the potential for anisotropic conduction pathways. These structural features can be advantageous under controlled flow conditions, potentially increasing directional thermal conductivity, though they also raise questions about long-term stability and uniformity of dispersion.

2.4.4 Economic and Practical Considerations

In addition to performance, the economic viability of hybrid nanofluids is increasingly important for large-scale adoption. High-cost materials such as Ag, graphene, carbon nanotubes may not be feasible for routine use in industrial systems. This has led researchers to explore cost-effective alternatives or combinations where a small proportion of a high-performance particle is used alongside cheaper carriers

(e.g. using SiC, BeO, or AlN with minimal Ag). The goal is to maintain thermal performance while keeping material costs and environmental impact within acceptable limits.

Furthermore, the long-term behaviour of hybrid nanofluids under real operating conditions—such as cyclic thermal loading, shear stress, and extended service time—requires more detailed investigation. Currently, much of the research focuses on short-term laboratory-scale experiments, and efforts are needed to assess the durability and performance consistency of hybrid and tri-hybrid formulations in practical systems.

Hybrid and tri-hybrid nanofluids represent a promising frontier in heat transfer fluid development, offering superior thermal performance, better dispersion behaviour, and greater design flexibility. By carefully selecting particle types, ratios, and stabilisation methods, it is possible to develop cost-effective and efficient coolants tailored for advanced thermal applications. However, further work is required to validate their long-term reliability, economic feasibility, and environmental sustainability under industrial conditions.

2.5 Bibliometric Analysis

A method of evaluating scientific output known as bibliometry involves the use of mathematical and statistical methods [127]. In this study, the Scopus database was used as it contains a wider range of publications in the field of engineering compared to Web of Science, to facilitate the research process [128,129]. The bibliometric analysis is performed to evaluate the impact and productivity of research, spot trends and patterns in research output, and identify research gaps for potential new areas of investigation. Additionally, it would also be helpful to provide valuable information for funding agencies, academic institutions, researchers seeking collaborations, and those looking to inform future research directions. The methodology adopted to conduct this study involves searching the Scopus database using the query string “(TITLE-ABS-KEY("heat exchanger") AND TITLE-ABS-KEY("nanofluid"))”. The data collection was conducted in May 2023, from the invention of nanofluid to 2022. The search returned 1940 documents, which included a variety of publication types such as original articles, books, review studies, conference papers, book chapters, conference reviews, errata, letters, and editorials.

The evaluation of the publications involved utilizing bibliometric analysis methodologies found in the relevant literature [129–131]. These methodologies suggested categorizing the publications based on various criteria such as publication type, language, yearly distribution, country and institution distribution per year, subject area, authors, journals, and keywords utilised. The analysis of correlations between authors and keywords was conducted using VOSviewer, a program designed for visualising and constructing bibliometric networks. VOSviewer is a powerful tool for presenting comprehensive bibliometric maps in a user-friendly and comprehensible manner [132]. Figure 2.11 illustrates the sequential process undertaken to carry out a bibliometric study.

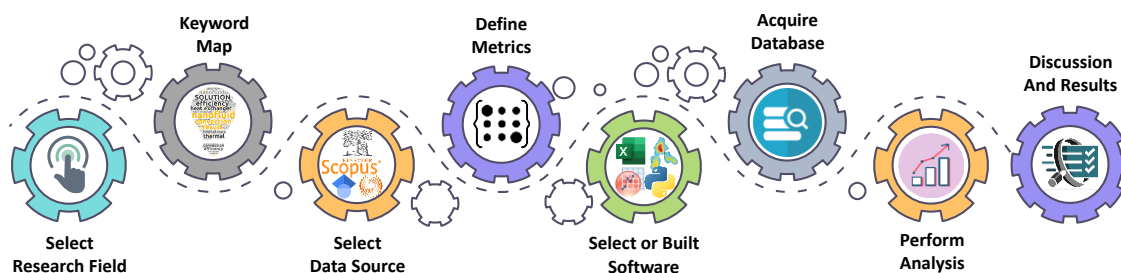


Figure 2.11. Stages of methodology for conducting a bibliometric study.

Figure 2.12 depicts the quantitative visualisation of the research trend based on the year of publication, as determined by the data obtained from Scopus. The graph also presents the annual count of experimental studies and numerical or theoretical studies. It is crucial to highlight that statistics for experimental and numerical studies were collected by filtering results with the terms "experimental" and "numerical or theoretical," respectively. The substantial surge in publications related to nanofluids in heat exchangers was first observed after 2008. This may be due to a number of factors, including the increasing availability of high-performance computing resources, formulation of new nanofluids, the development of innovative nanofluid synthesis methods, and realization of the potential benefits of nanofluids for heat exchanger applications.

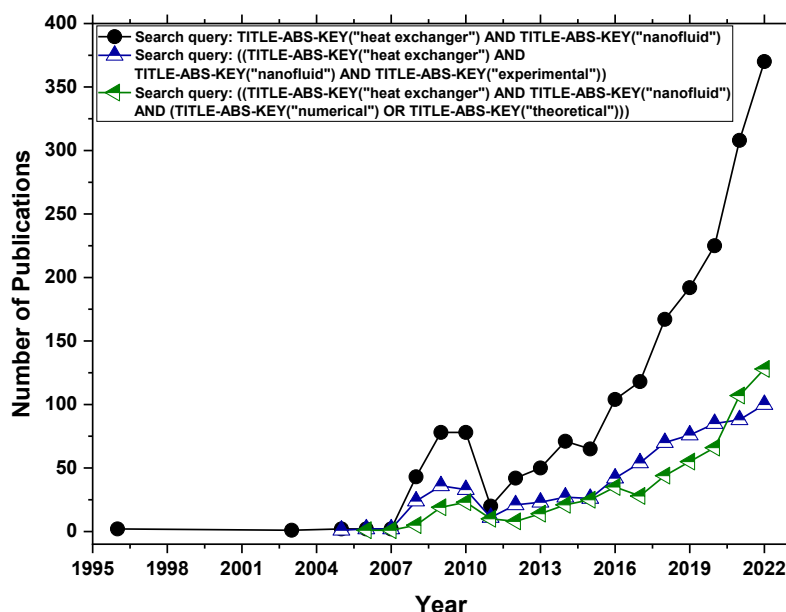


Figure 2.12. Number of publications over time (Scopus database).

Analysing the data, the first study was published in 1996, just after the invention of nanofluids in 1995, the number of documents increased steadily from 1996 to 2022, with some fluctuations along the way. It is noted that, the number of publications remained comparatively low from 1996 to 2011, ranging from 1 to 78 documents per year. However, starting from 2012, there has been a noticeable increase in the number of publications. The years 2021 and 2022 exhibit the highest number of publications, with 308 and 370 documents, respectively.

This data suggests a growing interest and research activity in the field, particularly in recent years. The substantial increase in publications from 2012 onwards indicates an accelerating research trend and emphasises the importance and relevance of the topic. However, it is important to note that this analysis is limited to the Scopus database, and other factors, such as the extent and inclusiveness of the database, may influence the results.

Figure 2.13(a) sheds light on the research productivity of the institutions based on the number of publications associated with each. Several institutions are renowned for their research contributions, here we mentioned the top ten. Universiti Malaya has the highest number of publications followed closely by Islamic Azad University and King Abdulaziz University. Performing such an analysis helps researchers identify areas where research on a particular topic is highly stimulated, as well as areas where a certain stagnation or limited activity can be observed. Figure 2.13(b) highlights the involvement of various funding bodies in supporting research endeavours. This analysis indicates the financial support provided by these funding bodies for research activities. The involvement of these funding bodies underscores their commitment to promoting scientific research and development in their respective regions. The data of these funding bodies helps researchers by providing valuable information on available funding sources and guiding them in aligning their research proposals with the funding priorities, increasing their chances of securing financial support for their work.

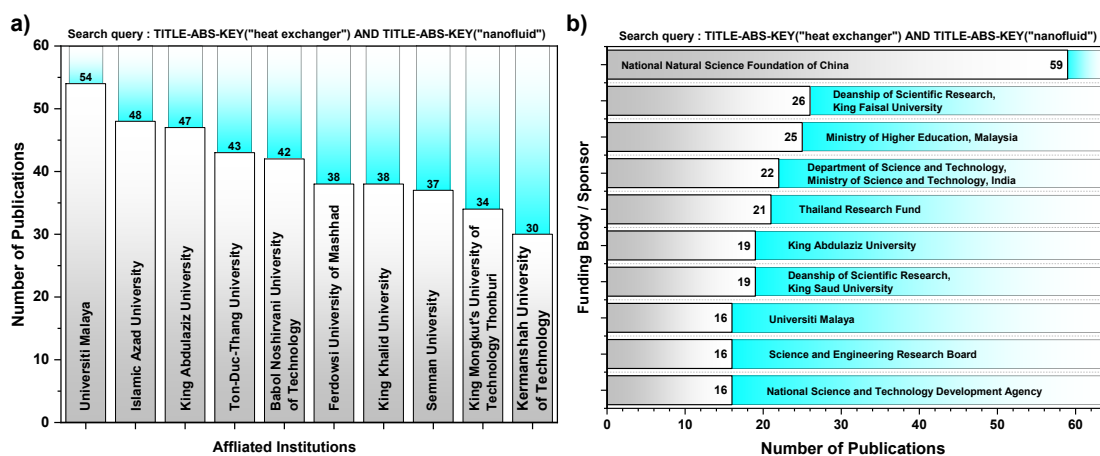


Figure 2.13. Stats of the top ten institutes and funding bodies.

Figure 2.14(a) depicts the distribution of research publications across different countries. The data indicates that research efforts are being made by several countries across the globe. India emerges as the leading country with 525 publications, followed by Iran (450), China (214), Saudi Arabia (167), and the United States (159). The stats provide valuable insights into the research productivity of various countries and highlight their contributions to the scholarly landscape. It underscores the global nature of research and the commitment of researchers worldwide to advancing knowledge and innovation in their respective fields.

Figure 2.14(b) provides insights into the relationship between countries publishing on the topic, revealing a strong interconnectedness among them. It is noteworthy that countries with significant contributions are not only conducting research in the field but also engaging in global collaborations to effectively leverage nanofluids for enhancing heat exchanger performance. This highlights the collaborative nature of research and the collective efforts towards advancing knowledge and applications in this domain.

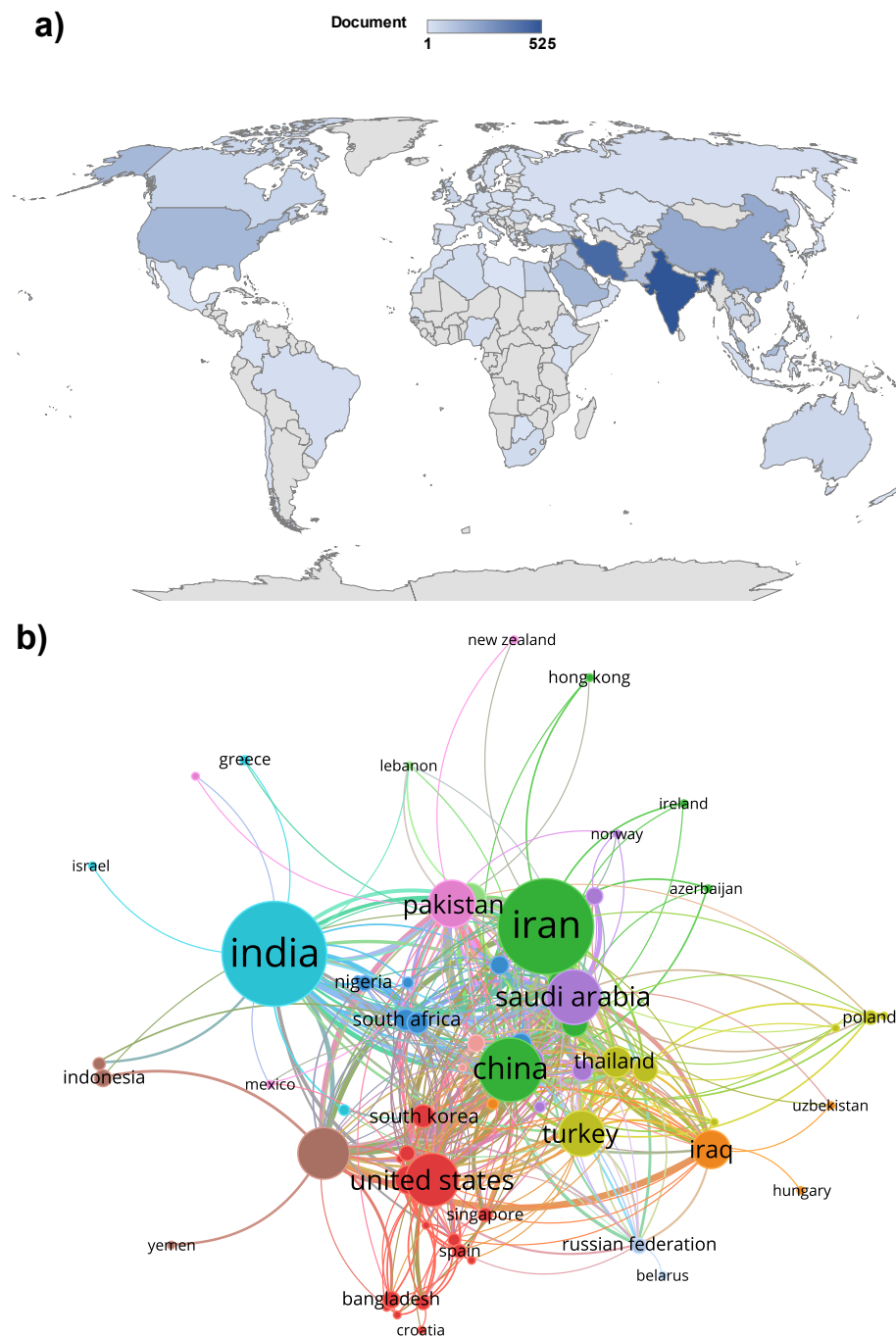


Figure 2.14. Global dissemination of published research and the interconnectedness of countries engaged in collaborative scientific efforts.

Figure 2.15 illustrates the distribution of research publications across various subject areas, highlighting the multidisciplinary nature of the field. Engineering emerges as the leading subject area with 1026 publications, followed by Physics and Astronomy with 811, and Chemical Engineering with 765. Next to it, there are a significant number of documents in the field of Chemical Engineering and Materials Science further emphasising the pivotal role in the development and characterization of nanofluids. The analysis proved the diverse range of subject areas involved in research related to the topic, highlighting the significance of interdisciplinary collaboration and the potential for cross-pollination of ideas and methodologies across multiple fields.

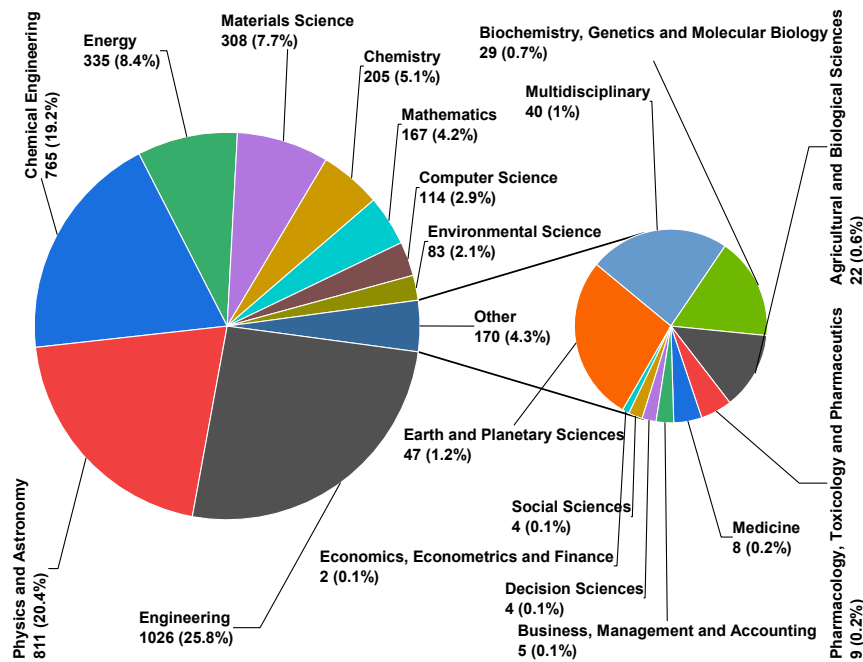


Figure 2.15. Distribution of publications across different subject areas.

To gain a deeper understanding of the relationship between the scientific content and the discussed bibliometric trends, a network analysis of keywords was conducted. Figure 2.16 illustrates the relationships and frequency of different keywords within the subject under investigation. The most frequent keyword in the literature on nanofluids is "nanofluid," occurring in 698 publications. The keywords "heat transfer" (291), "nanofluids" (284), "heat exchanger" (238), and "heat transfer enhancement" (135) are also frequently used by the authors.

Interestingly, "hybrid nanofluid" (113) appears to be a significant keyword, indicating the growing interest in combining different types of nanoparticles in nanofluids to achieve enhanced thermal properties. Other important keywords include "pressure drop" (112), "thermal conductivity" (107), "Nusselt number" (103), "entropy generation" (84), and "heat transfer coefficient" (80). The use of numerical simulations is evident from the appearance of "CFD", "finite element method", and "artificial neural network" as keywords. The keywords like "experimental study", "experimental", and "correlation" suggest the significance of experimental studies. The importance of thermal properties of

nanoparticles is also evident from the keywords "thermal resistance" and "thermal conductivity". In summary, the analysis demonstrates the emphasis on the fundamental understanding and practical applications of nanofluids in heat transfer systems.

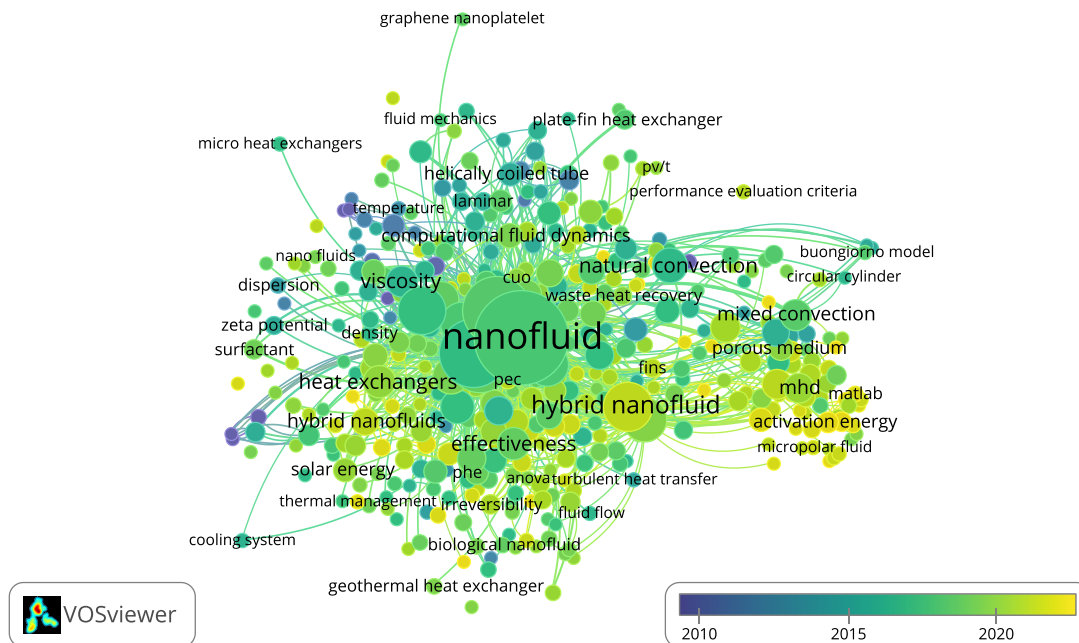


Figure 2.16. Co-occurrence and interconnection of keywords.

Figure 2.17 presents the co-citation statistics of the top fifteen authors in the field of nanofluids in heat exchangers, based on the Scopus database. The co-citation analysis provides insights into the influential authors within the research community. The presence of multiple authors from various institutions suggests collaborative research efforts and the exchange of ideas within the scientific community. Their research output contributes to advancing knowledge and understanding in the field, and their expertise can be valuable for researchers seeking authoritative references or collaboration opportunities. SUS Choi emerges as the most highly cited author, known for introducing the concept of nanofluids and has conducted pioneering research in this area. His research has focused on enhancing thermal conductivity and understanding the behaviour of nanofluids. Furthermore, he has collaborated on studies investigating the effects of various parameters on nanofluid thermal conductivity and the role of interfacial layers in enhancing thermal conductivity. Choi's research has contributed to the development of fundamental understanding and application of nanofluids in heat transfer, establishing him as a key figure in the field.

Somchai Wongwises is the second one on the list, a researcher from the Department of Mechanical Engineering at King Mongkut's University of Technology Thonburi, has made significant contributions to the field of nanofluids and related areas. He has authored numerous articles that centre around the utilization of nanofluids in diverse domains such as solar energy, improving heat transfer, and enhancing heat exchangers. Wongwises' research has covered a wide range of topics, including the thermal conductivity and viscosity measurements of nanofluids, heat transfer characteristics, and the

effects of nanofluids on evaporation rates and boiling heat transfer. He has conducted experimental studies, critical reviews, and modelling investigations to explore the behaviour and potential applications of nanofluids. Wongwises has conducted extensive research on heat transfer enhancement using nanofluids in heat exchangers. They have investigated the effects of different parameters, such as nanoparticle size, tube roughness, and thermophysical properties, on heat transfer efficiency and pressure drop. Wongwises' work also includes reviews of the current state of knowledge in areas such as flow and heat transfer characteristics in curved tubes, entropy generation in nanofluid flow, and electrohydrodynamic enhancement of heat transfer. Ranked third on the list, Saidur Rahman is a prolific author in the field of renewable and sustainable energy. Their research group has published numerous articles and reviews on a wide range of topics, including nanofluids, biomass fuel, solar energy, wind energy, energy savings strategies, and electrical motors. Their work covers various aspects of energy research, including applications, challenges, policy, analysis, and technology development. Saidur Rahman's research on nanofluids explores their applications and challenges, as well as their stability properties and characterization. Nanofluid-based coolants in automotive car radiators and the use of nanofluids as absorbers in direct solar collectors have also been investigated in their studies.

Next on the list is Mohsen Sheikholeslami, a highly accomplished author in the field of heat transfer and nanofluid dynamics. Sheikholeslami's research explores the impact of thermal radiation, magnetic fields, Lorentz forces, and porous media on nanofluid flow and heat transfer. Their research group developed innovative computational approaches and numerical simulations to analyse the behaviour of nanofluids and their application in diverse systems. His studies have examined the influence of magnetic fields on forced convection, natural convection, and free convection heat transfer in different geometries.

In addition to nanofluids, Sheikholeslami has also investigated the behaviour of ferrofluids, convective heat transfer in semi-annulus enclosures, and the use of innovative heat transfer enhancement methods. Their research has provided valuable insights into the mechanisms governing heat transfer and fluid flow, and has practical implications for designing efficient and sustainable energy systems.

Wei Yu is an accomplished author affiliated with Shanghai Second Polytechnic University, specializing in the field of advanced thermal materials, especially graphene-based thermal interface materials, silicone-based thermal greases with graphene additives, phase change materials, thermal gels, cooling films, and various types of nanofluids [133–138]. Professor Yu has also explored the influence of nitrogen doping on the thermal conductivity of carbon nanotubes, shedding light on the intricate relationship between doping, defects, and phonon scattering. Additionally, he has investigated modified graphene papers with alkaline earth metal ions, showcasing substantial improvements in thermal conductivities through ion chelating mechanisms. Collaborating with Xie and other colleagues, Yu has published numerous articles focusing on the preparation, stability mechanisms, and applications of nanofluids. Yu and the team have studied the influence of various nanoparticles, including TiO_2 , SnO_2 , MgO , diamond, and Ag/MWNT composites, on thermal transport and heat transfer performances.

Additionally, Yu extends beyond nanofluids to include the synthesis and characterization of different nanomaterials, such as copper colloids, heterostructured nanofibers, and nanocomposites for photocatalytic applications.

Jeffrey A. Eastman is a materials scientist who worked alongside SUS Choi to introduce the concept of nanofluids. He has worked extensively at the Argonne National Laboratory in Illinois, United States. Eastman and Choi have collaborated on several research articles exploring the thermal properties and applications of nanofluids. Their seminal paper, published in 1995 [17] introduced the concept of using nanoparticles to improve the thermal properties of fluids. This work opened up new possibilities for enhancing heat transfer in various industrial processes and thermal management applications. His expertise spans a wide range of materials science and engineering areas, and his contributions have been widely cited by the scientific community.

Masoud Afrand is a researcher known for his work on heat exchangers and nanofluids. He leads a highly active research group that has made significant contributions to the field. Afrand has investigated how various hybrid nanofluids behave rheologically and their impact on heat transfer. His work sheds light on the benefits and challenges of utilizing nanofluid potential in heat transfer systems. In multiple studies, he investigated the effect of temperature, nanoparticle concentration, and volume fraction on the viscosity and flow characteristics of nanofluids. These findings can help in designing more efficient heat exchangers by considering the fluid dynamics and flow properties of nanofluids. Afrand's research also involves the development of correlations and models for predicting the thermal and rheological properties of nanofluids. By establishing these correlations, engineers can estimate the heat transfer and fluid flow characteristics of nanofluids without extensive experimentation, facilitating the design and optimisation of heat exchanger systems. However, given the diverse nature of nanofluids and the various influencing factors, such as preparation techniques, particle characteristics, base fluid properties, and stability, it is important to note that the correlations developed by Afrand's group may not universally apply. In a more nuanced approach, it is suggested that employing a consistent preparation method and using the same particles could enhance the reliability of these correlations when predicting properties.

The work of Ali J. Chamkha encompasses various aspects of heat transfer, including natural convection, mixed convection, and forced convection in different fluid media and geometries. Chamkha has made contributions to the field of magnetohydrodynamics (MHD) and its applications to heat transfer [139–141]. Chamkha's work extends to the modelling and simulation of heat transfer processes in porous media, offering valuable insights into their ubiquitous presence in nature and wide-ranging engineering applications. He has studied the MHD flow of fluids in the presence of magnetic fields, heat generation/absorption, and chemical reactions. His research has elucidated the mechanisms of heat transfer in porous media, including conduction, convection, boundary layer formation, and phase change, and has led to the development of improved analytical and numerical methods for analysing these processes [142–144].

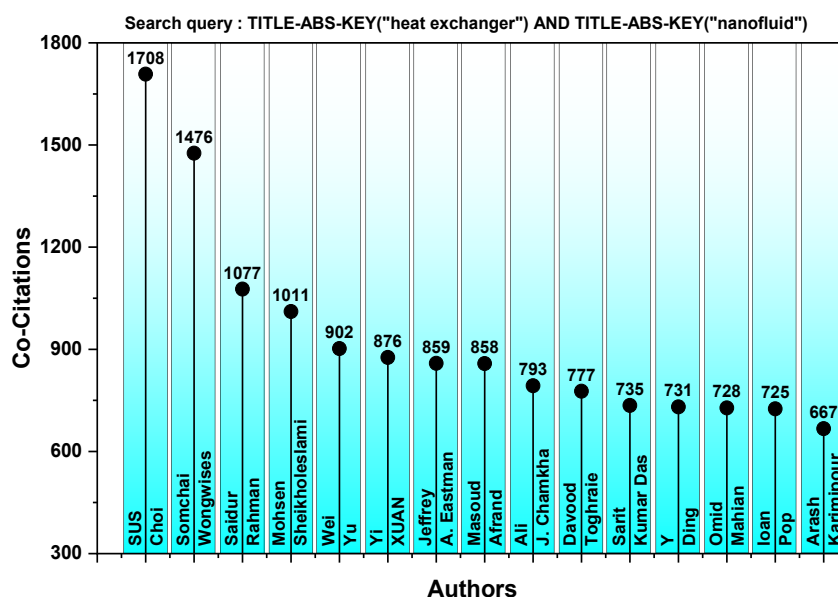


Figure 2.17. Co-citation matrices of the top 15 investigators around the world.

The bibliometric analysis conducted on the research efforts in the field of integrating nanofluids in heat exchange systems has yielded several significant advantages. The analysis helps in assessing the impact and visibility of research in this domain, aiding in the evaluation and recognition of the contributions made by researchers. In addition, such kind of analysis can aid policymakers and industry stakeholders in understanding the impact and potential applications of nanofluid-based heat transfer systems, leading to informed decision-making and investment strategies. It would be valuable for the identification of emerging trends and potential areas for further exploration. Ultimately, the study acts as a catalyst for advancing the integration of nanofluids in heat transfer systems, leading to enhanced efficiency and compactness, and paving the way for further advancements in the field.

2.6 Heat Transfer in Heat Sink Applications

The integration of nanofluids into heat sink systems has become a prominent area of research over the past two decades, driven by the pursuit of higher heat dissipation in increasingly compact electronic and mechanical devices. The efficiency of heat transfer in heat exchange devices is predominantly influenced by factors such as the choice of coolant or working fluid, the geometric configuration, and the material composition of the heat sinks or heat exchangers [145]. Researchers have explored and tested a diverse array of both traditional and contemporary thermal fluids, as well as different heat exchanger channel geometries, intending to identify optimal configurations for various applications. However, to improve heat transfer, various approaches can be adopted. These techniques have been classified as passive and active methods [146,147]. Passive techniques in heat sinks refer to methods that enhance heat transfer without the need for external energy input and typically involve structural modifications, specific material selections, or the exploitation of natural phenomena to facilitate the heat exchange process. Passive techniques might not be adequate for high-heat generating systems or

in high-temperature environments but can be effective in certain applications. The passive method mainly focuses on the geometry, material, and fins since the efficacy of the working fluids is not that impressive.

Active methods of heat transfer involve the deliberate application of external energy to enhance the efficiency of heat exchange processes. Unlike passive methods that rely on inherent properties or natural phenomena, active techniques provide a proactive approach to heat transfer improvement. In these systems, a cooling agent, typically air or liquid, is actively circulated to remove heat from the source. This method is advantageous in terms of flow control, allowing for customised flow modifications based on the system's requirements. For instance, the utilization of a magnetic field is particularly effective in controlling ferrofluid [148]. Other active methods include the implementation of pulsating flow, the vibration of heat transfer surfaces, and the application of an electric field, among others. Historically, active methods predominantly relied on water and air as primary coolants in heat transfer devices. However, the intrinsic thermal transportation and flow characteristics exhibited by these conventional fluids often fall short of meeting the intricate demands posed by contemporary thermal transport devices. Therefore, notable advancements have been made in improving the geometry of heat sinks and the development of modern thermal fluids. These advancements aim to overcome the challenges associated with temperature control and ensure optimal performance of the devices.

Scientists from various research laboratories have dedicated years to advancing the field of thermal fluids, with a focus on developing highly efficient solutions. Among the cutting-edge developments in thermofluids, nanofluids have emerged as a remarkable innovation, showcasing exceptional thermal transportation properties surpassing those of conventional fluids. This progress is particularly significant in the context of heat exchange devices, where the intricacies of geometrical designs and manufacturing challenges have contributed to increased costs. To enhance the performance of heat sinks and effectively navigate the intricacies of their designs, it becomes imperative to adopt a synergistic approach that combines forced convection heat transfer mechanisms with advanced thermal fluids like nanofluids, ionic liquids, superfluid helium, phase change material, graphene-based coolants, etc. The use of these thermal coolants, particularly in conjunction with forced convection, not only streamlines the cooling process but also underscores a commitment to pushing the boundaries of thermal management systems. This integrated approach addresses the dual challenges of intricate design complexities and the need for efficient heat transfer. As investigators and manufactures continue to explore and implement such synergistic solutions, the potential for innovation in heat exchanger technologies becomes increasingly promising.

The effectiveness of heat transfer devices is intricately influenced by several key factors, as illustrated in Fig. 2.18. It is crucial to give meticulous consideration to the flow channel, geometry, and effective surface area during the design of these devices. These elements play a vital role in optimising the heat transfer process. Another essential aspect that requires careful attention is the thermal and rheological characteristics of the flowing fluid. Properties like heat capacity, conductivity, and viscosity of the fluid

have a substantial impact on the overall efficiency of heat transfer. Hence, a thorough understanding of both the structural and fluid-related factors is indispensable for the effective design and performance of heat transfer devices.

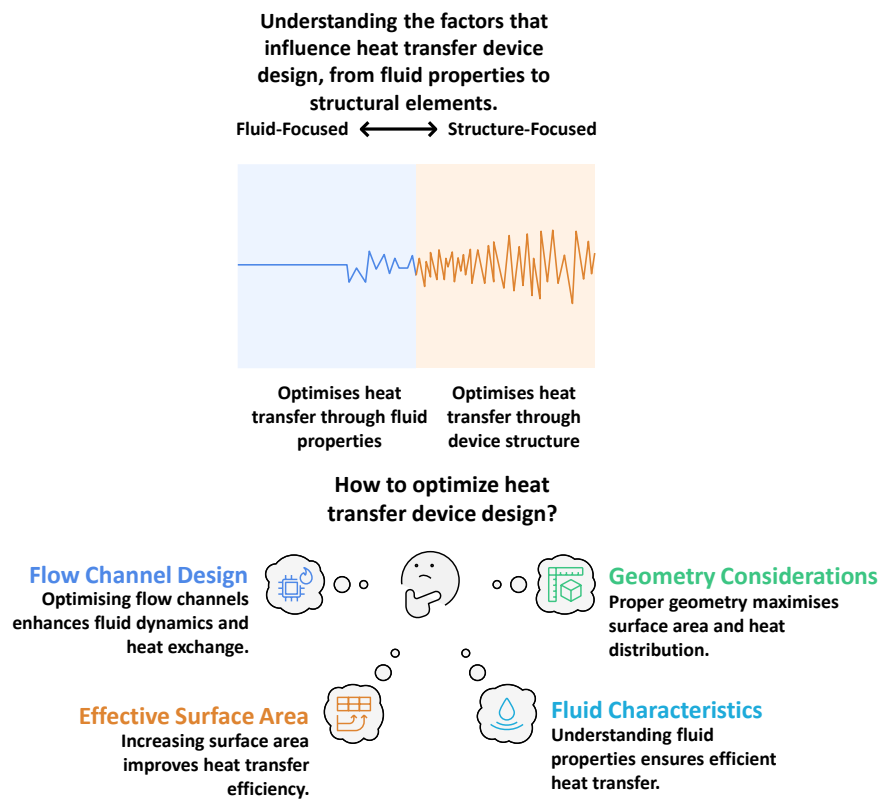


Figure 2.18. Key factors affecting heat transfer efficiency in nanofluid based heat transfer devices.

2.6.1 Experimental Studies

Heat sinks featuring microchannels, mini-channels, and pin-fin arrays are widely used in compact electronics due to their high surface area-to-volume ratios. When used with nanofluids, these systems benefit from enhanced convective heat transfer rates and more uniform temperature distributions. Studies have demonstrated that nanofluids can lead to substantial increases in Nusselt number and heat transfer coefficient compared to the use of pure base fluids. Despite their benefits, nanofluids can influence flow dynamics in ways that impact the overall energy efficiency of cooling systems. Increased viscosity, particle–wall interactions, and non-Newtonian behaviour at higher concentrations can contribute to elevated pressure drops. In microchannel and pin-fin heat sinks, where flow paths are narrow and often complex, even small increases in fluid resistance can significantly affect system-level performance.

Gorzin et al. [149] investigated a novel serpentine mini-channel heat sink (MCHS) for CPU liquid cooling. Experimental setup constructed to evaluate the performance of this heat sink is illustrated in Fig. 2.19. The heat sink, made of aluminium, square cross-section channels with a depth and width of 2 mm, and utilised pure water as the coolant fluid. The study examined the impact of varying mass flow

rates and inlet temperatures on the heat sink's efficiency. The results of the experiments revealed that the proposed serpentine "maze" design outperformed a conventional straight channel design. It demonstrated up to an 11.2% reduction in baseplate temperature and an impressive up to 4.2 times increase in the Nusselt number, especially at the highest tested mass flow rate. The study also found that increasing the mass flow rate and reducing the inlet temperature positively influenced the heat sink's performance. Wang et al. [150] proposed a novel butterfly-shaped channel structure for liquid cooling of prismatic battery modules. They compared the cooling performance of their design with traditional designs, including serpentine, straight, and leaf-shaped channels, considering factors like maximum temperature, temperature difference, and pressure drop. The butterfly-shaped channel demonstrated optimal overall performance based on desirability function calculations.

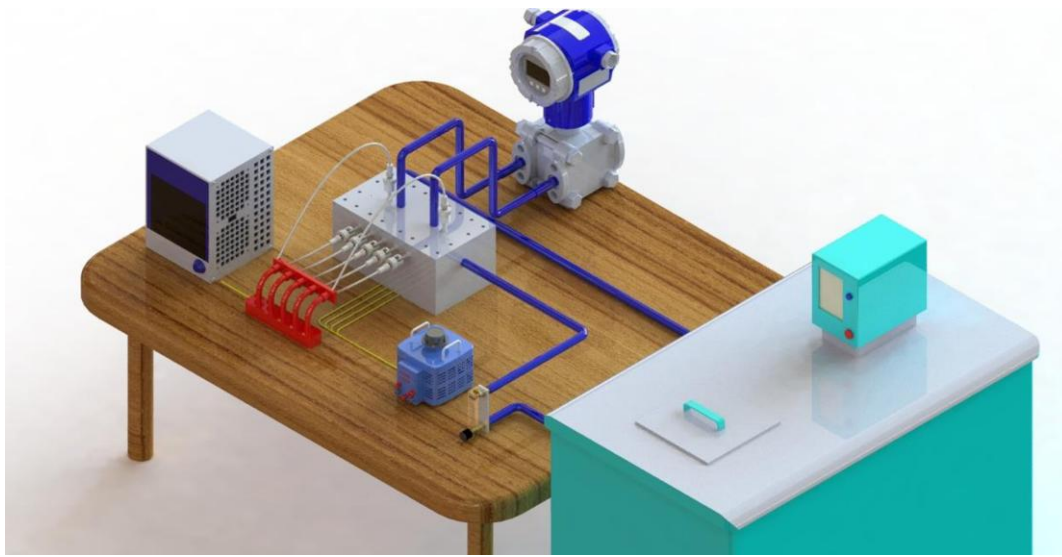


Figure 2.19. Schematic diagram of the experimental setup used to evaluate the performance of the serpentine mini-channel heat sink (MCHS) developed by Gorzin et al. [149].

After optimising structural parameters, they achieved a 29.1% decrease in maximum temperature compared to the other configuration. The authors also investigated the effect of mass flow on thermal performance, finding that increased coolant mass flow rate led to decreased maximum temperature and temperature difference, though the rate of descent gradually slowed. At a mass flow rate of 5 g/s, the maximum temperature was 30.86 °C with a 4.96 °C temperature difference. It was concluded that some complex bionic structures, while effective at cooling, can increase energy consumption due to higher pressure losses. The butterfly-shaped design emerged to strike a balance between enhanced cooling performance and manageable pressure drop. Zhao et al. [151] developed and experimentally studied leaf vein-inspired two-tiered and three-tiered open microchannel heat sinks (LTWOMC and LTHOMC) to enhance flow boiling performance. These bioinspired structures feature hierarchical, vein-like geometries oriented perpendicular to the flow direction to aid vapor escape and bubble detachment. According to the results, the three-tiered LTHOMC design demonstrated superior thermal stability and lower pressure drop, while the two-tiered LTWOMC exhibited earlier nucleate boiling and higher local

heat transfer coefficients, owing to direct contact between the vein-like channels and heated surface. The study conducted by Yan et al. [152] on the finned heat sink concluded that the flow splitting point was affected by the geometry of the fins and consequently effects the magnitude of the vortex at the trailing end of the fins. Byrne et al. [153] conducted experimental investigation on the thermal performance of mini channel heat sink (MCHS) exercising CuO/water nanofluid and revealed that the nanofluid without appropriate surfactant supplementation was affected negatively at the higher particle concentration. The results portrayed that the performance of Cu nanofluids was reduced due to the formation of clusters at a particle concentration of 0.1% by volume and suggested the usage of surfactant for better particles dispersion in base fluid. Selvakumar and Suresh et al. [154] studied the effect of CuO/water nanofluid in a rectangular shaped MCHS and found that the base temperature was reduced by 1.15 °C with a particle volume fraction of 0.2 %. According to the results, the HTC and pumping power were augmented up to 29.63% and 15.11 %, respectively, relative to the base fluid (de-ionized water). Investigators also observed an enhancement in HTC with increased flow rate while pumping power enhanced with the particle concentration. Tullius et al. [155] compiled a study to investigate the effect of several aspects such as pin fin shape, materials, spacing, and width. Investigators inspected the impact of six different pin fins shapes (hexagon, ellipse, triangle, square, diamond, circle) and four different materials (aluminum, CNT, copper, and silicon) on heat transfer characteristics and pressure drop with varying inlet velocity and heat flux. It was concluded that the plate with triangular fins could provide the highest Nusselt number while the pressure drop was minimum with the circular and ellipse shaped pin fins. However, both the Nusselt number and pressure drop augmented with the increase in fin height, spacing and width. The work carried out by Abbassi et al. [156] on rectangular-shaped mini-channels with Cu/water nanofluid suggested that an increase in heat transfer can be achieved by influencing the flow or changing the flow from laminar to the turbulent regime.

Sohel et al. [157] tested the nanofluid of alumina-water with MCHS for electronic devices thermal management. The work was conducted under the laminar regime, varying the flow rate and particle volumetric fraction ranging from 0.50–1.25 l/min and 0.1–0.25%, respectively. Nanofluids reduced the base temperature by about 2.7°C compared to the base fluid (water). It also augments the HTC up to 18% and lowers the thermal resistance to 15.72%. However, pumping power was found to be increased with the flow rate and particle concentration. Wu et al. [158] inspected the convective heat transfer and pressure drop employing the nanofluid of alumina and compared the results with the base fluid (water). The trapezoidal shaped silicon-based mini-channel heat sink (MCHS) was analysed considering the effect of particle volume fraction, Prandtl number, and Reynolds number. It was found that the friction factor and pressure drop were increased marginally compared to the conventional fluid. However, the Nusselt number (Nu) was also improved with Reynolds number, particle concentration, and Prandtl number. They also noticed the nanoparticles deposition on the walls, which becomes more significant at higher temperatures. Xie et al. [159] studied the influence of fins length on pressure drop and heat transfer rate in the laminar flow regime. It was observed that the overall thermal performance

augmented with an increase in fin length and the heat transfer capacity of finned surfaces was significantly higher than that of flat surfaces. Their results revealed that obstacles disrupt the boundary layer and boundary layer is destroyed and rebuilt across the fins, causing an increase in heat transfer rate. Wang et al. [160] conducted an experimental investigation into the thermal-hydraulic characteristics of liquid cooling heat sinks with novel pin fin designs, aiming to address the increasing thermal management demands of advanced avionics systems. As shown in Fig. 2.20, their study introduced and tested four innovative pin fin heat sinks: petaloid I, petaloid II, pinwheel-like, and honeycombed, comparing their performance to a conventional plate fin heat sink under varying inlet temperatures (10 and 20 °C), flow rates (400–2000 mL/min), and heat fluxes (60–150 kW/m²). These bio-inspired designs aim to enhance heat transfer area and induce turbulence without significantly increasing pressure drop. The results revealed that the honeycombed pin-fin heat sink exhibited the highest heat transfer coefficient and the lowest wall temperature, while petaloid I showed the highest Nusselt number due to its specific structural attributes.

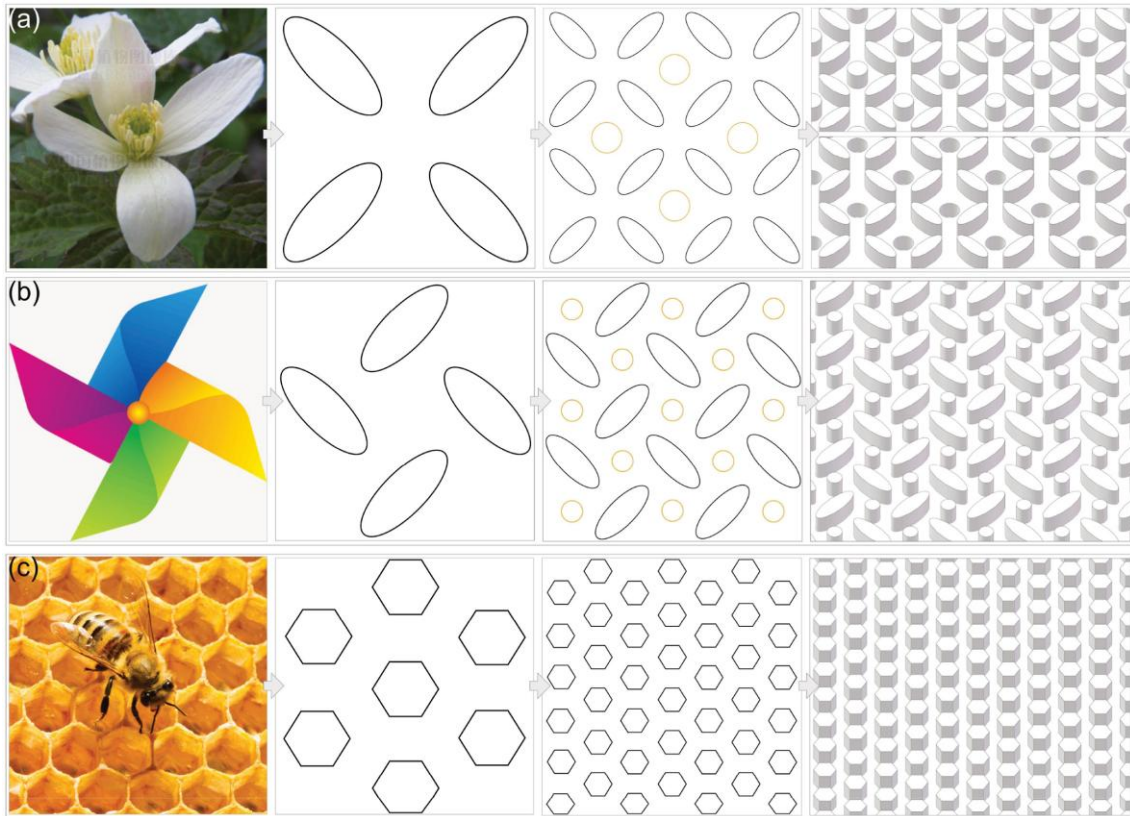


Figure 2.20. Bio-inspired pin-fin designs: (a) Petaloid from flower shape, (b) Pinwheel-like from windmill, and (c) Honeycombed from beehive, each design aimed at enhancing heat transfer through increased surface area and induced flow mixing [160].

Despite slightly lower Nusselt numbers, the honeycombed design outperformed others when considering overall performance metrics due to its minimal pressure loss. According to the results, the honeycombed pin-fin heat sink consistently demonstrated the highest heat transfer coefficient (HTC),

reaching up to $21.5 \text{ kW/m}^2\cdot\text{K}$ at the highest flow rate and moderate heat flux. It also maintained lower wall temperatures, indicating superior cooling effectiveness. Although petaloid PFHS I showed the highest Nusselt number, this was attributed to its smaller hydraulic diameter rather than better overall performance. The comprehensive performance factor (η) ranked the designs in the order: honeycombed > petaloid I > pinwheel-like > petaloid II > plate fin. Additionally, all PFHSs showed linear increases in HTC and Nu with Reynolds number, while the friction factor remained largely insensitive to inlet temperature and heat flux. Empirical correlations developed for Nu and f achieved mean absolute deviations under 5%, validating their predictive accuracy against experimental data.

Rimbault et al. [161] explored the effect of CuO-water nanofluid by varying the particle volume fraction as (0.24, 1.03, 4.5%) and employing it inside the rectangular shaped MCHS in laminar and turbulent regimes. According to the results, pressure drop, and friction factor were increased with the addition of nanoparticles into the base fluid. Heat transfer enhancement was observed at lower particle concentration (0.24, 1.03 %vol.), while a marked decrease in heat transfer was found at 4.5 %vol. Ho and Chen [162] inspected the effect of alumina nanofluid on the thermal performance of copper made MCHS. The study considered the penalty of particles supplementation and pumping power while investigating the HTC. It was found that the merits (in the form of augmented heat transfer parameters) of employing nanofluids compensated the penalty of pumping power and delivered excellent results. Jajja et al. [163] compared the thermal performance of MCHS with the flat plate sink varying fins spacing (0.1, 0.5, 1, 1.5 mm). The thermal resistance and base temperature were found to be reduced with an increase in flow rate. According to the results, thermal resistance was reduced from 0.216 K/W to 0.03 K/W with the addition of fins on the surface of sink. In addition, the HTC was enhanced from $1297 \text{ W/m}^2\cdot\text{K}$ to $2156 \text{ W/m}^2\cdot\text{K}$ using the sink of fin spacing of 0.2 mm.

The performance of an inline and staggered arrangement of square pin-fin was experimentally examined by Ali and Arshad [164]. Their study was conducted in the laminar flow regime employing water and some advanced thermal coolants. They stated that the staggered configurations could offer better thermal characteristics in comparison of inline fins arrangement. For sharp edge square-shaped fins, it was due to the interaction of more fluid with fins in a staggered arrangement. Duangthongsuk and Wongwises [165] studied the hydraulic and thermal performance of a circular finned heat sink using water-based SiO_2 and ZnO nanofluids. The comparative study showed an improvement of 3 to 9% for the ZnO nanofluid compared to SiO_2 . Moreover, pressure drop was found to be increased with flow rate and particle concentration. The experimental investigation of Sohel et al. [166] on thermal and frictional effects of alumina/water nanofluid through the copper made MCHS reported an enhancement in heat transfer rate with the increase of nanoparticles volume fraction and flow rate. They yielded that the frictional effects between the particles and with the channels inner surfaces increased with particle concentration, which increased the pumping power.

Experimental investigations have provided valuable insights into the thermal behaviour of nanofluids across a wide range of heat sink geometries and operating conditions. These studies have confirmed the

potential of nanofluids to improve cooling performance, reduce hotspot formation, and enable more compact thermal solutions. However, many experiments focus on isolated aspects such as particle selection, fluid stability, or heat sink design, often overlooking the potential synergy between bio-inspired geometries and tailored coolant formulations.

2.6.2 Numerical Studies

In addition to experimental investigations, numerical simulations have become an indispensable tool in the analysis and optimisation of heat sink performance. Computational techniques such as Computational Fluid Dynamics (CFD) allow for detailed exploration of temperature distributions, flow behaviour, and pressure variations within complex geometries often with greater flexibility and lower cost compared to experimental testing. Numerical studies are particularly valuable for evaluating a wide range of design configurations, operating conditions, and nanofluid properties, enabling researchers to predict performance trends, validate experimental findings, and guide design improvements.

This section reviews recent numerical studies focused on nanofluid-cooled heat sinks, highlighting their contributions to understanding thermal enhancement mechanisms, fluid–structure interactions, and multi-parameter optimisation strategies. Kuppusamy et al. [167] numerically investigated the effect of geometry and various other factors such as nanoparticles, particle diameter, base fluid, and particle concentration on the thermal and hydraulic performance of trapezoidal-shaped MCHS. According to the results, trapezoidal-shaped mini channels yielded excellent results, and the triangular shaped channels performed better than those of rectangular shape. They acquired the alumina nanofluids the most efficient among CuO, ZnO, and SiO₂. The optimum values of particle concentration and particle diameter for Al₂O₃ nanofluid in trapezoidal MCHS were found to be 0.04 vol.% and 25 nm, respectively. Zhang et al. [168] developed an innovative liquid cooling plate featuring bionic limulus-like fins (BLLFs) to overcome the common issues of high pressure drop and limited cooling efficiency associated with conventional channel-type battery thermal management systems. The study initially focused on optimising rectangular fins by adjusting their longitudinal and transverse spacing ratios. The best thermal and hydraulic performance was achieved when both spacing ratios were equal. Building upon this, the researchers introduced BLLFs, inspired by the hydrodynamic shape of the horseshoe crab, which significantly reduced vortex formation and associated pressure loss. Computational fluid dynamics (CFD) simulations demonstrated that the BLLF design outperformed traditional rectangular and elliptical fins, with a 7% improvement in overall thermal performance. Further enhancements included optimising inlet and outlet layouts, staggered fin configurations, and the internal geometry of the BLLFs by incorporating a central channel and secondary slant channels. A multi-objective optimisation process using variables such as outlet distance, fin channel width, and slant angle led to a final design that achieved a 4.61% reduction in average temperature and a 54.26% decrease in pressure drop compared to the initial model. Li et al. [169] proposed a novel single-phase microchannel heat sink featuring a pyramid thermal dissipation unit embedded with nature-inspired channel designs to

effectively manage ultra-high heat fluxes. Using a 3D conjugate heat transfer model, they demonstrated that the pyramid structure could degrade extreme heat flux from 10^3 to 10^2 W/cm², while maintaining chip temperatures below 120 °C. Their findings revealed that the integration of spiral cooling tubes with bionic microchannel patterns not only enhanced temperature uniformity and heat transfer but also allowed for a significant reduction in the minimum required thermal conductivity of materials, broadening material selection options and simplifying system complexity compared to existing high-flux cooling technologies. Wang et al. [170] numerically investigated the influence of microchannel geometry on heat transfer and fluid flow, considering three cross-sectional shapes: rectangular, triangular, and trapezoidal. The findings revealed that in rectangular microchannels, increasing the aspect ratio (height to width ratio) leads to decreased thermal resistance but increased pressure drop. A comparison of the three shapes with the same hydraulic diameter showed that rectangular microchannels have the lowest thermal resistance, followed by trapezoidal and triangular channels. Additionally, it was observed that increasing the number of microchannels reduces thermal resistance due to the greater surface area for heat transfer. However, a higher number of channels also results in increased pressure drop. Therefore, finding an optimal channel number is dependent on the available pumping power to minimise thermal resistance effectively. Advanced thermal coolants were also investigated in heat sinks to improve their thermal performance. Nimmagadda and Venkatasubbaiah [171] compiled a comparative study on the heat transfer enhancement of the nanofluids of alumina, silver (Ag) and their hybrid (Ag+ Al₂O₃) in a rectangular shaped MCHS. It was observed that hybrid nanofluid with a volume fraction of 3% (Ag (2.4%) + Al₂O₃ (0.6%)) delivered a higher rate of heat transfer compared to the metallic (Ag) and oxide (Al₂O₃) nanofluids. They recommended the hybrid nanofluids because it was found to be more stabilized and cost-effective. Rong et al. [172] proposed a bionic spider web microchannel heat sink structure to enhance cooling efficiency in high heat flux environments such as aerospace vehicles. Using numerical simulations, they found that while the channel centre angle had little impact on heat transfer, the channel width-to-spacing ratio (Wd/Wc) and inlet velocity significantly affected performance. Increasing Wd/Wc and inlet velocity improved the convective heat transfer coefficient and reduced temperature gradients, with optimal configurations yielding up to 25 K temperature reduction and enhanced uniformity. A predictive equation for the heat transfer coefficient was developed with a mean error of ~10%, suitable for design applications.

Acharya [173] conducted a comprehensive numerical study on the thermo-fluidic behaviour of a microchannel heat sink (MCHS) with various fin configurations, designed to dissipate a heat flux of 50 W/cm² typical for high-power electronic devices. The research investigated three fin shapes: square fins, 45° oriented square fins, and elliptical fins, arranged in both inline and staggered configurations. The number of fins varied from 11×3 to 79×3 (fins per row $\times$ rows), with heights ranging from 100 μ m to 300 μ m. To isolate the shape effect on heat transfer and frictional loss, the researchers maintained constant cross-sectional area and surface area for all fin types. Numerical simulations were performed using ANSYS Fluent, employing a Finite Volume Method based multigrid solver, considering laminar

flow conditions with Reynolds numbers ranging from 100 to 400. The findings revealed that heater surface temperature decreased monotonously with the increasing number of fins for heights above 200 μm , with elliptical fins showing marginally better heat transfer. Additionally, it was also observed that staggered configurations outperformed inline arrangements in terms of heat transfer and elliptical fins in a staggered arrangement showed the least frictional resistance. Mohammed et al. [174] numerically examined the important factors such as heat transfer coefficient (HTC), wall temperature, pressure drop, thermal resistance, friction factor, and wall shear rate in rectangular-shaped mini channel heat sinks employing alumina (Al_2O_3)/water nanofluid. They observed that the HTC augmented up to a certain particle concentration limit. It was revealed that the results became identical to the water at 5 vol.%. Factors such as wall shear rate and friction factor increased slightly with particle addition, while thermal resistance reduced. On the other hand, the pressure drop increased as the Reynolds number and particle loading increased.

Xie et al. [175] numerically studied the impact of various parameters like channel width, height, wall thickness, bottom thickness, and inlet velocity on the thermal resistance and pressure drop of water-cooled MCHS. A 3D numerical model was employed to simulate the conjugate heat transfer and fluid flow within the minichannels. According to the results, pumping power increased linearly with channel height at a constant inlet velocity, but it decreased with channel width. These results highlight the complex relationship between the geometric parameters of the MCHS and its hydraulic performance. Moghadassi et al. [176] studied the thermal performance of unitary and hybrid nanofluids of Al_2O_3 and Al_2O_3 -Cu in a uniformly heated circular tube and found that the binary fluid presents the better results, however, this usually depends on the combination of nanoparticles. It was concluded that the hybrid nanofluid showed an augmented Nusselt number of 4.73% relative to the unitary nanofluid of alumina. Maji et al. [177] examined the hydrothermal characteristics of fins with various shaped perforations such as diamond, elliptical, and circular. It was found that changing the fin shape from circular to elliptical could result in a significant increase in Nusselt number with a noticeable reduction in pressure drop. According to Cui et al. [178] the staggered arrangement and appropriate shape of fins could effectively reduce the boundary layer effect and optimise the hydrothermal performance. Chai et al. [179] comprehensively studied the effect of different shaped fins (rectangular, elliptical, diamond, and triangular) in the interrupted micro channels. Their study was conducted in the laminar flow regime and found that the elliptical fins in combination with interrupted channels delivered the best thermal performance compared to other fins. The maximum enhancement of 57% and 70 % was noticed for Nusselt number and friction factor over straight channels, respectively. Mehboob et al. [180] carried out a comprehensive numerical study to optimise bioconvective heat transfer in magnetohydrodynamic (MHD) Eyring–Powell nanofluids infused with motile microorganisms, considering the effects of variable viscosity and porous media in ciliated microchannels. Their results demonstrated that increasing the viscosity parameter leads to a reduction in nanofluid temperature.

Several studies have shown that interrupted or modified fin geometries including split fins, slotted fins, perforated fins, and interrupted pin-fin arrays can enhance heat-transfer performance even when the total solid surface area is reduced. The enhancement arises from improved flow mixing, disruption of thermal boundary layers, and the generation of secondary flows. Chin et al. [181] showed that perforated pin fins achieved a 45% increase in Nusselt number and an 18% reduction in pressure drop compared with solid pins, owing to recirculation and boundary-layer disruption around the perforations. Lin et al. [182] reported that interrupted fins improved the convective heat-transfer coefficient by breaking the thermal boundary layer and, for an optimised interruption pattern, delivered up to 80% higher heat-transfer performance with a 7% reduction in weight relative to continuous fins. Similarly, Mousavi et al. [183] found that interrupting and staggering plate fins led to higher thermal efficiency and identified an optimum interruption length that maximised heat transfer for a given pressure drop. These findings support the rationale behind the split pin-fin concepts used in this thesis, where partial removal of fin material is compensated by enhanced mixing, boundary-layer re-development, and more effective utilisation of the exposed fin surfaces.

Abdollahi et al. [184] used a heat sink with a V-type inlet/outlet to examine the thermal and hydrodynamic performance of various nanofluids (ZnO , SiO_2 , Al_2O_3 , and CuO). This numerical study also considered the effect of particle concentration and particle diameter. It was observed that the thermal performance of SiO_2 nanofluid was maximum followed by CuO , Al_2O_3 , and ZnO , while CuO nanofluid offered less pressure drop followed by Al_2O_3 , ZnO , and SiO_2 . Results revealed that the effect of particle volume fraction was more significant, however, a noticeable enhancement in Nu was also observed with decreasing particle diameter. Hung et al. [185] investigated the thermal and hydraulic performance of mini-channel heat sink (MCHS) made of porous copper with various channel configurations. The parameters such as heat transfer coefficient (HTC) and pumping power was observed against the Reynolds numbers in the laminar regime (45–1350). Their analysis stated that the porous media could improve the thermal performance, while a significant improvement was also noted with the increase in Reynolds number. It was observed that the sandwich distribution of porous medium performed well thermally and hydraulically among the investigated configurations. Alfaryjat et al. [186] studied the hydrothermal performance of heat sink having hexagonal shaped channels. Various nanofluids fluids (SiO_2 , CuO , ZnO , Al_2O_3) were tested during this numerical study and revealed that the nanofluid of alumina offered superior thermal performance comparatively due to its higher thermal conductivity. However, a larger pressure drop was observed for the SiO_2 nanofluid because of its higher viscosity. Zhou and Catton [187] studied numerically the hydrothermal performance of different plate fin heat sinks having different pin fin shapes (dropform, circular, square, NACA profile, and elliptical). Figure 2.21 shows the velocity streamlines and temperature contours insight of the channels. Recirculation zones at the rear end of pin fins were observed. Flow separated at the rear end because of stationary recirculation and reattached again, resulting in the formation of a dead zone. Velocity streamlines illustrated that flow separation was most prominent for square pin fins due to sharp edges.

Interestingly, the Nusselt number for square pin fins was comparatively higher, but at the same time, pressure drop was also much higher. So, the comparison was drawn based on the heat transfer effectiveness factor and found that elliptical and NACA shaped pin fins with plate fins delivered the best results.

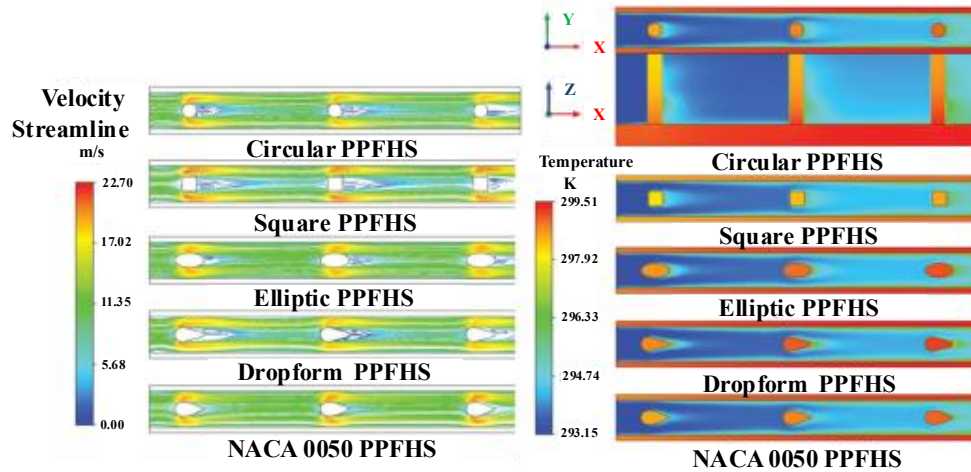


Figure 2.21. Velocity streamlines and temperature contours [187].

While numerical studies have greatly contributed to understanding fluid flow and heat transfer behaviour in nanofluid-enhanced heat sinks, they often oversimplify the complex nature of nanoparticle–fluid–surface interactions. Most simulations assume uniform particle dispersion, stable thermophysical properties, and idealised boundary conditions, thereby overlooking critical real-world challenges such as nanoparticle sedimentation, surface deposition due to overheating, and the formation of surfactant nanolayers on channel walls. These factors can significantly alter flow dynamics and heat transfer performance in practical systems but are rarely accounted for in computational models. Moreover, the long-term stability of nanofluids and the potential for particle agglomeration, especially under high thermal loads or cyclic conditions, remain difficult to simulate accurately. As a result, experimental investigations remain essential to validate and calibrate numerical findings and to explore phenomena that cannot yet be reliably captured computationally.

Table B.1 in Appendix B focuses on more recent studies involving innovative and advanced heat sink designs that go beyond traditional geometries. These include micro-structured channels, bio-inspired fins, slotted and grooved surfaces, and other topology-optimised or hybrid structures. It summarises cutting-edge research that integrates nanofluids both simple and hybrid formulations into novel heat sink architectures. The table highlights critical variables such as particle types and concentrations, geometric enhancements, base materials, and resulting improvements in Nusselt number, thermal resistance, and pressure drop. These studies underscore the increasing interest in synergistically optimising both coolant properties and heat sink design to achieve superior thermal performance.

Appendix B, Table B.2, provides a consolidated overview of important parameters from selected prior studies that have investigated heat sinks with various conventional geometrical configurations, such as

straight channels, microchannels, and regular pin-fin arrays, in conjunction with different nanofluid types. This table includes key details such as nanoparticle composition, base fluids, volumetric concentrations, Reynolds number ranges, and reported thermal–hydraulic performance outcomes. By capturing these essential metrics, the table offers a foundational understanding of how conventional heat sink designs have been thermally enhanced through nanofluid application. It also helps establish baseline performance benchmarks, which are essential for evaluating the relative effectiveness of newer, more complex configurations.

Together, these tables serve a dual purpose. First, they contextualise the evolution of nanofluid-based cooling solutions from conventional to more sophisticated and nature-inspired geometries. Second, they help to identify existing research gaps—most notably, the limited integration of biomimetic design principles with advanced nanofluids in experimental settings. This comparison not only justifies the novelty of the current research but also emphasizes the need for a more holistic approach that combines fluid innovation with geometrical optimisation. By positioning the present work within this landscape, the analysis highlights its potential contribution to the ongoing advancement of high-efficiency thermal management systems.

Summary

This chapter highlights significant progress in the development of advanced heat sink designs and nanofluid-based cooling strategies for high heat flux applications. A wide range of heat sink geometries have been explored, including straight and microchannel configurations, regular and perforated pin-fin arrays, and more recent bioinspired structures. These studies collectively show that geometric modifications can substantially influence flow behaviour, thermal boundary layer development, and overall heat transfer, although improvements in thermal performance often come with increased hydraulic losses. This underscores the importance of evaluating heat sink performance through combined thermal and hydraulic metrics rather than thermal indicators alone.

Nanofluids have similarly shown strong potential in improving the cooling performance of heat sink systems due to their tunable thermophysical properties and enhanced thermal conductivity. Their integration with advanced heat sink geometries can offer additional performance gains, particularly under conditions where conventional fluids reach their thermal limits. Nonetheless, challenges such as pressure drop penalties, long term stability, dispersion quality, and compatibility with system materials remain key barriers to large scale adoption. The evidence from the literature suggests that while nanofluids and innovative heat sink designs each offer measurable benefits, their effectiveness depends strongly on operating conditions, fluid formulation, and channel geometry.

Taken together, the literature indicates that the future of compact and efficient thermal management technologies will rely on solutions that balance heat transfer enhancement with hydraulic performance, while ensuring the practical viability of nanofluids in real applications.

CHAPTER 3

3 Experimental Setup, Heat Sink Design, and Preparation of Nanofluids

This chapter presents the detailed methodology for the experimental investigation, encompassing the design and fabrication of novel biomimetic heat sink geometries and the preparation of nanofluids used as advanced coolants. It begins with a description of the experimental setup, developed to assess the thermal and hydraulic performance of various heat sink configurations under controlled conditions. The subsequent sections outline the design rationale, dimensional parameters, and manufacturing techniques for a series of bio-inspired pin-fin heat sinks, drawing from the respiratory systems and streamlined morphologies of aquatic organisms.

The chapter additionally offers a concise overview of nanofluid preparation and characterisation. It describes the nanoparticle selection process and details the measurement techniques employed to evaluate essential thermophysical properties such as thermal conductivity, viscosity, and zeta potential. These aspects are explored in greater depth in the subsequent chapters. Together, these efforts lay the groundwork for evaluating the integrated performance of nanofluid-enhanced biomimetic heat sinks, aiming to optimise heat transfer efficiency while minimising pressure drop for high-performance electronic cooling applications.

3.1 Experimental Setup

The experimental setup, incorporating various measurement devices and temperature control mechanisms, allows for the thorough investigation of the thermal and hydraulic behaviour of the various heat sink configurations. The setup consisted of a storage tank with a temperature controlled water bath, a gear pump, a needle valve, a flow measuring device, a pressure transducer, a heat sink assembly section with an integrated microscope camera, and a radiator, as shown in Fig. 3.1.

The setup featured a storage tank placed within a refrigerated circulator water bath (ARCTIC A40) to maintain a stable and consistent inlet temperature. The coolant was drawn from the storage tank and circulated through the system using a MasterFlex Micro gear pump which ensured a controlled and continuous flow. Next in the loop, a precision flow control valve was installed to manually regulate and stabilize the fluid velocity. Positioned between the needle valve and the heat sink section, a micro-flow meter (Omega FTB332D) was incorporated to accurately measure the flow rate before the fluid entered the inlet manifold.

The heat sink itself was thermally insulated with wool and enclosed within an acrylic plate assembly to minimise heat loss and external thermal interference. To facilitate visualization of the coolant flow dynamics and bubble formation within the heat sink channels, a high-speed camera was mounted above

the microscope via an adaptor, allowing real-time observation and recording of intricate flow patterns. To ensure a stable and uniform heat input, three cartridge heaters (RS-860–6845, UK) were embedded within the heat sink, powered by a DC supply (EA-PS 2084-10B) to provide the required thermal energy. The pressure drop across the heat sink, a key performance parameter, was measured using a differential pressure transducer (Omega DPGM409-025HDWU, USA). The device was connected at both the inlet and outlet of the heat sink using precision fittings, as illustrated in Fig. 6(b). This transducer measures gauge pressure with high resolution, enabling accurate assessment of the pressure difference across the mini-channel configuration. The output was logged in real-time through a digital acquisition system.

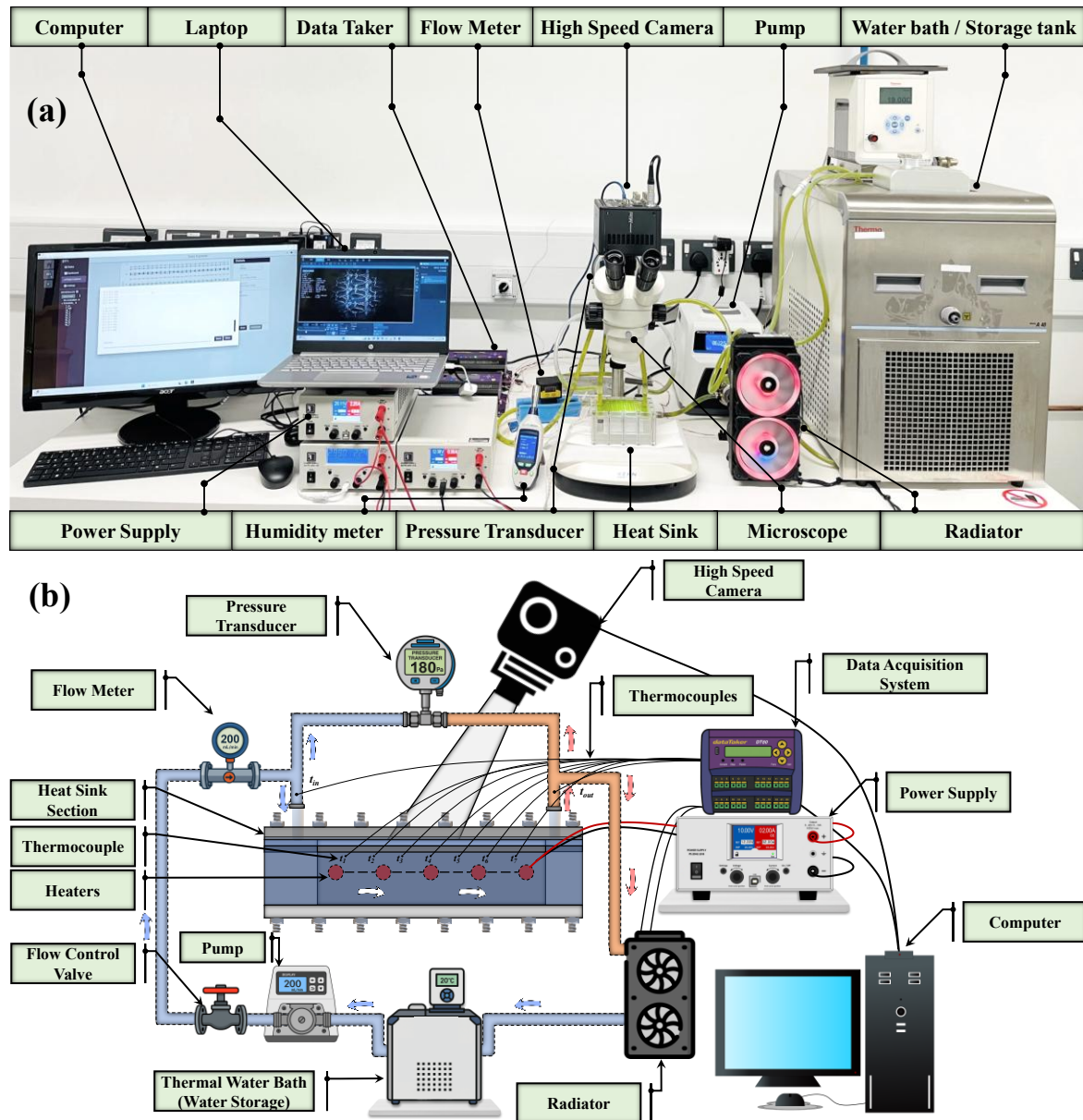


Figure 3.1. (a) Experimental test rig used to evaluate the thermal and hydraulic performance of the heat sinks; (b) schematic illustration of the experimental setup.

The working fluid continuously circulated through the microchannels of the heat sink, effectively absorbing the heat from the heat sink. To monitor the temperature distribution along the heat sink surface, seven K-type thermocouples (RS-397–1589, UK) were embedded at strategic positions along the base of the heat sink channels, positioned just below the wall surface. Additionally, one thermocouple was placed at the fluid inlet and another at the outlet to record the temperature variations at these critical points, ensuring a precise assessment of thermal performance. To ensure reliability and reduce transient noise, the temperature and pressure data were recorded at 5-second intervals over a 30-second period, after achieving steady-state conditions. The average of these readings was then used in subsequent calculations to enhance measurement accuracy. Following heat absorption in the heat sink, the fluid exited the system and passed through a radiator, which was positioned downstream to dissipate the absorbed heat into the surrounding environment. This radiator played a crucial role in maintaining the thermal balance of the experimental setup by effectively rejecting excess heat. Finally, the coolant completed its cycle by returning to the storage tank, where it was reconditioned to the desired temperature by the refrigerated circulator bath chiller, thereby ensuring a continuous and controlled experimental process.

Through this well-integrated system of components and instrumentation, the setup enabled a rigorous evaluation of the heat sink's performance, allowing for precise measurement and analysis of critical thermal and hydraulic parameters. This experimental configuration provided valuable insights into the efficiency of heat dissipation mechanisms, pressure drop characteristics, and flow behaviour, contributing to the development of optimised cooling solutions for high-performance electronic and thermal management applications.

3.2 Heat Sink Design Configurations, Manufacturing, and Features

An optimised heat sink design is characterised by its ability to maximise the heat transfer area and enhance interaction with the working fluid while maintaining minimal flow resistance. After an extensive review of current literature and recent advancements in heat sink technologies, it has been observed that most studies primarily focus on heat transfer performance as the defining criterion for efficiency. However, factors like pressure drop, an equally critical parameter, are often not given due consideration. For an efficient thermal management system, balancing heat transfer performance with flow resistance is essential to ensure the system's overall effectiveness.

This study investigates the hydrothermal performance of four uniquely shaped pin-fin heat sinks, each featuring a distinct geometrical configuration, alongside a conventional straight-channel heat sink used for benchmarking and validation. The new configurations were developed with the aim of achieving an optimal trade-off between thermal and hydraulic performance, guided by inspiration from aquatic respiratory systems known for their internal flow routing and low resistance body profiles. These designs reflect a deliberate emphasis on engineering heat sinks that are not only thermally efficient but also hydrodynamically favourable under real-world operating conditions.

3.2.1 Fins Design Inspiration

The present study introduces innovative heat sink designs inspired by the respiratory system of fish. In the realm of living organisms, humans, birds, and many creatures draw in air through a singular point, such as the nose or mouth, and expel it from the same opening. However, this is not the case for most fish. Fish utilise an exceptional mechanism for fluid movement, where water flows not only around their bodies but also inside-out through their gills, enabling effective oxygen exchange with minimal resistance. This continuous process occurs as the fish moves through the water, as illustrated in Fig. 3.2. A study conducted by Stevens on gas exchange in tuna revealed that the average rate of water flow over the gills was 2.8 L/min per kilogram of body weight [188].

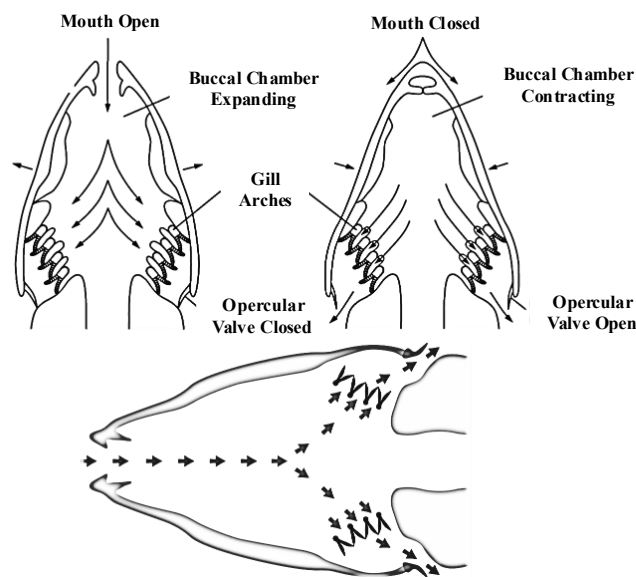


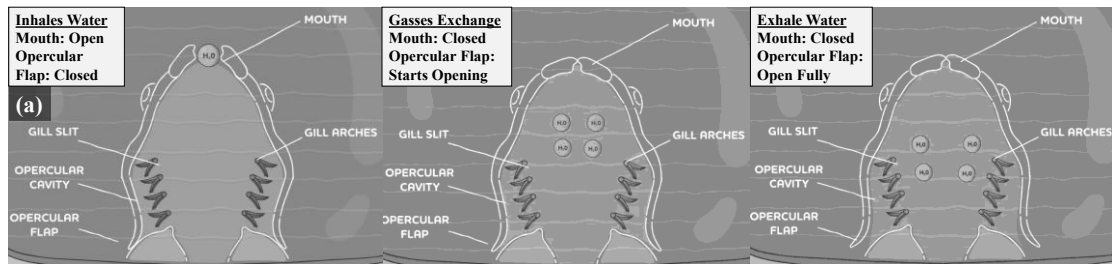
Figure 3.2. Schematic illustration of the fish respiratory system [189].

The perfection of nature is evident in the design of fish, where their external body and the inside-out flow of water through the mouth for respiration assist in smooth movement with minimal resistance. Drawing inspiration from these principles, novel hybrid pin-fin heat sink geometries have been designed and manufactured. These hybrid pin-fins are a combination of two distinct shapes, designed to allow water to flow both over and through a confined passage. The internal pin-fins, shaped like an airfoil, replace the fish's internal organs, while the external structure consists of curvilinear or corrugated curvilinear pin-fins inspired by the body shapes of tuna and the black ghost knifefish (BGKF).

The unique fins shape ensures improved heat transfer by increasing the effective surface area while maintaining low pressure drop characteristics. In this biomimetic design, an exit passage analogous to the opercular valve is strategically positioned at the trailing edges, rather than on either side just behind the mouth as it is in fish, as illustrated in Fig. 3.3(a). This adjustment aligns with the engineering requirements of the heat sink design while retaining the inspiration from natural fluid dynamics. The proposed configurations are named Inline Arranged Airfoil Integrated Curvilinear Pin-Fin Heat Sink (IACPF) and Inline Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin Heat Sink (AICCPF).

As this design evolves through further investigation, it holds the potential to be adapted for a variety of applications in the marine, automotive, and aerospace industries.

Design Inspiration Fish Respiratory System



Schematic representation of the fish respiratory system illustrating the sequential flow of water during inhalation, gas exchange, and exhalation phases—serving as the biological inspiration for the heat sink design.

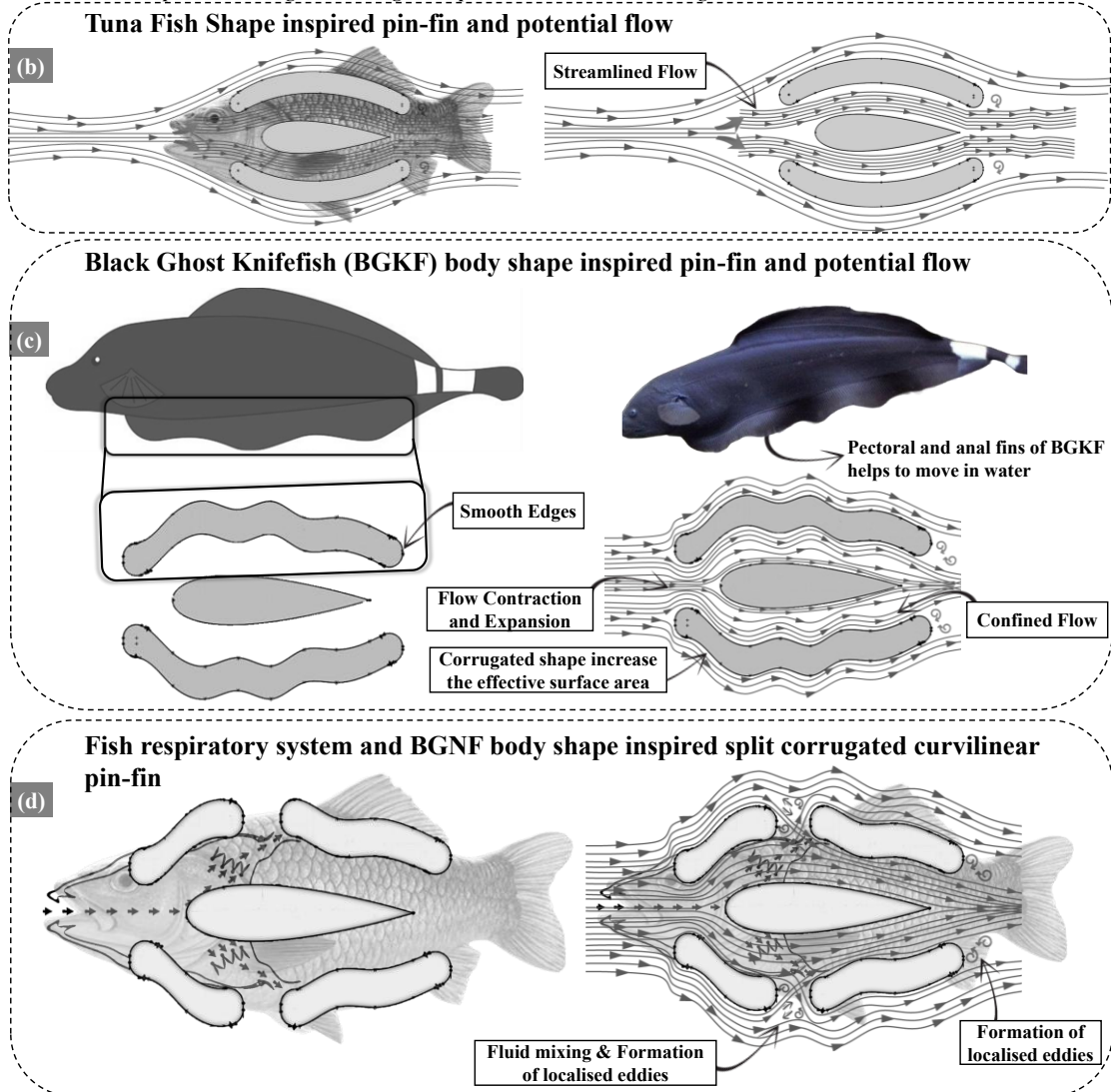


Figure 3.3. (a) Schematic representation of the fish respiratory system, Conceptual design sketches of hybrid pin-fin geometries inspired by fish morphology, (b) Tuna fish-shaped curvilinear fins for streamlined flow and low resistance, (c) Corrugated fins inspired by the pectoral and anal fins of the Black Ghost Knifefish (BGKF) for enhanced surface area and heat transfer performance, and (d) Split corrugated curvilinear pin-fin design inspired by both the fish respiratory system and BGKF body shape, promoting improved fluid mixing and providing alternate flow paths to mitigate bubble entrapment.

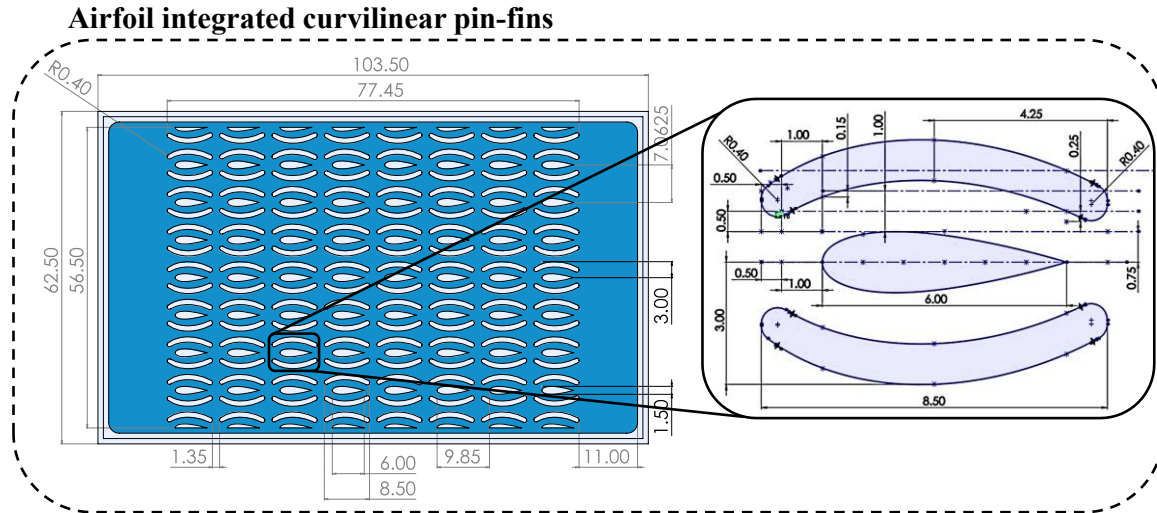


Figure 3.4. Dimensional specifications and fin arrangement of the Inline Arranged Airfoil Integrated Curvilinear Pin-Fin Heat Sink (IACPF), highlighting the integration of airfoil-shaped inner fins with outer curvilinear pin-fins.

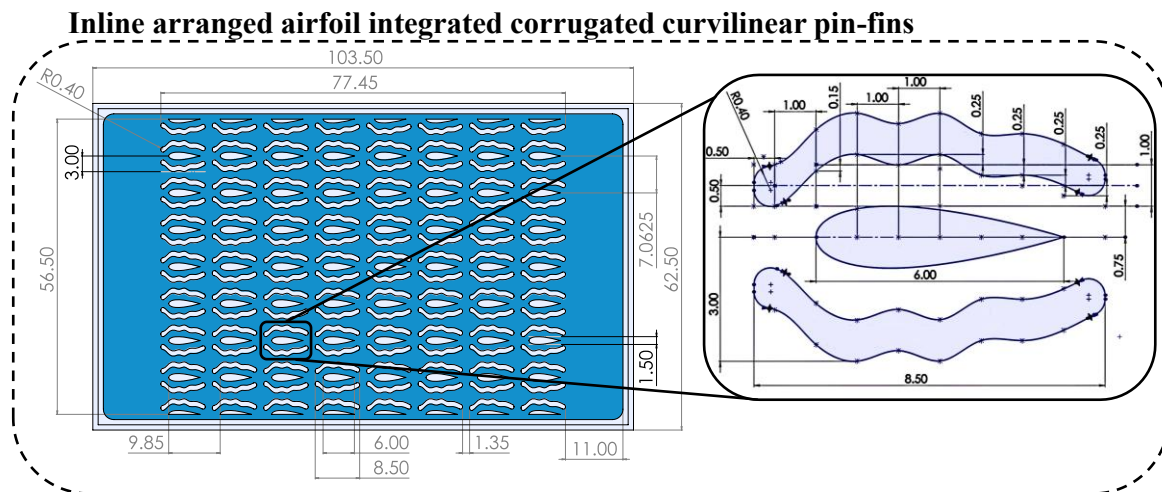


Figure 3.5. Inline Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin Heat Sink (AICCPF), showing the integration of airfoil inner fins and outer corrugated curvilinear fins inspired by BGKF morphology.

To the best of the authors' knowledge, such hybrid configurations have not been explored from this perspective before. This study is expected to attract the attention of researchers and encourage further exploration of these designs for various applications.

The first configuration features an inline arrangement of airfoil integrated curvilinear pin fins. The curvilinear geometry depicts the body shape of the tuna fish, known for its streamlined form that minimises resistance during movement in water. Figure 3.4 provides a detailed representation of the fins and their dimensional specifications. In the second configuration, AICCPF, the curvilinear pin fins are replaced with corrugated curvilinear pin fins.

These fins draw inspiration from the pectoral and anal fins of the BGKF, a species that lacks caudal fins and generates propulsion using its pectoral and anal fins to move in water. The corrugated shape not only offers a more effective surface area for heat transfer but also causes little disruption to fluid flow which ultimately improves the cooling capacity. The detailed dimensions and arrangement of the fins are illustrated in Fig. 3.5.

The third configuration, the Staggered Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin Heat Sink (SAICCPF), consists of airfoil-integrated corrugated curvilinear pin-fins positioned in a staggered layout. The detailed geometry and dimensional parameters of this heat sink configuration are presented in Fig. 3.6. This arrangement is specifically designed to explore the impact of pin-fin positioning on the hydrothermal performance of heat sinks. Traditionally, studies have compared inline versus staggered pin-fin configurations to identify thermally optimal patterns. However, the conceptual inspiration for this work is rooted in aquatic organisms particularly the schooling behaviour of tuna and BGNF which display various configurations while swimming in schools. In this context, Marras et al. [190] investigated the energetic benefits of fish swimming in schools, focusing on whether the spatial position of an individual within the group influences the energy savings gained from schooling. Their key findings demonstrated that all fish within a school, regardless of whether they were swimming ahead, besides, or behind their closest neighbour, experienced reduced energetic costs compared to solitary swimming.

Wei et al. [191] conducted a comprehensive numerical investigation into passive hydrodynamic interactions in minimal fish schools, focusing on three basic configurations: tandem, side-by-side, and staggered. Their study revealed that staggered formations offer distinctive hydrodynamic advantages due to beneficial pressure field interactions and improved vortex utilization. Ko et al. [192] found that fish in schools rarely maintained positions within a single horizontal plane. In their extensive three-dimensional tracking of giant danios, they discovered that only about 25% of fish pairs were coplanar at any given time. Even among these coplanar pairs, the spatial arrangements did not conform to the classic diamond formation often predicted by theoretical models. Instead, the majority of coplanar pairs were found to be inline (54.6%), meaning one fish was directly ahead of the other, staggered (30.0%), where fish were offset diagonally, or side-by-side (15.4%). The traditional diamond pattern, which has been considered the optimal configuration for hydrodynamic efficiency, was virtually absent in the observed data.

Instead, the most prevalent structure observed was the “ladder formation,” which appeared in 79% of all fish pairs. This ladder formation is characterised by its elongated and three-dimensional nature, with fish arranged in a way that resembles the rungs and sides of a ladder rather than a flat, two-dimensional shape. The dominance of this formation became even more pronounced at higher swimming speeds, suggesting that fish naturally adopt more three-dimensional, dynamic group structures in response to environmental demands. This finding highlights the flexibility and adaptability of real fish schools, which do not conform to the rigid, planar patterns suggested by earlier theoretical models.

The staggered arrangement of pin-fins can offer significant improvements in heat transfer performance compared to inline configurations. This enhancement is primarily due to the increased fluid disturbance and mixing induced by the offset alignment of the fins.

In an inline arrangement, the flow tends to develop streamwise channels between the fins, resulting in relatively stable boundary layers and limited cross-stream mixing. This can lead to thermal boundary layer thickening, reducing the overall convective heat transfer coefficient. In contrast, a staggered configuration forces the fluid to continually change direction, disrupting the thermal boundary layers on the surfaces of the fins. This repeated disturbance enhances vorticity generation and secondary flow formation, both of which promote higher local convective heat transfer rates.

Moreover, the staggered layout increases the wetted surface area exposed to the coolant by enabling fluid to sweep more effectively across adjacent fin surfaces. It also facilitates flow redistribution, helping bypass blocked or bubble-trapped regions particularly useful in applications involving nanofluids where particle agglomeration or microbubble entrapment may occur.

However, these thermal benefits come at the cost of hydraulic penalties. While the staggered arrangement of pin-fins offers clear advantages in terms of enhanced heat transfer, it also generally leads to an increased pressure drop across the heat sink. This is due to the flow obstruction and repeated deflections the fluid experiences as it navigates through the non-aligned rows of fins.

In a staggered configuration, the coolant cannot follow a straight path, as it must periodically change direction to pass around the fins. These frequent redirections result in higher form drag and frictional losses, contributing to a greater overall flow resistance. Additionally, the tighter flow passages and enhanced mixing while beneficial for convective heat transfer induce local turbulent eddies and vortex shedding, which further elevate the pressure drop.

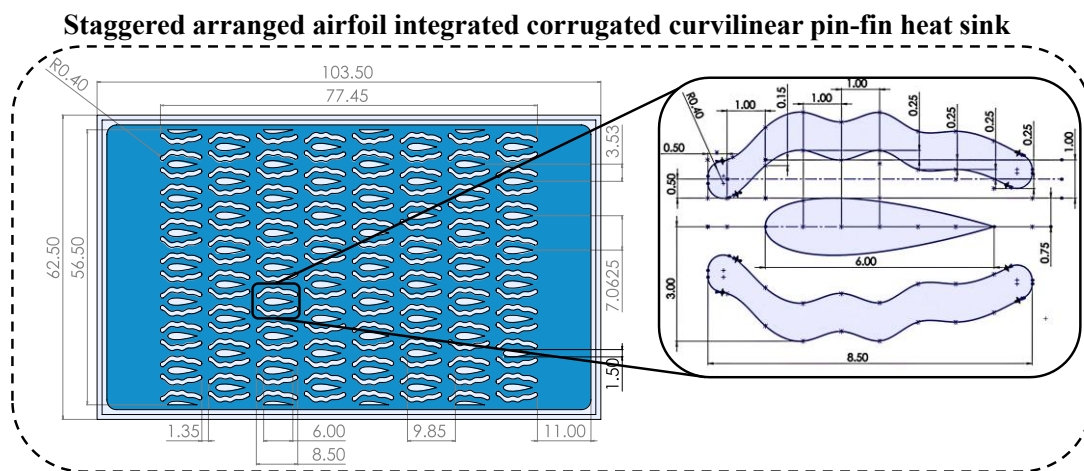
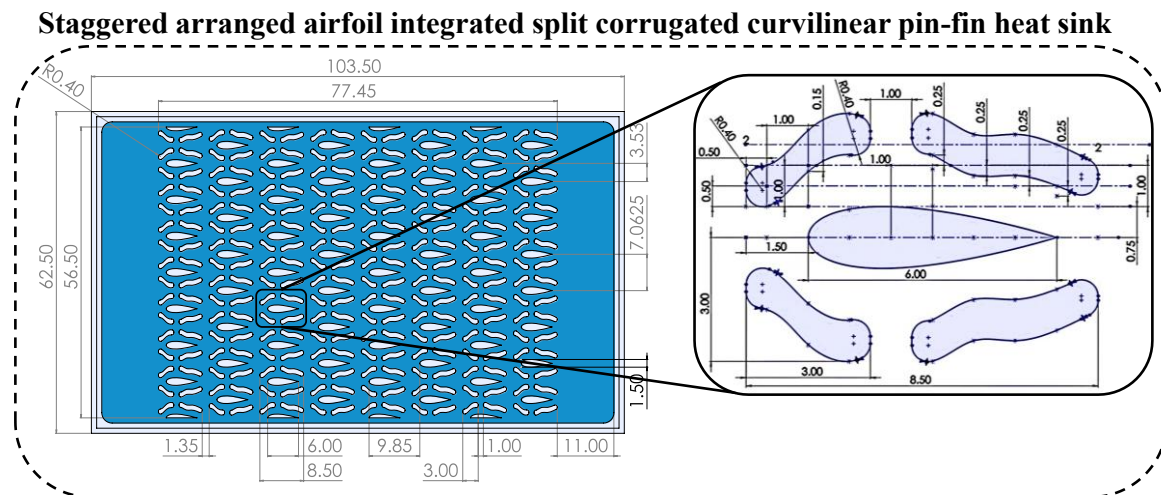


Figure 3.6. Top view of the Staggered Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin Heat Sink (SAICCPF), illustrating the fin arrangement and geometry.

Compared to an inline arrangement, where fluid can flow more smoothly between rows, the disruption and separation of boundary layers in the staggered layout require more pumping power to maintain the

same flow rate. In systems with high flow resistance, this may translate into increased operational costs or the need for more robust pumping solutions. Despite the higher pressure drop, staggered arrangements are often favoured in high-performance applications where thermal effectiveness is prioritised over minimal hydraulic losses. The thermal-hydraulic performance factor (or PEC – performance evaluation criterion), which considers both heat transfer enhancement and pressure loss, is typically used to assess the overall effectiveness. In many cases, the increase in heat transfer is sufficiently large to offset the rise in pressure drop, resulting in a net gain in cooling performance.



The inclusion of the split within the pin-fins creates alternative flow pathways, enabling the working fluid to bypass regions that may become blocked or stagnant. This ensures the continuity of flow and prevents the formation of dead zones, thereby enhancing the overall thermal effectiveness of the system. In addition to maintaining consistent flow, the split geometry significantly improves fluid mixing, which is especially beneficial when nanofluids are used. Enhanced mixing helps maintain uniform nanoparticle suspension, reducing the risk of particle agglomeration and sedimentation, and thereby promoting more consistent heat transfer performance.

Figure 3.9 presents the fabricated prototypes corresponding to the conceptual models. These heat sinks were manufactured with high-precision techniques to preserve design accuracy and dimensional integrity. These designs form the basis for all experimental investigations presented in later chapters. The geometrical configurations have been analysed using different nanofluids and compared to find the optimum one. To draw the comparative study, each configuration meticulously designed with a consistent fin count and identical baseplate dimensions. All dimensions are specified in millimetres (mm).

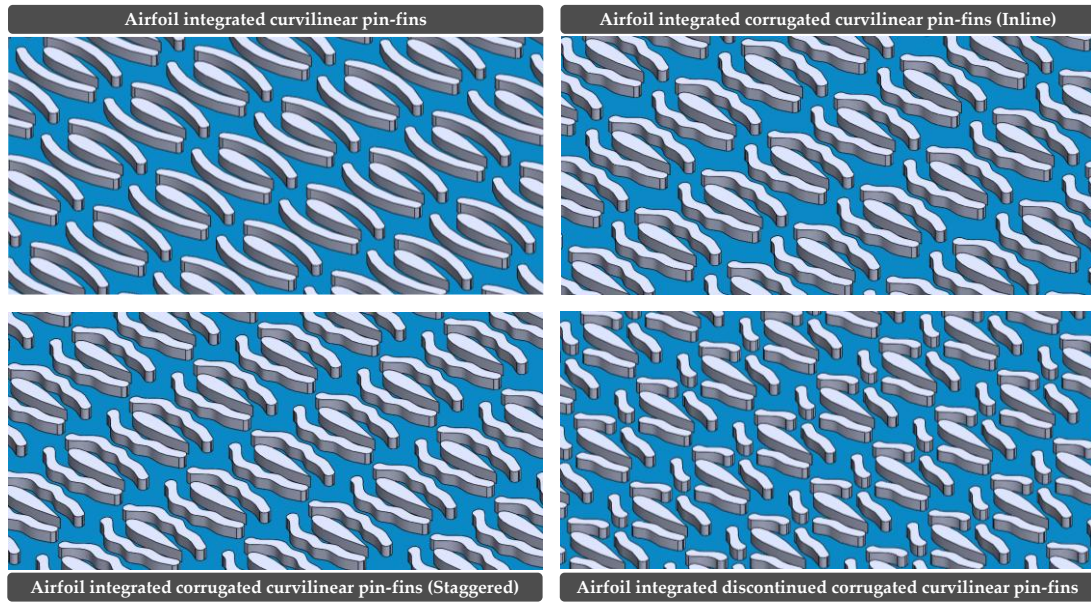


Figure 3.8. Closed isometric view of the various kind of pin-fin heat sinks.

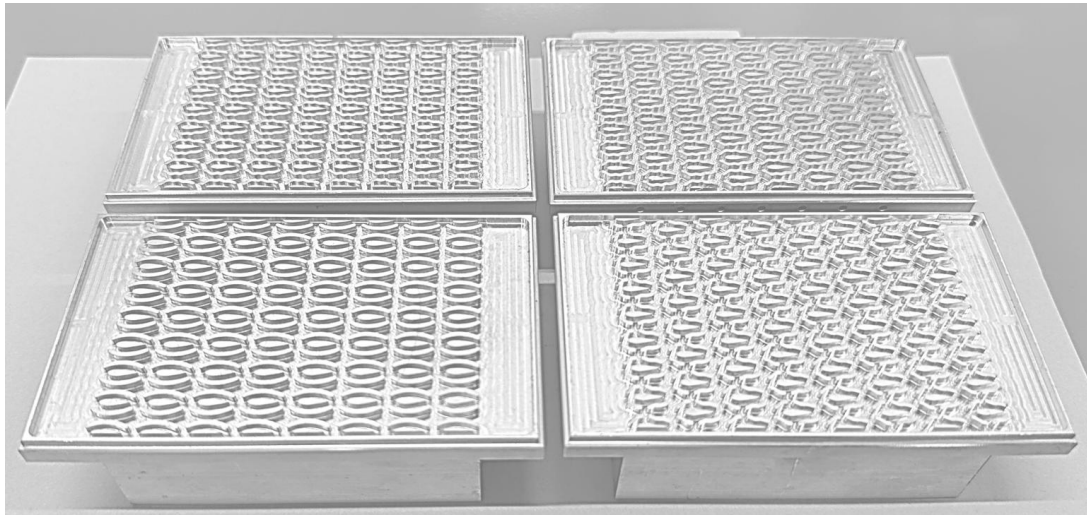


Figure 3.9. Pictorial representation of heat sinks fabricated to investigate in the experimental study.

3.2.2 Dimensional Considerations and Materials Selection

The dimensions of the finned section have been carefully determined to align with the size specifications of Intel® Xeon® processors, including the silver, gold, and platinum series, as depicted in Fig. 3.10.

These processors are widely recognised for their high-performance capabilities in applications such as multimedia processing, graphics rendering, engineering simulations, and large-scale transactional database servers. Additionally, they are integral to supporting Internet infrastructure and high-volume computational tasks. A 10mm space has been allocated for the inlet and outlet plenum on each side. The detailed arrangement and dimensions of the fins are discussed in Section 3.2.1. However, for the airfoil geometry, symmetrical NACA 0025 profile has been adopted. The detailed geometric coordinates used to construct the NACA 0025 profile are provided in Table C.1 (Appendix C). This design features a chord length of 6 mm and a fixed width of 1.5 mm. The airfoil-shaped fins are bordered by curvilinear and corrugated curvilinear pin fins, forming hybrid pin-fin configurations. These hybrid designs combine fins of varying shapes to synergistically enhance performance, ensuring both efficient thermal management and minimal flow resistance.



Figure 3.10: Intel Xeon processor package size.

A comprehensive study was conducted to analyse the thermal behaviour of Intel® Xeon® processors, which generate heat ranging from 50W to 300W under varying workloads. This range underscores the critical need for efficient thermal management solutions. Figure 1.4 in Chapter 1 provides the graphical illustration of the base temperatures and thermal design power (TDP) values for various Xeon® processor models, these parameters have been discussed in detail in Chapter 1. The values indicate the safe case temperature thresholds corresponding to specific TDP levels. Exceeding these temperature limits can result in a significant decline in processor performance, and in extreme cases, may lead to irreversible damage or burning of the processor.

The pin-fins on the heat sink surface are designed with a balance between manufacturability and thermal performance. To ensure practical fabrication, the channel width is set to accommodate machining tools of 1mm or smaller, preventing excessive manufacturing complexity and costs. While narrower channels

could enhance heat transfer, they would also lead to a significant increase in pressure drop and machining cost. The height of the pin-fins is maintained at 2mm, allowing for effective thermal contact while ensuring compatibility with confined spaces.

Aluminium stands out as the material of choice for heat sink fabrication due to its exceptional combination of properties. Its impressive thermal conductivity ensures efficient heat dissipation, while its lightweight nature makes it a practical option for applications where reducing overall weight is crucial. Compared to alternatives like copper and silver, aluminium is not only more affordable but also offers superior corrosion resistance, enhancing its durability in diverse environments. Furthermore, its ease of manufacturing allows for intricate designs, and its recyclability supports sustainable practices, making aluminium an ideal candidate for electronic and industrial applications demanding reliable thermal management solutions.

In this study, the heat sink dimensions have been tailored specifically for Xeon® processors. However, the versatile design of these heat sinks ensures their applicability across a wide range of devices and application areas. The proposed designs are engineered to not only meet the current thermal management requirements of Xeon® processors but also accommodate the demands of future, more advanced processors with higher TDP values. This adaptability positions these heat sinks as reliable solutions for both present and next-generation high-performance computing systems.

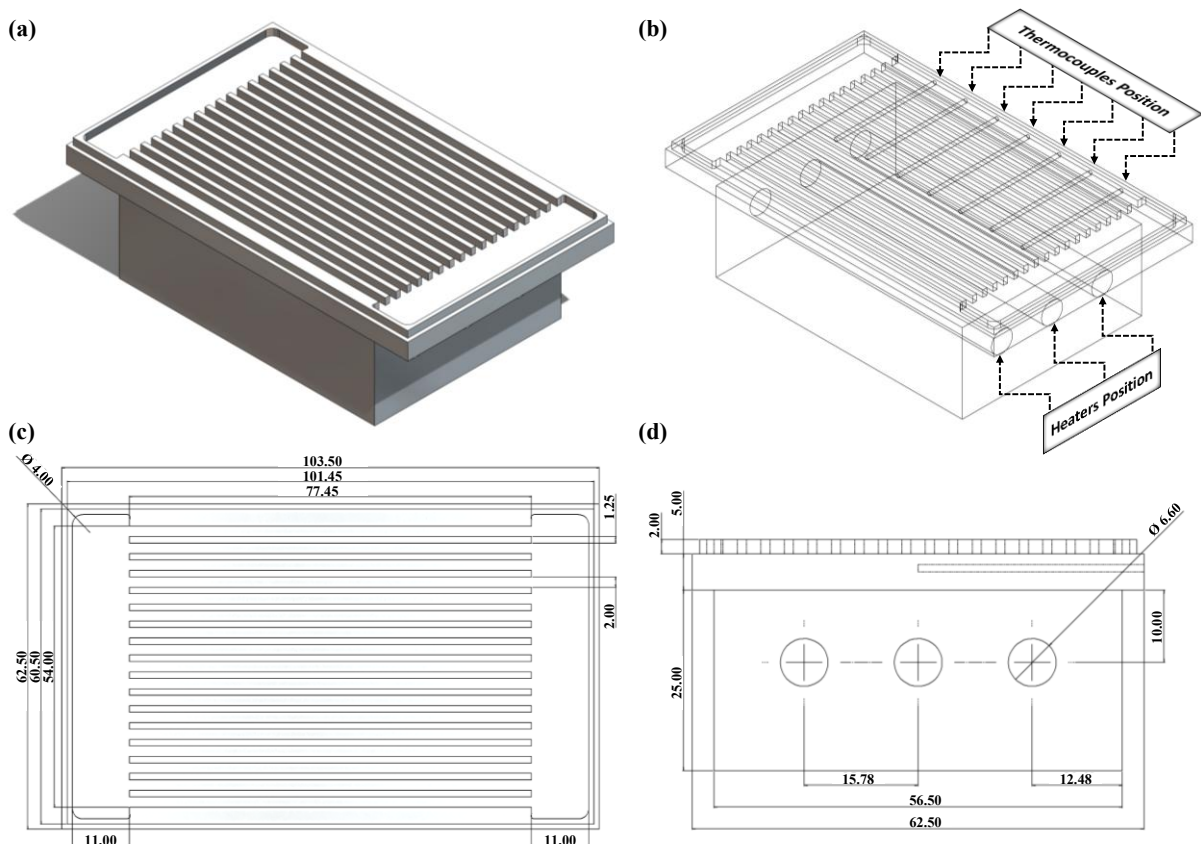


Figure 3.11. Geometrical configuration of the heat sink, illustrating the dimensional parameters and positions of heaters and thermocouples.

Building upon the practical and performance-oriented design considerations outlined above, a straight channel heat sink has been included in this study as a baseline reference for both experimental validation and comparative evaluation. While all proposed heat sink configurations share identical external dimensions such as length, width, height, and fin count to ensure a fair comparison, the straight channel design serves as a control model to benchmark the enhancements offered by the advanced geometries. The key differentiating factor among the proposed configurations lies in the shape and spatial arrangement of the pin-fins, which have been strategically modified to assess their impact on thermal and hydraulic performance. Figure 3.11 provides a detailed visual representation of the straight channel heat sink, including isometric, side, and top views. It also outlines the precise design layout and the positioning of integrated heaters and thermocouples. By comparing the performance of the proposed hybrid and biomimetic configurations against this baseline, the effectiveness and added value of the new designs can be quantitatively established.

3.2.3 Manufacturing

The heat sinks were fabricated using 3-axis CNC milling, chosen due to its widespread accessibility and precision capabilities, which made it an ideal method for producing intricate geometries while maintaining cost-effectiveness. The design was tailored to accommodate a 0.7 mm diameter tool for grooving all the channels, ensuring an efficient and streamlined manufacturing process, as evidenced in Fig. 3.12. Precision was a critical focus, with a tolerance of 0.05 mm being readily achievable. However, reducing the tolerance to 0.01 mm proved both technically challenging and cost-prohibitive. To optimise performance and manufacturability, the design emphasised key dimensions such as fin spacing and hole size over excessively tight tolerances. Key considerations in the design and manufacturing process include:

Tool Selection: A smaller 0.7 mm tool was used to address the size complexity, ensuring precision in channel grooving while maintaining structural integrity. Additionally, the design accommodated practical tooling and machining strategies to balance precision with cost and time constraints.

Impact of Reduced Spacing: Narrower channel spacings, such as 0.5 mm, significantly increase both processing time and cost. Maintaining precision in such cases required additional steps to avoid damaging adjacent fin walls, complicating production.

Tolerance Management: A practical tolerance of 0.05 mm was adopted to ensure manufacturability without incurring exponential cost increases.

Feasibility Limitations: Spacings as tight as 0.1 mm exceeded the capability of standard equipment, making machining impractical and misaligned with agile manufacturing principles due to the steep rise in costs and time demands.

Ultimately, the design struck a balance between manufacturability, cost-efficiency, and performance by focusing on achievable tolerances and practical geometries.

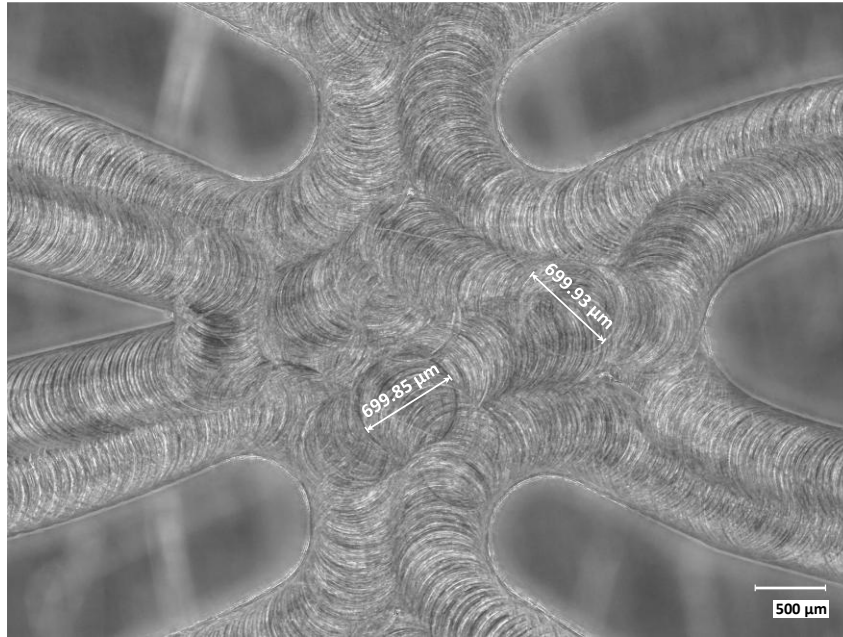


Figure 3.12. CNC-machined heat sink, showcasing the precision grooving and structural symmetry achieved using a 0.7 mm diameter tool.

3.2.4 Surface Morphology

The surface morphology of the fabricated heat sinks was examined using scanning electron microscopy (SEM) to analyse the texture and machining-induced features. The SEM images, as shown in Fig. 3.13, reveal distinct surface patterns characterised by tool movement during the milling process. These patterns result in micro-impressions that contribute to the overall surface roughness, which can influence thermal performance by promoting micro-turbulence in the working fluid. However, this surface roughness does not compromise the material's intrinsic thermal conductivity, ensuring that the overall efficiency of the heat sink remains intact. Additional smoothing would add complexity and expense to the manufacturing process without providing a proportional improvement in performance [193]. Upon closer inspection, the images depict the grooved channels, highlighting the uniformity and precision achieved during machining. These grooves are more pronounced along the curved sections of the channels, where tool path dynamics and material removal processes play a crucial role. Higher magnification views show a more intricate microstructure, with intersecting patterns possibly resulting from tool oscillations or feed variations. Moreover, the material's response to machining forces can be seen in certain regions, where localised roughness variations are present.

The surface roughness of the heat sinks was measured at multiple positions using a Mitutoyo Surftest SJ-500 profilometer. The roughness values (R_a) were found to vary between $0.36\text{ }\mu\text{m}$ and $0.58\text{ }\mu\text{m}$, reflecting minor inconsistencies across different sections of the heat sink. These roughness values are within an acceptable range for thermal management applications and indicate that the milling process effectively produced heat sinks with structurally stable fins and channels.

Although the fabrication of the heat sink structures was carried out with careful attention to dimensional accuracy and machining quality, it is important to recognise that even small variations due to manufacturing tolerances and surface roughness can influence thermal and hydraulic performance. Minor deviations in fin height, spacing, or channel width, though within acceptable tolerances, can locally alter the flow distribution, changing Reynolds number and affecting heat transfer uniformity across the heat sink. For example, a slightly narrower flow passage may result in elevated velocity and enhanced local convective heat transfer but also lead to increased pressure drop. Conversely, widened gaps can reduce turbulence intensity and lower thermal performance. These variations also introduce uncertainty when comparing closely performing configurations, emphasising the importance of consistent manufacturing practices when scaling up for practical applications.

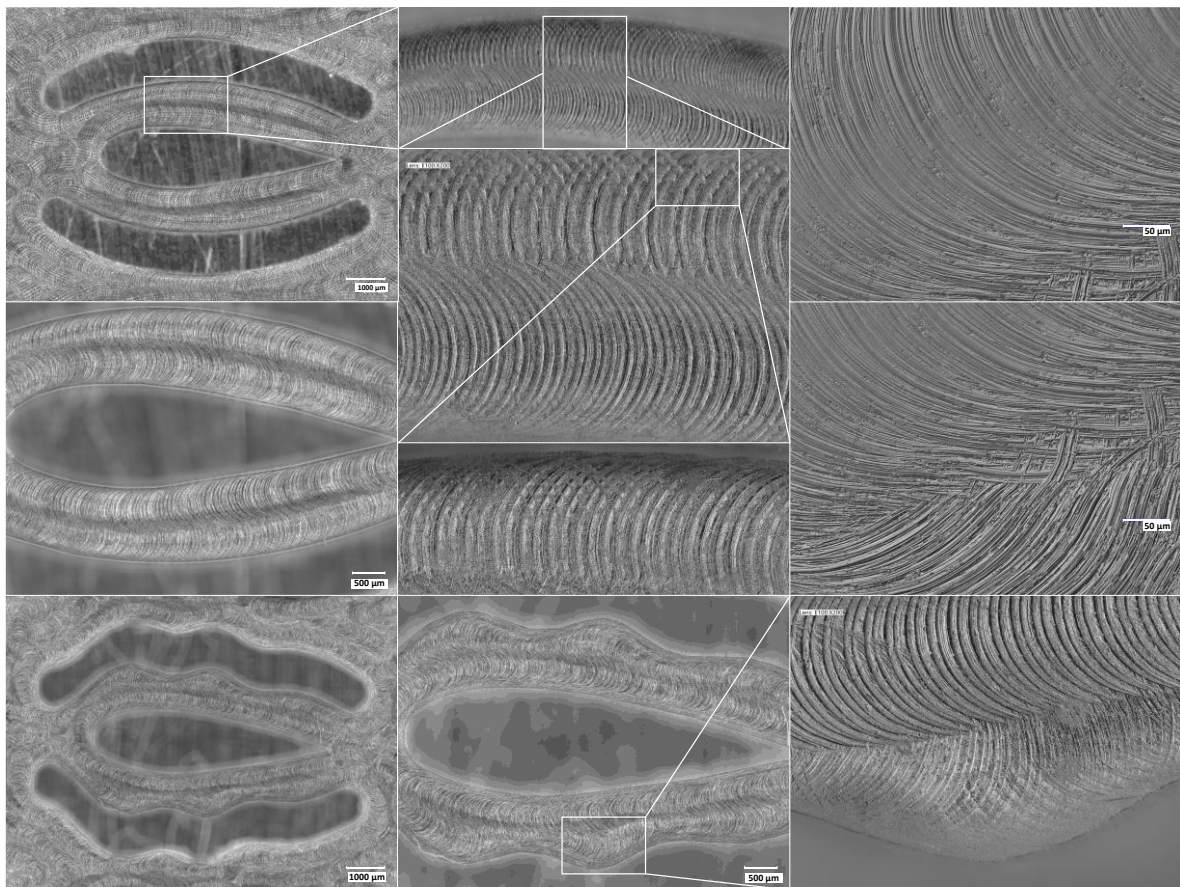


Figure 3.13. Scanning Electron Microscope (SEM) images of the fabricated heat sink surfaces showing tool-induced micro-patterns, grooved channels, and surface roughness characteristics. These textures contribute to micro-turbulence and heat transfer enhancement.

Surface roughness, resulting from CNC milling, also plays a dual role in system behaviour. On one hand, it can enhance convective heat transfer by disrupting the thermal boundary layer and promoting micro-scale turbulence. On the other hand, it increases wall friction and contributes to higher pumping power requirements. In nanofluid applications, rough surfaces may additionally act as nucleation or adhesion sites for suspended nanoparticles, potentially accelerating sedimentation and fouling under

prolonged operation. This can alter local flow dynamics, reduce effective surface area, and compromise long-term reliability. Thus, while the level of roughness observed in this study was beneficial in enhancing thermal transport without introducing excessive pressure loss, future optimisation may involve tuning surface texture or incorporating coatings to balance heat transfer gains with hydraulic efficiency and long-term stability.

3.3 Nanoparticles Selection and Nanofluid Preparation

Conventional heat transfer fluids such as water, ethylene glycol, engine oil, and acetone suffer from inherently low thermal conductivity, typically in the range of 0.1–0.6 W/m·K. As modern electronic and thermal systems become increasingly compact and power-dense, these fluids are no longer capable of providing the necessary cooling performance. In response to this challenge, researchers have turned toward nanofluid-based and hybrid cooling strategies, which involve suspending nano-sized particles typically metals, oxides, carbides, or carbon-based materials into base fluids to significantly enhance their thermal characteristics [194–196].

In recent years, hybrid nanofluids, which combine two or more types of nanoparticles, have emerged as a particularly promising class of advanced heat transfer media. These formulations aim to leverage the complementary strengths of different particles, such as the high thermal conductivity of metals and the improved stability of oxides, while offsetting their respective limitations. The current study employs this hybrid nanofluid approach to investigate the performance of advanced cooling systems in combination with novel biomimetic heat sinks.

3.3.1 Comparative Assessment of Commercial Nanoparticles and Selection Criteria

To rationalise the choice of nanoparticles for this study, a comparative evaluation was performed using commercially available options sourced from NanoAmor and Alfa Aesar. This analysis considered key parameters such as thermal conductivity, material cost, density, and commercial availability factors critical to both performance and practical application.

The data for this comparative assessment were obtained directly from supplier databases and product catalogues. Figure 3.14 presents a comprehensive comparison of nanoparticles offered by NanoAmor, showcasing their cost per 100 grams alongside corresponding material density. A wide range of metallic and metal oxide nanoparticles were examined, with notable variation in both cost and density. Similarly, Fig. 3.15 illustrates a comparative dataset for Alfa Aesar nanoparticles. These visual comparisons underscore the substantial variation in material cost and density across the available options. Readers seeking further details, supporting information can be found in Appendix D (Table D.1 and D.2).

Among the candidates, silver emerged as the material with the highest thermal conductivity, making it highly attractive for enhancing heat transfer. However, its high cost and density present challenges in terms of stability and scalability. On the other hand, ceramic nanoparticles such as silicon carbide, aluminium nitride, and beryllium oxide offer moderate thermal conductivities but excel in terms of

affordability, chemical stability, and dispersion behaviour making them viable alternatives for long-term application.

Multi-walled carbon nanotubes, although not represented in the comparative cost-density graphs, stand out as one of the most promising yet complex nanomaterials for thermal applications. Despite their relatively high cost, MWCNTs offer a unique combination of exceptional thermal conductivity, ultra-low density, and a remarkably high aspect ratio, which enables them to form thermally conductive networks even at low concentrations. Although stability remains a challenge, their exceptional heat transfer characteristics and compatibility with other materials make them ideal candidates for hybrid formulations.

To facilitate material selection for the experimental phase, this comparative approach helped identify nanopowders that deliver an optimal compromise between properties, stability, and cost-effectiveness. These observations point toward several potential hybrid nanofluid combinations that merit further investigation. Binary formulations such as Ag–BeO, Ag–SiC, Ag–AlN, MWCNTs–Ag, and MWCNTs–AlN offer the potential to balance high thermal conductivity with improved stability, reduced density, and cost-effectiveness. Additionally, tri-hybrid blends like MWCNTs/Ag/AlN stand out for their ability to integrate the distinct advantages of metallic, ceramic, and carbon-based nanoparticles within a single formulation. Such combinations are well-positioned to deliver enhanced thermal performance, manageable viscosity, and long-term suspension stability making them strong candidates for next-generation hybrid nanofluid development in advanced cooling applications.

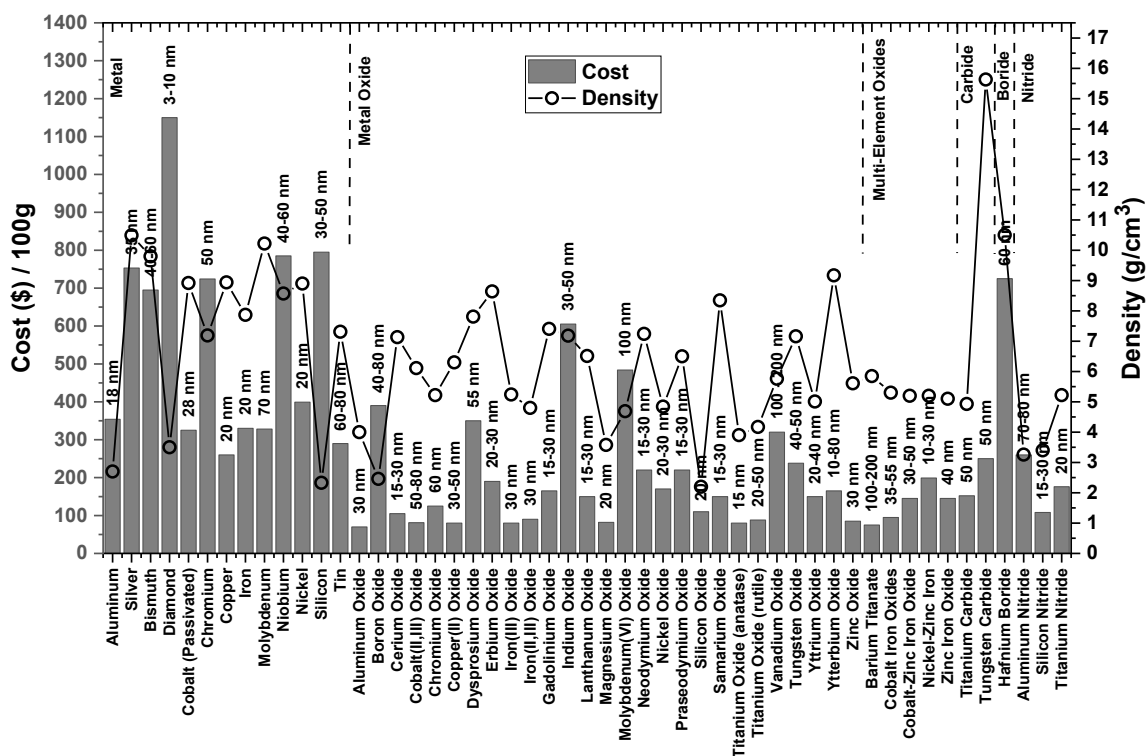


Figure 3.14: Various aspects of the commercially available nanoparticles offered by NanoAmor (accessed 10/06/2022).

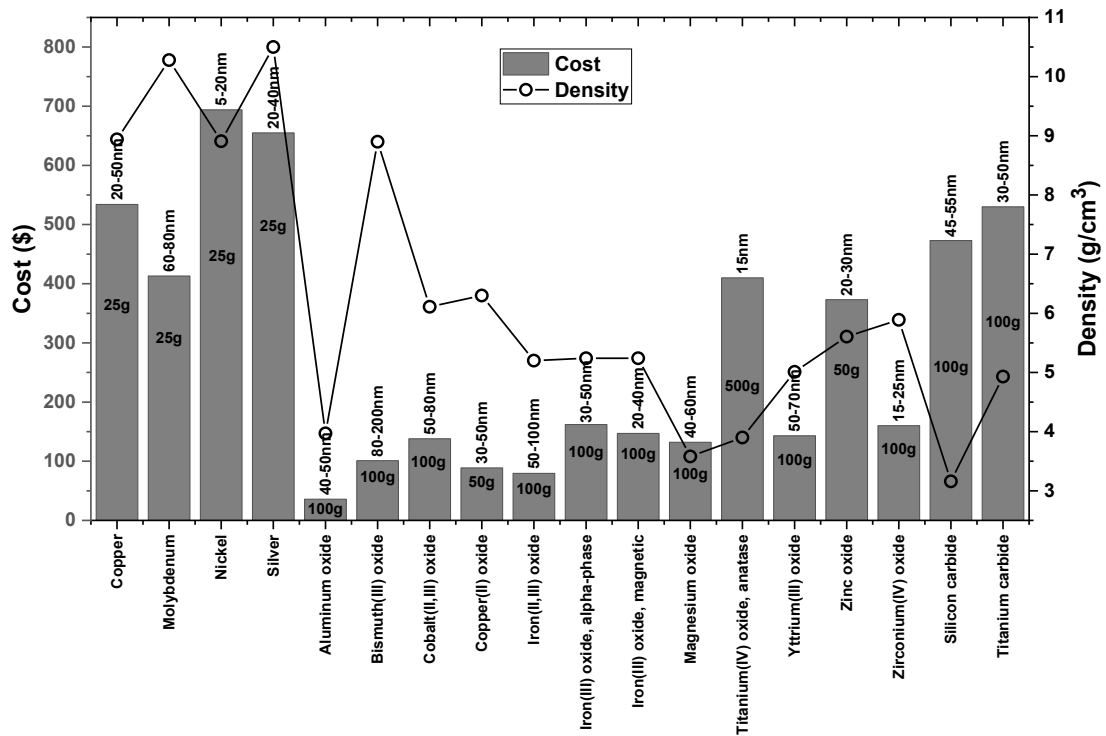


Figure 3.15: Various aspects of the commercially available nanoparticles offered by Alfa Aesar (accessed 13/06/2022).

3.3.2 Nanoparticle Selection

The selection of appropriate nanoparticles is a critical step in nanofluid development, as it directly influences not only the thermal performance but also the stability, cost-effectiveness, and long-term applicability of the formulation. Building on the comparative analysis presented in the previous section (Figure 3.14 & Figure 3.15), which evaluated commercially available nanoparticles from NanoAmor and Alfa Aesar, the most suitable candidates were identified by weighing key parameters such as thermal conductivity, density, price, and availability. This assessment helped establish a practical framework for selecting nanoparticles that offer the best trade-off between performance and feasibility for integration into water-based nanofluids.

Emerging from the comparative study, five types of nanoparticles were selected for further investigation, each representing a different material family. This diverse selection was intended to capture a broad spectrum of thermophysical characteristics, enabling a more comprehensive understanding of how particle type influences nanofluid performance.

- **Silver (Ag)** – A metallic nanoparticle with exceptionally high thermal conductivity ($\sim 429 \text{ W/m}\cdot\text{K}$) but relatively high cost and density. Selected for its superior thermal performance and as a benchmark material from the metal family.
- **Beryllium Oxide (BeO)** – Chosen from the metal oxide family for its high thermal conductivity ($\sim 250 \text{ W/m}\cdot\text{K}$), cost-effectiveness, and relatively low density. Offers a balanced alternative to pure metals.

- **Aluminium Nitride (AlN)** – A representative from the nitride family, AlN exhibits high thermal conductivity and relatively low density, making it attractive for weight-sensitive cooling systems.
- **Silicon Carbide (SiC)** – A durable and stable particle from the carbide family, selected for its moderate thermal conductivity, low cost, and high dispersion stability.
- **Multi-Walled Carbon Nanotubes (MWCNTs)** – Chosen from the carbon-based family due to their anisotropic thermal pathways and exceptionally high aspect ratio, which enables enhanced convective mixing and directional heat transport.

These particles were procured from reliable suppliers, including Alfa Aesar, Thermo Fisher Scientific, and Sigma Aldrich, and a detailed comparative analysis was conducted before selection. Figure 3.16 showcases photographs of the selected nanopowders, as received from Alfa Aesar and Sigma Aldrich.



Figure 3.16. Nanopowders procured from Alfa Aesar and Sigma Aldrich for use in nanofluid preparation.

3.3.3 Summary of Nanofluid Preparation Method

In this study, a widely adopted two-step method was used for the preparation of nanofluids, offering both flexibility in formulation and scalability for experimental evaluation. While this section provides a brief overview of the procedure, the complete methodology covering preparation, stability, thermophysical properties, and characterisation is presented in detail in the subsequent chapters.

The process began with the dispersion of individual nanoparticles into the base fluid using a combination of mechanical stirring, homogenisation, and ultrasonication. These steps were essential to ensure a uniform distribution of particles and to minimise agglomeration, thereby enhancing colloidal stability. Additional dispersion-enhancing techniques were used as required to promote colloidal stability.

For hybrid nanofluids, individual unitary nanofluids were first prepared separately. These were then combined using controlled mixing protocols to achieve a homogenous blend. The approach allowed for the investigation of synergistic effects between different nanoparticles while maintaining consistency in fluid preparation.

3.3.4 Safety, Environmental, and Practical Considerations

Beyond performance and cost metrics, the safety protocols, handling requirements, and practical implications of using such materials in real-world applications are equally important considerations.

While the selected nanoparticles offer promising thermophysical enhancements, their safe integration into thermal systems requires careful attention to potential health risks, environmental impact, and operational feasibility. Addressing these aspects ensures that the benefits of nanofluid-enhanced cooling technologies can be harnessed responsibly and sustainably, both in laboratory settings and practical deployment scenarios. While Ag, SiC, and AlN are generally regarded as safe at low concentrations and when handled in liquid suspension, BeO and MWCNTs poses greater concern due to its known toxicity in powder form, particularly via inhalation [54,197,198]. To ensure safety, all nanofluids were prepared and handled exclusively in liquid form within a controlled laboratory setting. Appropriate precautions including the use of fume hoods, sealed containers, and personal protective equipment (PPE) were strictly followed during all stages of preparation and testing. Additionally, instrument selection and experimental conditions were carefully controlled to minimise any risk of exposure. These additional safety measures, along with future end-of-life disposal requirements, contribute to slightly higher preparation and operational costs when working with nanomaterials.

In real-world applications, these nanofluids operate within closed-loop cooling systems, where the working fluid is fully contained, eliminating direct human or environmental exposure during operation. Under such conditions, the nanoparticles remain suspended in the liquid and circulate continuously through the system without contact with external surfaces. However, when decommissioning or replacing such systems, proper disposal practices are essential. Devices containing nanofluids, especially those with BeO and MWCNTs should be treated as hazardous waste and disposed of through certified channels in compliance with environmental and safety regulations. With these measures in place, the high thermal performance offered by nanofluid-enhanced cooling systems can be leveraged without compromising safety or environmental responsibility.

3.3.5 Cross-Referencing with Detailed Methodology

This section provides an overview of the nanoparticle selection strategy and nanofluid preparation approach. For a comprehensive understanding of the formulation process, readers are referred to Chapters 5 and 6, which present in-depth discussions on nanofluid characterisation. These chapters cover key aspects such as thermal conductivity, viscosity, particle morphology, and suspension stability parameters that are essential for evaluating the performance and applicability of nanofluids in advanced thermal management systems.

3.4 Nanoparticles characterization

A comprehensive characterisation of the selected nanoparticles was carried out to evaluate their morphological, structural, and chemical properties prior to nanofluid formulation. These properties significantly influence the thermophysical behaviour, dispersion quality, and long-term stability of nanofluids. Transmission Electron Microscopy (TEM) and X-ray Diffraction (XRD) characterisation techniques were employed in this study.

3.4.1 Transmission Electron Microscopy (TEM)

TEM was employed to observe the morphology and determine the size distribution of the nanoparticles at the nanoscale. Unlike conventional optical imaging, TEM uses an electron beam to generate high-resolution images, allowing detailed visualisation of particle shape, surface texture, and agglomeration tendencies. The TEM micrographs acquired in this study revealed the structural characteristics of each nanoparticle type highlighting, for instance, the elongated tubular shape of MWCNTs and the near-spherical morphology of Ag and AlN particles.

Post-processing of the images was performed using ImageJ software, which enabled accurate particle sizing and histogram-based analysis of particle dispersion. The observed size distributions were within the expected range reported by the suppliers, confirming the material quality and consistency required for reliable nanofluid formulation.

3.4.2 X-Ray Diffraction (XRD)

XRD analysis was carried out to examine the crystallographic properties and phase purity of the nanoparticles. The diffraction patterns were used to identify crystal structures, estimate average crystallite size (via the Scherrer equation), and detect any impurities or secondary phases present in the samples. Each nanoparticle type exhibited well-defined characteristic peaks corresponding to its crystalline form.

The results confirmed the high crystallinity and purity of the samples, which are essential for achieving predictable thermal behaviour and ensuring compatibility with water-based base fluids. Additionally, shifts or broadening in the diffraction peaks were used to infer changes in lattice strain or size effects associated with the nanoscale dimensions of the particles.

3.5 Thermophysical Properties and Stability of Nanofluids

Following characterisation, the nanofluids were evaluated in terms of their thermophysical properties and dispersion stability. These properties play a central role in determining their viability as advanced coolants in high-performance heat transfer systems. Understanding and accurately characterising the thermophysical properties of nanofluids is essential for evaluating their performance in practical heat transfer applications. In this study, key parameters such as thermal conductivity, viscosity, zeta potential, and density were measured to assess the suitability of the prepared mono, hybrid, and tri-hybrid nanofluids. These measurements also provide the necessary input for hydrothermal performance evaluation in the subsequent experimental work.

3.5.1 Thermal conductivity

Thermal conductivity was measured using the Hot Disk TPS 2500S thermal constants analyser, which operates based on the Transient Plane Source (TPS) technique. This method is well-established for precise, non-invasive thermal characterisation of liquid samples. A specially designed Kapton sensor

simultaneously acts as both a heat source and a resistance thermometer. During testing, a small heat pulse is introduced into the nanofluid, and the system records the transient temperature response to calculate thermal conductivity.

To maintain consistency, the fluid samples were held in a controlled environment using a temperature-stabilised bath. The measurement protocol was verified by testing distilled water and comparing results against established literature values. Minimal variation across repeated measurements confirmed the accuracy and repeatability of the experimental setup.

3.5.2 Viscosity

Viscosity plays a vital role in assessing the pumping requirements and flow resistance of nanofluids. In this study, the viscosity of the fluid samples was evaluated using a Brookfield DVNext Cone/Plate Rheometer, equipped with a cone spindle and precision temperature control. A water circulation bath system ensured temperature stability during testing, while the rheometer's built-in control ensured high accuracy and reproducibility.

Measurements were taken across a range of temperatures and nanoparticle concentrations. As expected, nanofluids exhibited higher viscosity compared to base fluids, with trends dependent on particle type, morphology, and interaction. The results confirmed that careful selection of nanoparticle combinations could mitigate excessive viscosity increases, thus preserving practical flow characteristics.

3.5.3 Density

Density measurements were performed using an Anton Paar DMA 35 density meter, offering high precision and repeatability. Fluid samples were equilibrated in a temperature-controlled bath before measurement to ensure accuracy. The device measures the oscillation frequency of a U-tube filled with the fluid sample to determine density based on standard calibration curves.

Density is critical for evaluating fluid inertia, buoyancy-driven flow, and mass flow rate calculations in system-level thermal management models. Results were collected at multiple temperatures and concentrations, allowing for comprehensive characterisation of how nanoparticle loading affects fluid density across different formulations

3.5.4 Zeta potential

The dispersion stability of nanofluids was assessed using zeta potential measurements, conducted with a Malvern Zetasizer equipped with a DTS 1070 cell. This setup is specifically designed for accurate analysis of colloidal suspensions. An electric field was applied to the fluid, and particle movement was tracked to calculate the electrokinetic potential using Smoluchowski's equation.

Zeta potential values exceeding ± 30 mV are generally indicative of stable suspensions. In this study, the zeta potentials of pure, hybrid, and tri-hybrid nanofluids consistently fell within the range of -45 mV to -70 mV, confirming excellent electrostatic repulsion and minimal agglomeration risk.

Summary

In summary, this chapter has provided a comprehensive account of the experimental methodology employed to evaluate the hydrothermal performance of nanofluid-enhanced biomimetic heat sinks. From the careful selection and characterisation of nanoparticles to the fabrication of nature-inspired geometries and precise measurement of thermophysical properties, each stage has been designed to ensure experimental accuracy, repeatability, and practical relevance. The integration of advanced nanofluids with geometrically optimised heat sinks offers a unique opportunity to investigate the synergistic effects of fluid properties and fin design on heat transfer efficiency and flow behaviour. By maintaining a consistent experimental framework and applying rigorous testing protocols, this study is well-positioned to deliver meaningful insights into the design of next-generation cooling systems. The results and analysis presented in the following chapter aim to quantify these effects, identify optimal configurations, and contribute to the broader understanding of high-performance thermal management in compact systems.

CHAPTER 4

4 Data Processing and Test Rig Validation

This chapter outlines the procedures followed for data processing and the validation of the experimental test rig used to assess the thermal and hydraulic performance of the developed heat sink configurations. Initially, it outlines the approach adopted for calculating the particle volume fraction and hydraulic diameter for non-uniform geometries, particularly relevant to the bio-inspired pin-fin designs studied. Performance parameters such as Nusselt number, Reynolds number, thermal resistance, and pressure drop were then derived from experimental measurements using standard heat transfer correlations.

To ensure measurement accuracy, an uncertainty analysis was performed for all key variables and derived parameters. The chapter also reviews thermophysical models commonly used in the literature for hybrid nanofluids, although these models were not applied in the present work. Finally, the test rig was validated through a series of experiments using a conventional straight channel heat sink. The experimental results were benchmarked against theoretical predictions using the Shah correlation and further compared with numerical simulations from a validated CFD model. This dual-validation approach confirmed the accuracy, repeatability, and reliability of the experimental setup, laying a robust foundation for the comparative performance analysis of advanced geometries presented in the following chapter.

4.1 Data Processing

During the experimental campaign, data was collected at regular intervals to capture the thermal performance of the liquid-cooled heat sink. The measured data included the inlet and outlet temperatures of the working fluid, as well as the temperatures at specific positions within the heat sink. In addition, essential flow parameters such as volumetric flow rate, pressure drop across the heat sink, and the input electrical power used to generate heat were continuously monitored and recorded. To analyse the experimental results obtained from the experimental study, several equations and calculations were employed to determine various parameters related to heat transfer and thermal performance. The application of these calculations enabled a comprehensive interpretation of the experimental data, allowing for a direct comparison of different nanofluids and heat sink geometries. By combining temperature, flow, and pressure measurements with analytical methods, this study ensured a reliable and systematic approach to performance evaluation, forming a critical foundation for the subsequent analysis presented in the following chapters.

4.1.1 Particle Volume Fraction

The mass of nanoparticles added to the base fluid was calculated using a mass balance approach based on the particle volume fraction (ϕ). This well-established method, frequently cited in the literature

[199,200], considers the relative densities of both the nanoparticles and the base fluid, as expressed in Eq. (4.1).

$$\varphi = \left[\frac{\frac{m_{np}}{\rho_{np}}}{\frac{m_{np}}{\rho_{np}} + \frac{m_{bf}}{\rho_{bf}}} \right] \quad (4.1)$$

In this expression, m_{np} and m_{bf} represent the mass of nanoparticles and base fluid, respectively, while ρ_{np} and ρ_{bf} denote their respective densities. The equation expresses the volume fraction of nanoparticles as the ratio of the volume occupied by the particles to the total volume of the suspension (particles plus fluid). This calculation is crucial for ensuring consistency across formulations and allows researchers to accurately control nanoparticle concentration, which significantly affects the thermal conductivity, viscosity, and stability of the resulting nanofluid.

4.1.2 Hydraulic Diameter Calculations

The hydraulic diameter plays a central role in evaluating the Reynolds number, which dictates whether the flow is laminar or turbulent, and influences boundary layer development and thermal entry length. Accurate calculation of hydraulic diameter is thus critical for reliable interpretation of the experimental results and for comparison with theoretical or numerical models. In conventional channels, the hydraulic diameter (d_h) is defined as four times the cross-sectional area divided by the wetted perimeter. However, when the channel cross section varies along its length, as this study used airfoil integrated curvilinear and corrugated curvilinear pin-fin heat sinks, this simple model no longer adequately represents the effective flow area. A modified approach is therefore used to account for these variations, following techniques reported in the literature [178,201,202]. To compute the hydraulic diameter for a channel with varying cross-sectional area, Eqs. (4.2–4.4) is used:

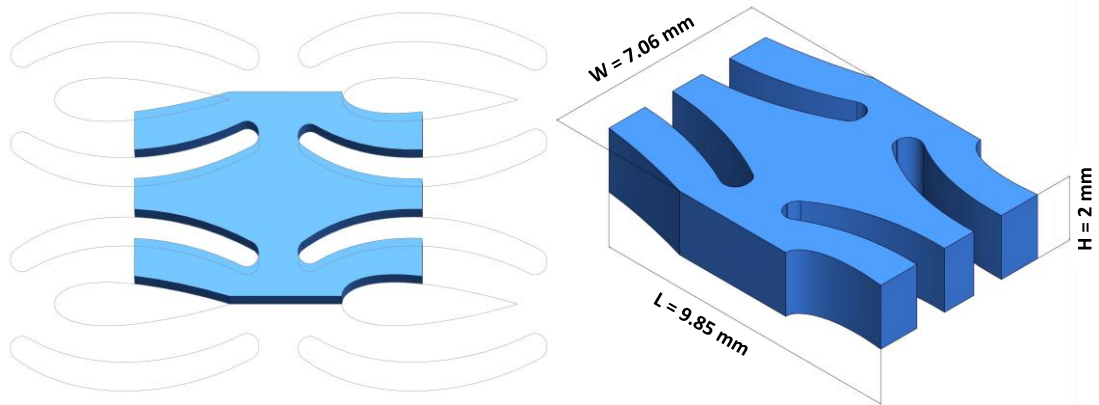
$$V_{sec} = (L \times W - A_{fin,top})H \quad (4.2)$$

$$S_{sec} = (P_{fin} \times H) + 2(L - L_{a,fin})H + (L \times W - A_{fin,top}) \quad (4.3)$$

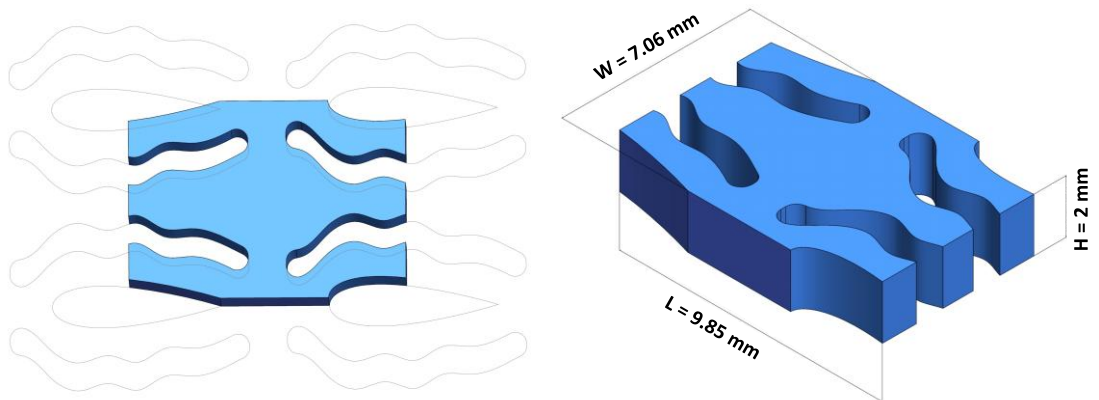
$$d_h = \frac{4V_{sec}}{S_{sec}} \quad (4.4)$$

In these equations, V_{sec} denoted the volume of the specific sections shown in Fig. 4.1, while L , W , and H symbolised the length, width, and height, respectively. $A_{fin,top}$ is the top surface area of the fin that is subtracted from the overall section area. S_{sec} represents the effective side surface area or wet area, which accounts for the contributions of the fin's lateral surfaces as well as the remaining section area. P_{fin} and $L_{a,fin}$ denoted the effective perimeter and length of the airfoil fin. By using these equations, the hydraulic diameter d_h is determined in a way that reflects the actual flow constraints imposed by the non-uniform channel geometry, ensuring a more accurate prediction of fluid flow, and heat transfer characteristics in such complex configurations.

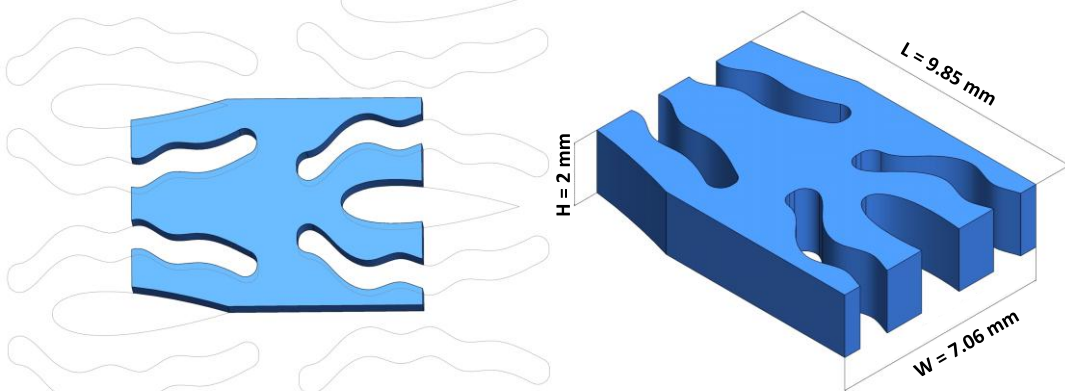
(a) Airfoil Integrated Curvilinear Pin-fin Heat Sink - Cut Section



(b) Inline Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin Heat Sink - Cut Section



(c) Staggered Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin Heat Sink - Cut Section



(d) Staggered Arranged Airfoil Integrated Split Corrugated Curvilinear Pin-Fins - Cut Section

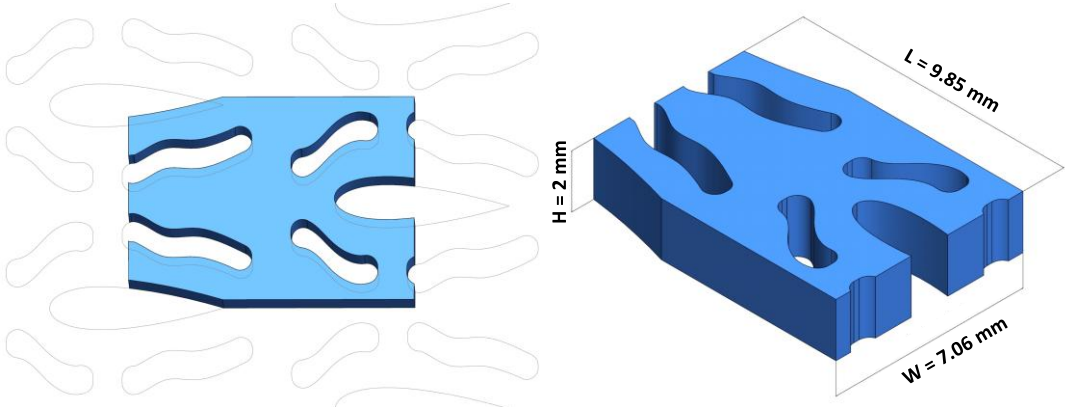


Figure 4.1. Cut sections and dimensional details of the heat sink configurations.

The hydraulic diameter is calculated based on the dimensions and geometry of the channel. For a straight channel heat sink with a rectangular cross-section, the hydraulic diameter (d_h) can be determined using Eq. (4.5) [203].

$$\text{Hydraulic diameter } (d_h) = \frac{4A}{P} \quad (4.5)$$

where A symbolised the cross-sectional area of the channel and P represented wetted perimeter of the channel. For rectangular channels, the A is calculated using Eq. (4.6), while P is computed with Eq. (4.7).

$$\text{Cross sectional area } (A) = \text{height } (h) \times \text{width } (w) \quad (4.6)$$

$$\text{Wetted parameter } (P) = 2 \times [\text{height } (h) + \text{width } (w)] \quad (4.7)$$

4.1.3 Performance Parameters

To evaluate the hydrothermal performance of the heat sink configurations, a range of thermodynamic and flow-based parameters were computed from the experimental data. These parameters collectively provide insight into the effectiveness of the system in terms of heat transfer, flow resistance, and efficiency.

The mean bulk temperature (T_{mean}) is calculated using Eq. (4.8) as the arithmetic average of the inlet and outlet temperatures.

$$T_{mean} = \frac{T_{inlet} + T_{outlet}}{2} \quad (4.8)$$

This equation provides an average temperature of the fluid, representing its thermal state as it flows through the channel.

The rate of heat transfer ($\dot{Q}$) from the heater into the fluid is derived using Eq. (4.9).

$$\dot{Q} = \dot{m}C_p(T_{outlet} - T_{inlet}) \quad (4.9)$$

here, $\dot{m}$ is the mass flow rate and C_p is the specific heat capacity of the fluid. This expression quantifies the heat absorbed by the fluid as it passes through the heat sink.

The channel wall temperature (T_w) is estimated by applying Eq. (4.10).

$$T_w = T_b - \left(\frac{\dot{Q}l_x}{k_s A_w} \right) \quad (4.10)$$

In this equation, T_b is the base temperature, l_x is the distance from the base to the channel wall, k_s is the thermal conductivity of the heat sink material, and A_w is the wall surface area. It models the temperature drop across the wall due to conduction. However, the wall surface area (A_w) is computed using Eq. (4.11).

$$A_w = L_s \times W_s \quad (4.11)$$

L_s and W_s are the length and width of the heat sink's finned area, respectively.

Since the temperature difference between the wall and the fluid is not constant along the flow direction, the logarithmic mean temperature difference (*LMTD*) is used, calculated by Eq. (4.12) [204–206].

$$LMTD = \frac{(T_w - T_{inlet}) - (T_w - T_{outlet})}{\ln \left[\frac{(T_w - T_{inlet})}{(T_w - T_{outlet})} \right]} \quad (4.12)$$

here, *LMTD* provides an effective average temperature difference that drives the heat transfer process. The convective heat transfer coefficient (*h*) is derived from the rate of heat transfer and the effective temperature difference using Eq. (4.13).

$$h = \left[\frac{mC_p(T_{outlet} - T_{inlet})}{A_{seff} \times (LMTD)} \right] \quad (4.13)$$

A_{seff} is the effective area over which convection takes place, and this coefficient indicates the efficiency of convective heat removal. It represents the area in contact with the flowing fluid.

The Reynolds number (*Re*) is a dimensionless parameter that characterises the flow regime, calculated using Eq. (4.14).

$$Re = \frac{\rho v d_h}{\mu} \quad (4.14)$$

In this equation, ρ is the fluid density, v is the average velocity, d_h is the hydraulic diameter, and μ is the fluid viscosity.

The average velocity (v) of the fluid is obtained by dividing the volumetric flow rate (q) by the cross-sectional area, determined using Eq. (4.15). However, the average cross-sectional area ($A_{avg.}$) of the channel is calculated with Eq. (4.16).

$$v = q/A_{avg.} \quad (4.15)$$

$$A_{avg.} = \frac{V_{sec}}{L} \quad (4.16)$$

here, V_{sec} represents the effective volume of the specific flow section, and L is the length.

Thermal resistance (R_{th}) is an inverse measure of the system's heat transfer efficiency and is given by Eq. (4.17) [157]. A lower thermal resistance indicates a more effective heat transfer process.

$$R_{th} = \frac{LMTD}{\dot{Q}} \quad (4.17)$$

The Nusselt number (Nu) is a dimensionless indicator of convective heat transfer enhancement over pure conduction, calculated using Eq. (4.18):

$$Nu = \frac{h d_h}{k_c} \quad (4.18)$$

Here, k_c is the thermal conductivity of the coolant. A higher Nu signifies improved convective performance.

The pumping power (PP) required to circulate the fluid is estimated using Eq. (4.19).

$$PP = q \times \Delta P \quad (4.19)$$

In this equation, q is the volumetric flow rate and ΔP is the pressure drop across the channel. This parameter is important for evaluating the energy cost of fluid circulation.

Lastly, the Darcy friction factor (f) is used to characterise flow resistance, computed using Eq. (4.20). This factor reflects the relative impact of pressure losses due to friction and geometry-induced flow disturbances within the channels [207,208].

$$f = \frac{2\Delta P d_h}{\rho L v} \quad (4.20)$$

In addition to individual thermal and hydraulic metrics, the overall performance of the heat sink was evaluated using a combined indicator that accounts for both the rate of heat transfer and the energy cost associated with fluid movement. This integrated performance metric is defined by Eq. (4.21) [209,210].

$$\text{Overall performance} = \frac{Q}{PP} \quad (4.21)$$

This dimensionless performance ratio reflects the thermal effectiveness per unit of hydraulic effort, making it particularly useful for comparing different configurations or coolant types in terms of energy efficiency.

A higher value of the overall performance metric indicates that the system is capable of transferring more heat for a given amount of pumping power, signifying a better thermal–hydraulic balance. This parameter is especially important in practical applications where improving thermal performance must not come at the expense of significantly increased flow resistance or energy consumption.

Each equation plays a critical role in the overall analysis of the heat sink's performance, linking the thermal and hydrodynamic characteristics to the design and operational parameters. Together, they provide a comprehensive framework for assessing the effectiveness of the cooling system.

4.1.4 Uncertainty Analysis

Uncertainty analysis is a critical aspect of micro- and mini-scale experiments, ensuring the accuracy and reliability of experimental findings while carefully assessing the errors associated with measuring instruments. To quantify the uncertainties in various measured parameters, the study adopted an approach consistent with methodologies employed by other researchers. This rigorous analysis enhances confidence in the experimental data and improves the precision of the reported results.

The uncertainties in different parameters were determined using a set of established equations, specifically Eq. (4.18–4.22). The analysis revealed that the maximum uncertainties for the Reynolds number, hydraulic diameter, and Nusselt number were 6.18%, 1.63%, and 6.26%, respectively. These values indicate an acceptable level of accuracy in the measurements. Additionally, Table 4.1 presents the accuracy specifications of the instruments used in the study.

To further ensure the reliability of the measurements, repeat trials were conducted at selected flow rates and heating powers. The results showed strong consistency across these trials, with variations in the Nusselt number remaining within $\pm 2\%$, and pressure drop variations within $\pm 4\%$ for water-based tests. However, in the case of nanofluids, the variability was slightly higher, observed within $\pm 3.5\%$ for Nusselt number and $\pm 6\%$ for pressure drop. These findings reinforce the stability of the test rig and the repeatability of the experimental methodology.

$$\frac{U_{d_h}}{d_h} = \sqrt{\left(\frac{U_h}{h}\right)^2 + \left(\frac{U_w}{w}\right)^2} \quad (4.18)$$

$$\frac{U_v}{v} = \sqrt{\left(\frac{U_{d_h}}{d_h}\right)^2 + \left(\frac{U_m}{m}\right)^2 + \left(\frac{U_A}{A}\right)^2} \quad (4.19)$$

$$\frac{U_{Re}}{Re} = \sqrt{\left(\frac{U_\rho}{\rho}\right)^2 + \left(\frac{U_v}{v}\right)^2 + \left(\frac{U_\mu}{\mu}\right)^2} \quad (4.20)$$

$$\frac{U_h}{h} = \sqrt{\left(\frac{U_m}{m}\right)^2 + \left(\frac{U_{(T_w-T_i)}}{(T_w-T_i)}\right)^2 + \left(\frac{U_{(T_w-T_o)}}{(T_w-T_o)}\right)^2 + \left(\frac{U_{C_p}}{C_p}\right)^2 + \left(\frac{U_{A_{eff}}}{A_{eff}}\right)^2 + \left(\frac{U_{(T_{out}-T_{in})}}{(T_{out}-T_{in})}\right)^2} \quad (4.21)$$

$$\frac{U_{Nu}}{Nu} = \sqrt{\left(\frac{U_h}{h}\right)^2 + \left(\frac{U_{d_h}}{d_h}\right)^2 + \left(\frac{U_{k_f}}{k_f}\right)^2} \quad (4.22)$$

Table 4.1. Accuracy and measurement range of experimental instruments.

Instrument	Accuracy	Operational Range
Flow Sensor	$\pm 6\%$	0.1 – 1 l/min
Temperature Probe	$\pm 1.5\text{ }^\circ\text{C}$	-75 to $260\text{ }^\circ\text{C}$
Pressure Gauge	$\pm 0.08\%$ BSL (incl. linearity, hysteresis, repeatability) and $\pm 0.15\%$ for analogue output	0 – 25 mbar
DC Power Supply	Current: $< 0.3\%$	0 – 10 A
	Voltage: $< 0.2\%$	0 – 84 V

4.1.5 Thermophysical Models for Hybrid Nanofluids

The accurate estimation of nanofluid thermophysical properties is essential for predictive modelling and system-level optimisation in heat transfer applications. Numerous studies in the literature have utilised classical theoretical models to estimate key thermophysical properties namely thermal conductivity, dynamic viscosity, heat capacity, and density for both mono and hybrid nanofluids. These models serve as important tools in both experimental data validation and numerical simulation frameworks, especially when direct measurements are not feasible.

Among the most commonly used models are those developed by Hamilton and Crosser [211] and Corcione [212] for predicting thermal conductivity and viscosity, respectively. For estimating specific heat capacity and density, models by Xuan and Roetzel [213] and Pak and Cho [104] have been widely applied. These formulations have served as the foundation for numerous computational and semi-empirical investigations exploring nanofluid performance [214–222].

In recent literature, extended versions of these classical models have been proposed to account for the unique characteristics of hybrid nanofluids, which involve two or more types of nanoparticles suspended in a base fluid. The studies [223,224] introduced modified correlations that incorporate multiple volume fractions, particle size effects, and particle–fluid interactions to better capture the complex behaviour of hybrid systems.

These extended models have shown good predictive accuracy at low particle concentrations (typically ≤ 0.1 vol.%), where nanofluids exhibit near-linear behaviour. However, at higher concentrations, significant deviations from experimental data have been reported, attributed to factors such as agglomeration, particle–particle interaction, and non-Newtonian flow effects phenomena that are often not captured by classical equations. Equations (4.23–4.26) provide the extended forms of the classical models of Hamilton–Crosser [211], Corcione [212], Xuan and Roetzel [213], and Pak and Cho [104] used for the calculation of thermal conductivity, viscosity, heat capacity, and density, respectively.

$$\frac{k_{hnf}}{k_{bf}} = \frac{\left(\frac{(\varphi_{p1}k_{p1} + \varphi_{p2}k_{p2})}{\varphi} + (n-1)k_{bf} + (n-1)(\varphi_{p1}k_{p1} + \varphi_{p2}k_{p2}) - (n-1)\varphi k_{bf} \right)}{\left(\frac{(\varphi_{p1}k_{p1} + \varphi_{p2}k_{p2})}{\varphi} + (n-1)k_{bf} - (\varphi_{p1}k_{p1} + \varphi_{p2}k_{p2}) + \varphi k_{bf} \right)} \quad (4.23)$$

$$\frac{\mu_{hnf}}{\mu_{bf}} = \left[\frac{1}{1 - 34.87 \times (d_f)^{0.3} ((d_{p1})^{-0.3}(\varphi_1)^{1.03} + (d_{p2})^{-0.3}(\varphi_2)^{1.03})} \right] \quad (4.24)$$

$$C_{p,hnf} = \left(\frac{\varphi_{p1}\rho_{p1}C_{p,p1} + \varphi_{p2}\rho_{p2}C_{p,p2} + (1-\varphi)\rho_{bf}C_{p,bf}}{\rho_{hnf}} \right) \quad (4.25)$$

$$\rho_{hnf} = \varphi_{p1}\rho_{p1} + \varphi_{p2}\rho_{p2} + (1-\varphi)\rho_{bf} \quad (4.26)$$

where k , d_f , φ , μ , ρ , n , d_p , M , and N symbolised the thermal conductivity, base fluid molecule diameter, particle volume fraction, viscosity, density, empirical shape factor, particle diameter, molecular weight, and Avogadro's number, respectively. Whereas the subscripts p , bf , and hnf denoted the nanoparticle, base fluid, and hybrid nanofluid, respectively.

Although these models offer useful approximations and have been employed across a wide range of studies, they were not adopted in the present work. Instead, all thermophysical properties relevant to this research were determined experimentally to ensure higher accuracy and real-world relevance. Nonetheless, these models are valuable for benchmarking and highlight the need for more robust

predictive tools that account for nanoparticle interaction, surface chemistry, and temperature effects especially in multi-particle hybrid nanofluids.

4.2 Validation

The experimental test rig was validated through a series of experiments using a specially designed and fabricated aluminium straight channel heat sink. The selection of this specific configuration was driven by its widespread use in thermal management applications and the availability of extensive literature on its thermal and fluidic performance. This approach was used as the heat sink designs explored in this study have not been previously investigated, and no prior experimental data exists for direct comparison. Therefore, employing a well-characterised conventional heat sink facilitated the benchmarking of experimental results against established theoretical and numerical predictions. In addition, the straight channel heat sink provided the advantage of having classical models available for predicting the Nusselt number. In this study, the experimental results were compared with the model developed by Shah et al. [225], which is widely accepted for predicting Nusselt numbers in laminar flow under constant heat flux boundary conditions. The Shah model provides a theoretical foundation for evaluating the convective heat transfer performance in ducts of various geometries, including parallel plates, circular tubes, and non-circular channels. In the present work, this model serves as a validation benchmark to compare against the experimentally obtained Nusselt numbers using a conventional straight-channel heat sink under identical boundary conditions. The choice of this model is justified due to its extensive application in previous heat transfer literature [226–229], particularly for evaluating microchannel and mini-channel systems operating under laminar regimes. The good agreement between the experimental data and Shah's prediction validates the reliability of the test rig and confirms the accuracy of the measured thermal performance parameters. Additionally, a computational fluid dynamics (CFD) analysis was performed using ANSYS Fluent to further validate the experimental findings.

The experimental tests were carried out by varying the Reynolds number within the range of 100–300 while maintaining a constant heating power of 100 W. The obtained Nusselt number values were then compared with those predicted by the Shah model, Eq. (4.27). Furthermore, a detailed CFD simulation was conducted to replicate the experimental conditions, and a mesh independence study was performed to optimise the accuracy of the numerical results. The simulations aimed to replicate the experimental conditions and assess the accuracy of the test rig through comparison of Nusselt number and temperature profiles. The steady-state forms of the continuity, momentum, and energy equations were solved to model laminar flow through the channels, as the maximum Reynolds number remained below 1000 across all test cases. The laminar flow model was therefore deemed appropriate and computationally efficient for this flow regime.

Pressure–velocity coupling was handled using the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) scheme, which provides stable convergence for incompressible, laminar flows. For spatial

discretisation, a second-order upwind scheme was used for all transport equations to ensure greater numerical accuracy, especially in resolving thermal gradients.

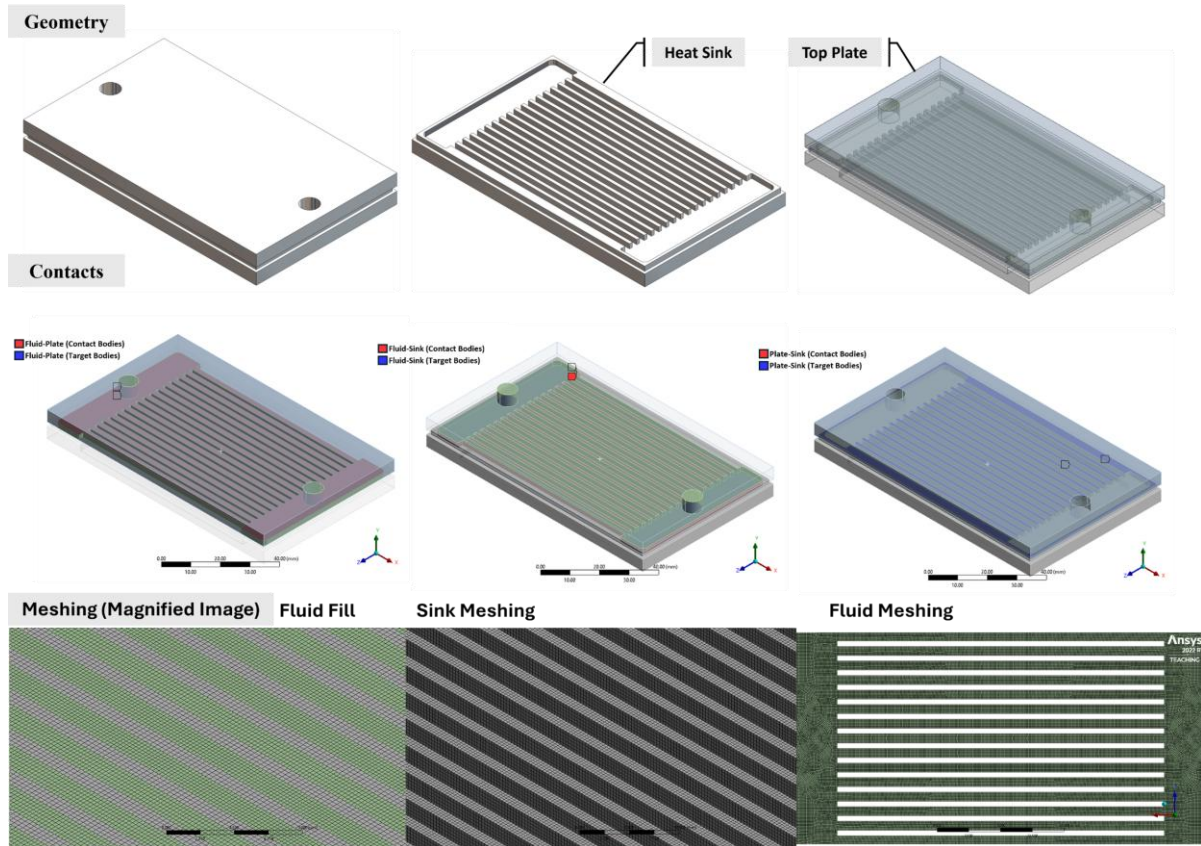


Figure 4.2. Geometric modelling, boundary contacts, and meshing details of the straight-channel heat sink.

The flux type was set to distance-based, which enhances precision in capturing interfacial behaviour, particularly in conjugate heat transfer problems. Figure 4.2 presents the geometry used in the numerical analysis, showing the sink body, fluid domain, and top plate. The figure includes isometric views with clear labelling of the key boundary interfaces, namely fluid–plate, fluid–sink, and plate–sink, which define the conjugate heat transfer domains within the model.

The mesh refinement process considered variations in base temperature, outlet temperature, and pressure drop, ensuring that the numerical model provided a reliable representation of the physical experiment. The outcomes of the mesh independence study, including the effects of mesh refinement on base temperature, outlet temperature, and pressure drop, are depicted in Fig. 4.3.

To quantitatively assess the deviation between experimental results and predictions from both the theoretical model and CFD simulations, the mean absolute error (MAE) was calculated using Eq. (4.28) [230,231]. The MAE serves as an effective measure of the average magnitude of the discrepancies between experimental and predicted values, offering insight into the consistency and accuracy of the validation process.

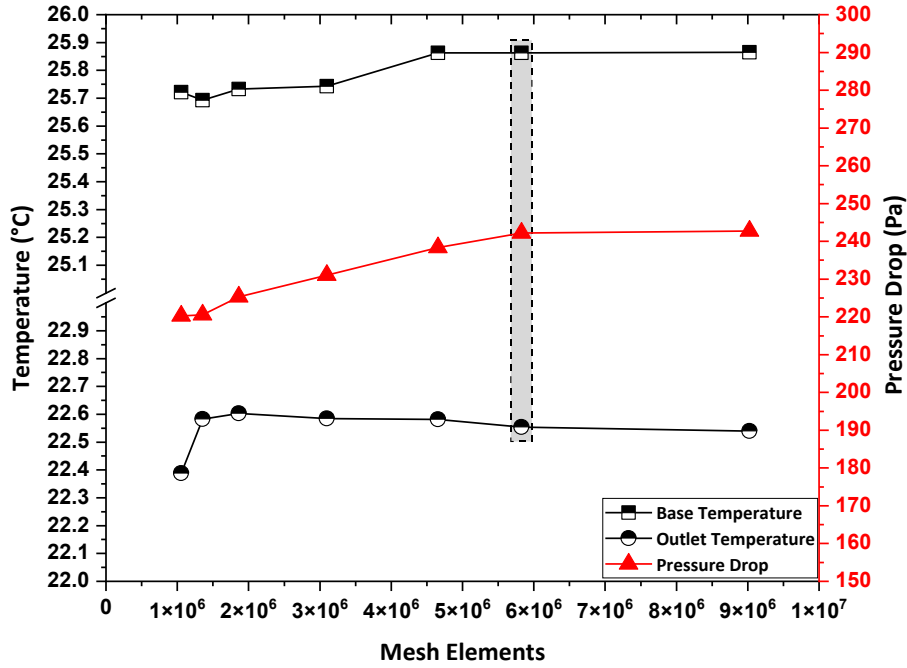


Figure 4.3. Variation of wall temperature, outlet temperature, and pressure drop with respect to mesh element count, mesh independence study for the straight-channel heat sink.

The results of the validation study demonstrated that the experimental data closely aligned with the theoretical predictions, with an MAE of 2.76% when compared to the Shah model. This low error margin underscores the reliability of the experimental test rig and the accuracy of the data acquisition process. However, when comparing the experimental results with the CFD simulations, a slightly higher MAE of approximately 5.7% was observed, as shown in Fig. 4.4. A closer inspection of the data revealed that the agreement between experimental and CFD results was strongest at lower flow rates, while deviations increased as the Reynolds number rose. This discrepancy at higher flow rates may be attributed to factors such as minor experimental uncertainties, limitations in numerical turbulence modelling, or variations in thermal boundary conditions that were not fully captured in the CFD model. The validation study confirms the robustness of the experimental setup, demonstrating its capability to produce reliable and reproducible results.

$$Nu = \begin{cases} 1.953 \left(Re Pr \frac{d_h}{l} \right)^{1/3} & \text{if } \left(Re Pr \frac{d_h}{l} \right) \geq 33.3 \\ 4.364 + 0.0722 \left(Re Pr \frac{d_h}{l} \right) & \text{if } \left(Re Pr \frac{d_h}{l} \right) < 33.3 \end{cases} \quad (4.27)$$

$$\text{Mean Absolute Error (MAE)} = \frac{1}{n} \sum_{j=1}^n \left[\frac{|x_{exp.} - x_{pred.}|}{x_{exp.}} \right] \times 100\% \quad (4.28)$$

In these equations, l represents the finned section length, Pr is the Prandtl number, and d_h denotes the hydraulic diameter. The variable n refers to the total number of data points, while $x_{exp.}$ and $x_{pred.}$ correspond to the experimental and predicted values, respectively.

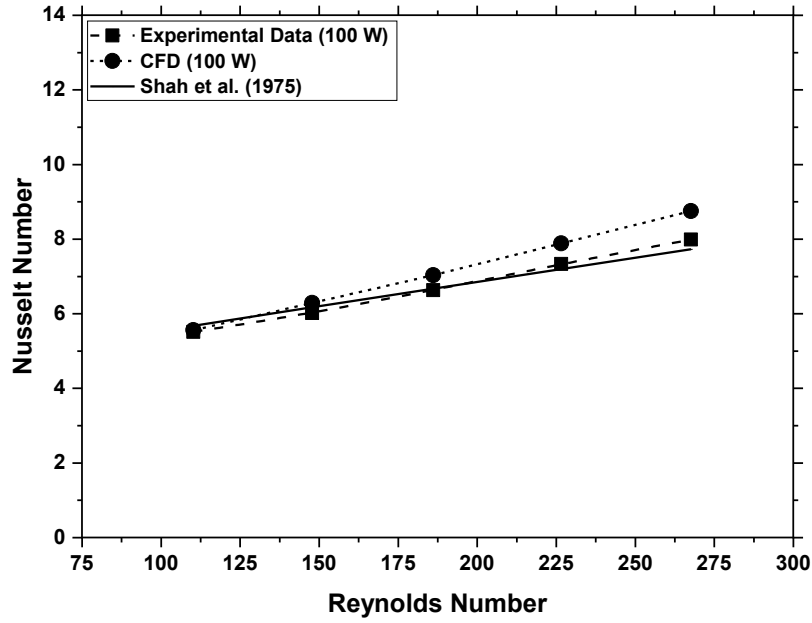


Figure 4.4. Validation of experimental results using Shah’s model and CFD simulations across varying Reynolds numbers, confirming the reliability of the test rig.

Additionally, to ensure the comprehensiveness of our analysis, the results were also compared with other models proposed by different researchers. Liu et al. [230] performed a series of experiments on a copper heat sink with square-shaped pin-fins, covering a range of Reynolds numbers from 60 to 800. The arrangement of the fins on the surface offered an interrupted passage to the flowing water, which effectively disrupted the flow and promoted better mixing and turbulence. The findings demonstrated that heat dissipation improved with increasing flow rate and surface temperature. Moreover, the researchers developed a model based on the experimental data to predict Nusselt number values for single-phase flow, represented by Eq. (4.29). The data was also correlated with the values predicted using the model developed by Kosar et al. [232] while investigating the thermal characteristics of microscale heat sink made of an array of hydrofoil-shaped pin fins. The correlation represented with Eq. (4.30) was found to be reliable, as provided a close approximation to the experimental values with a MAE of 4.1% for the specific configuration of the fins. However, for the presented study, the model provided predictions with an acceptable error range, as indicated by a MAE of 7.64%. Azizi et al. [233] examined the cylindrical microchannel heat sink employing water and the nanoparticles suspended fluid as a cooling agent. A new correlation was developed by modifying existing models to predict the Nusselt number, incorporating the effects of Reynolds number, Prandtl number, and nanoparticle volume fraction for the case of nanofluids. It was found that demonstrating a satisfactory agreement with the experimental data within a $\pm 10\%$ error range. The simplified form of the developed model, which considers a particle loading of 0%, is expressed by Eq. (4.31).

$$Nu = 0.1245 Re^{0.6106} Pr^{0.36} (Pr/Pr_s)^{0.25} \quad (4.29)$$

$$Nu = 0.238 Re^{0.488} Pr^{1/3} (Pr/Pr_s)^{0.25} \quad (4.30)$$

$$Nu = 0.293 Re^{0.485} Pr^{0.2} \quad (4.31)$$

In order to demonstrate the variation of results within an acceptable range, investigators took into consideration several recent studies. By plotting the data points, the Fig. 4.5 illustrates the range of variation observed among different experiments. This visualisation allows us to assess the extent to which our results align with the broader body of experimental findings. Feng et al. [234] conducted a numerical study focusing on the analysis of rectangular microchannel heat sinks in laminar flow conditions, comparing plain channels with those incorporating wire coils. The investigation revealed noteworthy findings regarding pressure drop and heat transfer performance. It was observed that the plain channel exhibited the most favourable pressure drop characteristics among all configurations due to the absence of flow disturbances caused by the wire coils. However, the heat transfer performance of the plain channel was significantly lower than the wire coil configurations. Uddin and Sifat [235] examined and compared different designs of MCHS to evaluate their thermo-hydraulic performance. These designs include conventional straight channels as well as rectangular channels with straight, oblique, and a novel rounded secondary channel configuration in both parallel and counter flow arrangements. To ensure the accuracy of their findings, the numerical results were validated by comparing them with experimental and simulation data from previous studies, which showed good agreement. The results revealed that in parallel flow configurations, the secondary channels were found to have a minimal impact on heat transfer when compared to the conventional heat sink design. However, in counter flow configurations, all secondary channel designs demonstrate improved heat transfer performance, characterised by higher Nusselt numbers and lower thermal resistances. Kumar et al. [236] carried out a study that combined numerical simulations and experimental investigations to analyse the hydrothermal characteristics of straight and branched wavy channel heat sinks. Both configurations were designed to have identical hydraulic diameters (0.75 mm) and footprint sizes. The primary mode of heat transfer in these heat sinks occurs through convection between the channel walls and the fluid. However, it was observed that the heat transfer coefficient decreases along the channel as the thermal boundary layer thickens, leading to a reduction in the convection heat transfer rate. Additionally, the velocity and temperature fields within the streamwise direction are found to be relatively uniform in the straight channel heat sink (SCHS) microchannel, as there is minimal fluid mixing or flow disruption. Chai et al. [237] present a numerical investigation focusing on fluid flow and heat transfer characteristics within an interrupted microchannel heat sink, featuring rectangular ribs in transverse microchambers. The study systematically explored the effects of rib width, length, position, and microchamber spacing on heat transfer and pressure drop. The findings indicate that increasing the rib width enhances heat transfer; however, this improvement comes at the cost of increased pressure drop. Fan et al. [238] conducted an investigation specifically focused on heat transfer and fluid flow characteristics within cylindrical oblique fin MCHS. The study employed computational

fluid dynamics (CFD) simulations, with the aim of exploring the impact of varying parameters such as oblique angle, Reynolds Number, and secondary channel gap on the system. By visualising the flow patterns, the researchers were able to observe how these parameters influenced the mixing and recirculation of the fluid within the channels. The findings indicated that these factors had a significant impact on the average Nusselt number, which serves as a crucial measure of convective heat transfer. This comparison and evaluation process helps us determine the effectiveness and reliability of the experimental test rig and its agreement with the established theoretical model proposed by Shah. It allows us to assess any discrepancies and analyse the performance of the rig under different operating conditions.

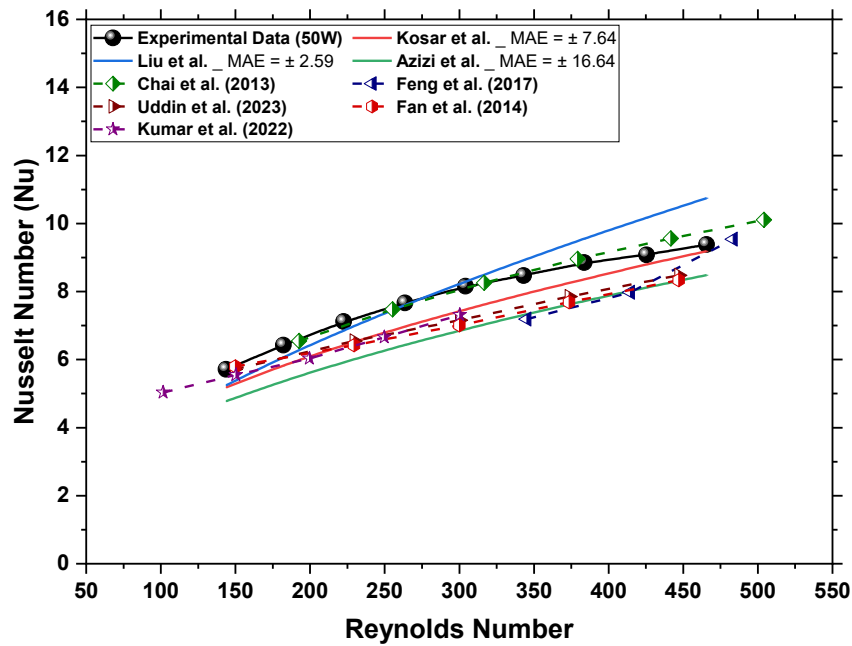


Figure 4.5: Comparison of the test results with the predicted values of various models, as well as the results from experimental and numerical studies conducted by different authors.

Summary

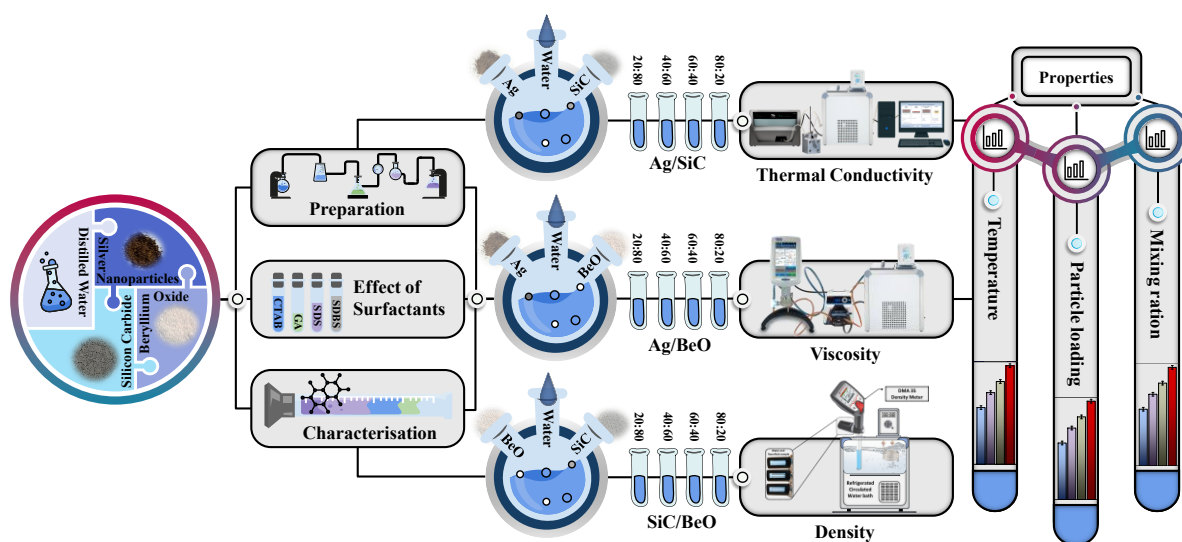
This chapter has established the validity and reliability of the experimental methodology through a rigorous data reduction framework and a comprehensive validation exercise using a baseline straight channel heat sink. The alignment of experimental results with classical correlations and CFD predictions demonstrates the accuracy of the test rig and supports its capability to capture both thermal and hydraulic performance trends under varying conditions. Furthermore, the uncertainty analysis provides confidence in the repeatability and precision of the derived parameters. While classical thermophysical models for hybrid nanofluids were reviewed, the decision to rely on experimental measurements ensures the fidelity of the performance evaluation. These validated methods form a critical foundation for the subsequent analysis of novel biomimetic heat sink configurations presented in the next chapter, where the interplay between fin geometry, coolant formulation, and operating conditions will be explored in detail to assess their potential for next-generation cooling applications.

CHAPTER 5

5 Thermophysical Characteristics of Silver, Beryllium Oxide, and Silicon Carbide in Hybrid Nanofluid Formulations

This chapter presents a detailed and self-contained study on the thermophysical behaviour of mono and hybrid nanofluids formulated using silver (Ag), beryllium oxide (BeO), and silicon carbide (SiC) nanoparticles. The findings presented herein have been published in the Journal of Molecular Liquids [DOI: 10.1016/j.molliq.2024.126175]. Given the comprehensive scope and publication-ready structure of this chapter, readers may observe that some concepts or methodological descriptions echo earlier sections of the thesis. This repetition is intentional. The chapter has been prepared in a way that ensures conceptual clarity and continuity, allowing it to function independently for readers who are primarily interested in this particular study. It consolidates the nanoparticle selection rationale, preparation methodology, and experimental characterisation of thermal conductivity, viscosity, density, and stability (via zeta potential), while also evaluating the effect of temperature and particle mixing ratios. By structuring this chapter as a complete study, the aim is to make it accessible to readers who may not require background from previous chapters but wish to engage directly with the experimental design, results, and interpretation of the thermophysical performance of these advanced nanofluid formulations.

Graphical Abstract



Abstract

Nanofluids, promising to improve heat transfer efficiency, encounter stability and durability challenges, hindering their industrial applications. The emerging concept of hybrid nanofluids, alongside surfactant-driven stability research, presents a promising solution to tackle challenges in heat transfer,

potentially revolutionizing thermal management systems and advancing nanomaterial science. This comprehensive study investigates the thermophysical properties of simple and hybrid nanofluid formulations composed of silver (Ag), beryllium oxide (BeO), and silicon carbide (SiC) nanoparticles dispersed in water. Hybrid nanofluids were prepared with varying volumetric ratios of 20:80, 40:60, 60:40, and 80:20 and examined across temperatures ranging from 15 to 45 °C. The influence of surfactants on stability was explored to augment thermal characteristics. Results revealed that the surfactants have a significant effect on stability and the specific mixing ratios can lead to more favourable thermal characteristics. Thermal conductivity enhancements, evaluated via the transient hot-wire method, demonstrated improvements of 7.43%, 7.17%, and 5.31% for Ag/SiC (60:40), Ag/BeO (60:40), and SiC/BeO (80:20) hybrid nanofluids, respectively, compared to water. Viscosity measurements revealed Newtonian behaviour for the Ag, SiC, and BeO nanofluids, with a minimum viscosity enhancement of 3.01% observed for the BeO nanofluid. Hybrid Ag/SiC nanofluid demonstrated a maximum viscosity enhancement of 4.90% for 20:80 formulation. Density analysis showed maximum augmentation of 0.25%, 0.097%, and 0.0775% for the Ag, SiC, and BeO nanofluids respectively at 0.025 vol% while hybrid Ag/SiC nanofluid exhibited a maximum of 0.23% density increase for the 80:20 composition. The statistical models were also developed to predict properties against temperature. Furthermore, the cost analysis identified Ag nanofluid as the most expensive option, while the SiC/BeO hybrid was the most economical. However, the Ag-SiC (60:40) hybrid nanofluid offered a balanced trade-off between properties and cost.

5.1 Introduction

Nanofluids, with their exceptional thermophysical characteristics, offer a promising avenue to tackle energy-related challenges. Nanoparticles suspended fluids not only present new possibilities for harnessing, storing, and transferring energy but also hold the potential to significantly enhance the efficiency of heat transferring systems. This improved performance can play a pivotal role in mitigating pressing energy concerns, including issues like global warming, climate change, and the impending fuel crisis.

Li et al. [239] examined the influence of several control factors such as ultrasonic duration, temperature, and nanoparticle loading on the stability and viscosity of copper-ethylene glycol (Cu-EG) nanofluids. Copper nanoparticles (50 nm) were mixed with ethylene glycol at various mass fractions (1%, 2%, and 3.8%), and subjected to ultrasonication for different durations in the range of 15-75 mins. Viscosity measurements were carried out over a temperature range of 20 °C to 60 °C. The key findings indicated that viscosity decreased initially with increasing ultrasonication time, promoting better dispersion by breaking down larger nanoparticle clusters. Beyond an optimal time, further ultrasonication caused re-aggregation and increased viscosity. The optimal times were 60 mins for 1% and 2% mass fractions, and 45 mins for 3.8%. Increasing temperature significantly decreased viscosity due to intensified Brownian motion, which disrupted clusters. A slight increase in mass fraction led to a marginal viscosity

rise. Kanti et al. [240] investigated graphene oxide (GO)-based hybrid nanofluids for thermal applications. The hybrid formulations of graphene oxide, silica, and titania were prepared with a 50:50 ratio, varying particle concentrations from 0.05 vol% to 1 vol%. The study examined viscosity and thermal conductivity between 30°C and 60°C and used the Performance Enhancement Ratio (PER), which is the ratio of thermal conductivity enhancement to viscosity enhancement, to rate their overall performance. It was observed that the pure GO nanofluids showed the highest thermal conductivity enhancement, 9.8% more than GO-TiO₂ and 14.4% more than GO-SiO₂ at 60°C and 1.0% volume concentration. However, pure GO also exhibited the greatest viscosity enhancement compared to the hybrid formulations. The PER analysis suggested that hybrid nanofluids are promising for high-temperature, cost-effective thermal applications above 45°C.

Esfe et al. [241] conducted an experimental study on the thermophysical properties and heat transfer characteristics of Ag-water nanofluids in turbulent flow through a straight tube. They investigated the impact of silver nanoparticle volume concentration (up to 1%) on thermal conductivity, dynamic viscosity, convective heat transfer, and pressure drop. The thermal conductivity of the nanofluid samples was measured experimentally using a KD2 Pro thermal property analyser, while the dynamic viscosity was determined using a Brookfield viscometer. The authors utilised mixing theory to calculate nanofluid density and the thermal equilibrium model to compute specific heat capacity [20,104]. Experimental thermal conductivity data were compared with various models reported in the literature, which were found to underestimate the calculated values. Additionally, a new correlation was proposed for dynamic viscosity of Ag-water nanofluids based on their findings. The results showed that increasing the nanoparticle concentration and Reynolds number led to an enhancement in the Nusselt number. At a volume concentration of 1% and a Reynolds number of approximately 22,000, the Nusselt number increased by 11.8%. However, the pressure drop also increased by an average of 15.75% with 1% volume concentration. The authors evaluated the thermal performance factor, finding that the heat transfer enhancement outweighed the pressure drop penalty for the range of concentrations studied, with a maximum thermal performance factor of 1.18 at 1% volume concentration. Chen et al. [242] developed a spiral microreactor for continuous, high-throughput synthesis of stable silica (SiO₂) nanofluids with precisely controlled particle size. The synthesised nanofluids were utilised for flow boiling heat transfer experiments, demonstrating significant enhancements in both critical heat flux (up to 124%) and heat transfer coefficient (up to 153%) on a micro pin-fins silicon chip surface at extremely low pressure drop. Maddah et al. [243] studied the effect of silver and alumina nanoparticles on the thermophysical properties of nanofluids. The samples were prepared by dispersing Ag and Al₂O₃ nanoparticles with nominal diameters of 40 nm and 20 nm respectively in distilled water at various volume concentrations ranging from 0.25% to 5%. Thermal conductivity and viscosity of the nanofluids were measured at 15 °C using a KD2 analyser and Brookfield viscometer. According to the results, the thermal conductivity, electrical conductivity, and viscosity of the nanofluids increased with increasing nanoparticle volume fraction. The thermal conductivity and electrical conductivity increased linearly,

while the viscosity showed a nonlinear increase at volume fractions above 2%. The nanofluids exhibited Newtonian behaviour at lower concentrations (0.25% to 2%) but transformed to non-Newtonian fluids at higher concentrations. It is concluded that although high thermal conductivity is desirable for heat transfer applications, the concurrent rise in viscosity is a crucial factor to consider for fluid flow.

Huminic et al. [244] studied the thermophysical properties of water-based nanofluids containing silicon SiC nanoparticles for heat transfer applications. They synthesised SiC nanoparticles via laser pyrolysis and prepared stable nanofluids with concentrations of 0.5 and 1.0 wt% using a carboxymethylcellulose surfactant. Their results revealed that increasing the surfactant concentration decreased the thermal conductivity but raised the viscosity and surface tension of the base fluid. Additionally, the study assessed the heat transfer performance of a two-phase closed thermosyphon utilising the SiC nanofluids as working fluids. These nanofluids demonstrated improved heat transfer rates of up to 24.4% for 1.0 wt%, along with enhanced evaporator heat transfer coefficients and reduced thermal resistance by up to 32.8% compared to water, with better performance observed at higher nanoparticle concentrations.

Abbasi et al. [245] employed molecular dynamics (MD) simulations to investigate the effects of particle shape and base fluid type on the density of nanofluids. They considered the ternary mixture formula, which accounts for the formation of a nanolayer around the nanoparticles, to predict the nanofluid density more accurately. Two base fluids, water and liquid argon, were examined along with four different nanoparticle shapes: spherical, planar, block, and rod-shaped with varying aspect ratios. The results revealed that the thickness of the nanolayer was influenced by the base fluid type, with liquid argon forming a slightly thicker nanolayer (1.3 nm) compared to water (0.9 nm). Additionally, the density of the nanolayer was found to be higher for planar nanoparticles than for spherical and rod-shaped particles. Furthermore, the density of the nanolayer was found to be higher for planar nanoparticles than for spherical and rod-shaped particles. This was attributed to the flat surfaces of planar particles being more effective in absorbing base fluid molecules to form the nanolayer. Furthermore, the density of nanofluids containing planar or spherical nanoparticles decreased with increasing particle diameter. Shoghl et al. [246] conducted a series of experiments to analyse the thermophysical properties of six different water-based nanofluids: CuO, TiO₂, MgO, MWCNT, Al₂O₃, and ZnO. They examined the density, viscosity, and electrical conductivity of these nanofluids as functions of nanoparticle concentration and temperature. The findings showed a considerable enhancement in electrical conductivity and viscosity of the base fluid upon the addition of nanoparticles, while the density showed a moderate increase. According to the results, a linear trend was observed between electrical conductivity and nanofluid concentration for all nanofluids except MWCNT, which exhibited a percolation threshold at 0.1 wt.%. The sample containing ZnO nanoparticles exhibited highest conductivity at lower concentrations, while CNT nanofluids showed peak values at higher concentrations. The study also concluded that the density values could be accurately predicted by the mixture rule, and the viscosity data agreed well with the Einstein model at low concentrations but deviated at higher concentrations, which was attributed to nanoparticle agglomeration. However, the

Maxwell model failed to predict the enhancement in electrical conductivity, leading the researchers to develop correlations for each nanofluid type based on the experimental data. A study conducted by Sitti et al. [247] examined the effect of temperature, volumetric concentration, and nanoparticle size on the density variation of various nanofluid samples. They measured the densities of nanofluids containing nanoparticles of Al_2O_3 , ZnO , CuO , TiO_2 , SiO_2 , and CNTs dispersed in a base fluid of 60:40 propylene glycol and water (PG/W) by volume. The measurements were carried out over a temperature range of 0–90 °C and with nanoparticle volumetric concentrations up to 6%. The experimental results were compared with the theoretical equation proposed by Pak and Cho, which relates the nanofluid density to the densities of the base fluid and nanoparticles, as well as the nanoparticle volumetric concentration. It was found that the measured densities agreed well with the theoretical predictions, with a maximum deviation of 3.8% observed for the copper oxide nanofluid. The average deviation between the experimental data and the theoretical equation was only 0.1% for all 874 data points.

The analysis of the Scopus database data presents a critical perspective on the state of research in the field of nanofluids and their hybrid combinations. The data reveals a growing interest in nanofluid research, as evident from the steady increase in the number of published articles, especially from 2005 onwards, as shown in Fig. 5.1. The stats indicate that nanofluids are an active and dynamic area of study. While there is substantial research on "Nanofluid" alone, the data illustrates that the hybrid nanofluid combinations (Ag-SiC, Ag-BeO, and SiC-BeO) have received considerably less attention throughout the years. This scarcity of research on these hybrid nanofluids emphasises the novelty of our study. The lower publication counts for the hybrid nanofluid combinations suggest that there is ample room for original research and contributions in this area. The study can address this gap and potentially lead to groundbreaking findings, further enhancing the understanding and applications of hybrid nanofluids. According to the bibliometric analysis, silver nanofluids have witnessed a period of steady growth in publications from 2005 to around 2014, suggesting a relatively established area of research. SiC nanofluids have displayed a consistently low and stagnant publication output, with only a slight increase in recent years, indicating an underexplored composition. BeO nanofluids, a newer addition to the literature starting around 2019, have seen limited attention, emphasising their underexplored nature.

The choice of nanoparticles for this study is based on a thorough consideration of their thermal properties, cost, and density. Silver nanoparticle was selected from the metal family due to its high thermal conductivity. However, its higher density poses challenges for maintaining long-term suspension in base fluids like water, while its elevated cost hinders practical implementation. In contrast, SiC and BeO nanoparticles were chosen from the carbide and oxide families, respectively, due to their lower cost and density. Despite these benefits, SiC and BeO have different properties that can be advantageous for specific applications. SiC may enhance thermal properties, making it suitable for applications in aerospace and automotive cooling, while BeO offers excellent electrical insulation, making it valuable for electronic cooling and nuclear applications. Hybrid nanofluids such as Ag-SiC

are particularly effective for high-performance cooling systems used in aerospace and automotive applications, as well as for precision machining processes due to their enhanced thermal properties. In contrast, Ag-BeO nanofluids capitalize on silver's thermal conductivity combined with BeO's electrical insulation, making them well-suited for electronic cooling systems, high-power laser applications, and nuclear reactors. Meanwhile, SiC-BeO nanofluids, are ideal for advanced energy storage systems, nuclear reactors, and high-temperature industrial processes. The potential synergistic effects of combining Ag-SiC, Ag-BeO, and SiC-BeO remain largely unexplored, highlighting the novelty and potential of these hybrid nanofluids. The limited prior research indicates significant opportunities for innovative discoveries and applications in these areas. Focusing future research efforts on these nanofluid combinations could provide new insights compared to the more established singular nanofluid types like silver or silicon carbide alone. The data-driven approach here demonstrates the value of conducting thorough background reviews and analyses to identify promising new research directions. As technology and industrial applications continue to advance, the development of new nanofluid combinations with unique properties will be in high demand.

This study aims to conduct a comprehensive examination of the thermophysical properties of these hybrid nanofluids. The investigation will encompass a wide spectrum of temperatures and involve varying mixing ratios. By doing so, this research seeks to address a notable lacuna in the existing scientific literature, thereby contributing substantively to the understanding of these unique nanofluid compositions. The outcomes of this research endeavour are anticipated to serve as a valuable resource with practical implications across a multitude of scientific and engineering applications, thereby advancing the field's knowledge base and utility.

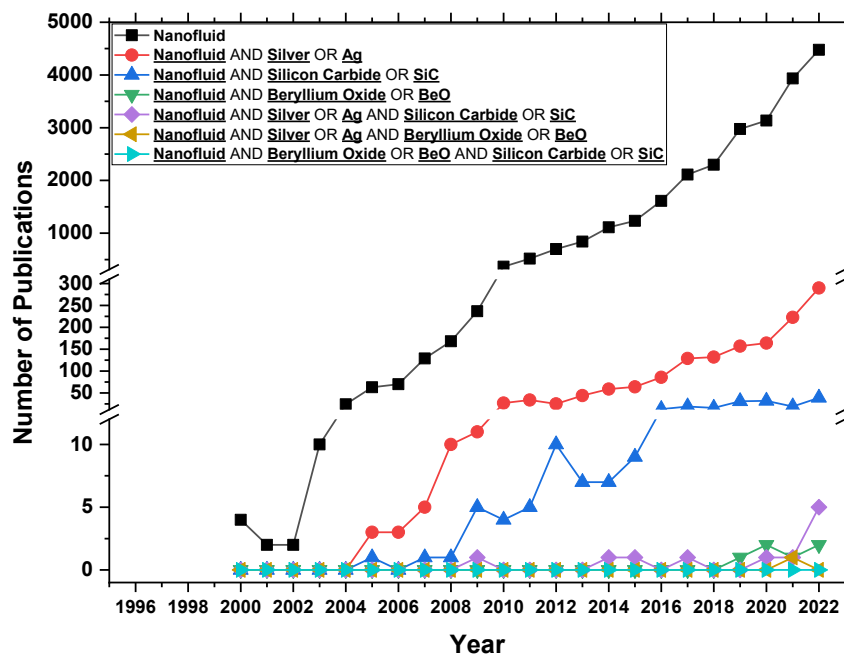


Figure 5.1. Publication trends on nanofluids and hybrid nanofluid combinations based on Scopus database.

5.2 Preparation of nanofluid

In this study, the two-step method was employed for the preparation of nanofluids, owing to its efficiency, scalability, and cost-effectiveness in producing large volumes of stable suspensions. The experimental investigation was organised into three distinct phases. The first phase focused on evaluating the effect of various surfactants on the stability of silver, beryllium oxide, and silicon carbide nanofluids, each formulated at a fixed particle concentration of 0.01 vol.%. In the subsequent phase, various fluids are prepared by altering particle concentrations within the range of 0.01 vol.% to 0.025 vol.%, aiming to assess stability and determine optimal concentrations for hybrid samples. The final segment encompasses the formulation of hybrid nanofluid samples (Ag/BeO, SiC/BeO, and Ag/SiC) at different mixing ratios, specifically examining the thermophysical properties across varying temperatures ranging from 15–45 °C. The nanoparticles utilised in this study were procured from Alfa Aesar and Thermo Fisher Scientific, two well-known suppliers in the field. Table 5.1 provides the properties of the nanoparticles including the details of the size, purity, thermal conductivity, density, and cost. All samples undergo a series of processes involving magnetic stirring, ultrasonication in a sonication bath, and final treatment with high-wave ultrasonication using a sonication probe.

To make unitary nanofluids, the following steps are followed: the calculated amount of nanoparticles is added to the desired quantity of base fluid while stirring for 1 hour. Subsequently, bath sonication and probe ultrasonication of the fluid are carried out for 2 hours and 30 mins, respectively, utilising an RS Pro ultrasonicator and NanoSight probe sonicator. These sonication processes are essential for breaking down agglomerated nanoparticles into individual particles, ensuring uniform suspension. Finally, to formulate the hybrid nanofluids having different mixture ratios, each nanofluid is prepared separately with the desired particle concentration and then mixed accordingly while carrying out continuous stirring with the help of a magnetic stirrer. To ensure the proper mixing of fluids, the processed solution will be further sonicated with the help of probe sonication for 15 mins. Figure 5.2 illustrates the schematic representation of the steps involved in the preparation of hybrid nanofluids.

Table 5.1. Properties of the particles.

Nanoparticle	Formula	Size	Purity	Thermal Conductivity (W/m.K)	Density (g/cm ³)	Quantity (g)	Cost (£)*	Reference
Silver	Ag	10-40 nm	99.9%	429	10.5	25	655	[248]
Silicon carbide – (beta-phase)	SiC	45-55nm		360	3.15	25	143	[249]
Beryllium oxide	BeO	85-140 nm	99%	285	3.01	25	131	[250,251]

**Prices as of February 1st, 2024*

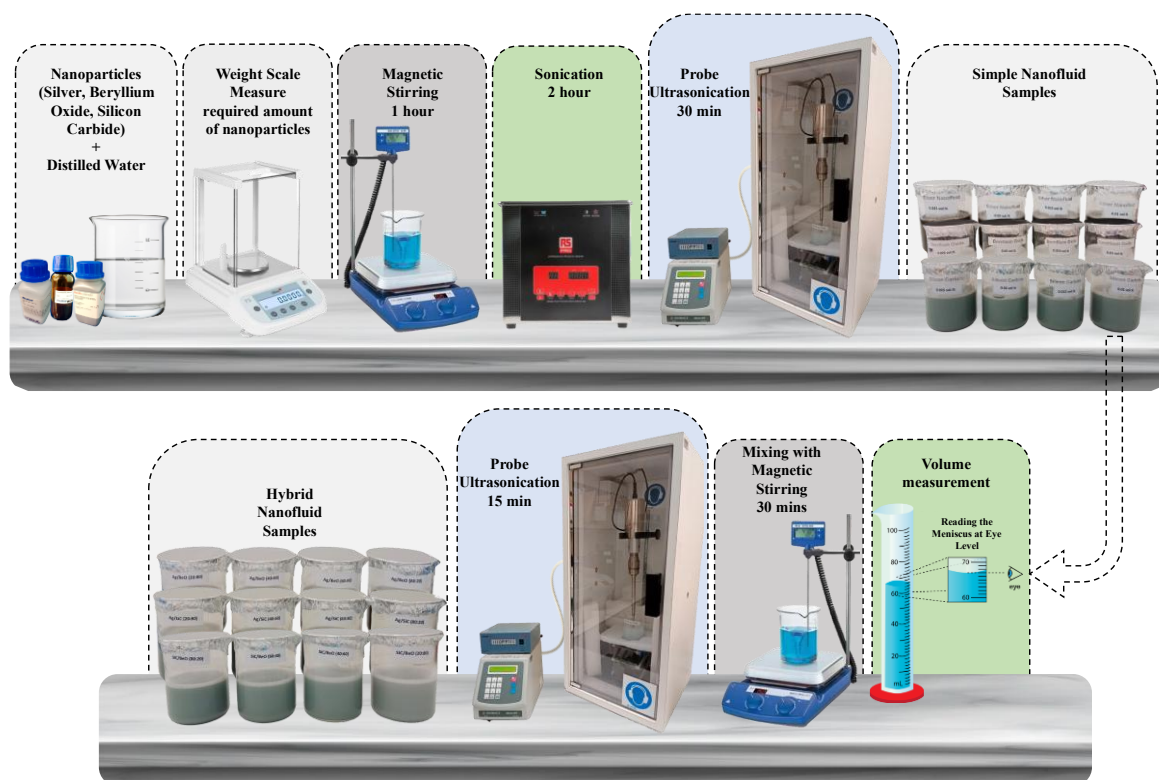


Figure 5.2. Schematic representation of the nanofluid preparation method.

5.3 Effect of surfactant on stability and pH value

A widely employed strategy for enhancing the stability of nanofluids involves the incorporation of surfactants, a class of compounds renowned for their ability to engender electrostatic or steric repulsion forces among nanoparticles. This judicious utilisation of surfactants serves as an effective means to prevent the undesired agglomeration of these minute particles, thereby bolstering the enduring stability of nanofluid systems. A study was carried out to delve into how different surfactants impact the overall stability of nanofluids, as well as their influence on the pH levels upon surfactant introduction. This investigation aims to shed light on the intricate interplay between surfactants and nanofluid stability while simultaneously observing their ramifications on pH values. The resulting repulsive interactions among nanoparticles not only thwart their agglomeration tendencies but also contribute to the preservation of the desired dispersion, ensuring the continued, homogeneous distribution of nanoparticles within the fluid medium.

The Hanna pH meter (HI 98128) used in this study has an accuracy of ± 0.05 pH, ensuring precise pH measurements. While the meter came with a calibration certificate, an additional calibration step was performed to ensure the utmost accuracy in the pH measurements. The calibration procedure utilised a specific method involving two buffer solutions provided with the instrument, having pH values of 4.01 and 7.01.

To commence the calibration process, the tailing side of the pH meter was immersed in a cleaning solution, which effectively cleaned the temperature sensor and pH electrode. Subsequently, the meter

was set to the calibration mode, and it was first submerged into the buffer solution with a pH of 4.01. The meter recorded the corresponding pH reading. After cleaning the sensor and electrode again, the meter was immersed in the second buffer solution, and its pH value was recorded. Following the completion of the calibration process, the pH of a neutral solution was measured to verify the accuracy of the meter's readings. This thorough calibration procedure ensured the reliability of the pH measurements throughout the study. The fluid preparations were conducted in an open environment, exposing the distilled water to atmospheric air. In such conditions, the pH range of the distilled water utilised could vary from 5.4 to 5.7 [252]. As observed in this study, the pH value of the base fluid was noted to be 5.67 ± 0.02 .

The stability of nanofluid suspensions is paramount, and the addition of surfactants has been widely acknowledged for their role in stabilising nanoparticles, impeding agglomeration, and altering surface characteristics. Silver, beryllium oxide, and silicon carbide nanofluids were prepared both without surfactants and with the addition of CTAB, SDS, Gum Arabic, and SDBS. The pH values were measured using a calibrated pH meter at 20 °C. Each measurement was repeated thrice to ensure accuracy and reliability. It was noticed that the addition of Ag and BeO nanoparticles made the nanofluid slightly basic compared to distilled water, while the SiC nanoparticles had an acidic effect. For this study, samples were formulated with a particle volume fraction of 0.01% vol. This study employed a preparation method that involved 1 hour of magnetic stirring, followed by 1 hour of sonication in a sonication bath, and ultimately 15 mins of sonication using an ultrasonication probe to produce the samples. During the sample preparation, an equivalent amount of surfactant, matching the quantity of particles, was introduced into the solution. The solutions were maintained at room temperature and monitored throughout the observation period.

The nanofluid samples were observed over 7 days to evaluate their long-term stability with the addition of different surfactants. The stability observation of nanofluids with different surfactants is depicted in Fig. 5.3. It was found that the solutions containing the anionic surfactant SDBS showed the best stability overall for the three nanoparticle types tested. The SDBS-containing nanofluids maintained their dispersion with minimal sedimentation and aggregation over the 7-day period. This indicates that SDBS provided excellent electrostatic and steric stabilization for the suspended nanoparticles.

For the beryllium oxide nanofluids specifically, the addition of the anionic surfactant SDS was found to have the worst effect on stability. The silicon carbide nanofluid with SDS had even poorer stability than the surfactant-free sample, with significant sedimentation and aggregation occurring within days. This suggests SDS interacted poorly with the silicon carbide surface, neutralizing surface charge and inducing rapid particle aggregation. After SDBS, the cationic surfactant CTAB provided the next best stability enhancement for the nanofluids. The CTAB-containing samples showed good dispersion stability over the 7 days, with only minor sedimentation in some cases. The positively charged CTAB likely electrostatically stabilized the nanoparticles.

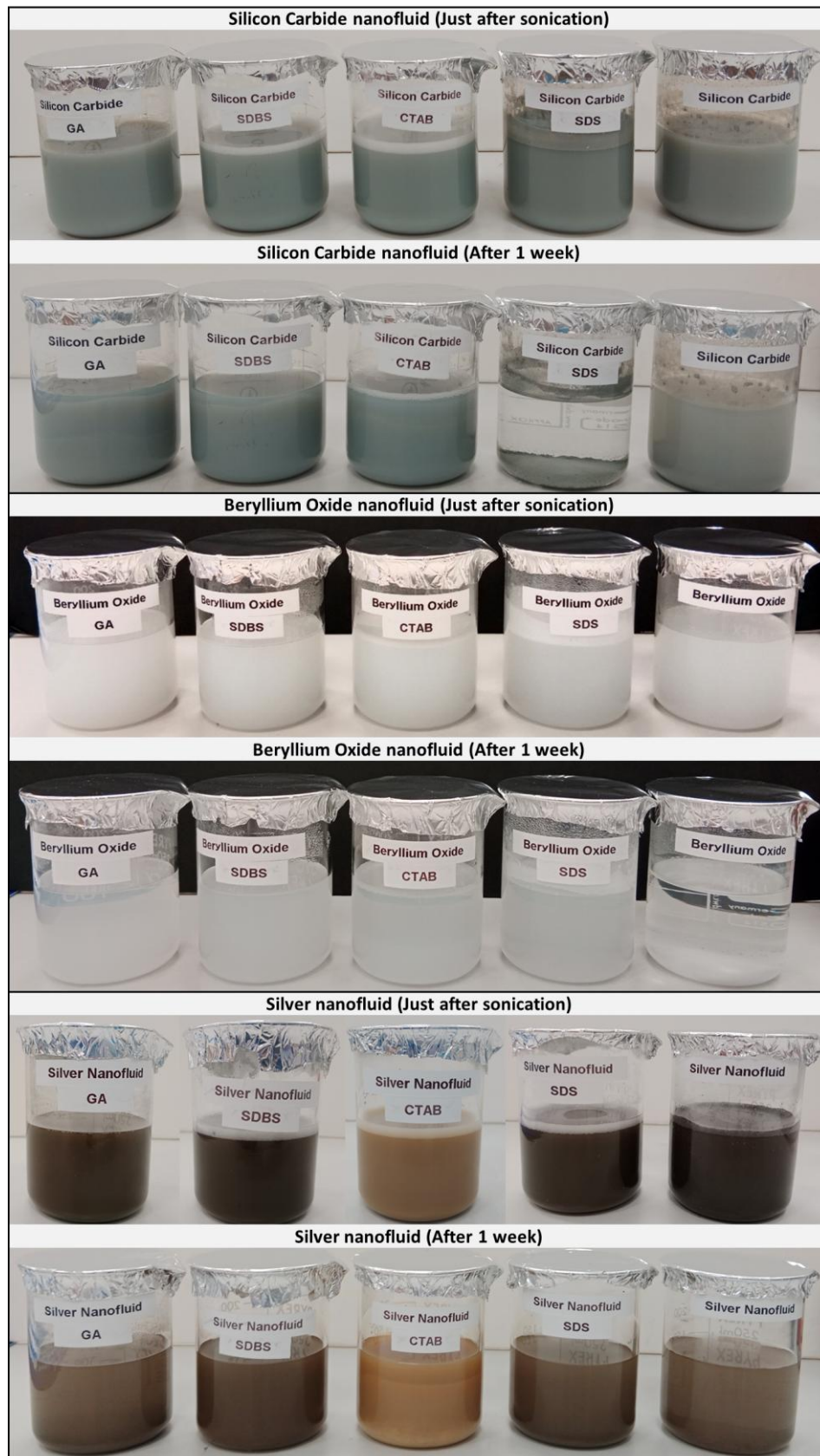


Figure 5.3. Stability observation of nanofluids with different surfactants.

The pH values exhibited distinctive variations in nanofluid samples treated with different surfactants compared to the surfactant-free nanofluids and the reference distilled water, as shown in Fig. 5.4. The

silver nanofluid experienced a shift towards both higher and lower pH values, contingent upon the type of surfactant introduced. Similar trends were observed in the beryllium oxide and silicon carbide nanofluids, indicating diverse responses to distinct surfactants.

For the silver nanofluid without surfactant, the measured pH was 6.24. The addition of the cationic surfactant CTAB caused a small decrease in pH to 6.1. This suggests that CTAB interacted with the silver nanoparticles, partially neutralizing the surface charge. The anionic surfactants SDS and GA also decreased the silver nanofluid pH, to 5.85 and 5.58 respectively. Interestingly, SDBS induced a considerable increase in pH from 6.24 to 7.2, indicating a more alkaline nature.

For the beryllium oxide nanofluid, the pH decreased from 5.95 to 5.57 upon the addition of CTAB. The inclusion of SDS resulted in a pH drop to 5.53, whereas Gum Arabic led to a slight increase in pH to 5.85. As anticipated, the SDBS demonstrated a significant pH increase, elevating the pH to 7.08. The surfactants affect the pH value of Silicon carbide nanofluid in a different way as the suspension of particles made the solution more acidic and noticed a pH value of 5.56. The supplementation of CTAB surfactant showed a slight increase in this value to 5.76 while SDS made the solution more acidic with a minor decrease in pH value to 5.31. Additionally, Gum Arabic resulted in a pH elevation of 6.1, while SDBS significantly increased the pH to 7.45.

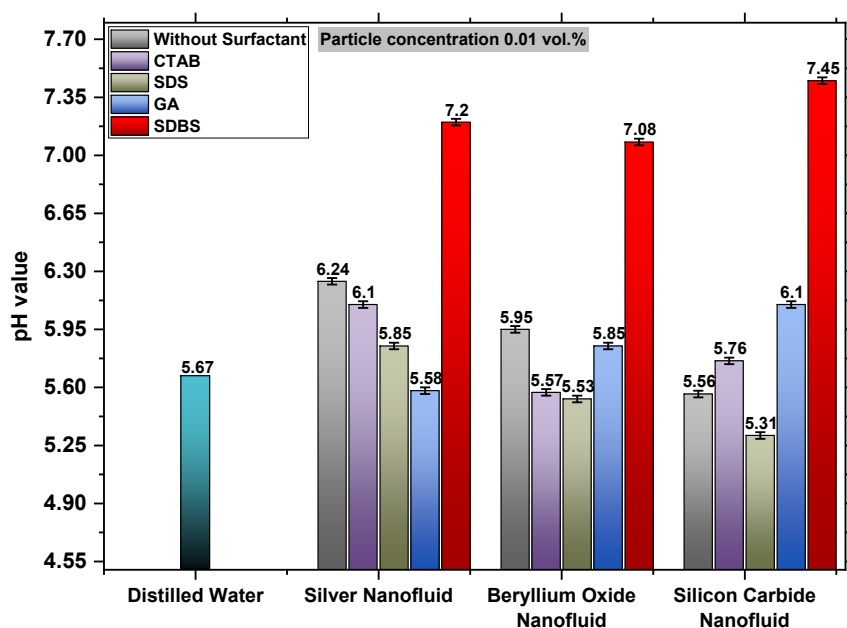


Figure 5.4. pH values of nanofluids with different surfactants.

Notably, the SDBS surfactant consistently induced a substantial rise in pH across all three types of nanofluids, significantly shifting the values toward neutrality. The addition of CTAB and GA to the nanofluids had a mixed effect on the pH. The addition of these surfactants decreased the pH of silver nanofluid and beryllium oxide but increased the pH of silicon carbide nanofluid.

The effect of SDBS on the pH of nanofluids is more complex. SDBS is an anionic surfactant, but it can also form micelles in aqueous solution [253]. Micelles are aggregates of surfactant molecules that have

a hydrophilic outer layer and a hydrophobic inner core. When SDBS is added to a nanofluid, it can form micelles around the nanoparticles. The micelles can trap the nanoparticles inside and prevent them from interacting with the water molecules. This can lead to an increase in the pH of the nanofluid. While the pH approximation to neutral by SDBS indicates potential stability, it is crucial to conduct further analysis to comprehend the precise mechanisms by which SDBS interacts with nanoparticles, stabilising the nanofluids. Such investigations can validate the observed pH effects and solidify the link between near-neutral pH and enhanced stability, offering insights for practical applications in various fields where stable nanofluids are indispensable.

Figure 5.5 showcases pH values of different nanofluids containing varying concentrations of nanoparticles, all prepared using SDBS surfactant in which the quantity of surfactant added in the solution is equal to the particles' weight. It displays the pH values corresponding to different particle concentrations of Ag, BeO, and SiC at 0.01, 0.015, 0.02, and 0.025 vol.%. According to the results, a noticeable elevation in the pH values for all types of nanofluids investigated was observed as the concentration of particles and relatively the amount of surfactant increased. Silver nanoparticles exhibited a relatively moderate increase in pH as the concentration raised from 0.01 to 0.025 vol.%, with a change from 7.2 to 7.35, however, beryllium oxide and silicon carbide displayed more pronounced shifts in pH values. The results revealed that the BeO nanofluid experienced a more significant increase in pH, from 7.08 to 7.22, across the same concentration range, while the SiC solution showed an even more substantial shift, moving from 7.45 to 7.63. This variation in the rate of pH change could be attributed to several factors specific to each type of nanoparticle. One influential factor could be the inherent chemical properties of the nanoparticles themselves. For instance, differences in surface charge, composition, or reactivity of the nanoparticles could lead to varied interactions within the solution, influencing the solution's pH differently.

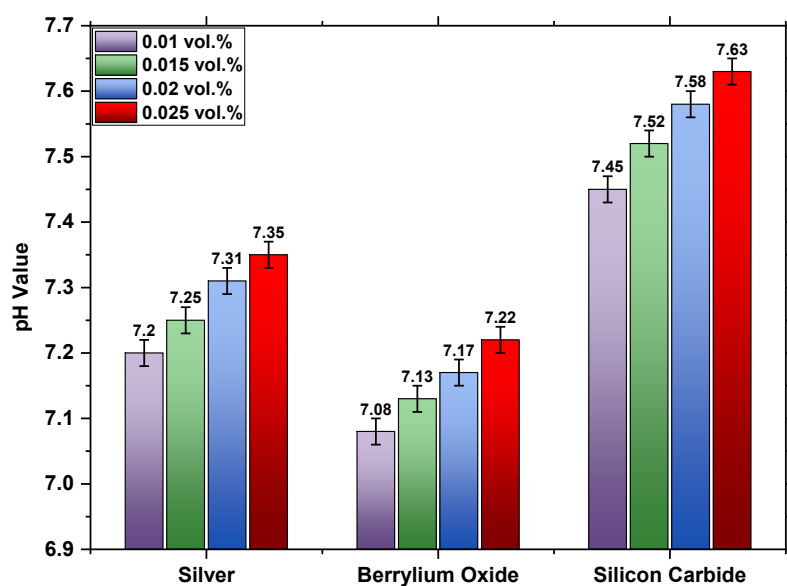


Figure 5.5. pH values of nanofluids with varying particle concentrations (0.01 - 0.025 vol%) using SDBS surfactant.

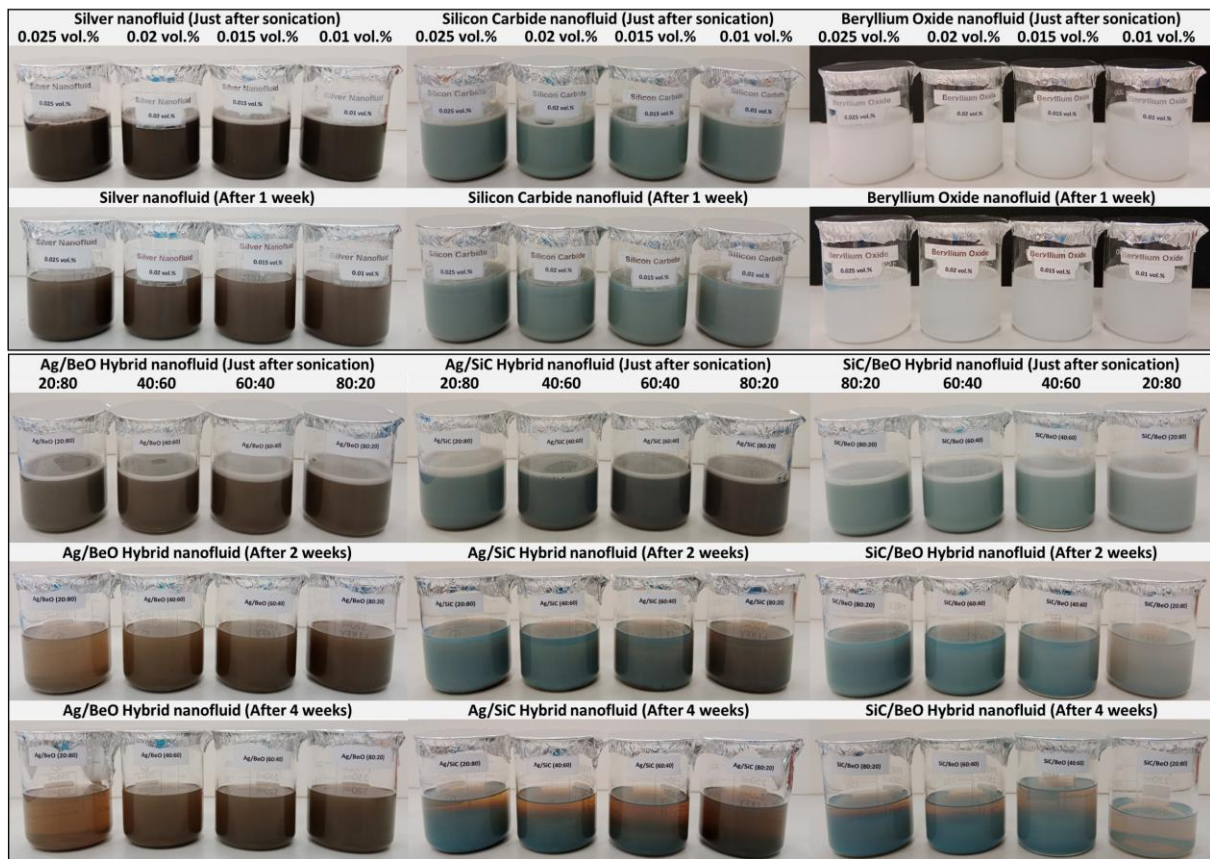


Figure 5.6. Stability observation of simple and hybrid nanofluids over time.

Importantly the interaction of these nanoparticles with the SDBS surfactant might not be uniform across all types. The diverse chemical affinities or reactions between nanoparticles and the surfactant may result in differing effects on pH, contributing to the observed variations.

Furthermore, factors such as nanoparticle size, shape, and concentration could also significantly contribute to this variability. Distinct physical properties of different nanoparticles could impact pH alterations differently. Smaller particles, in some cases, exert a more noticeable influence on solution pH compared to larger particles at similar concentrations.

The objective behind formulating nanofluids at different concentrations was to determine the most suitable concentration for the synthesis of hybrid nanofluids, focusing on their stability. All the suspensions were kept under observation over the course of a week, and it was observed that nanofluid samples containing Ag and BeO nanoparticles at a concentration of 0.025 vol.% began exhibiting nanoparticle settling after four days, resulting in the formation of a clear upper layer. In contrast, the SiC suspension remained stable during the observation period, as depicted in Fig. 5.6.

A study was also carried out to observe the pH value of various hybrid nanofluids prepared by mixing different ratios of individual nanofluids at a concentration of 0.025 vol.%, as depicted in Fig. 5.6. The study aimed to examine how these mixtures' pH values changed with varying proportions of the constituent nanofluids. The observed pH values of the hybrid nanofluids indicated intriguing trends across the different mixing ratios, as presented in Fig. 5.7.

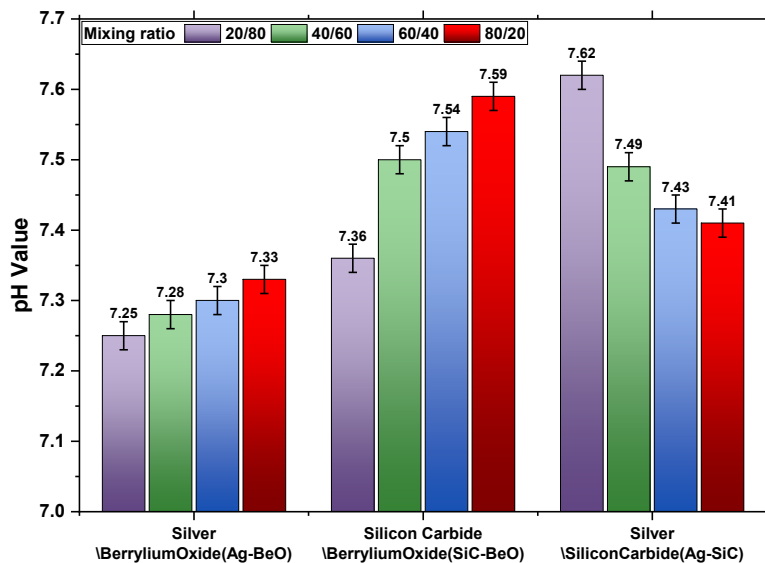


Figure 5.7. pH values of hybrid nanofluids (Ag/BeO, SiC/BeO, and Ag/SiC) with different mixing ratios (20/80, 40/60, 60/40, and 80/20).

The results revealed that the pH variations were not uniform across all hybrid combinations, suggesting specific interactions between the nanoparticles at different ratios. As anticipated, for the Ag/BeO hybrid nanofluid, an increase in the Ag concentration led to a gradual rise in pH, culminating in the highest pH value of 7.33 at the 80/20 ratio. This shift in pH can be attributed to the inherently higher pH value of Ag in comparison to BeO. Moreover, the SiC/BeO hybrid nanofluid showcased a consistent escalation in pH as the proportion of SiC increased. The pH values increased steadily, reaching a maximum of 7.59 at the 80/20 ratio, reflecting the notably higher pH value of the SiC solution compared to Ag. Finally, as the pH value of SiC solution was significantly higher than Ag, the hybrid nanofluid of Ag/SiC exhibited a decrease in pH values with an increase in the proportion of Ag.

Understanding pH variations is crucial for tailoring nanofluids for diverse applications. Controlling and predicting pH changes of hybrid nanofluids could aid in optimising their stability and functionality in specific technological or industrial applications, such as heat transfer systems or biomedical uses.

5.4 Characterisation

The comprehensive characterisation of nanoparticles and nanofluid dispersion involved a multifaceted approach, combining X-ray Diffraction (XRD) and Transmission Electron Microscopy (TEM) analyses to elucidate the structural properties of the nanoparticles. Additionally, the nanofluid stability and particle size distribution were meticulously examined using a Malvern Zetasizer, providing a holistic understanding of their physicochemical behaviour.

5.4.1 X-ray diffraction (XRD)

X-ray diffraction (XRD) is utilised to analyse the crystallographic structure, crystallite size, and phase composition of silver, beryllium oxide, and silicon carbide nanoparticles, revealing intricate details

about their atomic arrangements. X-ray diffraction tests have been reported in numerous research studies for the characterisation of nanoparticles as well as various pure or composite materials [254,255]. The analysis was carried out utilising an X-ray diffractometer (Bruker - D8 Advance) with Cu-K α radiation (wavelength: 1.5406 Å, energy: 8.05 keV). In the case of silver nanoparticles, four distinct peaks were identified at 2θ angles of approximately 38.12°, 44.30°, 64.45°, and 77.4°, as shown in Fig. 5.8(a). The XRD curve pattern and the positions of the peaks aligned with the previously reported literature data on silver [256,257]. These peaks were indexed to the (111), (200), (220), and (311) planes of a face-centred cubic (FCC) silver crystal structure.

The lattice parameter was determined as $a = 4.089$ Å, with a corresponding unit cell volume of $V = 68.39$ Å³. The findings also concurred with the reported data of the Joint Committee on Powder Diffraction Standards JCPDS data (JCPDS 04-0783) for silver nanoparticles. Moreover, the most prominent peak in the spectrum suggests that the nanoparticles exhibit a preferred orientation, with their (111) planes aligned parallel to the surface. Figure 5.8(b) shows the intensity of X-rays diffracted by a sample of beryllium oxide nanoparticles as a function of the 2θ angle.

The curve peaks indexed to the α -BeO phase, which is the most stable form of beryllium oxide at room temperature. The peaks observed at crystalline angles of 38.40°, 41.06°, 43.76°, 57.47°, 69.44°, and 76.70° correspond to the (100), (002), (101), (102), (210), and (103) reflections of α -BeO, respectively, as predicted by the JCPDS file for this material (JCPDS 35-0818). Additionally, the curve confirmed the presence of hexagonal wurtzite beryllium oxide nanoparticles with a random orientation. The lattice parameters for BeO nanoparticles were found to be $a = 2.705$ Å and $c = 4.39$ Å, yielding a unit cell volume of $V = 27.84$ Å³. Wang et al. [258] examined the characteristics of BeO nanoparticles at different temperature values and identified a consistent X-ray diffraction (XRD) curve pattern. Additionally, they observed an increase in the intensity of peaks with rising temperatures.

The XRD curve of the silicon carbide nanoparticle has been shown in Fig. 5.8(c). The number of sharp peaks indicated that the studied nanoparticles are highly crystalline and have a cubic and orthorhombic crystal structure. Notably, the peaks were observed at specific 2θ positions: 35.655° (111), 41.404° (200), 59.991° (220), 71.78° (311), and 75.52° (222). The curve exhibited consistency with the 3C-SiC polytype, as the peak positions match well with the JCPDS card (reference number 29-1129) for this material. In this case, the lattice parameter is calculated to be about 4.36 Å, which is in good agreement with the reported value for 3C-SiC. The analysis revealed a unit cell volume of 82.7 Å³, and the density of the substance was determined to be 3.15 g/cm³. Sultan et al. [259] investigated the X-ray diffraction (XRD) pattern of silicon carbide across a temperature range of 25 °C to 800 °C. The observed curve trend aligned with the findings of the present study.

To determine the average crystallite size from the peak widths observed in the XRD pattern a well known Scherrer equation was employed [260,261]. Crystallite size refers specifically to the size of the individual crystalline domains within the nanoparticle. Nanoparticles are often composed of crystalline materials, and the crystallites are the repeating, ordered structures within the particles.

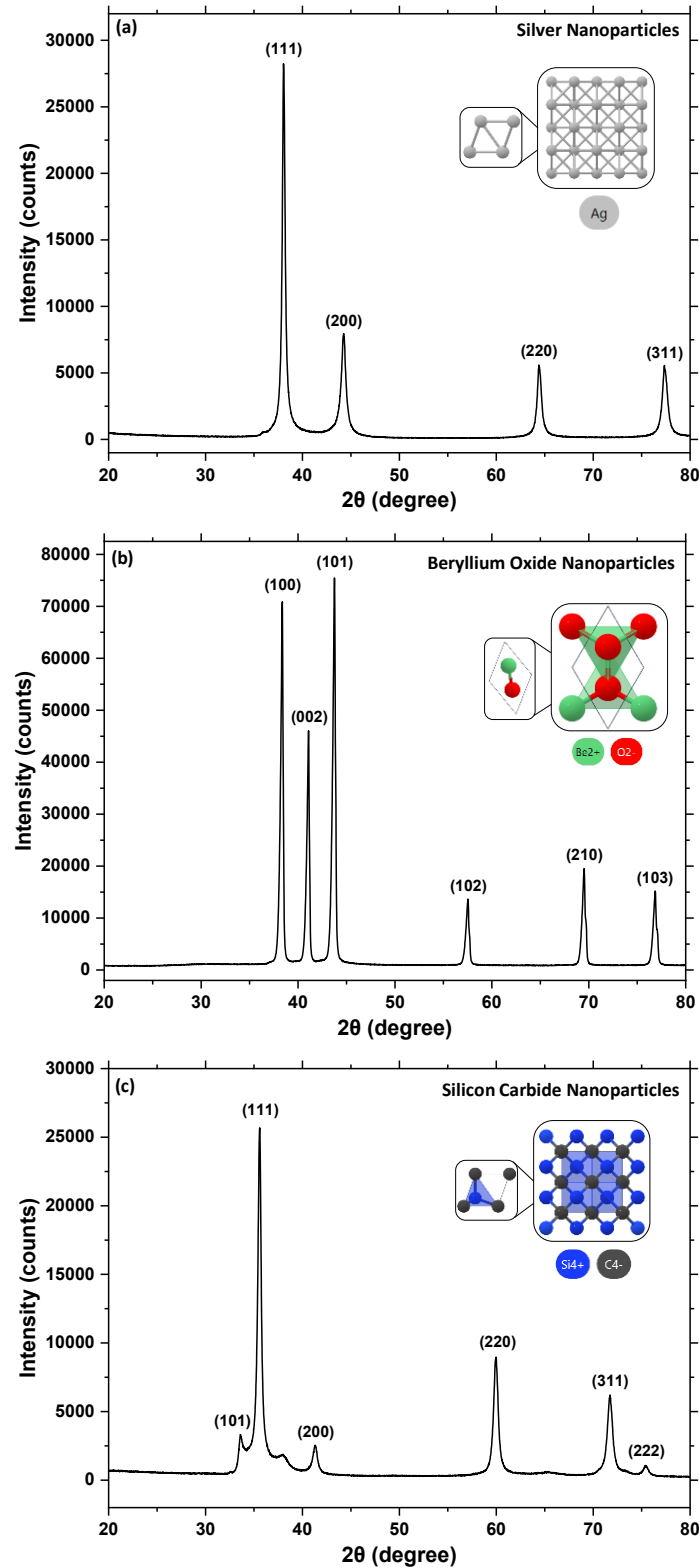


Figure 5.8. X-ray diffraction patterns of (a) silver nanoparticles, (b) beryllium oxide nanoparticles, and (c) beta-phase silicon carbide nanoparticles.

The Scherrer equation Eq. (5.1), widely employed in numerous studies, establishes a mathematical correlation among peak width, X-ray wavelength, and crystallite size. It is commonly utilised to estimate the crystallite dimensions from XRD data.

$$particle\ size\ (d_p) = \frac{\xi \lambda}{\beta \cos \theta} \quad (5.1)$$

where d_p is the crystallite size, ξ is a constant, λ is the wavelength of the X-rays (1.5406 Å for Cu K α radiation), β is the full width at half maximum of the peak, and θ is the Bragg angle. Applying the Scherrer equation, the calculated crystalline size of silver nanoparticles was determined to be 16.63 nm. However, for beryllium oxide and silicon carbide, the calculated crystalline size was 23.12 nm and 17.19 nm respectively.

5.4.2 Transmission Electron Microscopy (TEM)

To further analyse the particle morphology, nanoparticles were subjected to Transmission Electron Microscopy (TEM) JEOL JEM-1400 Plus instrument. This powerful analytical technique allows for high-resolution imaging of nanoparticles, enabling detailed examination of their size, shape, and structural characteristics. Figure 5.9 presented the TEM images showcasing three distinct types of nanoparticles under investigation in this study.

In the left column, the TEM images depicted the spherical morphology of Ag nanoparticles, which exhibited a tendency to form agglomerates or clusters comprising multiple individual nanoparticles. These agglomerates varied in size and degree of agglomeration. They exhibit a wide size distribution, with some particles appearing quite large (around 40 nm) and others being much smaller (below 20 nm). The particles seem to be agglomerated or aggregated, forming irregular clusters. Moving to the middle column, TEM images illustrated BeO nanoparticles.

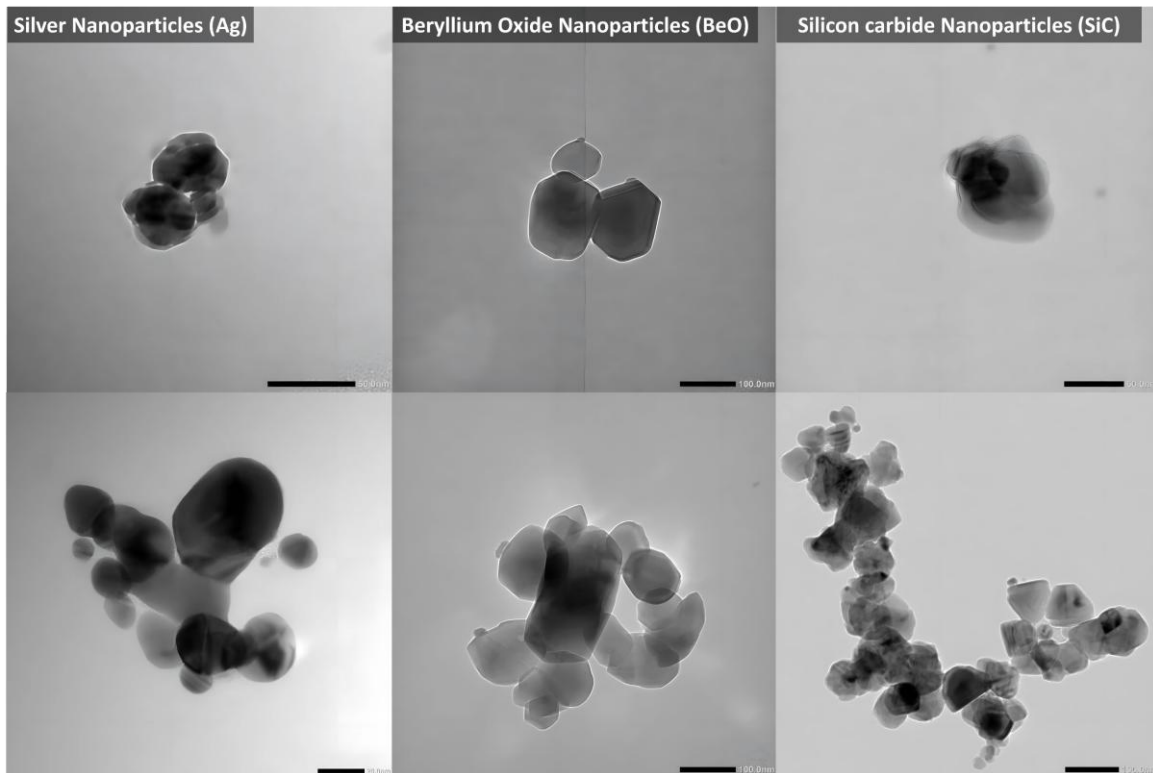


Figure 5.9. Transmission electron microscopy (TEM) images of silver, beryllium oxide, and beta-phase silicon carbide nanoparticles (left to right columns).

The beryllium oxide nanoparticles have a more distinct and well-defined shape compared to the silver nanoparticles. They appear as irregular hexagonal with particle sizes ranging from approximately 85 to 140 nm. Although BeO nanoparticles also exhibited a tendency to form agglomerates, their propensity for agglomeration was comparatively lesser than that observed in Ag nanoparticles. Lastly, in the right column, the SiC nanoparticles exhibited a wider range of shapes and sizes compared to the other nanoparticles. Some particles appear as distinct, well-defined shapes, while others have more irregular shapes. Notably, SiC nanoparticles demonstrated a unique tendency to form agglomerates in the form of chains, with connections between particles appearing weaker compared to those observed in Ag and BeO nanoparticles.

It is imperative to consider the sample preparation process, which involves sonication. During this process, some particles experienced breakdown, resulting in the generation of smaller particles. Consequently, the morphology of parent particles underwent alteration, with the emergence of child particles exhibiting smaller sizes. This phenomenon is particularly evident in the TEM images, where irregularities in particle shape and size can be observed.

5.4.3 Nanofluid Stability and Particle Size Distribution

The stability and particle size distribution of the nanofluids were assessed using a Malvern Zetasizer, providing crucial insights into their colloidal behaviour and dispersion characteristics [262,263]. Zeta potential characterises the intensity of electrostatic repulsion among particles suspended in a fluid medium. To perform the analysis, the sample was contained within a specialised DTS 1070 cell, designed for assessing zeta potential in controlled environments. This cell is particularly well-suited for evaluating emulsions, suspensions, and other samples where conventional cuvettes may be inadequate. During the measurement process, an electric field was applied to the sample within the DTS 1070 cell. The instrument then assessed the velocity of particles as they responded to this electric field. This velocity is directly linked to the zeta potential, typically calculated using the Smoluchowski equation or similar models. The instrument's software analyses the data collected from the scattered light to determine the zeta potential of the particles in the nanofluid.

Zeta potential analysis was conducted on both simple and hybrid nanofluid samples just after the sonication, revealing values within the range of -45 to -75 mV, as shown in Fig. 5.10. This range indicates a high level of stability in the nanofluid. In the context of particle suspension, a zeta potential exceeding ± 30 mV is generally considered indicative of good stability, as supported by existing literature [31]. The negative values observed indicate that the nanoparticles possess a net negative surface charge. Factors such as nanoparticle surface chemistry, the types of ions in the solution, surface-active agents, and the pH of the medium, can contribute to the acquisition of a negative charge by the particles. Several studies have also reported negative zeta potential values for these nanofluids [264–266].

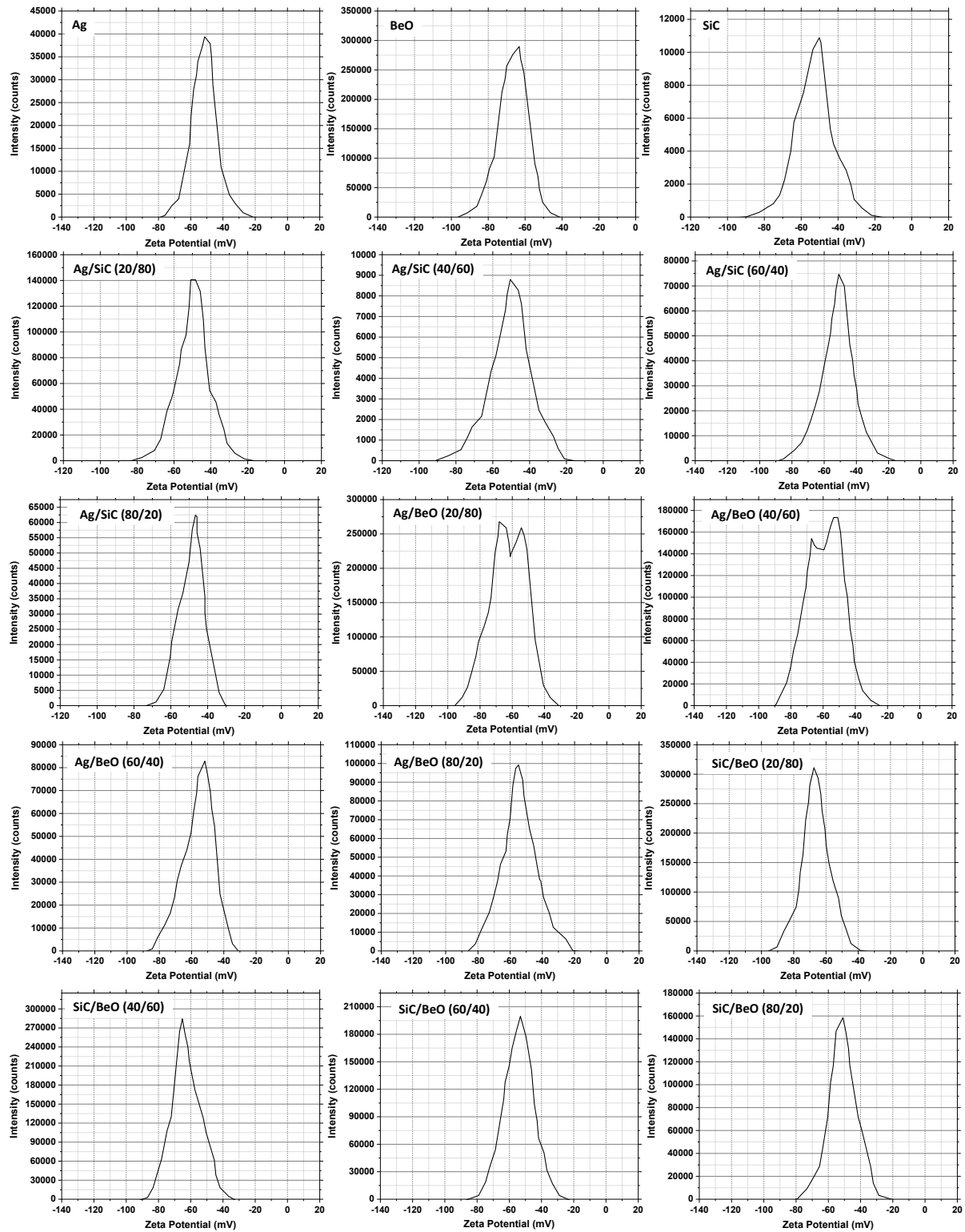


Figure 5.10. Zeta potential analysis of simple and hybrid nanofluids at different mixing ratios.

Comparing the nanofluids containing different nanoparticles, it was observed that the zeta potential value of BeO nanofluid is better compared to Ag and SiC nanofluids. However, a more extended observation revealed an interesting trend. However, BeO nanoparticles showed a tendency to settle down earlier, primarily attributable to their larger size, posing a significant limitation on the stability

over time. The observed limitations in the stability of individual nanofluids, such as BeO nanofluids, underscore the increasing interest in hybrid nanofluids. By combining particles with diverse properties and morphologies, hybrid nanofluids offer the potential to enhance the overall performance of the fluid. In contrast, if larger-sized denser silver nanoparticles were utilised instead of BeO nanoparticles, it would likely have a detrimental effect on the stability of the nanofluid and unsuitable for hybrid formulations.

The hybrid nanofluids displayed varying patterns based on the composition ratios. The Ag/SiC hybrid nanofluids showed distinct peaks corresponding to the individual nanoparticle components, with the peak heights and positions influenced by the ratio of Ag to SiC. It was noted that the Ag/SiC hybrids exhibited a dominant peak around -50 mV. The Ag/BeO hybrid nanofluids exhibited broader peaks compared to the Ag/SiC counterparts, likely due to the broader distribution of BeO nanoparticles. As the ratio of BeO increased, the peak shifted towards more negative zeta potential values, indicating the influence of BeO's higher zeta potential. Finally, the SiC/BeO hybrid nanofluids displayed patterns similar to the Ag/BeO samples, with the peaks becoming broader and shifting towards more negative zeta potential values as the BeO ratio increased.

To investigate the phenomenon of particle clustering or agglomeration and its impact on particle size following suspension, additional particle size analysis was conducted utilising the Malvern Zetasizer instrument. Figure 5.11 shows the size distribution of suspended particles in various nanofluid samples after 7 days of fluid preparation. The results revealed the formation of particle clusters or agglomerates, leading to an increase in the effective particle size compared to the initial nanoparticle dimensions.

For the monometallic nanofluid, the Ag sample exhibited a slightly asymmetric peak with a Z-average particle size of 218.4 nm, indicating the presence of relatively uniform and moderately sized agglomerates, significantly larger than the initial 10-40 nm Ag nanoparticles. The presence of a smaller side peak at the right indicates the existence of a small fraction of larger agglomerates or aggregates in the Ag nanofluid suspension. The SiC nanofluid displayed a similar narrow peak with a Z-average size of 230.9 nm, suggesting the formation of agglomerates approximately 4-5 times larger than the initial 45-55 nm SiC nanoparticles. While the BeO nanofluid showed a broader peak with a Z-average size of 404.3 nm, with the agglomerates being only 2-4 times larger than the initial 85-140 nm BeO nanoparticles.

In the case of hybrid nanofluids containing a blend of Ag and SiC nanoparticles (Ag/SiC), narrow peaks were observed across various mixing ratios, instead of a 20:80 ratio. The Ag/SiC (20:80) hybrid nanofluid exhibits a slightly flattened peak with a Z-average particle size of 223.8 nm. Additionally, the appearance of a small side peak indicates the presence of Ag nanoparticles within the hybrid nanofluid. As the proportion of Ag nanoparticles increases in the Ag/SiC (40:60) hybrid nanofluid, the peak becomes slightly narrower, with a Z-average size of 194.3 nm. This reduction in the average agglomerate size could be attributed to the existence of more Ag nanoparticles, however, a small proportion of larger-sized aggregates was also detected.

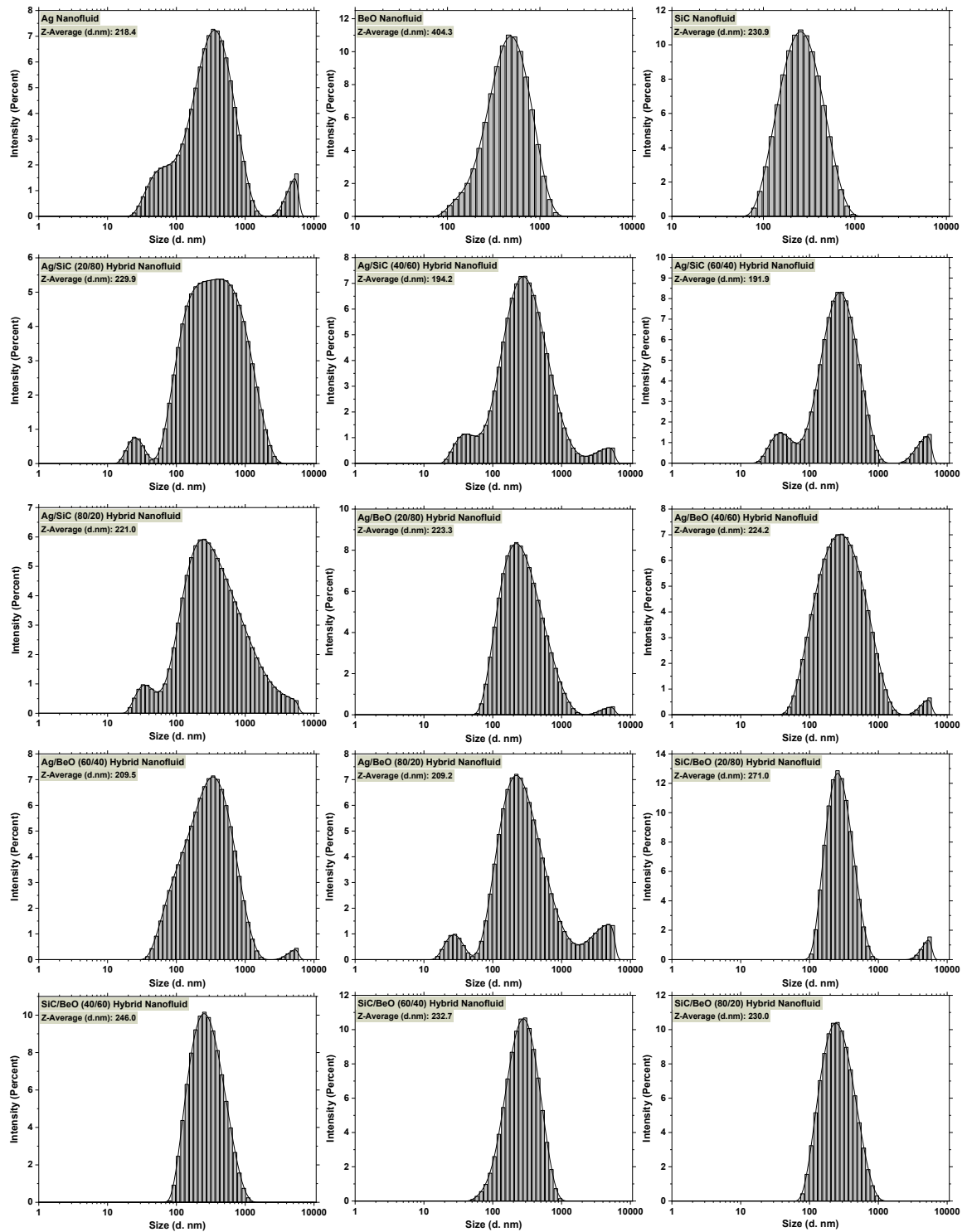


Figure 5.11. Particle size distribution curves showing the Z-average particle sizes of simple and hybrid nanofluids at different mixing ratios after 7 days of fluid preparation.

The Ag/SiC (60:40) hybrid nanofluid displays a similar narrow peak to the previous composition, with a Z-average size of 191.8 nm. The peak shape and size distribution suggest a more homogeneous agglomeration pattern with a higher Ag content. Finally, for Ag/SiC (80:20) hybrid nanofluid, where Ag is the predominant component, the peak becomes slightly broader, with a Z-average size of 221.0

nm. This broadening of the peak could be attributed to the increased interactions between the higher concentration of Ag nanoparticles, leading to a slightly wider distribution of agglomerate sizes.

In the Ag/BeO (20:80) hybrid nanofluid, a slightly sharper peak was discerned in comparison to Ag/SiC (20/80) hybrid nanofluid, with a Z-average particle size of 223.3 nm. With a rise in the concentration of Ag nanoparticles within the Ag/BeO (40:60) hybrid nanofluid, the distribution curve covered a broader range due to the augmentation of the smaller size of Ag nanoparticles, with a Z-average size of 224.2 nm. However, small peaks were also observed with the increasing proportion of Ag due to the tendency of the Ag nanoparticles to agglomerate. Analogous to the Ag/SiC (80:20) composition, a small peak was also detected at the smaller size end when the proportion of Ag reached 80%.

The SiC/BeO hybrid nanofluids exhibited unimodal size distribution curves across all composition ratios instead of a small peak observed for 20:80 sample at the larger size end, as depicted in Fig. 5.11. In the SiC/BeO (20:80) composition, the average particle size was found to be 271.8 nm, with a relatively narrow distribution curve. As the proportion of SiC increased in the SiC/BeO (40:60) hybrid nanofluid, the average particle size decreased to 246.0 nm.

Interestingly, the distribution curve appeared slightly broader compared to the 20:80 composition, suggesting a marginally wider range of particle sizes present in the sample. Subsequently, in the SiC/BeO (60:40) hybrid nanofluid, the average particle size decreased to 232.7 nm, further decreasing with the increasing SiC content. Additionally, the distribution curve slightly shifted towards smaller particle sizes. Finally, with a slight decrease in particle size, while maintaining the curve shape for the SiC/BeO (80:20) hybrid nanofluid, the average particle size was recorded to be 230.0 nm.

It is concluded that the hybrid nanofluids exhibit smaller agglomerate sizes compared to unitary nanofluids due to the unique interplay of different particle characteristics within the solution. The inclusion of nanoparticles, each differing in size, shape, and material properties, introduces heterogeneity that disrupts the natural tendency of particles to cluster together into larger agglomerates. In unitary nanofluids, where all the particles are of the same type, the forces of attraction, such as van der Waals forces, are stronger and more uniform. This leads to a greater likelihood of large agglomerate formation as similar particles tend to stick together more readily. In contrast, hybrid nanofluids benefit from the diversity of particle sizes and shapes, which creates an uneven distribution of attractive forces. This irregularity weakens the overall attraction between particles, making it easier to prevent large clusters from forming.

Another important factor in the formation of smaller agglomerates in hybrid nanofluids is the synergistic effect of the different materials involved. For example, when smaller particles such as Ag nanoparticles are combined with larger ones like SiC or BeO, the overall balance of forces within the fluid is altered. The smaller particles can help fill the gaps between the larger ones, leading to a more uniform and dispersed suspension. This reduces the tendency of the larger particles to form dense clusters and allows for a more stable distribution of particle sizes. As a result, hybrid nanofluids tend to have a smaller Z-average particle size for agglomerates compared to those formed in unitary nanofluids.

Over time, hybrid nanofluids also show improved stability compared to unitary systems. Larger particles like BeO, which may otherwise settle out of suspension in a unitary fluid, are more stable when combined with smaller particles in a hybrid formulation. The different particle types complement each other, reducing the probability of sedimentation and promoting long-term stability. This enhanced stability directly impacts the particle size distribution, as agglomerates that do form are smaller and more uniformly dispersed within the fluid. Therefore, the combination of varied particle types in hybrid nanofluids not only improves thermal and fluidic properties but also results in smaller, more stable agglomerates compared to unitary nanofluids.

These findings highlight the complexity of agglomeration behaviour in nanofluids, where the initial nanoparticle size, composition, and relative proportions in hybrid systems can significantly impact the effective particle size distribution in the suspension. Further investigation into the underlying mechanisms driving the observed agglomeration patterns and their implications for the stability and performance of these nanofluids is warranted.

5.5 Results and Discussion

5.5.1 Thermal Conductivity

The thermal conductivity of nanofluids, which are suspensions of nanoparticles in a base fluid, is a crucial property that significantly impacts their heat transfer capabilities. The transient plane source (TPS) technique, also known as the hot disk (HD) or Gustafsson probe, is a well-known and accurate method for measuring the thermal conductivity of fluids [267,268]. In this study, the thermal conductivities of water and nanofluid samples were determined using the Hot Disk 2500S thermal constant analyser. The analyser employs a sensor element designed in the configuration of a double spiral, served a dual purpose as a heat source for elevating the sample's temperature and as a resistance thermometer for capturing the temporal evolution of the temperature increase in the heat source itself. The sensor element is constructed with a fine nickel foil, around 10 micrometres in thickness, configured into a double spiral pattern. Both sides of the spiral are encased in an insulating layer of Kapton, a polyimide material. The meticulous design of this probe is centred around the optimisation of the heating area and length scale for a given sample size. This optimisation ensures a close alignment between the physical model employed and the actual experimental geometry. Notably, the probe's intricate design facilitates the maximization of heating efficiency, thereby enhancing the accuracy and reliability of the thermal conductivity measurements undertaken in our research. The setup comprises a constant temperature bath, a thermal constants analyser, and a purpose-built liquid sample holder. The unique design of the sample holder serves the crucial function of encapsulating the liquid within a confined cell or chamber. The sensor probe is vertically immersed in the liquid sample, and strategically positioned to avoid contact with the cell walls, thereby mitigating the potential impact of convection during measurements. The particularly engineered design of sample holder not only facilitates stable

temperature conditions but also effectively eliminates the potential impact of evaporation, given the absence of direct exposure of the liquid to ambient air. To acquire data across various temperature points, the sample holder is positioned within the thermal water bath, facilitating systematic temperature control and enabling the comprehensive investigation of thermal properties under diverse conditions. To facilitate the measurements, a sensor with a radius of 2.001 mm (designated as sensor Kapton 7577) was selected. The experimental setup involved applying a heating power of 60 mW and a measurement time of 2 seconds.

The uncertainty of the thermal conductivity measurements in this study was evaluated based on both the instrument specifications and the precision of the experimental procedures. The manufacturer specifies a measurement uncertainty of $\pm 5\%$ for the TPS method, which reflects the overall expected range of potential deviations in the reported thermal conductivity values. Despite this inherent uncertainty, a rigorous approach was adopted to minimise experimental errors and enhance the precision of the measurements.

To enhance precision, three measurements were taken at each temperature point and reported the average value to mitigate the influence of random errors. The standard deviation of the measurements for fluid samples was found to be less than 0.7%, which indicates a high level of precision in the data collected. This standard deviation is within the acceptable range and suggests that the variability between repeated measurements was minimal. Additionally, the system was calibrated using a stainless steel sample provided by the manufacturer. The standard deviation for these calibration measurements was less than 0.5%, demonstrating that the setup was well-tuned and capable of providing reliable data. The study conducted by Sundberg et al. [269] reported that the standard deviation for thermal conductivity measurements using the TPS method was remarkably low, with most samples showing deviations of less than 0.1%.

To validate the experimental setup, the thermal conductivity of distilled water was measured across a temperature range of 15 °C to 45 °C. The obtained results were subsequently compared with reference values for distilled water, as measured and supplied by Hot Disk [270]. The results showed a good agreement between the experimental values and the provided values, although minor deviations were observed, likely attributable to inherent discrepancies in water properties, as depicted in Fig. 5.12.

Several studies have reported the influence of surfactants on the thermal conductivity of nanofluids [271,272]. To investigate this, a study was carried out to examine the thermal conductivity of freshly prepared samples with those measured after 72 hours. The measurements were performed at 35°C, and the results are presented in Fig. 5.13. According to the results obtained immediately after sonication, a noticeable variation was observed in the thermal conductivity values between the surfactant-free and surfactant-added fluid samples. Notably, SDBS surfactant demonstrated better stability, with less pronounced changes in thermal conductivity compared to others. Subsequent measurements after 72 hours displayed diverse trends among different nanofluid samples. The surfactant-free silver nanofluid exhibited a considerable decrease in thermal conductivity, whereas this reduction was less pronounced

for samples containing SDBS and CTAB surfactants. Specifically, SDBS showed promising stability, while SDS proved less suitable for silver nanoparticle-containing fluids. Although GA performed better than SDS, it still fell short compared to SDBS for silver nanofluids.

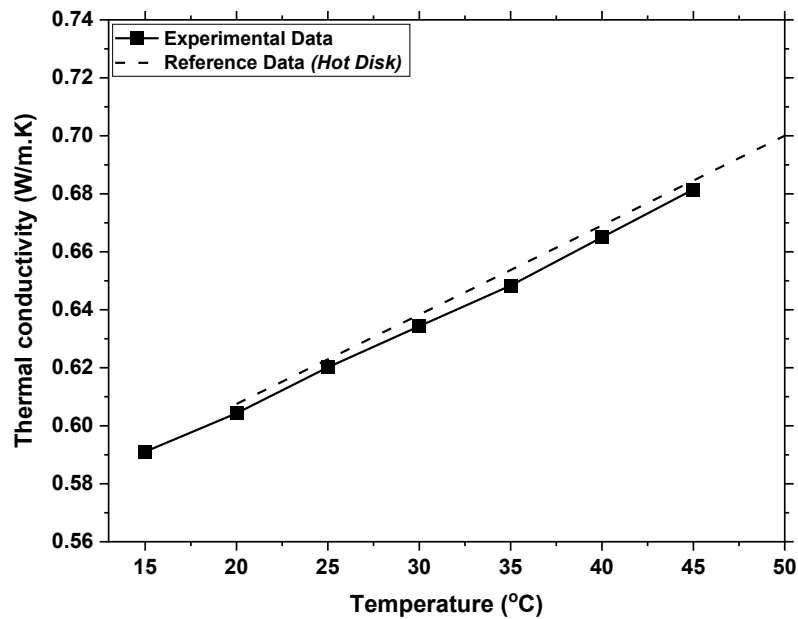


Figure 5.12. Thermal conductivity of distilled water as a function of temperature, comparison of experimental data with reference data.

As anticipated for silicon carbide nanofluids, a slight decrease in thermal conductivity was observed upon the addition of various surfactants. The thermal conductivity values were found to be in the following sequence with slight changes $WOS > SDBS > CATB > SDS > GA$. Notably, SDS surfactant exhibited a distinct behaviour with silicon carbide nanoparticles. After 72 hours, the sample containing SDS surfactant experienced a significant reduction in value, indicating an adverse effect on stability. The surfactant-free sample exhibited better stability and higher thermal conductivity compared to the SDS sample. Within a week, all particles had settled, leaving the water clear. The thermal conductivity of the SDS sample decreased from 0.664 W/m·K to 0.653 W/m·K within 72 hours. However, nanofluid samples containing SDBS and CTAB surfactants exhibited comparatively better values after 72 hours, measured to be 0.664 W/m·K and 0.664 W/m·K, respectively. As for GA, although the upper layer of the sample began clearing after 72 hours, a reduction in thermal conductivity was observed from 0.664 W/m·K to 0.661 W/m·K.

The beryllium oxide solution exhibited lower stability compared to others, but the addition of surfactants played a crucial role in stabilizing the suspension. According to the results collected just after the sonication, the thermal conductivity value of surfactant free sample was slightly higher than others like silver and silicon carbide suspensions. However, after 72 hours, the upper layer of the fluid became transparent as particles settled, resulting in a marginal decrease in thermal conductivity from 0.662 W/m·K to 0.6538 W/m·K. The addition of SDBS surfactant was found to enhance stability and mitigate the reduction in thermal conductivity by reducing particle agglomeration and settling. The

CTAB surfactant followed closely, offering improved stability albeit with slightly lower thermal conductivity than SDBS. A decrease in thermal conductivity values was noted for SDBS and CTAB samples, from 0.6626 to 0.6611 W/m·K and 0.6615 to 0.6609 W/m·K, respectively. Gum Arabic was found to be unsuitable for beryllium oxide nanofluids. The findings of this study strongly advocate for the use of surfactants in the preparation of beryllium oxide solutions to ensure effective stability maintenance.

This study reveals that the effectiveness of surfactants varies depending on the nanoparticles involved. SDBS and CTAB exhibit superior performance in some cases, but for other particles, GA or SDS may offer better stability. This suggests that the choice of surfactant should be tailored to the specific nanoparticles being used. Furthermore, ongoing investigations are exploring additional surfactants and combinations thereof to determine their effects on stability and thermal performance. Future research endeavours may focus on evaluating additional surfactants and assessing the synergistic effects of surfactant combinations to further optimise nanofluid properties.

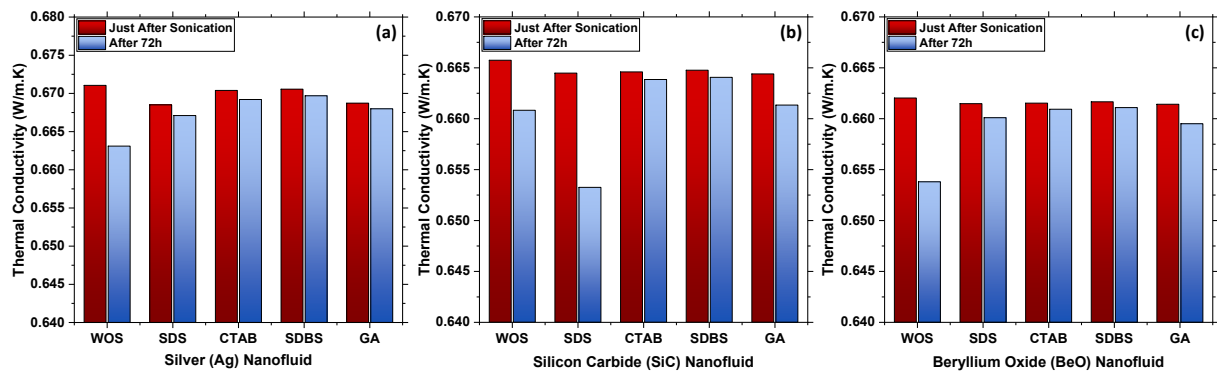


Figure 5.13. Thermal conductivity of nanofluids just after sonication and after 72 hours. (a) Silver nanofluid, (b) Silicon Carbide nanofluid, (c) Beryllium Oxide nanofluid.

Particle concentration is the other significant factor influencing the thermal conductivity of nanofluids [273,274]. Understanding how changes in particle concentration affect thermal conductivity is essential for optimising nanofluid formulations for various applications. A study was undertaken to investigate the influence of particle concentration on thermal conductivity within the range of 0.01 vol% to 0.025 vol%. This range was selected considering the importance of stability, particularly in applications such as thermal management of electronic components, especially for mini and microchannel heat sinks. Higher concentrations of particles can lead to various challenges. These include increased pressure drop and pumping power, as well as the risk of particle agglomeration leading to blockages within the channels, especially in cases where the flow is predominantly laminar. Such blockages can result in localised heating, potentially causing damage to the entire system.

Fig. 5.14 illustrates the impact of particle concentration on the thermal conductivity of various nanofluids. As the concentration of nanoparticles increased, there was a consistent rise in thermal conductivity enhancement. This enhancement can be attributed to factors such as increased particle-

packing density, enhanced Brownian motion, and greater surface area for heat transfer. The major contributing factor to the increase in thermal conductivity with higher concentrations is the inherently higher thermal conductivity of nanoparticles, amplified by the larger number of particles present in the nanofluid at higher concentrations. As more nanoparticles are dispersed within the fluid, they contribute more significantly to enhancing heat transfer capabilities. Additionally, the greater interaction between nanoparticles and the surrounding fluid facilitates more efficient heat transfer pathways, leading to higher overall thermal conductivity.

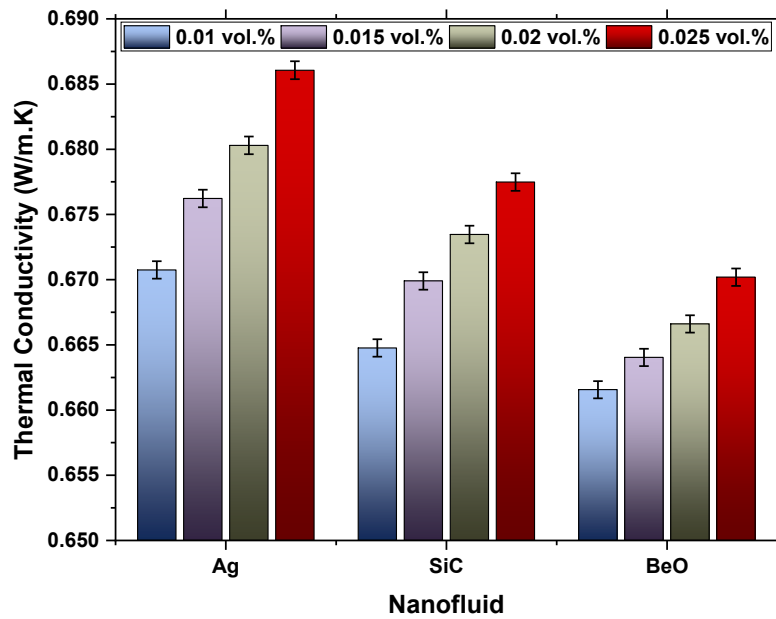


Figure 5.14. Variation of thermal conductivity with particle concentration for different nanofluids.

The fluid containing silver nanoparticles outperformed at all concentrations because of their better thermal properties. At 0.025 vol%, silver nanofluid achieved the highest thermal conductivity of 0.6861 W/m·K, showcasing its excellent heat transfer capabilities. For silicon carbide nanofluid, the thermal conductivity exhibited an increase with the augmentation of particle concentration, however, the enhancement was slightly lower compared to silver nanofluid. At a 0.01 vol% concentration of silicon carbide nanoparticles, the thermal conductivity of the nanofluid was measured to be 0.6707 W/m·K. This represented an enhancement of approximately 2.53% over pure water. When the nanoparticle concentration was increased to 0.025 vol%, the thermal conductivity further improved to 0.6861 W/m·K, indicating a 4.49% enhancement over water. The higher thermal conductivity of silicon carbide nanoparticles, coupled with improved dispersion within the fluid, facilitates enhanced heat transfer, resulting in increased overall thermal conductivity.

In contrast to silver and silicon carbide nanofluids, the thermal conductivity of beryllium oxide nanofluid exhibits a relatively modest increase with increasing particle concentration. At 0.01 vol%, the thermal conductivity is measured to be 0.6616 W/m·K, reaching 0.6702 W/m·K at 0.025 vol%. Despite this increase, the improvement in thermal conductivity is not as significant compared to other nanofluids, with enhancements ranging from 2.035% to 3.366% across the concentration range. This

may be attributed to the intrinsic properties of beryllium oxide nanoparticles and their interaction with the base fluid. However, even though the enhancement is modest, the presence of beryllium oxide nanoparticles still helps improve the fluid's ability to transfer heat.

Fig. 5.15 presented the variation of thermal conductivity with temperature for both simple and hybrid nanofluids, measured at 0.025 vol.% concentration over a temperature range of 15–45 °C. Notably, all samples exhibited a substantial increase in thermal conductivity as the temperature varied. However, it was observed that at lower temperatures, this increase was less pronounced compared to higher temperatures, with a noticeable acceleration in augmentation beyond 30 °C. This phenomenon may be attributed to the enhanced Brownian motion of nanoparticles at elevated temperatures, leading to improved dispersion and subsequently increased thermal conductivity. Such behaviour holds significant implications, particularly in applications where nanofluids serve as heat transfer fluids, as their performance is inherently linked to their ability to efficiently carry and disperse heat. Moreover, it is noteworthy that hybrid nanofluids, with an optimal mixing ratio, demonstrated superior thermal performance compared to simple nanofluids. This underscores the potential benefits of synergistic nanoparticle combinations, presenting promising avenues for enhancing thermal conductivity and overall performance in various practical applications.

The enhancement values, calculated by comparing the thermal conductivity of silver nanofluid to that of water, reveal a significant improvement in thermal conductivity with the addition of silver nanoparticles. The highest enhancement of 6.95% was observed at 45°C, as shown in Fig. 5.15(a). The SiC nanofluid sample also exhibited a consistent increase in thermal conductivity with rising temperatures. At each temperature point, the thermal conductivity of SiC nanofluid was higher than that of water, indicating the enhancement effect of silicon carbide nanoparticles on heat transfer properties. Comparing silicon carbide nanofluid to silver nanofluid, it was evident that silver nanoparticles generally resulted in higher thermal conductivity values across all temperature points. However, the enhancement values for SiC nanofluid are notably substantial, the maximum improvement was noted to be 5.11% at 45°C, indicating that silicon carbide nanoparticles effectively enhance the thermal conductivity of the nanofluid. The sample prepared by suspending BeO nanoparticles consistently exhibited lower thermal conductivity compared to silver and silicon carbide nanofluid across the temperature range. However, despite the lower values, BeO nanofluid still showed a notable enhancement compared to basefluid (water), reaching 4.47% at 45°C. The results indicated that while the thermal conductivity of BeO nanofluid may not have reached the levels observed in silver and silicon carbide nanofluids, the addition of beryllium oxide nanoparticles still led to significant improvements in heat transfer properties.

It is important to consider that in this study, the nanofluid samples were all prepared based on volume per cent (vol.%) instead of weight per cent (wt.%). While factors like the thermal conductivity of particles, base fluid, stability, particle size, shape, surfactant, and solution pH are well-known to influence the thermal properties of nanofluids, particle density also plays a significant role [273]. Since

density directly affects the number of particles added per unit volume, using particles with lower densities at the same volume fraction results in a greater number of particles. These additional particles act as heat carriers, potentially enhancing the thermal conductivity of the nanofluid. This effect is particularly important for hybrid nanofluids. In these fluids, particles with different thermal conductivities, densities, and crystalline structures are combined. The interplay between these diverse characteristics can lead to synergistic effects, further improving the thermal properties beyond what could be achieved with single-type nanoparticles.

Fig. 5.15(b) presented the thermal conductivity of silver and beryllium oxide hybrid solutions prepared with different mixing ratios. Across the studied ratios of 20/80, 40/60, 60/40, and 80/20, we observed a consistent trend of thermal conductivity enhancement compared to pure water with a noticeable fluctuation in the values at different mixing ratios. This enhancement, ranging from approximately 3.36% to 7.17% compared to water, underscores the effectiveness of incorporating Ag and BeO nanoparticles into the fluid matrix. The observed enhancement trends suggest that certain mixing ratios may yield more favourable thermal conductivity enhancements. Notably, the mixing ratio of 60/40 demonstrated the highest enhancement values. This optimal balance between Ag and BeO nanoparticles likely facilitates synergistic effects, resulting in enhanced thermal conductivity performance. The hybrid solution with a mixing ratio of 20/80 exhibited a maximum enhancement of 5.35% compared to water, falling between the enhancement values of pure silver and beryllium oxide nanofluids. Following this, the 40/60 solution showed a maximum enhancement of 6.88%, closer to the enhancement observed in pure silver nanofluids. However, the most significant enhancement of 7.17% was observed at the 60/40 mixing ratio. This increase could be attributed to the combined effects of the nanoparticles' distinct thermal characteristics, density values, crystalline structure, interactions, and suspension behaviours in the fluid. Furthermore, a slight decrease in thermal conductivity enhancement is noted as the mixing ratio shifts from 60/40 to 80/20, aligning the thermal conductivity values more closely with those of pure silver nanofluids. The findings from the investigation of Ag/BeO hybrid suspensions suggest that a mixing ratio of 60/40 represents the optimal concentration for achieving enhanced thermal conductivity.

Similar to the Ag/BeO hybrid suspension, the results obtained from the SiC/BeO suspension suggest that specific mixing ratios can lead to more favourable enhancements in thermal conductivity. Across the range of mixing ratios examined, it was observed that the fluid with a mixing ratio of 80/20 exhibited the highest enhancement in thermal conductivity compared to pure water and individual nanofluids, as depicted in Fig. 5.15(c). The thermal conductivity was observed to improve with increasing the ratio of SiC and reducing BeO. At the mixing ratio of 20/80, the maximum improvement in thermal conductivity relative to water was 4.92%, falling between the enhancements observed for pure SiC and BeO nanofluids. For the 40/60 hybrid sample, the thermal conductivity value reached 0.716 W/m·K at 45 °C, with an enhancement of approximately 5.06%, which was slightly lower and closer to that of the SiC nanofluid. However, the samples with mixing ratios of 60/40 and 80/20 demonstrated higher

enhancements compared to others, measuring 5.14% and 5.31%, respectively, as shown in Fig. 5.16. The results indicate that the mixing ratio of 80/20 is optimal for achieving higher thermal conductivity values in SiC/BeO hybrid suspensions.

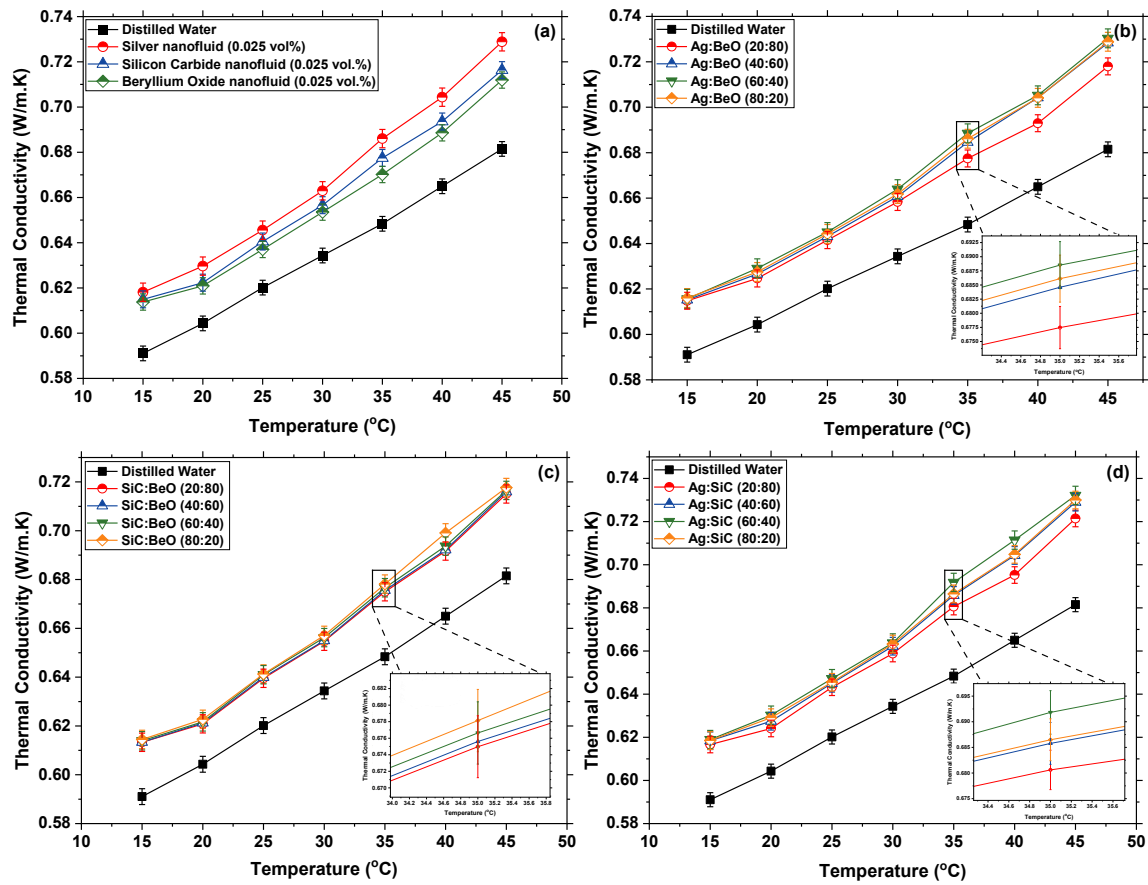


Figure 5.15. Thermal conductivity of simple and hybrid at different mixing ratios over the temperature range of 15-45°C.

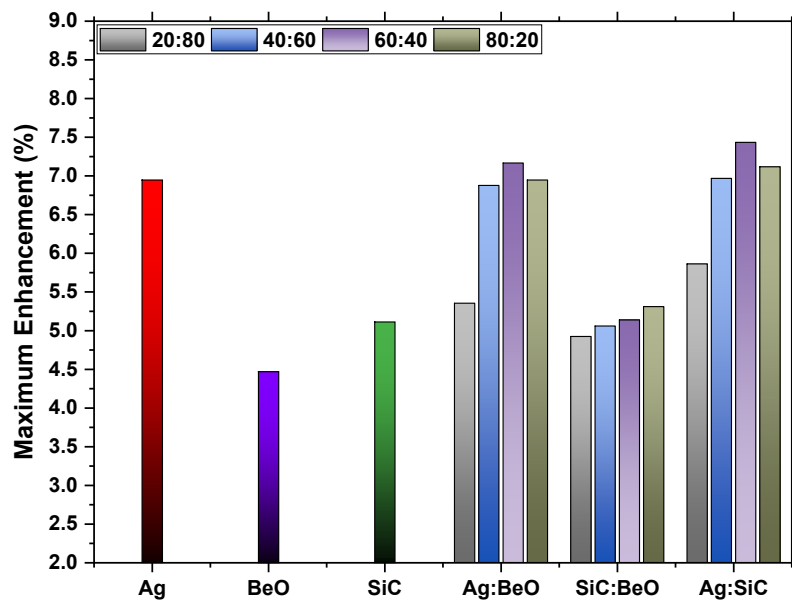


Figure 5.16. Maximum thermal conductivity enhancement compared to water for various nanofluids at different mixing ratios.

The results of Ag/SiC hybrid nanofluids, as depicted in Fig. 5.15(d), further corroborate the observations made in previous cases regarding the differential impact of specific mixing ratios on thermal conductivity enhancement in hybrid suspensions. The hybrid nanofluid with a mixing ratio of 20/80 exhibited a notable enhancement of 5.86%, elevating its thermal conductivity from 0.617 W/m·K to 0.7216 W/m·K over the temperature range of 15 °C to 45 °C. Although this hybrid suspension demonstrated improved stability and thermal conductivity compared to pure SiC nanofluid, it still fell short of the thermal conductivity achieved by simple silver nanofluid. As the mixing ratio changed to 40/60, a notable enhancement brought the thermal conductivity closer to that of pure silver nanofluid, reaching a maximum enhancement of 6.97% at 45 °C. Although this solution offers improved stability and cost-effective, its thermal conductivity is comparable to that of simple nanofluids.

The hybrid nanofluid suspension with a 60/40 mixing ratio outperformed all, showing an enhancement of 7.43%. This represents the maximum enhancement observed in this study. As the mixing ratio shifted from 60/40 to 80/20, a slight decrease in enhancement was noted, reaching 7.12%. A number of factors elaborated above are responsible for making the hybrid nanofluid preferable over pure nanofluids. It is evident from the results that careful selection of nanoparticle combinations and mixing ratios is crucial in maximising thermal conductivity enhancements in hybrid nanofluids. Based on these findings, it is recommended to utilise the Ag/SiC hybrid nanofluid with a 60/40 mixing ratio for applications requiring enhanced heat transfer efficiency. Further exploration and optimisation of mixing ratios could potentially lead to even greater enhancements in thermal conductivity, offering valuable insights for the design and development of advanced heat transfer fluids.

An analysis was carried out using Design Expert to study the relationship between temperature and thermal conductivity of various nanofluids [275]. In this study, a confidence level of 95% or a 5% significance level for the critical P-value was utilised. Through meticulous examination, a quadratic model was established to predict thermal conductivity with high precision, Eq. (5.2). The quadratic model considered both the linear and quadratic effects of temperature providing a comprehensive understanding of the phenomenon. This model was subjected to Analysis of Variance (ANOVA) analysis, a powerful statistical tool that dissected the significance of each model term. The ANOVA table provides information on the overall significance of the model and the statistical significance of different terms (A, B, AB, B²) in the model, as illustrated in Table 5.2. It revealed that the model as a whole was exceptionally significant, with a p-value<0.0001, indicating its robustness in explaining variations in thermal conductivity. Furthermore, individual model terms such as A-Fluid, B-Temperature, AB, and B² exhibited remarkable significance, further validating the model's efficacy.

$$\text{Thermal Conductivity } (k) = a + bT + 0.000038 T^2 \quad (5.2)$$

here a and b are coefficients representing the intercept and the linear coefficient respectively. The term T^2 represents the quadratic effect of temperature. Each nanofluid sample has its specific values for these coefficients as presented in Table 5.3.

Table 5.2. ANOVA for the quadratic model of thermal conductivity.

Source	Sum of Squares	df	Mean Square	F-value	p-value	Significance
Model	0.1531	32	0.0048	1049.5	< 0.0001	Significant
A-Fluid	0.0074	15	0.0005	107.68	< 0.0001	
B-Temperature	0.1439	1	0.1439	31573.93	< 0.0001	
AB	0.0006	15	0	8.87	< 0.0001	
B ²	0.0012	1	0.0012	261.86	< 0.0001	
Residual	0.0004	79	4.56E-06			
Std. Dev.	0.0021		R ²	0.9977		
Mean	0.6619		Adjusted R ²	0.9967		
C.V. %	0.3225		Predicted R ²	0.9949		
PRESS	0.000774		Adeq Precision	120.3633		

The standard deviation (Std. Dev.) of the model was calculated to be 0.0021. This value indicates the variability of the data points around the mean. Assessing the model's performance, metrics such as Predicted R² and Adjusted R² provided insights into the model's goodness of fit, showcasing its ability to accurately capture the relationship between temperature and thermal conductivity. The high values of these metrics, coupled with an Adeq Precision ratio exceeding 120, signified not only a strong signal but also a practical utility of the model in navigating the design space.

Table 5.3. The values of coefficients for the thermal conductivity of fluid samples.

Sample	a	b	Sample	a	b
DW	0.574933	0.000745	SiC/BeO (20:80)	0.585405	0.001183
Ag	0.586206	0.001468	SiC/BeO (40:60)	0.585192	0.001205
SiC	0.586782	0.001193	SiC/BeO (60:40)	0.585659	0.00122
BeO	0.587524	0.001045	SiC/BeO (80:20)	0.584672	0.001305
Ag/BeO (20:80)	0.58795	0.001182	Ag/SiC (20:80)	0.587144	0.001268
Ag/BeO (40:60)	0.581365	0.001569	Ag/SiC (40:60)	0.58487	0.001497
Ag/BeO (60:40)	0.582735	0.001595	Ag/SiC (60:40)	0.583829	0.001642
Ag/BeO (80:20)	0.582755	0.00155	Ag/SiC (80:20)	0.5855	0.001501

The coefficient of determination (R²) was found to be 0.9977, indicating that approximately 99.77% of the variability in the thermal conductivity data can be explained by the quadratic model. The Predicted R² value of 0.9949 demonstrates strong agreement with the Adjusted R² value of 0.9967. With a difference of less than 0.2 between the two metrics, it indicates that the model's predictive power remains consistently high even when applied to new data. The coefficient of variation (C.V. %) of 0.3225% indicates the relative variability of the thermal conductivity data around the mean. Finally, the PRESS (Predicted Residual Error Sum of Squares) is a measure of the model's predictive performance. It quantifies the difference between predicted values and actual observed values, with lower values indicating better predictive accuracy. In this case, a PRESS value of 0.000774 suggests that the model's predictions closely align with the actual observed data points.

Fig. 5.17(a) shows the relationship between the experimental thermal conductivity values with the predicted using the ANOVA model. The closer the points lie to the diagonal line, the better the model fits the data. In this case, the data aligns well with the diagonal line, reflecting a satisfactory model fit. The normal probability plot of studentized residuals reveals that the errors associated with the thermal conductivity are approximately normally distributed, Fig. 5.17(b). This plot is used to assess whether the residuals conform to a normal and independent distribution. The alignment of data points with the straight normal line suggests that the error values associated with the thermal conductivity values are distributed normally. As visualised in the plot, the data points appeared to be reasonably close to the diagonal line, signifying adherence to the expected normal distribution of errors in the model.

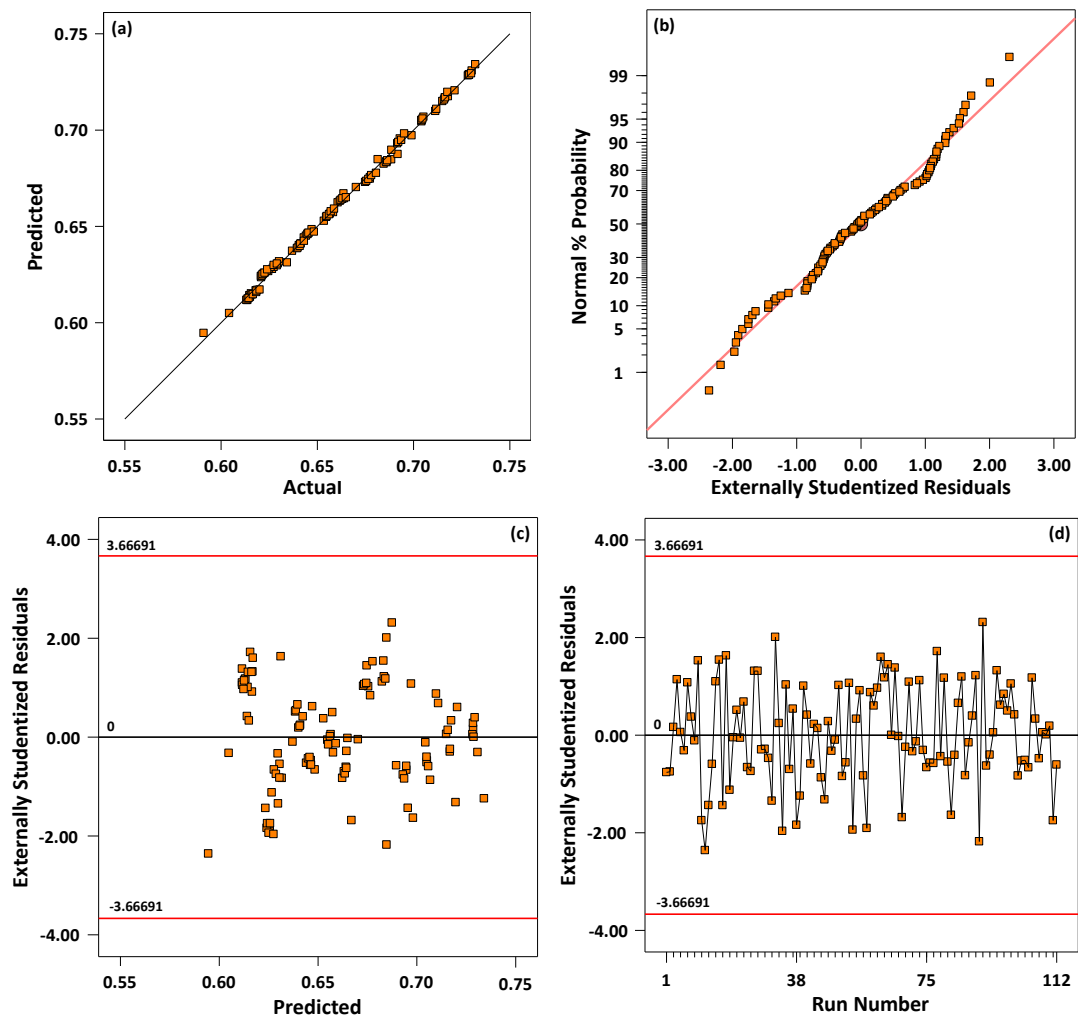


Figure 5.17. Thermal conductivity model plots (a) Predicted vs actual values, (b) Normal probability of studentized residuals, (c) Residuals vs predicted values, (d) Residuals vs run number.

The residual plots are utilised to assess the presence or absence of covariance among the errors concerning various independent variables, such as experiment number, prediction values, and time [276]. This analytical approach facilitated the identification of any potential covariance or lack thereof in the response variable. If no discernible pattern is evident in the dispersion plot, it suggests that the

errors are covariant. Conversely, if the model's accuracy is affirmed, and acceptance criteria are met, the residuals are expected to demonstrate an unstructured pattern and independence from other variables, including the response variable. This behaviour would indicate the absence of covariance among the errors. As depicted in Fig. 5.17(c) and Fig. 5.17(d), no conspicuous structures or discernible patterns are evident, with all points falling within the bounds of three standard deviations. Thus, it is inferred that errors exhibit covariance.

In Fig. 5.18, the thermal conductivity results of silver and Ag/SiC (60:40) nanofluids were compared to the literature values and predictions from classical models. It was found that the classical models such as Maxwell [277] and Hamilton and Crosser [278] failed to predict the values. Mahbubul et al. [279] also observed that experimental values exceeded those predicted by the models of Maxwell, Hamilton-Crosser, and Yu and Choi. These models are now considered outdated and often fail to provide accurate predictions. Consequently, recent studies have focused on experimental methods to better capture the thermophysical properties of nanofluids, which can then be applied to practical systems. The models developed in this study offer accurate predictions of the thermal conductivity of the nanofluid under investigation. Additionally, the results showed that the hybrid combinations used provided better thermal conductivity compared to many oxide-based and oxide-containing nanofluids. Dalkılıç et al. [280] examined the thermal characteristics of water-based CNT-SiO₂ hybrid nanofluids prepared with different mixing ratios. Their findings revealed that at a 0.1% volume fraction, the maximum enhancement was observed to be approximately 6.16% for the CNT:SiO₂ (80:20) ratio. Kazemi et al. [281] investigated the thermal conductivity of graphene and silica nanoparticles in both mono and hybrid nano-additive forms. The results revealed that the hybrid nanofluid G-SiO₂ achieved a notable thermal conductivity enhancement of approximately 5% and 8% at a concentration of 0.05% and 0.1%, respectively, outperforming the individual components. The findings suggested that while pure nanofluid contributed more significantly to thermal conductivity, the hybrid formulation was more cost-effective, making it a viable option for thermal applications. Sreekumar et al. [282] explored the properties of MXene/Carbon-dot hybrid nanofluid, which exhibited superior thermal conductivity and optical characteristics compared to conventional heat transfer fluids. Their findings showed that the thermal conductivity of the Carbon-dot nanofluid at 0.01 wt% and 45°C was approximately 0.71 W/m·K. Said et al. [283] studied the thermal conductivity of TiO₂/water nanofluids and concluded that fluids prepared with low particle concentrations had a negligible impact on pumping power in heat transfer applications. While TiO₂/water nanofluids demonstrated notable improvements in thermal conductivity and exhibited reasonable stability, challenges such as increased viscosity and particle aggregation over time could affect their long-term performance in heat transfer systems.

Zhang et al. [284] found that GPTMS-modified TiO₂/water nanofluids (G-TiO₂) showed better stability and higher thermal conductivity than surfactant-added nanofluids. The thermal conductivity enhancement for G-TiO₂ increased from 4.19% to 14.28% as the nanoparticle concentration rose from 0.08% to 2 vol%, while for surfactant-added TiO₂ (S-TiO₂), it ranged from 2.71% to 12.67%. He et al.

[285] investigated the thermal conductivity of ZnO-Ag (50%-50%)/water hybrid Newtonian nanofluid using Artificial Neural Networks (ANNs) and surface fitting methods. The study found that both methods could predict the nanofluid's behaviour, with the ANN method showing a better ability to predict thermal conductivity based on volume fraction and temperature. It was noted that despite higher concentrations, the thermal conductivity values were lower compared to those obtained in the current study, as ZnO has lower thermal conductivity than SiC and BeO. Moghadam et al. [286] developed a model to predict the thermal conductivity of a graphene oxide-titanium oxide/water hybrid nanofluid. Their results indicated that while the predicted values were close, the model is not recommended for use with other types of nanofluids. This comparative study concluded that no universal model exists for predicting nanofluid thermal conductivity. Models are generally developed for specific fluids and are reliable only if the exact protocols used in the original study are followed.

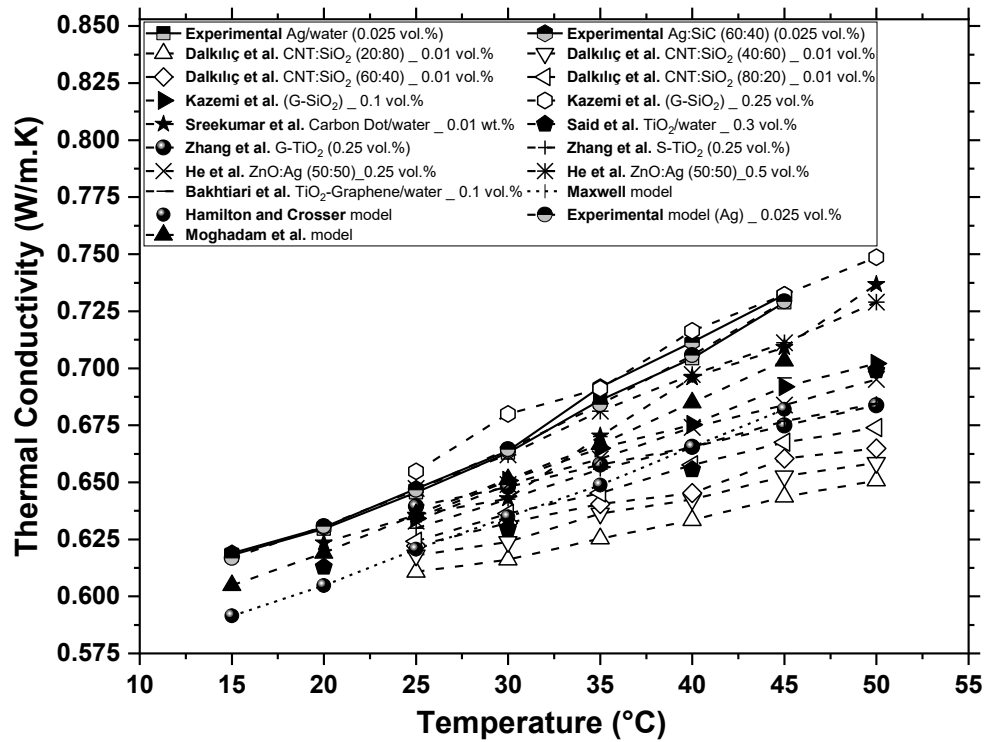


Figure 5.18. Comparison of experimental thermal conductivity values with data from literature and theoretical predictions.

5.5.2 Viscosity

Viscosity, a crucial property, requires thorough consideration when examining the characteristics of thermal fluids. To accurately measure the viscosity of prepared samples, we employed the Brookfield DVNext Cone/Plate Rheometer, utilizing a CPA-44PYZ Cup and CPM-40Z cone spindle [287,288]. The spindle rotation speed was set to 100 rpm, and each experiment was allowed to run for 45 seconds. Ensuring precise temperature control within the testing chamber, the cup was effectively connected to the thermal bath through pipes. Temperature regulation was achieved via a Masterflex L/S Pump, which

continuously circulated water throughout the system, maintaining optimal testing conditions. According to the procedural guidelines, a 5 ml sample was utilised for each experiment.

The rheometer used in this study has an accuracy of $\pm 1.0\%$ of its full-scale range, ensuring reliable viscosity measurements. The system's reproducibility is within $\pm 0.2\%$, further enhancing the precision of repeated measurements. To validate the test rig, the viscosity of distilled water was examined at different temperatures ranging from 20 °C to 45 °C and compared with the viscosity values of ordinary water available in the literature [289], as shown in Fig. 5.19. The measured values closely aligned with the literature, with a mean absolute error between the experimental and reference values noted to be 0.59%. This indicates a high level of accuracy and reliability in the experimental setup.

The study, conducted at 25 °C to investigate the behaviour of the nanofluid samples, revealed that the fluids of Ag, SiC, and BeO behaved as Newtonian fluids, with the shear stress increasing proportionally to the shear rate. To vary the shear rate, the spindle speed was adjusted in the range of 60 to 160 rpm. This finding suggests that the nanofluids of Ag, SiC, and BeO exhibit Newtonian behaviour, where the relationship between shear stress and shear rate remains linear within the specified range of spindle speeds, as depicted in Fig. 5.20.

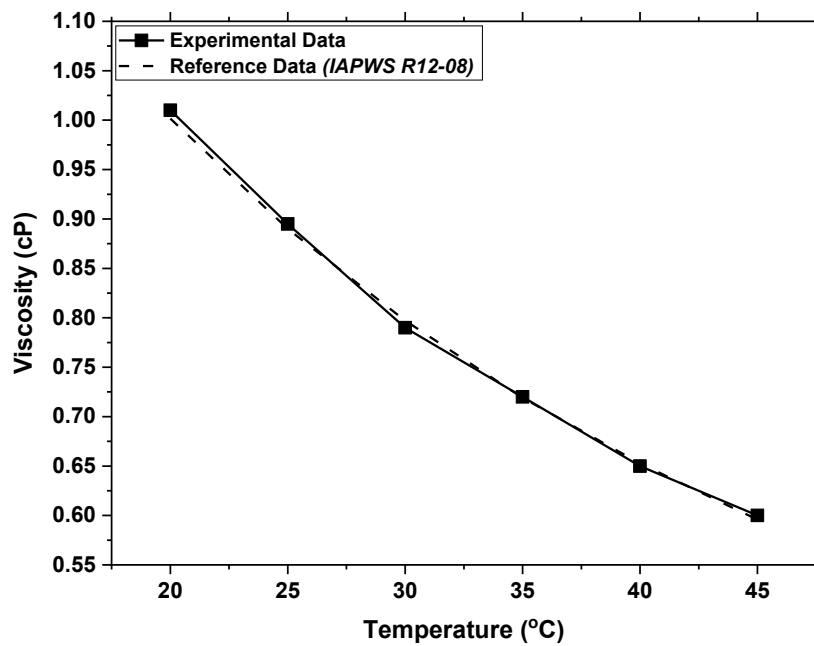


Figure 5.19. Comparison of experimental viscosity data for water with reference data from IAPWS R12-08.

Newtonian fluids, with their constant viscosity, are crucial in industrial applications as they ensure stable and predictable flow behaviour under varying shear conditions. This makes them particularly suited for processes such as mixing, pumping, and heat transfer, where precise control over fluid flow is critical. In industries like chemical manufacturing and cooling systems, the reliability of Newtonian fluids simplifies equipment design, improves operational efficiency, and enhances overall system performance.

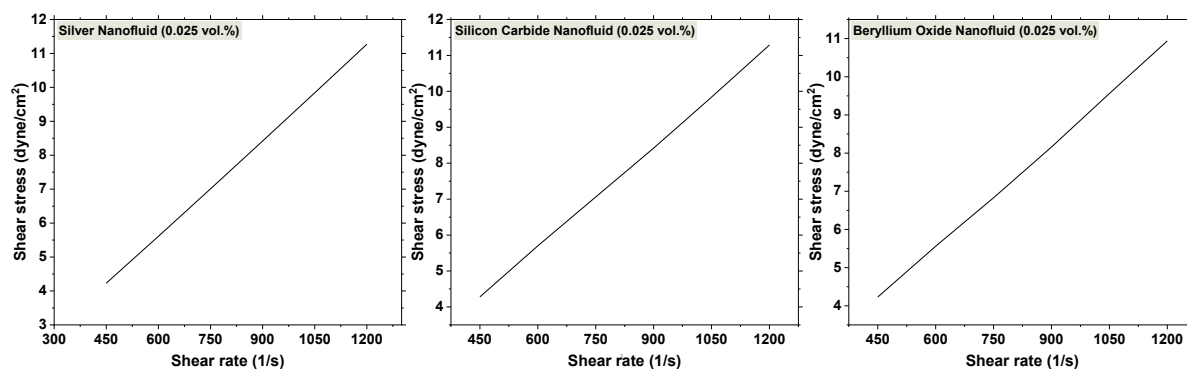


Figure 5.20. Shear stress vs shear rate plots for (a) Silver nanofluid, (b) Silicon Carbide nanofluid, and (c) Beryllium Oxide nanofluid at 0.025 vol% concentration, exhibiting Newtonian behaviour.

The concentration study conducted at 30 °C concluded that with the increase in particle concentration, the viscosity of nanofluid increased, as shown in Fig. 5.21. This is because more particles in the fluid increase the resistance to flow. In the case of the Ag nanofluid, viscosity demonstrated an incremental rise from 0.81 cP to 0.83 cP as nanoparticle concentration escalated from 0.01 vol.% to 0.025 vol.%. The SiC nanofluid exhibited a proportional increase in viscosity from 0.80 cP to 0.835 cP across the same concentration range. Likewise, the BeO nanofluid experienced a corresponding elevation in viscosity, progressing from 0.795 cP to 0.82 cP.

The results revealed that the silicon carbide nanofluid has the highest viscosity among the three, and attributes this to the fact that the SiC nanoparticles have more sharp edges and irregular shapes. Nanoparticles with sharp edges or irregular shapes can disrupt the flow of the fluid more effectively than nanoparticles with smooth, spherical shapes. It can also be observed in the TEM image of the SiC nanoparticles, which shows that they are indeed more angular and irregular than the other two types of nanoparticles. However, it is important to note that the particle shape is not the only factor which influences the viscosity, factors like particle size, density, etc are also important and need to be considered. Smaller particle size tends to result in higher viscosity due to increased surface area, resulting in more interaction between particles and the fluid [290,291].

The density of nanoparticles also influenced viscosity, with silver nanoparticles exhibiting a density around three times higher than that of SiC and BeO nanoparticles. The combined influence of these factors resulted in the silver nanofluid displaying the highest viscosity, while the BeO nanofluid exhibited comparatively lower viscosity values, as shown in Fig. 5.22(a). It was also observed that the viscosity values of the nanofluid samples started to converge as the temperature approached 35 °C. This convergence suggests that at higher temperatures and lower particle concentration, the influence of particle type on viscosity becomes less significant especially, resulting in narrowing differences in viscosity among the nanofluid samples.

Fig. 5.22(b) presents the viscosity values of Ag/BeO-water hybrid nanofluids at different compositions (20/80, 40/60, 60/40, and 80/20) and temperatures ranging from 15 °C to 45 °C. The results revealed

that as the percentage of Ag nanofluid increased in the hybrid nanofluid, there was a noticeable improvement in viscosity across all temperatures. It was observed that the viscosity enhancement was more significant with higher proportions of Ag nanoparticles in the hybrid sample. As temperatures approached 35 °C, the disparity in viscosity values among different compositions of the hybrid nanofluid became less pronounced. However, for fluids prepared with higher particle concentrations exceeding 0.1 vol.%, the variations in viscosity across different mixing ratios and in comparison to water might remain more pronounced even at elevated temperatures [292].

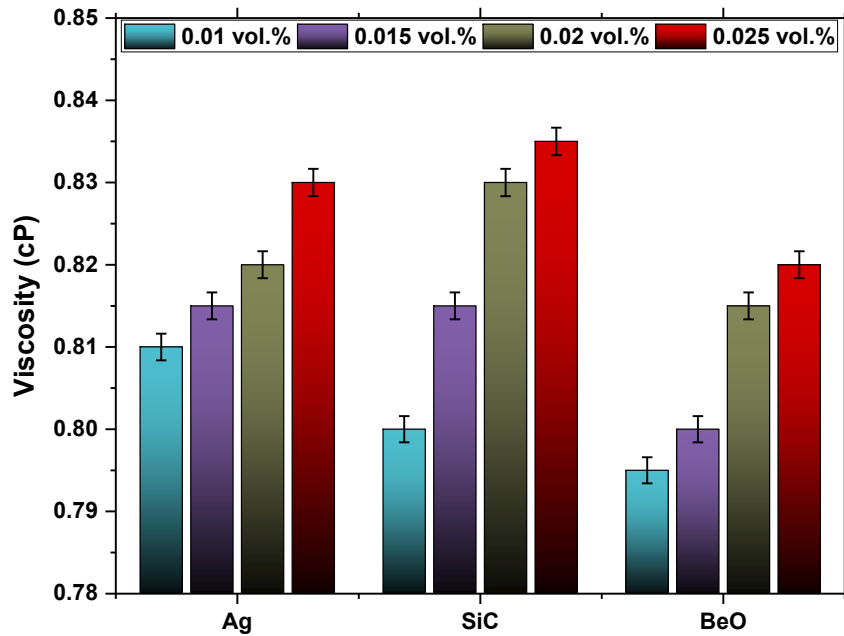


Figure 5.21. Viscosity variation at different particle concentrations.

The viscosity values of Ag and SiC nanofluids are closer to each other, resulting in minor variations in their hybrid fluids' viscosity, as shown in Fig. 5.22(c). It was noted that the fluid containing a higher percentage of SiC exhibited slightly higher viscosity values, akin to the behaviour observed in Ag/BeO hybrids, this difference did not manifest significantly at elevated temperatures. The viscosity of SiC/BeO-water hybrid nanofluids exhibited patterns similar to those observed in other hybrid nanofluid samples. Across temperatures ranging from 15 °C to 45 °C, there was a consistent decrease in viscosity across all compositions, which aligns with the typical behaviour of fluids wherein higher temperatures lead to reduced viscosity. However, the viscosity of SiC/BeO nanofluids tended to increase with the percentage of SiC, as illustrated in Fig. 5.22(d). For instance, at 15 °C, the viscosity of SiC/BeO with a mixing ratio of 80:20 was measured to be 1.205 cP, while for the highest SiC/BeO composition (80/20), it was 1.22 cP, indicating a rise in viscosity with increasing SiC concentration.

When comparing the viscosity enhancements of various simple and hybrid nanofluids to that of water, it is essential to analyse the average per cent increase across different compositions. Figure 5.23 provided average per cent increase values that offer valuable insights into the impact of different nanoparticle types and their combinations in altering fluid viscosity. In comparing the viscosity

enhancements of various simple and hybrid nanofluids to that of water, it's essential to delve into the nuanced details of their performance. The provided average per cent increase values offer valuable insights into the effectiveness of different nanoparticle types and their combinations in altering fluid viscosity.

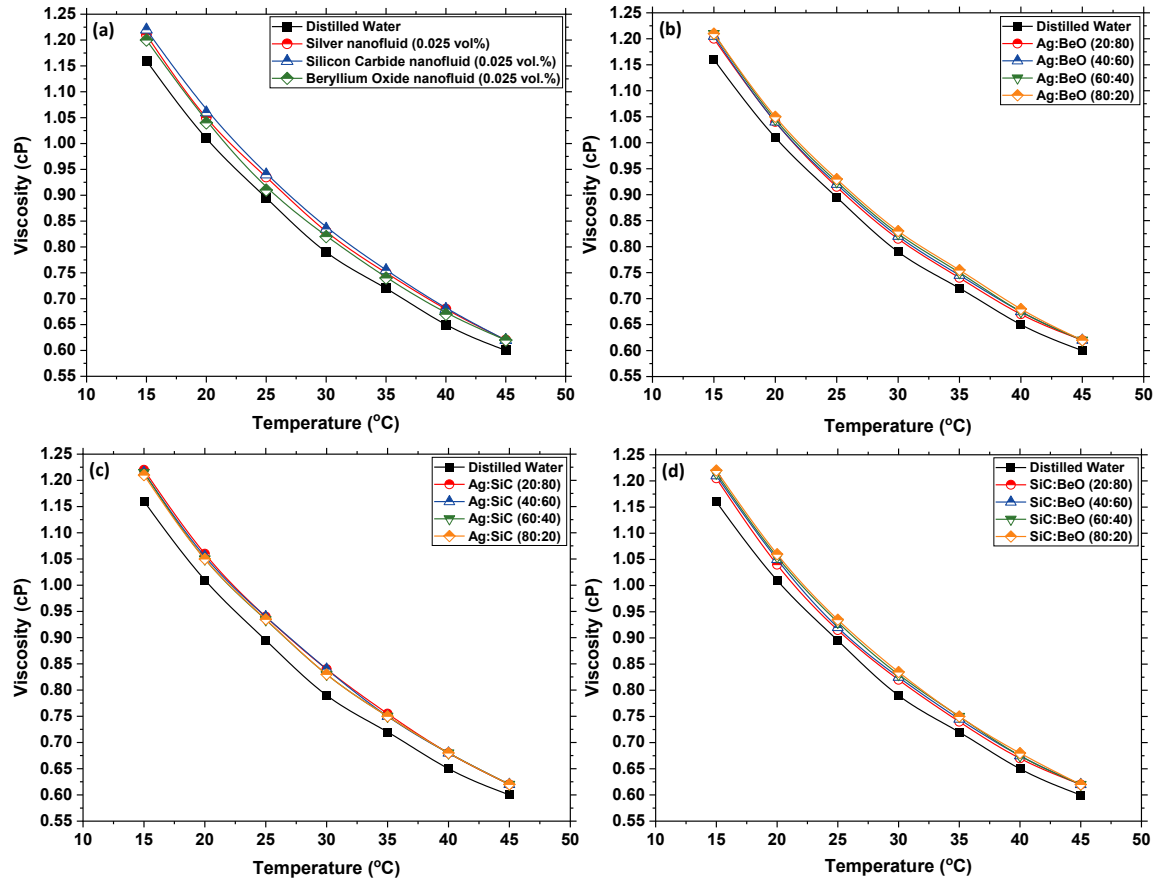


Figure 5.22. Viscosity of nanofluid formulations at different temperatures and mixing ratios.

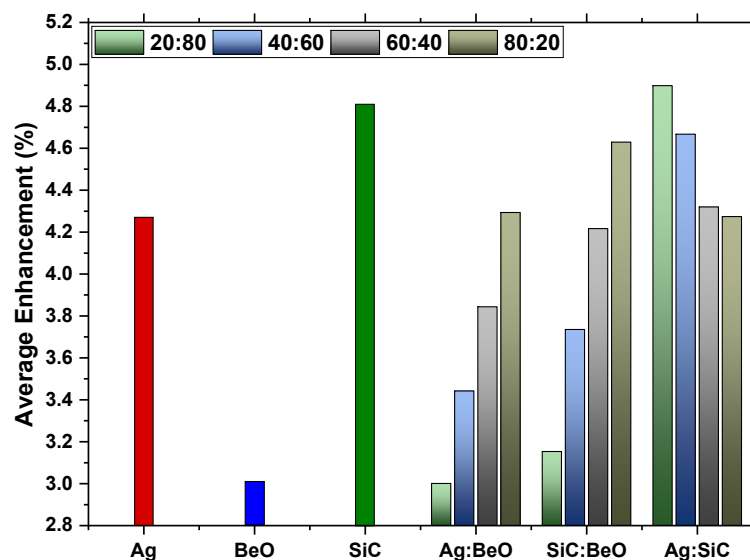


Figure 5.23. Average per cent increase in viscosity for different nanofluids and their hybrids compared to basefluid.

For Ag nanofluids, the observed average per cent increase in viscosity stands at approximately 4.27%. This suggests a moderate enhancement in viscosity when Ag nanoparticles are dispersed within the fluid medium. The SiC nanofluids exhibit a notably higher average per cent increase, at around 4.81%. This indicates a more significant impact on viscosity, implying that the studied SiC nanoparticles possess a pronounced influence on altering fluid behaviour. Moving on to BeO nanofluids, the average per cent increase is comparatively lower, standing at approximately 3.01%.

The results indicated that BeO nanoparticles had a less substantial effect on viscosity compared to Ag and SiC nanoparticles. Furthermore, exploring the hybrid nanofluids, both Ag/BeO and SiC/BeO hybrids showcased varying levels of viscosity enhancement across different compositions, Fig. 5.23. For Ag/BeO hybrids, the average per cent increase ranged from 3.00% to 4.29%, with the highest enhancement observed at the 80/20 composition. The SiC/BeO hybrid nanofluids exhibited an average per cent increase ranging from 3.15% to 4.63%, with the peak enhancement observed at the 80/20 composition. Finally, Ag/SiC hybrid nanofluids demonstrated moderate to high increases in viscosity across different compositions, with the average per cent increase ranging from 4.27% to 4.90%. These samples indicated a notably higher viscosity enhancement compared to the other hybrid fluids.

It is important to note that viscosity is influenced not only by the type of particles present but also by a myriad of other factors like particle shape, size, concentration, and various interparticle interactions. The shape of nanoparticles can significantly impact their ability to interact with the surrounding fluid molecules, thereby affecting viscosity. Similarly, the size of particles plays a crucial role, as smaller nanoparticles tend to exhibit greater surface area-to-volume ratios, potentially leading to stronger interactions with the fluid medium and consequently altering viscosity. Factors like the concentration of nanoparticles within the fluid also play a significant role, with higher concentrations often resulting in more pronounced changes in viscosity. Interactions between particles, like aggregation, further influence nanofluid viscosity. Thus, while particle type is crucial, considering particle characteristics and fluid interactions is vital for understanding viscosity enhancements in nanofluids.

ANOVA analysis was conducted to develop and assess the significance of the cubic model for the viscosity prediction of samples. The model represented with Eq. (5.3) as a whole exhibit's exceptional significance, as indicated by its substantial F-value (7628.77) and minuscule p-value (< 0.0001). Table 5.4 presents the breakdown of sources of variation, sums of squares, degrees of freedom, mean squares, F-values, and associated p-values. The model's goodness-of-fit was exceptional, as evidenced by the high R^2 value of 0.9998, meaning it explained 99.98% of the variability in viscosity data. Both the adjusted R^2 (0.9997) and predicted R^2 (0.9994) values were very close to the R^2 value, indicating minimal overfitting and strong predictive performance. Additionally, the adequate precision value of 275.2094, supports the model's effectiveness in exploring the design space.

Fig. 5.24(a) depicts a comparison between experimentally obtained viscosity values and predictions from the cubic model. The close alignment observed suggested that the model accurately predicted viscosity across different experimental conditions, with significant deviations indicating poorer

predictive performance. The close alignment of data points with the diagonal line indicates an excellent agreement between experimental data and model predictions.

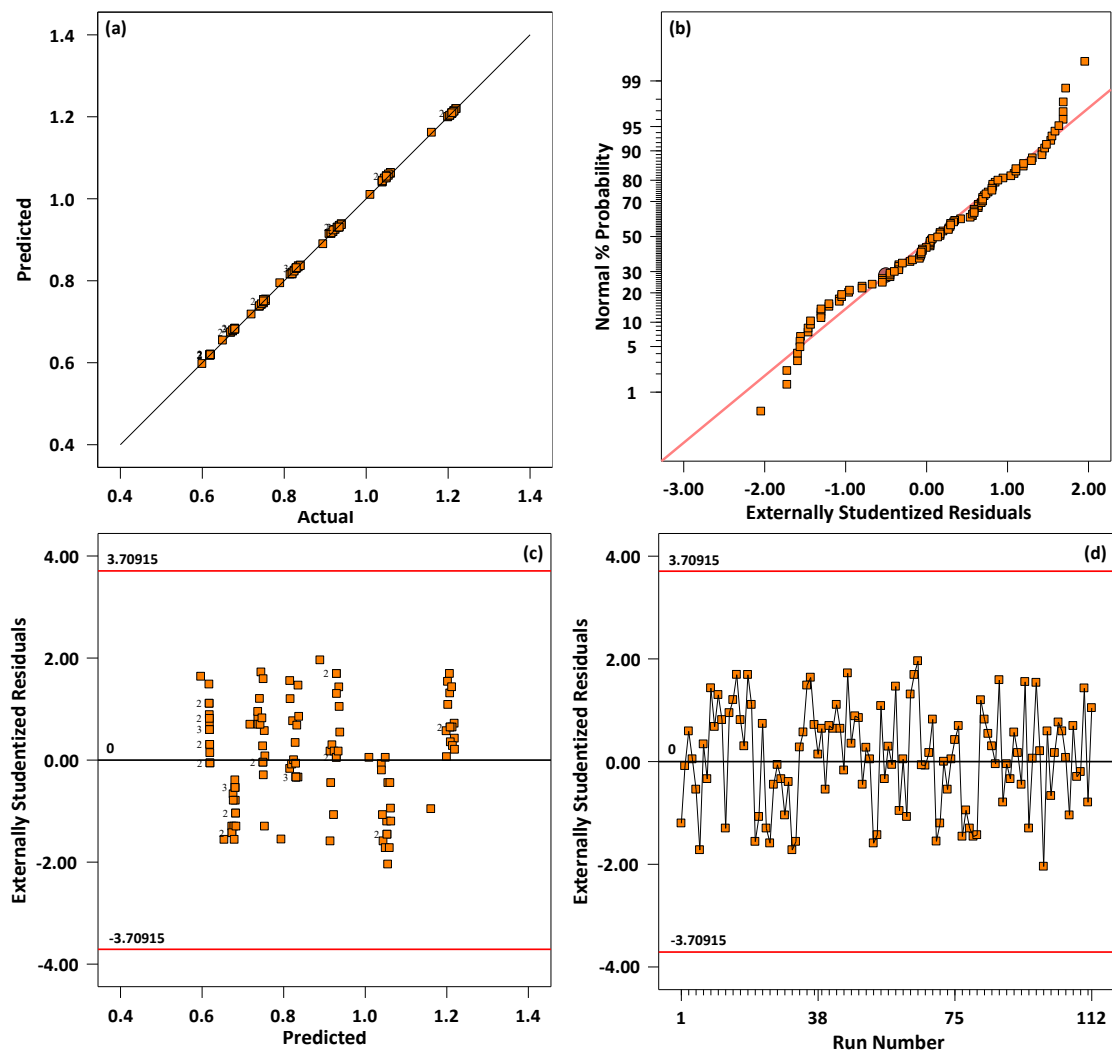


Figure 5.24. (a) Comparison of experimental and predicted viscosity values using the developed cubic model, (b) Normal probability plot of studentized residuals for the viscosity model, (c) Plot of studentized residuals vs predicted values for the viscosity model, (d) Plot of externally studentized residuals vs run number for the viscosity model.

Figure 5.24(b) illustrates a normal probability plot of residuals, confirming their adherence to a normal distribution, crucial for ensuring the validity of subsequent statistical analyses. Figure 5.24(c) provided a deeper dive into the data by plotting studentized residuals against predicted values. The outcomes showed studentized residuals scattered around zero against predicted values, indicating the model's compliance with assumptions of constant variance and error independence. Furthermore, Fig. 5.24(d) validates model assumptions, showing externally studentized residuals randomly distributed across observation numbers, mitigating concerns about biases related to experimental order. Together, these graphical analyses confirm the quadratic model's robustness and the data's compliance with fundamental statistical assumptions.

$$\text{Viscosity } (\mu) = c - dT + e(T^2) - 8.2778 \times 10^{-6}(T^3) \quad (5.3)$$

here c , d , and e are coefficients that vary for each specific nanofluid sample as listed in Table 5.5.

Table 5.4. ANOVA for the cubic model of viscosity.

Source	Sum of Squares	df	Mean Square	F-value	p-value	Significance
Model	4.28	48	0.0892	7628.77	< 0.0001	Significant
A-Fluid	0.0106	15	0.0007	60.25	< 0.0001	
B-Temperature	4.14	1	4.14	3.541E+05	< 0.0001	
AB	0.0010	15	0.0001	5.98	< 0.0001	
B ²	0.1252	1	0.1252	10714.94	< 0.0001	
AB ²	0.0003	15	0.0000	1.97	0.0320	
B ³	0.0037	1	0.0037	316.61	< 0.0001	
Residual	0.0007	63	0.0000			
Std. Dev.	0.00342		R ²	0.9998		
Mean	0.8639		Adjusted R ²	0.9997		
C.V. %	0.3957		Predicted R ²	0.9994		
PRESS	0.0026		Adeq Precision	275.2094		

Table 5.5. The values of coefficients for viscosity of fluid samples.

Sample	c	d	e	Sample	c	d	e
DW	1.86683	0.062009	0.001124	SiC/BeO (20:80)	1.94599	0.065116	0.001164
Ag	1.92064	0.062294	0.001114	SiC/BeO (40:60)	1.94683	0.06458	0.001152
SiC	1.93635	0.062651	0.001114	SiC/BeO (60:40)	1.9423	0.063651	0.001133
BeO	1.93647	0.064687	0.001159	SiC/BeO (80:20)	1.94635	0.063509	0.001128
Ag/BeO (20:80)	1.93945	0.064866	0.001162	Ag/SiC (20:80)	1.92945	0.06208	0.001105
Ag/BeO (40:60)	1.93457	0.064187	0.00115	Ag/SiC (40:60)	1.91921	0.061651	0.0011
Ag/BeO (60:40)	1.93397	0.063651	0.001138	Ag/SiC (60:40)	1.93487	0.063194	0.001127
Ag/BeO (80:20)	1.91849	0.062223	0.001114	Ag/SiC (80:20)	1.92064	0.062294	0.001114

5.5.3 Density

Density is a critical thermo-physical property to investigate, especially concerning its impact on enhancing pumping power and mass flow rate in various application areas. The density of both basefluid and nanofluid samples was measured using an Anton Paar DMA 35 density meter at different temperatures [293,294]. To achieve the desired temperature, the samples were poured into a sample tube immersed in a temperature-controlled bath. After allowing sufficient time for temperature stabilization, measurements were taken following a specific set of instructions. Prior to conducting the measurements and validation study, a water check was performed according to the supplier's instructions. The density meter used in this study has an accuracy of $\pm 0.001 \text{ g/cm}^3$ for density and $\pm 0.2 \text{ }^\circ\text{C}$ for temperature. The system's repeatability is excellent, with a standard deviation of $\pm 0.0005 \text{ g/cm}^3$ for density and $\pm 0.1 \text{ }^\circ\text{C}$ for temperature. To ensure precision, three measurements were taken at each temperature point, and the average was reported. The transparent glass top of the chamber facilitates ensuring the absence of air bubbles in the measurement section of the U-tube. For validation purposes, the density of water was measured over a temperature range of 15–45 $^\circ\text{C}$ and compared with

values provided by the supplier and those available in the literature [295], Fig. 5.25. The obtained data closely matched the literature and supplier values, with a mean absolute error of 0.02%.

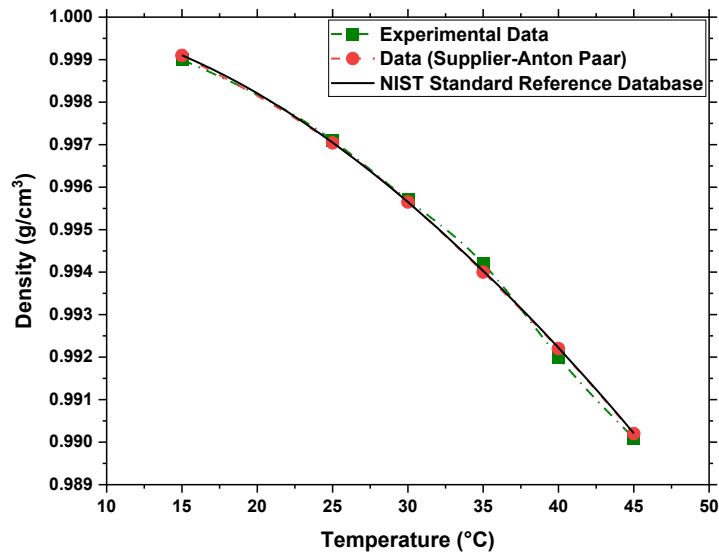


Figure 5.25. Validation of experimental density data against reference values for water.

A study was conducted by analysing the density of studied nanofluids by varying particle concentrations at 30 °C. The results revealed a noticeable enhancement in density values with changing particle concentration, attributed to the higher particle density compared to the base fluid. Among the nanofluids tested, silver nanofluid exhibited the most significant density increase, reaching a value of 0.9982 g/cm³ at a concentration of 0.025 vol%, which represents a 0.2410% enhancement compared to the base fluid. As depicted in Fig. 5.26, a consistent pattern was observed as the concentration increased from 0.01 to 0.025 vol% across all three types of nanofluids while the Ag nanofluid consistently displayed the highest density enhancement, followed by SiC and BeO nanofluids, respectively.

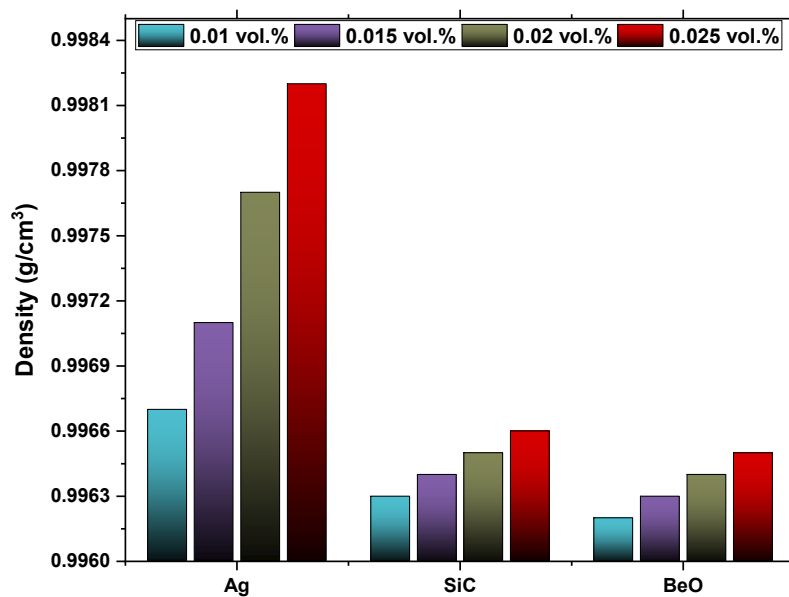


Figure 5.26. Variation of density with nanoparticle concentration at 30°C for Ag, SiC, and BeO nanofluids.

The density of SiC nanofluids ranged from 0.9963 g/cm³ to 0.9966 g/cm³ as the particle concentration varied from 0.01 to 0.025 vol%. The enhancement in density varied from 0.0502% to 0.08033% across these concentration levels. The beryllium oxide nanofluids displayed the least enhancement in density throughout all concentrations tested. At the maximum concentration of 0.025 vol%, the fluid only reached a density of 0.9982 g/cm³, which is a 0.07029% increase from the base fluid.

The density of simple and hybrid nanofluid samples was examined at various temperatures ranging from 15 °C to 45 °C. It was observed that as the temperature increased, the density values decreased significantly. This trend aligns with the expected behaviour, as higher temperatures typically lead to reduced fluid densities due to thermal expansion effects. However, the extent of the decrease varies slightly depending on the presence of nanoparticles. At 15 °C, water exhibited a density of 0.9990 g/cm³, which decreased to 0.9901 g/cm³ at 45 °C, indicating a notable reduction in density with increasing temperature. Similar trends were observed for other simple and hybrid nanofluid samples examined, as shown in Fig. 5.27. The density of Ag nanofluid is comparatively higher than that of water, with a value of 1.00195 g/cm³ compared to 0.9990 g/cm³ for water. Despite the decrease in density with temperature, Ag nanofluid maintained a slightly higher density compared to water and other unitary nanofluid samples throughout the temperature range. At 45 °C, the density of Ag nanofluid was noted to be 0.9926 g/cm³, while the density of water was 0.9901 g/cm³.

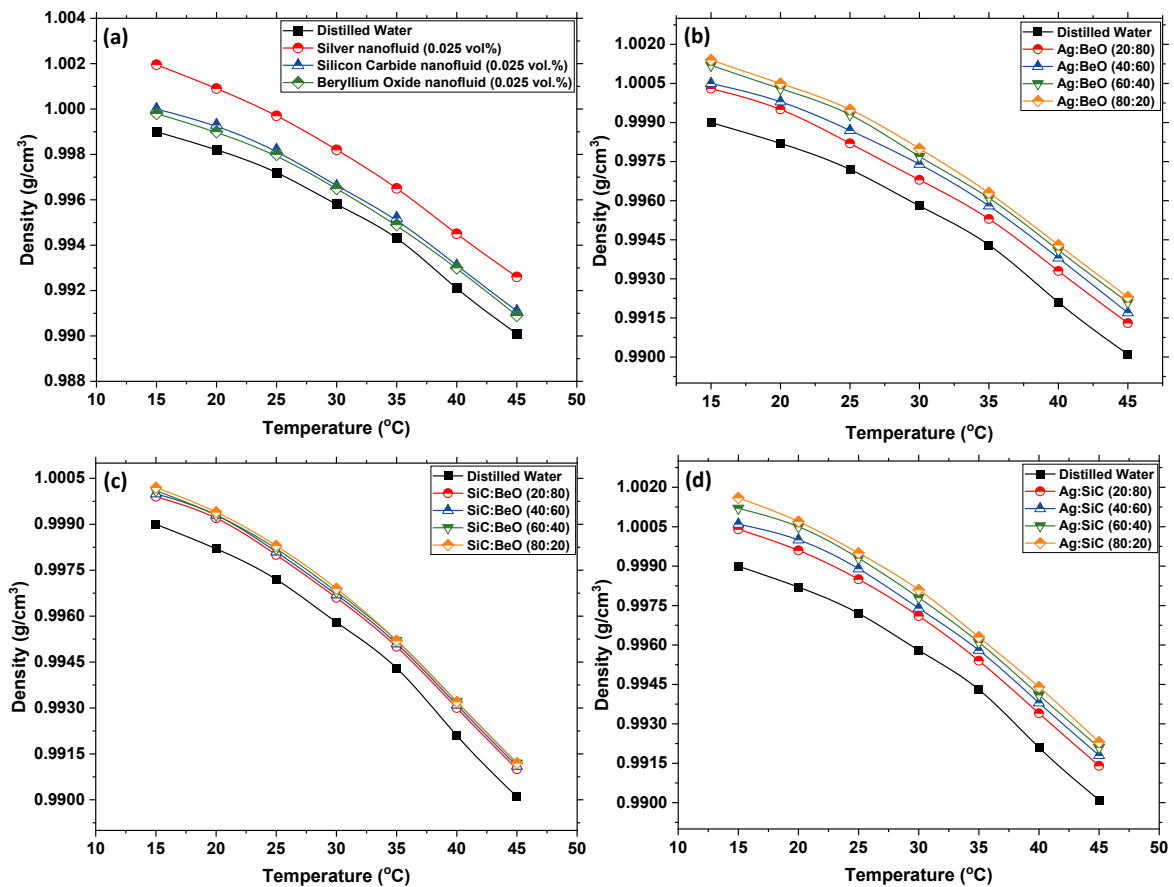


Figure 5.27. Temperature dependence of density for simple and hybrid nanofluid samples.

The density of SiC at the lower end of the temperature range was recorded to be 1.0 g/cm³. With increasing temperature, a consistent decrease in density was observed. At the upper end of the range, at 45 °C, the density had decreased to 0.9911 g/cm³. In comparison to water and BeO nanofluid, SiC exhibited a higher density but lower than that of Ag nanofluid. BeO nanofluid demonstrated a decreasing density trend from 0.9998 at 15 °C to 0.9909 at 45 °C, mirroring trends seen in water, Ag, and SiC nanofluids. Comparatively, its densities were slightly higher than water but lower than Ag and SiC nanofluids over the temperature range.

Figure 5.27(b) presents the density values for the hybrid nanofluids of Ag/BeO with mixing ratios of 20/80, 40/60, 60/40, and 80/20 across various temperatures. Upon analysing the hybrid nanofluid densities, it was observed that the mixing ratios significantly influenced the resulting densities. As the proportion of Ag increased relative to BeO (20/80 to 80/20), there was a discernible trend of increasing density across all temperature points. For instance, at 15 °C, the density of the hybrid nanofluid with a mixing ratio of 20/80 (Ag/BeO) was 1.0003 g/cm³, gradually increasing to 1.0014 g/cm³ for the 80/20 mixing ratio. This indicated that increasing the proportion of Ag in the hybrid nanofluid led to higher overall densities. Similarly, this trend persisted across all temperature points, with the densities of hybrid nanofluids at the 80/20 mixing ratio consistently surpassing those at the 20/80 mixing ratio.

As anticipated, the density of SiC/BeO hybrid nanofluids consistently decreased with rising temperature. However, slight differences in values were observed as the mixing ratio changed, attributed to the slight disparity in the individual densities of SiC and BeO nanoparticles, as depicted in Fig. 5.27(c). The results suggest that the density is more influenced by temperature than the specific mixing ratio of SiC and BeO nanoparticles. At 15 °C, the density of SiC/BeO hybrid nanofluid samples ranged from approximately 0.9999 g/cm³ to 1.0002 g/cm³, while at 45 °C, it decreased to approximately 0.9910 g/cm³ to 0.9912 g/cm³ across all mixing ratios. The density of Ag/SiC nanofluid, when compared to other hybrid nanofluids, generally exhibited higher values across all mixing ratios and temperature points, Fig. 5.27(d). However, there existed only a minor difference between the densities of Ag/SiC and Ag/BeO nanofluids.

Across different mixing ratios, the density of Ag/SiC hybrid nanofluids displayed slight variations, showing an increase in values as the ratio of Ag in the mixture increased. The average percentage increase for nanofluids and their hybrids presented in Fig. 5.28, offers valuable insights into the density rise across various mixing ratios. It is evident that the inclusion of silver nanoparticles notably enhanced the density values, whereas the density variation in SiC/BeO nanofluid was comparatively less significant due to the close density values of the particles themselves.

The results suggested that temperature, the choice of nanoparticles, and mixing ratio for the case of hybrid nanofluids significantly influenced the density, and understanding these variations was crucial for optimising the properties for specific applications.

As part of this study, an analysis was performed using Design Expert and a cubic model was developed to predict density based on temperature variations in various nanofluids, Eq. (5.4). ANOVA analysis

confirmed the model's overall significance ($p < 0.0001$) and the statistical significance of its terms, as presented in Table 5.6.

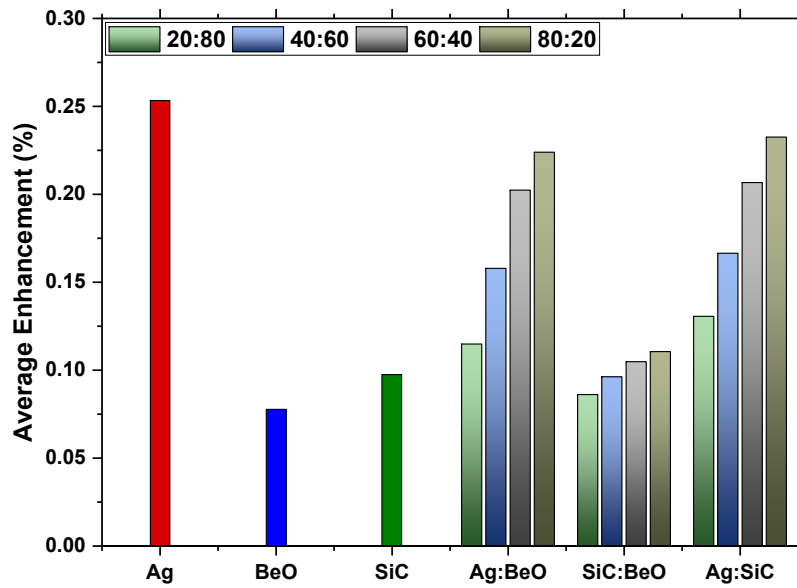


Figure 5.28. Average percentage enhancement in density for various nanofluids and their hybrids compared to the base fluid.

The model's Std. Dev. was calculated to be 0.0001, with an R^2 of 0.9998, indicating its ability to explain 99.98% of density variability. Predicted R^2 (0.9992) is closely aligned with Adjusted R^2 (0.9996), demonstrating consistent predictive power. The C.V. was 0.0065%, and the PRESS value was 8.95E-07, indicating precise predictions.

$$\text{Density } (\rho) = f + gT - h(T^2) + 5.90278 \times 10^{-8}(T^3) \quad (5.4)$$

here f , g , and h denote coefficients representing the intercept, linear coefficient, and quadratic effect of temperature, respectively. Specific values for these coefficients are assigned to each nanofluid sample, as listed in Table 5.7.

Table 5.6. ANOVA for the cubic model of Density.

Source	Sum of Squares	df	Mean Square	F-value	p-value	Significance
Model	0.0011	48	0	5416.8	< 0.0001	Significant
A-Fluid	0	15	3.27E-06	771.68	< 0.0001	
B-Temperature	0.001	1	0.001	2.43E+05	< 0.0001	
AB	3.01E-07	15	2.00E-08	4.73	< 0.0001	
B ²	0	1	0	5325.12	< 0.0001	
AB ²	1.31E-07	15	8.73E-09	2.06	0.0242	
B ³	1.88E-07	1	1.88E-07	44.4	< 0.0001	
Residual	2.67E-07	63	4.24E-09			
Std. Dev.	0.0001		R ²	0.9998		
Mean	0.9966		Adjusted R ²	0.9996		
C.V. %	0.0065		Predicted R ²	0.9992		
PRESS	8.95E-07		Adeq Precision	275.037		

Table 5.7. Coefficients values for the density of various fluid samples.

Sample	f	g	h	Sample	f	g	h
DW	0.998269	0.000199	0.000011	SiC/BeO (20:80)	0.999685	0.00016	0.000011
Ag	1.00262	0.000082	9.43E-06	SiC/BeO (40:60)	0.999785	0.00016	0.000011
SiC	0.999723	0.000165	0.000011	SiC/BeO (60:40)	0.999828	0.000161	0.000011
BeO	0.999421	0.00017	0.000011	SiC/BeO (80:20)	0.999938	0.000163	0.000011
Ag/BeO (20:80)	1.00047	0.000124	9.93E-06	Ag/SiC (20:80)	1.00014	0.000163	0.000011
Ag/BeO (40:60)	0.999771	0.0002	0.000011	Ag/SiC (40:60)	1.00014	0.000184	0.000011
Ag/BeO (60:40)	1.00117	0.000143	0.00001	Ag/SiC (60:40)	1.00114	0.000151	0.000011
Ag/BeO (80:20)	1.00123	0.000154	0.000011	Ag/SiC (80:20)	1.00171	0.000131	0.00001

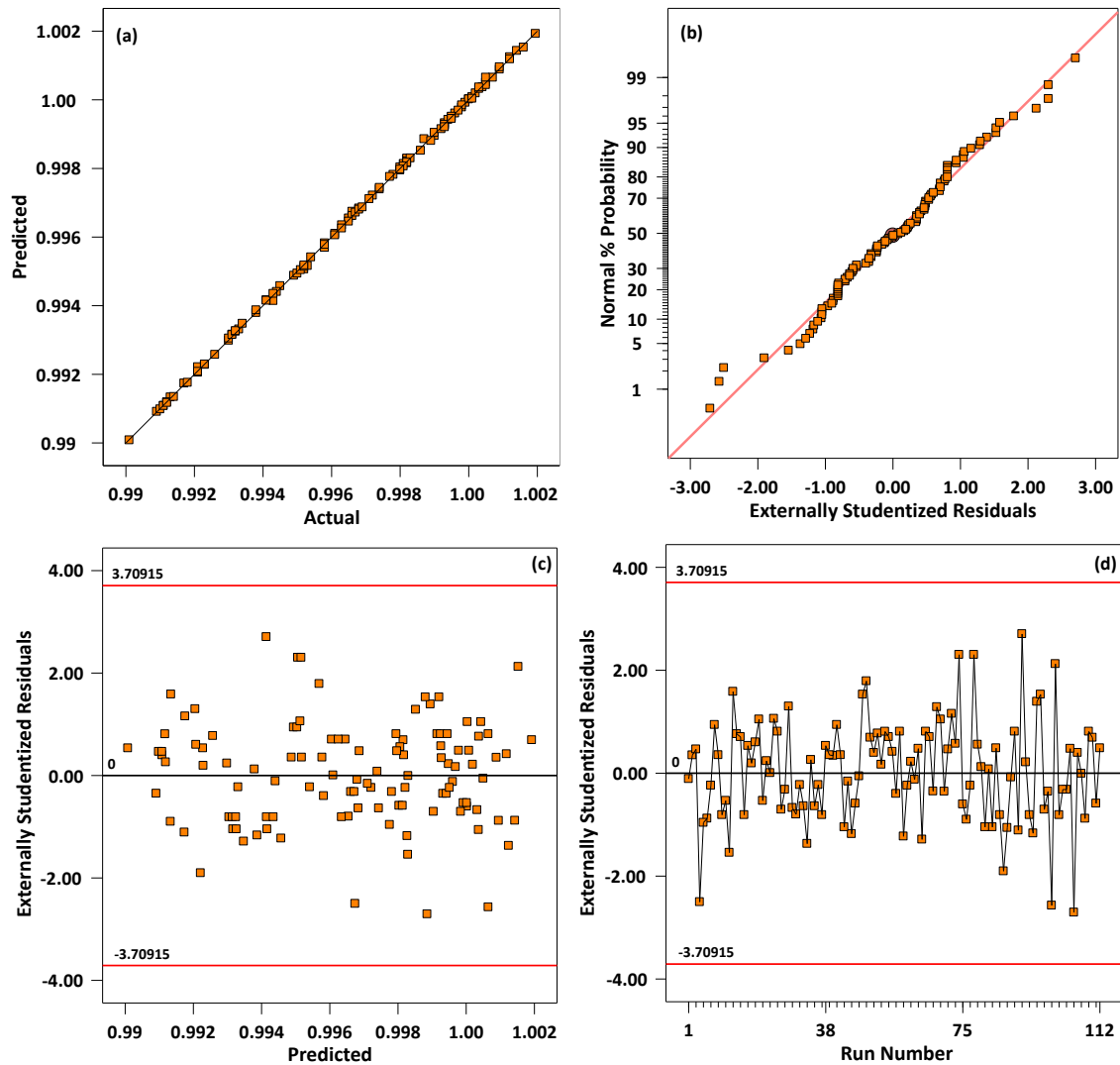


Figure 5.29. (a) Parity plot comparing experimental and predicted density values using the developed cubic model, (b) Normal probability plot of studentized residuals for the density model, (c) Residuals vs predicted values plot for the density model, (d) Externally studentized residuals vs run order plot for the density model.

The comparison between experimental and predicted density values using the ANOVA model revealed a satisfactory fit, with the alignment of points with the diagonal line in Fig. 5.29(a). Additionally, the normal probability plot of studentized residuals, depicted in Fig. 5.29(b), confirmed the normal distribution of errors associated with density values. Residual plots, shown in Fig. 5.29(c) and Fig.

5.29(d), assist in assessing covariance among errors related to independent variables. In this case, no discernible patterns or structures were observed, indicating the presence of covariance among errors.

5.6 Cost Analysis

The cost analysis was conducted to provide insights to investigators and manufacturers regarding the expenses associated with the preparation of various nanofluids and their hybrids. The evaluation takes into account the costs of nanoparticles, surfactants, and base fluid, excluding the costs related to electricity usage during operations such as sonication, stirring, and ultrasonication, as these are consistent across all samples. Moreover, laboratory resource utilization costs were not factored into this analysis.

The results of the cost analysis are depicted in Fig. 5.30, which illustrates the costs of preparing 1000 ml for various samples. Among all the studied fluids, silver nanofluid is the most expensive to prepare due to its particle price, while beryllium oxide and silicon carbide nanofluids are comparatively much cheaper to prepare. This is one of the major reasons why hybrid nanofluids are gaining more attention from the scientific community. The cost difference between beryllium oxide and silicon carbide nanofluids is minimal, although the silicon carbide nanofluid demonstrated better stability.

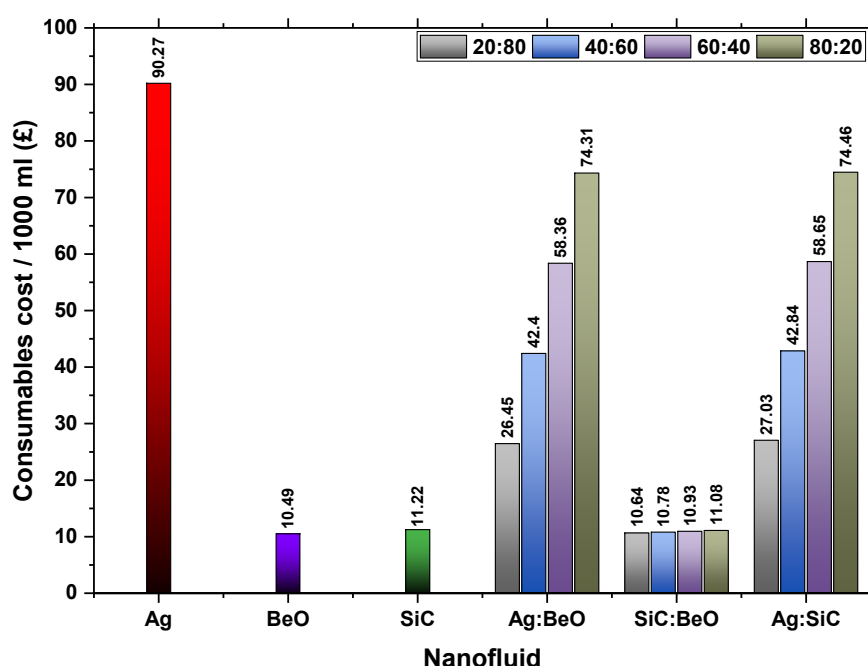


Figure 5.30. Consumables cost per 1000 ml of different nanofluids and their hybrids.

Hybrid nanofluids exhibited varying costs based on mixing ratios. The cost range for hybrid nanofluids of Ag-SiC and Ag-BeO varies between 25 and 75 pounds. However, SiC-BeO hybrid combinations fall within the range of 10.5 to 11.1 pounds across all mixing ratios from 20:80 to 80:20. Notably, the choice of hybrid nanofluid is not solely based on cost, it also considers thermal and rheological characteristics. The results suggest that the Ag-SiC hybrid nanofluid, particularly with a 60:40 mixing ratio stands out

as a good balance of characteristics and cost. The 20:80 and 40:60 ratios are less expensive, while the 80:20 ratio is the most expensive among the Ag-SiC combinations.

The cost analysis reveals that silver nanofluid is the most expensive among the studied fluids. However, the hybrid combinations, such as Ag-SiC and Ag-BeO, exhibit a more favourable cost range. This makes hybrid nanofluids an attractive option for those seeking cost-efficient thermal solutions.

5.7 Conclusion

This study thoroughly examined the thermophysical properties of nanofluids containing silver Ag, BeO, and SiC nanoparticles, with a particular emphasis on hybrid formulations. The results revealed significant improvements in thermal conductivity, viscosity, and density for pure and hybrid nanofluids compared to the base fluid, water. These findings underscore the potential of hybrid nanofluids to advance thermal management systems, offering a promising approach to improving heat transfer efficiency while addressing stability and cost issues. The key outcomes of this study are:

- The addition of surfactants played a crucial role in stabilising nanofluids and altering their pH values. The anionic surfactant SDBS demonstrated superior stability for all three nanofluids (silver, beryllium oxide, and silicon carbide) and consistently increased the pH values toward neutrality. At a particle concentration of 0.01 vol%, the pH values were recorded as 7.2 for Ag, 7.08 for BeO, and 7.45 for SiC, with pH increasing as concentration rose to 0.025 vol%.
- Hybrid nanofluid formulations prepared with different ratios exhibited varying pH trends. The Ag/BeO hybrid showed an increase in pH from 7.25 (20/80) to 7.33 (80/20) with higher Ag concentration, while the SiC/BeO hybrid exhibited a consistent rise from 7.36 (20/80) to 7.59 (80/20) with increasing SiC proportion. Conversely, the Ag/SiC hybrid displayed a decrease in pH from 7.62 (20/80) to 7.41 (80/20) with higher Ag concentration.
- Larger particle sizes, as observed for BeO nanofluid, led to earlier sedimentation and reduced long-term stability despite high zeta potential, while smaller Ag and SiC nanoparticles exhibited better dispersion due to less gravitational settling and aggregation.
- Hybrid nanofluids exhibited smaller agglomerate sizes (192-271 nm) compared to unitary Ag (218.4 nm), BeO (404.3 nm), and SiC (230.9 nm) nanofluids, indicating reduced agglomeration tendency due to the presence of different nanoparticles and uneven attractive forces in the hybrid suspension. Notably, SiC nanoparticles demonstrated a unique tendency to form agglomerates in the form of chains, with connections between particles appearing weaker compared to those observed in Ag and BeO nanoparticles.
- The thermal conductivity of the simple nanofluids increased with increasing particle concentration from 0.01 vol% to 0.025 vol%, with the silver nanofluid exhibiting the highest thermal conductivity enhancement of 6.95% at 0.025 vol% and 45 °C. Hybrid nanofluids also outperformed water, with the Ag/SiC (60/40) formulation demonstrating the maximum enhancement of 7.43% at 45°C.

- Nanofluids exhibited Newtonian behaviour, characterised by a linear relationship between shear stress and shear rate. Additionally, the viscosity of these nanofluids increased with nanoparticle concentrations due to increased internal resistance to flow. SiC nanoparticles, which had a more irregular shape and sharp edges, exhibited the highest viscosity among the unitary nanofluids, likely due to their ability to disrupt fluid flow more effectively.
- Among the hybrid nanofluids, Ag/SiC exhibited the highest average viscosity enhancement, ranging from 4.27% to 4.90% across different mixing ratios. The Ag/BeO hybrids showed a 3.00% to 4.29% increase, while SiC/BeO hybrids demonstrated a 3.15% to 4.63% enhancement compared to the base fluid. The extent of viscosity increase was influenced by the mixing ratio and the type of nanoparticles present.
- Silver nanofluids exhibited the most substantial increase in density, with the enhancement becoming more pronounced as particle loading increased. In the case of hybrid Ag/BeO nanofluids, the density increased with higher Ag ratios. However, Ag/SiC hybrid nanofluids generally exhibited the highest density values among all hybrid formulations, with the 80/20 Ag/SiC ratio reaching 1.0016 g/cm³ at 15 °C.
- Advanced statistical analyses, including ANOVA, yielded highly accurate models for predicting nanofluid thermal conductivity, viscosity, and density, with strong R² values and close alignment between experimental and predicted results.
- The cost analysis revealed that silver Ag nanofluid is the most expensive option among the studied nanofluids, with a cost of £90.27 per 1000 ml, due to the high cost of silver nanoparticles. Hybrid nanofluids, like Ag-SiC and Ag-BeO, cost between £25 and £75 per 1000 ml, offering a more economical alternative to pure silver nanofluid while potentially providing favourable thermal and rheological properties.

The study highlights the potential of hybrid nanofluids to revolutionize thermal management systems by offering a balanced trade-off between improved thermophysical properties and economic considerations. The Ag-SiC (60:40) hybrid nanofluid, in particular, emerged as a promising candidate, balancing performance and cost. Future research should focus on the long-term stability of these nanofluids and their practical applications in various industries to fully harness their potential in enhancing heat transfer efficiency and addressing energy challenges.

CHAPTER 6

6 Thermophysical and Performance Characteristics of Walled Carbon nanotubes (MWCNTs), Silver (Ag), and Aluminium Nitride (AlN) based Hybrid Nanofluids

In the previous chapter, the focus was placed on the thermophysical characterisation of mono and binary nanofluids containing silver, beryllium oxide, and silicon carbide. This chapter extends the previous findings by exploring new nanoparticle combinations, including tri-hybrid formulations, offering deeper insight into the trade-offs between thermal performance, stability, more complex set of particle interactions, and economic viability.

The current study presents an in-depth experimental investigation into the thermophysical behaviour, colloidal stability, and economic feasibility of hybrid and tri-hybrid nanofluids composed of multi-walled carbon nanotubes (MWCNTs), silver (Ag), and aluminium nitride (AlN). The study examines a variety of formulations prepared using different volumetric mixing ratios and explores the effect of various surfactants on the stability and performance of the suspensions.

While some of the concepts and procedures described here may resemble those introduced in earlier chapter, their repetition is intentional. Although the overall methodology such as the nanofluid preparation technique remains consistent, variations in operational parameters, observation periods, and analytical focus set this study apart, making it necessary to include a dedicated methodology discussion. For instance, while the two-step preparation method is employed again, differences in sonication time, mixing protocols, and stability monitoring duration are specific to the current formulations. This chapter has been structured as a self-contained study, allowing readers especially those interested solely in this work to access all necessary information without needing to reference the rest of the thesis. This approach ensures clarity and continuity for both integrated and standalone reading experiences.

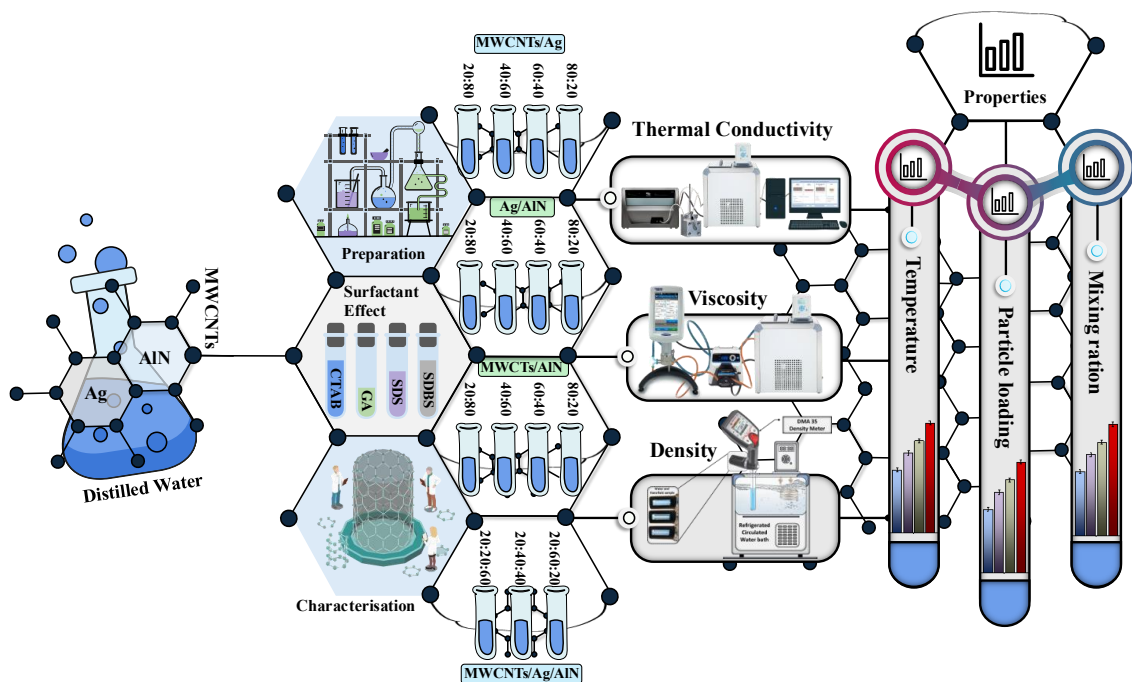
The prepared nanofluid formulations were characterised over a temperature range of 20 to 45 °C, and parameters such as thermal conductivity, viscosity, density, and zeta potential were measured to evaluate their potential for high-efficiency cooling applications. Additionally, cost considerations were analysed to guide the practical selection of nanoparticle combinations. The results presented in this chapter not only contribute to the broader understanding of hybrid nanofluid design but also offer guidance on the trade-offs between thermal performance, stability, and economic viability.

Abstract

Hybrid nanofluids are transforming the field of thermal management by significantly enhancing heat transfer efficiency through the synergistic interactions of different nanoparticles. This study meticulously investigates the effect of volumetric ratios and surfactant effects on the colloidal stability,

heat transfer characteristics, and cost-effectiveness of hybrid and tri-hybrid nanofluids comprising multi-walled carbon nanotubes (MWCNTs), silver (Ag), and aluminium nitride (AlN). Various formulations were prepared with volumetric ratios of 80:20, 60:40, 40:60, and 20:80 for hybrid combinations, and 20/20/60, 20/40/40, and 20/60/20 for tri-hybrid mixtures, and analysed over a temperature range of 20 to 45 °C. The effectiveness of surfactants, including sodium dodecyl sulfate (SDS), cetyltrimethylammonium bromide (CTAB), gum arabic (GA), and sodium dodecyl benzene sulfonate (SDBS), was evaluated for maintaining the stability of the nanoparticle dispersions. Experimental results revealed that SDBS consistently outperformed the others, by maintaining a stable suspension and thus preserving the enhanced thermal properties over extended periods. It was found that, among the nanofluids investigated, MWCNTs exhibited the highest thermal conductivity enhancement of 8.57%. The tri-hybrid nanofluid with a 20/60/20 MWCNTs/Ag/AlN ratio achieved a comparable enhancement of 8.14%, demonstrating that optimised nanoparticle combinations can provide excellent thermal properties, stability, and cost-efficiency. However, this tri-hybrid formulation also showed the highest viscosity increase noted to be 5.55%, compared to a 4.43% increase for simple Ag nanofluids. Additionally, the highest density increase was 0.25% for Ag nanofluid while among hybrid formulations the maximum was 0.22% % observed for 80/20 Ag/AlN. Finally, among tri-hybrid formulations, the 20/60/20 ratio had the highest increase at 0.19%, while the 20/40/40 ratio showed a more moderate increase. Cost analysis indicated that the tri-hybrid nanofluid with a 20/40/40 ratio is the most cost-effective option when cost considerations are as important as thermal performance. However, for applications where maximising thermal performance is crucial, the tri-hybrid with a 20/60/20 ratio is the preferred choice.

Graphical Abstract



6.1 Introduction

Researchers are actively exploring hybrid systems that combine different cooling strategies to optimise heat transfer efficiency [296–298]. Alongside efforts to design more efficient heat sinks, there has been a continuous push to develop thermal coolants with improved thermophysical properties. Hybrid nanofluids (HNFs), which incorporate two or more types of nanoparticles, offer even greater potential by combining the distinct properties of different materials to improve heat transfer.

This study focuses on a comprehensive exploration of the thermophysical characteristics of the hybrid and tri-hybrid nanofluids containing MWCNTs, AlN, and Ag nanoparticles. These nanoparticles, known for their unique properties, offer a synergistic effect when combined, potentially delivering superior thermal conductivity (TC), stability, and overall heat transfer capability. Understanding the behaviour of such complex nanofluids under varying conditions is crucial for optimising their application in high-performance cooling systems for electronics, data centres, and energy storage systems.

The field of nanofluids is inherently complex, as their thermophysical properties are influenced by a multitude of factors. Stability remains a significant challenge in the effective application of nanofluids, as agglomeration and sedimentation can severely hinder performance. Therefore, experimental investigations have become increasingly vital to understanding and optimising these materials. By systematically analysing the effects of various additives, surfactants, and preparation methods, researchers aim to enhance the stability and heat transfer characteristics of nanofluids, paving the way for their successful integration into advanced thermal management solutions. Xian et al. [299] examined the influence of various surfactants and ultrasonication duration on the stability and thermophysical properties of HNFs, using the two-step method to disperse titania (TiO_2) and graphene nanoplatelets (GnPs) in a water/ethylene glycol (W/EG) mixture. Their findings revealed that the addition of hexadecyltrimethylammonium bromide (CTAB) significantly enhanced stability, with minimal sedimentation observed over a 40-day period. The study also varied the sonication time between 15 and 90 minutes, revealing that longer sonication times further enhanced stability. Furthermore, thermal conductivity measurements exhibited a maximum enhancement of 23.74% when 0.1 wt% of carboxyl-functionalized GnPs was incorporated at 60°C, demonstrating that hybrid nanofluids outperformed their mono counterparts across varying concentrations and temperatures. Their findings suggested that the hybrid nanofluids possess promising properties for applications in heat transfer systems. Tiwari et al. [300] conducted an experimental study on CeO_2 -MWCNT/water hybrid nanofluid, examining synthesis, surfactant, sonication, and stability (4S consideration). The nanofluid was prepared using a two-step method, with varying ultrasonication times (30 to 180 minutes) and six different surfactants (anionic, cationic, and polymeric) tested at different nanoparticle-to-surfactant ratios. They concluded that optimal conditions for long-term stability included a surfactant-to-nanoparticle ratio of 3:2, a pH of 9.5, and 90 minutes of sonication, which produced the highest zeta potential. The CTAB surfactant

provided the best stability for up to 30 days, while the sodium dodecyl benzenesulfonate (SDBS) surfactant exhibited superior stability beyond that timeframe. A correlation between hybrid stabilization and thermal conductivity was observed, indicating that excessive surfactant reduced conductivity. Additionally, the impact of surfactants on surface tension was also investigated and proposed a correlation for predicting thermal conductivity values. Kumar et al. [301] prepared the hybrid nanofluid with the aim to improve the thermal conductivity of CuO/water nanofluids, which suffer from poor conductivity due to the stability and morphology of CuO nanoparticles. They proposed a novel strategy of mixing polyhedron-shaped MgO nanoparticles with CuO nanoparticles to enhance the thermal conductivity of the resulting nanofluid. The study used a CuO/MgO with a weight ratio of 7:3 and investigated volume fractions ranging from 0.25% to 1.5% in water at temperatures between 30°C and 55°C. A two-step approach was adopted for nanofluid preparation and conducted various analyses, including XRD and stability examinations, to characterise the nanoparticles and ensure the quality of the nanofluid. The findings demonstrated a notable improvement in thermal conductivity, particularly at higher temperatures, with a 12.5% increase observed at 55°C and a volume fraction of 1.5%. Mane et al. [302] studied the electrical conductivity of water-based nanofluids containing CuO, Fe₃O₄, and hybrid CuO/Fe₃O₄ nanoparticles, stabilized with biopolymer dispersants (gum arabica and chitosan) and a synthetic dispersant (SDBS). Nanofluids were prepared with a 0.1 wt% nanoparticle concentration and dispersant concentrations of 0.05 and 0.5 wt%, and electrical conductivity was measured over a temperature range of 25°C to 40°C. The results showed dispersants significantly influenced conductivity, while nanoparticle type had little effect. SDBS-stabilized nanofluids at 0.5 wt% showed conductivity 708.7 times more than the base fluid, while chitosan and gum arabic-stabilized nanofluids exhibited conductivities 144.2 and 12.8 times higher, respectively. Additionally, quadratic nonlinear polynomial equations were developed using response surface methodology (RSM) to predict conductivity, offering key insights into the electrical behaviour of biopolymer-stabilized nanofluids. Artificial neural networks (ANN) have been widely implemented across various research fields, including nanofluids, to predict their properties and heat transfer characteristics for diverse applications. Kumar et al. [303] carried out an experimental and artificial neural network (ANN) analysis on the thermophysical properties of oxide-MWCNT water hybrid nanofluids. HNFs were prepared by mixing water-based metal oxide nanofluids (ZnO, Al₂O₃, CeO₂, and TiO₂) with MWCNT nanofluids in an 80:20 volumetric ratio. The study tested nanofluid concentrations from 0.25% to 2.0% and temperatures ranging from 25°C to 50°C and measured key thermophysical properties such as dynamic viscosity, density, thermal conductivity, and specific heat. According to the results, the MWCNT-CeO₂/water HNF showed the best performance, with superior thermophysical properties and the highest Mouromtseff number. This highlights the significance of selecting the appropriate pair of nanoparticles. In addition, to predict the properties, a hyperparameter-optimised ANN model was developed, which showed excellent accuracy when compared to experimental data, with correlation coefficients over 0.999, mean square errors below 0.001, and deviations within ±5%. Said et al. [304] investigated the

synthesis, thermophysical properties, and stability of HNFs composed of Fe_3O_4 -coated MWCNTs through an AI approach for predictive modelling. The researchers employed an in-situ growth method combined with chemical reduction to synthesise the Fe_3O_4 -coated MWCNTs, and they validated their findings using X-ray diffraction, vibrating sample magnetometry, and scanning electron microscopy (SEM) techniques. They found that the highest zeta potential value of -48 mV was achieved at a 0.05% concentration. At 0.3% concentration, thermal conductivity improved by 13.78% and 28.33% at 20°C and 60°C, respectively, compared to water, while viscosity rose by 27.83% and 50%, respectively. Multi-Layer Perceptron ANN was utilised to model the relationships between temperature, concentration, and thermophysical properties. The model demonstrated high accuracy, effectively replicating experimental results across various conditions and highlighting the potential of AI in advancing the understanding of hybrid nanofluids for enhanced thermal management solutions.

The realm of nanofluid investigation has witnessed a noteworthy expansion in the last twenty years, as demonstrated by data in publications from the Scopus database, as shown in Fig. 6.1. In 2005, there were only 63 studies, but by 2023, this number had soared to 4666. This exponential growth trajectory is not merely a numbers game; it reflects the scientific community's recognition of nanofluids' enhanced thermal properties and their potential to revolutionise various applications. The steady rise in nanofluid publications suggests that investigators are still in the process of unlocking their full potential. Each new study seems to push the boundaries, whether it's optimising performance, exploring new application areas, or addressing challenges like cost, long-term stability, and scalability.

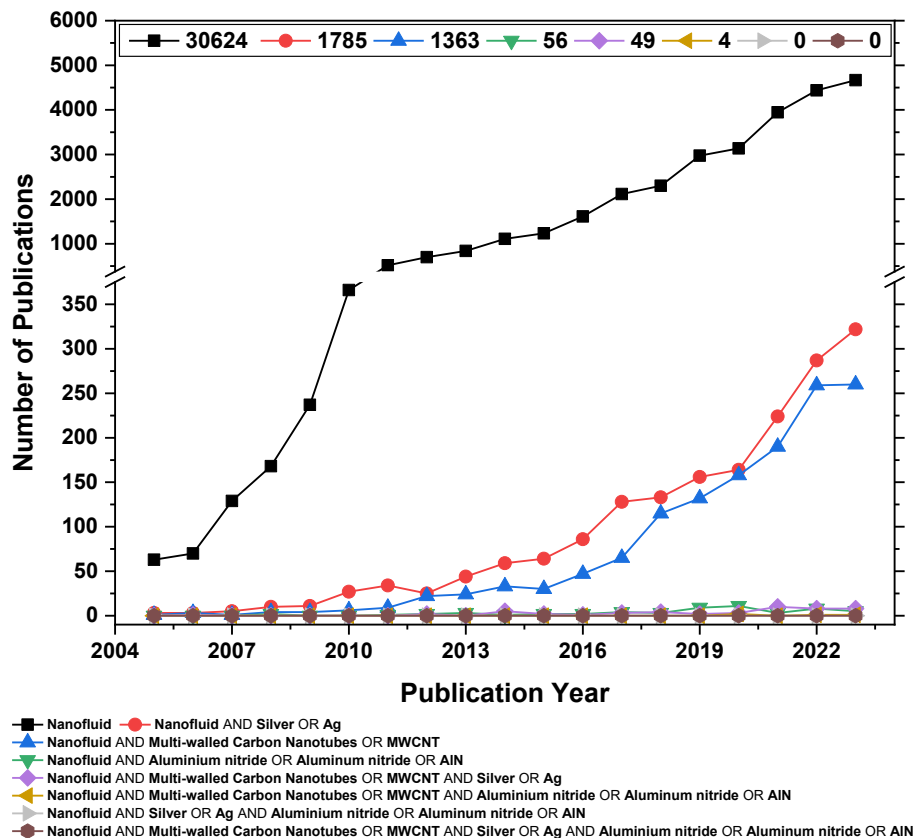


Figure 6.1. Number of nanofluid publications from 2004 to 2022 based on the Scopus database.

This study has not been confined to a single type of nanofluid but has expanded to include various categories: silver belonging to the metallic group, aluminium nitride from the category of nitrides, and multi-walled carbon nanotubes derived from carbon materials, each with its unique properties, limitations, and potential uses.

Silver nanoparticles are considered to be investigated in this study for their excellent thermal conductivity and antimicrobial properties, making them suitable for applications in thermal management and biomedical fields. As per statistics from Scopus, further filtered with “Silver” or “Ag” it was noticed that the Ag nanofluid gained significant attention over the years, with research publications increasing from 3 in 2005 to 322 in 2023. The steady rise in publications suggests ongoing exploration and optimisation of silver nanofluids to enhance their performance and broaden their application scope. Multi-Walled Carbon Nanotubes are known for their superior thermal conductivity and lower density, which can significantly enhance the heat transfer capabilities of nanofluids. In 2005, only one research study was documented on MWCNT's, however, by 2023, the number of studies had surged to 260, indicating a substantial rise in researchers' interest. Despite their superior thermal conductivity, MWCNTs face limitations, including high production costs and challenges with percolation network formation. The costliness of MWCNTs and the difficulty in breaking their percolation networks can hinder their practical application in nanofluids.

Aluminium Nitride (AlN) nanofluids have also been a subject of research, with the number of studies peaking at 11 in 2020 before slightly decreasing to 5 in 2023. AlN nanoparticles offer high thermal conductivity compared to oxides and many other nitrides and carbides, lower density, and are cost-effective, making these particles ideal as one of the potential candidates for hybrid nanofluids. These particles could be used in combination with particles that have higher thermal conductivity but face issues with stability and high cost. This underscores the significance of hybrid nanofluids, which combine particles with complementary properties to overcome individual limitations. Appendix B, Table B.3 offers an overview of additional studies on nanofluids, highlighting the different nanoparticles, base fluids, and surfactants investigated, along with the objectives and key findings of each research effort.

The introduction of hybrid nanofluids marks a novel approach in nanofluid research, offer versatility, tunability, and potential for improved thermal management by tailoring nanoparticle combinations. Finally, the results were further refined to include multiple particle types for analysing hybrid nanofluids. According to the findings, only a few studies have reported on MWCNTs-Ag hybrid nanofluids, while some have examined AlN and MWCNTs individually but not their hybrid combination. To date, there is no study reported on the Ag-AlN hybrid and tri-hybrid of MWCNT-Ag-AlN. This study aims to bridge the existing research gap by thoroughly investigating the thermal conductivity, viscosity, and density of nanofluids in both simple and hybrid forms, with the goal of improving thermal properties and stability while reducing costs. By overcoming the limitations of individual nanoparticles, this research will explore their synergistic behaviour in hybrid and tri-hybrid

combinations. The results will highlight the critical role of nanoparticle type, concentration, and mixing ratio in optimising the thermophysical properties of these fluids. This research is expected to contribute significantly to the body of knowledge in the field, providing practical insights that can be applied across various scientific and engineering disciplines. The findings could have a far-reaching impact, offering solutions that enhance both theoretical understanding and real-world applications.

Unlike many previous studies that limit their scope to thermal enhancement or basic formulation, this work adopts a more holistic approach that combines stability optimisation, thermophysical evaluation, and cost-performance analysis of hybrid and tri-hybrid nanofluids. The methodology begins with a systematic comparison of widely used surfactants (SDS, CTAB, GA, and SDBS) across different nanoparticle types to determine the most effective stabilising agent for long-term dispersion. In addition to surfactant screening, a detailed study was conducted to examine the effects of varying particle concentrations (0.01–0.03 vol.%) on both the pH behaviour and colloidal stability of the nanofluids over time. This allowed for the identification of optimal concentrations that balance thermal enhancement with long-term suspension stability, an often neglected but critical aspect for real-world deployment. Moving beyond simple or binary formulations, this study introduces novel tri-hybrid nanofluids (MWCNTs/Ag/AlN), enabling the exploitation of synergistic interactions among different nanoparticles to simultaneously improve thermal conductivity, stability, and cost-effectiveness. The prepared fluids were comprehensively characterised not only for thermal conductivity but also for viscosity, density, and pH within a practical temperature range. A comparative cost-performance analysis was also conducted, providing valuable insights into the economic viability of each formulation. Altogether, the methodology established in this study offers a robust and transferable framework for the development of advanced nanofluids, making it highly relevant for next-generation thermal management applications in electronics, energy systems, and transportation technologies.

6.2 Nanofluid preparation

The two-step method was employed in this study to prepare various simple, hybrid, and tri-hybrid nanofluid samples. However, prior to formulating the samples to analyse their thermophysical properties, a comprehensive study was carried out to examine the effects of different surfactants and particle concentrations on the stability of Ag, AlN, and MWCNT's nanofluids. This preliminary investigation was conducted to select the most appropriate surfactant and particle concentration for subsequent experiments.

To investigate the impact of surfactants, initial samples of Ag, AlN, and MWCNT nanofluids were prepared with a particle concentration of 0.01 vol.%. In the subsequent phase, particle concentrations were varied from 0.01 vol.% to 0.03 vol.% and observed sedimentation over time. Following the selection of suitable surfactants and particle concentrations, simple, hybrid, and trihybrid nanofluid samples were prepared. These samples were then used to further investigate thermal and rheological properties at various temperatures. The nanoparticles used in this experimental investigation were

purchased from well-known suppliers, Sigma-Aldrich and Alfa Aesar. Table 6.1 provides detailed information on their cost, size, density, thermal conductivity, and purity. To ensure the homogeneity and stability, a series of preparation processes were employed. These processes included magnetic stirring, surfactant addition, bath sonication, and high-intensity probe sonication.

To determine the required mass of nanoparticles corresponding to a specific particle concentration (ϕ), the widely used volume fraction equation, previously introduced in Eq. (4.1) of Chapter 4, was employed. Analytical balance was used to weight the particles prior to adding them in the basefluid water while continuously performing the stirring operation.

At this stage, the surfactant was also introduced in an amount equal to that of the particles. The solution was stirred for 1 hour using a magnetic stirrer, followed by sonication in a bath for another hour. Subsequently, the processed solution was ultrasonicated for 1.5 hours using a SONICS probe sonicator, set to 50% amplitude with a pulse sequence of 3 seconds ON and 2 seconds OFF. As the nanoparticles are suspended in the fluid, they tend to agglomerate and form clusters. The sonication process helps to break up these clusters, while stirring ensures a more uniform suspension. To prevent an increase in temperature due to sonication, the sample was kept in a water bath.

For hybrid and tri-hybrid nanofluids, each component fluid was prepared separately following the above steps, then the measured volumes were mixed while stirring. The hybrid solution was further ultrasonicated for 30 minutes with a probe sonicator to ensure a more homogeneous suspension. Figure 6.2 illustrates the steps followed to prepare the simple and hybrid nanofluid samples.



Figure 6.2. Schematic diagram of nanofluid preparation steps for simple and hybrid samples.

Table 6.1. Properties of the particles.

Nanoparticle	Formula	Density (g/cm ³)	Size	Purity	Thermal Conductivity (W/m.K)	Cost (£)*	Quantity (g)	Reference
Carbon nanotube, multi-walled	MWCNTs	2.1	O.D. × L 6-13 nm × 2.5-20 µm	> 98%	3000	1590	10	[305]
Silver	Ag	10.5	10-40 nm	99.9%	429	386	10	[306]
Aluminum Nitride	AlN	3.26	< 100 nm	—	285	119	10	[307,308]

**Prices as of June 12th, 2024*

6.3 Stability and pH characteristics

6.3.1 Effect of Surfactants

To select suitable surfactant and concentration for preparing both simple and hybrid samples, a study was conducted to assess the stability of AlN, MWCNTs, and Ag nanofluids across various concentrations and introducing different surfactants. Four types of surfactants SDS, GA, SDBA, and CTAB were chosen to investigate their impact on sample stability. Surfactants are known for their ability to induce electrostatic or steric repulsion forces among nanoparticles, which effectively prevent their undesirable agglomeration. This strategic use of surfactants plays a crucial role in maintaining the stability of nanofluid systems. A number of studies reported that the use of appropriate surfactant can improve the stability of the nanofluids.

This phase of the study involved monitoring the settling of particles in the base fluid over time. Furthermore, changes in pH values were analysed following the addition of surfactants and varying particle concentration. To measure the pH value, a Hanna pH meter (Model HI 98128) was utilised, accompanied by its calibration certificate. Additional calibration steps were undertaken to ensure precise pH measurements, these procedures are detailed in Chapter 5, Section 5.3. Following calibration, pH measurements of a neutral solution were conducted to validate accuracy.

To mitigate the influence of temperature fluctuations on pH measurements, each sample was kept in a thermal bath maintained at a constant temperature of 20°C, as depicted in Fig. 6.3. This controlled environment ensured consistent temperature conditions for accurate pH readings. Additionally, to minimise measurement variability, pH values were recorded three times for each sample.

The preparation of nanofluid samples involved rigorous processes including magnetic stirring and sonication, conducted within a fume cabinet to maintain safety and minimise contamination. These procedures exposed the fluid to atmospheric air. The setup for pH value determination was also conducted in an open environment. Under these conditions, the pH of the distilled water typically ranged between 5.4 and 5.7 [252]. As anticipated, in this study, pH of the base fluid was found to be 5.69±0.01. To study the impact of various surfactants on the stability, AlN, MWCNT's, and Ag nanofluids were prepared with a particle concentration of 0.01 vol.%. It was observed that the addition of nanoparticles

significantly affected the pH of the fluid, and the surfactants interacted differently with various particles, as shown in Fig. 6.4. Distilled water, used as the baseline in this study, exhibited an initial pH of 5.69. The introduction of silver nanoparticles increased the pH to 6.24. The addition of surfactants to the silver nanofluid further modified the pH, demonstrating the unique interactions between the surfactants and the nanoparticles. CTAB and SDS slightly lowered the pH to 6.1 and 5.85 respectively, while GA caused a more significant drop to 5.58. Notably, SDBS exhibited a unique behaviour by dramatically increasing the pH to 7.2, thereby making the silver nanofluid the most alkaline among those tested.

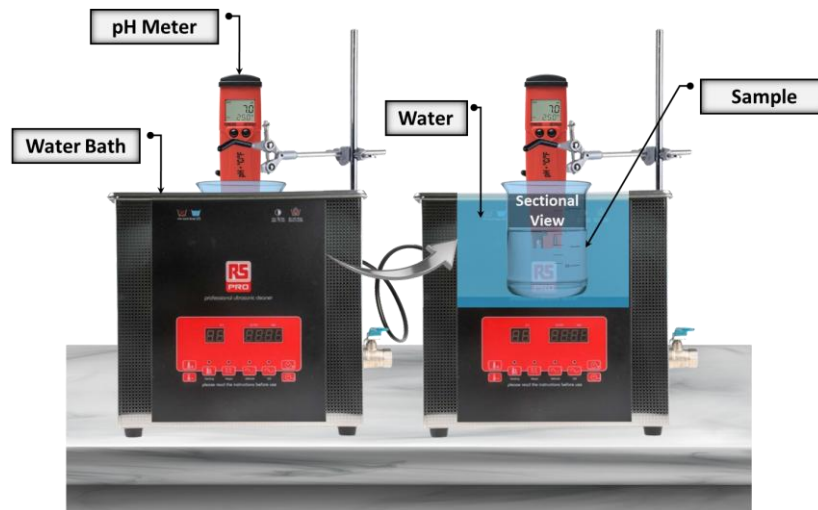


Figure 6.3. Setup for pH measurement of nanofluid samples in a thermal bath.

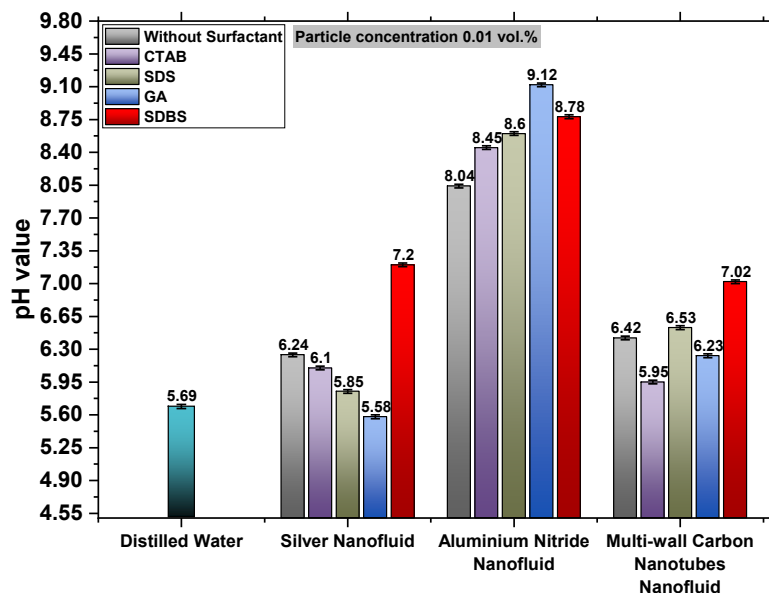


Figure 6.4. pH values of AIN, MWCNT, and Ag nanofluids with different surfactants at 0.01 vol% concentration.

The AIN nanofluid demonstrated a markedly different behaviour compared to the silver nanofluid. Without any surfactants, the AIN nanofluid had a notably high pH of 8.04. CTAB raised the pH to 8.45, while SDS pushed it slightly higher to 8.6. GA had the most pronounced effect, elevating the pH

substantially to 9.12. SDBS also significantly increased the alkalinity of the AlN nanofluid, though not to the extent of GA, reaching a pH of 8.78. The MWCNT nanofluid presented another distinct pH profile, highlighting the diverse behaviour of different nanomaterials in aqueous solutions. The solution had pH value measured to be 6.42 notably higher than the basefluid distilled water, however, like Ag and AlN the introduction of surfactants altered this pH in various ways. CTAB and GA lowered the pH value to 5.95 and 6.23 respectively, while SDS slightly increased it to 6.53. SDBS, consistent with its behaviour in the silver nanofluid, significantly increased the pH to 7.02. This alkalizing effect of SDBS across different nanomaterials was a notable trend, possibly related to its strong anionic character and its unique interaction with various nanoparticle surfaces. Consistent with its behaviour in the silver nanofluid, SDBS significantly increased the pH of the MWCNT nanofluid to 7.02, highlighting its strong alkaline effect.

The surfactant study revealed that while some surfactants improved the stability of the nanofluid, others had an adverse effect, reducing particle suspension stability. Over the course of a week, the nanofluid samples were examined to analyse particle sedimentation behaviour with the addition of different surfactants. It was observed that AlN nanosheets tended to agglomerate and form clusters, which began to settle after 24 hours. By the end of the observation period, complete particle settling had occurred in these samples, leading to the conclusion that SDS was unsuitable for use with AlN nanopowder.

Furthermore, the sample with CTAB surfactant showed signs of instability. The top layers of this sample began to clarify as the particles started to settle down, as shown in Fig. 6.5. The sample with GA surfactant showed improved stability over CTAB and SDS, however, the AlN sample containing SDBS surfactant outperformed all and exhibited better stability. The particles in this sample remained suspended for a longer duration, indicating that SDBS can enhance the stability of AlN nanofluids. For this study, samples were processed with 30 minutes of stirring and 1 hour of probe sonication to specifically examine the effects of surfactants. It is important to note that fluids prepared for property studies were processed for a longer duration.

For silver nanofluid, it was observed that sample without surfactant exhibited relatively poor stability. When comparing various surfactants, samples prepared with SDS and GA showed particles starting to settle down earlier than others. Introducing cationic surfactants resulted in a noticeable change in the fluid's colour and a significant decrease in pH value. Among the surfactants tested, CTAB demonstrated an improvement in the stability of the nanofluid. However, SDBS outperformed all other surfactants, maintaining the suspension's stability for a longer period. Thus, SDBS proved to be the most effective surfactant in enhancing the stability of the silver nanofluid.

The significance of surfactants is further underscored by the poor stability observed in MWCNT sample prepared without surfactant. The settling of particles is easily observed in the sample without surfactant, as the fluid's top layers start to clear. However, due to the dark colour of the suspension, it is somewhat challenging to observe sedimentation and agglomeration of particles in the samples containing surfactants. A glass pipette observation method was used to examine the aggregation of particles at this

stage, as depicted in Fig. 6.6. Additionally, TEM analysis was employed to assess the aggregation of particles in the subsequent section.

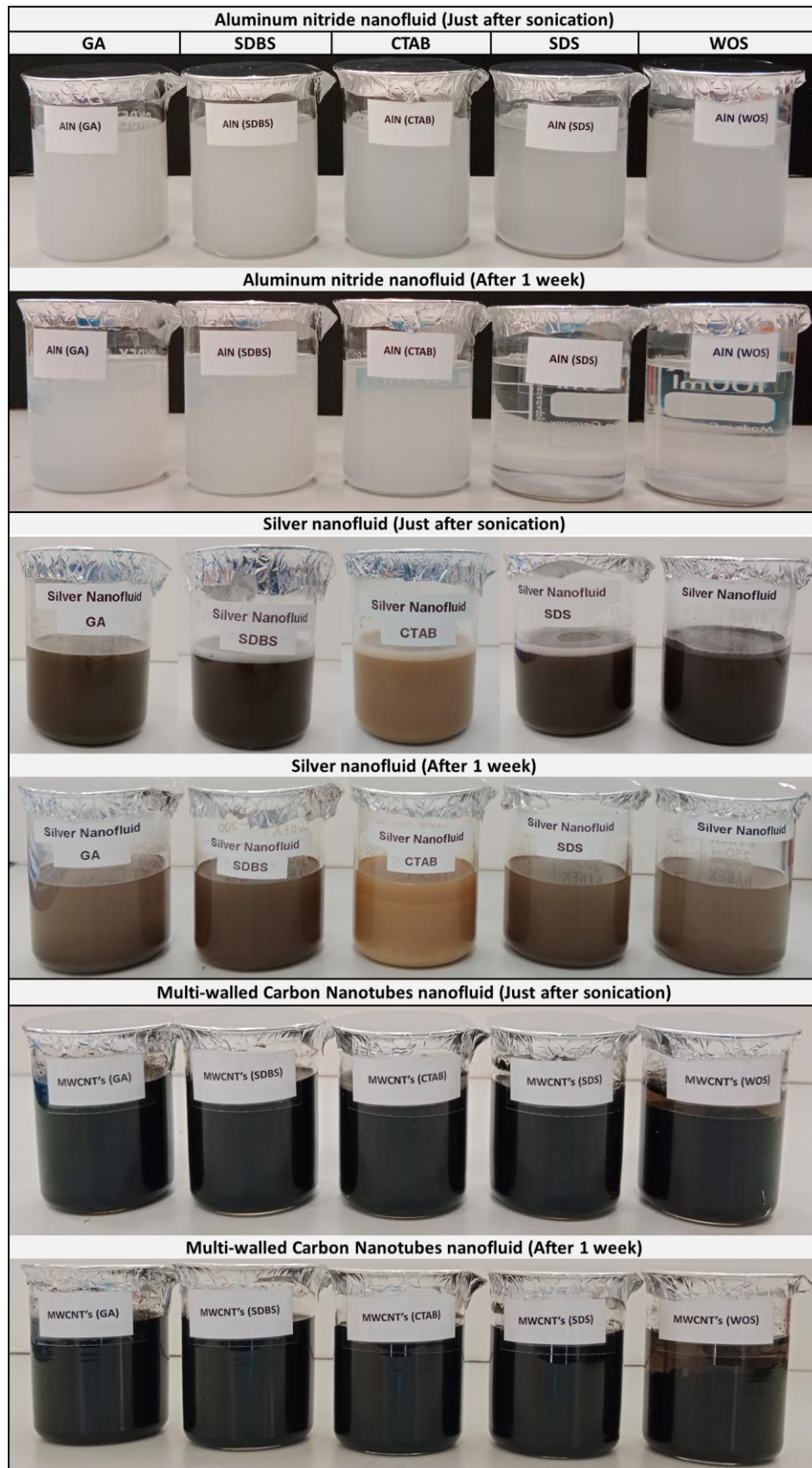


Figure 6.5. Sedimentation observation of nanofluid samples with different surfactants.

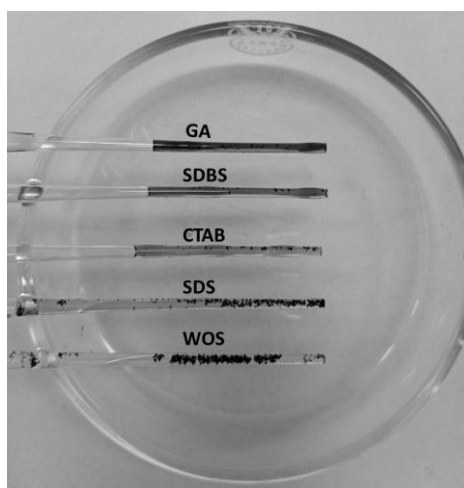


Figure 6.6. Glass pipette observation method for examining particle aggregation in MWCNT samples.

Among the surfactants tested, SDS demonstrated inadequate performance in stabilizing the particles, whereas SDBS and GA significantly enhanced suspension stability and reduced aggregate formation. The CTAB surfactant offered better stability than SDS, but it was not as effective as SDBS and GA. Prolonged observation further confirmed that SDBS is the most suitable surfactant for improving the stability of MWCNT suspensions. Additionally, the density of MWCNT's is relatively low, which allows small aggregates to remain suspended in the fluid rather than settling at the bottom. This low density contributes to the stability of the suspension, as the lighter aggregates are less prone to sedimentation. Conversely, Ag nanoparticles have a density that is approximately five times greater than that of MWCNTs. This significant difference in density means that silver nanoparticles have a much stronger tendency to settle at the bottom of the base fluid. This difference in density and the resultant sedimentation tendencies highlight the importance of considering particle characteristics.

Importantly, it has been observed that after the sedimentation or aggregation of particles in the base fluid, the solution containing AlN and MWCNT's requires significantly more sonication processing time to achieve uniform suspension compared to a solution containing silver nanoparticles. This increased sonication time is necessary due to the stronger bonding interactions between AlN and MWCNT particles. These interactions are largely influenced by the shapes of the particles involved.

The findings underscore the significant effects of different surfactants on the pH and stability of various nanofluids, which are essential for customizing their properties for specific applications. By selecting and optimising surfactants, researchers can improve nanofluid stability over time, which is crucial for applications in electronics cooling, automotive systems, and renewable energy technologies. This understanding paves the way for tailored solutions that enhance the efficiency of thermal management systems across various industries.

6.3.2 Effect of particles loading

In the second phase of the study focusing on stability and pH characteristics, nanofluids containing Ag, AlN, and MWCNTs were meticulously prepared across varying particle concentrations (0.01-0.03

vol.%) utilizing SDBS as a surfactant to enhance suspension stability. The investigation aimed to elucidate the interplay between particle concentration and pH values within each nanofluid type. It was observed that, while all three nanofluids exhibited a rise in pH with increasing particle concentration, the extent of change varies, as shown in Fig. 6.7. The study's findings revealed distinct pH characteristics among the nanofluids studied. The Ag and MWCNTs solutions were observed to be nearly neutral to slightly basic, while AlN nanofluids exhibited a basic nature that intensified with increasing particle concentration. For Ag nanofluids, pH levels showed a slight increase from 7.2 at 0.01 vol.% to 7.38 at 0.03 vol.%, indicating modest pH variation with concentration. In contrast, AlN nanofluids displayed a more pronounced elevation in pH levels as particle concentration increased, it varied significantly from 8.78 at 0.01 vol% to 10.21 at 0.03 vol%. Certain fuel cell technologies, such as anion exchange membrane fuel cells, utilize alkaline electrolytes. AlN nanofluids, if carefully engineered, hold promise for enhancing heat transfer within these cells, thereby boosting efficiency and overall performance. Moreover, the inherent alkalinity of AlN nanofluids makes them well-suited for the alkaline electrolyte environment typical of such fuel cell technologies [309]. This synergy suggests that AlN nanofluids not only improve thermal management but also contribute positively to the operational conditions required for optimal fuel cell performance. Meanwhile, MWCNT's nanofluids maintained relatively lower pH values across the concentration range compared to both Ag and AlN. The pH varied marginally from 7.02 to 7.17, suggesting minimal influence on pH by varying concentration.

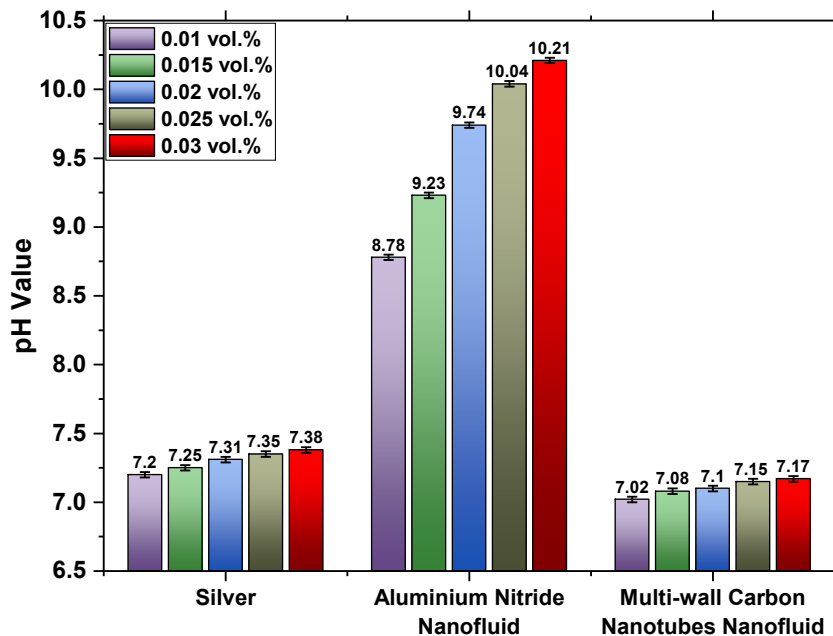


Figure 6.7. pH variation with particle concentration for Ag, AlN, and MWCNT nanofluids.

In the context of nanofluid stability, the concentration of particles plays a crucial role. The study observed that MWCNTs maintained stability throughout the examination period across all concentrations. It was revealed that for MWCNTs, the probability of nanotube aggregation is higher

than sedimentation due to their lower density, which is closer to that of the base fluid (water) compared to other nanoparticles such as AlN and Ag. Additionally, it was noted that some dispersed tubes became entangled like ropes, making them difficult to break or separate, while tubes connected at their ends were easier to break. In contrast, AlN nanofluids exhibited different stability characteristics, samples with concentrations above 0.02 vol.% began to settle after 72 hours. The AlN particles agglomerated, forming densely packed clusters that were difficult to break and disperse.

Upon extended observation, it was found that the settled particles in the conical test tube conformed to the shape of the tube bottom, forming a pellet that required high-frequency ultrasonic waves to disperse. This indicates that the attractive forces among these particles are strong, and even the addition of surfactants failed to sufficiently reduce these forces to maintain uniform suspension in the fluid for a longer period. This effect was more pronounced at higher particle concentrations. It is concluded that AlN nanoparticles are not an appropriate choice for use as a single particle to prepare nanofluids due to their tendency to form hard-to-disperse aggregates. However, they could potentially be utilised in combination with other particles or after specific surface treatments to enhance their dispersion stability. Researchers are encouraged to further explore the complex behaviour of AlN nanoparticles to develop more effective stabilization strategies. Silver nanoparticles (Ag) exhibit distinct sedimentation behaviour compared to both MWCNTs and AlN nanoparticles. Silver nanoparticles, despite their small size, face challenges in maintaining uniform suspension due to their relatively higher density. Specifically, the sample prepared with a concentration of 0.03 vol.% began to clear the upper layer of the fluid after 72 hours, attributed to the formation and settling of agglomerates. However, unlike AlN, Ag nanoparticles form aggregates that are relatively easier to disrupt, possibly due to weaker van der Waals forces and the spherical shape of these particles.

6.3.3 Hybrid and tri-hybrid nanofluid

The comprehension of the stability dynamics is essential for maximising the effectiveness of nanofluids across various applications, ranging from optimising thermal management systems to advancing biomedical devices. Moving forward, the exploration of hybrid and tri-hybrid nanofluids, such as MWCNTs/Ag, Ag/AlN, MWCNTs/AlN, and MWCNTs/Ag/AlN, becomes imperative. These combinations harness distinct nanoparticle properties to tackle specific challenges and enhance overall performance, focusing on optimising dispersion stability, improving heat transfer efficiency, and enhancing critical attributes for advanced industrial applications. Based on the stability study, a concentration of 0.025 vol.% was selected for the hybrid samples. This concentration was utilised for the preparation and further analysis of all hybrid and tri-hybrid nanofluid samples. The pH of the hybrid nanofluids tends to vary around the pH values of the individual mixing fluids. As shown in Fig. 6.8, for the Ag-AlN hybrid nanofluid samples, the pH values were observed to range from 9 to 9.61. A significant reduction in pH was noted as the proportion of Ag in the mixture increased. This trend suggests a direct influence of Ag concentration on the overall pH of the hybrid nanofluid, as the pH

value of the Ag nanofluid was 7.35. In the nanofluid comprising a suspension of MWCNTs and Ag nanoparticles, pH values were recorded to vary from 7.68 to 7.95. Notably, these values were slightly higher than those observed for the individual MWCNTs and Ag nanoparticles. This elevation in pH indicates a potential interaction between MWCNTs and Ag nanoparticles in the hybrid suspension, possibly altering the overall pH of the fluid. In comparison to samples containing AlN, the pH values measured for MWCNTs/Ag were noted to be lower. Similar to the Ag-AlN hybrid samples, the pH values of MWCNTs-AlN hybrid samples also demonstrated a trend where the pH increased with higher proportions of AlN. Specifically, the pH varied from 9.05 for the 80/20 ratio to 9.93 for the 20/80 mixing ratio. However, these pH values were slightly higher compared to those observed in MWCNTs/Ag hybrid samples. As anticipated, the pH values of the tri-hybrid nanofluid composed of MWCNTs/Ag/AlN varied with different mixing ratios. For a composition of 20% MWCNTs, 20% Ag, and 60% AlN, the pH was 9.76, indicating a more basic nature due to the high AlN proportion. As the proportion of Ag increased to 40%, with 20% MWCNTs and 40% AlN, the pH decreased to 9.35. This reduction indicates the influence of Ag nanoparticles, which tend to lower the pH of the solution. The pH further declined to 8.97 when the composition was adjusted to 20% MWCNTs, 60% Ag, and 20% AlN. The results demonstrate that increasing the concentration of Ag nanoparticles or reducing the AlN nanoparticles' loading shifts the pH towards a more neutral value.

The study findings emphasise the profound influence of surfactants, particle types, and concentrations on pH variations in nanofluids. These pH dynamics are pivotal for improving nanofluid stability and overcoming associated challenges. This understanding not only guides the optimisation of nanofluid formulations but also advances their reliability and performance across diverse technological applications.

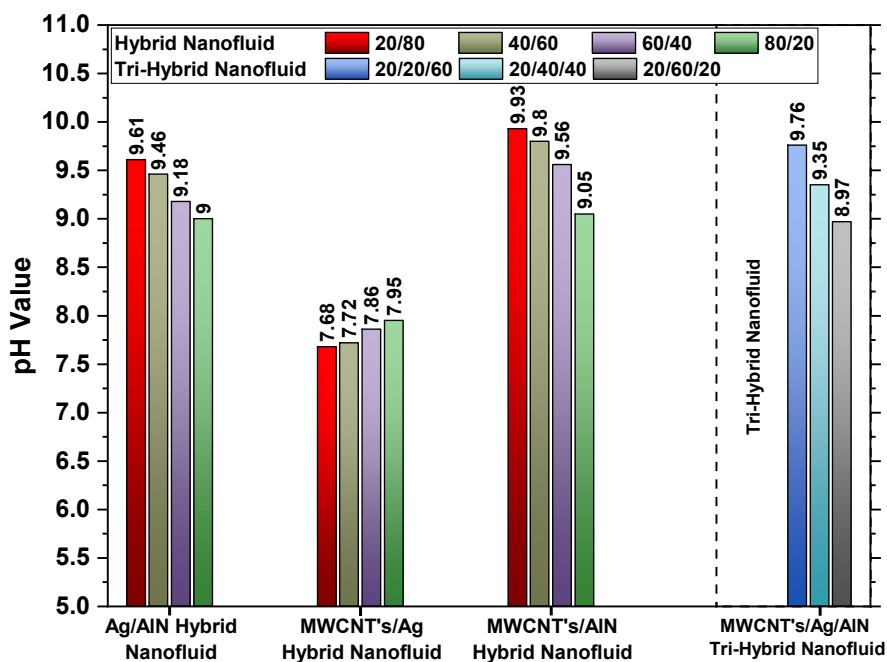


Figure 6.8. pH values of hybrid and tri-hybrid nanofluids with different mixing ratios.



Figure 6.9. Stability comparison of hybrid and tri-hybrid nanofluid samples.

The hybrid nanofluid samples demonstrated improved stability due to the synergistic interactions among different particles. However, Ag/AIN hybrid samples began to exhibit upper layer clarification after one week, attributed to particle sedimentation. Importantly, the presence of Ag nanoparticles in the hybrid samples prevented the formation of hard-to-break clusters typically observed in simple AIN nanofluid samples. In the case of pure AIN nanofluids, once clusters formed, it was challenging to break them apart and re-suspend the particles uniformly, even when high-frequency sonication was applied. Conversely, in the hybrid samples, the bonding among settled particles was not as strong, which facilitated easier re-dispersion and processing of the solution. This could be attributed to the rolling effect of the spherical shape of the Ag nanoparticles, which likely prevented the formation of tightly bound clusters. The rolling effect allowed the particles to remain more loosely connected, making it

easier to break them apart and achieve a uniform suspension once again. This observation underscores the significance of hybrid nanofluids and selecting a suitable combination of nanoparticles. The ability to maintain a stable and easily re-dispersible nanofluid is crucial for practical applications, where uniform particle distribution is essential for optimal performance.

The hybrid samples of MWCNT's/Ag and MWCNT's/AlN showed better stability, retaining it for a longer period, as shown in Fig. 6.9. The rate of particle agglomeration was significantly lower compared to the simple and other hybrid nanofluids containing Ag and AlN nanoparticles. This reduced tendency for agglomeration and sedimentation suggests that the hybrid nanofluids are less likely to experience these issues during operational conditions. Finally, the tri-hybrid nanofluid exhibited even greater stability, offering enhanced thermal characteristics. The distinct shapes and properties of the different nanoparticles in the tri-hybrid system contribute to a more effective dispersion and stability, leading to better thermal performance.

6.4 Characterisation

6.4.1 X-ray diffraction (XRD)

X-ray diffraction (XRD) is a powerful technique used to investigate the phase composition and crystallographic structure of nanoparticles such as aluminium nitride, silver, and MWCNT's. By examining the atomic arrangements within these materials, XRD provides detailed insights into their properties. Numerous research studies have employed XRD to characterise nanoparticles composed of pure or composite materials [310,311]. For this analysis, an X-ray diffractometer (Bruker - D8 Advance) with Cu-K α radiation (energy: 8.05 keV, wavelength: 1.5406 Å) was utilised. The XRD pattern for AlN nanoparticle showed several distinct peaks at specific 2θ angles, which correspond to the diffraction from different crystallographic planes of the AlN crystal, as shown in Fig. 6.10(a). The peaks are indexed with Miller indices (hkl), indicating the specific planes that contribute to the diffraction peaks. The presence of sharp, well-defined peaks indicates a highly crystalline nature of the AlN nanoparticles. The pattern suggests a hexagonal crystal structure, which is the typical structure for AlN. The diffraction peaks observed at 2θ values of approximately 33°, 36°, 38°, 48.8°, 59.31°, 66°, and 71.44° correspond to the (100), (002), (101), (102), (110), (103), and (201) planes of hexagonal AlN, respectively. The lattice parameters were found to be $a = 3.112$ Å and $c = 4.982$ Å.

These values result in a unit cell volume of $V = 41.8$ Å³ and a corresponding density of 3.26g/cm³. The results are aligned with the standard data from the Joint Committee on Powder Diffraction Standards (JCPDS), specifically JCPDS card number 25-1133, confirming the phase purity of the AlN nanoparticles being investigated. The results also correspond with the data reported by Hsu et al. [312] for AlN. In the analysis of the XRD pattern for silver nanoparticles, the prominent peaks observed at approximately 77°, 64°, 44° and 38° were indexed to the (311), (220), (200), and (111) planes of face-centered cubic (FCC) silver, respectively, Fig. 6.10(b). The lattice parameter was calculated to be 4.089

$\text{\AA}$, while the unit cell volume was determined as $68.39 \text{ \AA}^3$. These values are in excellent agreement with the established data for silver nanoparticles as documented in the JCPDS card number 04-0783. Additionally, the pronounced intensity of the (111) peak suggests a preferential orientation of the silver nanoparticles, with the majority of their (111) crystal planes aligned parallel to the substrate or sample surface.

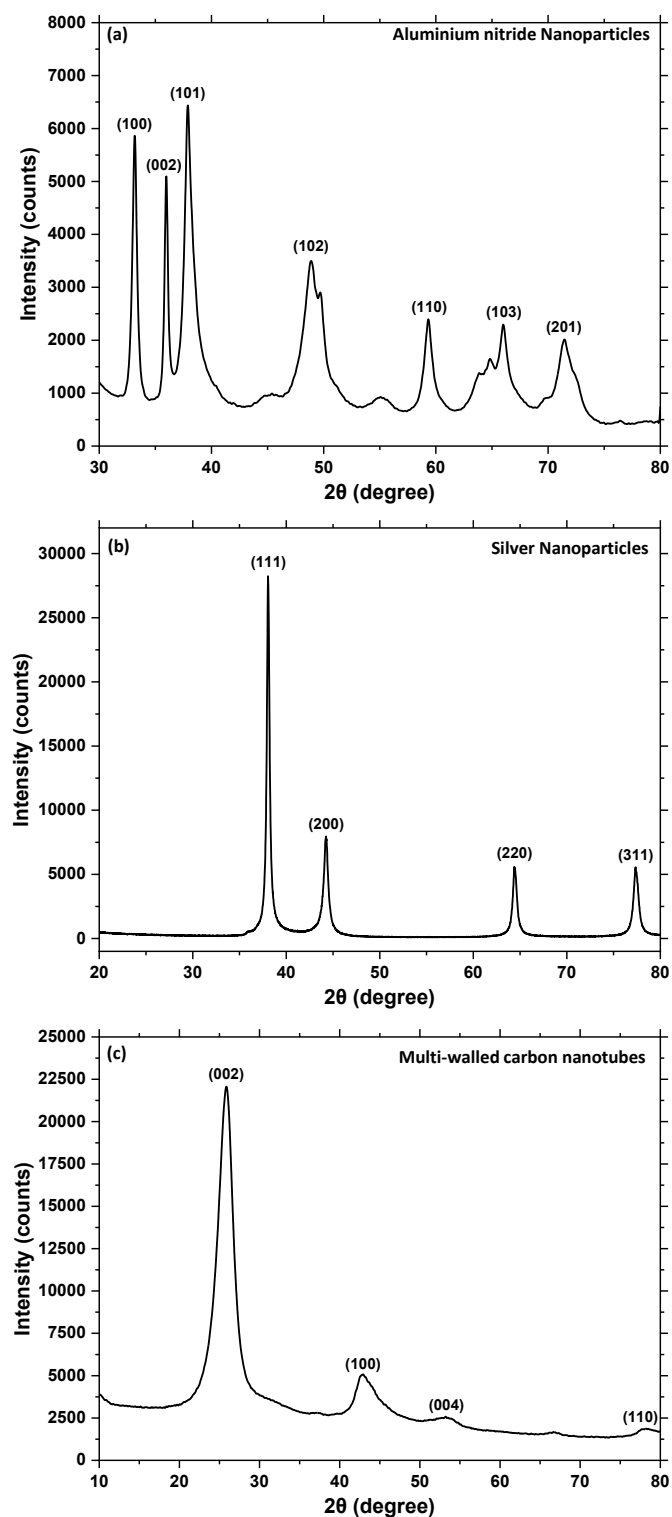


Figure 6.10. X-ray diffraction (XRD) patterns for (a) Silver nanoparticles, (b) Aluminium nitride nanoparticles, and (c) multi-walled carbon nanotubes.

The XRD pattern of MWCNT's exhibited broad peaks rather than sharp ones, indicating a relatively low degree of crystallinity. This is characteristic of MWCNTs due to their turbostratic structure, where the graphene layers have a random stacking arrangement. The most prominent peak was observed around $2\theta = 25.8^\circ$, corresponding to the (002) diffraction plane, as depicted in Fig. 6.10(c). This peak signified the graphitic structure of the MWCNTs and provided information about the interlayer spacing (d-spacing) between the graphene layers. Additionally, a less intense peak was often observed around $2\theta = 43^\circ$, corresponding to the (100) diffraction plane, further confirming the graphitic nature of the material. The XRD pattern exhibited weaker peaks at higher angles, specifically around $2\theta = 54^\circ$ and 77° . These weaker peaks corresponded to different crystallographic planes within the material. However, they were less pronounced compared to the more prominent peaks, likely due to the turbostratic nature of MWCNTs. The same pattern was observed and reported in various studies [313,314], corroborating the purity of the nanoparticles used in the current research.

The analysis revealed that AlN nanoparticles possessed a highly crystalline hexagonal structure, silver nanoparticles exhibited a face-centred cubic structure, and MWCNTs showed a typical turbostratic graphitic structure. The findings not only validated the phase purity and structural properties of the nanoparticles but also underscored the efficacy of XRD as a critical tool for detailed nanoparticle characterization.

6.4.2 Transmission Electron Microscopy (TEM)

To gain deeper insights into particle morphology, the nanoparticles of silver, aluminium nitride, and multi-walled carbon nanotubes were examined using the JEOL Transmission Electron Microscopy (TEM) JEM-1400 Plus instrument [315,316]. This advanced analytical technique offers high-resolution imaging, which is essential for a detailed examination of the nanoparticles' shape, size, and structural characteristics.

Figure 6.11 presents the TEM images, showcasing these three distinct types of nanoparticles under investigation in this study. Silver nanoparticles were observed to have a spherical shape with sizes ranging from 20 to 40 nm, while some particles broke down to sizes smaller than 20 nm when subjected to high-frequency waves during the sonication process. The results revealed that these nanoparticles tend to agglomerate or aggregate, forming irregular clusters. Second from the left in Fig. 6.11, multi-walled carbon nanotubes displayed their characteristic tubular structure, with lengths and diameters that varied in the range of 2.5-20 μm and 6-13 nm respectively. The TEM images clearly showed the elongated and intertwined nature of the MWCNTs, which contributed to their unique thermal characteristics. Aluminium nitride nanoparticles exhibited a different morphology, typically presenting as irregularly shaped particles with varying dimensions.

In the hybrid nanofluids combining MWCNTs, Ag, and AlN nanoparticles, the TEM images revealed a complex interaction between the different types of particles. The hybrid samples showed a more dispersed distribution, with the different nanoparticles maintaining their morphologies while interacting

with each other. The AlN nanoparticles acted as a bridge to transfer heat between the nanotubes. In the simple MWCNTs sample, while they exhibited better thermal characteristics, the interactions between particles restricted effective heat transfer. The introduction of AlN nanoparticles helped mitigate this issue by providing pathways for heat to flow between the nanotubes, thereby enhancing overall thermal conductivity. Additionally, it was observed that some of the silver nanoparticles became embedded within the AlN matrix, further facilitating heat transfer. The presence of silver nanoparticles also played a crucial role in reducing the strong interactions between AlN particles, preventing the formation of tightly bound clusters that are difficult to break apart. This reduction in strong interactions helped maintain a more stable suspension.

AlN nanoparticles also played a crucial role in minimising the interwinding of MWCNTs and reducing the agglomeration of Ag nanoparticles. This dual functionality of AlN not only enhanced thermal conductivity but also improved the overall dispersion stability of the hybrid nanofluids. The synergistic effect of AlN, Ag, and MWCNTs in the hybrid nanofluid demonstrated a balanced interaction, which is vital for achieving optimal thermal performance and stability.

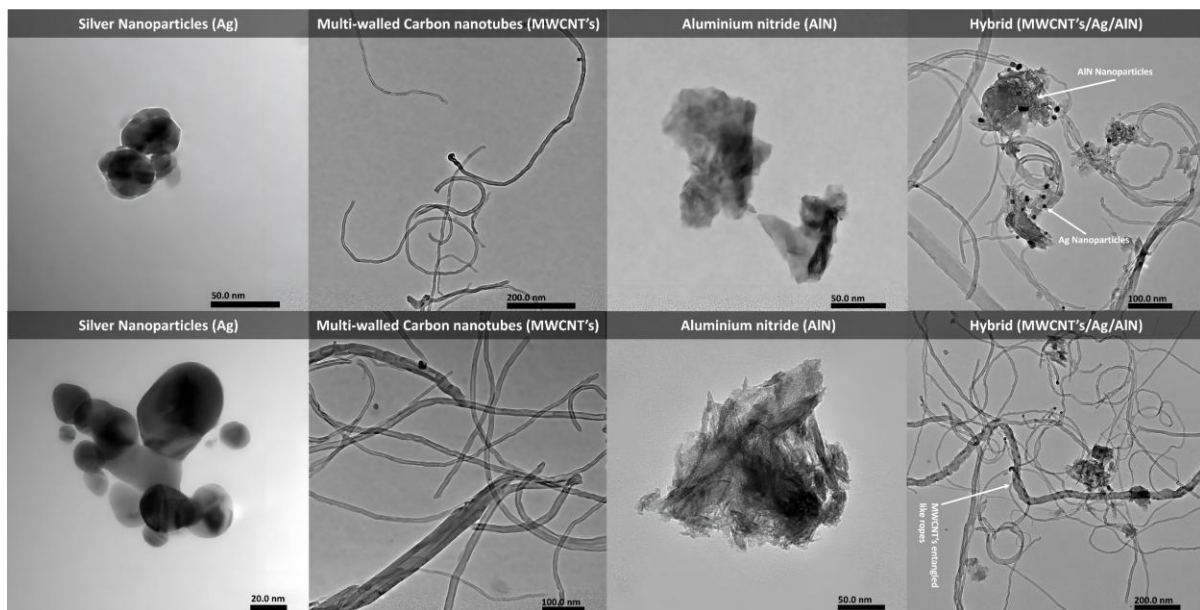


Figure 6.11. TEM images displaying the morphology and agglomeration nanoparticles.

The complex interplay among these nanoparticles ensured that the thermal pathways remained efficient while preventing detrimental agglomeration and clustering. This behaviour highlights the importance of carefully selecting and combining different nanoparticles to maximise the benefits of hybrid nanofluids. The detailed TEM analysis provided insights into these interactions, showcasing the potential of these hybrid systems for advanced thermal management applications where both stability and high thermal conductivity are required.

6.4.3 Stability and Particle Size Distribution

Zeta potential is a critical parameter that indicates the degree of repulsion (DOR) between adjacent, similarly charged particles in a dispersion. A higher absolute value of zeta potential generally suggests

better stability, as it implies that the particles will repel each other more strongly, preventing aggregation and maintaining a stable suspension. However, it is important to note that zeta potential is not the sole determinant of stability. Factors such as particle morphology, density, and size also play significant roles in the long-term stability of nanofluids and must be considered alongside zeta potential when evaluating overall stability. The zeta potential values presented in Fig. 6.12 provide insight into the stability of the pure, hybrid, and tri-hybrid nanofluids composed of Ag, AlN, and MWCNTs.

A Malvern Zetasizer, a renowned instrument for nanomaterial analysis, was used to examine the samples [317–319]. For a detailed description of the measurement procedure, readers are referred to Chapter 5 (Section 5.4.3).

The zeta potential values, which were measured immediately after sonication of both simple and hybrid nanofluid samples, fell within a range of -45 to -70 mV, as depicted in Fig. 6.12. This range is indicative of a high level of stability, with zeta potential values exceeding ± 30 mV generally being recognised as a marker of good stability in particle suspensions. The zeta potential value for pure AlN was recorded at -48.23 mV. This value suggests good stability, as zeta potential values greater than ± 30 mV generally indicate a stable colloidal system. The negative value indicates that the surface of the AlN particles carries a negative charge in suspension. In comparison, Ag nanoparticles showed a zeta potential of -51.9 mV, indicating slightly higher stability compared to pure AlN. This suggests that Ag nanoparticles, in isolation, have a reasonably strong electrostatic repulsion, which helps in maintaining dispersion stability. However, it is important to note that Ag nanoparticles are denser than AlN, which could negatively impact their overall stability. MWCNTs had the highest zeta potential magnitude at -65.9 mV among the pure nanofluids. This indicates the greatest stability, likely due to the high surface area and unique electronic properties of MWCNTs, which can lead to significant surface charge density. Notably, while MWCNTs have a small diameter, their elongated structure can cause some tubes to become entangled, forming rope-like bundles that are challenging to break or disperse and impact stability negatively.

The zeta potential for the Ag/AlN (20/80) hybrid was -54.3 mV, reflecting a stability level comparable to the individual components but slightly enhanced due to the interaction between Ag and AlN. As the proportion of Ag increases in the hybrid (Ag/AlN 40/60 and 60/40), the zeta potential values show a slight variation, with -56.7 mV for 40/60 and -49.7 mV for 60/40. The 40/60 ratio provides the highest stability within this series, likely due to an optimal balance of the electrostatic characteristics of Ag and AlN. With further increase in the Ag content (80/20), the zeta potential drops to -48.6 mV, closer to the value for pure AlN, suggesting that the higher proportion of AlN might dominate the stability behaviour. In case of MWCNTs/Ag hybrid formulation, 20/80 sample exhibited a zeta potential of -59.8 mV, indicating notable stability, although it was slightly less stable than pure MWCNTs. As the ratio changed to 40/60 and 60/40, the zeta potential values fluctuated, noted to be -51.9 mV for 40/60 and -55.4 mV for 60/40. These values suggested that MWCNTs significantly contributed to the dispersion stability, especially at higher concentrations.

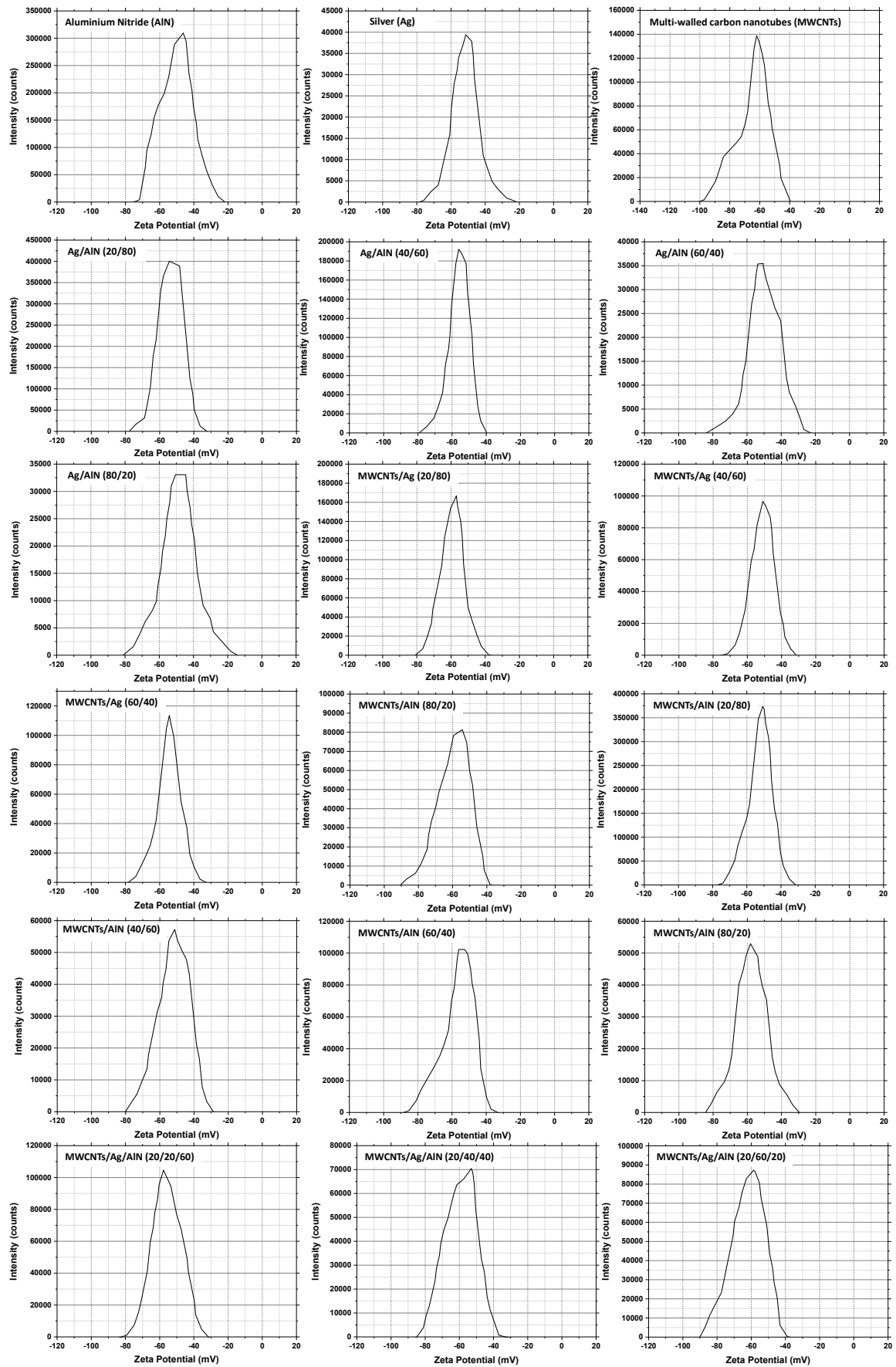


Figure 6.12. Zeta potential distributions for pure, hybrid, and tri-hybrid nanofluids composed of Ag, AlN, and MWCNTs in various ratios.

The zeta potential increased further to -60.2 mV in the 80/20 ratio, demonstrating enhanced stability as MWCNTs became more dominant. Similar to the MWCNTs/Ag hybrids, the zeta potential of MWCNTs/AlN formulations improved with increasing MWCNTs ratio. For the 20/80 hybrid, the zeta potential was found to be -53.1 mV, showing slightly better stability compared to pure AlN. As the proportion of MWCNTs increased in the 40/60 and 60/40 hybrids, the zeta potential rose to -52.1 mV and -57.5 mV, respectively. Among these ratios, the 60/40 hybrid exhibited the highest zeta value, highlighting the significant role of MWCNTs in enhancing colloidal stability. The value remained high recorded -56.3 mV for the 80/20 ratio, further demonstrating the effective stabilizing influence of MWCNTs in the hybrid nanofluids.

Tri-hybrid nanofluid with the composition 20/20/60 (MWCNTs/Ag/AlN) exhibited a zeta potential of -56.2 mV, indicating good stability, likely due to the synergistic effects of the three nanoparticles. As the ratio changed to 20/40/40, the zeta potential increased to -59.4 mV, reflecting even higher stability due to the balanced contributions of MWCNTs and Ag. Finally, the 20/60/20 ratio showed the highest stability among the tri-hybrid nanofluids with a zeta potential of -62.6 mV. This indicates that increasing the proportion of Ag, while maintaining a constant MWCNTs ratio and combining it with AlN, maximises electrostatic repulsion and effectively prevents particle aggregation. The findings concluded that carefully optimising the ratios of the constituent nanoparticles can significantly enhance the stability of nanofluids, making them more suitable for practical applications where long-term dispersion stability is critical.

The analysis of suspended particle size and agglomeration behaviour in nanofluids was also conducted using the Malvern Zetasizer, which provides insights into the stability and dispersion quality of the nanofluids. The histograms generated for each type of nanofluid indicate the particle size distribution, with the Z-average (mean) values listed for different formulations, as shown in Fig. 6.13. This study was carried out five days after sample preparation to assess the evolution of particle agglomeration over time. The Z-average particle size for the AlN suspension in basefluid was found to be 184.8 nm, significantly larger than its initial particle size of < 100 nm. This marked increase indicates that AlN particles have a tendency to agglomerate in suspension, leading to larger clusters. In comparison to other pure nanofluids, AlN exhibited a higher Z-average value, likely due to the inherently larger size of suspended particles. The histogram reflects a relatively symmetric peak, which indicates a uniform distribution of agglomerates, with minimal formation of significantly larger aggregates. The Ag nanofluid exhibited a Z-average of 111.8 nm, which, while larger than its initial size of 10-40 nm, was still considerably smaller than that of AlN. However, considering the initial size of particles and the relatively small difference in zeta potential between Ag and AlN, the formation of agglomerates observed in the Ag samples was substantial. The histogram is slightly asymmetric, with a tail on the right, indicating the presence of some larger agglomerates. Additionally, the broader base of the histogram suggested the existence of agglomerates of varying sizes. The MWCNT nanofluid showed a Z-average of 184.8 nm, similar to that of AlN. This large Z-average is due to the high aspect ratio of

MWCNTs, which tend to form entangled networks rather than simple spherical agglomerates. The histogram indicates a somewhat broad distribution, reflecting a range of agglomerate sizes due to the complex geometry and tendency of nanotubes to entangle.

Among the nanofluids studied, the Ag nanofluid had the smallest Z-average, which could be attributed to its smaller initial particle size. However, relying solely on the Z-average to assess the stability of nanofluids is not considered to be a good approach. Despite the lower Z-average, the higher density of Ag nanoparticles negatively impacted stability, leading to a tendency for sedimentation. Therefore, factors such as particle density and initial size should also be considered equally when evaluating nanofluid stability. It was evident that the stability of nanofluids is not governed by a single factor but is influenced by a combination of properties. Thus, while the Ag nanofluid exhibited a lower Z-average, this did not necessarily mean it outperformed the MWCNT or AlN nanofluids in terms of stability.

In the case of hybrid samples, the Z-average particle sizes for the Ag/AlN hybrids varied slightly, ranging from 136 nm to 112 nm. The Ag/AlN (20/80) nanofluid, having the lowest Ag content, exhibited a Z-average value of 136.7 nm, indicating the presence of larger-sized AlN nanoparticles. As the proportion of Ag increased, the Z-average particle size decreased, with the 40/60 and 60/40 ratios showing reduced average particle sizes of 134.5 nm and 116.2 nm, respectively. The Ag/AlN (80/20) nanofluid, with the highest Ag content, achieved the smallest Z-average value of 112.3 nm, demonstrating that a higher proportion of small-sized Ag nanoparticles was effective to some extent in reducing the size of larger AlN clusters. However, compared to pure AlN, the hybrid nanofluids showed slightly better stability. In the MWCNTs/Ag hybrid nanofluid samples, the Z-average particle sizes were observed to increase as the proportion of MWCNTs increased. The MWCNTs/Ag (20/80) nanofluid, with the highest Ag content, exhibited the smallest Z-average size at 115.8 nm, indicating that a higher proportion of Ag, combined with a lower MWCNT content, favoured the formation of smaller-sized nanoparticles. As the proportion of MWCNTs increased, the particle size also increased, with the Z-average values rising to 119.5 nm for the 40/60 ratio, 128.2 nm for the 60/40 ratio, and reaching the highest value of 133.1 nm for the 80/20 ratio. The histogram of 40/60 was slightly broader, with a wider base, reflecting a greater variation in particle sizes. For MWCNTs/AlN hybrid nanofluid samples, the Z-average particle size consistently decreased as the MWCNTs concentration increased. The MWCNTs/AlN (20/80) nanofluid, characterised by a higher proportion of AlN, exhibited the largest Z-average particle size of 174.0 nm. As the ratio of MWCNTs was increased, the particle sizes progressively reduced, with the Z-average values decreasing to 160.9 nm, 158.9 nm, and 157.2 nm for the 40/60, 60/40, and 80/20 ratios, respectively. However, the minor peaks observed towards the right end of the histograms indicate the presence of slightly larger particle agglomerates, particularly in samples with a higher AlN content.

Finally, the MWCNTs/Ag/AlN tri-hybrid nanofluid samples exhibited a consistent decrease in Z-average particle sizes as the proportion of silver increased relative to AlN. A 20/20/60 ratio (MWCNTs/Ag/AlN) resulted in a Z-average size of 123.2 nm.

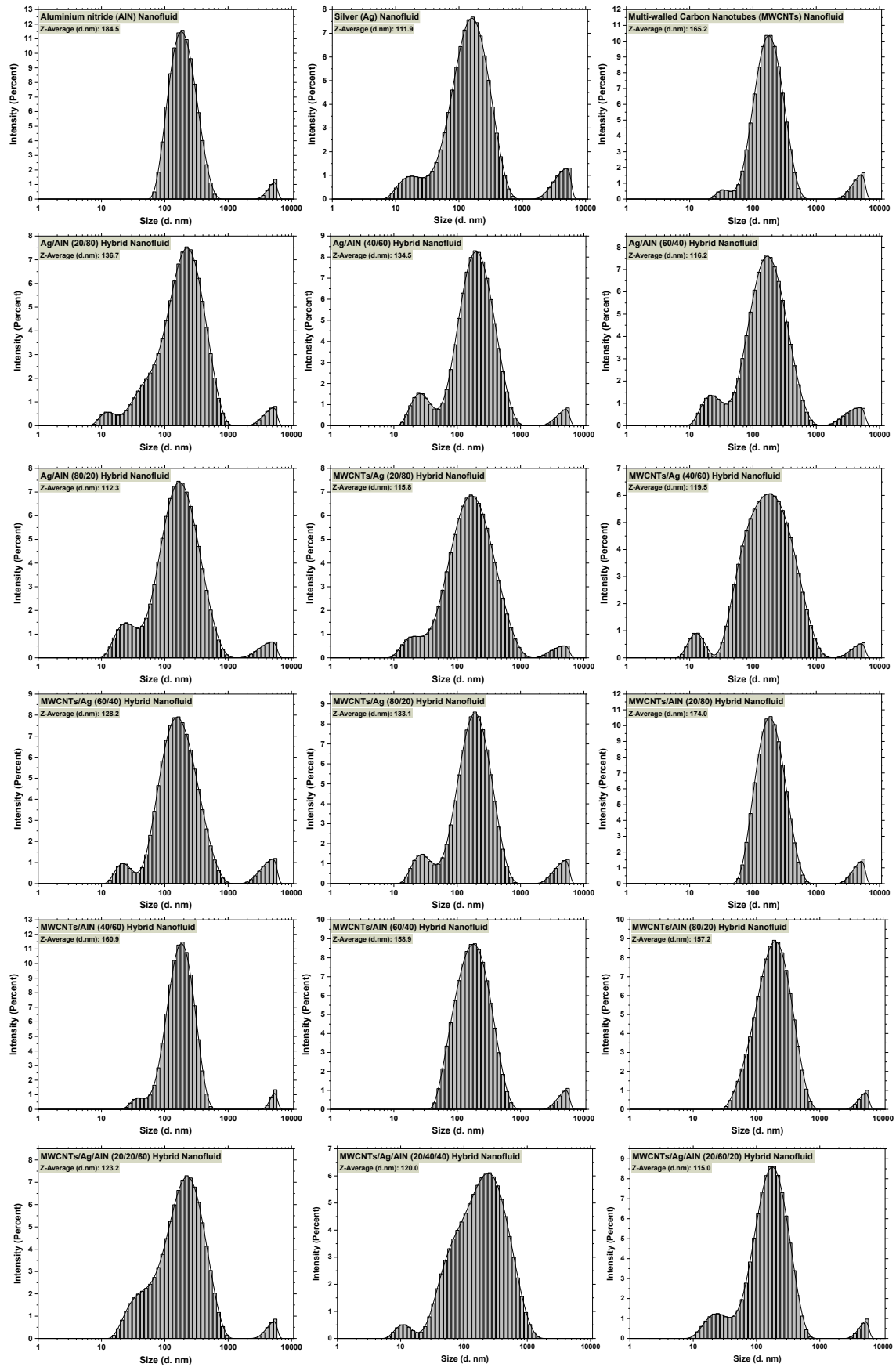


Figure 6.13. Particle size distributions and Z-average values for pure, hybrid, and tri-hybrid nanofluids composed of Ag, AlN, and MWCNTs in various ratios.

With an increased Ag content to a 20/40/40 ratio, the average size was slightly reduced to 120.0 nm. Further elevation of the Ag content to a 20/60/20 ratio led to the smallest observed particle size of 115.0 nm. This trend indicates that the inclusion of higher amounts of smaller Ag nanoparticles effectively disrupts the formation of larger AlN clusters, yielding a more uniform and reduced particle size distribution.

The comparative analysis of tri-hybrid nanofluids with other pure and hybrid nanofluids reveals that the inclusion of different sized and shaped particles in the tri-hybrid solution not only helps to enhance the thermal characteristics but also results in smaller Z-average particle sizes for the agglomerates formed. This effect is particularly evident in the histogram, where the wider base indicates the presence of a diverse range of particle sizes and the varying agglomerates or structures they create.

The incorporation of multiple particle types in the tri-hybrid formulation introduces heterogeneity in size and shape, which in turn weakens the attractive forces between particles. This weakening makes it easier to disrupt and redisperse the agglomerates, contributing to a more stable and uniform particle distribution. The Z-average particle size measurements obtained from the Malvern Zetasizer confirm that all nanofluids experience agglomeration to some extent, though the degree varies depending on the specific composition. This study underscores the importance of understanding and controlling agglomeration in nanofluids, as it directly impacts their stability, thermal efficiency, and overall performance. By optimising the composition and particle distribution within nanofluids, researchers can develop more effective solutions for applications that require enhanced thermal management and stability.

6.5 Results and discussion

6.5.1 Thermal conductivity

Fluids thermal conductivity is a critical property that significantly influences their heat transfer characteristics across various applications. Understanding and accurately measuring this property is essential for optimising the performance of nanofluids in practical use. The current study used the Hot Disk TPS 2500S thermal analyser, which employs the transient plane source (TPS) technique to accurately and reliably measure the thermal conductivity of both water and nanofluid samples. The experimental setup consists of a TPS analyser, constant temperature bath, and a liquid sample holder, as illustrated in Fig. 6.14. For a detailed discussion of the testing setup and configuration used in this study, see Chapter 5 (Section 5.5.1).

The uncertainty in thermal conductivity measurements was assessed based on the accuracy of experimental procedures and the instrument's specifications. The Hot Disk TPS 2500S thermal analyser has a manufacturer-specified maximum uncertainty of $\pm 5\%$. However, for the fluid sample, the maximum standard deviation was measured to be less than 0.7%, which reflects the high precision of the collected data. This low standard deviation demonstrates minimal variation between repeated

measurements and remains within acceptable limits. To improve the accuracy, three measurements were recorded at each temperature point. This careful approach was designed to reduce potential errors and ensure the reliability of the results. Furthermore, system calibration was performed using a stainless-steel reference sample provided by the supplier, which yielded a standard deviation of less than 0.5%. This suggests that the experimental setup was properly calibrated and capable of generating consistent and reliable results. The accuracy of the thermal conductivity measurement setup was validated by testing distilled water over a temperature range of 20 °C to 45 °C, with measurements taken at 5 °C intervals. As this validation procedure has already been detailed in Chapter 5, Section 5.5.1, it is not repeated here to avoid redundancy.

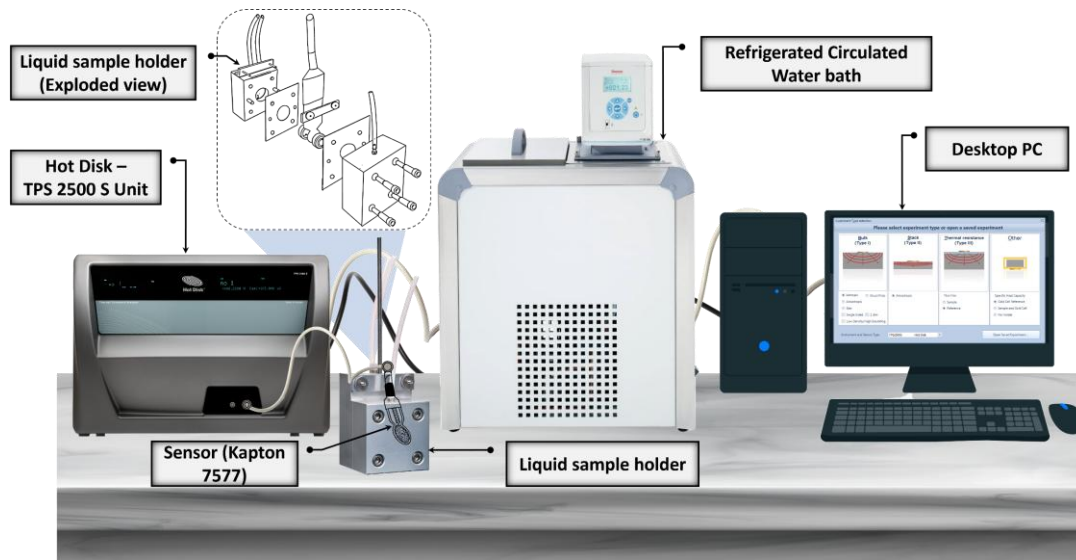


Figure 6.14. Schematic representation of the experimental configuration for measuring thermal conductivity.

The addition of surfactants is a common practice to enhance the suspension stability of nanoparticles [54,320]. However, selecting a suitable surfactant is crucial as some can adversely affect stability, resulting in reduced thermal conductivity of the fluid. While surfactants can significantly improve fluid stability, their effects vary with the type of particle used. An unsuitable surfactant can reduce stability, causing particles to agglomerate and settle more quickly.

A study was conducted to investigate the impact of different surfactants on the TC of prepared nanofluid samples. For this purpose, the conductivity of simple nanofluid samples prepared with 0.01 vol.% nanoparticles was measured just after the sonication and after 72 hours. According to the results, a significant reduction in thermal conductivity was observed in the AlN nanofluid prepared without any surfactant. The thermal conductivity decreased from 0.664 W/m·K to 0.657 W/m·K, with the enhancement dropping from 2.38% to 1.33%, as shown in Fig. 6.15. Among the surfactants tested, SDS was found to be the worst choice for AlN nanofluid, showing the most considerable reduction in thermal conductivity over time. In contrast, SDBS showed the minimum reduction, indicating better stability.

Gum Arabic was identified as a good surfactant after SDBS, while CTAB provided better stability than SDS. As anticipated, the silver nanofluid showed a notable decrease in thermal conductivity after 72 hours for the sample prepared without a surfactant. However, the decline was less pronounced in samples containing CTAB and SDBS surfactants. Among these, the SDBS sample exhibited superior stability, while SDS and Gum Arabic proved to be less effective. The thermal conductivity results of MWCNT nanofluids further underscore the significant impact of surfactants on thermal properties, which vary depending on the type of particles used. In case of MWCNTs, samples prepared with SDSBS and Gum Arabic demonstrated better particle suspension stability, with only a slight reduction in thermal conductivity after 72 hours. However, nanofluids prepared with other surfactants exhibited more pronounced decreases in thermal conductivity over the same period. Specifically, the thermal conductivity of the nanofluid without any surfactant was notably poor, dropping from 0.6790 W/m·K to 0.6740 W/m·K after 72 hours.

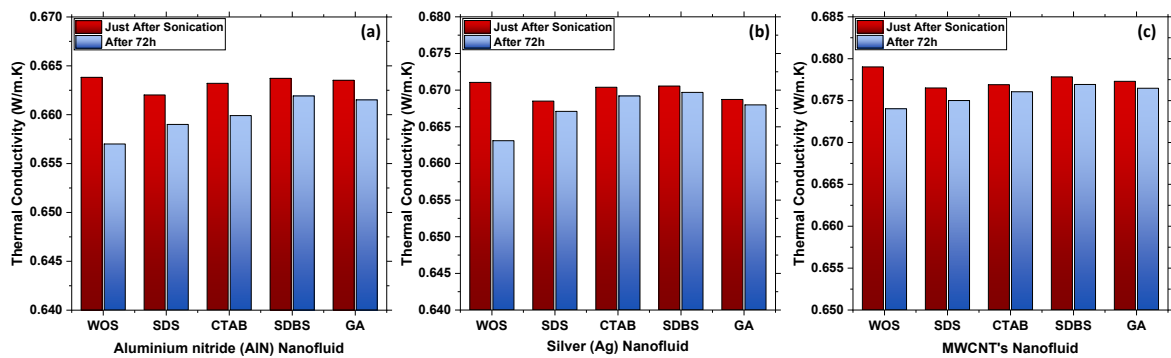


Figure 6.15. Effect of surfactants on the thermal conductivity of nanofluids over a 72-hour period.

The results revealed that surfactant choice greatly affects nanofluid stability and thermal conductivity. SDBS and CTAB proved most effective for AlN and silver nanofluids, showing minimal reductions in thermal conductivity. For MWCNT nanofluids, SDSBS and Gum Arabic were best at maintaining thermal properties. These findings underscore the importance of selecting the appropriate surfactant to improve nanofluid performance.

Particle concentration is another critical factor in optimising nanofluid performance [321]. To evaluate its impact, nanofluid samples containing AlN, Ag, and MWCNTs were prepared with particle concentrations ranging from 0.01-0.03 vol.%. This range was chosen to balance enhanced thermal properties with stability, crucial for applications like electronic cooling in mini and microchannel heat sinks. Higher particle concentrations can lead to the increase of pressure drop, higher pumping power, and the risk of particle agglomeration. Agglomerated particles may cause blockages in channels, resulting in localised heating and potential damage to the system. Thus, optimising particle concentration is key to maintaining fluid stability and system performance.

The thermal conductivity has been calculated at a constant temperature of 35°C and the results are presented in Fig. 6.16. While all types of nanoparticles exhibited an increase in thermal conductivity

with rising concentration, however, this enhancement varied among different nanoparticle types. According to the results, MWCNT's suspended nanofluid demonstrated the highest thermal conductivity values at all tested concentrations. At 0.01%, the thermal conductivity increased by 4.54%, and at 0.03%, it reached a 7.29% enhancement. The consistent rise in thermal conductivity across all concentrations demonstrated the strong impact of MWCNTs, making them highly effective for improving thermal performance in nanofluids. This superior performance is due to the high thermal conductivity and unique structure of carbon nanotubes, which enable efficient phonon transport, resulting in significant conductivity improvements even at lower concentrations. Silver nanoparticles also showed significant improvements in thermal conductivity, though their performance, while notable, was not as high as that of MWCNTs, although it was closely competitive. The enhancement ranges from 3.45% at the lowest concentration to 6.65% at the highest.

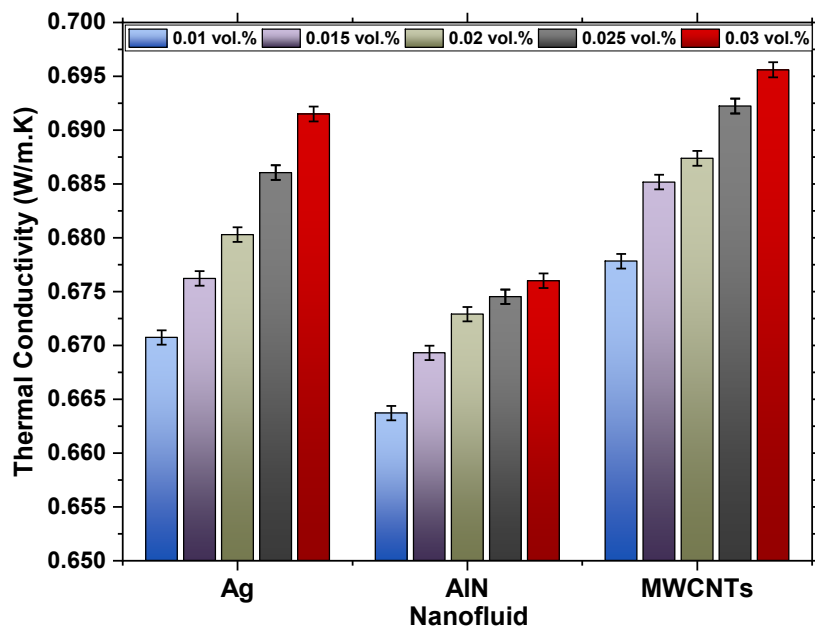


Figure 6.16. Thermal conductivity of nanofluids with varying particle concentrations.

This progressive increase in thermal conductivity with concentration underscores the effectiveness of silver nanoparticles in improving heat transfer properties. However, it is important to consider the stability of the nanofluid, as higher nanoparticle concentrations can impact dispersion and potentially affect thermal conductivity over time. Aluminium nitride nanofluids, on the other hand, exhibited a more modest increase in thermal conductivity compared to MWCNTs and Ag, due to AlN's inherently lower thermal conductivity. As the concentration of AlN nanoparticles increased from 0.01% to 0.03%, the thermal conductivity of the nanofluid improved steadily, with enhancements ranging from 2.37% to 4.26%. Although AlN did enhance thermal conductivity, its effect was less pronounced than others. The findings emphasise the importance of optimising particle concentration to balance thermal performance with stability, as in practical applications consistent heat transfer and long-term fluid stability are crucial. Ultimately, selecting the appropriate nanoparticle and concentration is key to achieving the desired thermal performance.

Figure 6.17 shows the thermal conductivity of water and various nanofluids containing Ag, AlN, and MWCNTs suspension over a temperature range from 20°C to 45°C. Each nanofluid was prepared with a particle concentration of 0.025 vol%. The study found that thermal conductivity increased significantly with temperature for all samples, with a more pronounced rise beyond 30°C, attributed to the enhanced Brownian motion of nanoparticles. As nanoparticles move more freely and uniformly within the fluid, they can more effectively transfer heat through the nanofluid. This improved thermal transfer is reflected in the higher thermal conductivity observed at elevated temperatures. In heat transfer applications, this means nanofluids are more effective at higher temperatures, making them ideal for scenarios where elevated temperatures are common. Water exhibited a steady increase in thermal conductivity from 0.604 W/m·K at 20°C to 0.681 W/m·K at 45°C, reflecting enhanced molecular motion and reduced viscosity at higher temperatures.

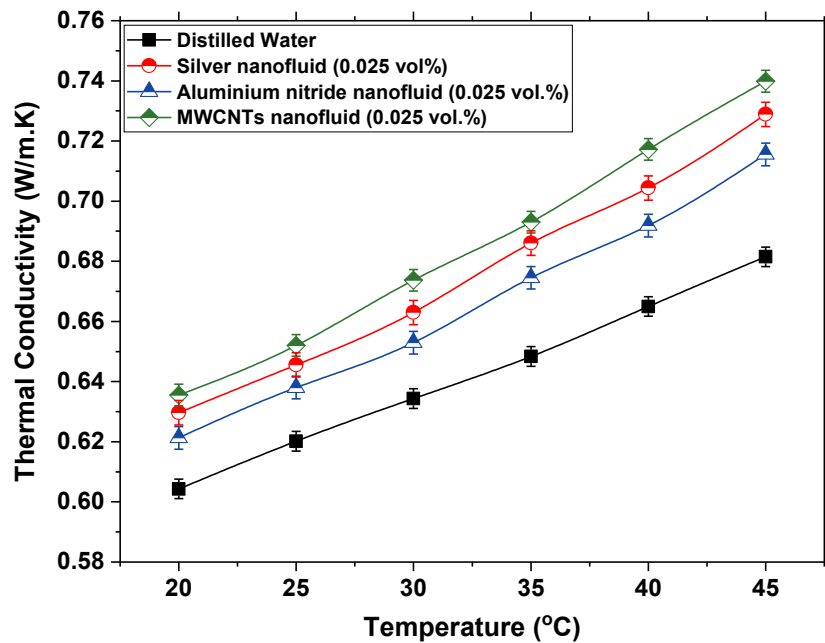


Figure 6.17. Temperature-dependent thermal conductivity of distilled water and nanofluids containing Ag, AlN, and MWCNTs at 0.025 vol% concentration.

Silver nanofluid consistently demonstrated superior thermal conductivity compared to water, rising from 0.630 W/m·K at 20°C to 0.729 W/m·K at 45°C, due to the high thermal conductivity of silver particles. Aluminium nitride nanofluid also showed improved thermal conductivity over water, increasing from 0.621 W/m·K at 20°C to 0.716 W/m·K at 45°C, however, the enhancement was less pronounced than with silver. Among the nanofluids tested, MWCNTs exhibited the highest thermal conductivity. The thermal conductivity of MWCNTs nanofluid increased from 0.636 W/m·K at 20°C to 0.740 W/m·K at 45°C. The exceptional increase is attributed to the unique structural and thermal properties of the multi-walled carbon nanotubes, which provide superior heat transfer capabilities.

Figure 6.18 presents the thermal conductivity values of various hybrid nanofluids, prepared with different mixing ratios of 80/20, 60/40, 40/60, and 20/80, across temperatures ranging from 20°C to

45°C. The outcomes demonstrated that the thermal conductivity of these hybrid samples was significantly influenced by the proportions of nanoparticles within the mixture, as well as by temperature variations. Notably, all the hybrid nanofluids demonstrated substantial enhancements in TC compared to water. The study conducted by Wanatasanappan et al. [322] reported similar trends in their investigation of $\text{Al}_2\text{O}_3/\text{CuO}$ hybrid nanofluids, demonstrating that the thermal conductivity enhancement was a function of both particle concentration and temperature.

As depicted in Fig. 6.18(a), the thermal conductivity of the Ag/AlN hybrid nanofluids was evaluated across various mixing ratios. The results showed that the hybrid nanofluid prepared with a 20/80 ratio exhibited intermediate thermal conductivity values, ranging from 0.6230 W/m·K at 20°C to 0.7216 W/m·K at 45°C, falling between those of pure Ag and AlN nanofluids. As the proportion of silver increased to 40% further improved the thermal conductivity, with values rising from 0.6257 W/m·K at 20°C to 0.7285 W/m·K at 45°C. Despite this enhancement, thermal conductivity remained slightly lower than that of the pure Ag nanofluid, indicating that while the inclusion of Ag had a beneficial effect, it did not surpass the conductivity provided by silver alone. However, at the 60/40 mixing ratio, thermal conductivity slightly exceeded that of both the individual Ag and AlN nanofluid, with values recorded to be 0.6275 W/m·K at 20°C and 0.7297 W/m·K at 45°C. This finding suggests a synergistic interaction between Ag and AlN at this specific ratio, where the combination of the two nanoparticles resulted in a hybrid nanofluid that outperformed its unitary counterparts. Finally, at the 80/20 ratio, the hybrid nanofluid's thermal conductivity improved further, approaching the values observed for the 60/40 hybrid sample, with thermal conductivities of 0.6280 W/m·K at 20°C and 0.7309 W/m·K at 45°C. These results indicate that the optimal interaction between highly conductive silver particles and AlN particles enhances nanoparticle dispersion and stability within the base fluid, leading to superior thermal performance of the hybrid nanofluid at the 60/40 and 80/20 mixing ratios.

The samples containing MWCNTs and AlN nanoparticles exhibited superior thermal conductivity values compared to Ag/AlN hybrid samples across all mixing ratios, due to the presence of MWCNTs. The study found that increasing the proportion of MWCNTs in the nanofluid resulted in higher thermal conductivity values. As shown in Fig 6.18(b), at 35°C, the thermal conductivity for the 20/80 MWCNTs/AlN mixture was 0.681068 W/mK, while the 80/20 mixture reached 0.690820 W/m·K. This observation is consistent with the known high thermal conductivity of MWCNTs, which appeared to dominate the thermal behaviour of the mixtures, enhancing their overall thermal performance. For this hybrid combination, the values varied in-between the individual thermal conductivities of MWCNTs and AlN. At 20°C, the thermal conductivity of Ag/AlN hybrid samples were recorded to be varied ranging from 0.6231-0.6280 W/mK, as demonstrated in Fig. 6.18(a). However, the thermal conductivity values for the MWCNTs/AlN nanofluids at the same temperature ranged from 0.6256 W/mK for the 20/80 ratio to 0.6330 W/mK for the 80/20 ratio. This trend of increased thermal conductivity in nanofluids persisted as the temperature increased. By 45°C, the thermal conductivity of Ag/AlN reached

0.7308 W/mK, whereas the values for the MWCNTs/AlN nanofluids were significantly higher, with the 80/20 mixture achieving a value of 0.7373 W/m·K.

Figure 6.18(c) presents the results of MWCNTs/Ag hybrid nanofluid, which delivered superior thermal conductivity compared to Ag/AlN and MWCNTs/AlN nanofluids across all mixing ratios. This enhanced performance can be attributed to the exceptional thermal properties of both MWCNTs and Ag, along with several other influencing factors such as particle shape, Brownian motion, density, better suspension, etc. As the MWCNTs loading increased, there was a noticeable rise in thermal conductivity, with values improving from 0.7341 W/m·K at a 20/80 ratio to 0.7392 W/m·K at 80/20 ratio.

The thermal conductivity of the tri-hybrid nanofluid was observed to be slightly lower compared to the MWCNTs/Ag hybrid solution across the temperature range studied, as shown in Fig. 6.18(d). As the MWCNT's ratio was the same, with the increase in Ag loading, the value increased, showing an enhancement in thermal conductivity. For the sample with a 20/60/20 mixing ratio, at 20°C, the thermal conductivity was noted to be 0.6339 W/m·K which was marginally lower than that of the MWCNTs/Ag hybrid solution with a conductivity of 0.6351 W/m·K. This trend persists at higher temperatures; for example, at 45°C, the tri-hybrid nanofluid exhibited a thermal conductivity of 0.7369 W/m·K, which remains slightly below the 0.7391 W/m·K recorded for the MWCNTs/Ag hybrid.

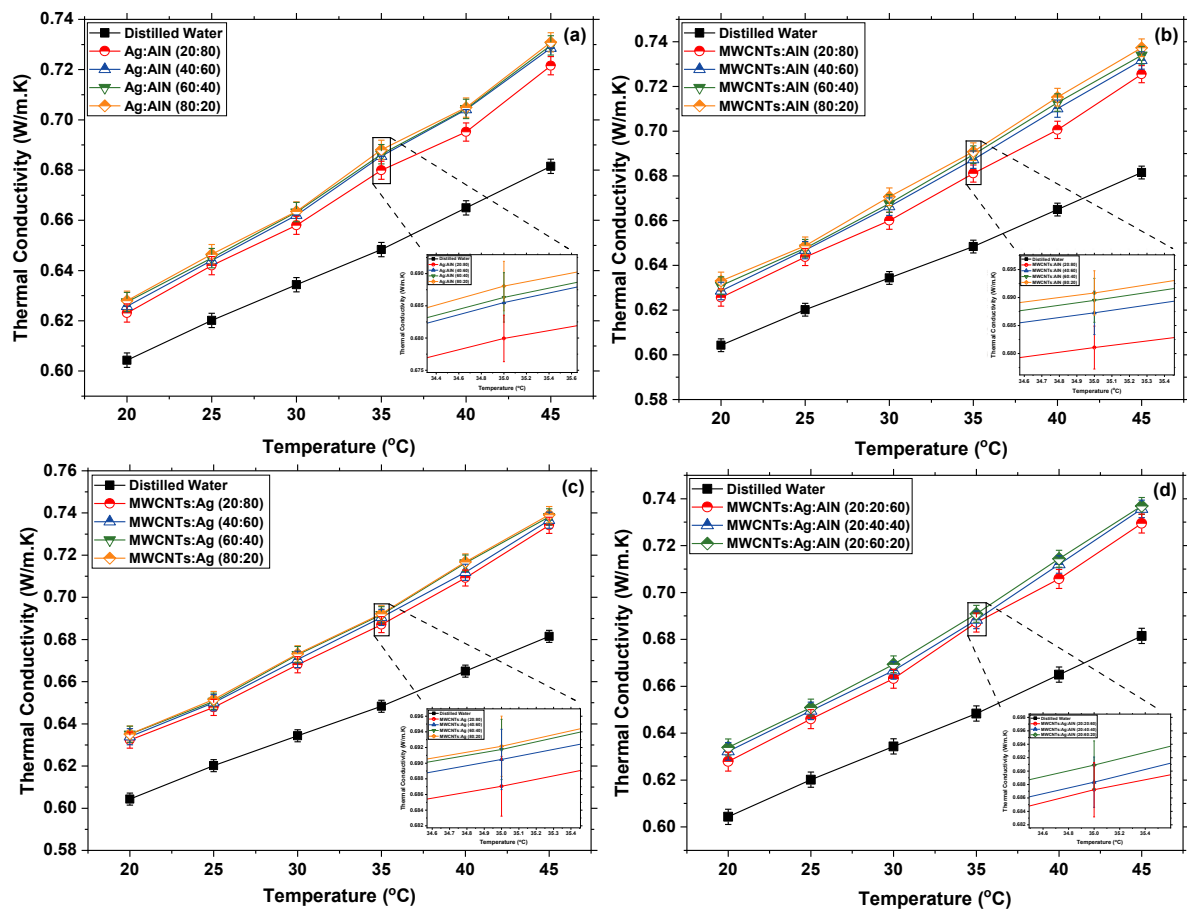


Figure 6.18. Temperature-dependent thermal conductivity of (a) Ag/AlN, (b) MWCNTs/AlN, (c) MWCNTs/Ag, (d) MWCNTs/Ag/AlN hybrid and tri-hybrid nanofluids with different mixing ratios.

The observed lower thermal conductivity in the tri-hybrid nanofluid can be attributed to the presence of AlN, which, despite its significant role in enhancing thermal pathways through its distinct shape and interaction with MWCNTs and spherical Ag particles, has a lower intrinsic thermal conductivity compared to MWCNTs. At lower temperatures, this difference is less pronounced, but as temperature increases, the thermal conductivity advantage of MWCNTs and Ag particles becomes more evident. However, the tri-hybrid nanofluid presents notable advantages in terms of long-term stability and cost-effectiveness, making it a viable alternative for applications where these factors are critical. The slightly reduced thermal conductivity must be weighed against these benefits, suggesting that the tri-hybrid formulation could be preferable in scenarios where stability and economic considerations are prioritized over marginal improvements in thermal performance.

Figure 6.19 presented the thermal conductivity enhancement of various nanofluids relative to the base fluid, water. The data highlighted the varying degrees of enhancement across different compositions at 45 °C. For the simple nanofluids, AlN exhibited a moderate enhancement of 4.997%, indicating that the inclusion of AlN nanoparticles offered a significant improvement over the base fluid. The addition of Ag nanoparticles results in a higher enhancement, with a value of 6.948%. MWCNTs provided the greatest enhancement among the simple nanofluids, with a value of 8.566%, consistent with their known superior thermal properties.

The hybrid nanofluids, which were combinations of two different nanomaterials, exhibited varying levels of thermal conductivity enhancement depending on the ratio of the components. The Ag/AlN hybrid nanofluid showed a progressive increase in thermal conductivity as the proportion of Ag increased: starting from 5.878% for a 20/80 ratio and reaching 7.244% for an 80/20 ratio. This trend highlighted the synergistic effects of combining Ag and AlN, with the thermal conductivity enhancement predominantly influenced by the higher conductive Ag component. Similarly, the MWCNTs/AlN hybrid nanofluid demonstrated increasing thermal conductivity with higher MWCNTs content, ranging from 6.455% at a 20/80 ratio to 8.191% at an 80/20 ratio. This suggested that MWCNTs dominated the enhancement due to their superior thermal conductivity properties compared to AlN. In the case of the MWCNTs/Ag hybrid nanofluid, the thermal conductivity enhancement values were higher compared to both the Ag/AlN and MWCNTs/AlN hybrids, starting at 7.723% for a 20/80 ratio and reaching 8.465% for an 80/20 ratio. The close proximity of these values to those of pure MWCNTs highlighted that while silver contributed positively, the MWCNTs largely dictated the thermal conductivity performance.

Tri-hybrid nanofluids, which combined MWCNTs, Ag, and, AlN demonstrated significant enhancements in thermal conductivity, highlighting the synergistic effects of these three materials. For the 20/20/60 formulation, thermal conductivity enhancement was recorded to be 7.036%. As the proportion of Ag increased in the 20/40/40 and 20/60/20 formulations, thermal conductivity further improved to 7.951% and 8.136%, respectively. This trend indicated that while MWCNTs played a pivotal role due to their inherent high thermal conductivity, the introduction of Ag and AlN further

amplified the heat transfer capabilities, likely due to their excellent thermal properties and ability to create a more efficient conductive network within the fluid.

When comparing the thermal conductivity enhancements across all nanofluids, it is evident that MWCNTs play a crucial role in boosting thermal performance, whether in simple, hybrid, or tri-hybrid formulations. The simple MWCNTs nanofluid achieves the highest enhancement outperforming all other simple and hybrid combinations. However, the tri-hybrid formulation with a 20/60/20 ratio nearly matches this performance, indicating that a well-balanced combination of MWCNTs, Ag, and AlN can deliver similar results. This combination also offers additional advantages, such as improved stability, cost-effectiveness, fine-tuned properties, and suitability for specific applications.

This study underscored the importance of selecting the right combination and ratio of nanomaterials to achieve the desired thermal conductivity enhancement. MWCNTs consistently demonstrated the highest potential for improving thermal conductivity, while the addition of Ag and AlN in hybrid and tri-hybrid formulations offered opportunities for fine-tuning the properties of the nanofluid to suit specific thermal management applications.

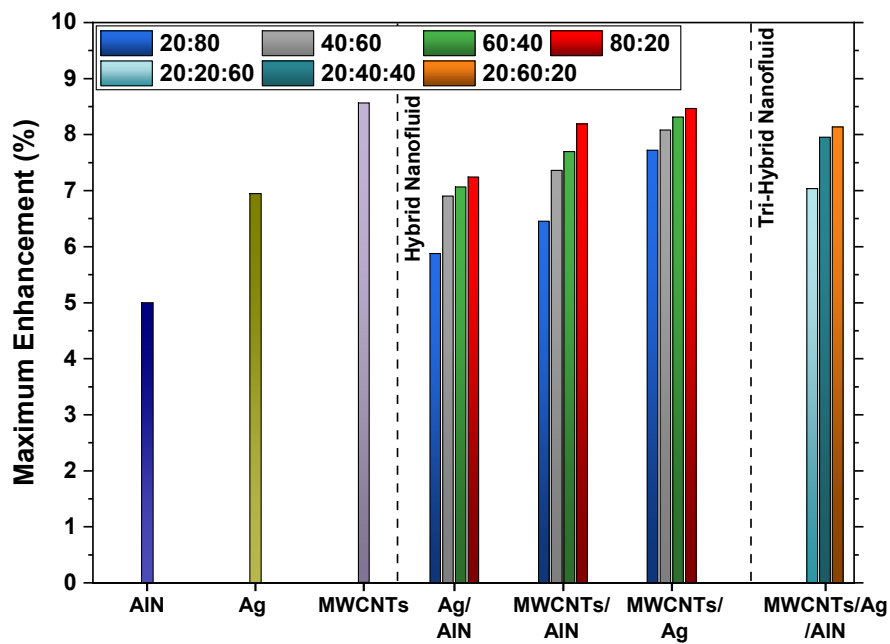


Figure 6.19. Maximum thermal conductivity enhancement of simple, hybrid, and tri-hybrid nanofluids relative to the base fluid (water).

In the pursuit of understanding how temperature influences the thermal conductivity of various nanofluids, a comprehensive analysis was conducted using Design Expert [275]. This study carried out with a high degree of statistical rigor, aimed to develop a predictive model that accurately reflects the relationship between temperature and thermal conductivity. The quadratic model that emerged from this analysis is expressed with Eq. (6.1):

$$\text{Thermal Conductivity } (k) = a + bT + 0.0000287 T^2 \quad (6.1)$$

here, k represents the thermal conductivity, T denotes temperature, and a and b are the coefficients determined through regression analysis, these coefficients are listed in Appendix E.1 (Table E.1). This model was developed with a confidence level of 95%, meaning the critical p-value threshold was set at 0.05.

The significance of the model and its individual components was evaluated through ANOVA, with the results presented in Appendix E.1 (Table E.2). As the procedure and underlying principles have already been explained in Chapter 5, they are not repeated here; instead, the resulting analysis is summarised in Appendix E.1. This analysis confirmed that the quadratic model is highly significant, demonstrating strong predictive capability and statistical reliability.

6.5.2 Viscosity

The viscosity of thermal fluid samples was assessed using the Brookfield DVNext Cone/Plate Rheometer, equipped with a CPM-40Z cone spindle and CPA-44PYZ Cup [323,324]. The spindle operated at 100 rpm, and each test lasted for 45 seconds. Temperature control within the testing chamber was ensured by connecting the cup to a thermal bath system through pipes. The Masterflex L/S Pump maintained continuous water circulation, stabilizing testing conditions, as illustrated in Fig. 6.20. A 5 ml sample was used for each experiment, following procedural guidelines. However, the level of accuracy and reproducibility is critical for obtaining reliable data, especially when assessing the performance of fluid samples under varying conditions.

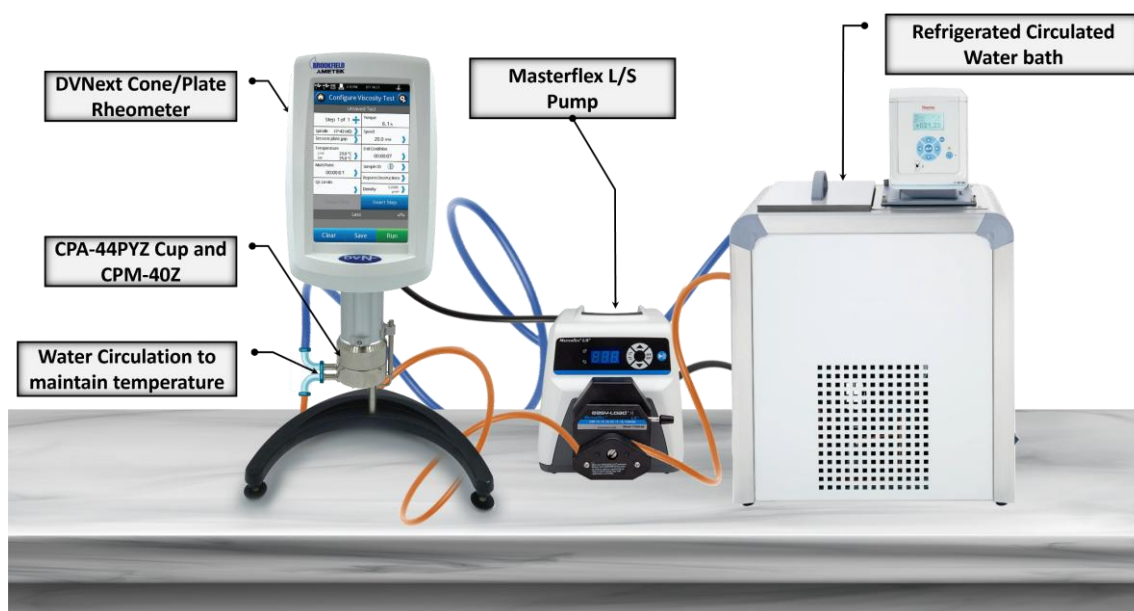


Figure 6.20. Schematic diagram of the experimental setup for viscosity measurement using the Brookfield DVNext Cone/Plate Rheometer.

The DVNext rheometer offers a measurement accuracy of $\pm 1.0\%$ of its full-scale range. Moreover, the system demonstrated excellent reproducibility, with variations between repeated measurements not

exceeding $\pm 0.2\%$. This high level of accuracy and reproducibility ensured that the data collected was consistent and dependable, minimizing the potential for significant variations between tests.

To ensure the reliability of the test rig, we conducted a series of viscosity measurements on distilled water at temperatures between 20 °C and 45 °C. These experimental values were then compared with established viscosity data for standard water found in the literature [289]. A detailed account of this validation process is provided in Chapter 5, Section 5.5.2, and is not revisited here to maintain focus and avoid duplication.

The investigation conducted at 25 °C focused on the behaviour of nanofluid samples containing 0.025 vol.% particle loading. It was observed that the AlN, Ag, and MWCNTs fluids exhibited Newtonian characteristics, where shear stress increased linearly with shear rate. To achieve variation in the shear rate, spindle speeds were adjusted between 60 and 160 rpm. The results, illustrated in Fig. 6.21, indicate that within this range, the nanofluids of AlN, Ag, and MWCNTs maintained a consistent linear relationship between shear stress and shear rate, confirming their Newtonian behaviour. However, it is important to consider the fact that increasing the particle concentration in the fluid could potentially lead to non-Newtonian behaviour [325].

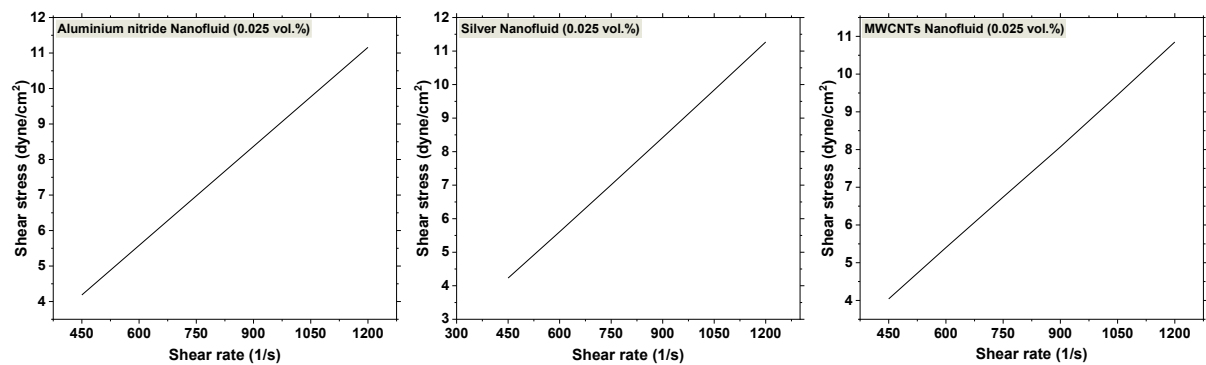


Figure 6.21. Shear stress versus shear rate graphs for (a) Aluminium nitride nanofluid, (b) Silver nanofluid, and (c) MWCNTs nanofluid, with a particle loading of 0.025 vol.%, demonstrating their Newtonian characteristics.

The concentration study carried out at 25 °C revealed a direct correlation between the increase in particle concentration and the rise in nanofluid viscosity, as depicted in Fig. 6.22. Across all three nanofluids, viscosity consistently increases as the particle concentration rises. This trend can be attributed to the fact that a higher particle load within the fluid amplifies the internal resistance to flow, leading to greater viscosity. According to the outcome, Ag nanofluid showed a gradual increase in viscosity, rising from 0.92 cP at a 0.01 vol.% concentration to 0.945 cP at 0.03 vol.%. The changes between each concentration step were relatively modest, reflecting a steady but notable rise in viscosity with the addition of more Ag nanoparticles. In a similar fashion, the AlN nanofluid showed a progressive increase in viscosity with higher particle concentrations. However, the viscosity values for AlN were slightly lower than those for Ag at each corresponding concentration, ranging from 0.915 cP

to 0.940 cP. This indicated that AlN particles contributed less to flow resistance compared to Ag particles.

In contrast, despite the high aspect ratio of MWCNTs and their potential for forming percolation networks, these particles exhibited lower viscosity. This was due to their lower density, better dispersion, and the rotational advantage of the tubes, which made the MWCNT-based fluid less viscous than those containing Ag or AlN. For MWCNTs, viscosity consistently increased from 0.90 cP to 0.925 cP, reflecting a steady trend but remaining lower compared to the other nanofluids.

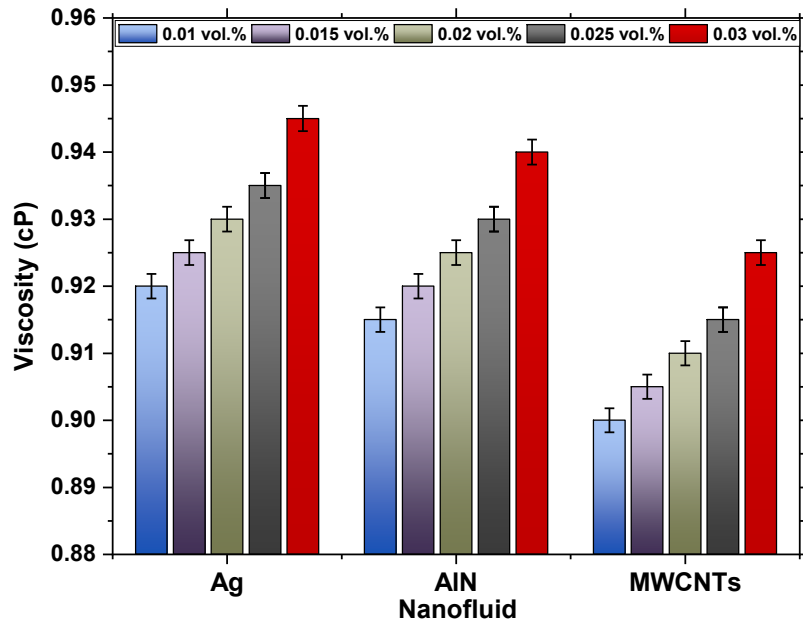


Figure 6.22. Viscosity of nanofluids at different particle concentrations.

These findings underscore the significant impact of particle concentration on the flow characteristics of nanofluids. As more particles are introduced into the fluid, they create additional frictional forces that impede the movement of the fluid layers, thereby increasing viscosity. The observed proportional increases in viscosity for each nanofluid type suggest that careful control of particle concentration is essential when tailoring the rheological properties of nanofluids for specific applications.

The viscosity of water and various nanofluids was plotted against temperature, as illustrated in Fig. 6.23. The results indicated a general trend of decreasing viscosity with increasing temperature across all fluids. Among the nanofluids, Ag nanofluid exhibited the highest viscosity enhancement compared to water, with values ranging from 1.06 cP at 20°C to 0.62 cP at 45°C. This significant enhancement was likely due to the higher density and potential agglomeration of Ag nanoparticles. Despite having a density three times lower than Ag, the AlN nanofluid showed viscosity values that closely approached those of the Ag nanofluid. This behaviour could be attributed to the unique morphology of AlN nanoparticles and the formation of clusters driven by strong attractive forces, which collectively augmented the viscosity. Notably, at temperatures above 35°C, the viscosity values of Ag and AlN became almost indistinguishable. This effect is particularly observed in formulations prepared with low

particle concentrations. However, at higher concentrations (above 1 vol%), the difference was expected to be more pronounced, persisting even at elevated temperatures. In contrast, the MWCNTs nanofluid showed lower viscosity values, ranging from 1.03 cP to 0.615 cP as the temperature increased from 20°C to 45°C.

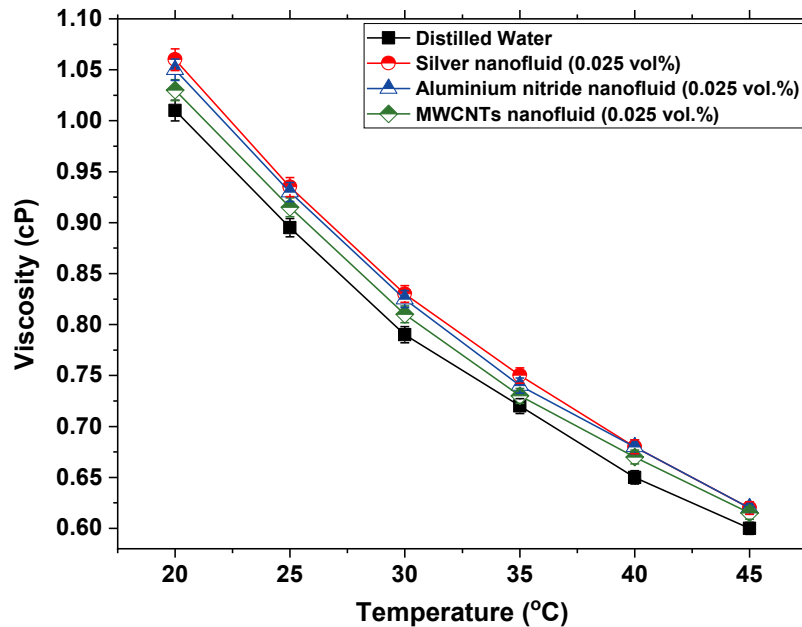


Figure 6.23. Temperature-dependent viscosity of distilled water and various nanofluids.

Throughout the observed temperature range, the viscosity of the MWCNTs nanofluid consistently remained below that of the Ag and AlN nanofluids. The lower viscosity in the MWCNTs nanofluid can be attributed to its lower density and the "rolling effect" of the carbon nanotubes, which reduces resistance to flow. Although the formation of a percolation network, where nanotubes form a continuous network, could have contributed to a slight increase in viscosity, it remained lower than that of the Ag and AlN nanofluids.

The findings highlight the complex interplay between nanoparticle characteristics such as density, morphology, and inter-particle interactions in determining the viscosity of nanofluids. The distinct behaviours of Ag, AlN, and MWCNTs nanofluids underscore the importance of considering these factors when formulating nanofluids for specific applications, particularly those where temperature-dependent viscosity is a critical parameter.

The viscosity of the hybrid nanofluids exhibited variations dependent on both the type of particles used and their mixing ratios, as shown in Fig. 6.24. For the MWCNTs/AlN hybrid nanofluid with a 20/80 ratio, like pure nanofluids viscosity exhibited a temperature-dependent behaviour, decreasing from 1.05 cP at 20°C to 0.62 cP at 45°C. Notably, these viscosity values were found to be marginally lower than those observed for the pure AlN nanofluid, while maintaining a similar overall trend. The observed reduction in viscosity can be attributed to the inclusion of MWCNTs, which generally possess lower viscosity and contribute to minimising particle clustering, thereby reducing overall viscosity. As the AlN content decreased to 60% and 40%, a modest decrease in viscosity was observed at lower

temperatures. However, at elevated temperatures, the viscosity values for these ratios converged closely. For the 80/20 ratio, viscosity values ranged from 1.035 cP at 20°C to 0.62 cP at 45°C. In this case, the difference in viscosity values was more noticeable; the values were closer to but higher than those of pure MWCNTs.

Fig. 6.24(b) presented the viscosity values for the Ag/AlN hybrid formulation, showing that its viscosity values consistently exceeded those of the MWCNTs/AlN hybrid samples across the temperature range studied. At a 20/80 mixing ratio, the fluid viscosity was noted to be 1.05 cP at 20°C, gradually decreased to 0.62 cP at 45°C. When the mixing ratio shifted to 40/60, the viscosity values exhibited a slight increase across all temperatures compared to the 20/80 ratio. At 20°C, the value augmented to 1.055 cP, indicating a slight enhancement due to the increased proportion of silver. This trend continued as the temperature increased, with the viscosity slightly higher than that of the 20/80 ratio at each corresponding temperature point. By 45°C, the viscosity aligned with the 20/80 formulation as the viscosity was observed to be 0.62 cP, indicating that the difference in viscosity between these two ratios diminished as the temperature increased. In the case of a 60/40 mixing ratio, the viscosity values were consistently the highest among all the Ag/AlN formulations. The viscosity at this ratio was noticeably higher than the other ratios, reflecting the combined effects of silver's higher density and the AlN nanoparticles' potential for forming an intricate particle network. As the temperature increased, the viscosity decreased more sharply, though it remained slightly above the other ratios and reached to 0.62 cP at 45°C, like the other mixing ratios. With a small decrease, the 80/20 mixing ratio produced viscosity values that were close to those of the 20/80 ratio, starting at 1.05 cP at 20°C and gradually reducing to 0.62 cP at 45°C.

Fig. 6.24(c) presented the results for the MWCNTs/Ag hybrid formulations. At a 20/80 mixing ratio, the viscosity values were observed to be the highest among the various ratios tested. The maximum viscosity value recorded was 1.06 cP at 20°C, which decreased to 0.63 cP as the temperature increased to 45°C. However, as the proportion of MWCNTs increased, due to the influence of low density particles, a noticeable decrease in viscosity value was observed. With a further increase in MWCNTs to a 60/40 ratio, the viscosity values decreased slightly more compared to the 40/60 ratio, reaching 1.04 cP at 20°C and 0.62 cP at 45°C. Finally, the 80/20 mixing ratio which had the highest MWCNTs content, exhibited the lowest viscosity values across all the MWCNTs/Ag ratios. This result indicated that the viscosity values of the 80/20 ratio were close to that of pure MWCNTs, suggesting that the influence of the silver nanoparticles was minimal at this composition.

The viscosity data for the tri-hybrid nanofluid, plotted in Fig. 6.24(d), revealed that the presence of particles with different shapes and the formation of complex structures or agglomerates result in slightly higher viscosity values. For the 20/20/60 formulation of MWCNTs/Ag/AlN, where the proportion of Ag is relatively low, the viscosity values were found to be close to those of pure Ag, ranging from 1.055 cP to 0.62 cP. However, when the formulation was altered to 20/40/40, the viscosity values augmented

to slightly higher than those of pure Ag. Further increasing the Ag content 20/60/20 formulation resulted in even higher viscosity, reaching 1.06 cP at 20°C and 0.625 cP at 45°C.

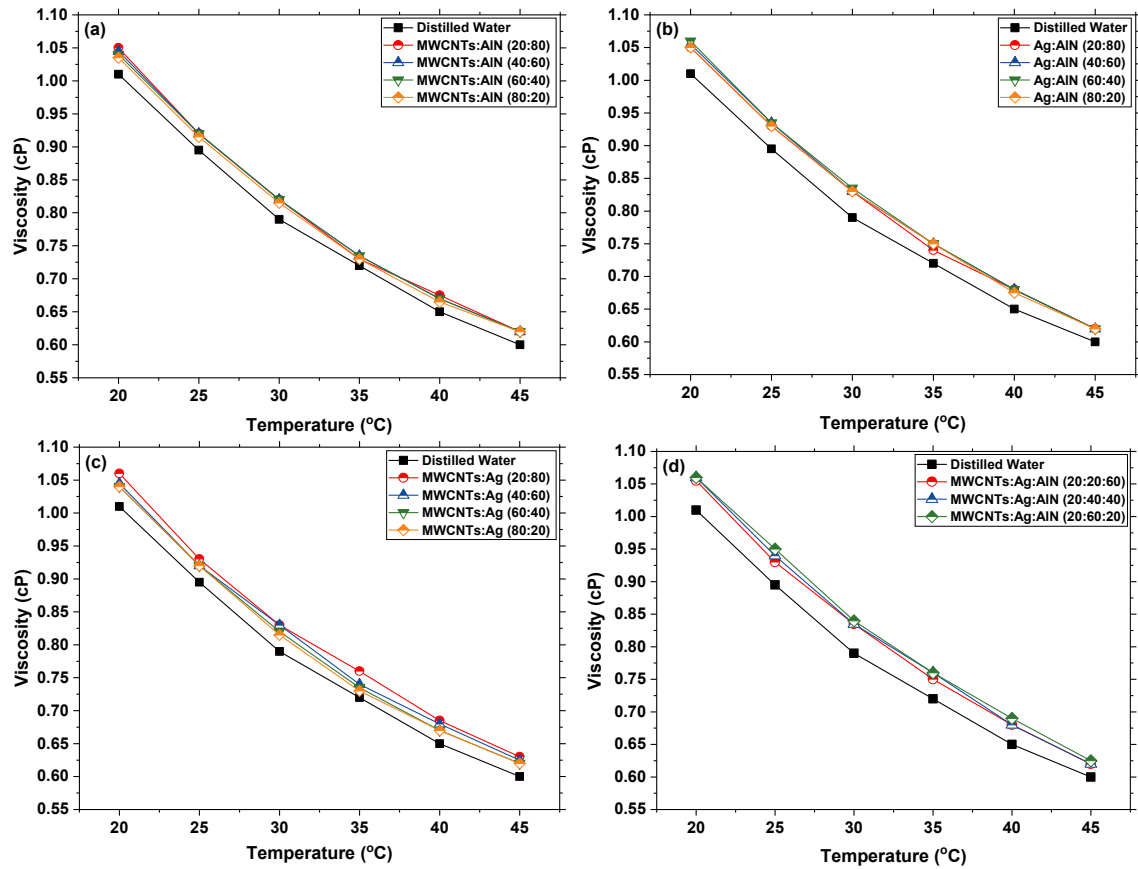


Figure 6.24. Temperature-dependent viscosity of (a) MWCNTs/AlN, (b) Ag/AlN, (c) MWCNTs /Ag, (d) MWCNTs/Ag/AlN hybrid and tri-hybrid nanofluids with different mixing ratios.

Comparing these mixing ratios, the viscosity differences are most pronounced at lower temperatures. At these lower temperatures, the impact of high-density particles on viscosity was more pronounced. As the temperature increases, the viscosity values converge, particularly at 45°C, where all mixing ratios show nearly identical viscosities. This convergence indicates that temperature plays a crucial role in the viscosity of these hybrid nanofluids. Notably, this effect is more evident in formulations with lower particle concentrations. However, with higher particle concentrations > 1 vol%, the viscosity differences could remain more pronounced, even at elevated temperatures. Figure 6.25 presents a comparison of the average percentage increase in viscosity for different types of nanofluids relative to water. The results concluded that among the unitary nanofluids, Ag nanofluid exhibited the highest average percentage increase in viscosity, with an average increase of 4.43%. This was followed by AlN nanofluid with a 3.84% increase and MWCNTs nanofluid with a 2.89% increase.

In the case of hybrid nanofluids, formulations containing Ag and AlN generally displayed higher viscosity enhancements compared to hybrids involving MWCNTs and AlN, or MWCNTs and Ag. However, the MWCNTs/Ag 20/80 hybrid stood out with a significant viscosity increase of 4.98%,

likely due to the formation of an intricate percolation network or agglomerates between MWCNTs and Ag at this ratio. Notably, the Ag/AlN hybrid with a 60/40 ratio achieved a significant viscosity increase of 4.54%. The MWCNTs/Ag/AlN ternary hybrid formulations exhibited even more pronounced effects, with the 20/60/20 ratio resulting in the highest average viscosity increase of 5.55%, indicating a strong synergistic interaction between the three components. These findings suggested that while all nanofluids increased viscosity compared to water, the extent of this increase was strongly dependent on the specific combination and ratio of nanoparticles used, with ternary hybrids offering the most substantial enhancements. This implied potential for tailored viscosity control in heat transfer applications, where both thermal conductivity and fluid dynamics were critical considerations.

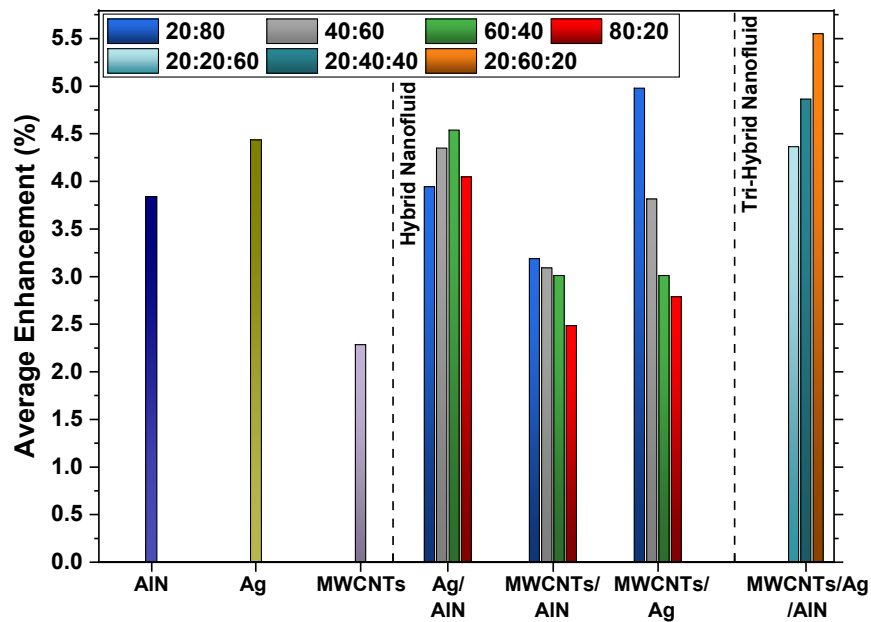


Figure 6.25. Average percentage increase in viscosity for different types of nanofluids relative to water.

An analysis was conducted to develop a predictive model for estimating nanofluids' viscosity values as a temperature function. In this study, a cubic model was formulated to capture the non-linear relationship between viscosity and temperature, represented with Eq. (6.2). The inclusion of the cubic term was crucial to account for the complex behaviour of viscosity at higher temperatures, which simpler linear or quadratic models might fail to capture adequately. This equation served as the basis for further analysis, where its predictive accuracy was evaluated using various statistical measures. The model's significance was assessed by performing an ANOVA analysis, which provided a detailed evaluation of how well the model explained the variability in viscosity data. As presented in Table Appendix E.2 (Table E.3), the results indicated that the model was highly significant, with a p-value < 0.0001. Temperature emerged as the most influential factor, exhibiting a very high F-value and low p-value. The type of nanofluid also played a crucial role in determining viscosity, as indicated by its significance in the model. Interaction terms between fluid type and temperature, as well as the quadratic

and cubic temperature terms, contributed to capturing the non-linear relationship between viscosity and temperature.

$$\text{Viscosity } (\mu) = c - dT + e(T^2) - 3.918 \times 10^{-6}(T^3) \quad (6.2)$$

Here, T denotes the temperature, and the coefficients c , d , and e are constants derived from the dataset. The values of these coefficients are given in Appendix E.2 (Table E.4).

The viscosity data were evaluated using ANOVA, and the detailed statistical outputs are presented in Appendix E.2. The findings verify that the developed model is statistically significant and reliably captures the temperature–viscosity relationship.

6.5.3 Density

Density is a vital thermo-physical property that plays a significant role in various applications, particularly in enhancing pumping efficiency and optimising mass flow rates. In this part of study, the densities of both base fluids and nanofluids were assessed using a DMA 35 density meter from Anton Paar at varying temperatures and concentrations or mixing ratios for hybrid nanofluids. The meter offers an accuracy of ± 0.2 °C for temperature and ± 0.001 g/cm³ for density measurements. Additionally, it demonstrates repeatability of ± 0.1 °C for temperature and ± 0.0005 g/cm³ for density. To perform the testing, the fluid samples were poured into a sample tube submerged in a temperature-controlled bath, as shown in Fig. 6.26. This setup ensured that the temperature of the samples could be accurately maintained throughout the testing process. Sufficient time was allowed for the samples to reach thermal equilibrium; density measurements were then conducted according to a predetermined protocol. Like thermal conductivity and viscosity, the density measurement setup was validated by recording experimental data across a temperature range of 15 °C to 45 °C.

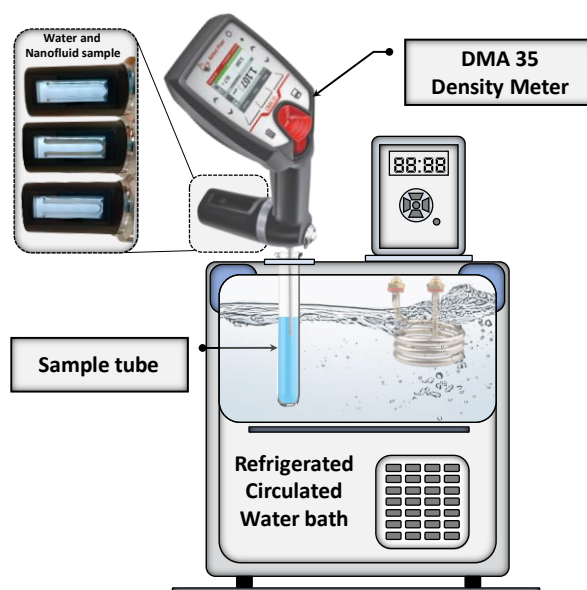


Figure 6.26. Schematic representation of the experimental rig used for density measurements.

The obtained experimental results were then compared with data provided by the supplier as well as with values reported in relevant scientific literature. This comparison served to validate the accuracy of the experimental setup. As this validation has already been addressed in detail in Chapter 5, Section 5.5.3, it is not reiterated here. This thorough comparison aimed to ensure the accuracy and consistency of the experimental findings. The results demonstrated a high degree of concordance with both the supplier's data and the published values, confirming the reliability and accuracy of the experimental measurements.

The density of samples prepared with varying concentrations ranging from 0.01 vol.% to 0.03 vol.% was evaluated at 30°C, as presented in Fig. 6.27. The findings indicate that fluids containing suspensions of denser particles exhibited higher density values. Notably, the density increased with particle concentration across all types of nanoparticles. Among the tested nanofluids, the Ag nanofluid demonstrated the highest density, with values ranging from 0.9967 g/cm³ to 0.9990 g/cm³ as the concentration increased from 0.01 vol.% to 0.03 vol.%. AlN samples secured the second place in the list displaying a moderate increase in density, with values rising from 0.9964 g/cm³ to 0.9968 g/cm³ over the same concentration range. Finally, MWCNTs followed a similar trend, with density values increased from 0.9962 g/cm³ at 0.01 vol.% to 0.9966 g/cm³ at 0.03 vol.%. However, the impact of MWCNTs on density was slightly less pronounced than that of Ag nanoparticles, due to the lower density of these particles.

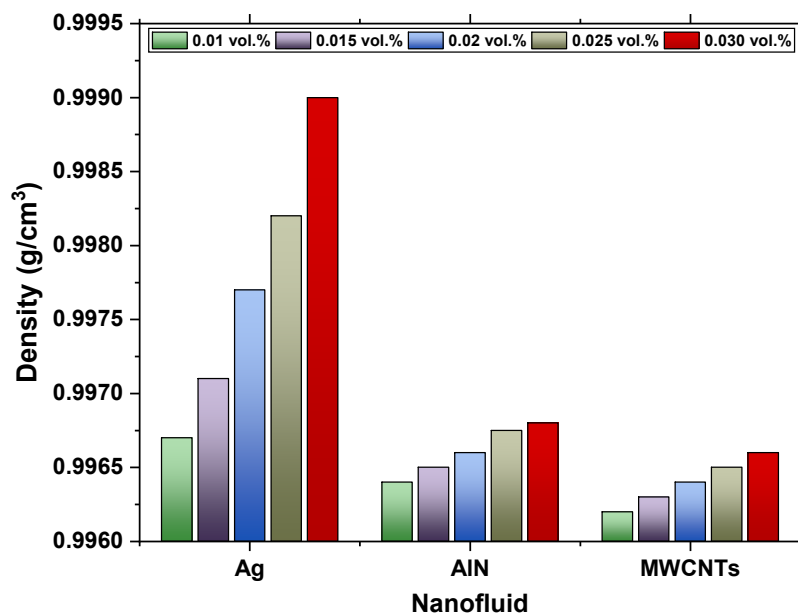


Figure 6.27. Density of Ag, AlN, and MWCNTs nanofluids at various concentrations.

As part of this study, the density of water, Ag, MWCNTs, and AlN nanofluids was measured across a temperature range of 20°C to 45°C, as depicted in Fig. 6.28. It was observed that the density of both water and nanofluids decreased with increasing temperature in a non-linear way. According to the results, for pure water, the density decreased from 0.9982 g/cm³ at 20°C to 0.9901 g/cm³ at 45°C. The addition of nanoparticles resulted in higher density values compared to pure water. Silver nanofluid

exhibited higher densities than pure water at all temperatures, ranging from 1.0009 g/cm³ at 20°C to 0.9926 g/cm³ at 45°C. Despite the decrease in density with temperature, the values remained higher due to the high density of silver nanoparticles. The smaller decrement in density with temperature, compared to water, suggested significant contributions from the silver nanoparticles.

As discussed earlier, AlN nanofluid displayed a moderate density, however, with temperature rise the values ranged from 0.99935 g/cm³ at 20°C to 0.9912 g/cm³ at 45°C. The AlN nanofluid density was higher than that of pure water but lower than Ag nanofluid. The MWCNTs nanofluid showed comparatively lower density values at all temperatures, ranging from 0.9988 g/cm³ at 20°C to 0.9907 g/cm³ at 45°C. The results concluded that all samples exhibited a decrease in density with rising temperature, consistent with the expected thermal expansion. This observation underscores the potential of hybrid nanofluids, where selecting and combining different nanoparticles could be strategically utilised to tailor properties for specific applications, optimising performance based on desired density and thermal characteristics.

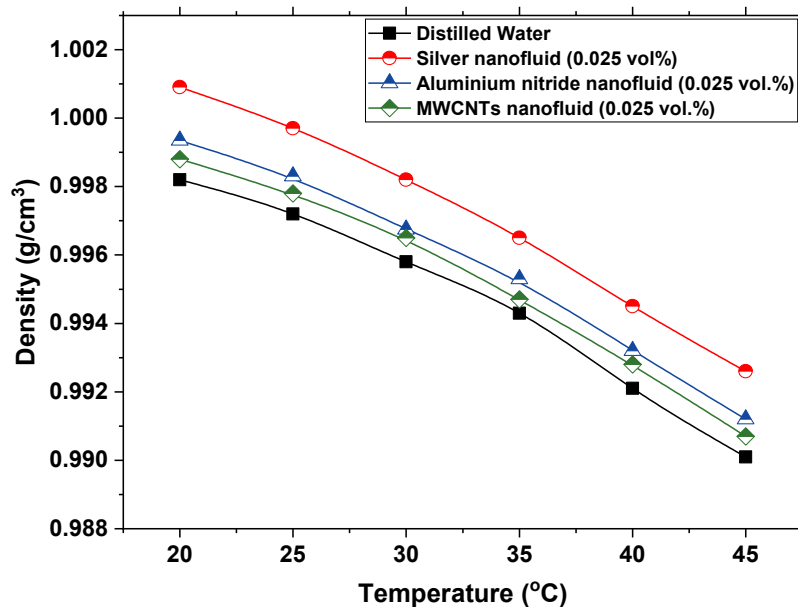


Figure 6.28. Density comparison of water, Ag, AlN, and MWCNTs nanofluids across a temperature range of 20°C to 45°C.

Similar to thermal conductivity and viscosity, in the case of hybrid and tri-hybrid nanofluids, the density varies based on the combination and mixing ratio of the nanoparticles, as illustrated in Fig. 6.29. The density results of the Ag/AlN hybrid nanofluid demonstrated that as the proportion of Ag increased, the overall density of the nanofluid also increased, with the 80/20 Ag/AlN mixture consistently exhibiting the highest density at all temperatures, as illustrated Fig. 6.29(a). Additionally, it was observed that across all mixing ratios, the density decreased with rising temperature.

For the 20/80 mixing ratio, the density decreased from 0.9997 g/cm³ to 0.9915 g/cm³ as the temperature increased from 20°C to 45°C, while for the 80/20 mixture, it decreased from 1.0005 g/cm³ to 0.9924

g/cm^3 over the same temperature range. The findings revealed that the rate of density decrease was slightly more pronounced in mixtures with lower Ag content, though the overall trend remained consistent, indicating a predictable thermal response across different compositions. For the MWCNTs/AlN hybrid sample, a notable decrease in density was observed with an increasing proportion of MWCNTs, as depicted in Fig. 6.29(b). However, this reduction was less pronounced compared to the Ag/AlN hybrid. The maximum and minimum density value was recorded to be 0.9992 g/cm^3 for the 20/80 mixing ratio at 20°C , and 0.9908 g/cm^3 for the 80/20 ratio at 45°C , respectively.

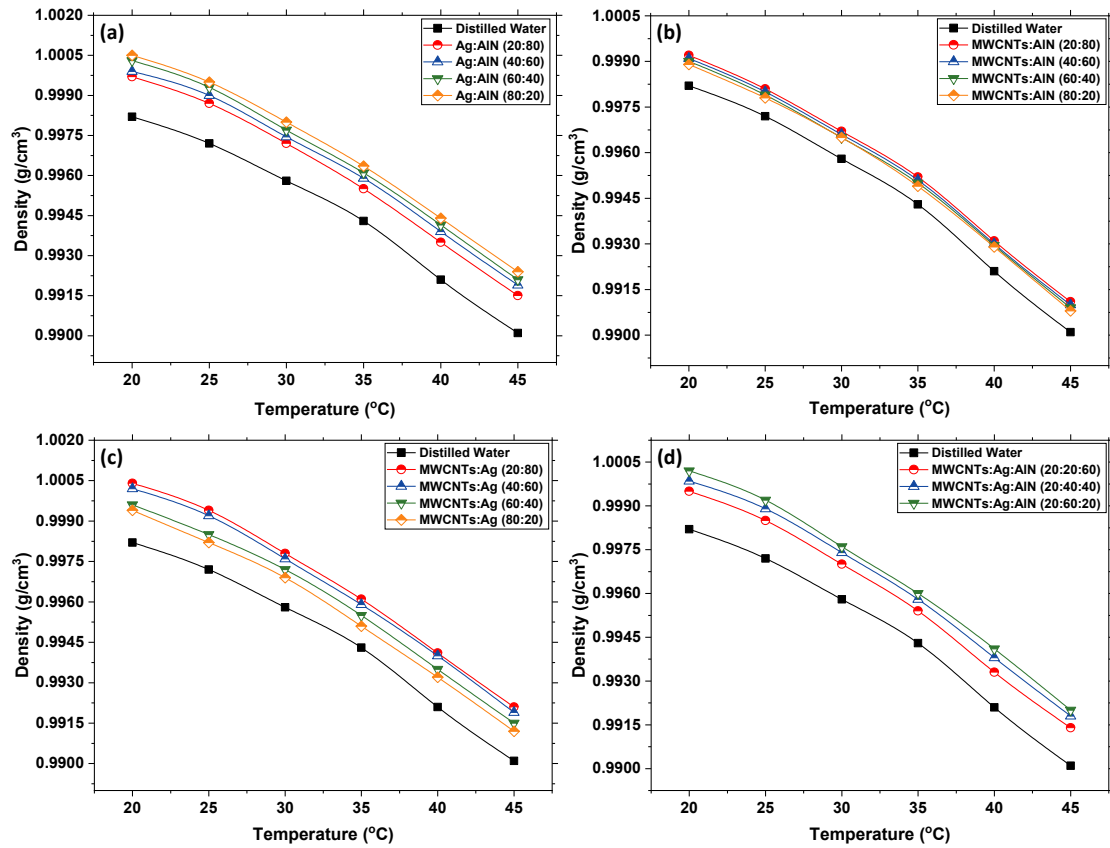


Figure 6.29. Density of (a) Ag/AlN (b) MWCNTs/AlN, (c) MWCNTs/Ag, (d) MWCNTs/Ag/AlN hybrid and tri-hybrid nanofluids hybrid nanofluids at various mixing ratios across a temperature range of 20°C to 45°C .

The density data for the MWCNTs-Ag hybrid nanofluid followed similar trends to those observed in other hybrid nanofluids. As the proportion of Ag in the MWCNTs-Ag hybrid sample increased, the overall density of the nanofluid also increased, with the 80/20 Ag/MWCNTs mixture showing the highest density at all temperatures, Fig. 6.29(c). This trend mirrored the behaviour observed in the Ag/AlN hybrids. At 20°C , the density ranged from 1.0004 g/cm^3 for the 20/80 Ag/MWCNTs mixture to 0.9994 g/cm^3 for the 80/20 mixture. By 45°C , the density values had decreased to between 0.9921 g/cm^3 and 0.9912 g/cm^3 . Finally, Fig. 6.29(d) illustrates the density results for the tri-hybrid nanofluid MWCNTs/Ag/AlN across various mixing ratios. The densities varied with the ratio of nanoparticles, at 20°C , the 20/20/60 formulation exhibited a density of 0.9995 g/cm^3 , the 20/40/40 sample showed a

slightly higher density of 0.99985 g/cm³, and the 20/60/20 ratio presented the highest density at 1.0002 g/cm³. As the temperature increased to 45°C, all formulations exhibited a consistent decrease in density, with the 20/20/60 ratio dropping to 0.9914 g/cm³, the 20/40/40 ratio to 0.9918 g/cm³, and the 20/60/20 ratio to 0.9920 g/cm³. The findings demonstrated that the overall trend of density reduction with rising temperature was uniform across all ratios, with the 20/40/40 mixture showing a moderate response relative to the other compositions.

Fig. 6.30 provided insights into the average percentage increase in density values of pure, hybrid, and tri-hybrid nanofluids relative to their base fluids. For pure fluids, the enhancements were recorded to be 0.10724%, 0.24631%, and 0.06033% for AlN, Ag, and MWCNTs, respectively. In hybrid formulations, the Ag/AlN mixtures exhibited increasing density with higher Ag content, peaking at 0.22538% for the 80/20 ratio, while the MWCNTs/AlN hybrids showed decreasing density as the proportion of AlN increased, ranging from 0.09552% for the 20/80 ratio to 0.06871% for the 80/20 ratio.

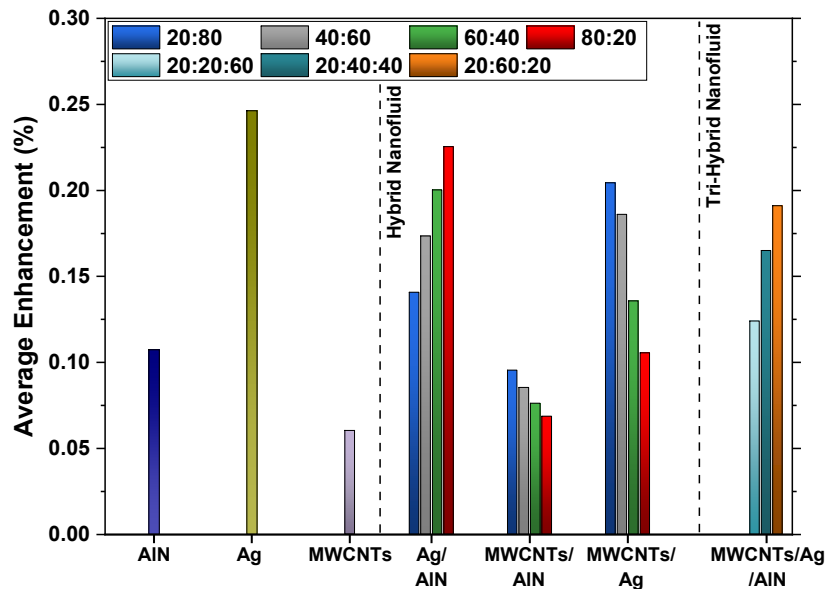


Figure 6.30. Average percentage increase in density values of pure, hybrid, and tri-hybrid nanofluids relative to their base fluids.

As anticipated, the density of the MWCNTs/Ag hybrid samples increased with higher silver content. The mixture with a 20/80 ratio achieved the highest density of 0.20441%, whereas the 80/20 mixture exhibited the lowest density at 0.10557%. For the tri-hybrid MWCNTs/Ag/AlN nanofluids, the density varied with different component ratios. The 20/60/20 ratio showed the greatest increase in density at 0.19102%, followed by the 20/40/40 ratio at 0.16506%, and the 20/20/60 ratio at 0.124%. Future work could explore the implications of these density changes on the thermal and flow properties of the nanofluids to further optimise their practical applications.

The ANOVA analysis was conducted to develop a predictive model for calculating the density of various fluids as a function of temperature. The statistical output indicates that the model is highly

significant, with a p-value of less than 0.0001 and an F-value of 3016.56. The results suggested that the model has a strong ability to predict density accurately. Additionally, the analysis revealed that both the fluid type and temperature significantly influenced density, with temperature having a particularly large effect (F-value of 1.62E+05) compared to the fluid type (F-value of 445.15). The resulting equation from the analysis for predicting density (ρ) was represented with Eq. (6.3).

$$\text{Density } (\rho) = f + gT - h(T^2) + 1.00975 \times 10^{-7}(T^3) \quad (6.3)$$

This equation captured the relationship between density and temperature, where T represented temperature, and the coefficients f , g , and h represented constants derived from the analysis, as listed in Appendix E.3 (Table E.6). The inclusion of both linear and non-linear terms (such as T^2 and T^3) allowed the equation to accurately model the complex temperature dependence of fluid density, full statistical results provided in Appendix E.3.

6.6 Cost Analysis

Cost analysis plays a crucial role in the development and application of nanofluids, as an increase in performance accompanied by a significant rise in cost is typically undesirable. In this section, we have evaluated and compared the preparation costs of various nanofluids, which include expenses related to nanoparticles, base fluids, and surfactants. However, the costs associated with laboratory resources, such as electricity used during sonication and stirring operations, are not included in this analysis since they remain constant across all samples. Additionally, the labour costs are also omitted for the same reason.

The primary contributor to the overall cost is the price of nanoparticles, underscoring the importance of selecting and optimising these materials carefully. This cost analysis also aims to encourage researchers to design more cost-effective methods for preparing nanofluids while enhancing particle suspension times. The costs for preparing 1000 ml of pure, hybrid, and tri-hybrid nanofluids with a 0.025 vol.% concentration have been estimated and are presented in Fig. 6.31. It is important to note that while the price of MWCNTs is significantly higher than that of silver nanoparticles, the fluids were prepared based on volume percentage rather than weight percentage. This approach required a larger quantity of silver nanoparticles to achieve the same volume fraction in the fluid, resulting in final costs that are nearly the same for both fluids. Consequently, despite MWCNTs having much higher thermal conductivity, the difference in thermal conductivity between the silver and MWCNTs nanofluids was not substantial. However, the cost for silver nanofluids was calculated to be £90.27, while for MWCNTs fluids, it was £89.39. On the other hand, the cost for AlN was much lower at £15.82. The lower cost and better thermal characteristics of AlN in comparison to other nitrides and oxides were the key factors in its selection for this study, particularly for use in combination with silver and MWCNTs to prepare hybrid nanofluids.

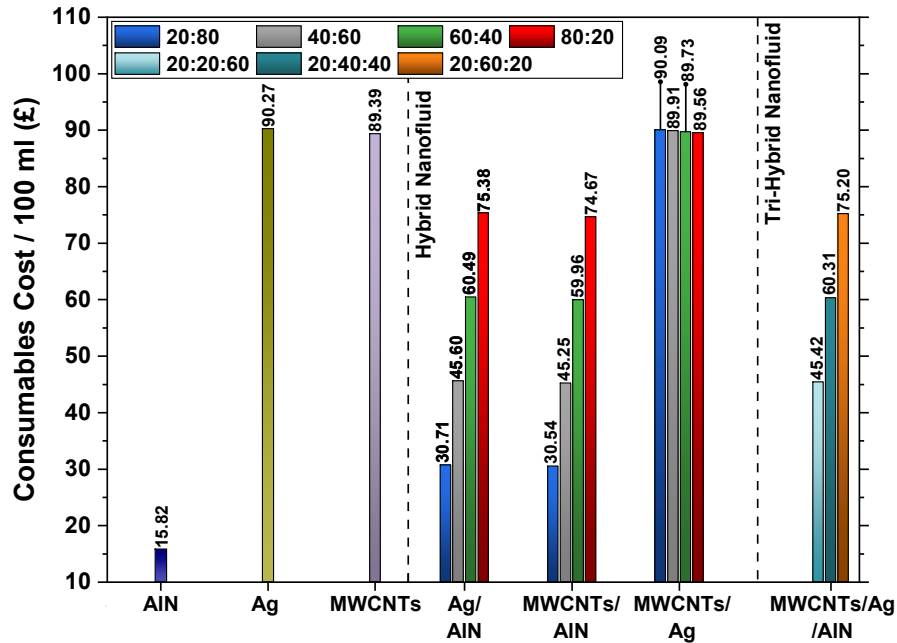


Figure 6.31. Estimated costs for preparing 1000 ml of pure, hybrid, and tri-hybrid nanofluids.

The cost of hybrid nanofluids varied depending on the mixing ratio and the specific nanoparticles used. For Ag/AIN hybrids, the cost ranged from £30.17 to £75.38 as the proportion of silver increased from 20% to 80%. Similarly, the cost of MWCNTs/AIN hybrids ranged from £30.54 to £74.67, with only minor variations. Since the preparation costs for Ag and MWCNTs nanofluids were nearly identical, the cost of their hybrids also hovered around £90. In the case of tri-hybrid nanofluids, where the MWCNTs content was fixed at 20% across all samples, the cost varied depending on the proportion of silver, ranging from £45.42 to £75.20. Based on these findings, when cost is given equal importance as thermal performance, the tri-hybrid with a 20/40/40 mixing ratio is the most cost-effective choice. However, in applications where thermal performance is a higher priority, the 20/60/20 tri-hybrid solution is recommended.

Interestingly, some hybrid nanofluids have costs comparable to tri-hybrids. However, tri-hybrid solutions are often preferred due to their longer-term stability and superior performance in high-flow-rate applications. This balance of cost and performance makes the tri-hybrid options particularly attractive for a wide range of practical applications.

6.7 Conclusion

This study has comprehensively examined the thermophysical properties of hybrid and tri-hybrid nanofluids composed of MWCNTs, AIN, and Ag, with the goal of optimising their thermal performance, stability, and cost-effectiveness for potential thermal management applications. The findings have highlighted critical aspects of nanofluid formulation, particularly the impact of volumetric

ratios, cost considerations, and surfactant selection on the performance of these advanced fluids. Through meticulous experimentation, several key insights were obtained, which are summarized below.

- The SDBS surfactant was identified as the most effective in maintaining nanoparticle suspension, contributing to the long-term stability of the nanofluids. The stability study revealed that hybrid and tri-hybrid nanofluids exhibited longer stability compared to pure fluids.
- The thermal conductivity of all nanofluid samples increased significantly with temperature, with more pronounced improvements observed beyond 30°C. Additionally, a substantial increase in thermal conductivity was observed with higher particle concentrations; however, it is crucial to select an appropriate concentration to maintain stability.
- Among the pure nanofluids, MWCNTs showed the highest improvement in thermal conductivity, achieving an 8.566% increase, followed by silver and AlN with enhancements of 6.948% and 4.997%, respectively.
- Hybrid and tri-hybrid nanofluids demonstrated significant enhancements in thermal conductivity. The tri-hybrid formulation MWCNTs/Ag/AlN (20/60/20) achieved a comparable thermal conductivity enhancement of 8.136%, with better stability and cost effectiveness, highlighting the effectiveness of combining multiple nanoparticles.
- Nanofluids containing AlN, Ag, and MWCNTs at a concentration of 0.025 vol.% exhibited Newtonian behaviour. Their viscosity remained constant across different shear rates, which is a characteristic property of Newtonian fluids.
- Viscosity decreased as temperature increased across all tested fluids; however, increasing nanoparticle concentration led to a corresponding rise in viscosity. Beyond 40°C, the difference in viscosity values was minimal due to the lower particle concentration, though it could be more significant for fluids prepared with higher concentrations.
- The most pronounced increase in viscosity was observed in the tri-hybrid nanofluid, due to the presence of particles with different morphologies. Among the pure nanofluids, Ag nanofluid exhibited the highest average percentage increase of 4.43% in viscosity, followed by AlN at 3.84% and MWCNTs at 2.89%. In hybrid nanofluids, the MWCNTs/Ag/AlN ternary formulation with a 20/60/20 ratio showed the most significant viscosity enhancement, with an average increase of 5.55% compared to water.
- The density of the nanofluids increased with particle loading and decreased with rising temperature. The highest density increase was recorded for Ag nanofluids at 0.24631%, while the maximum density for hybrid nanofluids was 0.22538%, observed in the 80/20 Ag/AlN formulation.
- The study found that while MWCNTs is the most expensive component, its superior thermal properties justify its inclusion in smaller proportions, particularly in tri-hybrid configurations. Among the formulations, the tri-hybrid nanofluid with a 20/40/40 ratio emerged as the most cost-effective, providing a balanced approach between performance and economic feasibility. For

applications where thermal performance is paramount, the tri-hybrid nanofluid with a 20/60/20 ratio offers the best compromise, despite its higher viscosity and cost.

- Finally, the developed models for predicting the properties as a function of temperature showed exceptional statistical reliability. However, to replicate results and enhance predictive accuracy, it is recommended to use particles with the same morphology and consistent preparation techniques.

This study lays the groundwork for further exploration into hybrid and tri-hybrid nanofluids, emphasizing the need for a balanced approach that optimises both performance and cost-effectiveness. Further investigations should explore the long-term stability and thermophysical performance of these nanofluids under dynamic flow and thermal cycling conditions that mimic real-world operating environments, such as those in electronic cooling systems, battery thermal management, or solar thermal collectors. Advanced characterisation techniques like in-situ TEM or SAXS could be employed to monitor nanoparticle dispersion and agglomeration over time. Moreover, machine learning models and optimisation algorithms could be integrated to predict and fine-tune optimal nanoparticle ratios for targeted applications. The exploration of eco-friendly or biodegradable surfactants and base fluids would also enhance the sustainability of nanofluid applications. Finally, pilot-scale or field-level demonstrations should be conducted to validate the laboratory findings and assess the practical feasibility and cost-effectiveness of deploying these advanced hybrids and tri-hybrid nanofluids in industrial thermal systems.

CHAPTER 7

7 Performance Evaluation of Bio-Inspired Hybrid Pin-Fin Heat Sinks Using Mono and Hybrid Nanofluids

In the previous chapters, the thermophysical characterisation of mono, binary, and tri-hybrid nanofluids was thoroughly explored, alongside a comprehensive presentation of the literature review, experimental setup, heat sink configurations, performance parameters, and validation procedures. Building upon those foundations, this chapter presents a detailed thermal and hydraulic performance comparison of two advanced biomimetic heat sink configurations: the Inline Arranged Airfoil Integrated Curvilinear Pin-Fin (IACPF) and the Inline Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin (AICCPF). These geometries were designed to promote enhanced fluid mixing and flow uniformity while maintaining manageable pressure drops.

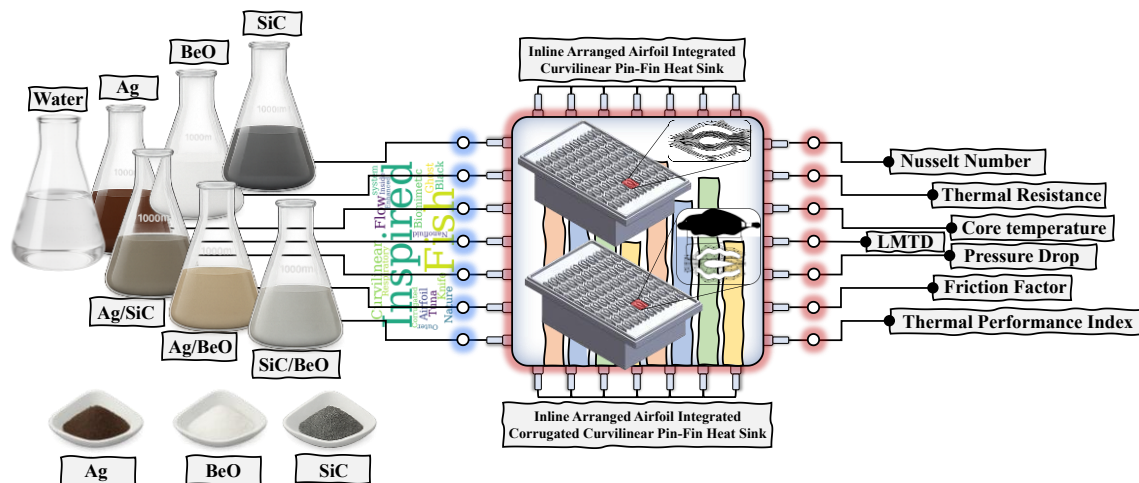
What sets this study apart is the novelty of the heat sink geometries, inspired by natural fluidic mechanisms observed in aquatic respiration. Specifically, the design draws from the concept that in fish, water flows not only along the body but also through it—entering via the mouth and exiting through opercular flaps. This bio-inspired principle was translated into hybrid pin-fin arrangements that allow for improved fluid mixing and alternative flow paths, resulting in better thermal uniformity and reduced risk of dead zones.

To avoid redundancy, details related to the geometrical configurations and experimental setup already comprehensively discussed in Chapter 3 are not repeated here. Instead, the focus lies on assessing the hydrothermal performance of these designs using the nanofluids developed and characterised in Chapter 5. The study investigates the influence of different nanofluids on parameters such as Nusselt number, thermal resistance, wall temperature, pressure drop, and overall system performance.

To ensure clarity for readers specifically interested in this section, cross-referencing has been made to relevant earlier chapters. This integrated approach allows readers to access supporting material seamlessly, whether they follow the thesis in sequence or engage with specific chapters independently. An important aspect of this chapter is its examination of nanoparticle agglomeration and sedimentation within complex heat sink channels, as observed under experimental conditions. These insights provide a more practical understanding of nanofluid behaviour under dynamic flow conditions and highlight the practical challenges encountered in real-world thermal management applications.

The findings presented here are particularly significant as they demonstrate how the synergy between advanced nanofluids and nature-inspired fin geometries can deliver substantial improvements in heat transfer performance. This reinforces the potential of such hybrid systems for next-generation thermal management solutions in high heat flux electronic applications, including data centres, electric vehicles, and power electronics.

Graphical Abstract



Abstract

Efficient thermal management remains a critical challenge in high-power-density systems, as conventional cooling methods increasingly fall short in handling elevated heat fluxes in compact electronics, electric vehicles, and data-driven technologies. This study investigates the combined effects of biomimetic heat sink configurations and advanced nanofluids on the thermal and hydraulic performance of liquid-cooled systems. Inspired by the respiratory efficiency and internal–external flow mechanisms of aquatic organisms, two novel heat sink configurations, Inline Arranged Airfoil Integrated Curvilinear Pin-Fin (IACPF) and Inline Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin (AICCPF) were designed to enhance fluid interactions while minimizing pressure drop. The experimental investigation evaluates these configurations over a flow rate ranging from 200 to 450 mL/min and heating powers varying between 75 and 300 W, using both mono and hybrid nanofluids formulated with silver (Ag), silicon carbide (SiC), and beryllium oxide (BeO) nanoparticles. These were selected for their high thermal conductivity, dispersion stability, cost-effectiveness, and compatibility with microscale flow systems. Performance parameters including Nusselt number, thermal resistance, wall temperature, pressure drop, and pumping power were evaluated. The results revealed that the AICCPF configuration consistently outperformed the IACPF and conventional straight-channel heat sink. Using water as the working fluid at a heating power of 75 W, the AICCPF showed a 10.23% improvement in Nusselt number over the IACPF and a 103% enhancement compared to the baseline straight-channel design. Among the newly designed configurations, the highest Nusselt number enhancement was observed for the AICCPF configuration using Ag/SiC hybrid nanofluid at the highest flow rate and thermal load, reaching a peak improvement of 22.29%. On average, this configuration yielded a 17.56% enhancement in convective heat transfer. The IACPF also demonstrated significant performance gains, achieving an average Nusselt number enhancement of 15.66% under comparable conditions. In terms of hydraulic performance, the highest pressure drop increase was recorded for the IACPF configuration using SiC nanofluid at 75 W, with an average enhancement of 16.93% relative to

water. The AICCPF configuration showed a slightly lower pressure drop increase of 15.86%, attributed to the enhanced fluid mixing caused by the corrugated fin geometry, which introduces local flow disturbances while maintaining smoother transitions compared to the IACPF layout. These findings confirm that the integration of biomimetic heat sink geometries with thermally optimised nanofluids significantly enhances heat transfer while maintaining manageable pressure penalties, offering a scalable solution for advanced cooling in electronics, automotive, and aerospace systems.

7.1 Introduction

Liquid cooling has become increasingly vital in modern electronics cooling, particularly as artificial intelligence (AI) and high-performance computing (HPC) workloads push the boundaries of thermal management and energy efficiency. Conventional air cooling, once sufficient for traditional processors, now struggles with thermal bottlenecks, making it an unsustainable choice for densely packed systems or devices with high heat flux densities. Liquid cooling offers superior thermal conductivity, enabling more effective heat dissipation and allowing for denser configurations without compromising performance.

According to the Data Centre Frontier Liquid Cooling Technology Transition Report, a staggering 93% of organisations are now adopting direct-to-chip liquid cooling in some capacity, from early pilots to full-scale deployments, with only 7% reporting no adoption plans [7]. This trend underscores the industry's recognition of liquid cooling as a critical component in meeting the demands of modern computing environments. Further emphasizing this shift, the Uptime Institute's 2023 Cooling Systems Survey indicates that direct liquid cooling is expected to surpass air cooling as the primary method for IT infrastructure cooling by the end of the decade [326]. Companies like Supermicro, Google, and Hewlett Packard Enterprise are leading the way by integrating liquid cooling solutions into their systems, highlighting the technology's growing importance in the industry.

However, simply adopting liquid cooling is not sufficient, the performance of the coolant itself plays a pivotal role in determining the overall thermal efficiency. The ongoing miniaturisation and increased functional density of electronic and power systems have led to a substantial rise in heat flux levels. This thermal intensification accelerates material degradation, compromises long-term reliability, and imposes significant limitations on device performance, energy efficiency, and operational safety. While liquid cooling has emerged as a viable approach to manage such heat loads, its effectiveness is fundamentally governed by the thermal properties of the working fluid. Therefore, enhancing coolant performance is critical to achieving high-efficiency thermal management in modern high-power-density applications. Conventional coolants like water and ethylene glycol, while widely used, often fail to provide sufficient heat dissipation in modern, high-density systems, prompting the need for more effective alternatives [327]. Their limited thermal conductivity and inability to efficiently transfer heat in high-density systems have prompted the search for alternative solutions. To address these

shortcomings, research is increasingly focused on the development of advanced working fluids like nanofluids suspensions of nanoparticles in base fluids.

Nanofluids have demonstrated improved convective heat transfer characteristics, thermal conductivity, and surface wettability in comparison to traditional fluids. The enhancement mechanisms, primarily attributed to Brownian motion, thermophoresis, and particle-fluid interactions, are further intensified in hybrid nanofluids, which incorporate two or more types of nanoparticles [328]. Hybrid suspensions are of particular interest due to their ability to exploit the distinct advantages of different nanoparticles, potentially offering a more stable and thermally efficient medium for heat dissipation. These fluids in combination with efficient heat sinks are now being considered not only in processors cooling but also in sectors such as electric vehicles (EVs), renewable energy, and space technologies. For instance, McKinsey estimates that electric vehicles will constitute over 30% of global vehicle sales by 2030, significantly amplifying the demand for efficient thermal management solutions in battery and power electronics systems.

In parallel with the development of advanced coolants, there has been considerable progress in the design of micro-scale heat exchangers. Among these, microchannel heat sinks (MCHSs) and mini-channel configurations embedded with pin-fin structures have received widespread attention [329,330]. These geometries not only increase the heat transfer surface area but also promote secondary flows and local turbulence, thereby improving the thermal performance of the system. However, the enhancement in heat transfer is often accompanied by a substantial increase in pressure drop, leading to higher pumping power requirements. This trade-off between thermal enhancement and hydraulic performance necessitates the careful optimisation of channel and fin geometries, as well as coolant selection.

Consequently, researchers have turned towards hybrid thermal management solutions that combine geometrical optimisation with tailored nanofluids. This integrated approach aims to achieve significant improvements in heat transfer while maintaining acceptable pressure drop levels. In particular, bio-inspired designs, mimicking structures found in nature, are gaining traction for their efficiency and adaptability. The fish gill structure, for instance, presents an elegant example of low-resistance, high-efficiency fluid exchange that has evolved to support respiration in aquatic environments. Such analogies offer valuable insights into the development of compact and high-performance heat sinks.

Alkhazaleh et al. [331] explored the thermal and hydraulic performance of micro-electromechanical systems (MEMS) heat sinks incorporating straight microchannels and square pin-fins, specifically designed for liquid cooling in microelectronic devices. Their work focused on understanding the effects of geometric design on thermal performance and pumping power. The study concluded that the inclusion of square pin fins reduced thermal resistance significantly, achieving up to a 51% decrease at higher Reynolds numbers. However, this improvement came at the cost of increased pumping power, attributed to enhanced boundary layer disturbances and the generation of secondary flows. The results also showed that enlarging the hydraulic diameter of the microchannel reduced both the pumping power and thermal resistance.

The configuration and layout of pin fins are critical factors affecting a heat sink's performance, particularly in terms of heat transfer enhancement and pressure drop behaviour. Parameters such as the spacing, height, orientation, and distribution of the fins influence the system's ability to optimise heat dissipation while limiting flow resistance. Well-optimised pin-fin arrangements can boost turbulence and improve the heat transfer coefficient, thereby enhancing thermal dissipation. However, such gains often result in higher pressure drops due to increased resistance to flow. Therefore, achieving a balance between thermal efficiency and acceptable pressure losses is vital, especially in compact and high-performance cooling systems. In another study, Duangthongsuk et al. [332] analysed how diamond-shaped pin-fin configurations impact the heat transfer and flow characteristics of nanofluid-cooled heat sinks. The researchers compared inline and staggered arrangements using copper heat sinks with dimensions of 33 mm $\times$ 30 mm. Tests were performed with de-ionized (DI) water and SiO₂–water nanofluids across various particle volume concentrations and Reynolds numbers from 100 to 600 under laminar flow conditions. Results indicated that both increased Reynolds numbers and higher nanoparticle concentrations enhanced thermal performance. Notably, the staggered configuration outperformed the inline design by 3–10% in terms of heat transfer. Furthermore, the use of nanofluids did not significantly affect pressure drop or pumping power. The authors developed predictive correlations for the Nusselt number and pressure drop, with most results aligning within $\pm 10\%$ of the experimental data. Gao et al. [333] analysed the pressure drop characteristics of microchannel heat sinks with various pin-fin arrangement patterns. Results revealed that partially uniform/gradient stagger pin-fin arrangements demonstrated higher pressure drops due to increased flow obstruction and narrower gaps between the fins and channel sidewalls. Additionally, they observed that pressure drop decreased with increasing heat flux due to the reduction in fluid viscosity and density as the fluid temperature rose. Gijoy et al. [334] performed a 3D numerical simulation to investigate the heat transfer characteristics of elliptical-cylindrical asymmetric pin fin heat sink (ECAPFHS) under turbulent flow, aiming to optimise its structure. The study revealed notable improvements in heat transfer efficiency with the ECAPFHS design. According to the results, in the first phase of their research, the highest fin effectiveness for solid ECAPFs was 1.43, achieved at a fin radius to channel height ratio of 0.9. However, further enhancements were observed by introducing perforations, with fins featuring 8 holes of 3 mm diameter reaching a maximum fin effectiveness of 2.25 at a Reynolds number of 3111. The perforated heat sink not only boosted thermal performance but also reduced fin volume by up to 60% compared to the reference cylindrical pin fin heat sink. The findings highlighted the potential of employing strategic techniques, which could be highly valuable in improving thermal performance while balancing other factors such as material usage and design complexity. Hamza and Ali [202] the thermal and hydraulic performance of aerofoil-shaped pin-fin heat sink using titania (TiO₂) and ferric oxide (Fe₂O₃) nanofluids, comparing the results with distilled water as the base fluid. The research focused on varying heating power and Reynolds number to analyse the heat transfer characteristics. Their findings revealed significant enhancements in heat transfer performance, with the average Nusselt

number increasing by 14.5% for TiO_2 -water and 15.89% for Fe_2O_3 -water nanofluids at 0.01 vol% concentration and 25 W heating power. However, these improvements came with increased pumping power requirements, with Fe_2O_3 nanofluid showing a 42.46% increase and TiO_2 nanofluid a 30.5% increase. The aerofoil shape was chosen for its superior fluid dynamics and heat transfer properties, offering delayed flow separation, enhanced heat transfer, reduced pressure drop, and optimised flow characteristics. The researchers emphasise the importance of using hybrid cooling techniques, such as mini-channel heat sinks combined with nanofluids, to address the challenges of heat dissipation in miniaturized devices.

Bahiraie et al. [335] carried out a two-phase numerical study analysing silver-water nanofluid flow within an elliptical pin-fin heat sink to enhance thermal management in electronic systems. The study examined various nanoparticle volume fractions, fin densities, and Reynolds numbers using a mixture-based two-phase model and the four-equation transition Shear Stress Transport (SST) model for turbulent flow. It was found that introducing nanoparticles to the base fluid significantly promoted uniform temperature distribution, reduced surface temperature and thermal resistance, and improved the heat transfer coefficient. Augmenting the volume fraction by 0.4% at a fin density of 0.168 and Reynolds number of 2500 led to a 16.2% reduction in thermal resistance and a 25.5% enhancement in heat transfer coefficient. Additionally, increasing fin density from 0.036 to 0.168 resulted in a 49.6% improvement in heat transfer coefficient. The study also noted that pumping power and figure of merit increased with higher volume fractions and fin densities. Han et al. [336] performed an integrated design and optimisation of a liquid-cooled heat sink for a 30 kW motor inverter in electric vehicles, addressing the challenges posed by high-power-density electronic systems. Their study compared three heat sink configurations: counter-flow, double U-shaped, and serpentine channels and the results of temperature distribution and fluid velocity fields revealed that the serpentine channel configuration provided superior temperature uniformity and cooling characteristics. The research also investigated how variations in geometric parameters (such as fin thickness) and flow rates affected overall thermal performance, leading to an optimised configuration. It is concluded that the serpentine configuration's superior performance can be attributed to its ability to provide better fluid mixing and heat transfer due to its winding path. A key aspect of this research is the emphasis on integrated design in heat sink development. By arranging cooling channels directly beneath power devices, the team ensured temperature uniformity and targeted cooling. This approach not only enhances cooling efficiency but also reduces pump power requirements compared to conventional designs.

This study presents a comprehensive investigation into two novel biomimetic heat sink configurations, IACPF and AICCPF, which draw inspiration from the fluidic architecture of aquatic respiration systems and are described comprehensively in Chapter 3. The central aim of this work is to evaluate the thermal and hydraulic performance of these geometries under varying operational and fluidic conditions, thereby assessing their suitability for next-generation thermal management in high heat-flux applications such as electronics cooling, power electronics, and compact energy systems.

To further augment the heat dissipation capability of these geometries, carefully selected mono and hybrid nanofluids were employed as working fluids. The nanofluids were formulated using Ag, SiC, and BeO nanoparticles, including binary hybrid combinations such as Ag/SiC, Ag/BeO, and SiC/BeO. These materials were chosen based on their complementary attributes: Ag for its exceptionally high thermal conductivity, SiC for its chemical and thermal stability, and BeO for its cost-effectiveness and favourable thermophysical behaviour compared to other oxides like titania, alumina, etc. The hybrid formulations are particularly promising due to synergistic effects that enhance thermal conductivity while maintaining acceptable viscosity and suspension stability. By integrating these advanced thermal coolants with biomimetic heat sink architectures, this study introduces an integrated thermal management strategy that synergistically combines geometric innovation with optimised coolant characteristics to enhance overall cooling performance.

Moving forward, these designs can be adapted and scaled for integration into various sectors where thermal constraints are increasingly becoming a performance bottleneck. In the electric vehicle (EV) sector, such systems could significantly improve the thermal regulation of battery packs and inverters, particularly under fast-charging or high-load conditions. Beyond traditional cooling applications, the design philosophy demonstrated here holds promise for novel engineering challenges. For instance, compact and efficient cooling structures could be embedded in drones, flying cars, and urban air mobility (UAM) platforms to manage the thermal loads of propulsion systems, battery units, and navigation electronics. Additionally, in wearable technologies and biomedical devices, these miniaturized systems could offer stable temperature control without bulk or noise.

Nanofluid Synthesis, Characterisation, and Thermophysical Properties

*The nanofluids employed in this study have been extensively investigated in our prior research, where their preparation methods, stability characteristics, and thermophysical properties were comprehensively detailed [324], for further details, the reader is referred to **Chapter 5**.*

7.2 Results and Discussion

7.2.1 Comparative Study

To evaluate the potential of the proposed heat sink design, a comparative study was conducted against a conventional straight-channel heat sink under identical experimental conditions. The experiments were carried out across a range of flow rates, varying from 200 ml/min to 450 ml/min, while maintaining a constant heating power of 150 W. The results demonstrated that the AICPPF heat sink achieved a twofold enhancement in Nusselt number compared to the conventional straight-channel heat sink. At the highest flow rate, the Nusselt number increased from 7.60 to 15.5, indicating an approximately 103% improvement in heat transfer efficiency, as presented in Fig. 7.1(a). This substantial enhancement is attributed to the biomimetic-inspired channel geometry, which optimises convective heat transfer by promoting more effective fluid mixing and surface interaction. Additionally, while the improved heat

transfer characteristics were evident, the study also noted a corresponding increase in pressure drop. The measured pressure drop across the AICCPF heat sink was found to be 37.5% higher than that of the conventional straight-channel design.

One of the most significant observations was the impact of the proposed design on thermal resistance. As anticipated, the improved heat dissipation characteristics of the AICCPF heat sink led to a notable reduction in both the average wall temperature and thermal resistance. The enhanced surface area facilitated more efficient heat transfer, lowering the average wall temperature by up to 4.52°C. This improvement directly contributed to a significant reduction in thermal resistance, with an average decrease of 138.1% compared to the straight-channel heat sink, as illustrated in Fig. 7.1(b). The optimised thermal performance of the proposed design underscores its effectiveness in maintaining lower operating temperatures while efficiently managing heat dissipation.

The findings of this study underscore the potential of the proposed biomimetic heat sink design for next-generation thermal management applications, particularly in high-performance electronics and AI-driven systems. The integration of AICCPF offers an optimised balance between heat dissipation and fluid flow resistance, making it a promising solution for advanced cooling technologies.

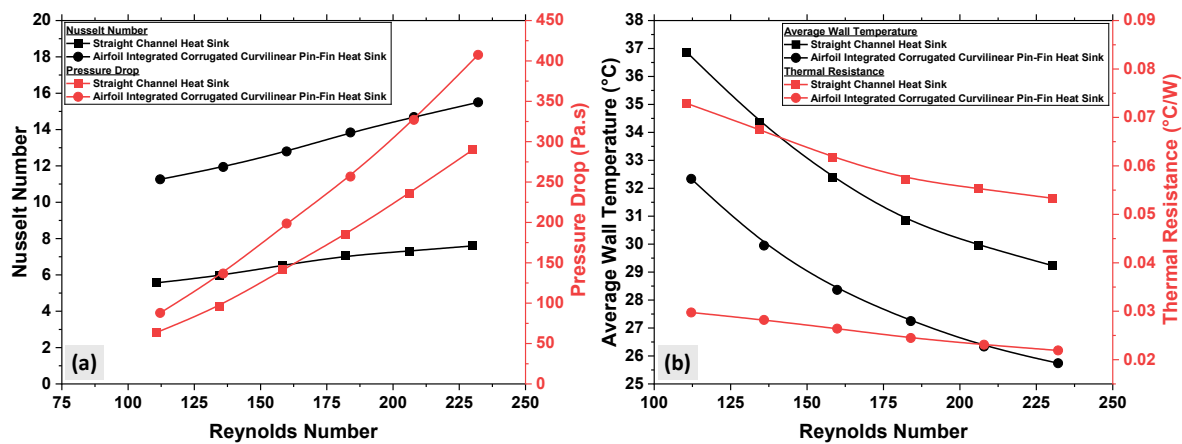


Figure 7.1. Comparison of thermal and hydraulic performance parameters for the AICCPF and conventional straight-channel heat sink.

7.2.2 Nusselt Number

The Nusselt number is a crucial dimensionless parameter that indicates the convective heat transfer performance of a system. Nusselt number of the Inline Arranged Airfoil Integrated Curvilinear Pin-Fin heat sink (IACPF) and the Inline Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin heat sink (AICCPF) was determined for simple and hybrid nanofluid samples over a range of heating powers and plotted against the Reynolds number (Re), as illustrated in Fig. 7.2. The comparative study demonstrated that AICCPF exhibited superior heat transfer characteristics compared to IACPF. Additionally, among the tested working fluids, the hybrid nanofluid comprising Ag and SiC nanoparticles outperformed all other samples, delivering enhanced heat transfer performance. The

results indicated a direct correlation between the Nusselt number, Reynolds number, and heating power. The minimum Nusselt number values were observed at the lowest Reynolds number and heating power, while the maximum values were recorded at the highest Reynolds number and heating power considered in this study. This trend aligned with fundamental heat transfer principles, as higher flow rates and increased thermal input contributed to greater convective heat transfer, reducing the thermal boundary layer thickness and enhancing heat dissipation [337].

A key factor contributing to the superior performance of AICCPF over IACPF is the integration of corrugated pin-fins. The unique corrugated shape not only provides a more efficient surface area for heat dissipation compared to the simple curvilinear pin-fins but also introduces localised flow disturbances, which promote enhanced fluid mixing and improve the overall heat transfer process [338]. Using water as the working fluid, the AICCPF configuration exhibited a maximum Nusselt number enhancement of 10.23% compared to IACPF at a heating power of 75W.

As the geometrical configuration of pin-fins significantly improved heat transfer, the utilization of advanced thermal coolants further enhanced this effect [339]. Among the simple nanofluids tested, Ag nanofluid exhibited the most significant improvement in Nusselt number, increasing from 10.50 to 16.47 in the IACPF configuration and from 11.31 to 18.53 in AICCPF, as both Reynolds number and heating power increased. These enhancements represent a substantial gain in heat transfer efficiency, highlighting the synergy between nanofluid properties and flow-optimised biomimetic designs.

In comparison, SiC nanofluid showed slightly better performance than BeO, though both were less effective than Ag nanofluid. For SiC, the Nusselt number ranged from 10.3 to 15.9 in the IACPF and from 11.1 to 17.2 in the AICCPF configuration as the heating power increased from 75 W to 300 W. BeO nanofluid yielded the lowest values, with a peak Nusselt number of 15.5 in IACPF and 16.9 in AICCPF at 300 W. These differences are primarily attributed to the lower thermal conductivity of SiC and BeO relative to Ag, which limits their overall heat transfer enhancement potential despite good dispersion stability.

The observed heat transfer enhancement with nanofluids can be attributed to several mechanisms. The inclusion of nanoparticles increases the effective thermal conductivity of the base fluid, allowing more efficient energy transport. Additionally, Brownian motion of the nanoparticles induces micro-convection within the fluid, disrupting the thermal boundary layer and promoting enhanced heat transfer at the solid–liquid interface [31,340]. Particle–fluid interactions, particularly in the presence of well-dispersed and thermally conductive materials like Ag, further improve the uniformity of temperature distribution across the channel walls. These combined effects explain the superior performance of nanofluid-cooled biomimetic heat sinks compared to water alone.

Hybrid nanofluids exhibited superior thermal performance, with Ag/SiC achieving the highest Nusselt number values among all tested samples. This improvement was attributed to the enhanced suspension stability of hybrid nanofluids and the synergistic effects of different nanoparticles [341]. The presence of both Ag and SiC particles resulted in improved thermal conductivity and effective heat dissipation.

Specifically, for the Ag/SiC hybrid nanofluid, the Nusselt number ranged from 10.87 to 16.94 with IACPF and from 11.81 to 18.35 with AICCPF. The Ag/BeO hybrid nanofluid closely followed the performance of Ag/SiC, with values fluctuating near those of the Ag nanofluid. Meanwhile, the SiC/BeO hybrid nanofluid exhibited comparatively lower Nusselt number values due to the inherently lower thermal conductivity of its constituent nanoparticles. However, this composition could be preferred in cost-sensitive applications, as both SiC and BeO were significantly more economical than Ag.

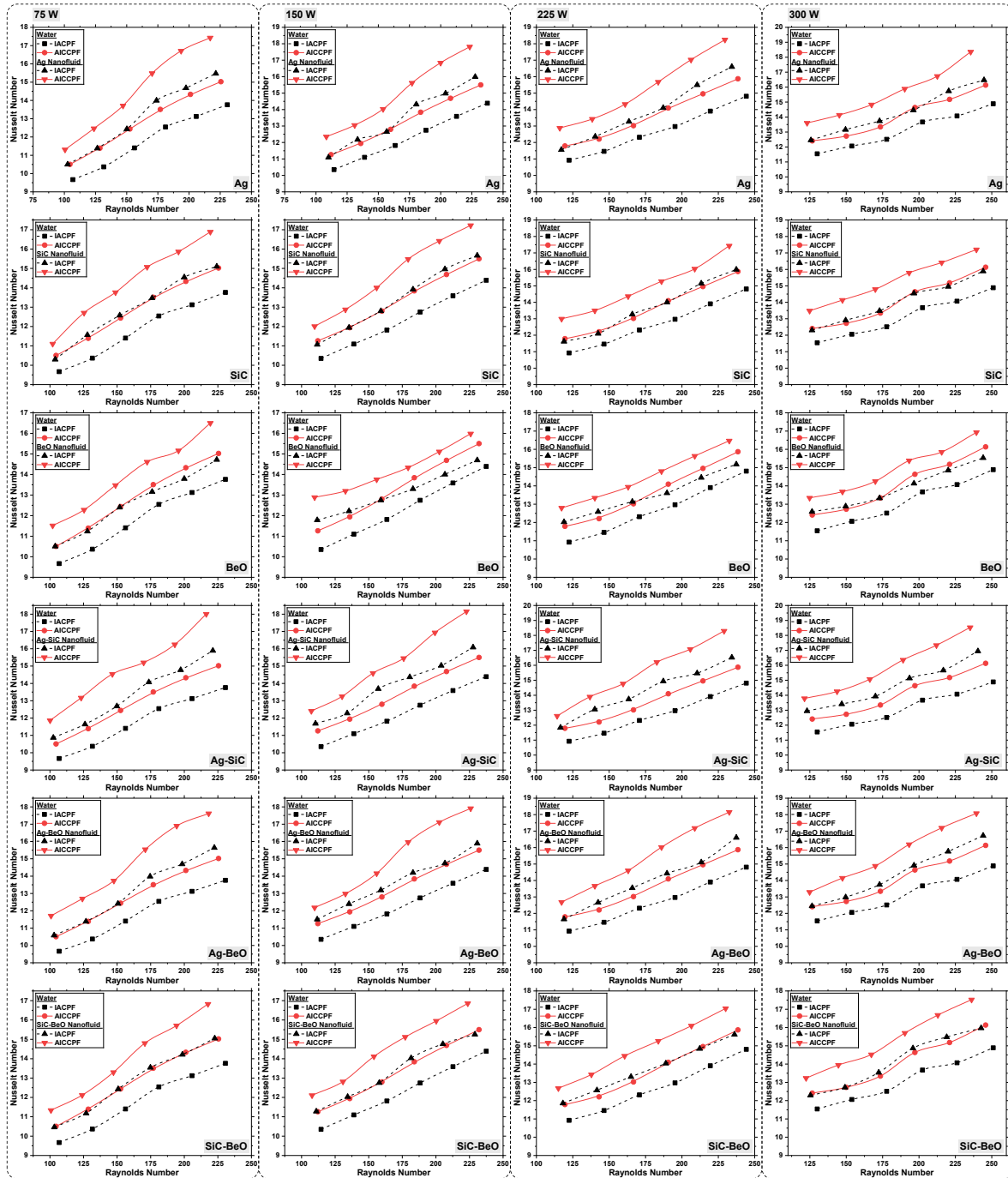


Figure 7.2. Effect of Reynolds number and heating power on the Nusselt number for IACPF and AICCPF using various nanofluids.

An important observation in this study was the behaviour of nanoparticles concerning sedimentation and agglomeration inside the heat sink channels. On a microscopic level, particle deposition on surfaces could have both positive and negative effects on heat transfer. Some particles may settle within micro-gaps, reducing the effective heat transfer surface area while simultaneously decreasing flow resistance by smoothing out roughness. Conversely, excessive particle accumulation on channel surfaces could increase flow resistance, potentially affecting heat transfer either positively by increasing contact area or negatively by restricting direct fluid contact with the surface [342].

However, differences in nanoparticle densities led to distinct sedimentation behaviour. For instance, Ag nanoparticles, which had a density approximately three times higher than SiC and BeO, were more prone to settling inside the channels. BeO nanoparticles, due to their relatively larger size compared to Ag and SiC, showed a pronounced tendency to agglomerate, forming clusters that were difficult to disperse. In contrast, SiC nanoparticles primarily formed chain-like agglomerates, which were easier to break and remix into the fluid, even at higher flow rates. As shown in Fig. 7.3, where it was evident that SiC particles did not agglomerate and form large clusters like Ag and BeO.

The role of surfactants in nanofluid stability could also not be overlooked. In this study, sodium dodecyl benzene sulfonate (SDBS) was used as a surfactant to improve dispersion. However, as the heat sink continuously experiences high thermal loads, surfactant accumulation on surfaces could negatively impact heat transfer efficiency due to the inherently lower thermal conductivity of surfactant materials.

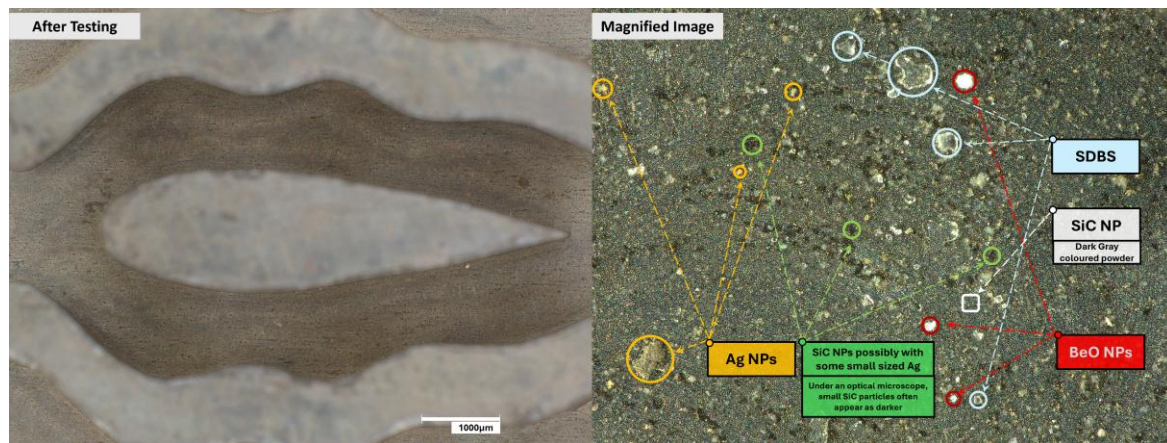


Figure 7.3. Microscopic observation of nanoparticle sedimentation and agglomeration inside the heat sink channels.

For mini and micro-channel heat sinks, prolonged use of nanofluids may have led to particle accumulation, increasing cluster sizes over time and potentially blocking the channels. This issue underscored the importance of hybrid nanofluids, as they offered a balanced composition of multiple particle types, each with distinct advantages and limitations. However, while hybrid nanofluids offer enhanced heat transfer by leveraging the synergistic properties of different nanoparticles, they are not immune to these effects. In addition, the incorporation of metallic nanoparticles can pose risks of

chemical reactivity, particularly when in contact with commonly used heat sink materials such as aluminium. This potential for corrosion or material degradation should be carefully considered in long-term applications.

To ensure the long-term viability of such systems, future work should investigate the rheological and chemical stability of nanofluids under extended operating conditions. This includes conducting accelerated ageing tests, thermal cycling, and characterising particle dispersion using techniques such as dynamic light scattering and scanning electron microscopy. Consideration will also be given to surface treatments or protective coatings on channel materials to mitigate corrosion, as well as the use of environmentally friendly stabilisers or surfactant-free formulations that reduce degradation risks. These strategies are essential to transition nanofluid-enhanced cooling systems from laboratory-scale demonstrations to practical, scalable thermal management solutions in industrial settings.

Fig. 7.4 presented the average percentage enhancement of the Nusselt number compared to the base fluid (water) for both the IACPF and AICCPF configurations across different heating powers. The results demonstrated a clear trend where the enhancement in the Nusselt number decreased as heating power increased. At 75 W, the highest percentage enhancement was observed, particularly in the case of the Ag-SiC hybrid nanofluid, which exhibited a Nusselt number enhancement of 15.66% for IACPF and 17.56% for AICCPF. Among the simple nanofluids, Ag performed the best, with 13.37% and 15.31% enhancement in IACPF and AICCPF, respectively, followed by SiC (10.73% and 12.67%) and BeO (8.62% and 10.29%). The hybrid nanofluids consistently outperformed the simple nanofluids, with Ag-BeO reaching 13.38% and 16.45%, while SiC-BeO showed the lowest enhancement among hybrid formulations at 10.43% and 11.58%.

At 150 W, a slight decline was observed across all cases, with Ag-SiC still exhibiting the highest enhancement of 4.75% (IACPF) and 16.27% (AICCPF). Ag and SiC experienced moderate reductions of 13.04% and 14.6%, and 10.01% and 11.51%, respectively. BeO, which had the lowest thermal conductivity among the tested nanoparticles, showed the sharpest decline, dropping to 8.26% in IACPF and 8.75% in AICCPF. The hybrid nanofluids maintained their relative advantage, though the gap between them and simple nanofluids narrowed.

As the heating power increased to 225 W, the reduction in enhancement became more evident. The Ag-SiC hybrid nanofluid continued to outperform all other cases, maintaining 14.3% and 16% enhancement in IACPF and AICCPF, respectively. The simple nanofluids experienced further reductions, with Ag at 11.68% and 13.84%, SiC at 8.42% and 10.96%, and BeO at 7.31% and 7.88%. The decreasing trend indicated that while these nanofluids enhanced heat transfer, their relative efficiency declined as the heating load increased, possibly due to the effects of temperature-dependent thermal properties and increased particle interactions. At the highest heating power of 300 W, the decline continued, with Ag-SiC maintaining its lead at 14.11% in IACPF and 15.68% in AICCPF. The Ag nanofluid, which initially exhibited strong performance, dropped to 10.59% and 13.41%, while SiC and BeO reached 7.91% and

10.19%, and 7.02% and 7.47%, respectively. The SiC-BeO hybrid nanofluid, which consistently showed lower enhancement, recorded the lowest values at 9.33% and 9.88%.

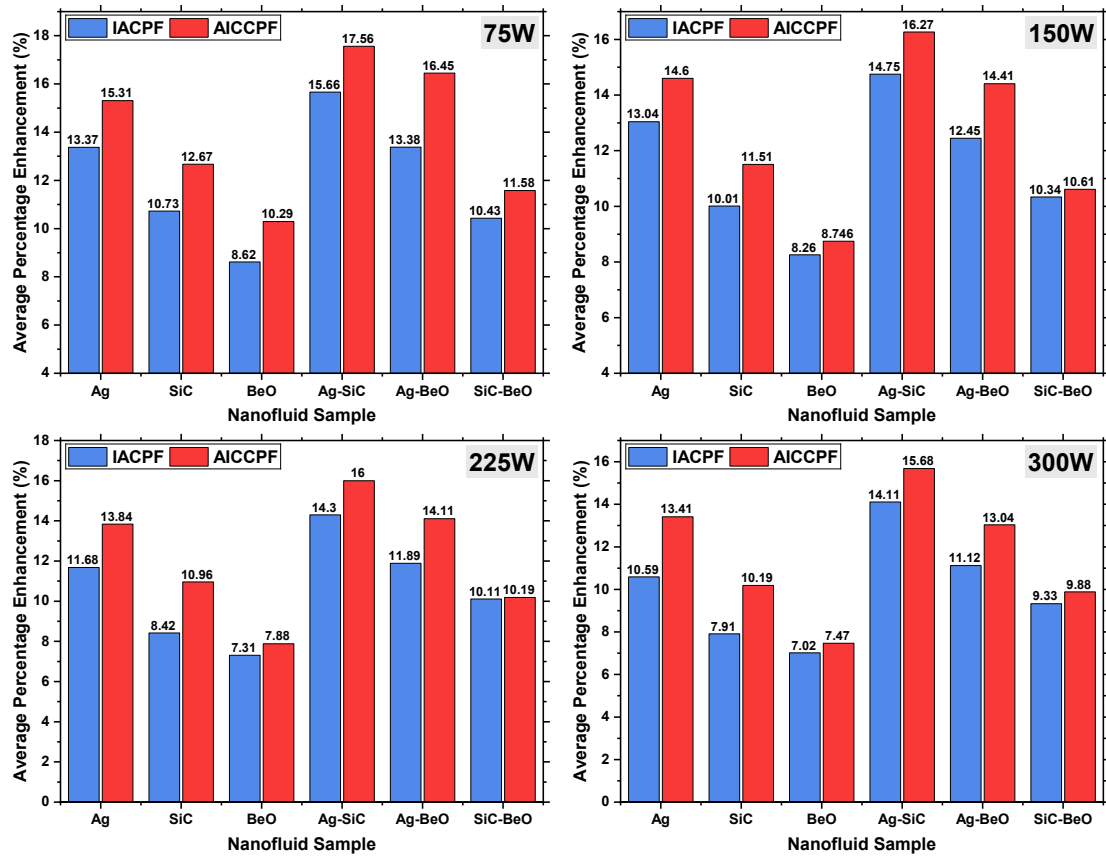


Figure 7.4. Average percentage enhancement in Nusselt number for various mono and hybrid nanofluids relative to water, evaluated for both IACPF and AICCPF configurations at different heating powers (75 W, 150 W, 225 W, and 300 W).

The results demonstrated that adopting a hybrid cooling approach, optimising heat sink geometry, and utilizing coolants with superior thermal characteristics significantly enhanced heat transfer performance. This combined strategy effectively improved thermal regulation, making it a viable solution for high-power applications where efficient heat dissipation is critical.

7.2.3 Thermal Resistance

The thermal resistance of a heat sink is a critical parameter that quantifies its ability to dissipate heat; lower thermal resistance indicates better heat dissipation performance. The thermal resistance of water, mono nanofluids, and hybrid nanofluids has been evaluated and discussed at a heating power of 300 W for IACPF and AICCPF. As anticipated, due to the maximum Nusselt number observed at this power, thermal resistance values are found to be the lowest for all fluids, as shown in Fig. 7.5.

Water exhibited the highest thermal resistance across all experimental cases. For the IACPF design, the thermal resistance of water decreased steadily from 0.02984 °C/W at a Reynolds number of

approximately 130 to 0.02365 °C/W at a Reynolds number near 251. A similar declining trend was observed in the AICCPF configuration, with thermal resistance dropping from 0.02631 to 0.02086 °C/W. The AICCPF heat sink consistently demonstrated better thermal performance compared to the IACPF.

When mono nanofluids were introduced, a noticeable improvement in thermal performance was observed. Silver nanofluid, owing to the exceptionally high thermal conductivity of nanoparticles, demonstrated significantly reduced thermal resistance in both configurations. In the IACPF arrangement, the resistance declined from 0.02595 to 0.0198 °C/W, whereas for AICCPF it ranged from 0.02269 to 0.01734 °C/W. This demonstrated the role of metallic nanoparticles in enhancing the convective heat transfer rate through improved thermal conduction pathways and nanoparticle–fluid interactions.

The SiC nanofluid also exhibited a reduction in thermal resistance compared to water, although their performance was slightly inferior to that of Ag nanofluids. For the IACPF system, the resistance decreased from 0.02606 and 0.02137 °C/W, while for the AICCPF counterpart, the values ranged from 0.02319 to 0.01886 °C/W. Beryllium oxide nanofluid behaved similarly, showing values between 0.02621 to 0.02197 °C/W in the IACPF design, and 0.02358 to 0.01925 °C/W in AICCPF. Though both BeO and SiC nanofluids demonstrated significant improvements over water, they were less effective than Ag nanofluids, due to their comparatively lower thermal conductivities.

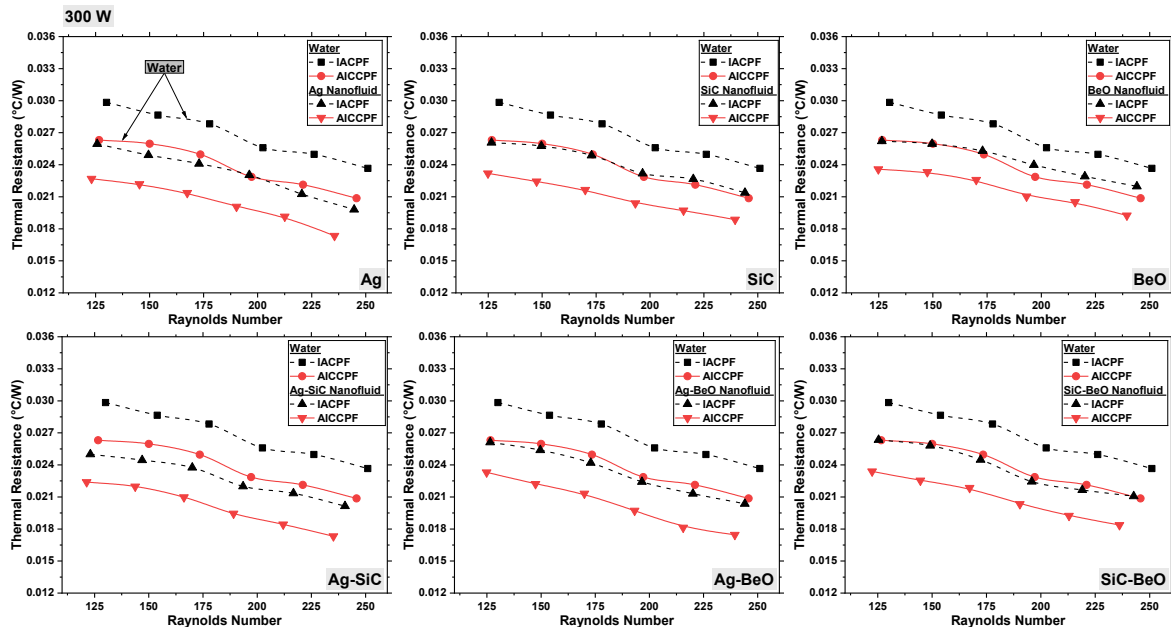


Figure 7.5. Variation in thermal resistance against Reynolds number for IACPF and AICCPF configurations using various nanofluids at a constant heating power of 300W.

The introduction of hybrid nanofluids led to even more promising outcomes. Ag/SiC nanofluids recorded thermal resistances as low as 0.02014 °C/W in IACPF and 0.01732 °C/W in AICCPF, making

them one of the most effective fluids tested. The combined effects of Ag superior thermal conductivity and SiC thermal stability and wettability likely contributed to this synergistic enhancement. Similarly, Ag/BeO nanofluids also demonstrated notable reductions, reaching values of 0.02036 °C/W and 0.01746 °C/W in IACPF and AICCPF, respectively. Although both Ag-based hybrids showed comparable performance, Ag/SiC slightly outperformed Ag/BeO in the AICCPF setup, indicating favourable interaction and dispersion characteristics in that particular configuration. The SiC/BeO hybrid nanofluid, although slightly behind the SiC nanofluid, still showed marked improvement compared to water and mono BeO nanofluid. Its thermal resistance reduced to 0.02106 °C/W in IACPF and 0.01837 °C/W in AICCPF.

Fig. 7.6 presents the average percentage reduction in thermal resistance achieved by simple and hybrid nanofluids when applied to IACPF and AICCPF heat sinks. Among the simple nanofluids, Ag nanofluid demonstrated the most significant reduction in thermal resistance, achieving 17.55% for IACPF and 18.29% for AICCPF. In comparison, SiC and BeO nanofluids showed lower reductions, with SiC resulting in 13.28% and 13.8%, while BeO gave the smallest improvement, with reductions of 11.49% and 11.85% in IACPF and AICCPF, respectively.

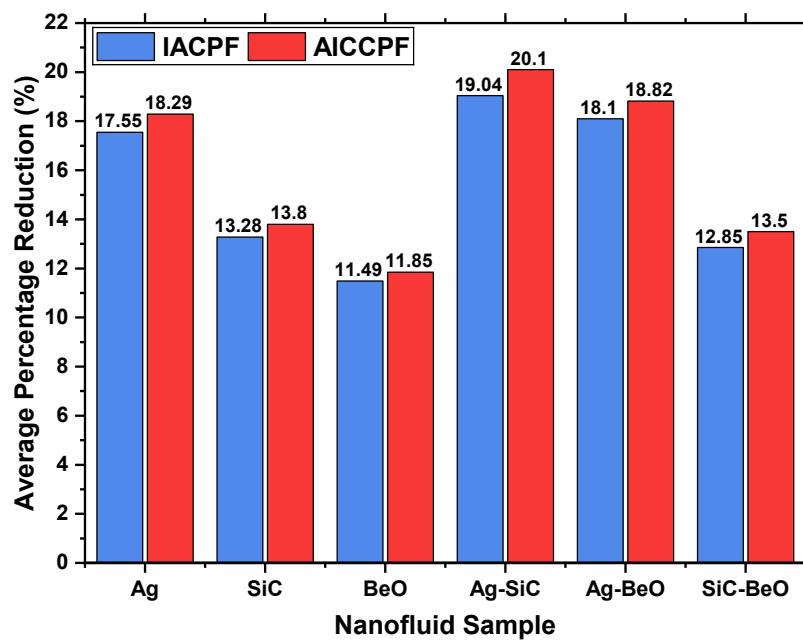


Figure 7.6. Average percentage reduction in thermal resistance for simple and hybrid nanofluids in IACPF and AICCPF configurations at a constant heating power of 300 W.

The hybrid nanofluids displayed an even greater impact on thermal resistance reduction. The Ag/SiC hybrid nanofluid emerged as the most efficient, with reductions of 19.04% for IACPF and 20.1% for AICCPF. Ag/BeO demonstrated a substantial reduction of 18.1% in IACPF and 18.82% in AICCPF, further supporting the role of silver as a dominant enhancer when used in combination with other particles. Finally, the SiC/BeO hybrid nanofluid resulted in a comparatively moderate reduction

(12.85% and 13.5%). This indicates that while hybridization can improve thermal performance, the specific properties and interactions of the constituent nanoparticles play a critical role in determining overall effectiveness.

The results confirmed that nanofluids, especially hybrid ones, significantly reduced the thermal resistance of heat sinks under high thermal loads. Among the various fluids studied, Ag/SiC hybrid nanofluid demonstrated the most efficient thermal performance. Furthermore, the AICCPF design consistently outperformed the IACPF configuration across all fluid types, underlining the importance of geometrical optimisation in thermal system design.

7.2.4 Wall Temperature and Logarithmic Mean Temperature Difference

Wall temperature and Logarithmic Mean Temperature Difference (LMTD) are pivotal indicators for evaluating the thermal performance of cooling systems. The wall temperature specifically represents the temperature of the heat sink surface in direct contact with the working fluid and serves as a measure of the system's capacity to remove heat from the solid domain. A lower wall temperature is indicative of more effective heat transfer from the surface to the fluid. On the other hand, LMTD offers a broader view of the temperature driving potential across the heat sink, capturing the average thermal gradient between the solid surface and fluid along the flow path.

The comparative trends illustrated in Fig. 7.7(a) demonstrate a consistent reduction in wall temperature when Ag/SiC nanofluid was employed instead of water, across both IACPF and AICCPF configurations. In the IACPF setup, water-cooled surfaces exhibited wall temperatures ranging from 45.20 °C at the lowest Reynolds number down to 32.28 °C at the highest. When Ag/SiC nanofluid was used, the wall temperatures were systematically lower, dropping from 43.04 °C to 31.46 °C. The AICCPF configuration showed an even greater reduction, with water-cooled surfaces reaching a minimum of 31.67 °C, whereas the Ag/SiC nanofluid reduced it further to 30.18 °C. These reductions suggest that the presence of high-conductivity Ag and ceramic SiC nanoparticles enhanced the thermal conduction pathways at the fluid-solid interface, leading to more efficient heat removal.

In Fig. 7.7(b), the top right-hand chart illustrates the variation in LMTD with Reynolds number. The behaviour of the LMTD followed a consistent trend, showing a gradual decline with increasing Reynolds number. As anticipated, the Ag/SiC nanofluid consistently demonstrated lower LMTD values compared to water under equivalent flow conditions. In the AICCPF design, LMTD dropped from 8.16 °C with water to 6.83 °C with Ag/SiC at lower Reynolds numbers, and further down to 4.81 °C at the highest. These results suggest that the nanofluid was more effective in minimizing the temperature differential required to sustain heat transfer, thereby achieving closer thermal equilibrium between the fluid and surface.

To assess the internal thermal behaviour of the heat sinks, seven thermocouples were strategically embedded along the length to record the core temperature profiles. This spatial resolution allows for evaluating the longitudinal thermal gradient under varying flow rates and working fluids. Figure

7.7(c,d) showed the axial temperature profiles for both the IACPF and AICCPF heat sinks using water and Ag/SiC nanofluid at flow rates ranging from 200 to 450 ml/min. It is important to note that the inlet fluid temperature was maintained close to 20 °C in all cases to ensure a consistent thermal condition across the experiments.

For both water and Ag/SiC nanofluid, the temperature consistently increased from the inlet to the outlet, as expected due to progressive heat accumulation along the flow direction. However, a distinct difference in the absolute temperature values and gradient steepness was observed between water and the nanofluid. At lower flow rates, the temperature rise along the heat sink length was steeper for water compared to Ag/SiC nanofluid, indicating inferior heat extraction capacity. As the flow rate increased, the temperature values at all locations along the length gradually decreased, reflecting enhanced convective cooling due to higher fluid velocity and reduced residence time within the channel.

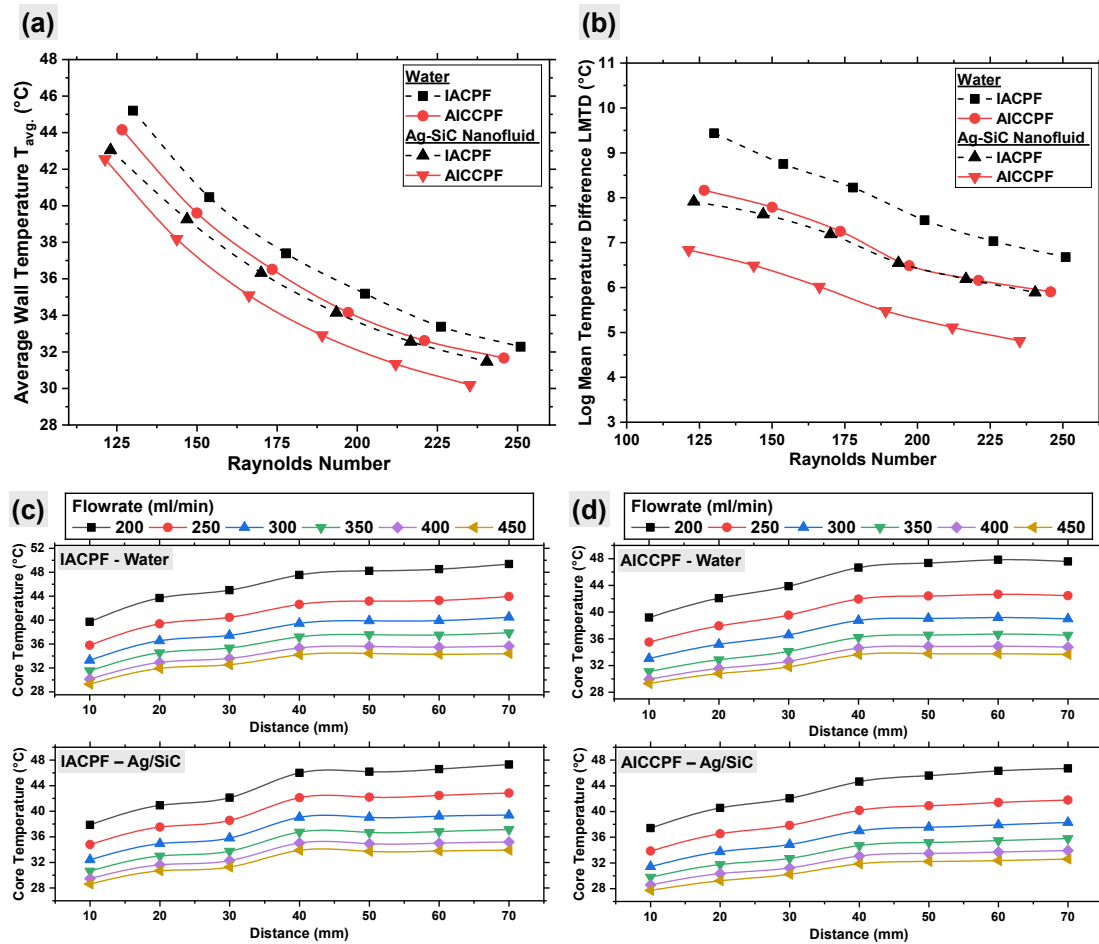


Figure 7.7. Variation in (a) Average wall temperature, (b) Logarithmic Mean Temperature Difference (LMTD) across flow rates for Ag/SiC nanofluid compared to water, (c) Axial wall temperature distribution along the heat sink length.

In the IACPF configuration with water, wall temperatures increased progressively from approximately 39.7 °C at the 10 mm position to 49.4 °C at 70 mm when the flow rate was 200 ml/min. As the flow rate increased to 450 ml/min, this temperature range dropped significantly to 29.3 °C and 34.4 °C,

respectively. A similar rising trend along the length was observed for all flow rates, although the gradient became less steep at higher flow rates due to enhanced convective cooling. When the Ag/SiC nanofluid was employed, the overall temperature values were notably reduced across all positions. At 200 ml/min, the temperature ranged from 37.9 °C to 47.3 °C, while at 450 ml/min, it further decreased to 28.6 °C and 33.9 °C. This reduction indicates improved heat transfer capability of the nanofluid, attributed to its superior thermal conductivity.

For the AICCPF configuration, the overall thermal performance was improved relative to IACPF, as reflected by the lower wall temperatures at corresponding positions and flow rates. With water, the wall temperature increased from around 39.2 °C to 47.6 °C at 200 ml/min and from 29.3 °C to 33.7 °C at 450 ml/min. The Ag/SiC nanofluid showed even better performance, with values spanning from 37.4 °C to 46.7 °C at 200 ml/min and from 27.7 °C to 32.6 °C at 450 ml/min.

Overall, a clear trend of decreasing wall temperature with increasing flow rate is observed for all configurations, owing to the higher convective heat transfer. Additionally, the Ag/SiC nanofluid consistently outperformed water, and the AICCPF design demonstrated enhanced thermal regulation compared to IACPF, highlighting the combined benefits of advanced coolant and structural enhancement.

7.2.5 Pressure Drop

Pressure drop is another critical parameter in the assessment of fluid flow and energy efficiency in thermal management systems. It arises due to frictional resistance and viscous dissipation as the fluid navigates through confined geometries. When nanofluids are employed to enhance heat transfer, their modified rheological properties can significantly impact the pressure drop characteristics. Therefore, understanding the interplay between flow rate (or Reynolds number) and pressure drop is essential to evaluating the trade-off between thermal performance and pumping power requirements.

The variation of pressure drop with Reynolds number has been investigated under different heating conditions, as shown in Fig. 7.8. In general, pressure drop increased with increasing Reynolds number across all fluid types and operating conditions. This is expected, as higher flow rates result in greater inertial effects and wall shear stresses, thereby increasing the frictional losses. Across all heating powers and fluid types, a consistent increasing trend of pressure drop with Reynolds number was observed. Additionally, it was observed that the AICCPF configuration consistently exhibited higher pressure drops than the IACPF configuration. This can be attributed to the presence of corrugated pin-fins in the AICCPF design, which increase flow resistance by disrupting boundary layers and inducing local turbulence [343]. While this enhances heat transfer, it simultaneously intensifies pressure losses due to increased form drag and surface interactions.

Comparatively, nanofluids exhibit higher pressure drops than water, a result of increased viscosity and density caused by the suspended nanoparticles. Among the simple nanofluids, SiC nanofluid exhibited the highest pressure drop, reaching up to 478 Pa at $Re \approx 220$ under 75 W in the AICCPF configuration,

which is approximately 15.86% higher than that of water at the same Reynolds number. This behaviour is attributed to the fact that silicon carbide nanoparticles possess sharp edges and irregular shapes, which disrupt the laminar flow more effectively than spherical particles, thereby increasing internal resistance and effective viscosity [324]. The irregular morphology enhances fluid-particle interaction and momentum exchange, leading to a higher pressure penalty. In comparison, Ag and BeO nanofluids followed closely, with pressure drops of 469 Pa and 462 Pa, respectively.

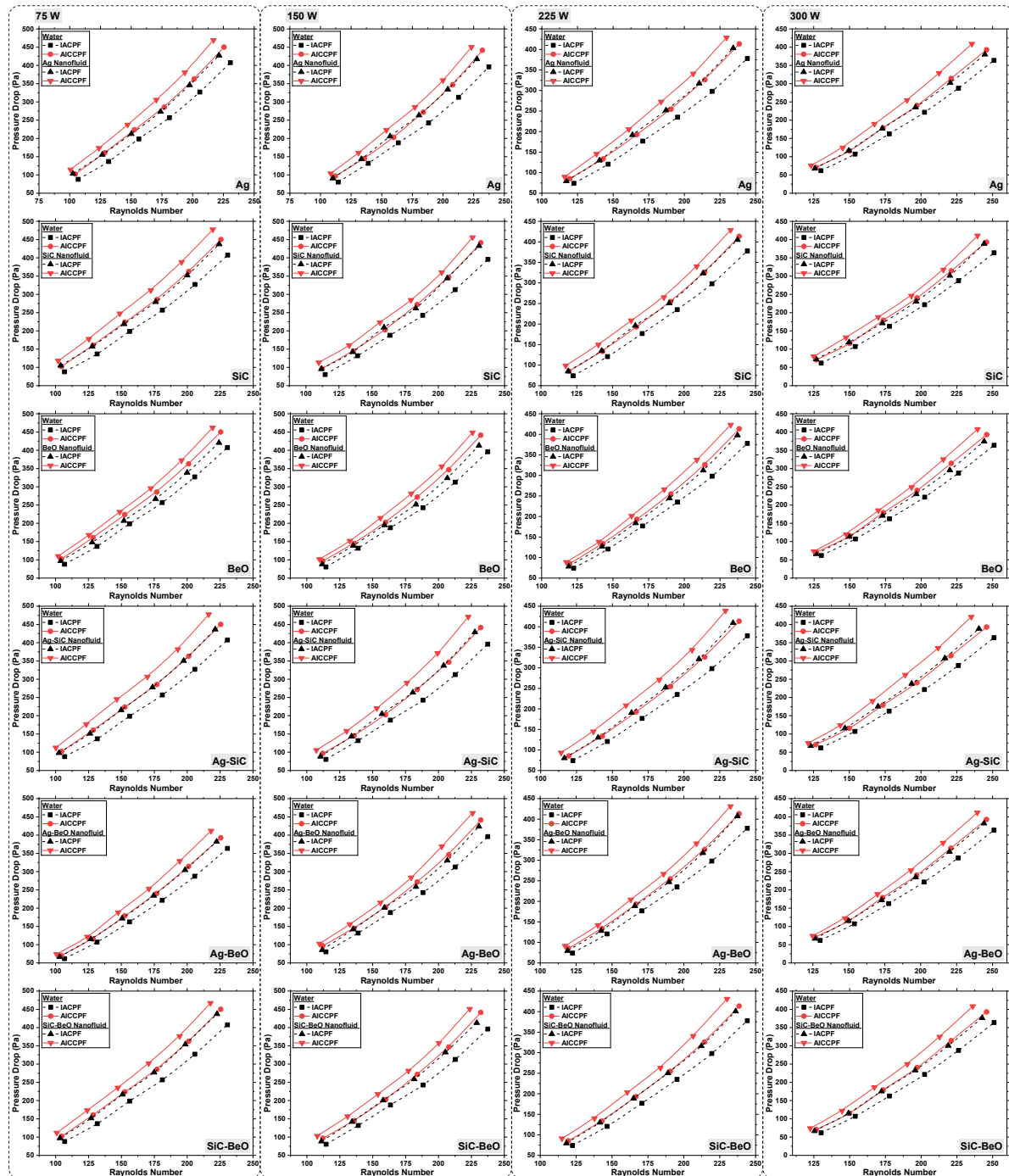


Figure 7.8. Variation of pressure drop with Reynolds number for IACPF and AICCPF configurations under different heating powers using various nanofluids.

Among the hybrid nanofluids investigated, the Ag/SiC nanofluid exhibited a pressure drop profile closely resembling that of the SiC nanofluid, despite having a higher proportion of Ag nanoparticles (mixing ratio: 0.6 Ag to 0.4 SiC). This trend suggests that the presence of SiC, with its irregular and angular morphology, exerts a dominant influence on the overall flow resistance, even when present in a lower fraction. The combined effect of metallic (Ag) and ceramic (SiC) nanoparticles likely contributes to increased fluid density and viscosity, which in turn amplifies the pressure drop across the channels.

However, the Ag/BeO hybrid nanofluid exhibited a relatively lower pressure drop, with values generally falling between those observed for pure Ag and BeO nanofluids. This outcome is consistent with the particle characteristics: BeO nanoparticles are larger in size (85–140 nm), possess a hexagonal wurtzite structure, and exhibit random orientation, which may induce mild flow resistance. However, their smoother morphology compared to SiC still allows more streamlined flow, particularly when combined with the smaller and smoother Ag nanoparticles. Meanwhile, the SiC/BeO hybrid nanofluid displayed pressure drop values slightly below Ag/SiC but consistently higher than Ag/BeO, reflecting the intermediate effect of SiC's irregular structure and BeO's larger but less disruptive particles. This configuration results in moderately elevated viscosity and flow resistance compared to Ag/BeO, but slightly less than that of Ag/SiC. These observations underscore the critical role of nanoparticle morphology, density, crystal structure, and size distribution in influencing the hydrodynamic performance of hybrid nanofluids.

Figure 7.9 shows the pressure drop enhancement of nanofluids relative to base fluid water across varying heating powers for both IACPF and AICCPF configurations. According to the results, a consistent decrease in pressure drop augmentation was observed with increasing thermal load, highlighting the temperature-dependent rheological behaviour of nanofluids.

At 75 W, the highest pressure drop enhancements were recorded across all nanofluids. In the IACPF configuration, SiC nanofluid exhibited the maximum enhancement of 16.93%, followed closely by the Ag/SiC and Ag hybrid nanofluids, with enhancements of 16.78% and 16.26%, respectively. BeO nanofluid showed the lowest enhancement of 12.21%. In the AICCPF system, values were slightly lower, 15.86% for SiC, 15.51% for Ag, and 9.05% for BeO nanofluid. At 150 W, a slight reduction in pressure drop was observed. SiC nanofluid showed an enhancement of 15.81% in IACPF and 15.25% in AICCPF. Ag nanofluid followed with 15.67% and 14.97% respectively, while BeO recorded 12.04% in IACPF and 9.32% in AICCPF. This downward trend continued at 225 W, where pressure drop enhancements decreased further. At the highest thermal load of 300 W, the pressure drop enhancements were the lowest. SiC and Ag nanofluids recorded 14.41% and 14.2% respectively in IACPF, and 13.71% and 13.52% in AICCPF. BeO further declined to 10.83% in IACPF and 8.04% in AICCPF.

Among the hybrid nanofluids, Ag/SiC consistently exhibited higher pressure drop values, closely following pure SiC. At 75 W, Ag/SiC showed an enhancement of 16.78% in IACPF and 15.44% in AICCPF, which gradually reduced to 14.28% and 13.54% respectively at 300 W. Ag/BeO presented

the lowest pressure drop among the hybrids, starting at 14.17% in IACPF and 12.98% in AICCPF at 75 W, reducing to 13% and 9.95% at 300 W. SiC/BeO hybrid nanofluid displayed intermediate performance, with values decreasing from 15.83% to 13.88% in IACPF and from 13.57% to 12.58% in AICCPF.

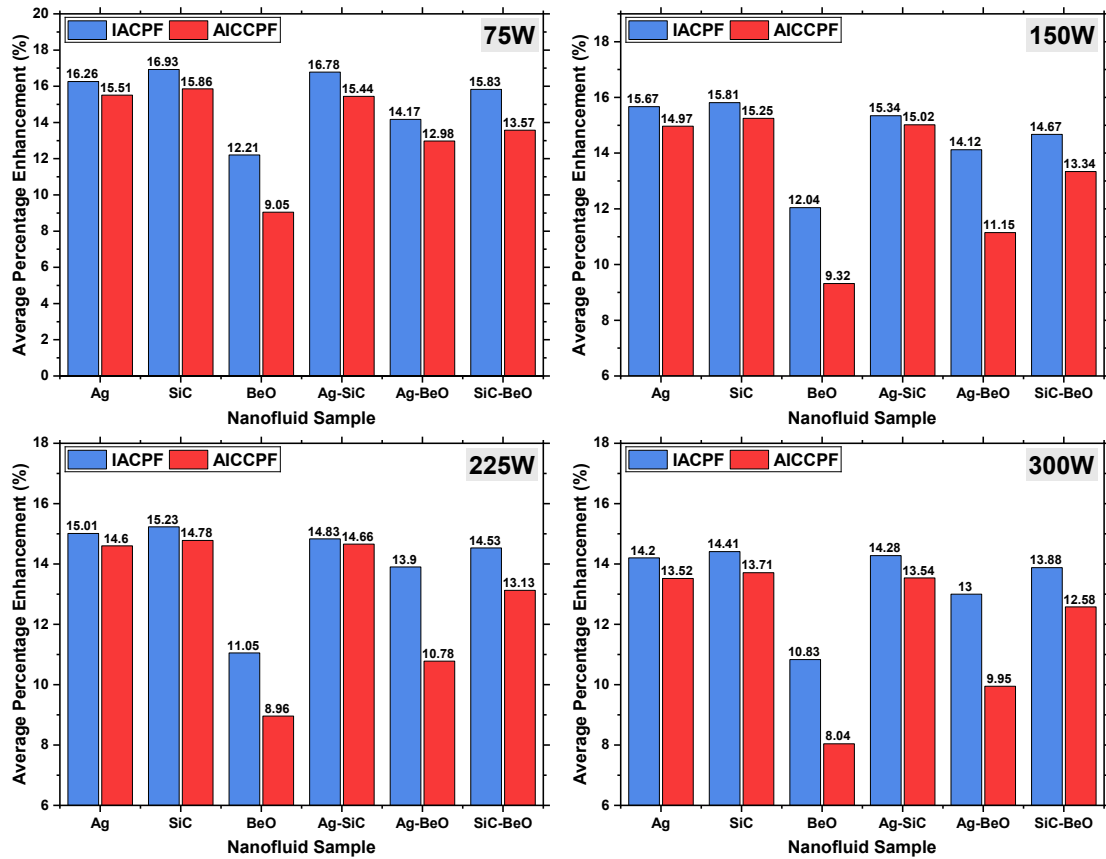


Figure 7.9. Pressure drop enhancement of nanofluids relative to water across varying heating powers for IACPF and AICCPF configurations.

These results confirm that increasing thermal power reduces the pressure drop enhancement due to lowered viscosity and improved flowability at higher temperatures. The hierarchy among the nanofluids remains consistent, with ceramic-based and hybrid nanofluids showing greater enhancements due to higher density and structural complexity.

The pressure drop study highlights not only the hydraulic performance of different nanofluids but also the broader influence of nanoparticle addition on fluid flow behaviour within mini-channel heat sinks. The introduction of nanoparticles increases the effective viscosity of the working fluid, thereby elevating flow resistance and contributing to the observed rise in pressure losses compared to water. This effect was particularly evident with SiC and Ag/SiC nanofluids, which consistently exhibited the highest pressure drops due to their higher viscosity and stronger particle–fluid interactions.

Beyond viscosity, nanoparticle size, shape, and surface properties also affect flow characteristics. For instance, irregularly shaped particles like SiC can disrupt the local laminar profile, promoting enhanced

micro-scale mixing while simultaneously increasing wall shear stress. In narrow channels, such effects are magnified due to the confined geometry, which makes particle–wall and particle–particle interactions more significant. Furthermore, regions of low flow velocity may experience temporary agglomeration or particle settling, leading to local constriction of flow pathways and non-uniform pressure distribution.

Despite the increase in hydraulic resistance, the presence of nanoparticles contributes positively to convective heat transfer by disturbing boundary layers and improving thermal conductivity. This presents a clear trade-off between enhanced thermal performance and increased pressure drop, which must be optimised based on the specific cooling requirements, allowable pumping power, and long-term operational stability of the system.

7.2.6 Performance Improvement Factor

The Performance Improvement Factor (PIF), also referred to as the thermal performance index (η), serves as a critical metric for evaluating the overall efficiency of a heat sink. It provides a balanced assessment by simultaneously considering enhancements in heat transfer and the associated rise in pressure drop or pumping power. Mathematically, the PIF is calculated as the ratio of the Nusselt number of the improved system to that of the base case, divided by the cube root of the corresponding friction factor ratio [344,345], represented with Eq. (7.1).

$$\text{Thermal Performance Index } (\eta) = \frac{Nu_{nc}/Nu_{bc}}{(f_{nc}/f_{bc})^{(1/3)}} \quad (7.1)$$

In the above equation, the term Nu_{nc} represents the Nusselt number corresponding to the new case, such as when a nanofluid is used or when the heat sink geometry is altered, for instance, in the AICCPF configuration. Nu_{bc} is the Nusselt number for the base case, typically calculated using water as the working fluid in the standard IACPF heat sink. Similarly, f_{nc} denotes the Darcy friction factor for the new case, accounting for the increased resistance to flow introduced by nanofluids or modified heat sink structures, whereas f_{bc} corresponds to the friction factor in the base case scenario.

This dimensionless index helps quantify how effectively a system can enhance heat transfer without disproportionately increasing flow resistance. In this study, the IACPF heat sink with water was considered as the baseline, while the AICCPF configuration was treated as the modified system. The comparative results between the two configurations are presented in Fig. 7.10. With water, the average thermal performance index of the AICCPF design was calculated to be 1.051, reflecting a moderate yet meaningful performance gain over the baseline.

When using nanofluids, all tested configurations demonstrated a PIF greater than unity, confirming that thermal performance improved relative to the water-cooled base case. Among the simple nanofluids, Ag nanofluid yielded the highest thermal performance index, with values of 1.074 for IACPF and 1.089

for AICCPF. This indicates a consistently superior heat transfer enhancement, even when accounting for the associated pressure drop.

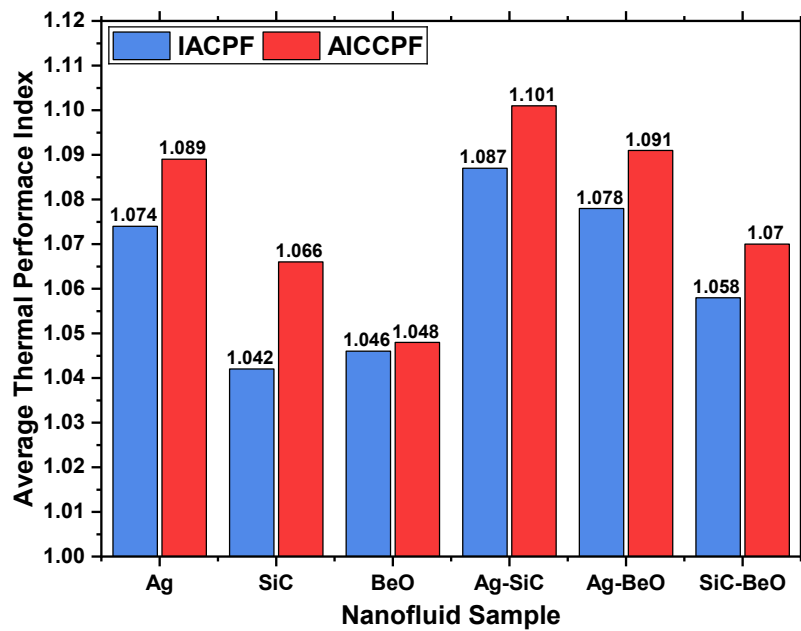


Figure 7.10. Performance index comparison for all tested nanofluids in IACPF and AICCPF systems, showing optimal thermal-hydraulic efficiency of the AICCPF design.

The hybrid nanofluids showed further improvement. The Ag/SiC hybrid nanofluid delivered the best results, with a PIF of 1.087 for IACPF and 1.101 for AICCPF, making it the most thermally efficient fluid among all tested. Similarly, Ag/BeO and SiC/BeO hybrid nanofluids also outperformed their simple counterparts, with values of 1.078 and 1.058 for IACPF, and 1.091 and 1.070 for AICCPF, respectively.

Overall, the AICCPF system consistently showed higher performance indices than the IACPF, across all nanofluids tested. The enhancement confirms that the improved geometry, coupled with optimised nanofluid composition, delivers better heat transfer performance without an excessive increase in pumping power demand.

7.3 Concluding Remarks, Limitations, and Future Outlook

This study presented a comprehensive experimental investigation into the integration of nature-inspired heat sink geometries and nanofluid-based coolants to advance thermal management solutions for high-power-density applications. Two novel biomimetic configurations, IACPF and AICCPF, were tested under varying flow rates, thermal loads, and coolant compositions. The objective was to evaluate how nature-inspired geometries, combined with thermally optimised coolants, can enhance heat dissipation while maintaining acceptable hydraulic performance in mini/microchannel domains. The key findings of this study are summarised as follows:

- The AICCPF configuration significantly outperformed the conventional straight-channel heat sink, achieving a 103% increase in Nusselt number with only a 37.5% rise in pressure drop at a heating power of 150 W. Additionally, it offered a 10.23% enhancement in Nusselt number over IACPF when using water at a lower thermal load of 75 W.
- Among all tested scenarios, AICCPF heat sink with Ag/SiC hybrid nanofluid exhibited the most effective heat transfer performance. At the maximum thermal load of 300 W, it achieved an average Nusselt number enhancement of 17.56%, reaching up to 22.29% at the maximum flow rate, compared to water, outperforming all other working fluids and configurations evaluated in this study.
- Thermal resistance showed notable variation depending on the fluid and configuration. All nanofluids outperformed water, with Ag nanofluid reducing resistance by 18.29%, while the Ag/SiC hybrid achieved a maximum reduction of 20.1% in the AICCPF design. However, in applications where cost constraints are more pressing, hybrid nanofluids like SiC/BeO still provided meaningful improvements, presenting a cost-effective alternative that balances thermal performance with affordability.
- Pressure drop increased consistently with Reynolds number for all tested fluids, with nanofluids exhibiting higher values than water due to their elevated viscosity and intensified particle–fluid interactions. Among the mono nanofluids, SiC recorded the highest pressure drop in the AICCPF configuration, reaching 478 Pa, which represents a 15.86% increase compared to water. This was followed by Ag and BeO nanofluids, which produced pressure drops of 469 Pa and 462 Pa, respectively, under the same operating conditions.
- For hybrid nanofluids, Ag/SiC showed pressure drop behaviour similar to pure SiC, with an enhancement of up to 15.44% over water in AICCPF at 75 W, gradually decreasing to 13.54% at 300 W, reflecting the temperature-dependent reduction in fluid viscosity. However, Ag/BeO demonstrated the lowest pressure drop among the hybrid formulations, with enhancements reducing from 12.98% to 9.95% over the same thermal range. This relatively low hydraulic penalty makes Ag/BeO a favourable choice for systems where minimising pumping power and flow resistance is essential.
- In terms of overall thermal-hydraulic efficiency, AICCPF combined with Ag/SiC hybrid nanofluid achieved the highest TPI of 1.101, indicating an optimal balance between heat transfer enhancement and pressure drop. All tested nanofluids delivered TPI values above unity, confirming the effectiveness of the proposed approach.

The results of this study demonstrate that combining bioinspired design with engineered nanofluids can significantly improve the cooling performance of compact systems without introducing excessive pressure losses. The corrugated airfoil-finned biomimetic geometry, in particular, enables superior fluid

mixing and surface interaction, which is further amplified by the enhanced thermal conductivity of hybrid nanofluids.

While this study primarily focused on the short-term thermal and hydraulic evaluation of biomimetic heat sink configurations using mono and hybrid nanofluids, it is recognised that long-term performance and reliability are critical for real-world deployment. Future research will therefore aim to assess the stability of nanofluids under extended operational conditions, including thermal cycling and continuous flow, to understand the effects of agglomeration, sedimentation, and surface fouling over time. These efforts will involve accelerated ageing tests, monitoring of thermophysical property variations, and in-depth surface analysis using SEM, EDX, and FTIR to investigate nanoparticle interaction with channel surfaces and potential corrosion effects, particularly in aluminium-based systems. Furthermore, alternative nanofluid formulations, including environmentally friendly dispersants and surfactant-free systems, will be explored to improve chemical durability and sustainability. There is also scope to investigate active control strategies, such as pulsed flow or periodic flow reversal, to enhance redispersion of particles and maintain heat transfer efficiency in mini- and micro-channel domains. These research directions aim to transform the promising short-term performance demonstrated in this study into robust, scalable, and low-maintenance thermal management solutions for industrial applications.

Looking ahead, the biomimetic heat sink designs developed in this study hold vast potential beyond conventional thermal management. While their immediate impact lies in enhancing cooling efficiency in applications such as electric vehicles, data centres, and compact electronics, the underlying design philosophy inspired by aquatic respiration systems offers opportunities far beyond heat dissipation. The proposed configurations demonstrated here can be adapted for use in emerging technologies such as drones, flying cars, and urban air mobility platforms where fluid flow optimisation, structural lightness, and multifunctionality are crucial. These geometries not only support effective thermal control but can also be reimagined as aerodynamic components, propulsion housings, or integrated passive ventilation systems. Thus, the nature-inspired approach showcased in this work establishes a design framework that merges thermal functionality with aerodynamic efficiency, paving the way for innovative, multifunctional systems in the future of mobility, aerospace, and smart device engineering.

CHAPTER 8

8 Experimental Assessment of Advanced Biomimetic Heat Sink Designs Using Hybrid Nanofluids Containing MWCNTs, Silver, and Aluminium Nitride

Building on the findings of the previous chapter, which demonstrated that the Airfoil-Integrated Corrugated Curvilinear Pin-Fin (AICCPF) heat sink outperformed the simpler airfoil-integrated curvilinear pin-fin configuration. To further enhance heat transfer effectiveness, the current chapter investigates the impact of fin arrangement by introducing a staggered layout while maintaining the same number of fins and overall footprint. This rearrangement implemented in the form of the Staggered Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin (SAICCPF) configuration, which was designed to promote increased flow disruption, enhance thermal boundary layer disturbance, and improve fluid mixing.

This chapter is structured into two comparative studies. The first phase focuses on the effect of fin positioning, while the second phase evaluates the influence of fin geometry modifications in conjunction with advanced nanofluid formulations.

In the first phase of this study, a comparative analysis was conducted between the inline AICCPF and staggered SAICCPF designs. The results clearly indicated that the SAICCPF configuration exhibited better thermal performance across a range of Reynolds numbers and heating powers. This improvement was attributed to the enhanced local turbulence and secondary flow induced by the staggered pin-fin layout.

Based on these findings, the second phase of this chapter focuses on evaluating the SAICCPF configuration against a further optimised design: the Staggered Arranged Airfoil Integrated Split Corrugated Curvilinear Pin-Fin (SAISCCPF) heat sink. The introduction of split fins in this final configuration aimed to further intensify internal fluid motion, improve coolant distribution, and mitigate the risk of stagnant zones especially under complex flow conditions. Additionally, this phase employed the nanofluids previously prepared and characterised in Chapter 6, which included unitary formulations of MWCNTs, Ag, and AlN, as well as tri-hybrid nanofluids at volumetric ratios of 20:20:60, 20:40:40, and 20:60:20. These were integrated into the SAICCPF and SAISCCPF geometries to assess their combined effect on heat transfer enhancement and flow resistance.

To avoid redundancy, the detailed descriptions of the experimental setup, heat sink configurations, data processing, and nanofluid preparation methods already presented in Chapters 3, 4, and 6 are not repeated here. Where appropriate, cross-referencing is provided to guide the reader to the relevant sections for additional context.

The significance of this chapter lies in its contribution to understanding how geometry-induced flow manipulation and nanofluid formulation strategies can be synchronised to optimise thermal performance. By identifying the most effective heat sink–nanofluid combination, this work advances the development of high-efficiency, compact cooling solutions for next-generation electronics and power systems.

Phase I – Comparative Evaluation of Inline and Staggered Pin-Fin Heat Sinks (AICCPF vs SAICCPF)

This section investigates the impact of fin arrangement on the hydrothermal performance of biomimetic heat sinks by comparing the Inline Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin (AICCPF) with the Staggered Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin (SAICCPF) design.

8.1 Results and Discussion

8.1.1 Nusselt Number

Nusselt number was calculated for both the Inline (AICCPF) and Staggered (SAICCPF) pin-fin heat sink configurations under various heating powers. The results, plotted against Reynolds number, provide a clear comparative understanding of how fin positioning affects thermal performance across different flow conditions. Figure 8.1 presents the variation of the Nusselt number with Reynolds number for both the inline and staggered pin-fin configurations at heating powers of 50 W, 150 W, 250 W, and 350 W. Across all operating conditions, the SAICCPF configuration consistently exhibited higher Nusselt numbers compared to the Inline AICCPF counterpart, indicating superior convective heat transfer performance.

At the lowest heating power, the Nusselt number for the inline configuration ranged from 8.99 to 12.74, while the staggered design recorded values from 9.47 to 13.04 across the tested Reynolds number range. The staggered configuration achieved a maximum Nusselt number of 13.04, compared to 12.74 for the inline geometry at the maximum flow rate used in this study. The minimum values also followed this trend, with the staggered design starting at 9.47, higher than the inline's 8.99. As presented in Fig. 8.2, the average enhancement in Nusselt number at this power level was calculated to be approximately 5.23%. The relatively modest enhancement at this power level is attributed to the lower thermal gradient and weaker buoyancy forces, which limit the development of secondary flows. Nonetheless, the staggered arrangement still shows better performance due to its ability to disturb the thermal boundary layer earlier in the flow path. At 150 W, the Nusselt number improved more significantly, with average values increasing by 5.69% for the staggered configuration. For the inline design, values ranged from 9.24 to 13.45, while the staggered configuration recorded values from 9.79 to 13.97.

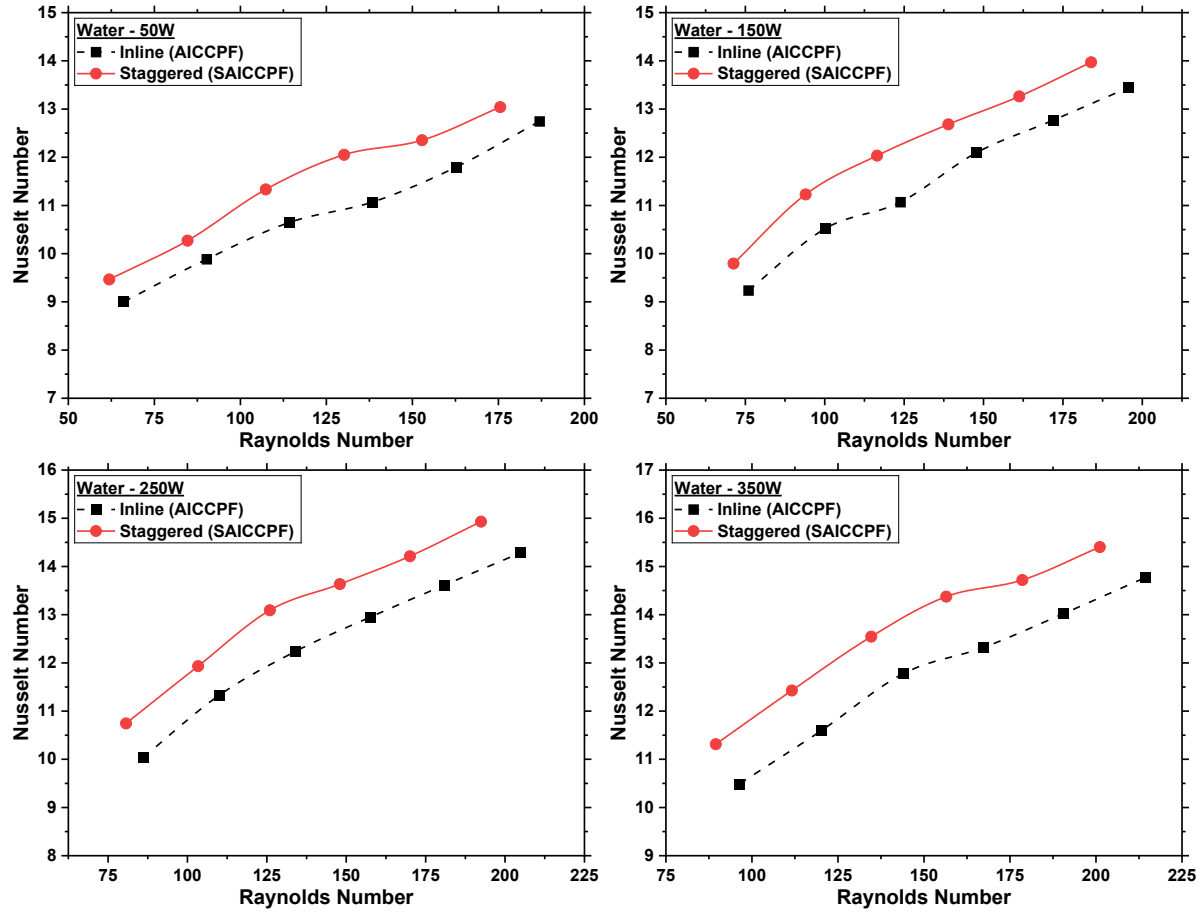


Figure 8.1. Variation of Nusselt number with Reynolds number for Inline (AICCPF) and Staggered (SAICCPF) heat sink configurations at different heating powers: (a) 50 W, (b) 150 W, (c) 250 W, and (d) 350 W.

As the heating power increases, the temperature gradient between the heat sink surface and the coolant intensifies, leading to stronger convective currents. The staggered fins interrupt the flow in a more distributed manner and enhancing local mixing. This disrupts the thermal boundary layer more effectively than the inline configuration, thereby boosting the convective heat transfer rate. When the heating power is increased to 250 W, the staggered design maintains its advantage with an average enhancement of 5.86%. The staggered layout once again outperformed the inline across all data points. The inline configuration yielded Nusselt numbers between 10.03 and 14.28, while the staggered configuration produced a higher range of 10.74 to 14.89. At the highest input power of 350 W, the staggered geometry again outperforms the inline design, with a maximum average improvement of 6.36% in Nusselt number. At this level, the benefits of the staggered configuration are fully realised. The increased heating power causes higher fluid temperatures and more rapid boundary layer growth, which the staggered arrangement effectively interrupts through periodic redirection and flow separation. This enhances turbulence intensity, even within the laminar regime, and results in improved surface heat transfer.

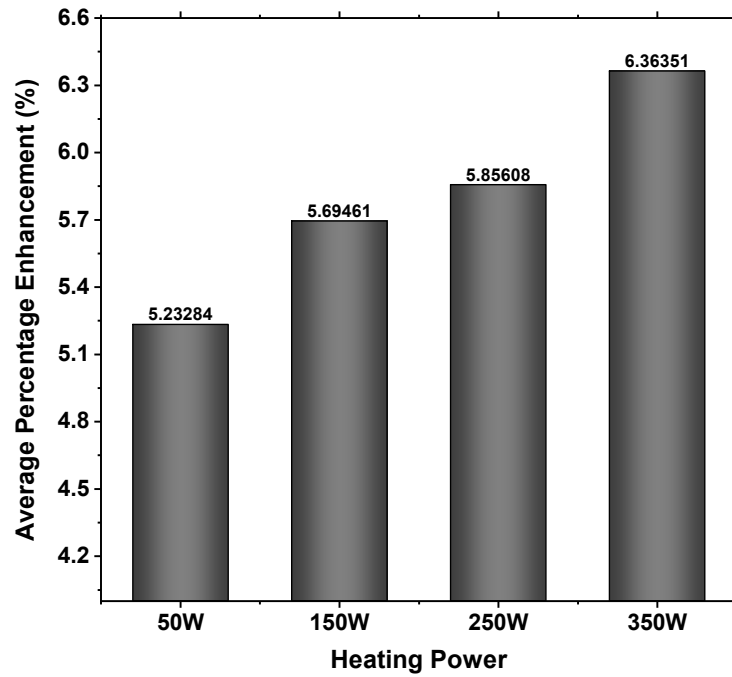


Figure 8.2. Average percentage enhancement in Nusselt number for the staggered (SAICCPF) configuration compared to the inline (AICCPF) configuration at different heating powers.

The progressive improvement suggests that the benefits of staggered fin arrangements become more pronounced at higher thermal loads, where increased turbulence and intensified boundary layer disruption significantly enhance convective heat transfer. While the introduction of turbulence typically leads to higher pressure drop, the proposed design of the staggered pin-fin configuration offers a balanced approach promoting enhanced fluid mixing and heat transfer while maintaining relatively low flow resistance. This optimisation between thermal enhancement and hydraulic penalty underscores the effectiveness of the staggered geometry in managing high heat flux applications with improved efficiency and minimal compromise on pumping power.

The observed improvements in Nusselt number with the staggered fin layout can be explained through several interrelated mechanisms:

Enhanced Flow Disruption: The staggered fins prevent the formation of streamlined paths through the channels, forcing the fluid to change direction frequently. This disrupts thermal boundary layers and prevents the development of thermal dead zones.

Increased Secondary Flows and Mixing: The staggered configuration induces lateral and vertical components of flow, promoting mixing across the channel cross-section. This increases the effective thermal conductivity of the coolant by improving heat distribution.

Surface Area Reutilisation: By redirecting the flow, staggered fins allow different sections of the coolant to interact with previously untapped fin surfaces, increasing the utilisation of the heat sink geometry.

Minimised Flow Shadowing: Unlike inline arrangements where downstream fins may lie in the wake of upstream fins, staggered arrangements expose each fin more uniformly to the incoming flow, improving local heat transfer conditions.

The growing enhancement trend with heating power also suggests that the staggered arrangement is particularly effective in managing high thermal loads, where boundary layer effects are more significant and the need for improved convective mechanisms is greater.

8.1.2 Wall Temperature and Logarithmic Mean Temperature Difference

In thermal management applications, surface temperature is a critical indicator of a system's cooling effectiveness. The average wall temperature provides a direct measure of the ability of a heat sink to maintain a safe operational temperature under varying heat loads and flow conditions. A lower wall temperature suggests improved heat dissipation from the heated surface into the working fluid. In parallel, the LMTD helps to quantify the average temperature gradient between the wall and fluid along the flow path and is an essential parameter for evaluating convective heat transfer efficiency. Both indicators are key in understanding the interplay between geometry, flow regime, and coolant properties.

As anticipated, the experimental results show that for all heating powers and Reynolds number ranges, the staggered (SAICCPF) configuration consistently outperformed the inline (AICCPF) configuration in terms of lowering the average wall temperature, as shown in Fig. 8.3. At the lowest heat input of 50 W, the staggered design maintained marginally lower wall temperatures, starting at 26.40 °C and dropping to 22.24 °C, compared to the inline configuration which ranged from 26.68 °C to 22.31 °C, as illustrated in Fig. 8.5(a). According to the results, the staggered arrangement led to an average temperature reduction of 0.45%. Although the difference was small, this behaviour reinforces the benefit of early boundary layer disruption and enhanced coolant engagement in staggered geometries. As the heating power increased to 150 W, the advantage became more evident, with surface temperatures reduced by up to 0.44 °C compared to the inline design. On average, this translated to a 1.18% reduction in wall temperature across the tested Reynolds number range. This difference becomes thermally meaningful at higher fluxes where even small improvements can prevent overheating and material stress.

The advantage of the staggered configuration grew more prominent under high heat loads. At 250 W and 350 W, the wall temperature gap widened noticeably. At 250 W, the staggered layout reduced the maximum surface temperature by about 0.56 °C, while at 350 W, the temperature difference reached nearly 1.8 °C. The most significant reduction was observed at 350 W, where the average wall temperature in the staggered configuration decreased by 2.97% compared to the inline arrangement. This effect is attributed to the more chaotic flow induced by the staggered arrangement, which increases coolant recirculation, reduces thermal resistance, and enhances surface wetting.

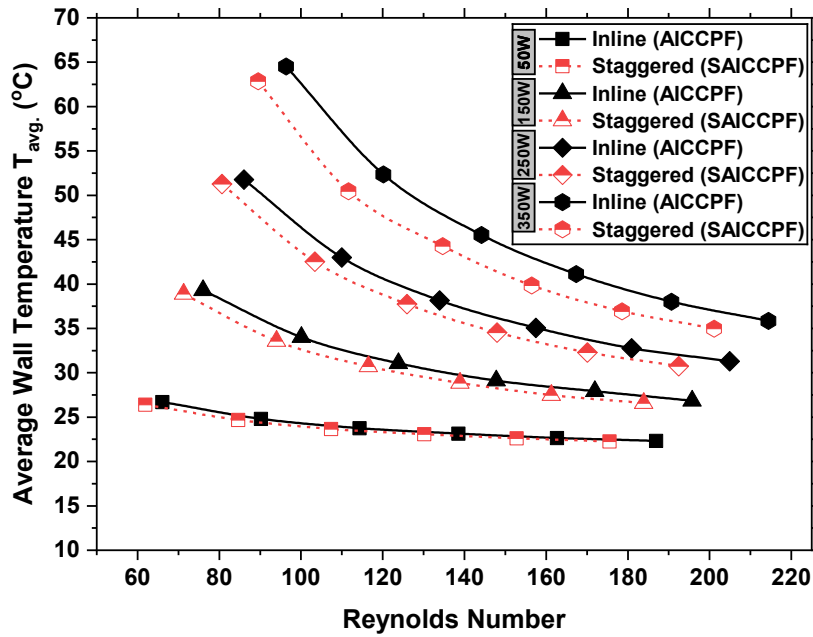


Figure 8.3. Comparison of average wall temperature trends for inline and staggered heat sink configurations across increasing Reynolds numbers at four discrete heating powers.

The focus now turns to the temperature gradient between the heat sink surface and the working fluid, a key parameter governing the overall driving force for convective heat transfer. While wall temperature reflects the surface thermal state, LMTD provides a more holistic view of heat exchange efficiency across the full length of the heat sink.

Figure 8.4 illustrates the variation of LMTD with Reynolds number for both inline and staggered configurations at different heating powers. In all cases, LMTD decreases with increasing Reynolds number, which is expected due to improved convective cooling and reduced temperature differential between the wall and the bulk fluid. At the lowest thermal load of 50 W, LMTD values ranged from 2.08 °C to 1.23 °C for the inline design, while the staggered configuration showed a tighter and lower range from 1.72 °C to 1.10 °C. Although the absolute LMTD values were relatively small, the staggered configuration consistently exhibited lower values across the entire Reynolds number spectrum. This reduction in LMTD indicates that the staggered fins promoted more uniform heat transfer and stronger fluid-wall interaction even under minimal heat flux. At a moderate heat input of 150 W, the trend continued, with LMTD values decreasing as flow rate increased for both designs. The inline configuration recorded values from 5.73 °C at the lowest Reynolds number to 3.52 °C at the highest. In contrast, the staggered layout achieved 4.79 °C to 3.07 °C.

As the power was increased to 250 W, the inline heat sink exhibited LMTD values ranging from 8.52 °C to 5.58 °C, whereas the staggered design ranged from 7.06 °C to 4.79 °C. The maximum LMTD difference of 1.47 °C occurred at the lowest Reynolds number, further affirming that the staggered geometry significantly improved thermal transport under high flux conditions. The steeper gradient of

reduction with Reynolds number in the staggered case highlights its superior ability to sustain efficient heat transfer with increasing coolant velocity.

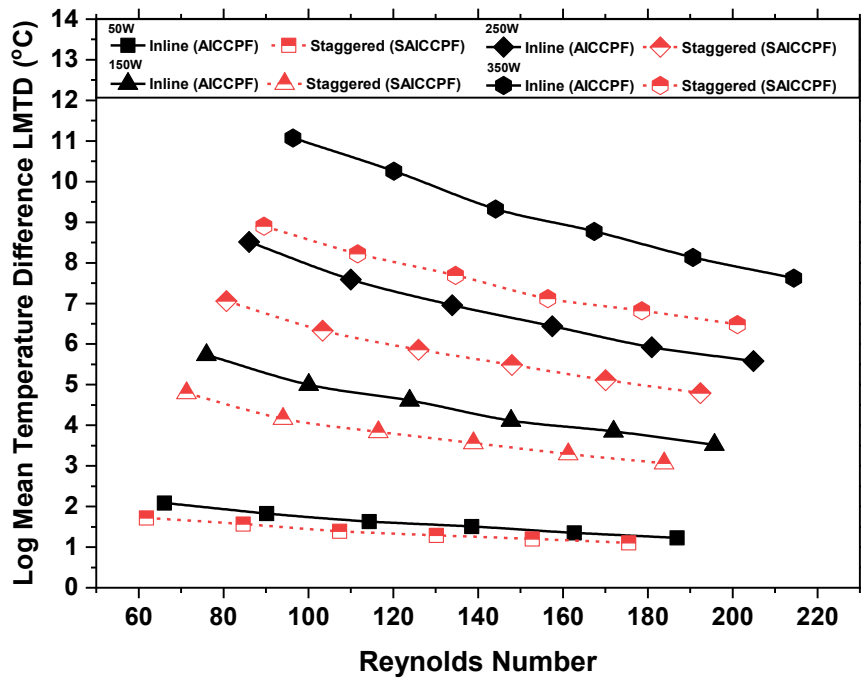


Figure 8.4. Variation of Logarithmic Mean Temperature Difference (LMTD) with Reynolds number for inline (AICCPF) and staggered (SAICCPF) heat sink configurations under different heating powers.

At the highest heating power of 350 W, the inline configuration displayed LMTD values from 11.07 °C to 7.62 °C, while the staggered configuration maintained a reduced range of 8.90 °C to 6.48 °C. The maximum LMTD observed was 11.07 °C (AICCPF at Re = 96), while the minimum LMTD was 1.10 °C (SAICCPF at Re = 176, 50 W). This significant spread reflects the thermal sensitivity of the system to both geometry and heating input. However, the largest difference between the two configurations at this power level was nearly 2.17 °C, clearly indicating that staggered fins enhance cooling effectiveness by facilitating more robust fluid mixing and improving the coolant's access to high-temperature regions. Figure 8.5(b) graphically illustrates the minimum and maximum LMTD values recorded during the study, highlighting the thermal performance boundaries of both configurations across all tested conditions.

Alongside the average wall temperature and LMTD, it is also important to consider how temperature varies along the length of the heat sink. Typically, the fluid enters the channel at a lower temperature and progressively absorbs heat as it moves downstream, resulting in a temperature gradient from inlet to outlet. This axial rise in fluid temperature reduces the local temperature difference between the wall and fluid, weakening the driving force for heat transfer. Therefore, geometric configurations that promote mixing and disturb the thermal boundary layer such as staggered fin arrangements can help maintain a higher local temperature difference, thus sustaining a stronger heat transfer rate along the full channel length.

Figures 8.5(c) and 8.5(d) depict the core temperature variation along the length of the inline (AICCPF) and staggered (SAICCPF) heat sink configurations, respectively, at the highest heating power studied (350 W). These plots provide valuable insights into how each geometry manages the thermal gradient as the coolant progresses through the channel.

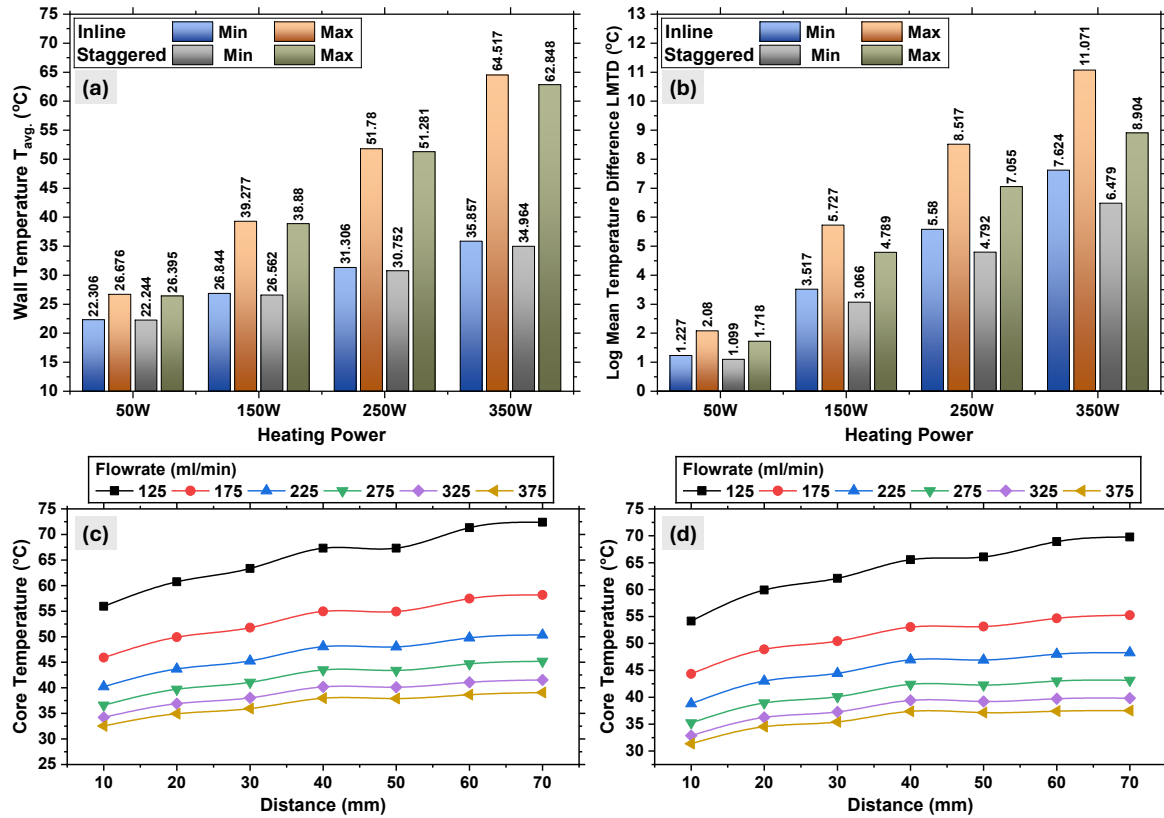


Figure 8.5. Comparison of thermal performance parameters for inline (AICCPF) and staggered (SAICCPF) heat sink configurations.

In both cases, the core temperature increases gradually from the inlet to the outlet due to continuous heat absorption by the working fluid. However, the rate of temperature rise differs significantly between the two configurations. In the inline design (Fig. 8.5c), the temperature curves are bit steeper, indicating the more rapid accumulation of thermal energy and limited mixing along the flow path. This is especially evident in the central and downstream sections, where the fluid becomes thermally saturated more quickly, reducing the local temperature gradient and weakening convective heat transfer.

Conversely, the staggered configuration (Fig. 8.5d) shows a more moderated temperature rise along the same axial length. The comparatively gentler slope of the temperature profiles suggests more effective thermal distribution and mixing, which helps maintain a stronger wall-to-fluid temperature differential throughout the heat sink. This behaviour confirms that the staggered fin arrangement disrupts the thermal boundary layer more efficiently and facilitates better fluid redistribution, especially in high thermal load conditions. As a result, thermal performance is enhanced, and the risk of hot spot formation near the outlet is reduced.

These findings reinforce the thermal advantage of the SAICCPF configuration, particularly in high-power applications where maintaining uniform temperature distribution and delaying fluid thermal saturation are crucial for reliable system operation.

Overall, the staggered arrangement demonstrated superior thermal performance across all power levels. This performance is especially important in applications where maintaining a low thermal gradient is essential for safe operation and efficient energy dissipation. The findings further support the advantage of staggered biomimetic pin-fin arrangements in high-performance thermal systems.

8.1.3 Thermal Resistance

Thermal resistance is a key performance indicator representing the system's ability to resist heat flow from the heated surface to the coolant. Lower thermal resistance indicates more efficient heat dissipation and less thermal bottlenecking between the heat source and the fluid medium. Unlike temperature-based indicators, TR combines the effect of both surface temperature and heat input, making it highly relevant for comparing geometries under consistent power loads.

At 50 W, the inline configuration recorded TR values decreasing from 0.038 °C/W to 0.027 °C/W as Reynolds number increased, while the staggered configuration achieved a reduction from 0.032 °C/W to 0.023 °C/W. The greater drop in TR with increasing flow rate also shows that the staggered geometry responds more effectively to increased convective cooling. As the heating power increased to 150 W, the benefits of the staggered geometry became more pronounced. The inline design exhibited TR values from 0.036 °C/W to 0.025 °C/W, whereas the staggered counterpart improved further, ranging from 0.030 °C/W to 0.0216 °C/W. The enhanced fluid mixing and improved surface wetting in the staggered configuration result in less temperature rise per unit of heat input, reinforcing its role in achieving thermally stable performance at higher power levels. When the heat input reached 250 W, TR values for the inline configuration ranged from 0.0318 °C/W to 0.0236 °C/W, while the staggered layout delivered even lower values—starting at 0.0264 °C/W and reaching as low as 0.0201 °C/W. The continued reduction in thermal resistance reflects the staggered design's capacity to delay coolant thermal saturation and promote consistent surface cooling across a broader temperature differential. At the highest heating power of 350 W, the inline configuration's TR dropped from 0.0294 °C/W to 0.0226 °C/W, while the staggered design achieved a more significant reduction from 0.0243 °C/W to 0.0192 °C/W. These results confirm the staggered heat sink's superior ability to manage heat flow, maintaining a lower thermal gradient and maximising the heat extraction potential of the coolant. Importantly, the marginal improvement becomes even more valuable at high power levels, where each degree of temperature reduction directly contributes to system reliability and operational safety.

These findings are further supported by Fig. 8.6, which shows the variation of thermal resistance with Reynolds number for both configurations across all heating powers. The consistent downward trend in TR values for the staggered geometry, especially at higher Reynolds numbers, highlights its superior thermal management capabilities. Additionally, to present a summarised view of the performance

boundaries, Fig. 8.7 displays the minimum and maximum thermal resistance values observed for both configurations. The staggered design consistently achieves lower values across all power levels, visually reinforcing its thermal superiority and confirming its suitability for high heat flux applications where thermal reliability is paramount.

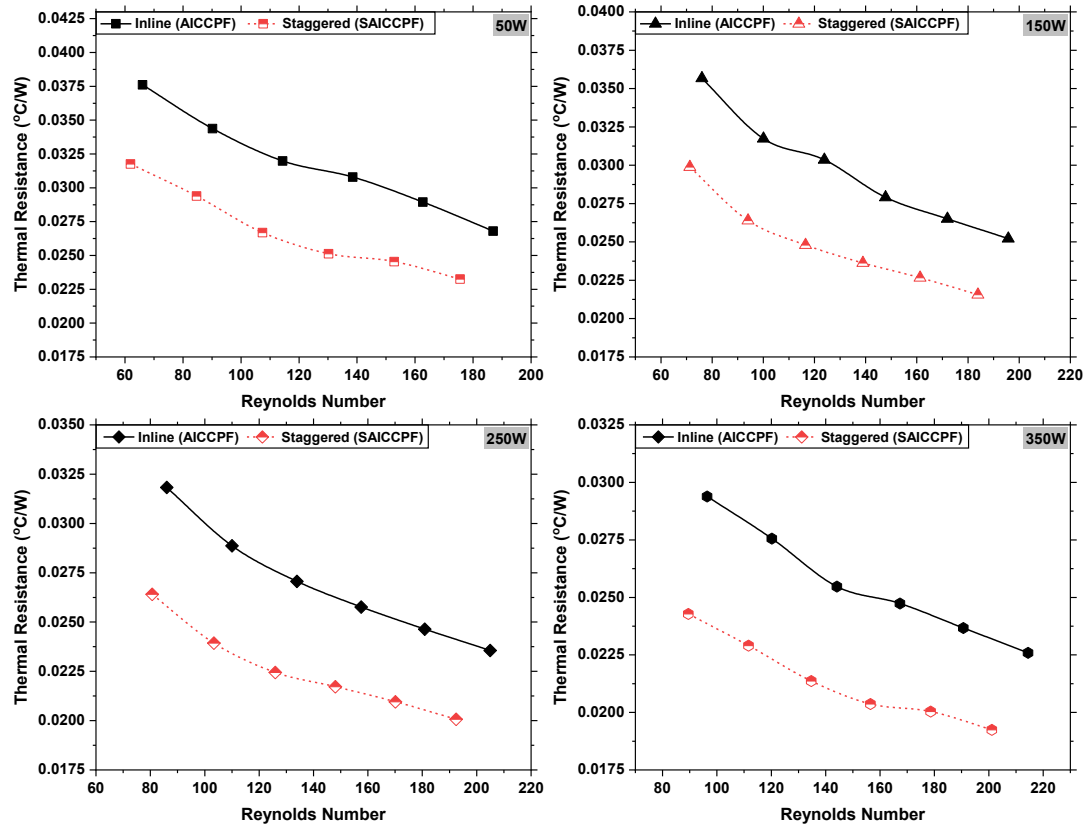


Figure 8.6. Thermal resistance trends for inline and staggered heat sink configurations across various heating powers.

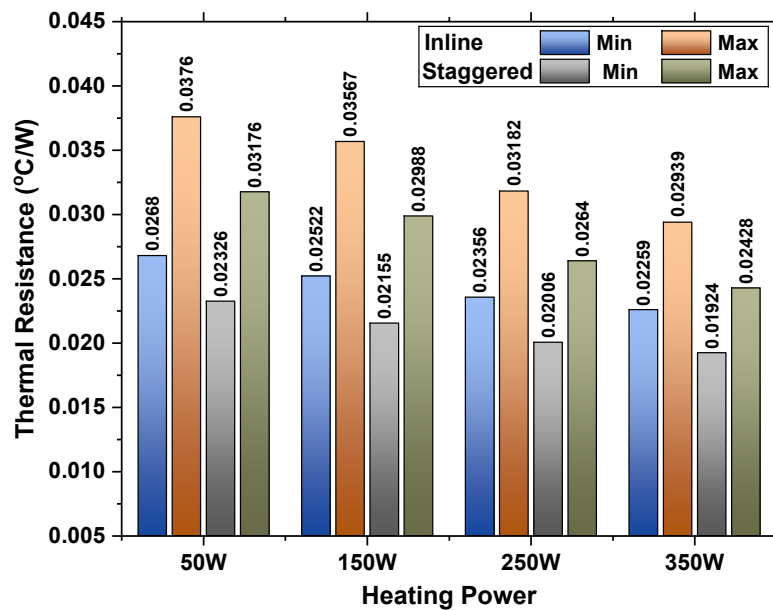


Figure 8.7. Comparison of minimum and maximum thermal resistance values observed for Inline and Staggered configurations at each heating power.

The staggered (SAICCPF) configuration consistently yielded lower thermal resistance values across all tested conditions, reaffirming its enhanced convective behaviour and ability to maintain thermal stability under increasing heat flux. These improvements, though numerically moderate, are practically significant for compact thermal systems where reducing resistance can directly influence performance and longevity.

8.1.4 Pressure Drop

In compact liquid-cooled systems, pressure drop is a fundamental parameter that directly impacts energy efficiency, pump selection, and system longevity. While improved heat transfer performance is desirable, it must not come at the cost of excessive pressure losses, which would lead to increased pumping power requirements and higher operational costs. Therefore, evaluating pressure drop alongside thermal metrics such as Nusselt number and thermal resistance is essential for a comprehensive assessment of a heat sink's hydrothermal performance.

Figure 8.8 presents the variation in pressure drop with Reynolds number for both the inline (AICCPF) and staggered (SAICCPF) configurations across four heating powers: 50 W, 150 W, 250 W, and 350 W. In all cases, pressure drop increased with Reynolds number, as expected, due to the rise in fluid momentum. The staggered configuration consistently resulted in higher pressure drop values than the inline configuration. This is primarily due to increased turbulence, secondary flow formation, and directional changes induced by the staggered fin arrangement, which disrupt the flow and enhance mixing.

At 50 W, the pressure drop in the inline heat sink increased from approximately 31 Pa to 285 Pa across the tested Reynolds range. In comparison, the staggered configuration ranged from about 35 Pa to 299 Pa, reflecting an average increase of 10.61%. Notably, this pressure drop enhancement exceeded the 5.23% improvement in Nusselt number observed at this power level, indicating that the thermal-hydraulic trade-off is less favourable under lower thermal loads. At these conditions, the flow remains largely laminar, and the additional flow resistance from the staggered fins is not fully offset by enhanced convective benefits.

At 150 W, the pressure drop for the inline design varied between approximately 28 Pa and 270 Pa, while the staggered design ranged from about 32 Pa to 286 Pa. This corresponds to an 8.82% increase in pressure drop, with a 5.69% gain in Nusselt number, representing a more balanced trade-off between thermal and hydraulic performance. The improved buoyancy and turbulence effects at this power level help the staggered configuration capitalise more effectively on its geometry for heat transfer enhancement.

The gap narrowed further at 250 W, where the inline configuration recorded pressure drops from approximately 24 Pa to 259 Pa, while the staggered layout ranged from about 27 Pa to 271 Pa. The resulting 7.46% increase in pressure drop is more closely aligned with the 5.86% enhancement in Nusselt number, suggesting a more efficient hydrothermal response at mid to high thermal loads.

At 350 W, the most thermally demanding condition, the inline configuration exhibited pressure drop values from approximately 27.5 Pa to 245 Pa, while the staggered configuration showed a modest increase, ranging from about 30 Pa to 261 Pa. This equated to a 6.92% pressure drop increase, closely matching the 6.36% improvement in Nusselt number, thereby indicating a well-balanced thermal-hydraulic performance at elevated power input.

It is important to highlight that although the staggered configuration induces slightly higher pressure losses, the magnitude of this increase is considered acceptable in engineering practice. The study maintained consistent fin count and shape only modifying their arrangement. Thus, no additional physical restrictions were introduced. The observed pressure increase is a direct result of enhanced mixing and localised flow reorientation, which are necessary for disrupting the thermal boundary layer and improving convective performance.

This reinforces the key insight that geometric rearrangement alone, even without altering fin shape or channel size, can produce meaningful gains in heat transfer while keeping pressure losses within reasonable bounds. Moreover, in practical systems such as electronics cooling, electric vehicles, or high-performance computing hardware, the slight increase in pumping effort is often outweighed by the benefits of lower surface temperatures, reduced thermal hotspots, and greater reliability.

All in all, the staggered (SAICCPF) configuration demonstrates a consistent, controlled increase in pressure drop that is proportional to its heat transfer improvement. These findings validate the effectiveness of staggered fin placement in achieving a superior balance between thermal and hydraulic performance without introducing excessive flow penalties.

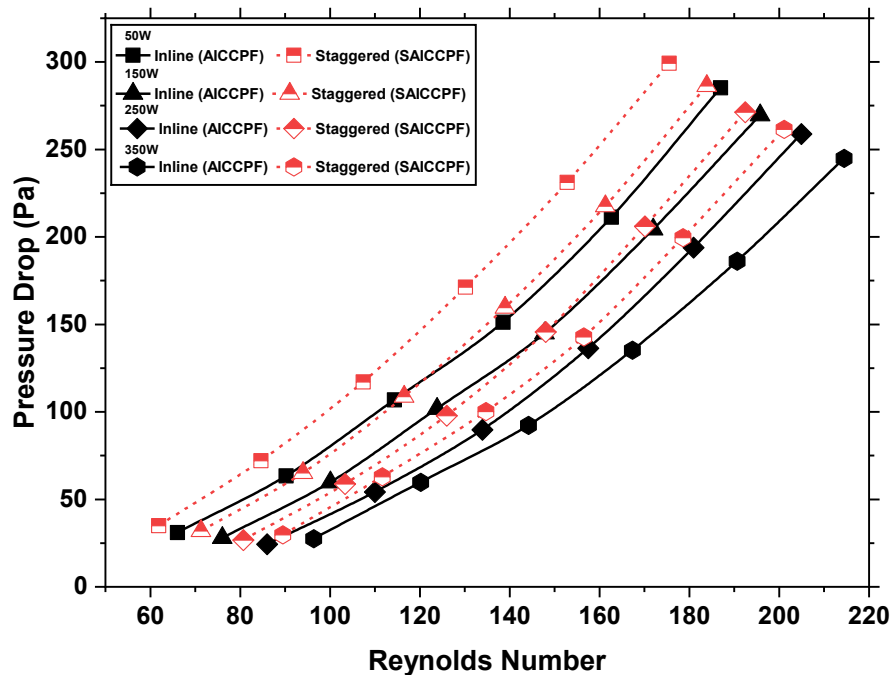


Figure 8.8. Pressure drop as a function of Reynolds number for inline (AICCPF) and staggered (SAICCPF) heat sink configurations under various heating powers.

Summary

This phase of the study investigated the hydrothermal performance of two biomimetic heat sink configurations: the inline (AICCPF) and staggered (SAICCPF) airfoil-integrated corrugated curvilinear pin-fin designs. Both geometries were experimentally evaluated under varying Reynolds numbers and heating powers using distilled water as the coolant. The staggered configuration demonstrated superior heat transfer characteristics, evidenced by higher Nusselt numbers, reduced wall temperatures, lower thermal resistance, and improved temperature distribution along the heat sink. Although it exhibited slightly higher pressure drops, the increase remained within acceptable limits, particularly at higher heating powers where thermal advantages became more pronounced. The findings clearly highlight the effectiveness of staggered fin arrangements in enhancing convective heat transfer without incurring significant hydraulic penalties, making it a promising configuration for advanced thermal management applications.

Phase II – Performance Assessment of SAICCPF vs SAISCCPF Using Unitary and Tri-Hybrid Nanofluids

This section examines the thermal and hydraulic performance of the best-performing configuration from Phase I (SAICCPF) against the newly developed Staggered Arranged Airfoil Integrated Split Corrugated Curvilinear Pin-Fin (SAISCCPF), using advanced unitary and tri-hybrid nanofluids based on MWCNTs, Ag, and AlN. Notably, the SAISCCPF configuration not only offers enhanced thermal transport but also more closely mimics the natural flow behaviour observed in fish respiration. Unlike earlier designs, where flow primarily exits beneath the central pin-fin structure, the split-fin layout enables fluid discharge through both the core and the trailing end, providing improved flow continuity and thermal management. For detailed geometrical descriptions of these heat sink configurations, please refer to Chapter 3.

8.2 Results and Discussion

8.2.1 Nusselt Number

This phase of the study builds upon the findings of Phase I by comparing the best-performing geometry, SAICCPF, with a further refined split pin-fin design (SAISCCPF), which introduces a novel split pin-fin structure aimed at improving flow dynamics and thermal performance. Both configurations were experimentally tested at heating powers of 100 W, 175 W, 250 W, and 325 W, across comparable Reynolds number ranges. The study aimed to evaluate whether further geometric optimisation beyond the staggered arrangement could yield meaningful improvements in thermal performance.

Figure 8.9 illustrates the variation of Nusselt number with Reynolds number for both configurations. Across all tested conditions, the SAISCCPF consistently yielded higher Nusselt numbers than

SAICCPF, indicating more effective convective heat transfer. At 100 W, the SAICCPF configuration exhibited Nu values ranging from 9.68 to 15.29, while the SAISCCPF showed improved values from 10.04 to 15.51. The average Nusselt number enhancement for this case was 3.72%. Though modest, this improvement suggests that even at low thermal loads, the split design begins to positively influence fluid dynamics.

At 175 W, the Nusselt number for SAICCPF ranged from 10.50 to 15.82, while SAISCCPF reached values from 11.00 to 16.19, showing a more noticeable average enhancement of 4.45%. This increase reflects the growing influence of geometric modifications as the heat input and resulting thermal gradients intensify.

At 250 W, the average enhancement in Nu rose to 5.29%, as shown in Fig. 8.10. SAISCCPF achieved a peak Nusselt number of 16.72, compared to 16.08 for SAICCPF. At higher Reynolds numbers, the thermal boundary layers are thinner, and the enhanced surface interaction from the split fins yields greater convective efficiency.

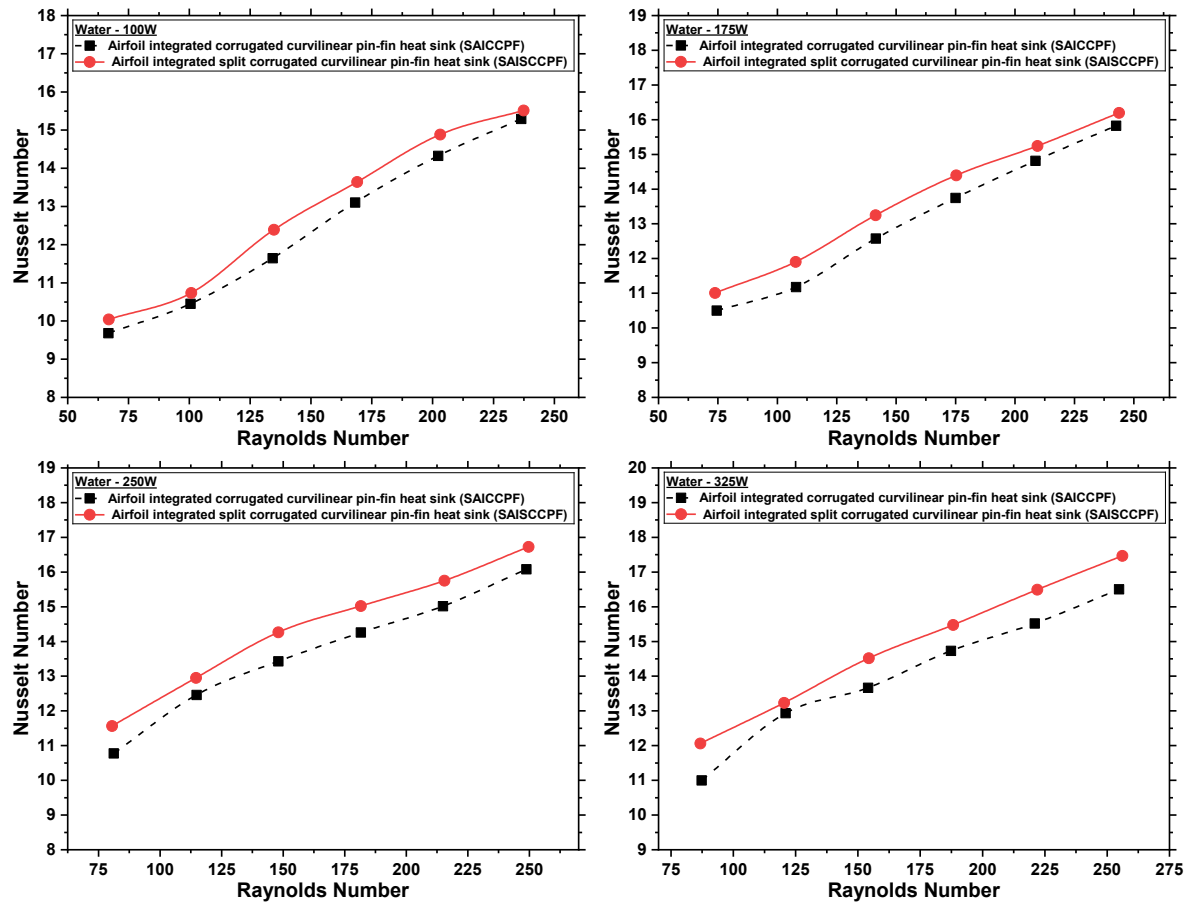


Figure 8.9. Variation of Nusselt number with Reynolds number for SAICCPF and SAISCCPF heat sink configurations under different heating powers (100 W, 175 W, 250 W, and 325 W).

Finally, at 325 W, the SAISCCPF configuration reached its highest performance advantage, with an average Nu enhancement of 5.90%. The improved Nusselt number values (from 12.06 to 17.47) clearly

outperform those of SAICCPF (from 11.00 to 16.50), demonstrating that the thermal benefit of the split-fin design becomes more pronounced at elevated heat flux levels.

The superior thermal performance of the SAISCCPF configuration is attributed to several key fluid dynamic mechanisms. The introduction of split pin-fins effectively disrupts the thermal boundary layer and promotes greater internal mixing, which is particularly beneficial at high Reynolds numbers. Additionally, the design introduces alternative flow pathways—a feature that becomes critical in complex thermal environments, especially under conditions that may involve two-phase flow.

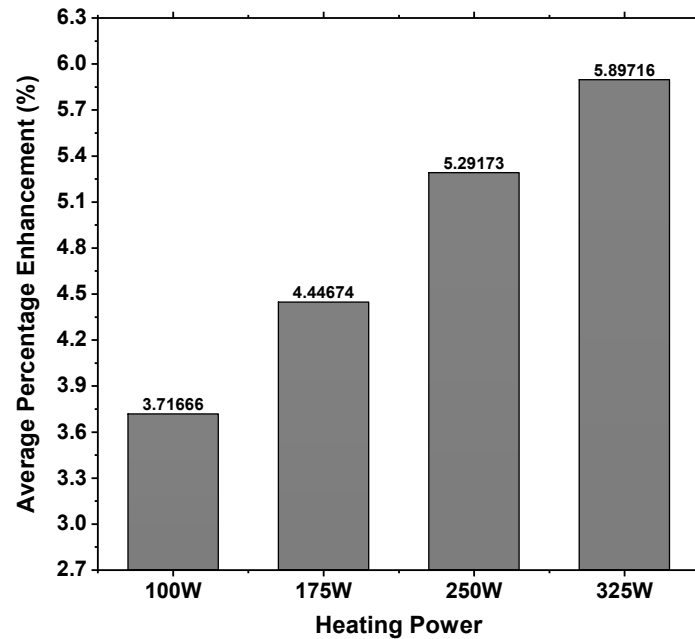


Figure 8.10. Average percentage enhancement in Nusselt number achieved by the SAISCCPF configuration compared to SAICCPF at each heating power level.

During boiling or high-flux operations, air bubbles or vapour pockets may form and become trapped within pin-fin passages. In the conventional SAICCPF configuration, these blockages can lead to flow dead zones, diminishing heat transfer and creating localised hotspots. However, the split geometry in SAISCCPF offers multiple parallel pathways for the coolant to bypass obstructed regions. This ensures more continuous and stable flow, maintaining effective heat exchange even under perturbations.

In summary, the SAISCCPF outperforms SAICCPF not just by increasing turbulence, but by introducing structural resilience against flow blockages, promoting more uniform cooling, and improving heat extraction under high thermal loads. These advantages are achieved without a substantial increase in pressure drop, as will be evaluated in the following sections.

8.2.2 Thermal Performance of Unitary and Tri-Hybrid Nanofluids

In the second part of this investigation, the thermal performance of unitary nanofluids (MWCNTs, Ag, AlN) and tri-hybrid nanofluids (MWCNTs/Ag/AlN) was assessed using the SAICCPF heat sink configuration. The aim was to evaluate the influence of nanoparticle composition and mixing ratios on

convective heat transfer under varying thermal loads and flow rates. For nanoparticle details, synthesis procedures, stability assessment, and thermophysical properties, readers are referred to Chapter 6. The Reynolds number and heating power conditions used were the same as those employed in the earlier comparison between SAICCPF and SAISCCPF.

Figure 8.11 presents the variation in Nusselt number with Reynolds number for all tested fluids across four heating powers ranging 100 W–325 W. As anticipated, all nanofluids exhibited higher Nusselt numbers than the base fluid (water), confirming their enhanced convective heat transfer capabilities.

Among all the samples, the MWCNT-based nanofluid consistently achieved the highest Nusselt number at each thermal condition. This is attributed to the exceptionally high thermal conductivity of MWCNTs, which enhances energy transport within the fluid. For instance, at 325 W and the highest Reynolds number tested, the MWCNT nanofluid recorded a Nusselt number of 18.73, outperforming other fluids by a significant margin. However, this high performance comes with a critical caveat: as discussed in Chapter 6, MWCNTs are prone to agglomeration, and once aggregated, they are difficult to re-disperse uniformly. Due to their low density, the agglomerates tend to float rather than settle, giving an illusion of dispersion. These floating clusters may obstruct flow paths and accumulate inside the channels, especially under prolonged or high-flux operation, leading to inconsistent thermal performance.

In contrast, Ag and AlN nanofluids, while not matching MWCNTs in thermal conductivity, demonstrated more stable dispersion behaviour. Their denser particles are more likely to settle but can be more predictably managed with appropriate surfactants or flow design. Among them, Ag-based nanofluids showed better thermal performance than AlN, with Nusselt numbers ranging from approximately 11.0 to 18.34 depending on the operating conditions. AlN, being the least conductive of the three, recorded the lowest Nusselt numbers but still outperformed water significantly.

The tri-hybrid nanofluids, incorporating MWCNTs, Ag, and AlN in different volumetric ratios, aimed to balance the thermal conductivity, stability, and cost. Among the tested combinations, the mixtures with ratios of MWCNTs/Ag/AlN (20:60:20) and (20:40:40) stood out. The (20:60:20) formulation performed particularly well, achieving Nusselt number values close to those of MWCNTs and, in many cases, exceeding those of Ag-based nanofluids. At the maximum heating power of 325 W and a Reynolds number of 243, the 20:60:20 tri-hybrid fluid recorded a Nusselt number of 18.53, while MWCNTs and Ag recorded 18.73 and 18.34, respectively. This suggests that the addition of MWCNTs in a moderate proportion of 20% is sufficient to elevate thermal conductivity, while the higher proportion of secondary or tertiary nanoparticles contributes to improved stability, more uniform particle dispersion, and greater cost-effectiveness.

The 20:40:40 nanofluid also showed reliable performance, slightly lower than 20:60:20 formulation but with reduced risk of particle instability compared to pure MWCNT suspensions. The 20:20:60 formulation, with a higher AlN content, demonstrated more stable but slightly lower thermal performance, staying below MWCNT and Ag in most cases.

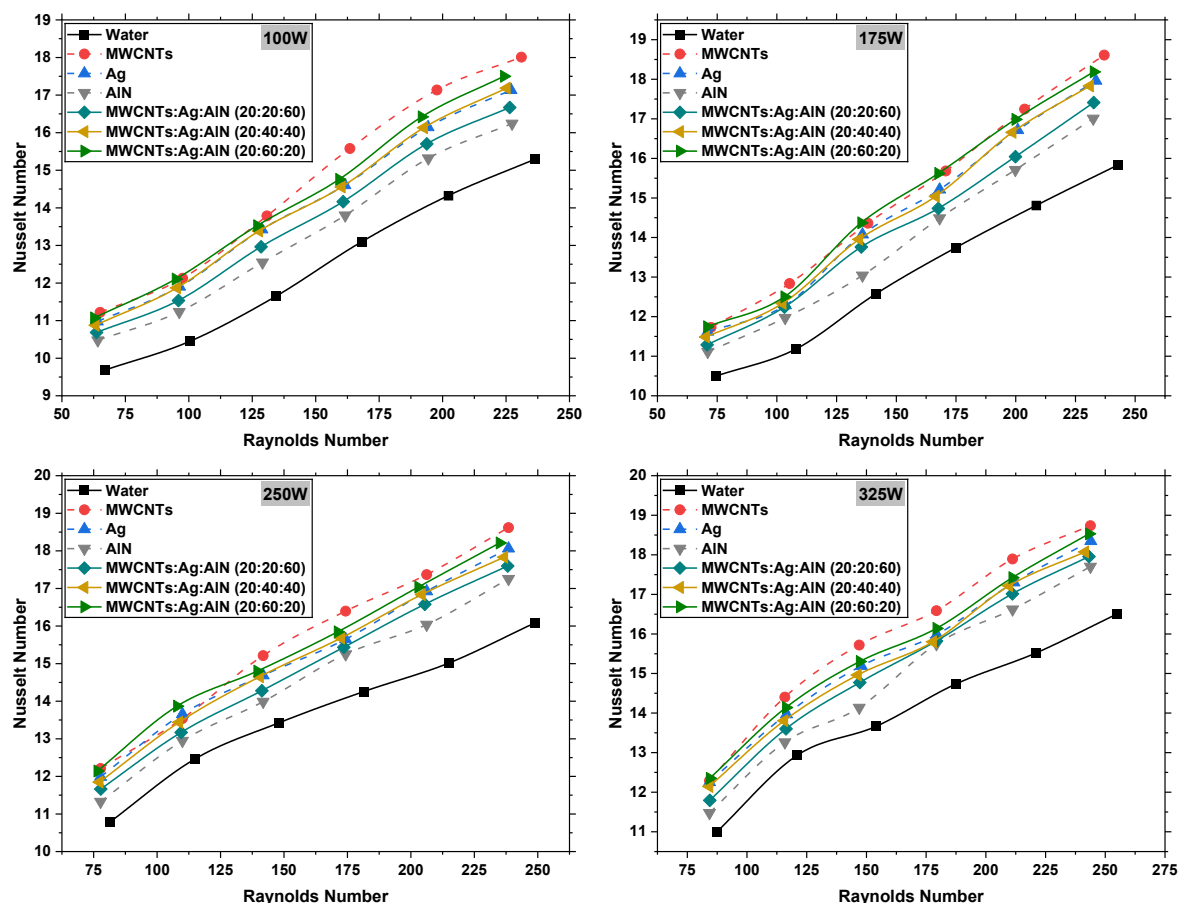


Figure 8.11. Nusselt number variation with Reynolds number for different nanofluids tested in the SAICCPF configuration at heating powers of 100 W, 175 W, 250 W, and 325 W.

Figure 8.12 provides a summarised view of the average percentage enhancement in Nusselt number for each nanofluid relative to water, across all heating powers. At 100 W, the MWCNT nanofluid led with an 18.52% enhancement, followed by the (20:60:20) tri-hybrid, which showed an enhancement of 16.09%, and the (20:40:40) mixture with 13.74%. As heating power increased to 175 W, the enhancements reduced slightly due to thermal saturation effects, but the ranking remained similar, MWCNTs demonstrated an improvement of 15.74%, the (20:60:20) tri-hybrid reached 14.74%, and the (20:40:40) blend recorded 12.12%. At 250 W, MWCNTs offered a 15.05% increase in performance, while the (20:60:20) and (20:40:40) formulations followed with 13.90% and 11.77%, respectively. Finally, under the highest heat input of 325 W, MWCNTs delivered a 13.88% gain, closely followed by the top-performing tri-hybrid at 12.42%, reaffirming its potential as a stable and high-performing alternative to pure MWCNT-based nanofluids.

This trend indicates that while the absolute Nusselt number increases with heating power for all fluids, the percentage enhancement over water gradually narrows. This trend is likely attributed to the increasing thermal efficiency of water at elevated temperatures, coupled with a reduction in surfactant effectiveness, which can lower the stability of the suspension. As the fluid's viscosity decreases with rising temperature, the intermolecular attraction between nanoparticles intensifies, increasing the risk

of agglomeration. These factors collectively diminish the relative advantage offered by nanofluid additives at higher thermal loads.

Figure 8.12 not only confirms the previously discussed numerical findings but also demonstrates that well-formulated tri-hybrid nanofluids can closely match, and in certain operating conditions approach, the performance of MWCNTs while offering better dispersion characteristics and long-term stability. The enhancement values for AlN remain the lowest across all conditions, which aligns with its relatively lower thermal conductivity and heavier particle mass, although it plays a valuable role in hybrid suspensions by aiding dispersion and preventing sedimentation.

These findings reinforce that thermal performance is not solely dictated by the inclusion of highly conductive nanoparticles, but by how well they are stabilised and synergistically combined. The (20:60:20) and (20:40:40) fluids offer compelling evidence that a strategic balance of nanoparticle types and proportions can yield results close to the best-performing single-phase nanofluid, while significantly reducing the risks of sedimentation, agglomeration, or operational instability.

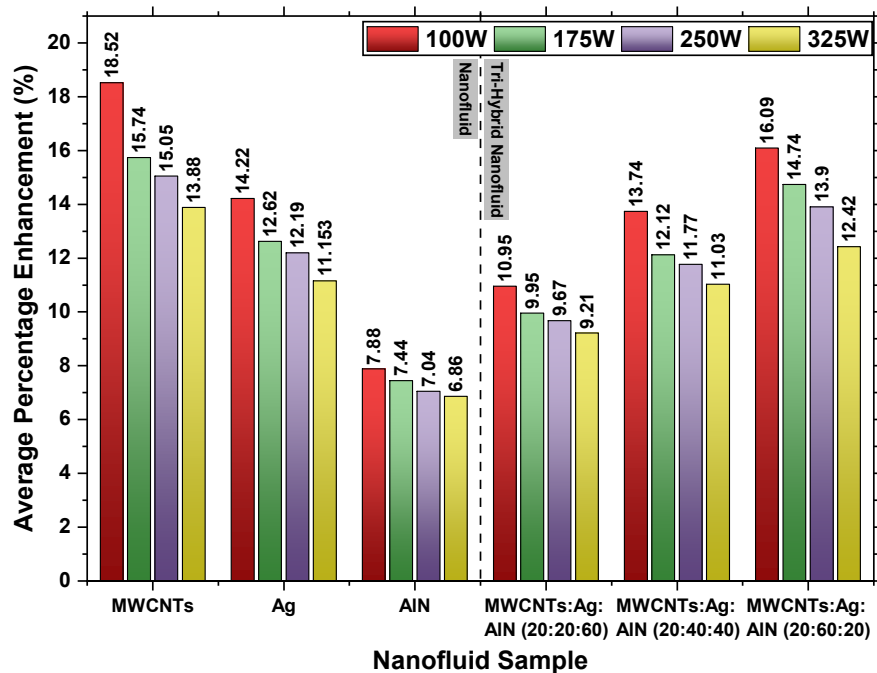


Figure 8.12. Average percentage enhancement in Nusselt number over water for various unitary and tri-hybrid nanofluids at different heating powers.

8.2.3 Thermal Performance of Hybrid Nanofluids in SAISCCPF Configuration

Moving forward with the study, the SAISCCPF configuration, previously shown to outperform SAICCPF in geometric optimisation, was now tested using the best-performing tri-hybrid nanofluids identified in the earlier sections, the MWCNTs/Ag/AlN mixtures with 20:40:40 and 20:60:20 volume ratios. The Reynolds number and heating power conditions remained consistent with prior experiments to make a comparative analysis.

Figure 8.13 illustrates the variation in Nusselt number with Reynolds number at different heating powers for both tri-hybrid nanofluids, benchmarked against water. As expected, both formulations significantly outperformed water across all flow conditions and thermal loads, demonstrating the strong potential of tri-hybrid nanofluids when used in an optimised split-fin heat sink geometry. At 100 W, the (20:60:20) nanofluid achieved a peak Nusselt number of 17.94 at Re around 224, while the (20:40:40) mixture reached 17.79 at a Re of approximately 226. These values are noticeably higher than those recorded for water in the same configuration, and also surpass the corresponding values observed in the SAICCPF setup, highlighting the effectiveness of combining enhanced fluid composition with improved geometry. As heating power increased to 175 W, the performance trend persisted. The (20:60:20) formulation achieved up to 18.90, and (20:40:40) reached 18.48 at their respective peak Reynolds numbers. This performance was not only higher than the water baseline but also exceeded the same formulations when tested in SAISCCPF, suggesting that the SAISCCPF geometry is better able to exploit the thermal potential of these advanced fluids.

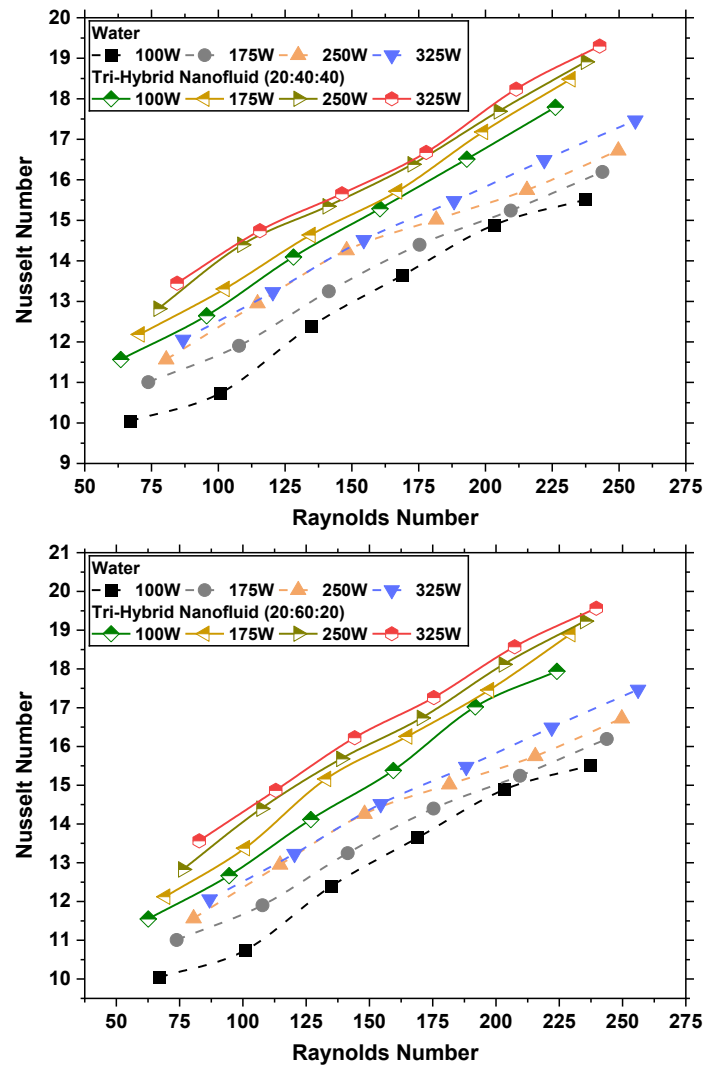


Figure 8.13. Nusselt number variation with Reynolds number for tri-hybrid nanofluids (MWCNTs/Ag/AlN) at 20:40:40 and 20:60:20 mixing ratios, compared to water, using the SAISCCPF heat sink configuration.

At 250 W, both nanofluids showed continued performance gains. The (20:60:20) formulation reached a maximum Nusselt number of 19.23, while (20:40:40) attained 18.91. The narrowing difference between the two mixtures at this higher power level indicates that the relative advantage of the additional silver content in the (20:60:20) formulation may diminish slightly as thermal saturation effects start to influence the heat transfer dynamics more uniformly.

Finally, at 325 W, the highest thermal load studied, both tri-hybrid nanofluids continued to perform strongly. The (20:60:20) fluid recorded a peak Nu of 19.44, while the (20:40:40) mixture followed closely with 19.30, confirming the thermal consistency of both formulations under high-stress conditions.

To provide a more concise comparison of thermal improvement, Figure 8.14 presents the average percentage enhancement in Nusselt number over water for both nanofluids across all heating powers. At 100 W, the (20:60:20) fluid led with a 17.18% enhancement, followed by the (20:40:40) mixture at 15.48%. These enhancements are comparatively higher than those previously recorded in the SAICCPF configuration, where the same nanofluids (20:60:20 and 20:40:40) exhibited average improvements of 16.10% and 13.74%, respectively, under similar operating conditions. This demonstrates that the SAISCCPF geometry further amplifies the benefits of nanofluids, particularly at lower to mid-range heating powers where flow structures are more sensitive to internal channel design.

At 175 W, the enhancements were 15.53% for (20:60:20) and 13.12% for (20:40:40), again outperforming their respective values from the SAICCPF case (14.74% and 12.12%). As heat input increased to 250 W, the enhancements recorded were 14.86% for (20:60:20) and 12.64% for (20:40:40). The trend continues at 325 W, where (20:60:20) maintained a 13.36% gain over water, with the (20:40:40) fluid showing 11.85%.

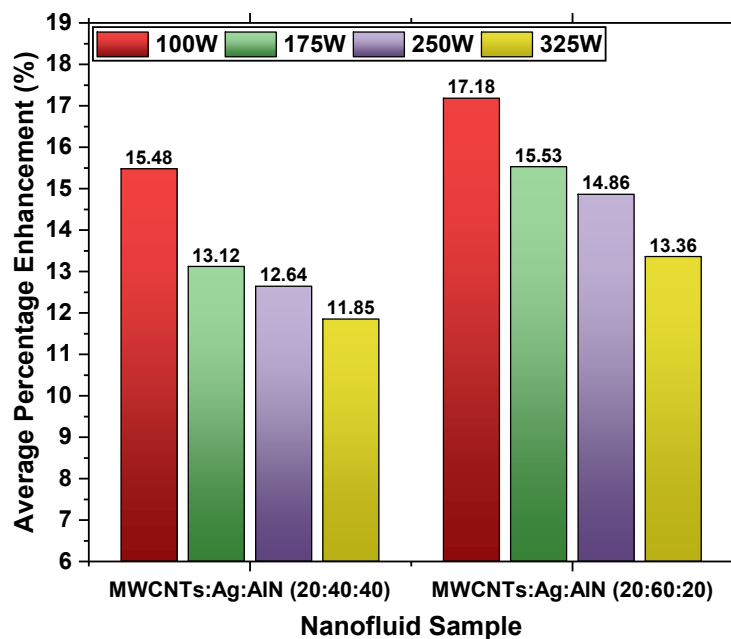


Figure 8.14. Average percentage enhancement in Nusselt number over water for MWCNTs/Ag/AlN nanofluids with 20:40:40 and 20:60:20 ratios.

The results confirms that the SAISCCPF configuration, when paired with optimised tri-hybrid nanofluids, delivers superior thermal performance compared to both water and the earlier SAICCPF design. The split-fin architecture not only promotes better fluid mixing and boundary layer disruption but also accommodates the dynamic behaviour of nanofluids more effectively. However, the 20:40:40 formulation is also considered a promising and practical alternative, particularly for applications where cost sensitivity is a key concern and the system operates below maximum thermal loads. Its balanced composition offers a compelling trade-off between performance, stability, and affordability, making it well-suited for moderate-duty cooling environments.

8.2.4 Thermal Resistance and Wall Temperature Analysis

To gain deeper insight into the thermal performance of the tested heat sink configurations and nanofluids, thermal resistance (TR) and wall temperature (WT) were analysed at the highest heating power of 325 W, where maximum convective activity and fluid–surface interaction are expected. The two most promising tri-hybrid nanofluids, MWCNTs/Ag/AlN in 20:40:40 and 20:60:20 ratios, were evaluated in both SAICCPF and SAISCCPF configurations. The corresponding variations in TR and WT are presented in Figures 8.15(a) and 8.15(b), respectively, while Figures 8.15(c) and 8.15(d) illustrate the temperature distribution along the length of the heat sinks using water at various flow rates. Figure 8.15(a) displays the variation in thermal resistance with Reynolds number for water and both tri-hybrid nanofluids in both heat sink designs. As expected, TR decreased with increasing Reynolds number across all cases due to the enhanced convective heat transfer at higher flow rates. Among the fluids tested, water showed the highest thermal resistance in both configurations. In SAICCPF, it reduced from 0.0252 °C/W to 0.0181 °C/W, whereas in SAISCCPF, it ranged from 0.0237 °C/W to 0.0162 °C/W. The lower TR values for SAISCCPF across all Reynolds numbers confirm the effectiveness of the split pin-fin geometry in facilitating superior heat dissipation.

The 20:40:40 tri-hybrid nanofluid in SAICCPF exhibited improved thermal performance, with TR reducing from 0.0213 °C/W to 0.0158 °C/W, while in SAISCCPF, it dropped even further, from 0.0197 °C/W to 0.0137 °C/W. Similarly, the 20:60:20 mixture showed a TR range of 0.0210 °C/W to 0.0153 °C/W in SAICCPF, and a more favourable range of 0.0196 °C/W to 0.0135 °C/W in SAISCCPF. These results reinforce that both the nanofluids and the heat sink geometry contribute significantly to lowering thermal resistance, with SAISCCPF paired with the 20:60:20 formulation yielding the lowest overall TR values. The data highlights the synergistic effect of enhanced nanofluid thermal conductivity and optimised flow design.

The average wall temperature trends shown in Figure 8.15(b) follow an inverse relationship with Reynolds number, as anticipated. Water recorded the highest wall temperatures across both configurations, reflecting its lower heat transfer capability. In SAICCPF, water's average wall temperature dropped from 60.1 °C to 30.8 °C as Re increased. For SAISCCPF, the corresponding

reduction was from 58.3 °C to 30.1 °C, indicating more effective thermal extraction due to the split-fin design.

The 20:40:40 nanofluid recorded lower wall temperatures, ranging from 58.4 °C to 29.5 °C in SAICCPF, and 57.4 °C to 28.6 °C in SAISCCPF. Similarly, the 20:60:20 formulation resulted in further reductions, with SAICCPF showing 57.7 °C to 29.4 °C, and SAISCCPF achieving 56.6 °C to 28.4 °C. These results align well with the thermal resistance findings and further validate the thermal benefit of using advanced nanofluids in an optimised geometry.

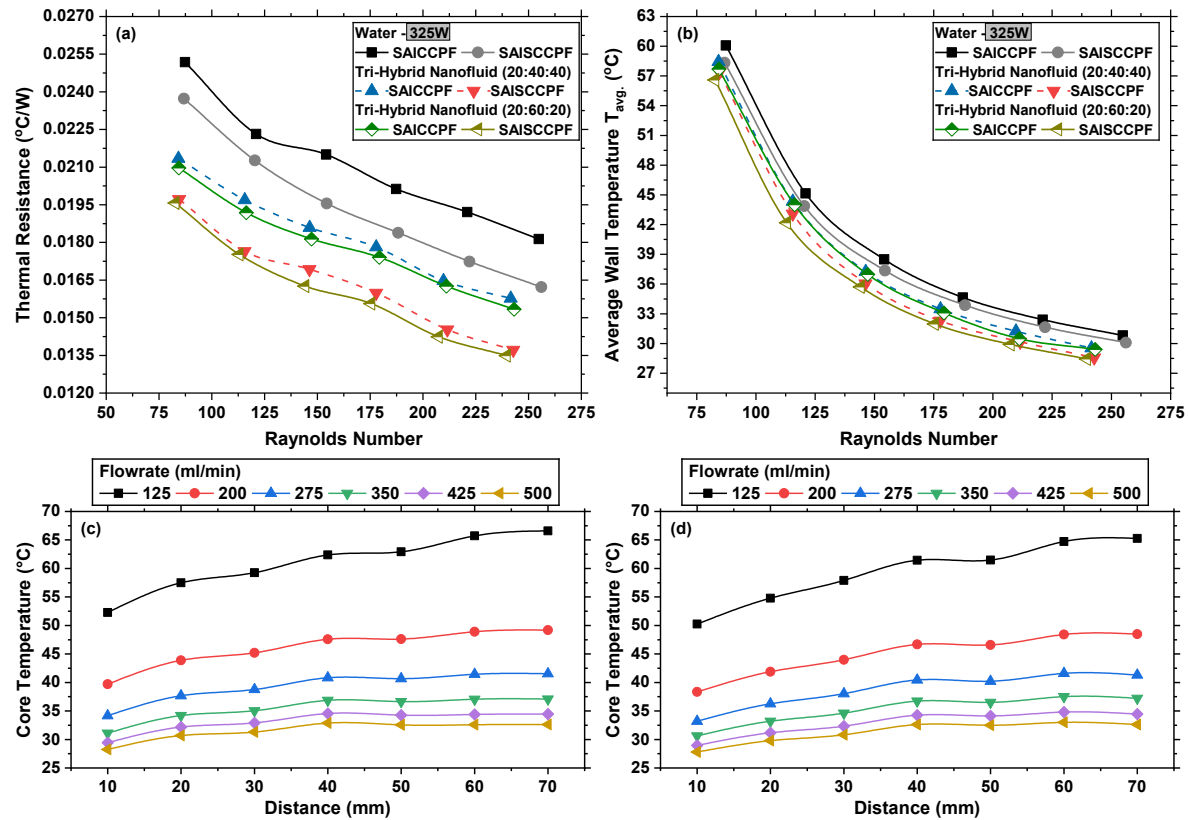


Figure 8.15. Thermal performance comparison of SAICCPF and SAISCCPF at 325 W. (a) Thermal resistance and (b) average wall temperature vs Reynolds number for water and tri-hybrid nanofluids. (c–d) Temperature distribution along heat sink length using water at various flow rates, showing improved cooling uniformity in SAISCCPF.

Figures 8.15(c) and 8.15(d) provide insight into the temperature distribution along the axial length of the heat sink channels for SAICCPF and SAISCCPF, respectively. These profiles were plotted for water only, at the maximum heating power of 325 W, under various flow rates.

For both configurations, the temperature consistently increases from inlet to outlet, reflecting heat accumulation along the flow direction. However, the rate of increase diminishes with higher flow rates, due to reduced fluid residence time and improved convective cooling.

In SAICCPF, at the lowest flow rate of 125 ml/min, the temperature rose from 52.3 °C at the inlet to 66.6 °C at the outlet, showing significant thermal buildup. In contrast, at 500 ml/min, the inlet

temperature began at 28.2 °C and only reached 32.6 °C at the outlet, indicating much more uniform cooling and limited thermal saturation.

In SAISCCPF, the trend is similar, but the overall temperatures were slightly lower for each corresponding flow rate. For example, at 125 ml/min, the outlet temperature was 65.3 °C, nearly 1.3 °C lower than SAICCPF, and at 500 ml/min, it reached 32.6 °C, similar in value but consistently lower at intermediate points along the length. This suggests that the SAISCCPF geometry enhances intermediate heat removal, providing more evenly distributed cooling.

The combined analysis of thermal resistance, average wall temperature, and longitudinal temperature distribution confirms that the SAISCCPF heat sink design, when used with optimised tri-hybrid nanofluids, offers superior thermal performance across all tested metrics.

8.2.5 Pressure Drop

Pressure drop is one of the most critical parameters in evaluating the practical feasibility of any thermal management solution, particularly in forced liquid-cooled systems. It defines the energy required to drive the coolant through the channels and directly impacts the system's overall power consumption. Importantly, the high Nusselt number values are desired to ensure efficient heat transfer, an associated increase in pressure drop could lead to excessive pumping requirements, undermining the overall energy efficiency of the system. Therefore, an optimal heat sink design must strike a balance between enhanced thermal performance and acceptable flow resistance.

While one of the objectives of this study was to develop configurations that minimise flow resistance and maintain high cooling performance, however, it is important to acknowledge that the introduction of extended fin geometries inevitably introduced varying degrees of flow obstruction.

The pressure drop observed in the SAISCCPF configuration was found to be moderately higher than in the SAICCPF design, as shown in Figure 8.16(a–d). Although the increase was not drastic, it highlights the classic trade-off between thermal enhancement and hydraulic resistance.

The SAICCPF configuration presents narrower yet continuous flow channels, enabling comparatively smoother fluid motion between pin-fins. In contrast, the SAISCCPF features a split geometry at the outer corrugated curvilinear pin-fins. This split design creates local disturbances and fluid re-direction, which boosts mixing and enhances thermal boundary layer disruption. However, this also leads to slightly elevated pressure drop. At the same time, this geometry is advantageous in real-world scenarios where vapor bubbles or nanoparticle agglomerates could obstruct flow paths offering alternative passages for coolant and maintaining local heat transfer effectiveness. This resilience makes SAISCCPF particularly suitable for systems prone to two-phase flow conditions or fouling.

At 100 W, the SAISCCPF configuration consistently shows slightly higher pressure drop values than SAICCPF for all Reynolds numbers. The maximum recorded pressure drop for SAISCCPF reaches approximately 486 Pa, while SAICCPF tops out around 460 Pa. This difference becomes more

noticeable at higher Reynolds numbers due to the greater influence of flow-induced turbulence and the split-fin structure that causes additional mixing and redirection in SAISCCPF.

A similar trend is seen at 175 W, where SAISCCPF again demonstrates higher pressure drop throughout the Reynolds number range. Here, the pressure drop difference between the two configurations narrows slightly compared to 100 W. At higher Re of approximately 244, SAISCCPF reaches a peak of around 470 Pa, while SAICCPF follows at approximately 449 Pa. The slightly reduced percentage difference at this power level may indicate that thermal effects begin to mitigate the added resistance from geometric complexities, such as split fins.

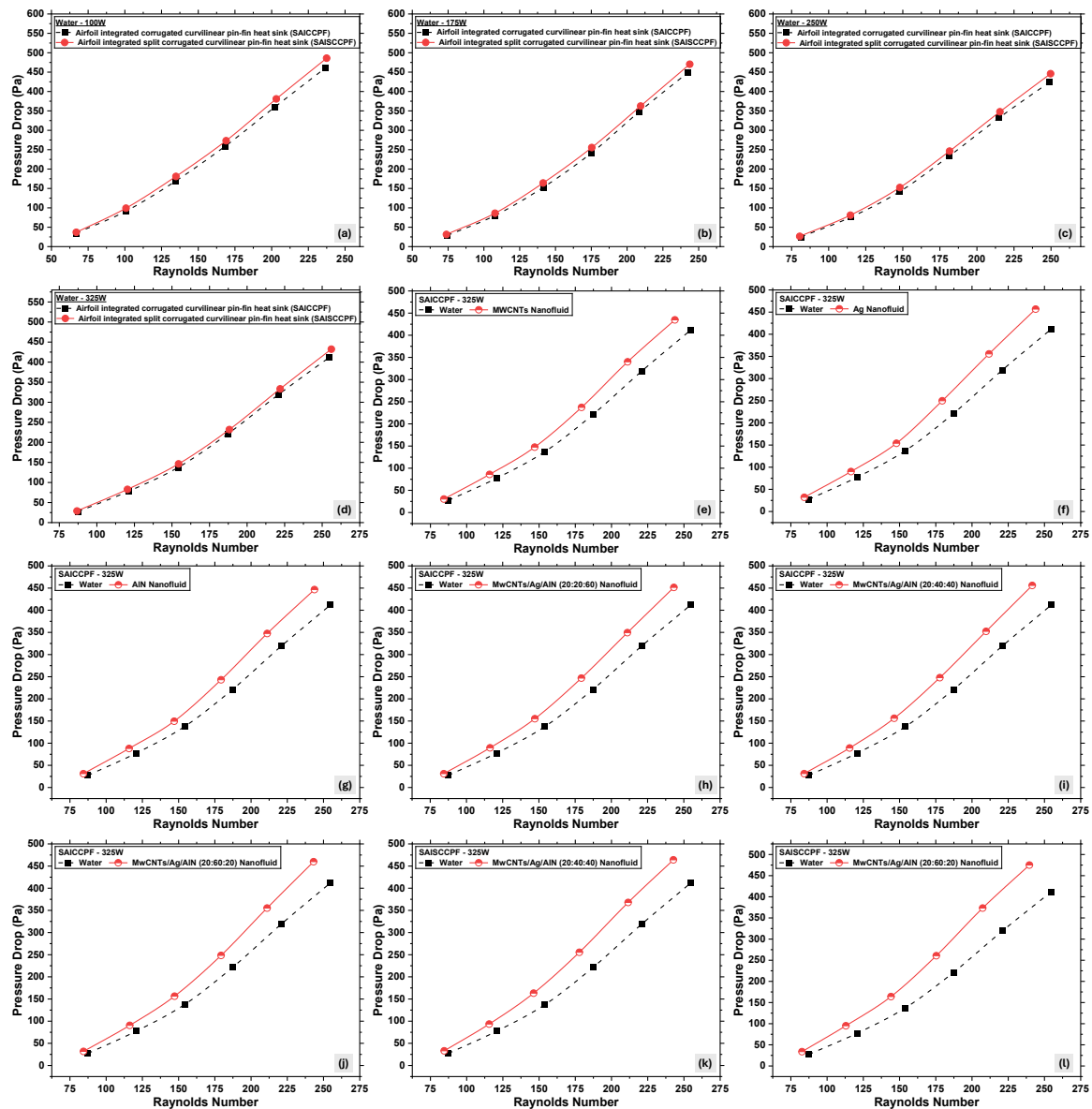


Figure 8.16. Pressure drop variation with Reynolds number: (a–d) comparison of water flow in SAICCPF and SAISCCPF at various heating powers; (e–j) pressure drop behaviour of unitary and hybrid nanofluids in SAICCPF; (k–l) pressure drop trends of selected tri-hybrid nanofluids in SAISCCPF.

As the heating power raised to 250 W, the overall pressure drop levels decrease slightly compared to the 175 W condition, particularly at low Reynolds numbers, though both configurations follow a similar upward trajectory with increasing flow rate. SAISCCPF maintains its trend of higher pressure drop values, topping around 446 Pa, versus about 424 Pa in SAICCPF. The gap here is again moderate, reinforcing that although the SAISCCPF design introduces some added resistance, it remains within manageable limits and is predictable across the range.

Finally, at 325 W, both configurations reach their highest thermal load, and yet the percentage increase in pressure drop from SAICCPF to SAISCCPF is the smallest observed among the four cases. SAISCCPF records a maximum of approximately 432 Pa, while SAICCPF reaches around 412 Pa. This suggests that at higher thermal loads, the role of heating power in elevating fluid temperature, and hence reducing viscosity, becomes more dominant, thereby diminishing the relative impact of geometric complexity on hydraulic resistance.

Figure 8.17(a) presents the average percentage enhancement in pressure drop observed for the SAISCCPF configuration compared to SAICCPF under different heating powers. This graphical comparison highlights how the hydraulic penalty evolves across increasing thermal loads. At 100 W, the enhancement is approximately 6.75%, representing the highest difference recorded. As heating power increases, this enhancement gradually decreases, reaching around 5.68% at 325 W. This trend suggests that the relative difference in flow resistance between the two configurations diminishes at higher thermal input levels. This can be partly attributed to the reduced viscosity of the coolant at elevated temperatures, which mitigates the influence of complex geometrical features on flow resistance. Moreover, the consistent downward trend in percentage enhancement reflects that while SAISCCPF introduces marginally higher pressure losses due to its extended split-pin layout, these losses become increasingly manageable as operating power rises. This reinforces the design's practicality for moderate to high heat flux applications, where thermal benefits outweigh the slight hydraulic cost.

Overall, the findings confirms that the added complexity of the SAISCCPF geometry does not impose a prohibitive pressure drop, especially at higher loads, making it a thermally superior yet hydraulically acceptable option for enhanced heat sink design.

In the next part of the investigation, Figures 8.16(e–j) examine the pressure drop characteristics for various unitary and hybrid nanofluids within the SAICCPF configuration at a heating power of 325 W. This section evaluates how different nanoparticle compositions influence the hydraulic performance of the heat sink, particularly under elevated thermal conditions. Among the unitary nanofluids, the Ag-based nanofluid exhibited the highest pressure drop, with values reaching approximately 457 Pa at a Reynolds number of around 244. This can be attributed to the higher density of Ag particles, which results in more pronounced frictional losses and increased flow resistance. In contrast, the MWCNT-based nanofluid displayed the lowest pressure drop, peaking at around 435 Pa, due to the lower density and tubular morphology of the carbon nanotubes, which streamline their movement through the fluid.

The MWCNTs have the lowest density among all tested particles, but if the fluid lacks stability, the tubes can agglomerate, forming clusters that are difficult to break and redisperse within the fluid. This can drastically alter flow characteristics, potentially leading to greater flow resistance and turning MWCNTs into the nanofluid with a higher pressure drop penalty rather than the lowest.

The AlN nanofluid produced intermediate results, with a pressure drop of around 447 Pa at maximum Reynolds number. This behaviour is expected as AlN particles have a density between those of Ag and MWCNTs. However, factors such as particle shape, size distribution, and base fluid compatibility also contribute to the overall resistance observed.

For the hybrid nanofluids, the MWCNTs/Ag/AlN (20:20:60) formulation recorded a peak pressure drop of approximately 451 Pa, slightly lower than that of Ag and AlN unitary fluids. This composition leverages the lightweight nature of MWCNTs to balance the denser metal and ceramic particles, achieving reasonable suspension stability and moderate flow resistance.

The 20:40:40 mixture, on the other hand, registered a marginally higher pressure drop, reaching about 456 Pa, which was nearly equivalent to the Ag-based nanofluid. This increase is possibly due to the inclusion of a higher fraction of metallic particles and their diverse morphologies, leading to greater drag and micro-scale flow disturbances. The 20:60:20 formulation exhibited the highest pressure drop among all hybrid nanofluids, reaching close to 460 Pa at the maximum Reynolds number. This behaviour aligns with expectations since the larger presence of high-density Ag particles elevates suspension viscosity and intensifies the fluid-particle and particle-particle interactions, ultimately increasing the overall flow resistance.

The nanofluids that performed well in terms of Nusselt number within the SAISCCPF configuration were further evaluated for their hydraulic behaviour. Shifting to Figures 8.16(k, l), the investigation extends to compare the pressure drop performance of the hybrid nanofluids of MWCNTs/Ag/AlN (20:40:40) and (20:60:20) mixtures at 325 W. As anticipated, both mixtures showed higher pressure drops in SAISCCPF than they did in SAICCPF. This was due to the split-pin geometry, which, while beneficial for heat transfer through enhanced local turbulence and multiple flow paths, also introduces additional mixing zones, thereby increasing frictional resistance. For the 20:40:40 fluid, pressure drop peaked at approximately 464 Pa. Similarly, for the 20:60:20 formulation, the pressure drop rose to around 475 Pa, representing the highest value recorded across all tested fluids and configurations. These increases are not excessive but indicate a trade-off between improved thermal performance and added hydraulic penalty.

Moving to Figure 8.17(b), the average percentage increase in pressure drop relative to water is illustrated. This figure is pivotal in understanding the hydraulic penalty associated with improved thermal performance, especially when integrating nanofluids into complex pin-fin geometries like SAICCPF and SAISCCPF.

In the SAICCPF configuration, unitary nanofluids showed varied enhancements. MWCNTs-based nanofluid, which had previously demonstrated the highest Nusselt number improvement, exhibited a

pressure drop increase of approximately 9.3% compared to water. This relatively modest increase reflects the benefit of MWCNTs' high thermal conductivity and low density, though, as discussed earlier, their tendency to agglomerate could potentially influence hydraulic characteristics if stability is not properly maintained.

For Ag-based nanofluids, the pressure drop enhancement was more pronounced, reaching 12.5%. This can be attributed to the higher density of silver nanoparticles, which increases fluid inertia and internal shear forces, thereby raising flow resistance. Similarly, AlN nanofluid showed an enhancement of around 11.0%, likely due to its intermediate density and particle size compared to MWCNTs and Ag.

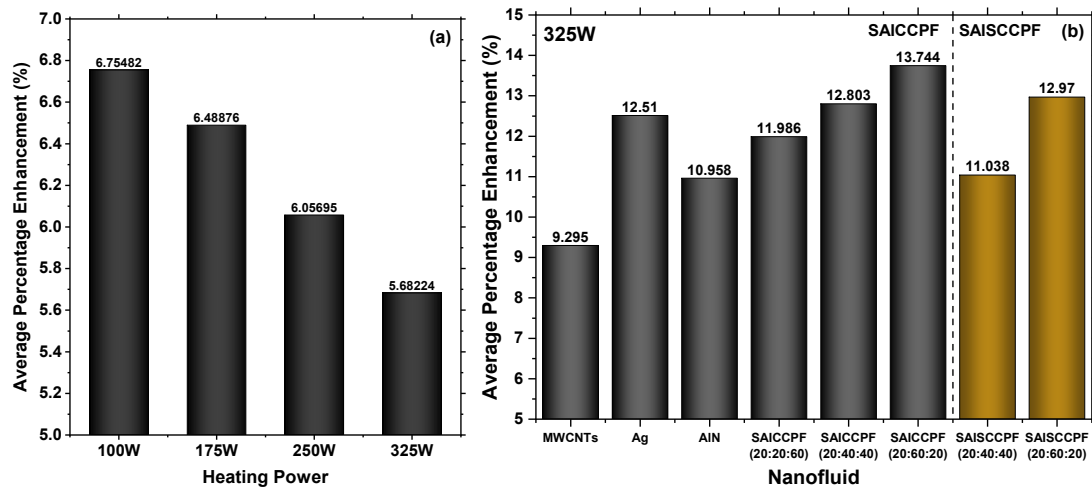


Figure 8.17. (a) Average percentage increase in pressure drop of SAISCCPF over SAICCPF at various heating powers; (b) Comparative enhancement in pressure drop for each nanofluid type tested in SAICCPF and SAISCCPF configurations at 325 W.

The trend continued with hybrid formulations, where the MWCNTs/Ag/AlN (20:20:60) nanofluid recorded an increase of nearly 12.0%, closely followed by (20:40:40) at 12.8%, and (20:60:20) at the highest level of 13.7%. The escalation in pressure drop for these formulations stems from the combination of particle interactions, varying shapes, and enhanced viscosity, which collectively increase flow resistance. Particularly, the (20:60:20) mixture, with a greater proportion of Ag, likely incurs higher viscous effects due to increased metallic particle loading.

In the SAISCCPF configuration, although the nanofluids followed the same formulation, the pressure drop enhancement was marginally lower than in SAICCPF: 11.0% for (20:40:40) and 13.0% for (20:60:20). The enhancement in pressure drop was slightly lower than that observed in SAICCPF. This could be due to the fact that fluid mixing, generation of local swirls, or turbulence improves particle suspension or mixing in the fluid as it flows through the complex channels of the SAISCCPF geometry. Additionally, these hydrodynamic effects help reduce localised particles agglomeration.

It is also noteworthy that the Nusselt number enhancements previously observed for these hybrid nanofluids in SAISCCPF were significant often exceeding 17% and observed to be more than 13% at 325W compared to water. This substantial thermal gain helps to justify the modest increase in pressure drop. Moreover, the enhanced swirl intensity and secondary flow generation in the SAISCCPF

geometry not only boosts heat transfer but also contributes to maintaining particle dispersion, reducing the risk of agglomeration, and improving thermal uniformity under high thermal flux conditions.

Together, these observations reinforce that pressure drop correlates strongly with both particle density and mixture composition. While adding metallic particles may enhance thermal conductivity and Nusselt number, it also introduces a penalty in terms of pumping power, which must be carefully considered in real-world applications.

For a deeper understanding of the viscosity behaviour and stability mechanisms influencing these fluids, readers are referred to Chapter 6, particularly Sections 6.4 and 6.5, where the rheological properties and performance implications of these nanofluids are discussed in detail.

Summary

This chapter presented a comprehensive experimental investigation into the thermal and hydraulic performance of advanced biomimetic heat sink configurations, particularly focusing on the SAICCPF and SAISCCPF designs. Initially, a comparative study was conducted between staggered and inline fin arrangements under varying heating powers to determine the optimal configuration. The staggered arrangement demonstrated superior heat transfer performance, with Nusselt number enhancements ranging from approximately 5% to 6.4% compared to the inline configuration, and only a marginal increase in pressure drop.

Building upon this, the second phase evaluated the novel SAISCCPF design against the best-performing SAICCPF configuration. The SAISCCPF exhibited enhanced thermal performance due to its split and curvilinear pin-fin structure, which improved coolant redistribution, suppressed thermal boundary layer growth, and offered alternative flow channels. Comparative to SAICCPF, the design was particularly effective at higher heating powers, delivering average Nusselt number improvements of up to 5.9%, with an acceptable pressure drop trade-off of under 7%.

The study was further extended by incorporating unitary and hybrid nanofluids including tri-hybrid combinations of MWCNTs, Ag, and AlN to assess their contribution to thermal enhancement. Among the unitary fluids, MWCNTs demonstrated the highest thermal conductivity but suffered from stability concerns. The hybrid formulations, particularly 20:60:20 and 20:40:40 ratios, offered a better balance between thermal performance and fluid stability. When tested in SAISCCPF, these fluids achieved Nusselt number enhancements exceeding 17% while maintaining pressure drops within tolerable limits (under 475 Pa), highlighting the strong potential of such fluids for high-performance thermal management applications.

In summary, the chapter confirmed that synergistic integration of biomimetic geometry and engineered nanofluids can significantly boost the thermal effectiveness of heat sinks without imposing excessive hydraulic penalties. The findings not only validate the proposed designs but also provide a promising path forward for future research in compact and efficient cooling solutions for advanced electronics and energy systems.

CHAPTER 9

9 Research Outlook, Concluding Remarks and Future Recommendations

The overarching goal of this thesis was to develop a scalable and efficient liquid cooling solution capable of addressing the growing thermal management challenges in compact and high-power electronic systems. The research originated from the observation that conventional cooling approaches whether air-cooled heat sinks or basic liquid-cooled straight-channel systems are increasingly unable to cope with the rising heat densities associated with modern technologies. These limitations become especially critical under constrained conditions such as limited space, high energy use, and the demand for sustainable operation.

To bridge this performance gap, the study pursued a dual-pronged approach: the exploration of advanced working fluids in the form of engineered nanofluids, and the development of novel heat sink geometries inspired by natural flow mechanisms. The thesis was structured to reflect this progression. The first part was devoted to the synthesis, characterisation, and evaluation of mono and multi-component nanofluids based on silver, silicon carbide, beryllium oxide, aluminium nitride, and multi-walled carbon nanotubes. Extensive testing revealed the influence of nanoparticle type, concentration, and hybridisation on thermal conductivity, viscosity, density, and long-term dispersion stability key attributes for real-world application in thermal systems.

The second part of the thesis turned towards heat sink geometry and optimisation. Starting with straight-channel and basic pin-fin arrangements, the study gradually advanced to more intricate biomimetic designs. These included inline and staggered airfoil-integrated geometries and culminated in the final configuration split pin-fin (SAISCCPF). Inspired by the fluid redirection and multi-path flow observed in aquatic animals, this configuration was designed to generate local turbulence, minimise dead zones, and provide alternative flow routes in the event of partial blockages. All designs and nanofluids were subjected to a thorough experimental campaign using a bespoke test facility capable of replicating high heat flux scenarios. The findings clearly demonstrated that both the geometry of the heat sink and the nature of the working fluid play decisive roles in determining performance.

By integrating geometrical innovation with customised nanofluids, this thesis not only achieved higher heat transfer rates but also addressed concerns such as elevated pressure drop penalties and flow uniformity. The outcomes serve as both a proof-of-concept and a practical guideline for the future development of compact, efficient, and robust thermal management systems suitable for next-generation electronics, energy storage devices, and high-performance computing platforms.

9.1 Research Questions

This section reflects on how the core research questions outlined at the beginning of this thesis were addressed across the individual chapters. The thesis was structured into nine primary chapters (excluding concluding section), each designed to systematically investigate critical aspects of nanofluid-based biomimetic heat sink development. While specific conclusions for each chapter have already been presented at the end of each chapter, this section summarises how each research objective was met through experimental findings, comparative analysis, and conceptual innovation.

What are the emerging challenges in thermal management for compact, high-performance systems, and how can advanced cooling technologies address them?

Chapter 1 established the technological motivation behind the research, focusing on the growing demand for reliable thermal management in electronics, artificial intelligence systems, data centres, and electric vehicles. The chapter outlined the limitations of conventional cooling solutions, particularly in addressing high heat flux densities within compact devices. It proposed that an integrated approach combining advanced heat sink designs and nanofluid-enhanced liquid cooling could offer a viable pathway to overcoming these challenges. The chapter defined the research aims, formulated the key research questions, and outlined the overall methodology, setting the stage for the experimental investigations that followed.

What are the key limitations of existing cooling technologies, and what potential do nanofluids and biomimetic heat sink geometries offer in overcoming them?

Chapter 1 & 2 provided an in-depth review of the existing thermal management strategies and benchmarked the limitations of conventional cooling systems, including air-cooled and straight-channel liquid-cooled designs. The review highlighted challenges such as poor convective efficiency, high thermal resistance, and limited adaptability to modern compact systems. The chapter further explored the emergence of nanofluids, noting their superior thermophysical properties, and examined a range of mono, hybrid, and tri-hybrid formulations based on metallic, ceramic, and carbonaceous nanoparticles. In parallel, the concept of biomimetic heat sink geometries taking inspiration from aquatic biological structures was introduced as a novel solution to achieve improved flow dynamics and heat transfer. The combination of these approaches was proposed as a potentially transformative solution to modern thermal management demands.

Additionally, chapter 2 included a comprehensive bibliometric analysis, offering valuable insights into the global research trends in nanofluids. It highlighted active research groups, publication patterns, and collaboration networks. This analysis is especially beneficial for early-career researchers and those new to the field, providing a structured overview of the knowledge landscape and identifying potential areas for future exploration.

How can a reliable experimental platform be developed to evaluate the hydrothermal performance of nanofluid-enhanced biomimetic heat sinks under varied flow and thermal loads?

Chapter 3 directly addressed this question by detailing the development of a sophisticated and modular experimental setup capable of measuring key performance parameters such as Nusselt number, pressure drop, wall temperature, and flow rate. The chapter thoroughly described the integration of components including a refrigerated water bath, micro gear pump, precision flow meter, needle valve, pressure transducers, cartridge heaters, and thermocouples. Additionally, this chapter outlined the conception, design, and fabrication of bioinspired heat sinks drawing from aquatic species such as tuna and the black ghost knifefish to explore the impact of flow-altering geometries on cooling efficiency. Multiple geometrical variants including inline and staggered airfoil-based pin-fin designs were prototyped using CNC milling and were thermally insulated and visually monitored using an integrated microscope and high-speed camera system.

Furthermore, the chapter presented a rigorous approach to nanofluid synthesis, involving a two-step method with surfactant-assisted dispersion and ultrasonication to ensure stability. It included justification for nanoparticle selection (Ag, SiC, BeO, AlN, MWCNTs), preparation of mono, binary, and tri-hybrid nanofluids, and assessment of their thermal conductivity, viscosity, density, and zeta potential using standardised measurement instruments.

Together, these efforts laid a comprehensive experimental and material foundation for the subsequent performance analysis, addressing the research question through both system-level integration and material-level customisation.

How can the experimental setup be validated and the collected data systematically processed to ensure accurate and reliable evaluation of thermal and hydraulic performance?

Chapter 4 addressed this research question by first establishing a comprehensive data processing framework and then validating the experimental setup to ensure the integrity of the measurements. The chapter opened with a detailed explanation of the methods used to process raw data collected from the experimental facility. This included the transformation of sensor readings into thermophysical parameters such as Reynolds number, Nusselt number, thermal resistance, and pressure drop.

The latter part of the chapter focused on the validation of the custom-built test rig. Water was used as a reference fluid in a conventional straight-channel heat sink to establish a baseline for performance. Repeated experiments under varying flow rates and heating powers were conducted, and the results were compared against well-known empirical correlations. The high degree of agreement confirmed the system's ability to accurately measure thermal and hydraulic parameters. Moreover, these trials confirmed the repeatability of the setup, which was critical for the comparative studies conducted in later chapters.

By combining precise data processing protocols with systematic experimental validation, Chapter 4 provided a solid methodological foundation for the subsequent investigations into nanofluid behaviour and advanced heat sink geometries.

How do various nanoparticles and their hybrid combinations influence the thermophysical properties of nanofluids across a range of temperatures and concentrations?

Chapter 5 systematically examined the impact of Ag, BeO, SiC nanoparticles, both in mono and hybrid formulations, on the thermophysical behaviour of nanofluids. The findings revealed that thermal conductivity increased consistently with temperature and nanoparticle loading. Among the simple nanofluids, Ag exhibited the highest thermal conductivity enhancement, with a maximum of approximately 6.95% at 0.025 vol% and 45 °C. Hybrid formulations such as Ag/SiC (60:40) further improved thermal performance, achieving enhancements around 7.43%. The study also noted Newtonian flow characteristics across all fluids, with viscosity generally rising alongside concentration. In terms of density, Ag nanofluids showed the greatest increase, followed by Ag/SiC hybrids. These results confirmed that hybridisation allows synergistic tuning of properties balancing thermal enhancement with acceptable flow resistance making hybrid nanofluids more versatile for high-efficiency cooling applications

What are the optimal volumetric mixing ratios and surfactants that ensure maximum thermal enhancement and colloidal stability of the nanofluids?

The study adopted a phased experimental approach to identify the most effective combinations of nanoparticles and surfactants for stable, high-performance nanofluids. For binary hybrid nanofluids, volumetric mixing ratios such as 60:40 (Ag/SiC and Ag/BeO) demonstrated the most promising results, offering significant thermal conductivity enhancement while maintaining acceptable viscosity and long-term colloidal stability. Among the surfactants tested including SDS, SDBS, CTAB, and gum Arabic, SDBS consistently proved to be the most effective in dispersing particles uniformly and suppressing sedimentation, especially in metallic and hybrid formulations.

However, it is important to note that the optimum volumetric ratios are not universal and can vary depending on the combination of nanoparticles, their morphology, concentration, and the fluid's base properties. Researchers using different synthesis techniques, nanoparticles, or dispersion methods may require re-optimisation based on their system-specific requirements. The results presented in this study thus serve as a guideline, but successful application in other contexts should be supported by tailored experimentation and stability assessment.

How do different nanoparticle combinations and mixing ratios affect the stability, performance, and economic viability of nanofluids when used in engineered cooling systems?

Chapter 5 presented a thorough evaluation of the techno-economic trade-offs associated with various mono and hybrid nanofluid formulations. While silver-based nanofluids exhibited the highest thermal conductivity enhancement, their elevated cost approximately £90.27 per 1000 ml posed challenges for large-scale implementation. In contrast, hybrid formulations such as Ag–SiC and Ag–BeO emerged as more economically viable alternatives, offering considerable thermal performance at significantly lower

costs (ranging between £25 and £75 per 1000 ml). Among these, the Ag–SiC hybrid with a 60:40 volumetric ratio stood out by achieving a favourable balance between thermal conductivity enhancement, moderate viscosity, and long-term stability. This combination demonstrated not only improved heat transfer capabilities but also reduced flow resistance and better economic feasibility. Thus, the findings underscore that carefully engineered hybrid nanofluids can provide optimised thermal performance while meeting practical constraints of cost, stability, and compatibility with cooling system components.

Ultimately, the choice of nanoparticle type and mixing ratio depends heavily on the application's priorities, whether the focus is on maximising thermal performance, ensuring long-term colloidal stability, or minimising operational cost. It is also important to note that the costs of nanofluid preparation are dynamic and may fluctuate based on market prices and nanoparticle purity or origin. While this research provides experimentally validated guidelines to inform such decisions, further tailoring may be necessary when applying these fluids in alternative configurations or under transient and cyclic thermal loads.

How does temperature variation influence the thermophysical properties such as viscosity, thermal conductivity, and density of mono and hybrid nanofluids?

Chapter 5 & 6 explored how thermophysical properties evolve with temperature for mono and hybrid nanofluids across a working range from 15°C to 45°C. According to the findings of Chapter 6, As the temperature increased, viscosity exhibited a consistent decline, facilitating reduced flow resistance and making the fluids more pumpable in thermal systems. For instance, MWCNT-based nanofluids showed a sharper viscosity drop compared to Ag or AlN due to their structural characteristics.

Thermal conductivity, on the other hand, experienced a gradual increase at higher temperatures, attributed to intensified Brownian motion and better interaction between nanoparticles and the base fluid. MWCNT and Ag-based fluids in particular responded well to temperature rise, enhancing heat conduction. Density followed the expected trend of decreasing slightly with rising temperature due to volumetric expansion. Collectively, these temperature-driven effects have practical benefits for the design of thermally responsive nanofluids.

What is the impact of particle concentration and volumetric mixing ratio on the stability and performance of unitary and hybrid nanofluids?

Chapter 6 evaluated nanofluids at various volumetric concentrations ranging from 0.01% to 0.03% and multiple tri-hybrid mixing ratios, including (20:60:20), (20:40:40), and (20:20:60). Increasing nanoparticle concentration generally resulted in improved thermal conductivity but also led to greater viscosity, particularly at 0.3% loading. Among these, the (20:60:20) mixture provided a strong thermal enhancement while retaining manageable viscosity.

Mixing ratio played a critical role in determining the trade-off between thermal performance and fluid stability. Among tri-hybrid nanofluids, formulations with higher Ag content (20:60:20) demonstrated superior conductivity, while those with more AlN content (20:20:60) showed better colloidal stability and lower viscosity. The 20:40:40 formulation emerged as a balanced performer, combining respectable conductivity with stability over time. These findings highlight that both concentration and mixing strategy are essential parameters for tailoring nanofluids to application-specific requirements.

How does the biomimetic airfoil-inspired heat sink design (AICCPF) compare to conventional straight-channel configurations in terms of thermal and hydraulic performance under identical conditions, and what role do different nanofluid formulations play in enhancing its effectiveness?

Chapter 7 investigates a novel heat sink configuration airfoil integrated corrugated curvilinear pin-fin inspired by aquatic organisms. A comparative study was conducted against a conventional straight-channel heat sink using water as the working fluid under the same flow rates (200–450 ml/min) and a fixed heating power of 150 W. The results revealed that the AICCPF design achieved approximately 103% higher Nusselt numbers due to its optimised curvilinear pin-fin structure, which promotes enhanced turbulence, fluid redirection, and surface area utilisation. However, these thermal gains came with a 37.5% increase in pressure drop, indicating a trade-off between performance and flow resistance. In addition to the geometric effects, the performance of the AICCPF configuration was further evaluated with various nanofluids based on silver (Ag), beryllium oxide (BeO), and silicon carbide (SiC), including mono and binary combinations. Ag-based nanofluids consistently delivered the best thermal enhancements, while BeO provided lower pressure penalties. Hybrid mixtures, particularly Ag–SiC (60:40), showed a promising balance between heat transfer augmentation and hydraulic efficiency. These results not only validated the performance benefits of the AICCPF design but also highlighted the importance of tuning nanofluid properties according to specific application goals.

How do proposed biomimetic heat sink configurations influence thermal and hydraulic performance when integrated with optimised mono, hybrid, and tri-hybrid nanofluids?

Chapter 8 presents a comprehensive comparative assessment of the Staggered Arranged Airfoil Integrated Corrugated Curvilinear Pin-Fin (SAICCPF) and the further refined Staggered Arranged Airfoil Integrated Split Corrugated Curvilinear Pin-Fin (SAISCCPF) configurations. These biomimetic geometries were evaluated using a range of nanofluids mono, binary, and tri-hybrid suspensions with experimental testing conducted under controlled heating powers and Reynolds numbers. The study revealed that the SAISCCPF configuration consistently achieved higher thermal performance than SAICCPF, primarily due to its split-pin design, which enabled greater fluid mixing, alternative flow paths, and enhanced turbulence.

The Nusselt number values increased progressively with both Reynolds number and heating power, confirming stronger convective heat transfer at higher flow rates and thermal loads. For instance, at

325 W, the SAISCCPF heat sink combined with MWCNTs/Ag/AlN (20:60:20) achieved an approximate 17% enhancement in Nusselt number compared to water. In contrast, SAICCPF with the same fluid recorded slightly lower gains, illustrating the geometric influence on heat transfer.

However, this performance improvement came with a modest rise in pressure drop. In SAISCCPF, the maximum pressure drop reached approximately 475 Pa for the (20:60:20) tri-hybrid nanofluid, whereas in SAICCPF, it was around 460 Pa. The increased frictional resistance was a result of additional mixing zones and extended flow paths. Nevertheless, the enhancement in heat transfer justified this trade-off. The chapter also noted that SAISCCPF maintained more uniform cooling and reduced the likelihood of channel blockage, especially when bubbles or nanoparticle agglomerates were present owing to the design's multi-path structure and swirl-inducing features. These results highlight the value of integrating tailored nanofluids with bioinspired geometrical innovation for future compact, high-performance thermal management systems.

Can the proposed biomimetic heat sinks maintain efficient cooling under varying thermal loads (50–300 W) typically encountered in high-performance electronic processors like Intel® Xeon®?

The proposed biomimetic heat sink configurations demonstrated strong thermal management capabilities across a wide range of thermal loads, specifically between 50 W and 300 W, which aligns with the typical power consumption profiles of high-performance processors such as the Intel® Xeon® family. In terms of thermal response, the maximum core temperature recorded during testing was approximately 78.6 °C under the highest applied thermal load of 325 W, at the lowest tested flow rate of 125 mL/min using the base fluid (water). This temperature remains within the generally accepted safe operating threshold for high-performance processors, indicating that even under conservative flow conditions, the cooling system is capable of preventing thermal failure. As the flow rate increased, a significant decrease in core temperature was observed. For example, at a flow rate of 375 mL/min, the core temperature under the same thermal load reduced to approximately 66.2 °C when using the optimised tri-hybrid nanofluid in the SAISCCPF configuration. This inverse relationship highlights the critical role of coolant velocity in enhancing convective heat transfer, reducing thermal resistance, and improving temperature uniformity across the heat sink surface. The combined effect of increased flow-induced turbulence and enhanced nanofluid thermal conductivity contributes to the substantial improvement in cooling performance with rising flow rate.

Moreover, these designs are not exclusive to Intel® Xeon® processors. Their underlying flow-enhancing and turbulence-inducing features make them equally applicable to other high-performance chips, including AMD EPYC™, NVIDIA Grace Hopper™, and custom-designed processors used in edge computing, data centres, and AI inference engines. These systems often operate under similar or even greater thermal loads, making them ideal candidates for adopting the proposed biomimetic cooling approach.

Is it possible to develop a generalisable design strategy for compact cooling solutions that can be adapted to other high heat-flux applications beyond electronics, such as EV battery packs or renewable energy inverters?

The findings of this research demonstrate that it is indeed possible to develop a generalisable design strategy for compact cooling solutions that can be extended to a wide range of high heat-flux applications beyond electronics. The biomimetic design framework introduced in this study grounded in nature-inspired geometrical concepts and validated through experimental analysis offers a scalable and modular approach adaptable to various thermal management challenges. The heat sink configurations developed, particularly the SAISCCPF design, are not confined to the specific form factors or operating conditions of microelectronic devices. Rather, they are characterised by their flexible geometry, distributed fin arrangement, and enhanced flow dynamics, all of which can be tailored for other domains such as electric vehicle battery modules or power electronic inverters in renewable energy systems.

Furthermore, the research incorporated nanofluid formulations optimised for performance, stability, and cost, which can be re-engineered for compatibility with cooling loops in different applications. The modular experimental rig and operating ranges employed (flow rates, heating powers, Reynolds numbers) mirror conditions found in thermal management systems beyond microelectronics, suggesting direct translatability. Additionally, the study's emphasis on low pressure drop and high Nusselt number performance aligns well with the cooling requirements of battery packs and inverter systems, where energy efficiency and thermal uniformity are crucial.

Therefore, the synergy of biomimetic design and nanofluid enhancement forms a universal strategy that can be adapted with minimal modifications to other high-flux applications. Further domain-specific optimisation such as scale adjustment, coolant material compatibility, or integration with phase change materials or heat pipes can build on the foundational design principles established in this work.

This section has addressed the core research questions by presenting the purpose and key findings of Chapters 1 to 8. Each question has been answered with reference to experimental outcomes, design evaluations, and nanofluid performance assessments, demonstrating how the thesis contributes to advancing compact, high-performance, and sustainable thermal management solutions. The responses collectively demonstrate how the study achieved its objectives by delivering compact, thermally efficient, and scalable cooling solutions, thereby advancing the state of knowledge in high-performance thermal management systems.

9.2 Contributions to Knowledge

This thesis introduces a set of original contributions to the field of thermal management, with a focus on developing compact, high-performance cooling systems using biomimetic heat sink designs and nanofluid-enhanced liquid cooling. The contributions span experimental methodologies, design

innovation, fluid dynamics, nanomaterial engineering, and performance characterisation. The key contributions to knowledge are summarised below:

9.2.1 Development of Novel Biomimetic Heat Sink Geometries:

This research introduces a new class of biomimetic heat sink designs that, for the first time, replicate both the internal and external flow dynamics observed in aquatic respiration systems. Inspired by the streamlined body structures and opercular flow mechanisms of aquatic organisms, the proposed geometries incorporate alternative flow passages through and around split pin-fins, enabling more effective coolant distribution. These pathways allow the working fluid to bypass obstructions such as vapour pockets or nanoparticle agglomerates, thereby sustaining continuous heat removal and improving mixing within the flow domain. Unlike conventional microchannel designs that rely solely on turbulence or extended surface area, these biomimetic configurations implement a dual-path flow strategy, enhancing both reliability and thermal performance in electronics cooling applications. Beyond their practical impact, these designs pave the way for future investigators to view and interpret nature from a new functional perspective not just as a source of form, but as a blueprint for solving complex engineering challenges through dynamic, adaptive, and resilient flow systems.

9.2.2 Novel Integration of Advanced Hybrid and Tri-Hybrid Nanofluids

This study presents a comprehensive experimental investigation into the formulation and thermophysical characterisation of mono, hybrid, and tri-hybrid nanofluids. Through systematic testing, the research evaluates key thermophysical properties such as thermal conductivity, viscosity, and density of newly developed hybrid formulations, offering valuable insights into their behaviour under varying temperatures and concentrations. The work also analyses the influence of different surfactants on colloidal stability and pH, identifying critical factors that govern dispersion quality and long-term performance.

In addition to quantifying performance, the study critically highlights the limitations of mono (unitary) nanofluids, including poor dispersion and sub-optimal thermal enhancement, thereby justifying the transition to hybrid and tri-hybrid formulations. These multi-component combinations were shown to offer synergistic thermal benefits while maintaining acceptable viscosity levels, making them viable for use in forced convection systems. The research further identifies optimal mixing ratios that strike a practical balance between thermal performance and hydraulic compatibility, supporting the broader applicability of nanofluids in real-world thermal management solutions.

9.2.3 Characterisation of Nanoparticle Dispersion and Agglomeration Behaviour

This thesis presents a detailed investigation into the dispersion stability and agglomeration patterns of mono and hybrid nanoparticles, with implications for long-term thermal and hydraulic performance. Notably, SiC nanoparticles exhibited chain-like agglomeration structures, while MWCNTs showed a

tendency to form entangled clusters due to their high aspect ratio and van der Waals interactions. Beyond suspension-level analysis, the study also examined in-channel behaviour, revealing that nanoparticles can settle and form micro-scale agglomerates along channel surfaces and fin walls, particularly under low flow or recirculation conditions. These insights are critical for understanding the performance limitations of nanofluids in real-world applications and for developing strategies to mitigate clogging, fouling, or local thermal resistance buildup in long-term operation.

9.2.4 Simultaneous Optimisation of Thermal and Hydraulic Performance

This research demonstrates that it is possible to achieve substantial improvements in heat transfer performance without compromising hydraulic efficiency. The proposed biomimetic heat sink configurations exhibited notable enhancements in Nusselt number compared to conventional straight-channel designs, while maintaining an acceptable pressure drop. Further optimisation through design modifications such as staggered and split fin arrangements and the integration of advanced nanofluids led to additional performance gains.

Unlike many existing studies that focus primarily on thermal enhancement with limited attention to flow resistance, this work adopts a balanced approach, giving equal emphasis to both thermal and hydraulic behaviour. The hybrid pin-fin structures were shown to enhance convective heat transfer through improved flow mixing and alternative flow paths, while keeping the pressure drop within practical limits. This dual consideration ensures the proposed designs are not only thermally efficient but also energy-conscious and suitable for real-world implementation.

9.2.5 Bibliometric Analysis Highlighting Emerging Trends

A supporting bibliometric analysis was conducted to map the global research landscape in the areas of advanced thermal coolants, nanofluids. The study identified key publication trends, leading contributors, and evolving research hotspots, revealing a growing interest in hybrid nanofluids and nature-inspired thermal systems. The analysis also highlighted a notable gap in integrated studies combining biomimetic geometries with advanced coolant formulations, thereby reinforcing the originality of this thesis. These insights not only validate the research direction but also provide a strategic reference for guiding future interdisciplinary work in advanced thermal management.

9.2.6 Application-Relevant Testing and Design Validation

The custom-built experimental setup developed in this study offers a flexible platform for evaluating the hydrothermal performance of heat sinks with varying geometries, dimensions, and operating conditions. While the rig is broadly adaptable, the testing in this thesis was specifically aligned with the thermal design power (TDP) range of high-performance processors such as Intel® Xeon®, ensuring that the findings are directly relevant to real-world applications. By replicating realistic thermal loads and flow conditions, this work effectively bridges the gap between conceptual heat sink design and

practical engineering implementation, providing validated data that supports the deployment of advanced cooling strategies in processor-level thermal management.

9.2.7 Framework for Scalable and Cross-Domain Cooling Strategies

The outcomes of this research extend beyond the domain of electronics, offering a generalisable and scalable design framework that integrates biomimetic heat sink geometries with engineered nanofluids. The principles demonstrated in this work can be readily adapted to other high heat-flux applications such as electric vehicle (EV) battery thermal management, renewable energy inverters, and high-density power electronics. The modularity of the proposed configurations, combined with their proven thermal-hydraulic performance, makes them suitable for a wide range of compact, high-power systems where efficient and reliable cooling is critical.

9.2.8 Environmentally and Operationally Sustainable Cooling Strategy

This research presents a cooling approach that combines bioinspired heat sink geometries with high-performance coolants, achieving enhanced heat dissipation while maintaining low pressure drop. This dual optimisation reduces pumping power requirements and overall energy consumption, making the system not only thermally efficient but also operationally sustainable. By improving thermal performance without introducing complex or energy-intensive components, the proposed strategy supports the development of low-carbon, energy-efficient cooling technologies. These outcomes align with broader environmental objectives and regulatory frameworks such as the EU Green Deal, the UK Net Zero Strategy, and international commitments under the Paris Agreement.

9.2.9 Global and Industrial Significance

With real-world testing conditions representative of industrial systems, the designs and materials presented here can be directly adapted for commercial deployment. The study offers particular value to regions undergoing rapid electrification and digitalisation, including Europe, North America, and Asia, where data centres, electric vehicles, and industrial automation are primary growth sectors.

9.2.10 Foundations for Future Research in Topology-Informed Bioinspired Design

This research demonstrates how biologically inspired internal–external flow mechanisms modelled on aquatic respiration systems can be effectively translated into engineered cooling architectures. By validating these principles through experimental studies, the work lays a strong foundation for future research in areas such as topology optimisation, multiphase flow management, and microfluidic cooling for miniaturised electronic systems. The novel flow-routing strategies introduced here offer new design possibilities for researchers seeking to develop adaptive, high-efficiency cooling systems, thereby opening interdisciplinary avenues at the intersection of bioinspired engineering, fluid dynamics, and thermal sciences.

9.3 Limitations of the Study

While this study presents substantial advancements in the development and experimental validation of biomimetic heat sinks enhanced with nanofluids, several limitations must be acknowledged. These limitations, both practical and methodological, offer valuable context for interpreting the findings and defining directions for future research.

9.3.1 Scope of Nanoparticle Selection and Formulations

Although a wide range of nanoparticles was explored including metallic (Ag), ceramic (AlN, SiC, BeO), and carbon-based (MWCNTs) the selection was necessarily limited by cost, availability, and compatibility with the experimental setup. Other promising materials, such as graphene nanoplatelets, copper oxide, or organic–inorganic hybrids, were not examined. Furthermore, the mixing ratios of hybrid and tri-hybrid nanofluids were constrained to specific formulations due to time and resource limitations, potentially excluding other high-performing combinations.

9.3.2 Short-Term Stability Assessment of Nanofluids

The stability analysis of nanofluids in this study was conducted over a short-to-medium duration under static and flow conditions. While surfactant performance and pH sensitivity were evaluated, long-term behaviour including sedimentation, oxidation, or chemical degradation over extended cycles was not systematically tested. This leaves open questions regarding durability, maintenance, and reusability in continuous industrial systems.

9.3.3 Experimental Constraints in Flow Range and Heating Power

The custom-built test rig was designed to simulate realistic thermal loads (50–350 W) and flow rates typical of electronics cooling applications. However, the system was not equipped to handle ultra-high heat flux conditions or low-Reynolds-number flow regimes characteristic of passive or natural convection systems. As a result, the findings may not be directly transferable to all thermal management scenarios, such as large-scale battery cooling or low-energy HVAC systems.

9.3.4 Lack of Dynamic or Transient Thermal Testing

All experiments in this study were performed under steady-state conditions. In real-world systems, thermal loads often fluctuate due to changes in operating mode, ambient temperature, or computational demand. The dynamic response of the proposed heat sinks and nanofluids such as start-up time, thermal lag, and recovery behaviour was not captured in this study. Including transient tests would provide a more complete understanding of system responsiveness.

9.3.5 Simplified Geometrical and Manufacturing Constraints

Although the biomimetic designs were inspired by complex natural systems, their translation into physical prototypes was subject to the geometric constraints of CNC machining. This led to simplifications in fin curvature, spacing, and split-fin implementation. More advanced manufacturing methods such as additive manufacturing (3D printing) could enable the realisation of more intricate geometries that were beyond the scope of this study.

9.3.6 Limited Investigation of Fouling and Channel Blockage

While the study highlighted the formation of micro-scale agglomerates and potential flow obstruction due to nanoparticle settling, a detailed quantitative analysis of fouling dynamics, clogging behaviour, and cleaning cycles was not performed. These factors are critical for long-term operational reliability, especially in closed-loop industrial systems.

9.3.7 Single-Loop Cooling Configuration

The experimental setup was based on a single-loop forced convection system with a uniform heating source. Multi-zone heating, parallel flow networks, or two-phase cooling systems (e.g., heat pipes, vapor chambers) were not explored. As such, the interaction between biomimetic geometries and complex flow networks remains untested.

9.3.8 Environmental and Lifecycle Impact of Nanofluids

Although the system design reduces operational energy consumption, the environmental implications of nanoparticle production, disposal, and potential toxicity were beyond the scope of this work. A comprehensive lifecycle assessment (LCA) of nanofluid-based cooling systems would be required to fully evaluate their environmental sustainability.

9.3.9 Absence of CFD or Analytical Modelling

The study relies exclusively on experimental analysis. While this provides robust and application-relevant data, the lack of complementary computational fluid dynamics (CFD) modelling or theoretical analysis limits the generalisability and scalability of the findings. Incorporating simulation-based optimisation could have enabled deeper insights into flow patterns, thermal gradients, and parametric sensitivity.

9.3.10 Generalisation Beyond Electronics Cooling

While the proposed designs show promise for broader application areas such as EVs and renewable energy systems, the study did not conduct sector-specific validation for these domains. Material compatibility, space constraints, vibration tolerance, and fluid handling in automotive or outdoor environments were not evaluated, which may influence system integration and reliability.

In summary, while the findings of this thesis offer meaningful advances in bioinspired thermal management and nanofluid application, the limitations highlighted above should be considered when interpreting results or attempting to generalise them across sectors. These constraints also provide valuable direction for future work aimed at improving robustness, scalability, and commercial feasibility.

9.4 Recommendations for Future Work

Building on the findings, contributions, and limitations of this study, several promising directions for future research are proposed. These recommendations aim to extend the scope of the current work,

improve practical deployment, and explore interdisciplinary opportunities that can lead to more advanced, adaptive, and sustainable thermal management systems.

9.4.1 Long-Term Stability and Ageing of Nanofluids

Future studies should focus on evaluating the long-term stability and performance degradation of mono, hybrid, and tri-hybrid nanofluids under real operating conditions. This includes cyclic thermal loading, prolonged flow circulation, nanoparticle sedimentation, chemical stability, and interaction with system materials. Accelerated ageing tests and extended-duration experiments will help assess practical reliability and maintenance requirements.

9.4.2 Investigation of Fouling, Deposition, and Cleaning Strategies

The observed formation of micro-agglomerates within channels warrants a deeper study into fouling dynamics. Future work should quantify deposition rates, assess their impact on heat transfer over time, and explore strategies for mitigation such as surface coatings, back-flushing, or magnetic/chemical control. This is critical for scaling the technology in long-life industrial systems.

9.4.3 Transient and Dynamic Thermal Load Analysis

To simulate real-world operational behaviour more accurately, future research should incorporate transient thermal load testing, mimicking processor power fluctuations, on/off cycling, or EV battery charging conditions. Time-resolved temperature mapping and thermal response analysis will offer insights into system responsiveness and control strategies.

9.4.4 Integration with Two-Phase and Passive Cooling Technologies

The effectiveness of the proposed biomimetic heat sink geometries could be further enhanced by integrating them with two-phase cooling methods (e.g., heat pipes, vapor chambers) or passive systems (e.g., thermosyphons, phase change materials). Hybrid systems could reduce energy consumption further and broaden the application scope, especially in space-constrained or power-limited environments.

9.4.5 Use of Additive Manufacturing for Complex Topologies

Advanced manufacturing techniques such as metallic 3D printing (e.g., SLM, DMLS) can overcome the geometric limitations of CNC machining and enable more intricate, topology-optimised biomimetic structures. Future work could explore lattice-based heat sink configurations or multifunctional structures for simultaneous thermal, structural, and fluidic performance.

9.4.6 CFD and AI-Driven Optimisation of Heat Sink Design

While this study focused on experimental validation, incorporating computational fluid dynamics modelling and machine learning-based design optimisation could significantly accelerate the development of next-generation geometries. Parametric studies using numerical tools can help identify optimal design variables under various constraints and broaden understanding of local flow/thermal interactions.

9.4.7 Expanded Nanomaterial Exploration and Green Alternatives

Future research should explore a wider range of nanoparticles, including biodegradable, biosafe, or green-synthesised materials such as cellulose-based, plant-extract-coated, or metal-organic frameworks (MOFs). The environmental impact, cost, and reusability of nanofluids should be assessed through lifecycle and techno-economic analysis.

9.4.8 System-Level Testing in Real-World Applications

The proposed cooling strategy should be evaluated at the system level in real application domains such as high-performance servers, electric vehicle battery modules, or photovoltaic inverters. Prototype-level testing under actual service conditions (e.g., ambient fluctuations, vibration, dust exposure) will provide insights into integration challenges and practical benefits.

9.4.9 Development of Smart Cooling Control Systems

With the advancement of IoT and embedded sensing technologies, future work could explore the design of intelligent cooling systems that adaptively adjust flow rates or select coolant types based on thermal demand, fluid health, or energy pricing. Coupling biomimetic heat sinks with smart controls would enable efficient and responsive operation in dynamic environments.

9.4.10 Policy, Safety, and Standardisation Considerations

As nanofluid-based cooling systems move toward commercialisation, future work should also consider regulatory frameworks, health and safety implications, and standardisation for coolant handling, disposal, and system design. Collaboration with policymakers and industry stakeholders will be essential to ensure responsible and safe adoption.

This thesis establishes a solid foundation for bioinspired and nanofluid-enhanced cooling systems, but many research and development opportunities remain. Advancing in these areas will further enhance the performance, scalability, and sustainability of next-generation thermal management solutions across multiple high-impact industries.

9.5 Concluding Remarks

This thesis has addressed a pressing challenge in modern engineering: the need for compact, efficient, and scalable thermal management solutions capable of handling the rising heat fluxes generated by advanced electronics and power-dense systems. Through a novel integration of biomimetic heat sink geometries and high-performance nanofluids, the study has demonstrated how nature-inspired engineering and material innovation can jointly enhance thermal performance while maintaining manageable hydraulic characteristics.

By experimentally validating multiple geometrical configurations most notably the SAISCCPF design and systematically assessing the thermal and flow behaviour of mono, hybrid, and tri-hybrid nanofluids, this work provides a comprehensive evaluation framework rooted in real-world processor-level

conditions. The dual emphasis on heat transfer enhancement and pressure drop management ensures that the proposed solutions are not only academically significant but also industrially relevant.

Beyond technical performance, the thesis contributes to sustainable engineering by proposing system-level solutions that reduce energy consumption and are compatible with future trends in electric vehicles, renewable energy, and high-performance computing. The biomimetic approach, inspired by the adaptive flow regulation mechanisms of aquatic organisms, also broadens the design space for future cooling technologies and invites researchers to explore functional mimicry in fluidic systems.

Although the study acknowledges limitations related to nanoparticle long-term stability, geometrical manufacturing constraints, and dynamic operating conditions, it offers a strong foundation for future research in advanced cooling systems. The recommendations provided outline several promising directions, including the adoption of additive manufacturing, CFD-driven design optimisation, system-level testing, and environmentally conscious material development.

In conclusion, this research advances the state of knowledge in thermal management by demonstrating that a synergistic approach combining bioinspired geometry and engineered nanofluids can unlock new capabilities in compact and energy-efficient cooling technologies. It is anticipated that the concepts and findings presented here will inspire continued innovation across both academic and industrial domains.

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Appendix A

Table A.1: Intel® Xeon® processors specifications.

Product	Case Temperature	Thermal Design Power	Package Size
Intel® Xeon® Platinum 8362 Processor	82°C	265 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8358 Processor	81°C	250 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8352Y Processor	81°C	205 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8380 Processor	83°C	270 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8351N Processor	76°C	225 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8368Q Processor	58°C	270 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8352S Processor	81°C	205 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8352V Processor	78°C	195 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8368 Processor	84°C	270 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8360Y Processor	80°C	250 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8352M Processor	77°C	185 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8358P Processor	80°C	240 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8360HL Processor	—	225 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8360H Processor	—	225 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8356H Processor	—	190 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8376HL Processor	—	205 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8380H Processor	—	250 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8353H Processor	—	150 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8354H Processor	—	205 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8376H Processor	—	205 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 8380HL Processor	—	250 W	77.5mm x 56.5mm
Intel® Xeon® Platinum 9222 Processor	—	250 W	—
Intel® Xeon® Platinum 9221 Processor	—	250 W	—
Intel® Xeon® Platinum 9282 Processor	—	400 W	—
Intel® Xeon® Platinum 9242 Processor	—	350 W	—
Intel® Xeon® Platinum 8253 Processor	87°C	125 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8256 Processor	72°C	105 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8276 Processor	89°C	165 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8280L Processor	84°C	205 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8260 Processor	90°C	165 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8276L Processor	89°C	165 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8280 Processor	84°C	205 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8260Y Processor	90°C	165 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8268 Processor	84°C	205 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8270 Processor	84°C	205 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8260L Processor	90°C	165 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8153 Processor	87°C	125 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8156 Processor	71°C	105 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8158 Processor	85°C	150 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8160 Processor	85°C	150 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8164 Processor	85°C	150 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8168 Processor	85°C	205 W	76.0mm x 56.5mm

Intel® Xeon® Platinum 8170 Processor	89°C	165 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8176 Processor	89°C	165 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8160T Processor	93°C	150 W	76.0mm x 56.5mm
Intel® Xeon® Platinum 8180 Processor	84°C	205 W	76.0mm x 56.5mm
Xeon Gold			
Intel® Xeon® Gold 5315Y Processor	81°C	140 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6338 Processor	81°C	205 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6330N Processor	86°C	165 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6348 Processor	80°C	235 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6346 Processor	78°C	205 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6330 Processor	86°C	205 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6354 Processor	77°C	205 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6314U Processor	81°C	205 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6338N Processor	83°C	185 W	77.5mm x 56.5mm
Intel® Xeon® Gold 5318Y Processor	87°C	165 W	77.5mm x 56.5mm
Intel® Xeon® Gold 5317 Processor	84°C	150 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6334 Processor	69°C	165 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6326 Processor	78°C	185 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6342 Processor	81°C	230 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6338T Processor	87°C	165 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6336Y Processor	80°C	185 W	77.5mm x 56.5mm
Intel® Xeon® Gold 5318N Processor	83°C	150 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6312U Processor	80°C	185 W	77.5mm x 56.5mm
Intel® Xeon® Gold 5320T Processor	86°C	150 W	77.5mm x 56.5mm
Intel® Xeon® Gold 5320 Processor	79°C	185 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6330H Processor	—	150 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6328H Processor	—	165 W	77.5mm x 56.5mm
Intel® Xeon® Gold 5318H Processor	—	150 W	77.5mm x 56.5mm
Intel® Xeon® Gold 5320H Processor	—	150 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6348H Processor	—	165 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6328HL Processor	—	165 W	77.5mm x 56.5mm
Intel® Xeon® Gold 6230R Processor	85°C	150 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6250 Processor	60°C	185 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6256 Processor	64°C	205 W	76.0mm x 56.5mm
Intel® Xeon® Gold 5218R Processor	87°C	125 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6240R Processor	90°C	165 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6238R Processor	89°C	165 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6226R Processor	85°C	150 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6208U Processor	85°C	150 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6258R Processor	74°C	205 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6248R Processor	75°C	205 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6242R Processor	76°C	205 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6246R Processor	75°C	205 W	76.0mm x 56.5mm
Intel® Xeon® Gold 5220R Processor	86°C	150 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6250L Processor	60°C	185 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6230T Processor	92°C	125 W	76.0mm x 56.5mm
Intel® Xeon® Gold 5218T Processor	93°C	105 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6234 Processor	79°C	130 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6226 Processor	86°C	125 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6238L Processor	92°C	140 W	76.0mm x 56.5mm

Intel® Xeon® Gold 6240L Processor	85°C	150 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6222V Processor	83°C	115 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6246 Processor	76°C	165 W	76.0mm x 56.5mm
Intel® Xeon® Gold 5220T Processor	93°C	105 W	76.0mm x 56.5mm
Intel® Xeon® Gold 6209U Processor	87°C	125 W	76.0mm x 56.5mm
Intel® Xeon® Gold 5215 Processor	77°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Gold 5115 Processor	76°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Gold 5119T Processor	90°C	85 W	76.0mm x 56.5mm
Xeon Silver			
Intel® Xeon® Silver 4310T Processor	88°C	105 W	77.5mm x 56.5mm
Intel® Xeon® Silver 4310 Processor	82°C	120 W	77.5mm x 56.5mm
Intel® Xeon® Silver 4309Y Processor	76°C	105 W	77.5mm x 56.5mm
Intel® Xeon® Silver 4316 Processor	84°C	150 W	77.5mm x 56.5mm
Intel® Xeon® Silver 4314 Processor	86°C	135 W	77.5mm x 56.5mm
Intel® Xeon® Silver 4215R Processor	79°C	130 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4210T Processor	91°C	95 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4214R Processor	79°C	100 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4210R Processor	84°C	100 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4208 Processor	78°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4214Y Processor	77°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4214Y Processor	77°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4216 Processor	79°C	100 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4215 Processor	77°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4214 Processor	77°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4210 Processor	78°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4209T Processor	91°C	70 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4116 Processor	76°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4116T Processor	91°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4114T Processor	92°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4112 Processor	76°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4114 Processor	78°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4109T Processor	90°C	70 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4110 Processor	77°C	85 W	76.0mm x 56.5mm
Intel® Xeon® Silver 4108 Processor	77°C	85 W	76.0mm x 56.5mm

Appendix B

Table B.1. Summary of some recent literature on nanofluid-enhanced heat sinks, highlighting nanoparticle types, concentrations, heat sink configurations, base materials, and associated thermal–hydraulic performance outcomes.

Reference	Nanofluid		Heat Sink Configuration			Objectives	Results (Key Points)
	Particles-Basefluid	Particle concentration (φ)	Fins or channel shape	Material	Dimensional parameters		
Wang et al. [160]	Water	–	Plate fin (baseline), Petaloid I (circular pins), Petaloid II (pit pins), Pinwheel-like, Honeycombed	Copper	- Heat sink external dimensions: 200 mm $\times$ 100 mm $\times$ 7 mm - Flow channel area with fins: 160 mm (length) $\times$ 90 mm (width) - Fin/channel height: 1.5 mm - Inlet/outlet pipe inner diameter: 6 mm	Experimentally investigate the thermal-hydraulic performance of four novel pin-fin heat sink geometries (petaloid I & II, pinwheel-like, and honeycombed) compared to a conventional plate-fin heat sink	- Honeycombed PFHS showed the highest heat transfer coefficient (21.5 kW/m ² ·K) and lowest friction factor among all designs. - Petaloid I achieved the highest Nusselt number due to its smaller hydraulic diameter.
Zhang et al. [168]	Water	–	Bionic limulus-like fins (BLLF) inspired by the horseshoe crab (Limulus)	Aluminium	- Length: 140 mm, Width: 65 mm, Thickness of cooling plate: 3 mm, Microchannel thickness: 2 mm, Splitter length: 120 mm, Splitter width: 6.876 mm - Horizontal distance between fins: 3.437 mm	- Improve the cooling efficiency and reduce pressure loss in channel-type liquid cooling plates for battery thermal management systems (BTMS) in electric vehicles. - Optimise fin geometry and arrangement (spacing ratios) for best thermal and hydraulic performance.	- Best performance (lowest average temperature and pressure drop) achieved when the fin size and spacing were equal in both directions. - Proposed BLLF outperformed conventional rectangular and oval fins in both average temperature and pressure drop.
Duangthongsuk et al. [332]	Silica (SiO ₂)-water	Particle volume fractions tested were 0.2%, 0.4%, and 0.6%.	Diamond-shaped micro-pin-fin. Inline and staggered layouts.	Copper	- 30 mm x 33 mm dimensions - 1.0 mm hydraulic diameter	Examine the effects of pin-fin layout, Re, and φ on cooling performance, performance index (PI), and pressure drop (ΔP).	- Thermal performance augmented with increasing Re and φ . - Staggered layout had 3-10% higher thermal performance than inline. - Small effect on ΔP and pumping power. - New correlations for Nusselt number and ΔP proposed.

Ghadikolaei et al. [346]	Functionalized Graphene Nanoplatelets (CGNPs) - water	0.025%wt, 0.050%wt, 0.075%wt, and 0.100%wt	Sneaky fins with nature-inspired baseplate designs (honeycomb, ternate veiny, snowflake, spider netted)	Copper, Nickel, and Silver	40 mm x 40 mm	To investigate the combined effect of nature-inspired geometries and eco-friendly nanofluids on thermal performance and fluid flow for CPU cooling.	- Spider netted baseplate reduced maximum liquid block temperature by 8.5 K compared to ternate veiny design. - Optimal thermal output improvement (8.5% vs. simple model) achieved with spider netted baseplate and 0.075%wt nanofluid. - Copper heat sink outperformed nickel in cooling efficiency due to superior thermal properties.
Shahsavari et al. [347]	Silver (Ag)-water	$\phi = 0 - 1\%$	The heat sink configuration explored in the study features Tesla valve-based helical channels.	Copper	- 11.48 mm length, 9.60 mm width, 0.4 mm height. - 0.2 mm thick cover. - Circular inlet (0.7 mm diameter) and four circular outlets (0.4 mm diameter each)	- Investigate hydrothermal performance of nanofluid-cooled heat sink. - Analyse entropy generation in Tesla valve-based microchannels.	- Improved CPU cooling and lowered thermal resistance with a higher Reynolds number. - Heat sink with Tesla valve-based helical channels outperforms plain channels. - Pumping power increased with higher Re. - Peak Performance Evaluation Criterion was 1.642 for Re = 500 and $\phi = 0\%$
Kong et al. [348]	Not explicitly nanofluid; DI water used	—	Microchannels fabricated on silicon wafers.	Silicon wafers Coated with Copper inverse opals	Channel Dimensions: Width = 50, 100, 200 μm ; Height = 100 μm . - Coating (6-8 μm thickness, 5 μm pore size). - Manifold: PDMS 3D structure, 900 μm height.	- Achieve extreme cooling for electronics with high heat flux ($>1 \text{ kW/cm}^2$). - Optimise microchannel and manifold designs for efficient thermal and hydraulic performance.	- Heat flux removal up to 1147 W/cm^2 with a convective thermal resistance of $0.068 \text{ cm}^2 \cdot \text{K/W}$ and total pressure drop of 32 kPa. - Enhanced thermal uniformity ($<6 \text{ K}$ deviation). - Promotes nucleate boiling at higher heat fluxes.
Sun et al. [349]	Silicon carbide (SiC)-water	$\phi = 0.01, 0.03,$ and $0.1 \text{ vol}\%$	Matrix rib micro-jet	Copper	- 6x6 matrix rib design - Channel (30 mm $\times$ 30 mm), Fin (3 mm $\times$ 3 mm $\times$ 1 mm)	- Optimise cooling performance for concentrated solar cells. - Combine impinging jet and microchannel for enhanced cooling. - Evaluate influence of nanofluid concentration on heat sink performance.	- 6.5% increase in convective heat transfer coefficient compared to water. - 2.8% reduction in cooling surface temperature. - Improved temperature uniformity.
Gupta and Subbarao [350]	Alumina (Al_2O_3)-water	The concentration of the nanofluid	Parallel arrays of channel or tunnel-like structures	—	—	- Assess cooling efficacy, heat transfer coefficient, thermohydraulic performance,	- 51.54% reduction in back axial conduction compared to base fluid.

		varied from 1% to 4% (w/w).				and loss in concentration of alumina nanofluids in MCHS - Investigate the impact of nanofluids on back axial conduction at low Reynolds numbers ($10 \leq Re \leq 50$) - Develop correlations to predict Nusselt number and friction factor for MCHS based on nanofluid concentration - Explain the increase in heat transfer coefficient considering thermophoresis and Brownian motion of nanoparticles.	- Up to 29% lower surface temperatures in the microchannel heat sink. - Enhancement in heat transfer coefficient up to 43.34%. - Nusselt number increased up to 35.85% at Reynolds number 50. - Optimal thermohydraulic performance of 1.17 at 3% (w/w) nanoparticle concentration and Reynolds number 50.
Ma et al. [351]	Ag (Silver), SiO ₂ (Silica), Al ₂ O ₃ (Alumina), Water as Base Fluid	Volume Fraction: 0–6%	Three shapes: - Rectangular (MC-R) - Trapezoidal (MC-T) - Omega-shaped (MC-O)	Silicon	- 0.4 mm width, 0.3 mm height, 10 mm length - Hydraulic Diameter: 0.2 mm	- Investigate the thermal-hydraulic performance of nanofluids. - Optimise microchannel design. - Compare performance with and without nanoparticles. - Analyse the impact of different cross-sectional geometries. - Assess entropy generation and energy efficiency.	- Al ₂ O ₃ nanofluids increased HTC by 12.3% at Re = 500. - MC-O showed the highest HTC and lowest max temperature. - SiO ₂ exhibited the lowest performance improvement. - Best COP observed with Ag in MC-R. - Total entropy generation reduced in MC-O.
Zhao et al. [352]	TiO ₂ -water	0.0% – 0.5% wt%	Rectangular grooves and cylindrical bulges Arrangements: Aligned, Staggered	Copper	Depth: 1 mm, 2 mm; Width: 2 mm; Material: Copper; Dimensions: 50 mm x 50 mm (external).	- Investigate the thermo-hydraulic performance of nanofluids in enhanced CPU heat sinks. - Explore exergy efficiency as a function of nanofluid concentration and Reynolds number. - Assess comprehensive evaluation indices for different configurations and conditions.	- Best cooling performance at 0.3% (rectangular grooves) and 0.4% (cylindrical bulges). - Surface temperature reduction: up to 12.4% for grooves, 11.7% for bulges compared to water. - Higher Reynolds numbers improve heat transfer but may reduce exergy efficiency due to increased pressure drops.
Göksu [353]	CuO/Water CuO + Fe/Water	2% volume 1% CuO + 1% Fe)	- Block-type structure - Horizontal and vertical arrangements	–	- Fins Thickness: 0.3–0.6 mm - Spacing: 1–1.5 mm	- Optimise thermal performance by evaluating mono- and hybrid nanofluids - Investigate effects of block thickness and spacing on cooling efficiency - Compare mono and hybrid nanofluids	CuO/Water - Lowest thermal resistance: 0.272 K/W in horizontal arrangement - Improved cooling efficiency compared to water. CuO + Fe/Water - Lowest thermal resistance: 0.28 K/W in horizontal arrangement

							- Higher thermal resistance than mono nanofluid - Horizontal configurations outperform vertical in cooling efficiency - Increasing block thickness reduces thermal resistance and temperature range
Qi et al. [354]	Al₂O₃-water TiO₂-water	0.1–2.0 wt% 0.1–1.0 wt%	Plate	Copper	Plate Size: 50 mm × 50 mm Plate Thickness: 2 mm Inlet/Outlet Diameter: 5 mm	- Investigate thermo-hydraulic performance of nanofluids in CPU cooling. - Study effects of nanoparticle mass fraction on heat transfer.	Al₂O₃-water - Reduced CPU temperature by 23.2% compared to water. - Best thermal performance at a critical concentration of 1.0%. TiO₂-water - Reduced CPU temperature by 14.9% compared to water. - Best thermal performance was noted at a concentration of 0.4%.
Marseglia et al. [355]	Al₂O₃-water Silver (Ag)-water Gold (Au)-water	1 wt% 1 wt% 0.5 wt%, 0.75 wt%, 1 wt%	Rectangular straight channel	- Base Plate AISI 304 Stainless Steel - Micro-channel Fabrication Polydimethylsiloxane (PDMS)	Varied widths (0.25-0.75 mm), Wall Width: 0.50 mm Channel Height: 1 mm; Length: 20 mm	- Evaluate cooling performance with a focus on thermal stability and sedimentation effects. - Optimise nanoparticle concentration for enhanced heat transfer while minimizing clogging and sedimentation. - Investigate the potential benefits and challenges of two-phase flow.	Enhanced heat transfer compared to water but prone to significant sedimentation and clogging. Improved heat transfer, better stability than Alumina. Two-phase flow conditions do not consistently lead to significant heat transfer improvement due to the occurrence of instabilities. Best heat transfer performance, stable sedimentation even at low flow rates, and significant improvement with higher particle loadings.
Yusof et al. [356]	Boron nitride nanotubes (BNN)-water	0.001% – 0.03% by weight	Rectangular micro-channel heat sink	–	Dimensions: Length=1 cm, Width=1 cm, Height=533 µm, Channel Height=320 µm, Wall Thickness=213 µm	- Minimise thermal resistance and pressure drop. - Investigate optimal coolant concentration. - Explore efficient microchannel geometries using a heuristic approach.	- Reduction in thermal resistance by 5.34% at 0.01% concentration compared to water. - Lowest thermal resistance achieved: 0.0711 K/W at 0.01% concentration. - Pumping power increased with channel narrowing and higher fluid viscosity.
Baig et al. [357]	Al ₂ O ₃ -water, TiO ₂ -water	0.005 vol%, 0.01 vol%	Dual flow slotted fin mini-channel heat sink	Copper	Slot thickness: 0.5 mm Angle: 45° Fin Spacing: 0.5 mm	Investigate heat transfer enhancement using nanofluids in slotted fin configurations	- Reduction in base temperature up to 15.28%. - Heat transfer increased by 4.35%.

Ghasemi et al. [358]	Al ₂ O ₃ -water	–	Circular structure of mini-channel heat sink	Aluminium	Three different heat sinks with varying hydraulic diameters (4, 6, 8 mm) Fabrication: Wire-cutting technique	- Optimise heat sink geometry for enhanced CPU cooling. - Investigate trade-offs between heat transfer and pressure drop. - Evaluate heat sink performance under various flow rates.	- TiO₂-H₂O increases heat transfer but is less efficient than Al₂O₃-H₂O. - Minor pressure drop increase noted.
							- Reduced hydraulic diameter improves heat transfer. - Increased flow rate enhances heat transfer. - Nanofluid increases convective heat transfer but at the cost of higher pressure drop.

Table B.2. Important parameters of the studies conducted on mini-channel heat sinks employing nanofluids (various studies).

Reference	Study Type	Sink Type	Heat Sink Material	Hydraulic Diameter	Reynolds Number	Nanofluid	Particle Concentration	Nusselt Number	Pressure drop	Other important Factors
[154]	Experimental	Rectangular	Copper	8 mm	2985–9360	CuO/water	0.1, 0.2 vol.%	–	–	Pumping power increased by 15.11 % by 0.2 vol.%
[157]	Experimental	Rectangular	Copper	–	395–989	Al ₂ O ₃ /water	0.1–0.25 vol.%	–	–	HTC increased 18% and thermal resistance reduced 15.72% by 0.25 vol.% and
[158]	Experimental	Rectangular	Silicon	194.5 µm	190–1020	Al ₂ O ₃ /water	0.15, 0.26 vol.%	Increased 10.2–15.8% by 0.26 vol.%. Increased 3.4–5.5% by 0.26 vol.%. Increased 70% by 4.5 vol.%. Increased with particle concentration and flow rate while observed no effect of particle type.	Increased 3.4–5.5% by 0.26 vol.%. Increased 70% by 4.5 vol.%. Increased with particle concentration and flow rate while observed no effect of particle type.	Thermal resistance reduced 11.5% by 0.26 vol.%. Particles deposited on the walls at higher temperature.
[161]	Experimental	Rectangular	Aluminium	–	100–5000	CuO/water	0.24, 1.03, 4.5 vol.%	–	Increased 70% by 4.5 vol.%. Increased with particle concentration and flow rate while observed no effect of particle type.	–
[162]	Experimental	Rectangular	Copper	–	133–1515	Al ₂ O ₃ /water	0.5–10 wt.%	–	–	HTC increased 72% by 10 wt.
[165]	Experimental	Circular pin fin	Aluminium	1.2 mm	700–3800	SiO ₂ /water, ZnO/water	0.2–0.6 vol.%	–	Increased with particle concentration and flow rate while observed no effect of particle type.	3-9% increase for ZnO compared to SiO ₂ in the concentration range of (0.2-0.6 vol.%)
[166]	Experimental	Rectangular	Copper	–	–	Al ₂ O ₃ /water	0.05–0.2 vol.%	–	–	Frictional effects found to increase with the supplementation of nanoparticles in the base fluid.

[171]	Numerical	Rectangular	–	–	200–600	Al ₂ O ₃ /water , Ag/water, Ag- Al ₂ O ₃ /water	3 vol.%	–	–	HTC enhanced by 26–148%, 111–144%, and 17–18% for Ag+Al ₂ O ₃ , Ag, and Al ₂ O ₃ respectively.
[167]	Numerical	Trapezoidal grooved	–	–	266–799	Al ₂ O ₃ /water , CuO/water, ZnO/water, SiO ₂ /water	1–4 vol.%	Increased 120.22% in trapezoidal grooved MCHS compared to simple MCHS	–	Friction factor increased up to 52.24%.
[174]	Numerical	Rectangular	–	339.15 µm	100–1000	Al ₂ O ₃ /water	1–5 vol.%	–	–	Thermal resistance reduced and pumping power increased 57.6% and 0.0173 W by 5 vol.% respectively.
[184]	Numerical	Micro channel with V-type inlet/outlet	Silicon	–	–	SiO ₂ /water, Al ₂ O ₃ /water , ZnO/water, CuO/water	1.0, 1.5, 2.0 vol.%	Increased with an increase in particle concentration and decrease of particle diameter	Increased with particle concentration and particle diameter	–
[359]	Numerical	Rib grooved	–	–	10,000– 40,000	SiO ₂ /water, ZnO/water, Al ₂ O ₃ /water , and CuO/water	1–4 vol.%	–	–	–

Table B.3. Summary of the nanofluid research, highlighting the nanoparticles, base fluid, surfactants studied, objectives, and key findings.

Reference	Nanofluid investigated		Surfactant studied	Objective	Findings
	Nanoparticles	Basefluid			
Rehman et al. [360]	Al ₂ O ₃ -TiO ₂ hybrid	W-EG mixture (60:40)	CTAB, SDS Poly (vinyl alcohol), Polyvinylpyrrolidone (PVP), Polyethylene glycol (PEG), Oleic acid (OA)	Identify best surfactant for long-term heat transfer applications. Investigate surfactant effects on nanofluid stability, viscosity, and thermal conductivity (TC).	PVP is the most suitable surfactant for hybrid nanofluids. PVP enhances thermal conductivity and stability for long- term applications.

Wusiman et al. [361]	MWCNTs	Water	SDS, SDBS	Investigate thermal conductivity and study the effect of surfactants	MWCNTs with SDBS showed better thermal conductivity enhancement (TCE). SDS had a negative impact on thermal conductivity of MWCNTs. Optimum pH value was found to be around 9.
Mehta et al. [362]	Al ₂ O ₃	Water	CTAB	Prepare stable Al ₂ O ₃ -water nanofluid using CTAB surfactant Enhance thermophysical properties and stability of nanofluid	The use of CTAB as a surfactant significantly improves the stability of Al ₂ O ₃ -water nanofluids. With CTAB, the mean particle sizes after one month were 80 nm, compared to 536 nm without surfactant, leading to better thermal conductivity and dynamic viscosity improvements of 8.5% and 76.2% respectively at a 1% volume concentration.
Saraswat and Sengwa [363]	ZnO	EG-glycerol (90:10)	PVP	Analyse optical, dielectric, and rheological properties	Alcohol mixture based nanofluids show improved optical, dielectric, and rheological properties.
Yalçın et al. [364]	Graphite	Water	Gum Arabic, Cetrimonium bromide, Ammonium citrate	Investigate how different surfactants affect nanofluid viscosity.	Surfactant types and proportions affect nanofluid viscosity differently. Different surfactant usages distinctly change nanofluid dynamic viscosity.
Poloju et al. [365]	SiO ₂ , ZnO, and TiO ₂ ternary	Water	SDBS	Investigate TC and dispersion properties of SDBS nanofluid. Analyse impacts of sonication time, surfactant inclusion, and ageing.	SDBS decorated ternary nanofluid showed enhanced thermal conductivity. Surfactant inclusion, sonication time, and ageing affected dispersion properties.
Borode et al. [366]	Graphene nanoplatelets (GNP)	Water	SDBS, SDS, GA, and Tween 80	Study effects of surfactants on GNP nanofluids properties. Analyse stability, thermal, electrical conductivity, and viscosity of nanofluids.	SDBS-based nanofluids showed the best dispersion and stabilization. Electrical and thermal conductivity increased with surfactant addition.
Wang et al. [367]	Fe ₃ O ₄ , CNT, Fe ₃ O ₄ -CNT hybrid	Water	Colace, Trisodium citrate dihydrate (TSC), PVP, CTAB, Tetramethylammonium hydroxide (TMAH), Acacia Senegal, SDBS, SDS, and Sodium lauryl sulfonate (SLS)	Investigate the effect of surfactants on stability and thermo-physical properties Propose empirical formulas for nanofluid viscosity predictions	Nanoparticle size, volume fraction, and temperature affect nanofluid viscosity. Surfactants TMAH, SDS, and SLS improve stability and TC.
Dalkılıç et al. [368]	CNT-SiO ₂ hybrid	Water	No surfactant used for 0.1%, 0.5%, and 1% concentrations Gum Arabic used as surfactant only for 2% concentration samples	Measure and analyse the TCE of water-based CNT-SiO ₂ hybrid nanofluids at different concentrations, temperatures, and CNT:SiO ₂ ratios.	Hybrid nanofluid exhibited better TCE compared to individual nanoparticles. Gum Arabic surfactant enhanced stability, but at the cost of increased viscosity.
Esfahani et al. [369]	ZnO-Ag (50%-50%) hybrid	Water	—	Study the effect of particle loading (0.125-2 vol.%) and temperature (25-50°C) on TC and develop a new correlation.	At higher temperatures, increasing volume fraction had a greater effect on TC due to enhanced Brownian motion.

					A new correlation was developed to predict the TC, with a margin of deviation of 1.3% compared to experimental results.
Dezfulizadeh et al. [370]	Cu-SiO ₂ -MWCNT ternary hybrid	Water	—	Investigate the dynamic viscosity and TC of the ternary hybrid at different temperatures and nanoparticle concentrations.	The ternary formulation exhibited Newtonian behaviour. The nanofluid sample showed greater TC and dynamic viscosity enhancements compared to mono and binary nanofluids. Mathematical correlations estimate the TC and dynamic viscosity, with maximum errors of 1.167% and 1.327% respectively.
Adun et al. [371]	Al ₂ O ₃ -ZnO-Fe ₃ O ₄ ternary hybrid /	Water	—	Investigate the thermal properties and examine the effects of temperature, volume concentration, and mixture ratio (1:1:1, 1:2:1, and 1:1:2) Develop a machine learning model for accurate prediction of properties	Optimum TCE of 36.018% recorded at 1.25% volume concentration at 65°C Gaussian process regression showed excellent prediction
Sepehrnia et al. [372]	Fe ₃ O ₄ , TiO ₂ , and graphene oxide (GO)	Hydraulic oil HLP 68	—	Improve the efficiency of hydraulic systems with nano-additives.	Dynamic viscosity increases significantly with nano-additives and lower temperatures.
Ajeena et al. [373]	ZrO ₂ (Zirconium Dioxide) and SiC (Silicon Carbide) in a 50-50 ratio	Distilled water	—	Determine the dynamic viscosity by studying its rheology. Assess the characteristics and stability of the ZrO ₂ and SiC nanoparticles in the base fluid.	The hybrid samples displayed Newtonian fluid behaviour across a range of temperatures, demonstrating their suitability for use in various devices as a Newtonian fluid.
Qu et al. [374]	SiO ₂ -Al ₂ O ₃ -MWCNTs	Water	—	Examine the effect of nanoparticles loading and temperature. Develop a new model for viscosity prediction using nonlinear curve fitting techniques.	Viscosity rose from 1.55 to 3.26 cP when the volume fraction increased from 0.1% to 0.5%. Viscosity decreases with increasing temperature. At 0.3% volume fraction, the viscosity reduced from 3.3 to 1.73 cP when temperature increased from 20°C to 60°C
Mande et al. [375]	TiO ₂ -CuO hybrid	Water	—	Investigate thermal transport properties of TiO ₂ /CuO hybrid nanofluids. Study morphological characteristics using SEM, XRD, and EDX.	Thermal conductivity enhanced with particle loading. Density and viscosity increased while specific heat decreased with concentration.
Ghafouri and Toghraie [376]	ZnO-SiC hybrid	Ethylene glycol	CTAB	Evaluate TC of SiC-ZnO hybrid nanofluid. Analyse the effects of nanoparticle size, temperature, and volume fraction.	Thermal conductivity enhanced by 15.91% at optimal conditions. New multivariate correlation accurately predicts thermal conductivity.

Appendix C

Table C.1: Coordinates of the NACA 0025 Airfoil.

Upper Surface		Lower Surface		Camber Line	
x	y	x	y	x	y
0	0	0	0	0	0
0.00151	0.035091	0.00151	-0.03509	0.00151	0
0.00604	0.069696	0.00604	-0.0697	0.00604	0
0.013584	0.1038	0.013584	-0.1038	0.013584	0
0.024136	0.137385	0.024136	-0.13739	0.024136	0
0.037683	0.170431	0.037683	-0.17043	0.037683	0
0.054214	0.202914	0.054214	-0.20291	0.054214	0
0.073711	0.234805	0.073711	-0.23481	0.073711	0
0.096154	0.266077	0.096154	-0.26608	0.096154	0
0.121521	0.296696	0.121521	-0.2967	0.121521	0
0.149787	0.326628	0.149787	-0.32663	0.149787	0
0.180922	0.355836	0.180922	-0.35584	0.180922	0
0.214896	0.384283	0.214896	-0.38428	0.214896	0
0.251675	0.41193	0.251675	-0.41193	0.251675	0
0.29122	0.438736	0.29122	-0.43874	0.29122	0
0.333494	0.464663	0.333494	-0.46466	0.333494	0
0.378452	0.489669	0.378452	-0.48967	0.378452	0
0.42605	0.513715	0.42605	-0.51372	0.42605	0
0.476239	0.536762	0.476239	-0.53676	0.476239	0
0.52897	0.558773	0.52897	-0.55877	0.52897	0
0.584189	0.57971	0.584189	-0.57971	0.584189	0
0.641841	0.599541	0.641841	-0.59954	0.641841	0
0.701867	0.618233	0.701867	-0.61823	0.701867	0
0.764207	0.635756	0.764207	-0.63576	0.764207	0
0.828798	0.652085	0.828798	-0.65209	0.828798	0
0.895575	0.667195	0.895575	-0.6672	0.895575	0
0.964472	0.681068	0.964472	-0.68107	0.964472	0
1.035418	0.693685	1.035418	-0.69369	1.035418	0
1.108342	0.705036	1.108342	-0.70504	1.108342	0
1.183171	0.715109	1.183171	-0.71511	1.183171	0
1.259829	0.723901	1.259829	-0.7239	1.259829	0
1.33824	0.73141	1.33824	-0.73141	1.33824	0
1.418324	0.737639	1.418324	-0.73764	1.418324	0
1.5	0.742594	1.5	-0.74259	1.5	0
1.583187	0.746285	1.583187	-0.74629	1.583187	0
1.6678	0.748728	1.6678	-0.74873	1.6678	0
1.753755	0.749939	1.753755	-0.74994	1.753755	0
1.840965	0.749939	1.840965	-0.74994	1.840965	0
1.929341	0.748754	1.929341	-0.74875	1.929341	0
2.018796	0.74641	2.018796	-0.74641	2.018796	0
2.109239	0.742937	2.109239	-0.74294	2.109239	0
2.200579	0.738369	2.200579	-0.73837	2.200579	0
2.292723	0.732741	2.292723	-0.73274	2.292723	0
2.38558	0.726091	2.38558	-0.72609	2.38558	0
2.479055	0.718456	2.479055	-0.71846	2.479055	0
2.573055	0.709879	2.573055	-0.70988	2.573055	0
2.667485	0.700401	2.667485	-0.7004	2.667485	0
2.76225	0.690066	2.76225	-0.69007	2.76225	0
2.857254	0.678918	2.857254	-0.67892	2.857254	0
2.952402	0.667001	2.952402	-0.667	2.952402	0
3.047598	0.654361	3.047598	-0.65436	3.047598	0
3.142746	0.641043	3.142746	-0.64104	3.142746	0

3.23775	0.627093	3.23775	-0.62709	3.23775	0
3.332515	0.612556	3.332515	-0.61256	3.332515	0
3.426945	0.597477	3.426945	-0.59748	3.426945	0
3.520945	0.581901	3.520945	-0.5819	3.520945	0
3.61442	0.565873	3.61442	-0.56587	3.61442	0
3.707277	0.549436	3.707277	-0.54944	3.707277	0
3.799421	0.532633	3.799421	-0.53263	3.799421	0
3.890761	0.515508	3.890761	-0.51551	3.890761	0
3.981204	0.498102	3.981204	-0.4981	3.981204	0
4.070659	0.480457	4.070659	-0.48046	4.070659	0
4.159035	0.462614	4.159035	-0.46261	4.159035	0
4.246245	0.444613	4.246245	-0.44461	4.246245	0
4.3322	0.426493	4.3322	-0.42649	4.3322	0
4.416813	0.408294	4.416813	-0.40829	4.416813	0
4.5	0.390055	4.5	-0.39006	4.5	0
4.581676	0.371814	4.581676	-0.37181	4.581676	0
4.66176	0.353609	4.66176	-0.35361	4.66176	0
4.740171	0.335477	4.740171	-0.33548	4.740171	0
4.816829	0.317458	4.816829	-0.31746	4.816829	0
4.891658	0.299587	4.891658	-0.29959	4.891658	0
4.964582	0.281901	4.964582	-0.2819	4.964582	0
5.035528	0.264439	5.035528	-0.26444	5.035528	0
5.104425	0.247237	5.104425	-0.24724	5.104425	0
5.171202	0.230331	5.171202	-0.23033	5.171202	0
5.235793	0.213758	5.235793	-0.21376	5.235793	0
5.298133	0.197555	5.298133	-0.19756	5.298133	0
5.358159	0.181757	5.358159	-0.18176	5.358159	0
5.415811	0.166402	5.415811	-0.1664	5.415811	0
5.47103	0.151523	5.47103	-0.15152	5.47103	0
5.523761	0.137157	5.523761	-0.13716	5.523761	0
5.57395	0.123338	5.57395	-0.12334	5.57395	0
5.621548	0.110099	5.621548	-0.1101	5.621548	0
5.666506	0.097474	5.666506	-0.09747	5.666506	0
5.70878	0.085495	5.70878	-0.0855	5.70878	0
5.748325	0.074192	5.748325	-0.07419	5.748325	0
5.785104	0.063596	5.785104	-0.0636	5.785104	0
5.819078	0.053734	5.819078	-0.05373	5.819078	0
5.850213	0.044634	5.850213	-0.04463	5.850213	0
5.878479	0.036321	5.878479	-0.03632	5.878479	0
5.903846	0.028817	5.903846	-0.02882	5.903846	0
5.926289	0.022144	5.926289	-0.02214	5.926289	0
5.945786	0.016321	5.945786	-0.01632	5.945786	0
5.962317	0.011365	5.962317	-0.01137	5.962317	0
5.975864	0.00729	5.975864	-0.00729	5.975864	0
5.986416	0.004107	5.986416	-0.00411	5.986416	0
5.99396	0.001828	5.99396	-0.00183	5.99396	0
5.99849	0.000457	5.99849	-0.00046	5.99849	0
6	0	6	0	6	0

Appendix D

Table D.1: Different facets of the particles offered by NanoAmer (accessed 10/06/2022)

	Nanoparticle	Formula	Size	Purity	Density (g/cm ³)	Quantity (g)	Cost (\$)
Metal							
	Aluminum	Al	18 nm	99+%	2.7	100	354
	Silver	Ag	35 nm	99.5%	10.49	100	753
	Bismuth	Bi	40-60 nm	99.5%	9.8	100	695
	Diamond	C	3-10 nm	98+%	3.5	100	1150
	Cobalt (Passivated)	Co	28 nm	99.8%	8.92	100	325
	Chromium	Cr	50 nm	99.5%	7.19	100	724
	Copper	Cu	20 nm	99%	8.94	100	260
	Iron	Fe	20 nm	99%	7.87	100	330
	Germanium	Ge	20-50 nm	99.9+%	5.32	100	2995
	Molybdenum	Mo	70 nm	99.5%	10.22	100	328
	Niobium	Nb	40-60 nm	99.9%	8.57	100	785
	Nickel	Ni	20 nm	99.5%	8.9	100	399
	Palladium	Pd	20-30 nm	99.95%	12.02	5	1550
	Platinum	Pt	20-30	99.95%	21.45	25	4375
	Ruthenium	Ru	20-30 nm	99.95%	12.45	5	595
	Silicon	Si	30-50 nm	99%	2.33	100	795
	Tin	Sn	60-80 nm	99%	7.31	100	290
	Tantalum	Ta	40 nm	99.9%		100	590
	Tungsten	W	40-60 nm	99.9+%	19.3	25	120
	Zinc	Zn	80 nm	99.5%	7.14	25	95
Metal Oxide							
	Aluminum Oxide	Al ₂ O ₃	30 nm	99.99%	4.00	100	70
	Boron Oxide	B ₂ O ₃	40-80 nm	98%	2.46	100	390
	Cerium Oxide	CeO ₂	15-30 nm	99.9%	7.132	100	105
	Cobalt(II,III) Oxide	Co ₃ O ₄	50-80 nm	99%	6.11	100	81
	Chromium Oxide	Cr ₂ O ₃	60 nm	99+%	5.22	100	125
	Copper(II) Oxide	CuO	30-50 nm	99+%	6.3-6.49	100	80
	Copper(I) Oxide	Cu ₂ O	30-50 nm	99%		100	145
	Dysprosium Oxide	Dy ₂ O ₃	55 nm	99.9%	7.81	100	350
	Erbium Oxide	Er ₂ O ₃	20-30 nm	99.9%	8.64	100	190
	Iron(III) Oxide	Fe ₂ O ₃	30 nm	99%	5.24	100	80
	Iron(II,III) Oxide	Fe ₃ O ₄	30 nm	99%	4.8-5.1	100	90
	Gadolinium Oxide	Gd ₂ O ₃	15-30 nm	99.9%	7.407	100	165
	Indium Oxide	In ₂ O ₃	30-50 nm	99.99%	7.18	100	605
	Lanthanum Oxide	La ₂ O ₃	15-30 nm	99.99%	6.51	100	150
	Magnesium Oxide	MgO	20 nm	99+%	3.580	100	82
	Molybdenum(VI) Oxide	MoO ₃	100 nm	99.5%	4.69	100	484
	Neodymium Oxide	Nd ₂ O ₃	15-30 nm	99.9%	7.24	100	220
	Nickel Oxide	Ni ₂ O ₃	20-30 nm	99.9%	4.84	100	170
	Praseodymium Oxide	Pr ₆ O ₁₁	15-30 nm	99.9%	6.5	100	220
	Silicon Oxide	SiO ₂	20 nm	99+%	2.2-2.6	100	110
	Samarium Oxide	Sm ₂ O ₃	15-30 nm	99.9%	8.347	100	150
	Titanium Oxide (anatase)	TiO ₂	15 nm	99%	3.9	100	80
	Titanium Oxide (rutile)	TiO ₂	20-50 nm	99.8%	4.17	100	88
	Vanadium Oxide	VO ₂	100 - 200 nm	99.9+%	5.76	100	320
	Tungsten Oxide	WO ₃	40-50 nm	99.9+%	7.16	100	238
	Yttrium Oxide	Y ₂ O ₃	20-40 nm	99.995%	5.01	100	150
	Ytterbium Oxide	Yb ₂ O ₃	10-80 nm	99.9%	9.17	100	165
	Zinc Oxide	ZnO	30 nm	99%	5.610	100	85
	Zirconium Carbide	ZrC	60 nm	97%	6.73	100	230
Multi-Element Oxides							

Barium Titanate	BaTiO ₃	100-200 nm	99.5%	5.85	100	75
Cobalt Iron Oxides	CoFe ₂ O ₄	35-55 nm	98%	5.3	100	95
Cobalt-Zinc Iron Oxide	Co _{0.5} Zn _{0.5} Fe ₂ O ₄	30-50 nm	99.5%	5.2	100	145
Nickel-Zinc Iron	Ni _{0.5} Zn _{0.5} Fe ₂ O ₄	10-30 nm	98.5%	5.2	100	199
Nickel-Iron-Molybdenum Permalloy	Ni ₈₀ Fe ₁₇ Mo ₃	70 nm	99+%		100	350
Strontium Titanate	SrTiO ₃	100 nm	99.5+%		1000	485
Zinc Iron Oxide	ZnFe ₂ O ₄	40 nm	98.5%	5.1	100	145
Carbide						
Boron Carbide	B ₄ C	50nm	> 97%	2.52	1000	1,850
Silicon Carbide (alpha)	SiC	55 nm	99.9%	3.22	500	435
Titanium Carbide	TiC	50 nm	97+%	4.93	100	152
Tungsten Carbide	WC	50 nm	99.9%	15.63	100	250
Boride						
Hafnium Boride	HfB ₂	60 nm	99+%	10.5	100	725
Nitride						
Aluminum Nitride	AlN	70-80 nm	99.5 %	3.26	100	260
Silicon Nitride	Si ₃ N ₄	15-30 nm	98.5+%	3.4	100	108
Titanium Nitride	TiN	20 nm	97+%	5.22	100	176

Table D.2: Different facets of the particles offered by Alfa Aesar (accessed 13/06/2022).

Nanoparticle	Formula	Size	Purity	Density (g/cm ³)	Quantity (g)	Cost (£)
Metal						
Cobalt	Co(core) / Co ₃ O ₄ (shell)	25-30nm	99.8%		25	188.00
Copper	Cu(core) / CuO(shell)	20-50nm	99.9%	8.94	25	534.00
Gold	Au	20-25nm	99.95+%	19.32		On demand
Manganese	Mn(core) / Mn ₃ O ₄ (shell)	30-50nm			25	669.00
Molybdenum	Mo	60-80nm	99%	10.28	25	413.00
Nickel	Ni(core) / NiO(shell)	5-20nm	99.9%	8.908	25	694.00
Silver	Ag	20-40nm	99.9%	10.5	25	655.00
Metal Oxide						
Aluminum oxide	Al ₂ O ₃	40-50nm	99.5%	3.97	100	35.80
Antimony tin oxide	Sb ₂ O ₅ :SnO ₂ 15:85 wt%	13-22nm	99.5%		100	92.30
Bismuth(III) oxide	Bi ₂ O ₃	80-200nm	99.9%	8.9	100	101.00
Cobalt(II,III) oxide	Co ₃ O ₄	50-80nm	99%	6.11	100	138.00
Copper(II) oxide	CuO	30-50nm		6.3	50	88.80
Iron(II,III) oxide	Fe ₃ O ₄	50-100nm	97%	5.2	100	79.60
Iron(III) oxide, alpha-phase	Fe ₂ O ₃	30-50nm	98%	5.24	100	162.00
Iron(III) oxide, magnetic	Fe ₂ O ₃	20-40nm		5.24	100	147.00
Magnesium oxide	MgO	40-60nm	99+%	3.58	100	132.00
Titanium(IV) oxide, anatase	TiO ₂	15nm	99.7%	3.9	500	410.00
Yttrium(III) oxide	Y ₂ O ₃	50-70nm	99.995%	5.01	100	143.00
Zinc oxide	ZnO	20-30nm	99%	5.606	50	373.00
Zirconium(IV) oxide	ZrO ₂	15-25nm	99%	5.89	100	160.00
Carbide						
Silicon carbide	SiC	45-55nm		3.16	100	473.00
Titanium carbide	TiC	30-50nm		4.93	100	530.00

Appendix E

E.1. Thermal Conductivity

The significance of the model and its components were evaluated using ANOVA (Analysis of Variance), with the results summarised in the provided Table D6.2. The overall model was highly significant, with an F-value of 2149.09 and a p-value of less than 0.0001, indicating that the model has strong predictive power. The residual sum of squares was very small (0.0001), further demonstrating the model's accuracy. Additionally, the predicted R^2 of 0.9979 is very close to the adjusted R^2 , suggesting that the model has excellent predictive capability. The low coefficient of variation (C.V.%) of 0.1976 indicates high precision, and the Adeq Precision of 171.02 exceeds the threshold of 4, signifying an adequate signal.

Table E.1. Values of coefficients for the thermal conductivity quadratic model of various fluid samples.

Sample	a	b	Sample	a	b
DW	0.571282	0.001186	MWCNTs/AlN (60:40)	0.572631	0.002318
Ag	0.575327	0.002107	MWCNTs/AlN (80:20)	0.573279	0.002367
AlN	0.572419	0.001872	MWCNTs/Ag (20:80)	0.575753	0.002202
MWCNTs	0.576665	0.002342	MWCNTs/Ag (40:60)	0.577041	0.002239
Ag/AlN (20:80)	0.573077	0.001983	MWCNTs/Ag (60:40)	0.57665	0.002308
Ag/AlN (40:60)	0.569932	0.002234	MWCNTs/Ag (80:20)	0.576418	0.002333
Ag/AlN (60:40)	0.572001	0.002202	MWCNTs/Ag/AlN (20:20:60)	0.572785	0.002196
Ag/AlN (80:20)	0.572628	0.002213	MWCNTs/Ag/AlN (20:40:40)	0.574169	0.002281
MWCNTs/AlN (20:80)	0.57268	0.002081	MWCNTs/Ag/AlN (20:60:20)	0.576012	0.002286
MWCNTs/AlN (40:60)	0.571805	0.002283			

Table E.2. ANOVA results for the thermal conductivity quadratic model.

Source	Sum of Squares	df	Mean Square	p-value	F-value	Significance
Model	0.146	38	0.0038	< 1.0E-04	2149.09	Significant
Fluid-A	0.0102	18	0.0006	< 1.0E-04	318.1	
Temperature-B	0.1348	1	0.1348	< 1.0E-04	75419.29	
AB	0.0006	18	0	< 1.0E-04	17.53	
B ²	0.0004	1	0.0004	< 1.0E-04	204.72	
Residual	0.0001	75	1.79E-06			
Mean	0.67644		R²	0.9991		
Std. Dev.	0.0013369		Predicted R²	0.9979		
PRESS	0.0003043		Adjusted R²	0.9986		
C.V. %	0.19764		Adeq Precision	171.0224		

To ensure the validity and reliability of the model, several diagnostic plots were examined. These plots are critical for assessing whether the assumptions underlying the regression analysis are met and for identifying any potential issues with the model. Figure E.1(a) compares the predicted thermal conductivity values with the actual measured values. Ideally, if the model were perfect, all points would lie exactly on the 45-degree line. According to the results, the data points were found to be closely aligned with this line, demonstrating a high degree of accuracy in the model's predictions. The close alignment suggests that the model has captured the underlying relationship between temperature and thermal conductivity effectively, with minimal deviation between predicted and observed values.

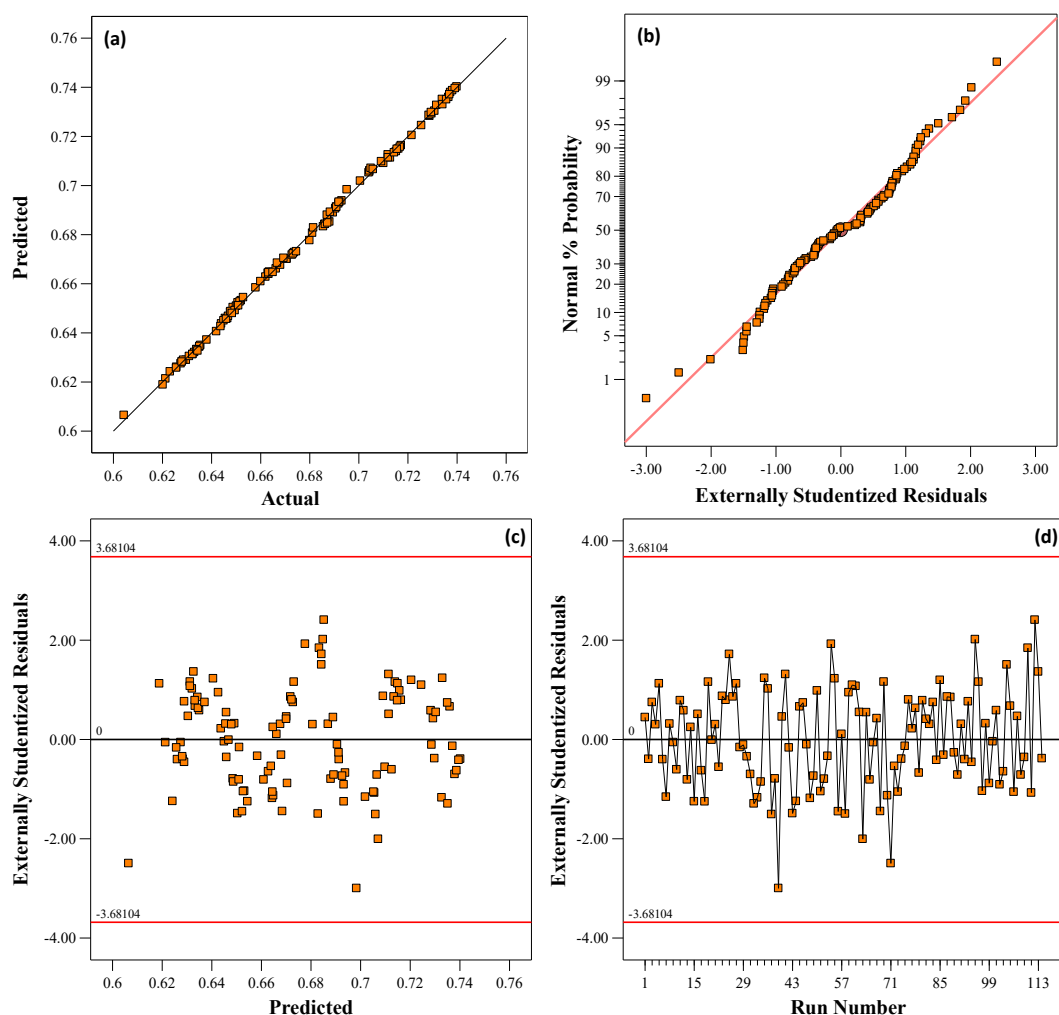


Figure E.1. Diagnostic plots for the quadratic model of thermal conductivity: (a) Predicted vs. Actual values, (b) Normal probability plot of residuals, (c) Externally Studentized Residuals vs. Predicted values, and (d) Externally Studentized Residuals vs. Run Num.

Figure E.1(b) shows the normal probability plot of residuals analysed to assess the normality of the residuals. In this plot, the residuals are plotted against the expected values from a normal distribution. The data points follow a straight line quite closely, indicating that the residuals are approximately normally distributed. As shown in Fig. E.1(c), the externally studentized residuals are plotted against the predicted values of thermal conductivity. The absence of any discernible pattern in the spread of residuals suggests that points are randomly distributed, with no signs of increasing or decreasing variance. This randomness is what we expect in a well-behaved model, indicating that the model's predictions are not biased and that the residuals have constant variance. Finally, the residuals against run number plot was examined to detect any potential patterns related to the order in which the data were collected, as depicted in Fig. E.1(d). The purpose of this plot is to identify if there are any time-related or sequence-related effects influencing the residuals. The residuals appear to be randomly scattered without any noticeable trend, indicating that there are no sequence-related biases affecting the model.

E.2 Viscosity

Residual analysis demonstrated the model's robustness, as evidenced by a low residual sum of squares and an exceptionally high R^2 value of 0.9997. This indicates that the model accounted for almost all the variability in

viscosity. Additionally, the high Adjusted R^2 and Predicted R^2 values reaffirm the model's accuracy and its capability to generalize well to new data. The Adequate Precision ratio also exceeded the minimum threshold significantly, further validating the model's reliability. Figure E.2 presents diagnostic plots that offer visual evidence of the model's effectiveness. The Predicted vs. Actual plot revealed close agreement between predicted and actual viscosity values, with points clustered along the diagonal line. This demonstrated a strong correlation between model predictions and observed data. The Normal Probability plot of residuals confirmed the residuals followed a normal distribution, which is essential for the validity of the analysis. Plots of Externally Studentized Residuals against predicted values and run number showed no discernible patterns, suggesting independent residuals with constant variance.

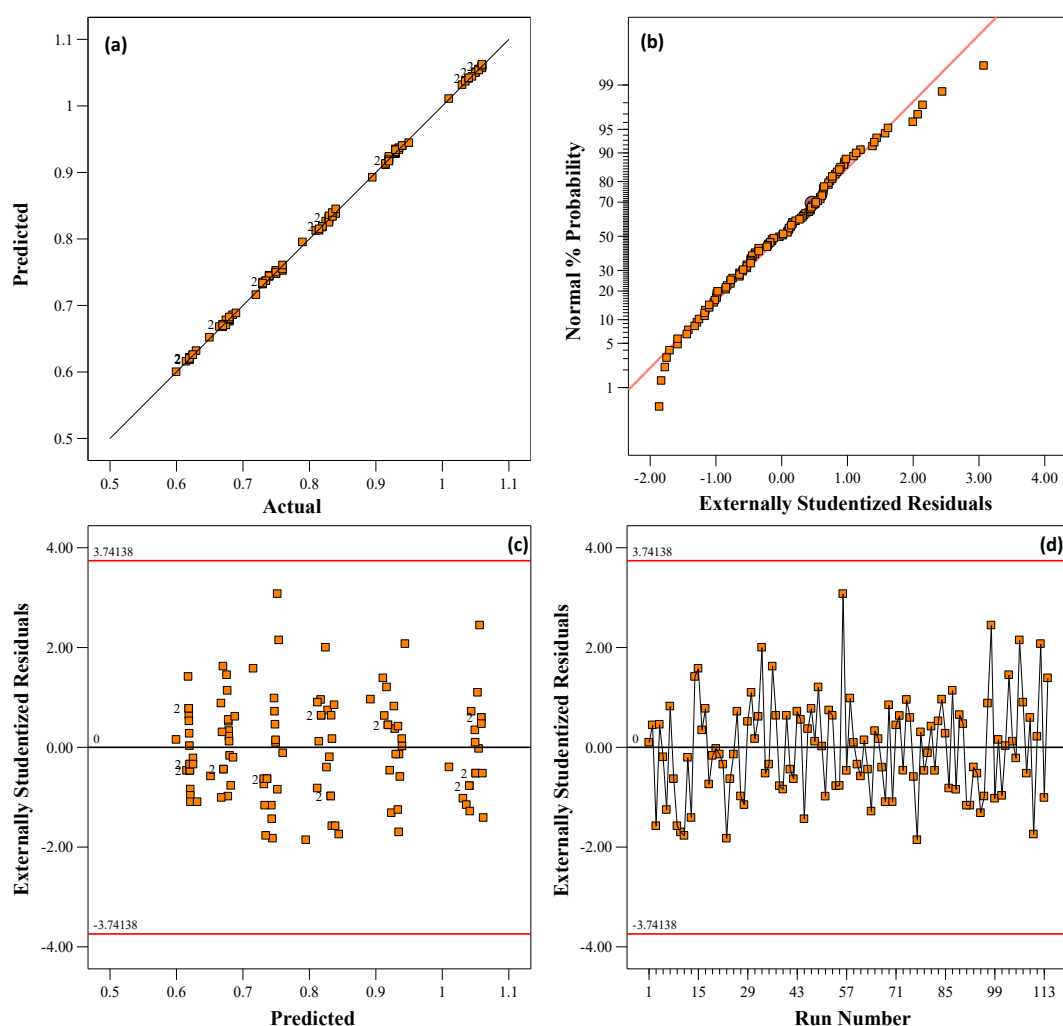


Figure E.2. Diagnostic plots for the cubic model of viscosity.

Table E.3. ANOVA results for the viscosity cubic model.

Source	Sum of Squares	df	Mean Square	p-value	F-value	Significance
Model	2.47	57	0.0433	< 1.0E-04	3620.76	Significant
Fluid-A	0.0108	18	0.0006	< 1.0E-04	50.3	
Temperature-B	2.4	1	2.4	< 1.0E-04	2.01E+05	
AB	0.001	18	0.0001	< 1.0E-04	4.57	
B ²	0.0487	1	0.0487	< 1.0E-04	4074.61	
AB ²	0.0004	18	0	0.0405	1.86	

B ³	0.0003	1	0.0003	< 1.0E-04	24.72
Residual	0.0007	56	0		
Mean	0.8057		R ²	0.9997	
Std. Dev.	0.003456		Predicted R ²	0.9987	
PRESS	0.00328		Adjusted R ²	0.9995	
C.V. %	0.4267		Adeq Precision	188.51	

Table E.4. Coefficients of the cubic viscosity model for various fluid samples.

Sample	c	d	e	Sample	c	d	e
DW	1.75275	0.049824	0.000714	MWCNTs/AIN (60:40)	1.8085	0.051442	0.000732
Ag	1.82303	0.05091	0.000714	MWCNTs/AIN (80:20)	1.81725	0.05246	0.00075
AIN	1.81743	0.051264	0.000725	MWCNTs/Ag (20:80)	1.81668	0.05086	0.000721
MWCNTs	1.78728	0.050721	0.000725	MWCNTs/Ag (40:60)	1.79564	0.050371	0.000718
Ag/AIN (20:80)	1.80514	0.050364	0.000711	MWCNTs/Ag (60:40)	1.8085	0.051442	0.000732
Ag/AIN (40:60)	1.8	0.049607	0.000696	MWCNTs/Ag (80:20)	1.83493	0.053299	0.000761
Ag/AIN (60:40)	1.81075	0.05001	0.0007	MWCNTs/Ag/AIN (20:20:60)	1.7876	0.048853	0.000686
Ag/AIN (80:20)	1.78232	0.048767	0.000686	MWCNTs/Ag/AIN (20:40:40)	1.78257	0.047949	0.000668
MWCNTs/AIN (20:80)	1.86325	0.054689	0.000778	MWCNTs/Ag/AIN (20:60:20)	1.77332	0.047139	0.000657
MWCNTs/AIN (40:60)	1.8333	0.052924	0.000756				

E.3 Density

As the data presented in Table E.5, the model exhibited an R² value of 0.9997, indicating that it explained 99.97% of the variance in the density data, which demonstrated an excellent fit. The Adjusted R² of 0.9993 supported this, showing that the model remained robust even after accounting for the number of predictors. Additionally, the Predicted R² of 0.9985 suggested that the model had strong predictive power when applied to new data. The Std. Dev. was very low at 7.46248e-05, indicating minimal deviation between observed and predicted values. Furthermore, the C.V.% was 0.00749, signifying the high precision and reliability of the model. The Adequate Precision ratio of 203.42, which measures the signal-to-noise ratio, confirmed that the model provided an adequate signal for navigating the design space. The diagnostic plots provided further insights into the model's performance, as shown in Fig. E.3. The diagnostic plots provided significant insights into the model's performance. The Predicted vs. Actual plot demonstrated a strong linear relationship between the predicted and actual density values, with the points aligning almost perfectly along the diagonal. This alignment confirmed the high R² value, indicating that the model's predictions closely matched the observed data. Similarly, the Normal Probability plot of the externally studentized residuals showed that the residuals followed a normal distribution, as the points closely followed the straight line. This observation suggested that the errors were normally distributed, validating one of the key assumptions of ANOVA.

Further examination of the model through the Externally Studentized Residuals vs. Predicted plot revealed no patterns in the residuals, indicating that the model was well-specified without signs of heteroscedasticity. Additionally, the Externally Studentized Residuals vs. Run Number plot displayed a random distribution of residuals throughout the sequence of data collection, which suggested the absence of time-related trends or autocorrelations that could introduce bias. Taken together, these analyses supported the conclusion that the developed model was both statistically significant and highly predictive, accurately estimating the density of the fluids studied across different temperatures.

Table E.5. ANOVA results for the cubic model of Density.

Source	Sum of Squares (SOS)	df	Mean Square	p-value	F-value	Significance
Model	0.001	57	0	< 1.0E-04	3016.56	Significant
Fluid-A	0	18	2.48E-06	< 1.0E-04	445.15	
Temperature-B	0.0009	1	0.0009	< 1.0E-04	1.62E+05	
AB	1.29E-07	18	7.15E-09	0.2335	1.28	
B ²	0	1	0	< 1.0E-04	2017.26	
AB ²	7.76E-08	18	4.31E-09	0.7199	0.774	
B ³	1.96E-07	1	1.96E-07	< 1.0E-04	35.22	
Residual	3.12E-07	56	5.57E-09			
Std. Dev.	7.46248e-05		R ²	0.9997		
C.V. %	0.00749		Predicted R ²	0.9985		
PRESS	1.38872e-06		Adjusted R ²	0.9993		
Mean	0.99597		Adeq Precision	203.42		

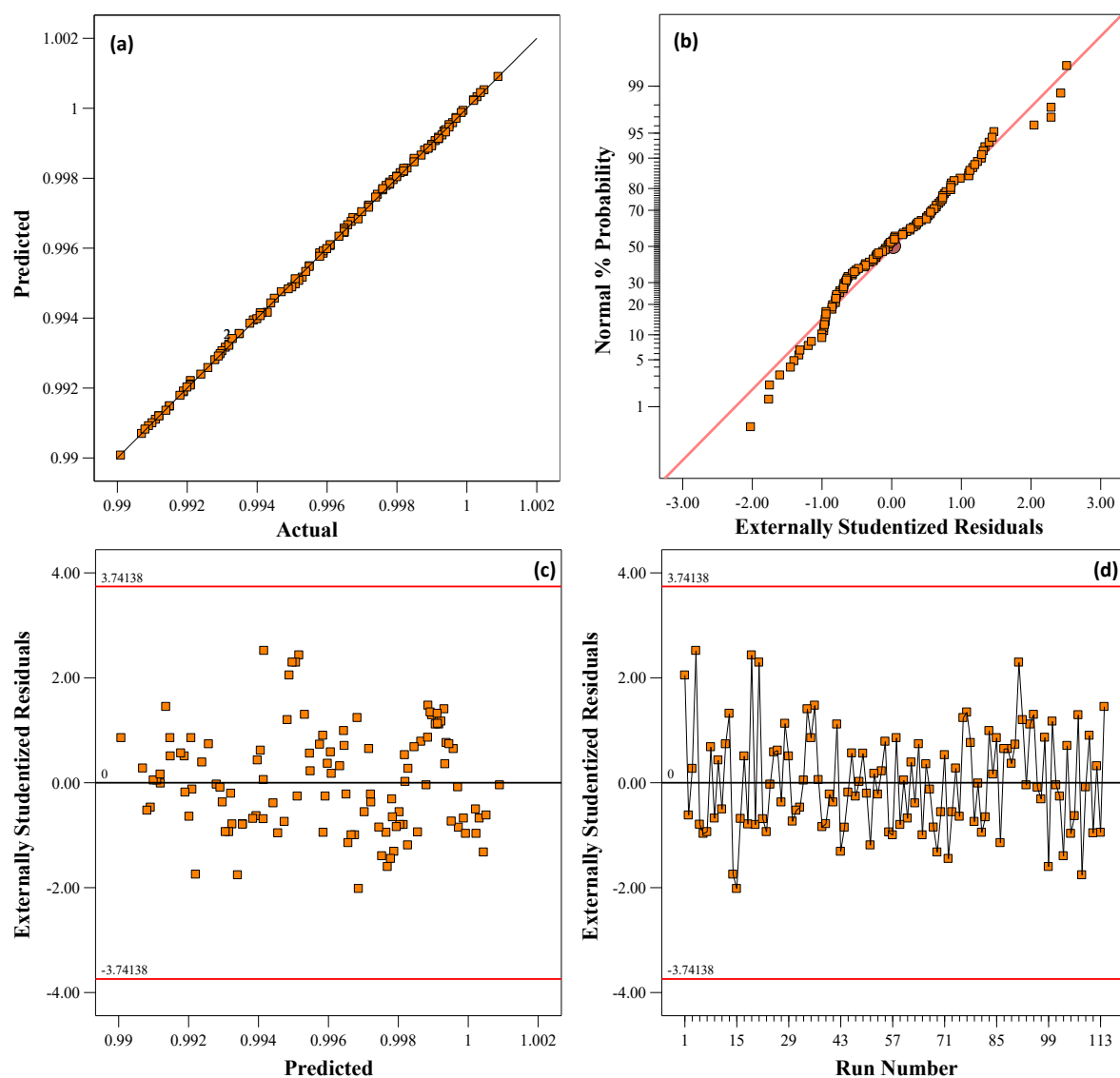


Figure E.3. Model validation plots for density: (a) parity plot, (b) normal probability plot, (c) externally studentized residuals vs predicted values, and (d) externally studentized residuals vs run order.

Table E.6. Density coefficient values for different fluid samples.

Sample	f	g	h	Sample	f	g	h
DW	0.996447	0.000361	0.000016	MWCNTs/AlN (60:40)	0.997718	0.000324	0.000015
Ag	1.00107	0.000227	0.000014	MWCNTs/AlN (80:20)	0.997318	0.000345	0.000015
AlN	0.998428	0.000301	0.000015	MWCNTs/Ag (20:80)	0.999938	0.000276	0.000015
MWCNTs	0.997257	0.000347	0.000015	MWCNTs/Ag (40:60)	0.999629	0.000282	0.000015
Ag/AlN (20:80)	0.998875	0.000299	0.000015	MWCNTs/Ag (60:40)	0.99841	0.000319	0.000015
Ag/AlN (40:60)	0.99872	0.000321	0.000015	MWCNTs/Ag (80:20)	0.998854	0.000274	0.000014
Ag/AlN (60:40)	0.999666	0.000284	0.000015	MWCNTs/Ag/AlN (20:20:60)	0.998667	0.000298	0.000015
Ag/AlN (80:20)	0.999699	0.000295	0.000015	MWCNTs/Ag/AlN (20:40:40)	0.998728	0.000317	0.000015
MWCNTs/AlN (20:80)	0.997973	0.00032	0.000015	MWCNTs/Ag/AlN (20:60:20)	0.999512	0.000287	0.000015
MWCNTs/AlN (40:60)	0.997873	0.00032	0.000015				