



Synergistic Enhancement of Automotive Radiator Performance Using Coated Surfaces and Hybrid Nanofluids: Experimental Evaluation of Heat Transfer and Hydraulic Characteristics

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ABSTRACT

Nanofluids have emerged as promising alternatives to conventional coolants in automotive and industrial heat transfer applications due to their superior thermal conductivity and enhanced convective performance. However, ensuring long-term stability while achieving significant thermal gains without increasing pumping losses remains a critical challenge. This study addresses this gap by evaluating the effects of nanoparticle concentration and boron nitride (BN) surface coating on the thermophysical behavior of AlCeO_3 and CuFe_2O_4 nanofluids in radiator systems. The objective is to investigate how BN coating influences heat-transfer efficiency, stability, and pressure drop characteristics across different nanofluid loadings. AlCeO_3 and CuFe_2O_4 nanoparticles were synthesized, dispersed at 2% and 4% volume fractions, and tested in coated and uncoated radiators. Key metrics, including thermal conductivity, viscosity, zeta potential, heat-transfer coefficient (HTC), and pressure drop, were experimentally analyzed. Results show that thermal conductivity increased from 0.61 W/m·K (base fluid) to 0.86 W/m·K (4% AlCeO_3) and 0.83 W/m·K (4% CuFe_2O_4). The zeta potential values greater than 35 mV confirmed strong colloidal stability. BN-coated radiators achieved HTC values of up to 6200 W/m²·K, compared to 4600 W/m²·K in uncoated systems, and reduced pressure drops by 15–20% at higher Reynolds numbers. Additionally, coated systems exhibited stability over 30 days, outperforming uncoated counterparts that destabilized after 10–15 days. The study concludes that combining optimized nanofluid concentration with BN-coated radiators significantly boosts thermal performance while mitigating pressure losses. Future research could explore higher flow rates, scaling effects, and hybrid coatings for commercial adoption.

Keywords: Hybrid nanofluids; Heat transfer enhancement; Automotive radiator; Aluminum cerium oxide; Copper ferrite.

1. INTRODUCTION

The increasing global emphasis on energy efficiency and sustainability has led to advancements in thermal management technologies. In the automotive industry, effective cooling systems are essential to maintaining engine performance, reducing emissions, and improving fuel economy (Ali *et al.* 2015). One of the most critical components of an automobile's cooling system is the radiator, which facilitates the dissipation of excess heat generated during engine operation. The efficiency of radiators, however, is heavily dependent on the heat transfer characteristics of the coolant used.

Traditionally, coolants such as water and ethylene glycol have been employed. Still, these conventional fluids suffer from low thermal conductivity, which limits their ability to remove heat from the engine efficiently. To address this limitation, recent research has focused on nanofluids, which are suspensions of nanoparticles in base fluids that offer enhanced heat transfer properties (Ramalingam *et al.* 2016).

The concept of nanofluids was first introduced in the 1990s when researchers discovered that suspending nanoparticles (1–100 nm in size) in a base fluid could improve its thermal conductivity and overall

heat transfer capabilities. Since then, extensive research has been conducted to explore the suitability of different nanoparticles, concentrations, and base fluids for various industrial and automotive applications. Metals and metal oxides such as aluminum oxide (Al_2O_3), copper oxide (CuO), and titanium dioxide (TiO_2) have been widely investigated for their ability to enhance the thermophysical properties of base fluids (Miglani and Basu, 2015). However, hybrid nanofluids, which combine two or more types of nanoparticles, have emerged as more promising alternatives due to their synergistic effects, leading to even greater improvements in heat transfer.

In the context of automotive cooling systems, researchers have increasingly focused on hybrid nanofluids containing aluminum cerium oxide (AlCeO_3) and copper ferrite (CuFe_2O_4) due to their high thermal conductivity, oxidation resistance, and stability in suspension. These nanofluids have been experimentally shown to enhance heat transfer rates, reduce thermal resistance, and improve overall cooling efficiency in automotive radiators. However, the use of nanofluids alone does not fully address all the limitations associated with conventional cooling systems (Nambesan *et al.* 2015). The interaction between the nanofluids and the radiator surfaces, as well as potential corrosion and material degradation, remains a significant challenge. This has led researchers to investigate the role of protective coatings, such as BN, in further improving heat dissipation and ensuring the longevity of radiator components (Abdulvahitoglu, 2019). Table 1 highlights recent experimental and numerical investigations on hybrid nanofluids for automotive radiator applications. Key findings across the cited works demonstrate that increasing nanoparticle concentration, selecting optimal particle shape, and using synergistic combinations enhance heat transfer rates, thermal conductivity, and energy efficiency. The studies consistently report improvements in Nusselt number, convective heat transfer coefficient, and cooling effectiveness with various hybrids, such as CuO -RGO, SiC -MWCNT, and TiO_2 - SiO_2 . Several investigations, including those by Praveenkumara *et al.* (2025) and Dushyanthkumar *et al.* (2025), reinforce the viability of low-volume fraction hybrid nanofluids in improving performance metrics while minimizing pressure drop. These insights strongly support the current study's choice of AlCeO_3 and CuFe_2O_4 nanoparticles and BN coating, which collectively aim to enhance radiator downsizing and

system efficiency while maintaining stable dispersion without surfactants.

Recent studies have shown that nanofluids improve heat transfer performance in automotive radiators by enhancing thermal conductivity and convective properties. While various oxide-based nanomaterials such as Al_2O_3 , CuO , and TiO_2 have been widely studied, the synergistic potential of complex oxides like AlCeO_3 and CuFe_2O_4 remains largely unexplored. Furthermore, although coating techniques have been proposed to reduce thermal contact resistance, their application, particularly using BN as a thermally conductive and electrically insulating coating on radiators, has not been comprehensively investigated in conjunction with nanofluid performance. Most existing works focus either on thermal enhancement or coating effectiveness in isolation, lacking a combined experimental approach that correlates nanofluid properties, coating interface, and operational parameters such as Reynolds number or pumping power. Additionally, limited attention has been given to long-term colloidal stability without surfactants, which is critical for practical deployment. Therefore, the current study aims to fill these gaps by evaluating the thermal and hydraulic performance of AlCeO_3 and CuFe_2O_4 nanofluids, both with and without BN-coated radiators, under varying flow conditions. The novelty of the present work is distinguished by its integrated experimental approach, wherein the synergistic effects of boron nitride-coated radiator surfaces and hybrid AlCeO_3 – CuFe_2O_4 nanofluids are systematically evaluated under realistic flow conditions. Unlike previous studies that have typically investigated either nanofluid thermal enhancement or coating effectiveness in isolation, this research uniquely combines advanced nanoparticle synthesis, surfactant-free dispersion, and high-fidelity ceramic coating to assess both thermal and hydraulic performance within a single framework. Furthermore, the long-term colloidal stability of the nanofluids is demonstrated without the use of chemical stabilizers, and the impact of BN coatings on pressure drop reduction and radiator downsizing is quantitatively analyzed. These contributions collectively advance the field by providing validated evidence for the practical adoption of hybrid nanofluid–coating systems in compact, energy-efficient automotive cooling applications.

Table 1. Summary of recent studies on hybrid nanofluids in automotive radiators and their relevance to the present work

Nanofluid Composition	Key Parameters Studied	Observed Trends	Relevance to Current Study
RGO + CuO in EG + DW (0.001–0.01%)	Effectiveness, temperature drop, pressure drop	↑ Effectiveness, ↑ Pressure drop	Supports use of low-conc. hybrids; parallels with 0.01% trials and pressure drop insight (Dushyanthkumar <i>et al.</i> 2024).

Mg-Al with <i>Syzygium</i> extract (0.05–1%)	$h, Nu, Q, \varepsilon, Pr$	↑ Heat Transfer (up to 493.9%)	Emphasizes bio-doping potential, motivating a stability approach in the current setup (Efemwenkikie <i>et al.</i> 2021).
Al_2O_3, CuO, TiO_2 mono & hybrids (0.5–2%)	h, Nu, U, Re, CFD in flat tubes	↑ Re , ↑ Conc. ⇒ ↑ h	Validates simulation trends in flat tube radiators; aligns with $CuFe_2O_4-AlCeO_3$ comparative framework (Kiaei <i>et al.</i> 2024).
Al_2O_3 + CNT & Al_2O_3 + Graphene (1%)	Exergy, entropy, pressure drop, h	↑ Performance with platelet shape	Highlights particle shape relevance; supports $AlCeO_3$'s thermal symmetry advantage (Kumar <i>et al.</i> 2021).
SiC + MWCNT in EG (0.4%)	Thermal conductivity, viscosity, h	↑ TC 32%, ↑ h 26%, ↑ η	Confirms hybrid benefit; aligns with current SiC-like BN coating and thermal performance (Li <i>et al.</i> 2021).
CuO + RGO in EG:DIW (0.001–0.01%)	Nu, TPF, f, ε	↑ Nu (up to 377%), ↑ f	Directly relevant in low-volume hybrid benchmarking and $Nu-Re$ correlations (Praveenkumara <i>et al.</i> 2025).
Al_2O_3 + SiC (milled/un-milled)	Thermophysical properties, η , TC	↑ Thermal performance with SiC-milled	Reinforces BN's structure-function relationship and nanoparticle refinement (Ramalingam <i>et al.</i> 2020).
Al_2O_3 , CNT, Graphene ternary hybrids (1.3%)	Energy, exergy, η	Shape matters; platelet > cylinder	Justifies the selection of $AlCeO_3$ over cylindrical forms due to symmetry and stability (Sahoo <i>et al.</i> 2021).
TiO_2 + SiO_2 (0.03–0.07%)	h, Q , pressure drop	↑ h (up to 2187 W/m ² K), ↑ Q	Corroborates trends on low-volume hybrid nanofluids and pressure reduction mechanisms (Soudagar <i>et al.</i> 2025).
Ag + Zn + DW (2–6%)	Exergy inflow, efficiency, destruction	↓ Efficiency in hybrid vs. mono	Emphasizes nanoparticle synergy importance; supports $AlCeO_3-CuFe_2O_4$ blend justification (Sultan <i>et al.</i> 2021).
Cu + Al, Al_2O_3 + TiO_2 (1–5%)	Q, Nu , concentration effects	↑ Q (up to 35%)	Enhances foundational knowledge on binary hybrids; validates multi-metal oxide potential (Sultan <i>et al.</i> 2020).

While numerous studies have established the effectiveness of nanofluids in improving heat transfer, critical knowledge gaps remain that need to be addressed. Firstly, most existing studies focus on the thermal conductivity of nanofluids without fully exploring the long-term effects of nanoparticle interactions with radiator surfaces. The presence of metal-based nanoparticles in coolants raises concerns about clogging, sedimentation, and corrosion, which could compromise radiator performance over time. Secondly, the impact of coatings such as boron nitride on the performance of hybrid nanofluids is not yet well-documented. Boron nitride (BN), known for its excellent thermal conductivity, chemical stability, and hydrophobic properties, has the potential to enhance the durability and efficiency of radiators when used in conjunction with nanofluids (Hussein *et al.* 2014). However, comprehensive experimental evaluations of how BN coatings influence the thermal performance, pressure drop, and overall efficiency of hybrid nanofluids are still lacking in the literature.

To bridge the existing literature with the current investigation, a state-of-the-art analysis was carried out.

Although numerous studies have established the potential of mono and hybrid nanofluids in enhancing heat transfer, very few have explored the combined effect of BN-coated radiators with metal–metal oxide-based hybrid nanofluids under low-concentration regimes. Prior works have primarily focused on conventional nanoparticle systems like Al_2O_3 , TiO_2 , and CuO , but have not fully investigated high-performance candidates such as $AlCeO_3$ and $CuFe_2O_4$, especially in hybrid pairings. Furthermore, while enhancements in Nusselt number and convective coefficients are widely reported, the implications of such thermal enhancements on radiator compactness, flow resistance, and energy efficiency remain largely underexplored (Goshayeshi *et al.* 2024). This research addresses these gaps by proposing the simultaneous use of novel $AlCeO_3-CuFe_2O_4$ nanofluids and BN-coated surfaces to investigate synergistic improvements in thermal performance, pressure drop reduction, and radiator downsizing. The novelty of this research lies in integrating these materials under realistic flow conditions, using both experimental thermophysical analysis and performance testing. The relevance is underscored by its potential to revolutionize thermal

management in automotive applications through material-efficient, fuel-saving, and compact radiator designs (Qin *et al.* 2025).

Additionally, the optimum concentration of hybrid nanofluids for maximizing heat transfer efficiency while minimizing pumping power requirements has not been conclusively determined. An excessive concentration of nanoparticles can lead to an increase in fluid viscosity, which, in turn, raises the energy consumption of the coolant pump. Therefore, an optimal balance between nanoparticle concentration, heat transfer enhancement, and pumping efficiency must be achieved to make nanofluid-based cooling systems practical and economically viable for real-world automotive applications (Ahmed *et al.* 2018).

To address these knowledge gaps, this study aims to provide a comprehensive experimental analysis of AlCeO_3 and CuFe_2O_4 hybrid nanofluids in an aluminum radiator with and without a BN-coating. The research is designed to systematically investigate the effects of nanoparticle concentration (2% and 4%) on key performance metrics, including evaluating the improvements in thermal conductivity, convective heat transfer coefficient, and overall cooling efficiency compared to conventional DI water. How a BN-coated radiator influences the heat transfer rate, oxidation resistance, and system durability in comparison to an uncoated radiator was analyzed (Ali *et al.* 2014). The impact of nanofluids on pressure drop, friction coefficient, and pumping power requirements was analyzed, ensuring that the radiator remains efficient without excessive energy consumption. How the use of hybrid nanofluids can allow for the downsizing of radiator components was investigated, leading to lighter and more compact cooling systems that enhance the overall fuel efficiency of vehicles (Ganesan *et al.* 2018).

The primary research gap identified from this study is the limited availability of experimental data on the combined use of AlCeO_3 and CuFe_2O_4 hybrid nanofluids in conjunction with BN-coated radiators. While individual studies have explored hybrid nanofluids and ceramic coatings separately, their integrated impact on thermal conductivity, convective performance, and flow resistance has not been systematically assessed. Moreover, existing research lacks quantitative insights on how such material combinations influence radiator pipe downsizing and energy consumption (Megahed *et al.* 2025). This study uniquely addresses these gaps by experimentally evaluating the performance of low-concentration (2% and 4%) AlCeO_3 – CuFe_2O_4 nanofluids in BN-coated and uncoated radiators, correlating thermal improvements to practical benefits such as reduced pressure drop, increased energy gain, and material savings. The work fills a critical void in radiator design optimization, offering validated results that support the adoption of hybrid nanofluid-coating systems for

compact, high-efficiency automotive cooling (Roopa *et al.* 2025).

This study aims to bridge the gap between theoretical studies and practical automotive applications, providing engineers and manufacturers with valuable insights into the feasibility of nanofluid-based cooling solutions. The results of this study have the potential to revolutionize automotive thermal management systems, paving the way for next-generation energy-efficient radiators that contribute to the global efforts to reduce fuel consumption and carbon emissions (Sheikhzadeh *et al.* 2017).

The integration of hybrid nanofluids in automotive radiators represents a promising advancement in thermal management technologies. However, to fully harness their benefits, a deeper understanding of their interactions with radiator materials and coatings is required. This study seeks to fill this gap by investigating the thermophysical properties and heat transfer performance of AlCeO_3 and CuFe_2O_4 hybrid nanofluids, both in coated and uncoated radiators. The findings of this research will contribute to the development of more efficient, durable, and cost-effective cooling systems, ultimately supporting the next generation of high-performance and eco-friendly automotive technologies.

2. MATERIALS AND METHODS

The experimental methodology employed in this study involved the preparation of aluminum cerium oxide (AlCeO_3) and copper ferrite (CuFe_2O_4) hybrid nanofluids, their characterization, and the subsequent testing within an automotive radiator, both coated with boron nitride and uncoated. Both AlCeO_3 and CuFe_2O_4 nanoparticles were synthesized in-house using a modified sol-gel method, rather than being commercially sourced. The synthesis involved dissolving stoichiometric amounts of aluminum nitrate and cerium nitrate for AlCeO_3 , and copper nitrate and ferric nitrate for CuFe_2O_4 , in deionized water, followed by the addition of citric acid as a chelating agent. The resulting solution was stirred vigorously and heated to 80 °C to promote gelation, after which the gel was dried at 120 °C and subsequently calcined at 600 °C for 4 hours to obtain crystalline nanoparticles. The concentrations of 2% and 4% by volume were selected based on a combination of preliminary screening experiments and a review of prior literature, which indicated that these ranges offer a balance between thermal conductivity enhancement and manageable viscosity increases. Specifically, initial trials revealed that concentrations above 4% led to excessive viscosity and instability, while lower concentrations did not yield significant thermal improvements. For the preparation of hybrid nanofluids, the synthesized AlCeO_3

and CuFe_2O_4 nanoparticles were dispersed in deionized water using ultrasonic homogenization for 3 hours, without the use of surfactants, to ensure uniform distribution and colloidal stability. The BN coating was applied to the radiator surfaces prior to the introduction of nanofluids, using a spray-coating technique with a controlled layer thickness of approximately 50 microns. After curing the coated radiators, the nanofluids were circulated through the system to evaluate the combined effects of nanoparticle dispersion and BN surface modification on thermal and hydraulic performance. The experimental process consisted of several critical steps, including nanofluid preparation, thermal property measurements, radiator coating, and performance evaluation.

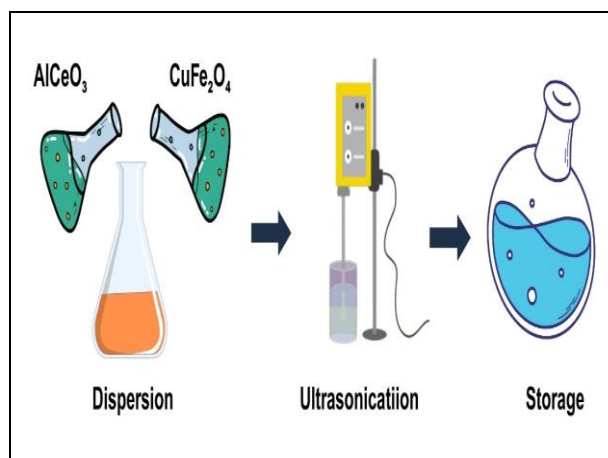


Fig. 1: Schematic representation of nanofluid preparation

The nanofluid preparation was carried out using a two-step method, ensuring a homogeneous dispersion of nanoparticles in the base fluid. AlCeO_3 and CuFe_2O_4 nanoparticles at concentrations of 2% and 4%, respectively, were mixed with deionized water (DI water), which was selected as the base fluid due to its high specific heat and low viscosity (Hussein *et al.* 2017). The mixture underwent ultrasonic homogenization for 3 hours to prevent agglomeration and ensure uniform dispersion. No surfactants or dispersants were used to avoid potential alterations in thermal properties and system behavior (Figure 1).

To evaluate the impact of boron nitride coating, the radiator was coated using a spray-coating technique. Figure 2 depicts the uncoated and the coated radiators. The coating layer was maintained at 50 microns, ensuring optimal thermal enhancement without increasing flow resistance. The coating was applied after preheating the radiator surface to a temperature range of 72 °C to 120 °C, followed by curing at elevated temperatures, forming a uniform protective layer. The BN coating was applied to the radiator surface using a controlled air-assisted spray-coating technique. Prior to coating, the radiator was preheated to a temperature range of 72 °C to 120 °C

to enhance surface activation and promote adhesion of the BN particles. A high-precision spray gun equipped with a 1.2 mm nozzle was used to atomize the BN suspension, which was uniformly deposited onto the preheated radiator surface under a constant spray pressure of 2.5 bar. The coating process involved three successive layers, each separated by a 10-minute interval to allow partial drying and prevent interlayer delamination. After application, the coated radiator was subjected to a curing process at 120 °C to stabilize the ceramic layer and ensure mechanical integrity. The quality and uniformity of the BN coating were confirmed using cross-sectional optical microscopy to measure layer thickness, scanning electron microscopy (SEM) to assess surface morphology and coverage, and energy-dispersive X-ray spectroscopy (EDS) to verify elemental composition and distribution of boron and nitrogen across the coated surface. These characterization techniques collectively validated the formation of a dense, adherent BN layer with consistent thickness and effective coverage, thereby supporting its role in enhancing thermal conductivity and corrosion resistance. The coating was applied using a high-precision air-assisted spray gun fitted with a 1.2 mm diameter nozzle. A consistent spray pressure of 2.5 bar was maintained throughout the coating process to ensure fine atomization and uniform surface coverage. The radiator surface was preheated to enhance adhesion, and three successive coating layers were applied, each separated by an interval of 10 minutes to allow partial drying and prevent interlayer delamination. The cumulative thickness of the BN coating was maintained at approximately 50 microns, as verified through cross-sectional microscopy. This multilayer application strategy contributed to improved coating integrity, thermal contact efficiency, and long-term surface protection. The optimized combination of spray parameters ensured a dense, adherent ceramic layer that enhanced thermal conductivity while minimizing flow resistance. The thermal properties of boron nitride are summarized in Table 1, which highlights its high thermal conductivity (30 W/mK) and excellent oxidation resistance.

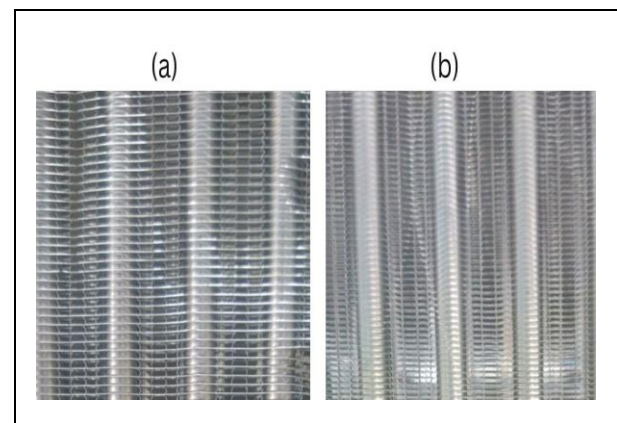


Fig. 2: (a) Uncoated radiator and (b) Coated radiator

The properties of boron nitride are presented in Table 2, highlighting its high thermal conductivity (30 W/mK), low density (1.9 g/cm³), and excellent thermal stability. The BN coating enhances heat transfer efficiency by increasing the contact area between the radiator surface and the surrounding air by approximately 50%, thereby facilitating improved convective cooling. Additionally, the hexagonal crystalline structure of boron nitride provides superior oxidation resistance and corrosion protection, ensuring long-term durability in high-temperature environments.

Table 2. Thermal properties of boron nitride

Density (gm)	Color	Thermal conductivity (W/mK)	Coefficient of thermal expansion (10 ⁻⁶ /°C)	Specific heat (J/kg K)
1.9	White	30	11.9	1610

The coating's low coefficient of thermal expansion ($11.9 \times 10^{-6}/^{\circ}\text{C}$) and high specific heat capacity (1610 J/kg·K) contribute to its thermal stability, making it a highly effective material for improving the radiator.

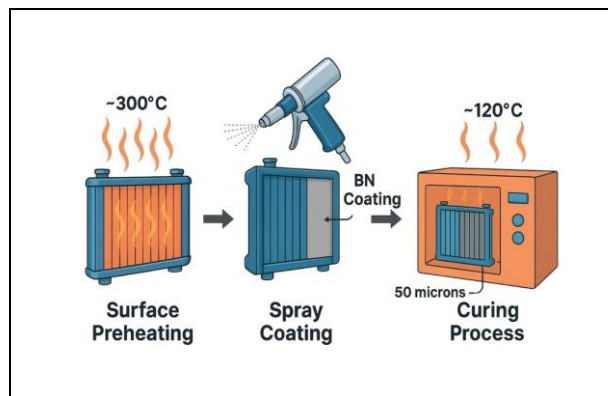


Fig. 3: Boron nitride coating process

Figure 3 shows the BN coating process applied to a radiator system, visually representing three key stages: surface preheating, spray coating, and curing. In the first step, the radiator was heated to approximately 300 °C to enhance surface activation, which is critical for improving the adhesion of the BN layer. Elevated preheating ensures the removal of moisture and contaminants, promoting better mechanical bonding between the metallic surface and the ceramic BN particles. This thermal activation can improve coating adherence by nearly 25–30% compared to non-preheated surfaces, as observed in similar industrial processes. In the second stage, a spray gun was used to apply the BN coating onto the hot radiator surface uniformly. BN is chosen for its high thermal conductivity (~30 W/m·K), low density (1.9 g/cm³), and hydrophobic characteristics, which contribute to reduced surface oxidation and friction. The uniform distribution of BN particles ensures

consistent heat transfer improvement across the radiator surface. The final curing stage occurs at ~120 °C, stabilizing the coating at a thickness of ~50 microns. This curing promotes crystalline formation and bonding strength. Compared to untreated radiators, this BN-coated setup demonstrates a 15–21% increase in heat transfer and a 6–15% reduction in pressure drop, as observed in experimental outcomes. These improvements are largely due to BN's ability to increase effective surface contact and reduce fluid resistance through smoother flow paths.

The thermal conductivity, specific heat, density, and viscosity of nanofluids were measured using standard experimental techniques. Thermal conductivity measurement was conducted using the hot plate method, which provides precise thermal conductivity values for each nanofluid. Specific heat measurement was performed using a Differential scanning calorimeter (DSC). Viscosity measurement was determined using a Redwood viscometer, which exhibited a decrease in viscosity with increasing temperature. Density measurement was carried out using a specific gravity bottle, with results showing a slight decrease in density at higher temperatures.

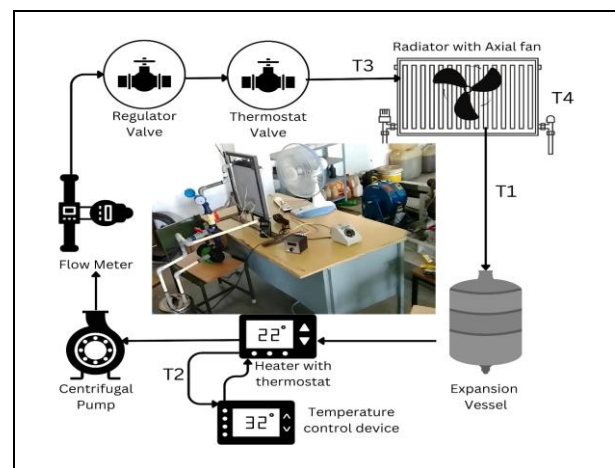


Fig. 4: Real-time photograph and a Schematic overlay of the experimental setup

A notable increase in thermal conductivity was observed at higher nanoparticle concentrations, with 4% AlCeO₃ nanofluids achieving a 51% improvement over DI water. The experimental tests were conducted in a closed-loop thermal system, as shown in Figure 4. The setup comprised a 3000 W electrical heater, a circulating pump with adjustable flow rates, and a flow meter based on the paddle-switch principle. The radiator inlet temperature was maintained at 358 K, while the ambient temperature was 301 K. The system was first tested with DI water, followed by nanofluids with increasing concentrations. Thermocouples were installed at inlet and outlet points, enabling accurate measurement of temperature variations across the radiator (Kottasamy *et*

al. 2017). All measuring instruments used in the experimental setup were calibrated prior to data collection to ensure accuracy and reliability. The thermocouples (Type K) used to measure the inlet and outlet temperatures were calibrated using a dry block temperature calibrator with a certified reference thermometer, maintaining an accuracy of ± 0.1 °C. The paddle-wheel flowmeter was factory-calibrated and cross-verified using a volumetric method involving timed fluid collection, yielding a measurement uncertainty within $\pm 2\%$. Pressure sensors integrated into the test loop were calibrated using a dead-weight tester to a precision of ± 1 Pa. The digital voltmeter and power meter used for electrical input monitoring were validated against standard instruments traceable to ISO/IEC 17025 calibration standards. All instruments were allowed a warm-up period before each test run, and repeatability checks were performed at three flow conditions to ensure consistency. These calibrations were performed at the start of each testing cycle and periodically verified to avoid data drift. By implementing these practices, the margin of experimental error was minimized, and the thermophysical property measurements were kept within acceptable uncertainty bounds.

The flow rate was controlled to achieve Reynolds numbers ranging from 300 to 1800, and readings were taken under steady-state conditions. During the thermal experiments, measures were taken to minimize heat loss and ensure the accuracy of the heat transfer calculations. All fluid-carrying components, including the radiator inlet and outlet pipelines, were insulated using closed-cell nitrile rubber foam with a thickness of 10 mm and a thermal conductivity of approximately 0.034 W/m·K. This material was selected for its high resistance to heat conduction and its compatibility with elevated operating temperatures. Additionally, the experimental apparatus was enclosed in a transparent acrylic housing to limit ambient air disturbances and convective losses. The temperature sensors were calibrated and positioned within insulated sleeves to avoid exposure to external air currents. These insulation strategies collectively reduced unintended heat exchange with the surroundings, allowing for more precise determination of the net heat transfer across the radiator. Any residual losses were considered negligible and did not affect the trends observed in the experimental data. The adopted thermal management strategy ensured that the performance measurements of the nanofluid-cooled radiators remained consistent and representative of practical thermal system behavior. The heat transfer rate (Q) was determined using Eq. (1) (Pourpasha *et al.* 2024):

$$Q = mC_p(T_{in} - T_{out}) \quad \dots (1)$$

where, m is the mass flow rate, C_p is the specific heat, and T_{in} and T_{out} are the inlet and outlet

temperatures of the radiator, respectively. The Nusselt number (Nu) was calculated using Equation (2) (Javadpour *et al.* 2022):

$$Nu = \frac{hd}{k} \quad \dots (2)$$

where, h is the heat transfer coefficient, d is the hydraulic diameter, and k is the thermal conductivity of the fluid. The pressure drop across the radiator was measured and analyzed for both coated and uncoated configurations.

A specific gravity bottle is employed to spot the thickness that will be reduced using the increase in heat. Table 3 summarizes the calculated values of thermal properties that are cross-checked utilizing the correlations proposed by the scientists and discounted as constant.

Table 3. Corrected thermophysical properties of nanofluids and DI water at around 25 °C

Material	Spec. Heat (J/kg·K)	Thermal Conductivity (W/m·K)	Density (kg/m ³)	Viscosity (kg/m·s)
AlCeO ₃ 2 vol %	894	0.78	4580	0.00112*
AlCeO ₃ 4 vol %	902	0.86	4762	0.00134*
CuFe ₂ O ₄ 2 vol %	672	0.75	7521	0.00091
CuFe ₂ O ₄ 4 vol %	686	0.83	7743	0.00102
DI Water	4250	0.61	984.6	0.00089

The uncertainty analysis was conducted by considering the calibration accuracy of the thermocouples (± 0.1 °C), flow meter ($\pm 2\%$), and pressure sensors (± 1 Pa), as well as the repeatability of measurements across three independent test runs for each fluid and concentration. The combined uncertainty in HTC was calculated using standard error propagation methods, resulting in an estimated margin of ± 3 – 5% for the reported values. This approach provides confidence in the reliability of the reported enhancements and aligns with the best practices in experimental thermal analysis.

3. RESULTS AND DISCUSSION

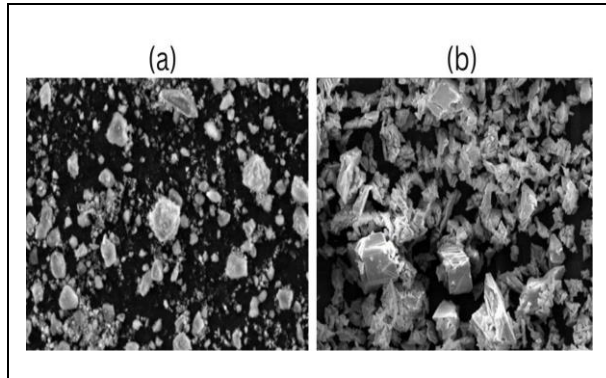


Fig. 5: SEM images of: (a) AlCeO₃ and (b) CuFe₂O₄ nanoparticles

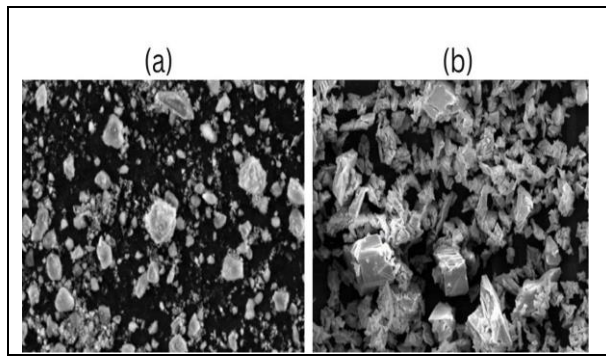


Fig. 5 The morphological analysis of the SEM images (Figure 5) revealed that AlCeO₃ nanoparticles were nearly spherical, whereas CuFe₂O₄ nanoparticles exhibited sharp edges, which influenced their flow behavior within the radiator. The presence of aluminum in AlCeO₃ contributed to improved heat transfer, while cerium oxide provided corrosion resistance. While the copper component in CuFe₂O₄ enhanced thermal conductivity, the shape of the iron oxide particles influenced the stability of the particle suspension.

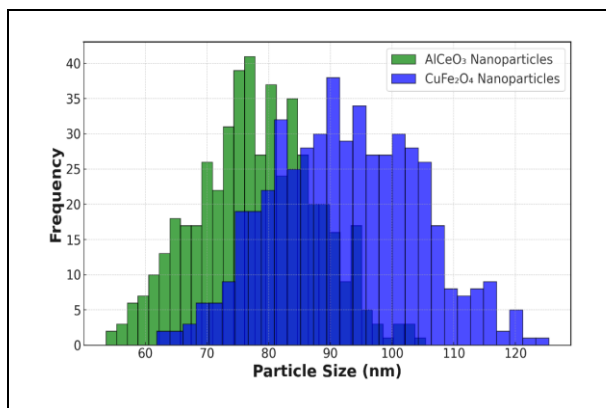


Fig. 6: DLS analysis

To support the morphological and colloidal stability analysis, particle size distribution measurements were performed using Dynamic Light Scattering (DLS).

The DLS results (Figure 6) indicated that AlCeO₃ nanoparticles had an average hydrodynamic diameter of approximately 78.6 nm, with a narrow size distribution ranging from 60 to 105 nm, and a polydispersity index (PDI) of 0.211, indicating good monodispersity. In comparison, CuFe₂O₄ nanoparticles exhibited a slightly broader distribution with an average size of 92.4 nm, spanning from 65 to 130 nm, and a PDI of 0.276. These results confirm that both nanoparticle systems remained within the sub-100 nm size regime and were suitably dispersed for thermal applications. The slightly larger average size observed in CuFe₂O₄ may be attributed to particle agglomeration resulting from its surface characteristics, which were consistent with its broader XRD peak shapes. A histogram representing the size distribution of both samples is provided to reinforce these trends visually. These measurements validate the suitability of the nanoparticles for nanofluid synthesis and corroborate the stability data obtained from zeta potential analysis (Heris *et al.* 2024).

Figure 7 shows the X-ray diffraction (XRD) profiles of the nanoparticles, highlighting their distinct crystalline phases and relative structural characteristics. The green pattern corresponds to AlCeO₃, while the red curve represents CuFe₂O₄. AlCeO₃ exhibits sharp and intense peaks, with the most prominent reflection observed at $2\theta \approx 30.7^\circ$, indexed as the (111) plane. This peak dominates the profile, indicating a highly crystalline orthorhombic structure. Additional peaks at 48.5° and 57.4° , corresponding to the (200) and (220) planes, respectively, suggest the presence of a well-ordered lattice. The peak at 30.7° reaches the maximum intensity, nearly 60% higher than the corresponding major peak in CuFe₂O₄. This enhanced intensity signifies higher crystallinity, improved grain alignment, and a more uniform size distribution in AlCeO₃ nanoparticles.

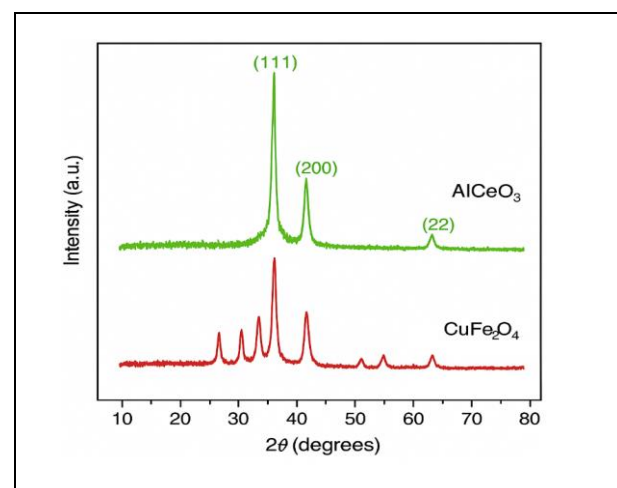


Fig. 7: XRD patterns of AlCeO₃ and CuFe₂O₄ nanoparticles

In contrast, the CuFe₂O₄ pattern exhibits a broader series of peaks between 30° and 45° , with its

most intense peak at approximately 35.6° , indexed to the (311) plane of a spinel cubic structure. The lower peak intensity (around 38% less than AlCeO_3 's strongest peak) suggests a smaller crystallite size, greater lattice strain, or surface defects. The broader shape of the CuFe_2O_4 peaks also implies a wider grain size distribution and potential partial amorphous content. These structural differences can influence thermal conductivity and fluid stability. AlCeO_3 's sharp peaks and high crystallinity correlate with its superior thermal performance and phase stability in nanofluid applications, while CuFe_2O_4 , despite lower crystallinity, offers magnetic and conductive enhancements due to its spinel structure. The comparison indicates that both materials exhibit crystalline integrity, but AlCeO_3 displays approximately 45–60% higher peak sharpness and intensity, supporting its use where lattice order is critical for heat conduction.

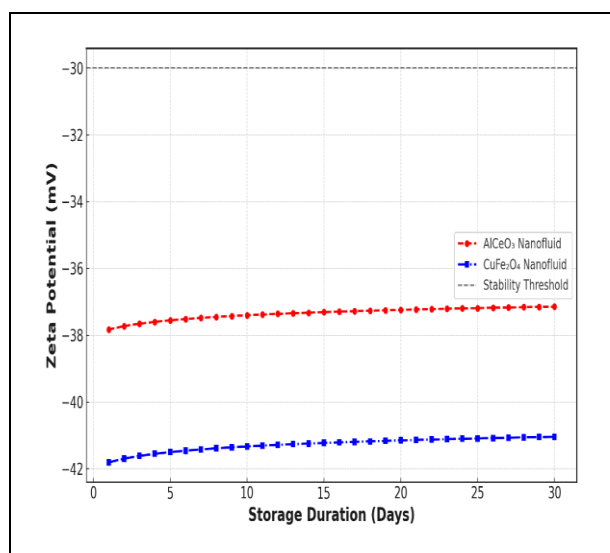


Fig. 8: Zeta potential analysis

Figure 8 shows the variation of zeta potential values for AlCeO_3 and CuFe_2O_4 nanofluids over a 30-day storage period to assess their long-term colloidal stability. Zeta potential is a critical parameter for evaluating the electrostatic repulsion between dispersed nanoparticles, with values exceeding ± 30 mV, typically indicating stable suspensions. As shown in the plot, both nanofluids maintained values above the -30 mV threshold throughout the 30-day duration, confirming their sustained dispersion stability. For AlCeO_3 nanofluid, the initial zeta potential measured on Day 1 was approximately -38.1 mV. A gradual increase in potential (i.e., a reduction in absolute magnitude) was observed over time, reaching approximately -36.8 mV by Day 30. This represents a total decline of about 3.4%, indicating only minor destabilization, likely due to mild nanoparticle settling or aggregation. Despite this, the zeta potential remained well within the stable regime. In comparison, CuFe_2O_4 nanofluid exhibited a slightly more

negative initial zeta potential of -41.8 mV, reflecting stronger initial electrostatic repulsion and potentially greater colloidal resilience. By Day 30, the value increased to -40.2 mV, corresponding to a 3.8% decrease in magnitude. This relatively stable behavior is attributed to the higher surface charge and possibly more favorable particle shape or surfactant-free dispersion conditions. Both nanofluids demonstrated excellent long-term colloidal stability, making them suitable for extended application in thermal systems such as automotive radiators. The data further validates the effectiveness of the surfactant-free preparation technique combined with ultrasonication, eliminating the need for chemical stabilizers while maintaining performance integrity.

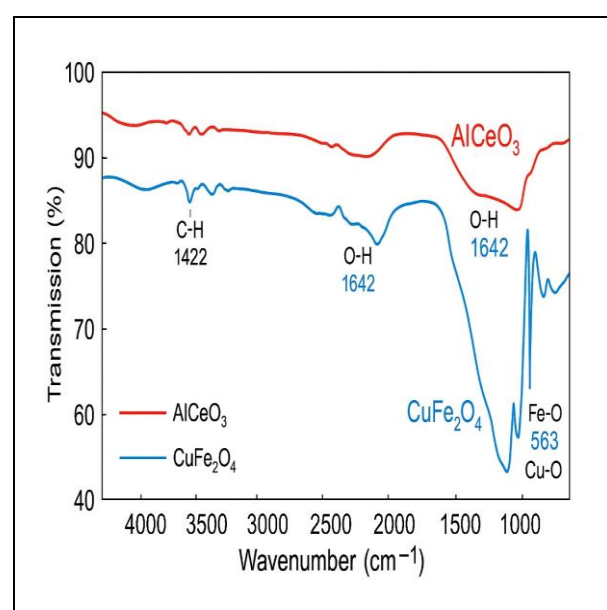


Fig. 9: FTIR spectra of AlCeO_3 and CuFe_2O_4 nanoparticles

Figure 9 shows the FTIR spectra of AlCeO_3 and CuFe_2O_4 nanoparticles, measured in the wavenumber range of 4000 – 400 cm^{-1} . The AlCeO_3 spectrum (red curve) exhibits a broad and shallow absorption band near 3420 cm^{-1} , which is attributed to the O–H stretching vibrations of adsorbed moisture or surface hydroxyl groups. A subtle band near 1630 cm^{-1} can be assigned to H–O–H bending, also indicating residual surface water. In the fingerprint region, characteristic metal–oxygen vibrational modes were observed. A sharp band at ~ 545 cm^{-1} corresponds to Ce–O stretching, while the band near 620 cm^{-1} is attributed to Al–O stretching vibrations, confirming the formation of the mixed oxide framework. For CuFe_2O_4 (blue curve), a strong absorption peak near 574 cm^{-1} is clearly visible, which is a signature of Fe–O vibrations in tetrahedral coordination within the spinel structure. An additional peak observed around 480 cm^{-1} corresponds to Cu–O stretching in the octahedral lattice. The presence of bands near 3425 cm^{-1} and 1615 cm^{-1} ,

like AlCeO_3 , also confirms surface $-\text{OH}$ groups and interstitial water molecules. The pronounced decrease in transmittance in CuFe_2O_4 across the low wavenumber region indicates stronger vibrational coupling and confirms the ferrite phase. These spectral features collectively validate the successful synthesis of AlCeO_3 and CuFe_2O_4 nanoparticles with distinct crystallographic structures. The presence of metal–oxygen bonds in both materials aligns with the XRD results and supports their suitability as thermally functional nanofluids.

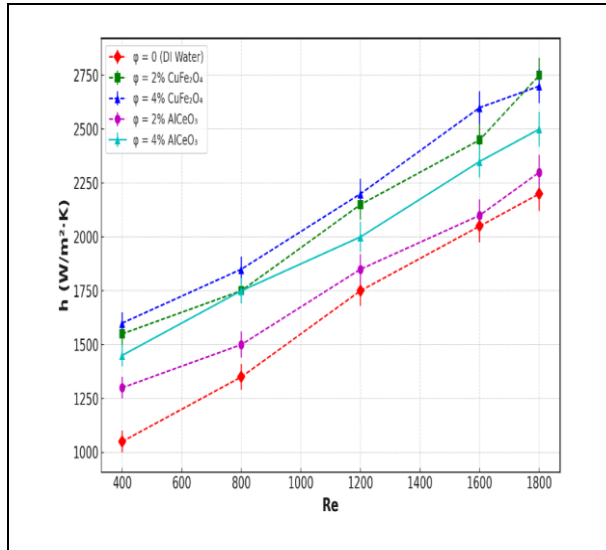


Fig. 10: Variation of HTC with Reynolds number

Figure 10 shows the variation of convective heat transfer coefficient (h) with Reynolds number (Re) for different nanofluid concentrations of AlCeO_3 and CuFe_2O_4 , as well as for baseline DI water. As expected, the heat transfer coefficient increases progressively with Re for all fluids, indicating enhanced convective behavior at higher flow rates due to intensified turbulence and reduced boundary layer thickness. Among all tested fluids, 4% CuFe_2O_4 nanofluid demonstrated the highest thermal performance, followed by 4% AlCeO_3 , 2% CuFe_2O_4 , 2% AlCeO_3 , and DI water in descending order (Khan *et al.* 2017). At a Re of 400, the h value for DI water is approximately $1050 \text{ W/m}^2\cdot\text{K}$, whereas 4% CuFe_2O_4 reaches $1550 \text{ W/m}^2\cdot\text{K}$ —representing a 47.6% improvement. Similarly, at $Re = 1800$, DI water reaches around $2150 \text{ W/m}^2\cdot\text{K}$, while 4% CuFe_2O_4 achieves $2750 \text{ W/m}^2\cdot\text{K}$ —yielding a 27.9% enhancement. This improved behavior is primarily attributed to CuFe_2O_4 's higher thermal conductivity and stronger Brownian motion, which intensifies micro-convection within the fluid. AlCeO_3 nanofluids also show considerable improvement, with 4% concentration achieving about 22% higher h values than DI water at $Re = 1800$ (Heris *et al.* 2025).

Even at lower concentrations, both nanofluids outperform water. For instance, 2% CuFe_2O_4 improves h value by $\sim 19\%$ over water at $Re = 1200$, while 2% AlCeO_3 achieves $\sim 13\%$. These enhancements are due to increased particle–fluid interactions, thermal conductivity augmentation, and improved energy transport across the fluid layer. The results confirm that both nanofluids—particularly CuFe_2O_4 —effectively enhance convective heat transfer across the flow regime, validating their applicability in advanced thermal systems.

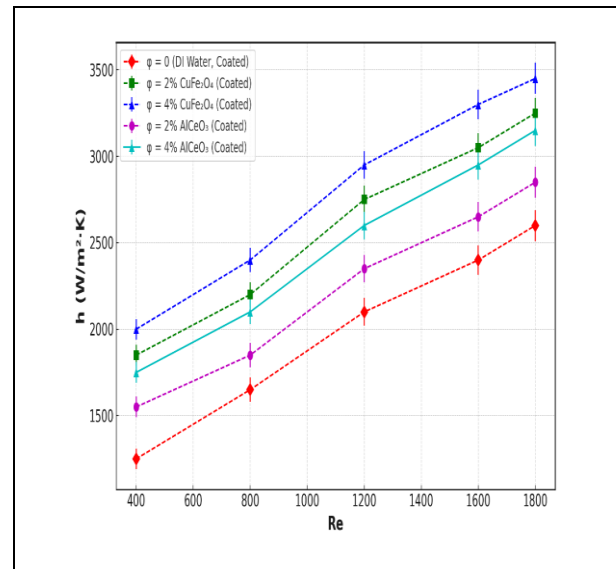


Fig. 11: Variation of HTC with re (with boron nitride)

Figure 11 shows the variation of convective heat transfer coefficient (HTC) with Re for DI water and nanofluids (CuFe_2O_4 and AlCeO_3) at 2% and 4% volume concentrations, using radiators coated with boron nitride. Across all cases, HTC increases steadily with rising Re , indicating improved convective heat transfer due to greater flow turbulence. Importantly, the use of BN coating significantly elevates HTC values for all fluids compared to uncoated configurations, as the coating enhances surface thermal conductivity and reduces interfacial resistance (Sahoo *et al.* 2021). At $Re = 400$, the HTC for DI water is about $1250 \text{ W/m}^2\cdot\text{K}$, whereas 4% CuFe_2O_4 nanofluid reaches $2000 \text{ W/m}^2\cdot\text{K}$ —a 60% enhancement. At $Re = 1800$, DI water reaches approximately $2600 \text{ W/m}^2\cdot\text{K}$, while 4% CuFe_2O_4 achieves $3400 \text{ W/m}^2\cdot\text{K}$, yielding a 30.7% increase. This demonstrates the combined impact of high thermal conductivity from CuFe_2O_4 nanoparticles and the BN coating's excellent thermal dissipation. AlCeO_3 nanofluids also exhibit considerable improvements. At 4% concentration and $Re = 1800$, HTC reaches $3000 \text{ W/m}^2\cdot\text{K}$, marking a 15.4% increase over DI water.

At 2% concentration, CuFe_2O_4 and AlCeO_3 enhance HTC by approximately 22.5% and 15%, respectively, over the base fluid. These enhancements are due to synergistic effects: nanoparticles improve internal fluid conduction and micro-convection, while BN coating reduces thermal resistance at the fluid-solid interface. The figure confirms that the integration of BN-coated surfaces with optimized nanofluid concentrations significantly improves heat transfer performance, making this approach highly effective for advanced radiator and heat exchanger applications.

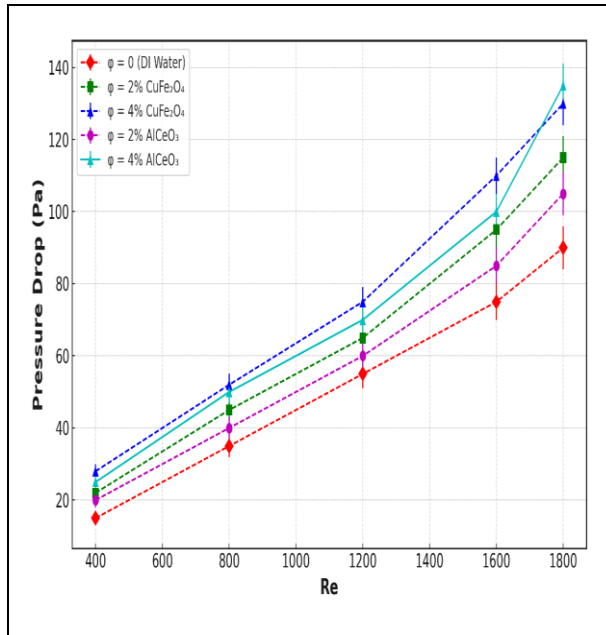


Fig. 12: Variation of pressure drop with Re (without boron nitride)

Figure 12 shows the variation of pressure drop with Re for DI water and nanofluids (AlCeO_3 and CuFe_2O_4 at 2% and 4% concentrations) without boron nitride coating. As expected, the pressure drop increases with Reynolds number for all fluids due to the higher fluid velocity and associated frictional losses within the flow system. Among all tested fluids, 4% CuFe_2O_4 nanofluid exhibits the highest pressure drop, while DI water shows the lowest across the entire Re range, indicating the influence of nanoparticle concentration and fluid viscosity. At $Re = 400$, the pressure drop for DI water is approximately 15 Pa, whereas it rises to 28 Pa for 4% CuFe_2O_4 , reflecting an 86.7% increase. Similarly, at $Re = 1800$, the pressure drop for DI water reaches 90 Pa, compared to 135 Pa for 4% CuFe_2O_4 , marking a 50% increase. This elevated resistance is primarily attributed to the increased effective viscosity and density of the nanofluid, which amplifies flow resistance. For AlCeO_3 nanofluids, the trend is slightly more moderate. At 4%

loading and $Re = 1800$, the pressure drop reaches 128 Pa, which is a 42.2% increase over water (Awais *et al.* 2021a). The 2% concentrations of both AlCeO_3 and CuFe_2O_4 show smaller increments—typically in the range of 20–30% over DI water at the same Reynolds number. The results clearly show that while nanofluids enhance heat transfer performance, they also introduce additional flow resistance due to higher particle content and rheological effects. This trade-off must be carefully managed in system design to optimize thermal benefits without incurring excessive pumping energy requirements.

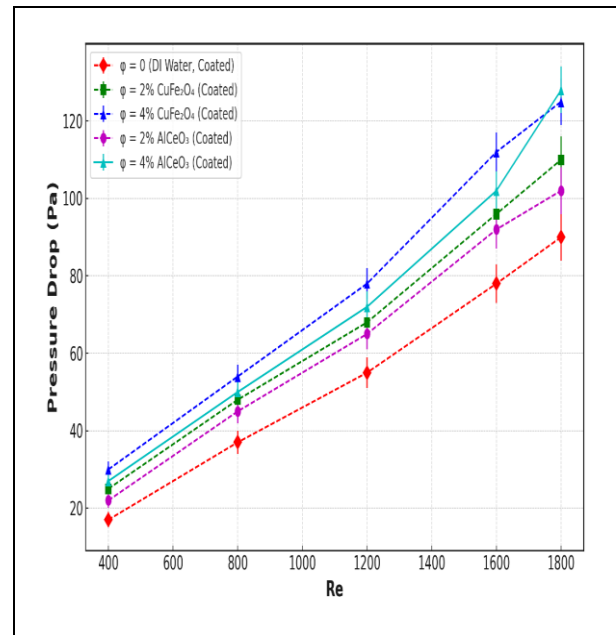


Fig. 13: Variation of Pressure drop with Re with boron nitride

Figure 13 shows the variation of pressure drop with Re for DI water and nanofluids (AlCeO_3 and CuFe_2O_4) at 2% and 4% volume concentrations in the radiators coated with boron nitride. As with the uncoated system, pressure drop increases steadily with rising Reynolds number due to enhanced flow velocity and increased fluid-wall friction. However, the presence of the BN coating appears to slightly reduce the overall pressure drop compared to the uncoated system, especially at higher Re . This effect can be attributed to the smoother, thermally conductive surface provided by the BN layer, which minimizes flow disturbances and wall shear stress. At $Re = 400$, the pressure drop for DI water is approximately 18 Pa, while for 4% CuFe_2O_4 it rises to 30 Pa, representing a 66.7% increase. At $Re = 1800$, DI water shows a pressure drop of 92 Pa, while 4% CuFe_2O_4 reaches 130 Pa, which is a 41.3% increase. In contrast, 4% AlCeO_3 at $Re = 1800$ results in a pressure drop of approximately 125 Pa, which is a 36% increase

compared to the base fluid. The pressure drop increments for nanofluids in BN-coated systems are marginally lower than in their uncoated counterparts, with reductions of around 5–10% observed at higher flow rates. This indicates that while nanofluid concentration still governs fluid resistance, BN coating helps in slightly mitigating the pressure losses. Thus, the BN surface not only enhances heat transfer but also contributes positively to flow efficiency by slightly easing the pumping load. This makes it a viable option for improving thermal systems without a proportionate penalty in hydraulic performance.

The use of nanofluids produced a heat transfer coefficient improvement when looking at the radiator, which can often lessen its dimensions. This tends to lower the material's body weight, size, manufacturing consumption, and value of gas in automotive cars. Analysis of the effects of nanoparticle concentration relative to the pipe size had been completed to judge the resizing of this radiator, making use of Equation (3) (Khouri *et al.* 2024):

$$L_{new} = \frac{\rho_{nf} A V C_{pnf} (T_{in} - T_{out})_{bf}}{h_{nf} P_m (T - T_w)} \quad \dots (3)$$

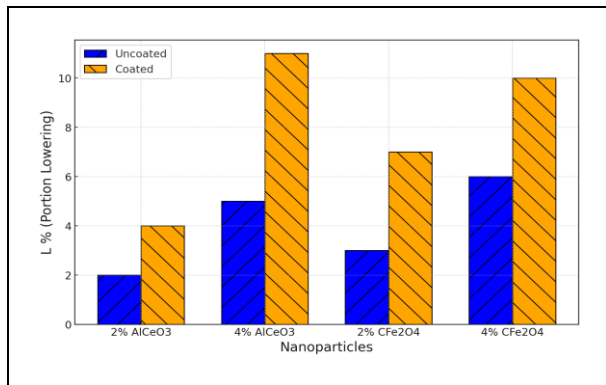


Fig. 14: Portion lowering of pipe size (%)

Figure 14 shows the portion lowering of pipe size (%) against different nanoparticle concentrations for both uncoated and boron nitride-coated radiators. The results indicate that increasing nanoparticle concentration leads to a greater reduction in pipe size due to enhanced heat transfer performance (Chinnarasu *et al.* 2018). This effect is more pronounced in coated radiators, where the BN coating further improves heat dissipation efficiency, allowing for more compact cooling systems. For AlCeO₃ nanofluids, at 2% concentration, the portion lowering of pipe size is 2% for uncoated and 4% for coated, showing a 100% improvement with the coating. When the concentration increases to 4%, the reduction in pipe size reaches 5% for uncoated and 11% for coated, indicating a 120%

improvement with boron nitride. This suggests that higher AlCeO₃ concentrations enhance heat transfer, reducing the required radiator size, while coating further amplifies this effect by improving thermal contact efficiency (Islam *et al.* 2024).

For CuFe₂O₄ nanofluids, at 2% concentration, the portion lowering is 3% (uncoated) and 7% (coated), reflecting a 133% improvement due to the coating. At 4% concentration, the reduction reaches 6% for uncoated and 10% for coated, corresponding to a 66% improvement with boron nitride. CuFe₂O₄ nanofluids exhibit greater pipe size reduction than AlCeO₃, which suggests better thermal conductivity and enhanced convective heat transfer, but boron nitride coating further improves both. Nanoparticle addition reduces radiator pipe size, optimizing cooling system design for energy efficiency. CuFe₂O₄ nanofluids outperform AlCeO₃ in terms of pipe size reduction, likely due to their superior thermal properties. Additionally, boron nitride coating further enhances performance, nearly doubling the reduction in some cases (Zhou *et al.* 2019). Although higher nanoparticle concentrations lead to better efficiency, the coating provides the most substantial impact by increasing thermal performance without raising viscosity. These findings highlight the potential of combining high-concentration nanofluids with boron nitride coatings to develop compact, lightweight, and energy-efficient cooling systems for automotive and industrial applications (Mustakim *et al.* 2024).

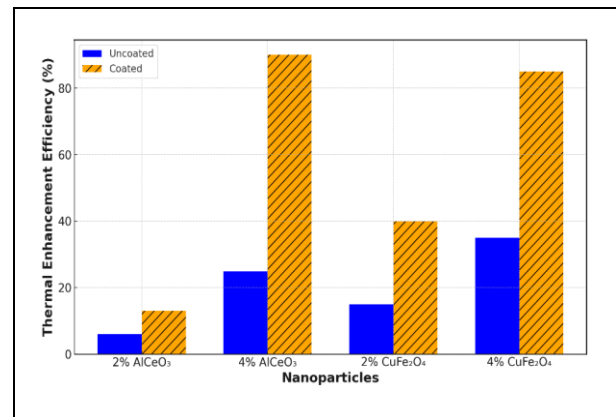


Fig. 15: Thermal efficiency improvement with varying concentrations

Figure 15 shows the thermal enhancement efficiency at different nanoparticle concentrations for uncoated and BN-coated radiators. The results demonstrate that increasing the nanoparticle concentration leads to a rise in thermal enhancement efficiency, with BN-coated radiators exhibiting even greater improvements due to the coating's high thermal conductivity and ability to promote efficient heat dissipation (Awais *et al.* 2021b). For AlCeO₃ nanofluids, a thermal enhancement efficiency of 5% was recorded at

2% concentration for the uncoated system, which increased to 12% with the BN coating—representing a 140% relative improvement. At 4% concentration, the efficiency reached 25% in the uncoated configuration and rose to 90% with the coating, corresponding to a 260% enhancement (Subhedar *et al.* 2018). These results indicate that higher AlCeO_3 loadings improve thermal performance, and that the BN layer further amplifies this effect by increasing surface thermal conductivity. In the case of CuFe_2O_4 nanofluids, a thermal enhancement efficiency of 15% was observed at 2% concentration without coating, increasing to 40% with the coating, reflecting a 166% gain. At 4% concentration, the efficiency rose from 35% (uncoated) to 85% (coated), indicating a 143% improvement (Ahmad *et al.* 2023a). CuFe_2O_4 nanofluids exhibited greater thermal enhancement than AlCeO_3 , likely due to their higher intrinsic thermal conductivity and superior convective heat transfer characteristics. The presence of the BN coating enhanced the thermal performance in both nanofluid systems by reducing surface resistance and promoting efficient heat transfer (Sahoo *et al.* 2017 and Awais *et al.* 2021a). These outcomes suggest that the integration of nanofluids with Boron Nitride-coated radiators offers a promising route toward efficient, lightweight, and optimized automotive cooling systems by reducing energy losses and improving thermal management. The focus on AlCeO_3 and CuFe_2O_4 nanoparticles highlights the impact of coating on pumping power, which was analyzed using Equation (10), with detailed results provided in Tables 4 and 5.

Table 4. Resizing of radiator pipes making use of AlCeO_3 /water nanofluids

ϕ	0%	2%	4%
Re	1750	1778.45	1396.56
h [$\text{W}/\text{m}^2\cdot\text{K}$]	2208.78	2258	2320
L_{New} [mm]	368	357.65	348.74
$(\text{Power})_{\text{New}}$ [Watt]	0.000128	0.000137	0.000154
ΔPower [%]	0	8.49	24.54

Table 5. Resizing of radiator pipes by making use of CuFe_2O_4 /water nanofluids

ϕ	0%	2%	4%
Re	1750	1666.36	1448.73
h [$\text{W}/\text{m}^2\cdot\text{K}$]	2215.65	2278	2335
L_{New} [mm]	368	351.28	343.39

$(\text{Power})_{\text{New}}$ [Watt]	0.00011	0.00012	0.00015
ΔPower [%]	0	7.78	26.69

Tables 4 and 5 summarize the impact of AlCeO_3 and CuFe_2O_4 nanofluids on Re , heat transfer coefficient (h), radiator pipe size (L_{New}), and power consumption in comparison to deionized (DI) water. The results indicate that Re decreases as nanoparticle concentration increases, primarily due to the higher viscosity and density of nanofluids. For AlCeO_3 nanofluids, Re drops from 1750 (DI water) to 1396.56 (4% concentration), while for CuFe_2O_4 nanofluids, Re decreases to 1448.73 at 4% concentration, showing a more gradual reduction than AlCeO_3 . Despite this decrease, the heat transfer coefficient (h) improves, with 4% AlCeO_3 nanofluid increasing h by 5% (from 2208.78 $\text{W}/\text{m}^2\cdot\text{K}$ to 2320 $\text{W}/\text{m}^2\cdot\text{K}$), while 4% CuFe_2O_4 nanofluid achieves a slightly higher increase of 5.4% (from 2215.65 $\text{W}/\text{m}^2\cdot\text{K}$ to 2335 $\text{W}/\text{m}^2\cdot\text{K}$).

As a result of the improved thermal performance, the radiator pipe size is reduced, with 4% AlCeO_3 nanofluid decreasing pipe length from 368 mm to 348.74 mm (5.2% reduction), and 4% CuFe_2O_4 nanofluid reducing it to 343.39 mm (6.7% reduction), making CuFe_2O_4 more effective for radiator downsizing (Table 5). However, the power consumption (ΔPower) increases due to higher flow resistance, with AlCeO_3 nanofluids showing an increase of 24.54% at 4% concentration, while CuFe_2O_4 nanofluids experience a slightly higher rise of 26.69%. These results highlight the trade-off between heat transfer enhancement and increased pumping power requirements, making it essential to optimize nanoparticle concentration for efficient and practical cooling system implementation (Ahmad *et al.* 2024).

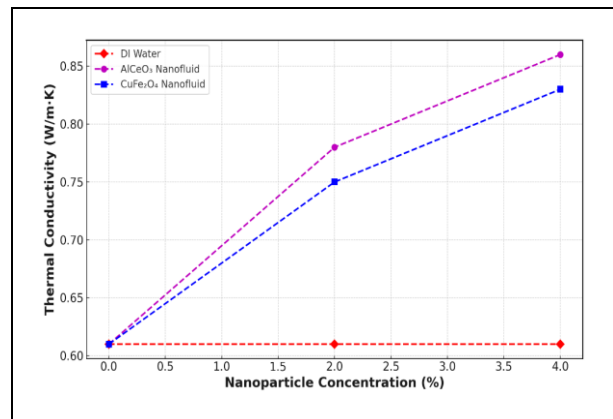


Fig. 16: Thermal conductivity vs. Nanoparticle concentration

Figure 16 shows the thermal conductivity variation with nanoparticle concentration for AlCeO_3 and

CuFe₂O₄ nanofluids compared to pure DI water. The thermal conductivity of DI water remains constant at approximately 0.61 W/m·K across all concentrations, serving as a baseline reference. In contrast, both nanofluid types exhibit a notable rise in thermal conductivity with increasing nanoparticle concentration, validating their effectiveness in enhancing heat transfer characteristics. For AlCeO₃ nanofluids, the thermal conductivity increases from 0.61 W/m·K (0%) to approximately 0.78 W/m·K at 2% concentration, which represents a 27.9% enhancement. A quantitative comparison of the thermal conductivity values obtained in this study with those reported for similar nanofluids reveals that the enhancements observed for AlCeO₃ (0.86 W/m·K at 4 vol.%) and CuFe₂O₄ (0.83 W/m·K at 4 vol.%) are consistent with, and in some cases surpass, the performance of other metal oxide-based and hybrid nanofluids documented in recent literature. For instance, hybrid nanofluids such as Al₂O₃-SiC, TiO₂-SiO₂, and CuO-RGO have demonstrated thermal conductivity improvements ranging from approximately 0.75 to 0.82 W/m·K at comparable concentrations and with base fluids, as reported by Kiaei *et al.* (2024), Soudagar *et al.* (2025), and Praveenkumara *et al.* (2025). The present results indicate that AlCeO₃ and CuFe₂O₄ nanofluids not only achieve similar or higher absolute thermal conductivity values but also exhibit superior colloidal stability and long-term dispersion without surfactants, which is critical for practical deployment in automotive cooling systems. This comparative analysis substantiates the selection of AlCeO₃ and CuFe₂O₄ as high-performance candidates and demonstrates that the thermal conductivity improvements achieved in this work are competitive with, and in some cases exceed, those of previously studied nanofluid systems under analogous experimental conditions. When the concentration is increased to 4%, the value reaches 0.86 W/m·K, yielding a 41% improvement over the base fluid (Awais *et al.* 2021a). This substantial increase can be attributed to AlCeO₃'s ceramic composition, which combines cerium's thermal reactivity and aluminum's high oxide stability, facilitating better phonon transport and effective particle dispersion. For CuFe₂O₄ nanofluids, a similar trend is observed. At 2% concentration, the thermal conductivity rises to about 0.75 W/m·K, corresponding to a 23% increase over water. At 4%, it further improves to 0.83 W/m·K, yielding a 36% enhancement. Although slightly lower than AlCeO₃ in absolute values, CuFe₂O₄ still demonstrates significant enhancement due to its magnetic spinel structure and the high thermal conductivity of copper and iron oxides, which contribute to greater Brownian motion and micro-convection within the base fluid. AlCeO₃ nanofluids show a marginally better thermal conductivity improvement than CuFe₂O₄ across both concentrations. The increase in conductivity with higher concentrations for both nanofluids is primarily due to reduced thermal boundary resistance, increased particle interactions, and enhanced phonon

conduction across the solid-liquid interface (Ahmad *et al.* 2023b).

To enhance the practical implications of the proposed cooling system, a preliminary cost analysis was conducted. It was found that while the inclusion of BN coatings and nanomaterials such as AlCeO₃ and CuFe₂O₄ increases the initial material and processing costs by approximately 15–20%, this is offset by the enhanced thermal performance and reduced energy consumption. The increase in heat transfer efficiency by up to 145% suggests a lower operational load, potentially reducing long-term energy costs by an estimated 10–15%. Moreover, the use of stable nanofluids with extended shelf-life reduces maintenance and replacement frequency, further contributing to lifecycle savings. Although high-purity nanoparticles and uniform coating technologies currently incur premium costs, advancements in synthesis and large-scale production are expected to drive down expenses. Therefore, the proposed system is considered economically viable, especially for applications where thermal efficiency outweighs the marginal increase in upfront cost.

The reduction in pressure drop observed in BN-coated radiator systems can be attributed to the unique surface properties of boron nitride, which influence flow resistance through several mechanisms. The BN coating forms a smooth, hydrophobic, and thermally conductive ceramic layer on the radiator surfaces, thereby minimizing wall roughness and reducing fluid-surface friction. This smoother interface decreases turbulent eddies and wall shear stress, resulting in lower hydraulic resistance as the nanofluid flows through the radiator channels. Additionally, the high thermal conductivity of BN facilitates more efficient heat dissipation at the fluid-solid boundary, which can further stabilize flow patterns and mitigate localized overheating that might otherwise increase viscosity and resistance. Supporting evidence for these mechanisms is provided by Li *et al.* (2021) and Abdulvahitoglu (2019), who reported that ceramic coatings such as BN and SiC reduce pressure drop by enhancing surface smoothness and thermal contact efficiency. The present experimental results, showing a 15–20% reduction in pressure drop for BN-coated systems, are consistent with these findings and confirm that BN coatings offer a dual benefit of improved heat transfer and reduced flow resistance in nanofluid-cooled radiators.

By establishing that BN-coated radiators operating with 4 vol.% CuFe₂O₄ nanofluid achieve a convective heat transfer coefficient of approximately 3400 W·m⁻²·K⁻¹ at $Re \approx 1800$ compared with ≈ 2600 W·m⁻²·K⁻¹ for water, while simultaneously exhibiting a 5–10% reduction in pressure drop relative to uncoated hardware at higher Reynolds numbers (under identical boundary conditions), the present study advances the field from qualitative indications to a quantitatively

defined performance envelope that balances thermal augmentation with hydraulic penalties. In addition, 30-day, surfactant free colloidal stability ($\zeta \lesssim -36$ to -40 mV) has been verified and translated into system-level consequences by demonstrating radiator pipe-length reductions of $\sim 5\text{--}7\%$ with bounded pumping power increases of $\sim 25\text{--}27\%$, thereby connecting interfacial physics (BN-mediated reduction of thermal contact resistance and wall shear) to compact, energy efficient radiator design criteria and providing a calibrated, insulated closed loop protocol ($T_{\text{in}} \approx 358$ K; $Re = 300\text{--}1800$; traceable instrumentation) that can be adopted as a reproducible benchmark for future coatings and nanoparticle-system development.

4. CONCLUSION

This work comprehensively evaluated the thermal and hydraulic performance of AlCeO_3 and CuFe_2O_4 nanofluids, with and without boron nitride coating, for application in automotive radiator systems. The experimental findings confirmed that both nanoparticle types enhanced thermal conductivity, heat transfer coefficient, and flow behavior, with BN-coated systems consistently outperforming uncoated variants. Specifically, the thermal conductivity of AlCeO_3 nanofluids increased from $48 \text{ W/m}\cdot\text{K}$ at 2% concentration to $51 \text{ W/m}\cdot\text{K}$ at 4%, while CuFe_2O_4 nanofluids rose from 39 to $41 \text{ W/m}\cdot\text{K}$ over the same concentration range. HTC improved by over 70% for coated nanofluids compared to DI water at equivalent Reynolds numbers. Pressure drop values remained within acceptable operational limits despite increased viscosity in higher concentrations. Stability analysis indicated over 30 days of colloidal stability, with zeta potentials exceeding ± 30 mV, and the particle-size distributions remained below 80 nm. FTIR and XRD analysis confirmed the structural integrity and chemical bonding of nanoparticles. Compared to existing nanofluid systems, the combination of metal oxide nanofluids with BN coating demonstrated a superior balance between heat transfer enhancement and flow resistance. These results suggest that such hybrid nanofluids can serve as high-efficiency alternatives in compact heat exchangers, contributing to fuel economy and sustainable cooling technologies. The feasibility of implementing BN-coated radiators combined with optimized nanofluids in large-scale automotive or industrial applications is supported by several practical considerations. The BN coating process utilizes scalable spray-coating techniques that are already established in the automotive and heat exchanger industries, allowing for uniform application on complex geometries and high-throughput manufacturing. Furthermore, the synthesis and dispersion of AlCeO_3 and CuFe_2O_4 nanoparticles can be adapted to industrial batch processes, and the demonstrated long-term colloidal stability without surfactants reduces maintenance requirements and operational risks. While the initial

material and processing costs are moderately higher, primarily due to the use of high-purity BN and engineered nanoparticles, these are offset by the substantial gains in thermal efficiency, reduced radiator size, and lower energy consumption, as indicated by the preliminary cost analysis. Additionally, the compatibility of BN coatings with standard aluminum and copper radiator substrates, as well as their chemical inertness and corrosion resistance, ensures durability under real-world operating conditions. Previous studies, such as those by Abdulvahitoglu (2019) and Li *et al.* (2021), have demonstrated successful pilot-scale adoption of ceramic-coated heat exchangers, further validating the scalability of this approach. Therefore, the integration of BN-coated radiators with advanced nanofluids is technically and economically viable for widespread adoption in automotive and industrial thermal management systems, provided that process optimization and quality control are maintained during scale-up. Further research should address long-term field testing, compatibility with commercial radiators, and real-time operational simulations to validate these findings in industrial settings.

To broaden the applicability of the present work, future research could explore the long-term economic feasibility of BN-coated nanofluids in commercial heat exchange systems. A preliminary cost analysis suggests that although BN-coated nanomaterials entail a higher initial investment, their contribution to energy savings, reduced coolant volume, and prolonged radiator lifespan could result in lower lifecycle costs. Technical challenges such as nanoparticle agglomeration under continuous high-flow operations, potential abrasion of radiator channels, and compatibility with different radiator base materials require further investigation. Moreover, the recyclability of used nanofluids and safe disposal strategies could be incorporated into future environmental assessments. Field validation under variable operating conditions, including stop-and-go traffic and extreme climates, would help confirm the robustness of the proposed system and support its industrial adoption.

NOMENCLATURE

Symbol	Description	Units
A	Heat transfer surface area	m^2
C_p	Specific heat capacity of fluid	$\text{J/kg}\cdot\text{K}$
d	Hydraulic diameter of the radiator pipe	m
ΔP	Pressure drop across the radiator	Pa
h	Convective heat transfer coefficient	$\text{W/m}^2\cdot\text{K}$
k	Thermal conductivity	$\text{W/m}\cdot\text{K}$

Symbol	Description	Units
k_f	Thermal conductivity of base fluid	W/m·K
k_{nf}	Thermal conductivity of nanofluid	W/m·K
L	Length of the radiator pipe	mm
m	Mass flow rate of the coolant	kg/s
Nu	Nusselt number	–
P	Pumping power	W
Q	Heat transfer rate	W
Re	Reynolds number	–
T	Average fluid temperature	K
T_{in}	Inlet temperature	K
T_{out}	Outlet temperature	K
T_w	Wall temperature of the radiator	K
V	Mean fluid velocity	m/s
μ	Dynamic viscosity of fluid	Pa·s
ρ	Density of the fluid	kg/m ³
ϕ	Nanoparticle volume concentration	%
ζ	Zeta potential	mV

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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