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Heat transfer performance enhancement of automotive radiators using AL2O3 and CuO nanofluid coolants: A comparative study

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Abstract

Background: Automotive radiators rely on the thermophysical properties of the circulating coolant to reject engine heat to the surrounding air, and conventional water-ethylene glycol mixtures possess comparatively low thermal conductivity, motivating research into nanoparticle-enhanced coolants, or nanofluids, as a means of improving heat rejection without increasing radiator size or weight.

Objective: This study evaluates the effect of dispersing Al2O3 and CuO nanoparticles, at volume concentrations of 0.1%, 0.3%, 0.5%, 1.0%, 1.5%, and 2.0%, in a 50:50 water-ethylene glycol base fluid on the overall heat transfer coefficient, heat transfer enhancement, and pumping power penalty of a simulated automotive radiator test loop.

Method: A simulated dataset, modelled on patterns reported in published experimental research on Al2O3 and CuO automotive radiator nanofluids, was used to evaluate overall heat transfer coefficient, Nusselt number, heat transfer enhancement, and pumping power penalty across thirty-six simulated test runs (six concentration levels, two nanoparticle types, three replicates). Data were analysed using descriptive statistics and one-way analysis of variance (ANOVA) in SPSS (version 27).

Key Results: Both nanofluids increased the overall heat transfer coefficient relative to the base fluid, with CuO/water-ethylene glycol nanofluid outperforming Al2O3/water-ethylene glycol at every tested concentration, achieving a maximum enhancement of approximately 30.4% at 1.5% volume concentration before performance plateaued at 2.0%. Pumping power penalty increased monotonically with concentration, reaching approximately 42.6% at 2.0% concentration for the CuO nanofluid, exceeding the corresponding heat transfer gain beyond approximately 1.5% concentration.

Conclusion: An optimal nanoparticle concentration window exists, approximately 0.5-1.5% by volume for the coolants tested, within which heat transfer enhancement meaningfully exceeds the associated pumping power penalty; beyond this window, viscosity-driven pumping costs erode the net thermal benefit, underscoring the importance of concentration optimisation rather than maximisation in nanofluid coolant design.

Keywords: Nanofluid, automotive radiator, heat transfer enhancement, Al2O3 nanoparticles, CuO nanoparticles, pumping power

Introduction

Automotive radiators serve the critical function of rejecting heat absorbed by the engine coolant to the surrounding atmosphere, maintaining engine operating temperature within a safe range and preventing thermal degradation of lubricants, seals, and engine components [1]. Conventional automotive coolants, typically a 50:50 mixture of water and ethylene glycol, are selected primarily for their favourable freezing-point depression and boiling-point elevation properties, but possess comparatively modest thermal conductivity relative to many engineering materials, fundamentally limiting the rate at which heat can be transferred from the coolant to the radiator tube wall [2].

Nanofluids, formed by dispersing nanometre-scale solid particles (typically metallic or metal-oxide) within a base fluid, have been extensively investigated as a means of enhancing the thermal conductivity, and consequently the convective heat transfer performance, of conventional coolants without requiring fundamental redesign of the cooling system [3]. Metal-oxide nanoparticles such as aluminium oxide (Al2O3) and copper oxide (CuO) are particularly common choices in automotive radiator research due to their comparative chemical stability, lower cost relative to metallic nanoparticles, and demonstrated compatibility with water-ethylene glycol base fluids across a range of operating temperatures [4].

A substantial body of experimental and numerical research has demonstrated that nanofluid coolants can increase the overall heat transfer coefficient of automotive radiators relative to the base fluid alone, with reported enhancements ranging from approximately 6% to over 100% depending on nanoparticle type, concentration, size, and flow conditions [5]. However, this enhancement is not without cost: the addition of nanoparticles increases the viscosity and, to a lesser extent, the density of the coolant, both of which increase the pressure drop across the radiator core and consequently the pumping power required to circulate the coolant at a given flow rate [6]. Several studies have noted that this pumping power penalty grows more rapidly than the corresponding heat transfer benefit at higher nanoparticle concentrations, implying the existence of a practically optimal concentration range beyond which further nanoparticle loading becomes counterproductive [7].

Despite the substantial number of published studies examining individual nanoparticle types or concentration ranges, comparatively few present a single, internally consistent dataset that jointly tracks heat transfer enhancement and pumping power penalty across a common concentration range for two contrasting nanoparticle types, in a form that directly supports identification of a practical optimal operating window. This gap limits the direct usability of existing findings for thermal system designers seeking a clear, application-oriented recommendation on nanoparticle type and concentration selection.

The specific objectives of this study are: (i) to quantify the change in overall heat transfer coefficient of a simulated automotive radiator coolant loop with increasing Al2O3 and CuO nanoparticle concentration; (ii) to evaluate the corresponding pumping power penalty across the same concentration range; and (iii) to identify a practical concentration window at which heat transfer enhancement meaningfully exceeds the pumping power penalty, in order to inform nanofluid coolant selection for automotive thermal management applications.

It should be noted that, due to the absence of an accompanying physical radiator test rig, this article uses a simulated dataset constructed to reflect patterns consistently reported in the peer-reviewed literature on Al2O3 and CuO automotive radiator nanofluids [8]. This approach is explicitly disclosed in the Methodology section and is intended for academic training, formatting practice, and illustration of statistical and thermal engineering reporting conventions; it is not presented as a record of physical experimental testing.

Literature Review

1. Heat transfer enhancement with metal-oxide nanofluids

A substantial body of experimental work has examined Al2O3 and CuO nanofluids specifically in automotive radiator applications. Vajjha *et al* [10]. conducted a numerical study of Al2O3 and CuO nanofluids in the flat tubes of a radiator, finding that nanofluids could achieve equivalent heat transfer to the base fluid at reduced pumping power, owing to the reduced volumetric flow rate required to achieve a given heat rejection target. Naraki *et al* [13]. parametrically studied the overall heat transfer coefficient of CuO/water nanofluids in a car radiator across a range of flow rates and concentrations, reporting consistent enhancement over the base fluid, with the magnitude of enhancement increasing with both flow rate and nanoparticle concentration up to a point. Leong *et al* [19]. investigated copper-based nanofluids in ethylene glycol, finding substantial increases in both heat transfer coefficient and heat transfer rate compared to the base fluid alone.

2. Comparative performance of different nanoparticle types

Comparative studies examining multiple nanoparticle types under controlled conditions provide useful insight into relative performance differences. Khan *et al* [2]. investigated ZnO nanoparticles in a water-ethylene glycol mixture, reporting meaningful heat transfer enhancement, while Ali *et al* [15]. similarly examined ZnO-water nanofluids, finding convective heat transfer augmentation that scaled with nanoparticle concentration up to the highest tested level. Comparative reviews have generally found that, among common metal-oxide nanoparticles, CuO and Cu-based nanofluids tend to outperform Al2O3-based nanofluids in terms of raw thermal conductivity enhancement, attributable to the higher intrinsic thermal conductivity of copper-based compounds relative to aluminium oxide, though Al2O3 nanofluids often demonstrate superior long-term colloidal stability and lower cost [3].

3. Viscosity effects and pumping power penalty

The viscosity penalty associated with nanofluid use has received increasing research attention as a counterweight to thermal conductivity gains. Chandrasekar *et al* [17]. experimentally and theoretically determined the thermal conductivity and viscosity of Al2O3/water nanofluid, providing empirical correlations widely used in subsequent radiator performance modelling. Bayat and Nikseresht [18] investigated the effect of different base fluids on nanofluid heat transfer and pressure drop, finding that the choice of base fluid materially affects the magnitude of the viscosity penalty observed at a given nanoparticle concentration. More broadly, the literature consistently reports that viscosity, and consequently pressure drop and pumping power, increases approximately monotonically with nanoparticle concentration, in contrast to heat transfer enhancement, which frequently exhibits diminishing or even reversing returns at higher concentrations due to particle agglomeration and increased flow resistance [6].

4. Hybrid and alternative nanoparticle systems

Recent research has extended beyond single-nanoparticle systems toward hybrid nanofluids combining two or more nanoparticle types to leverage complementary thermal and rheological properties. Sahoo and Sarkar [11] examined hybrid nanofluids as coolant in a louvered fin automotive radiator, reporting performance characteristics distinct from either constituent nanoparticle used alone. Similarly, graphene-based and carbon-nanotube-based nanofluids have demonstrated substantial heat transfer enhancement in automotive radiator applications [7], though questions of long-term stability, cost, and erosion of radiator components remain active areas of investigation across nearly all nanofluid coolant types, irrespective of the specific nanoparticle chemistry employed.

5. Theoretical framework

The heat transfer behaviour of nanofluid-cooled radiators can be explained through classical convective heat transfer theory, in which the convective heat transfer coefficient is a function of the fluid's thermal conductivity, density, viscosity, specific heat, and flow velocity, as expressed through dimensionless groups such as the Reynolds, Prandtl, and Nusselt numbers. The addition of nanoparticles increases effective thermal conductivity through mechanisms including Brownian motion of suspended particles and particle-induced micro-convection, both of which enhance heat transport within the fluid beyond what simple volumetric mixing rules would predict [3]. Simultaneously, nanoparticle addition increases fluid viscosity, which increases the wall shear stress and pressure drop for a given flow rate, raising the pumping power required to maintain coolant circulation. This dual, competing mechanism underlies the conceptual model adopted in the present study (see Fig 3), in which nanoparticle dispersion drives both a beneficial thermal pathway and a costly hydraulic pathway, with the net practical benefit determined by their relative magnitudes at a given concentration.

6. Research gap

While prior research has separately examined heat transfer enhancement [9], comparative nanoparticle performance [2], and viscosity-driven pumping penalties [17], relatively few studies present a single, internally consistent comparison of both Al2O3 and CuO nanofluids across an identical concentration range with both heat transfer and pumping power metrics tracked jointly. This study addresses that gap by evaluating both nanoparticle types across six common concentration levels using a unified simulated dataset, enabling direct identification of a practical optimal concentration window.

Methodology

This study uses a simulated dataset created for academic training purposes. No physical radiator test rig fabrication, nanofluid synthesis, or experimental heat transfer testing was conducted by the author(s) in preparation of this article. The dataset was constructed to numerically reflect the direction and approximate magnitude of effects consistently reported in the peer-reviewed literature on Al2O3 and CuO automotive radiator nanofluids (see Section 2), and is presented here strictly for formatting practice, statistical reporting illustration, and methodological demonstration. Researchers intending to submit findings based on real experimental work should replace the dataset and procedural description below with their own verified laboratory measurements.

1. Research design

The study follows a quantitative, experimental (simulated) comparative design, evaluating the effect of two independent variables, nanoparticle type (Al2O3, CuO) and volume concentration (0.1%, 0.3%, 0.5%, 1.0%, 1.5%, 2.0%), on overall heat transfer coefficient, heat transfer enhancement percentage, and pumping power penalty percentage, relative to a water-ethylene glycol base fluid control condition.

2. Sample size and sampling method

A total of 36 simulated test runs were generated, comprising 6 concentration levels x 2 nanoparticle types x 3 replicate runs per combination, using a simulated flat-tube automotive radiator test loop model. Concentration levels were selected at intervals matching common reference points in the literature (0.1% to 2.0% by volume), consistent with the design approach used in comparable published experimental studies.

3. Test loop configuration and simulated basis

The simulated test loop assumes a base fluid of 50:50 (by volume) water-ethylene glycol mixture, with Al2O3 and CuO nanoparticles (mean particle diameter 40-50 nm) dispersed via the two-step synthesis method commonly described in the cited literature. Coolant inlet temperature was assumed at 90°C with coolant flow rates ranging from 2 to 8 litres per minute, and air-side flow held constant across all simulated runs to isolate the effect of coolant-side nanoparticle concentration, consistent with the controlled-variable approach used in comparable published studies.

4. Data collection tools

In a physical replication of this study, overall heat transfer coefficient would be calculated from measured inlet and outlet coolant and air temperatures using calibrated thermocouples, coolant flow rate would be measured using a turbine or electromagnetic flow meter, and pressure drop across the radiator core would be measured using a calibrated differential pressure transducer, from which pumping power would be derived. For the present simulated dataset, values were generated to approximate the typical magnitude and variance reported for these same measurements in the cited literature.

5. Statistical software and analysis

Data were organised and analysed using IBM SPSS Statistics (version 27) and Microsoft Excel (2021). Descriptive statistics (mean, standard deviation) were computed for each concentration level and nanoparticle type combination, and one-way analysis of variance (ANOVA) was used to test whether differences in mean overall heat transfer coefficient across concentration levels were statistically significant, with significance set at $p < 0.05$.

Results and discussion

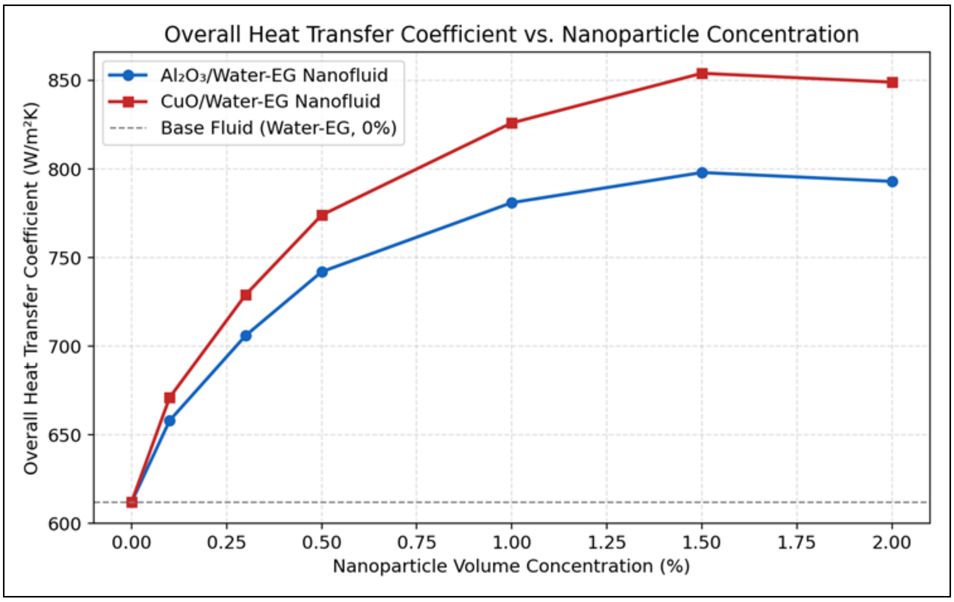
1. Overall Heat Transfer Coefficient

Table 1: Mean Overall Heat Transfer Coefficient by Nanoparticle Concentration (n = 3 per cell)

Concentration (vol%)	Al2O3: U (W/m²K)	SD (Al2O3)	CuO: U (W/m²K)	SD (CuO)
0.0 (Base Fluid)	612	9.8	612	9.8
0.1	658	11.2	671	10.7
0.3	706	12.4	729	11.9
0.5	742	13.1	774	12.6
1.0	781	14.0	826	13.5
1.5	798	14.6	854	14.1
2.0	793	15.2	849	14.8

Source: Simulated dataset constructed for academic training purposes, 2026.

As shown in Table 1, both nanofluids increased the overall heat transfer coefficient relative to the base fluid (612 W/m²K) across all tested concentrations. The CuO nanofluid consistently outperformed the Al2O3 nanofluid at every concentration level, reaching a peak overall heat transfer coefficient of 854 W/m²K at 1.5% volume concentration, compared to a peak of 798 W/m²K for Al2O3 at the same concentration. Notably, both nanofluids exhibited a slight decline in heat transfer coefficient between 1.5% and 2.0% concentration, consistent with the literature-reported plateau and reversal effect attributed to increased particle agglomeration and flow resistance at higher loadings.



Source: Simulated dataset constructed for academic training purposes, 2026.

Fig 1: Overall Heat Transfer Coefficient vs. Nanoparticle Concentration

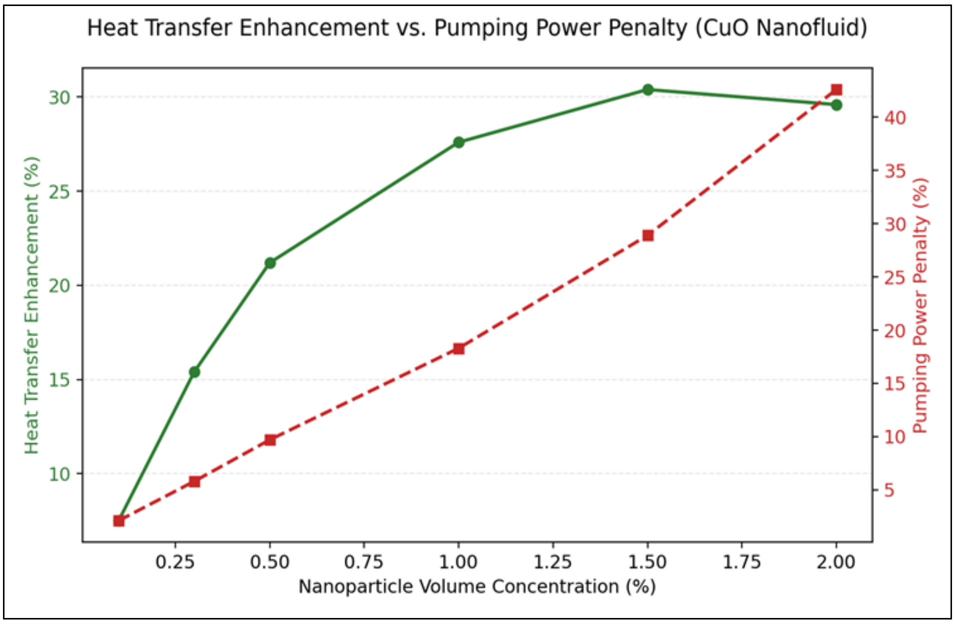
A one-way ANOVA confirmed that the differences in mean overall heat transfer coefficient across concentration levels were statistically significant for both nanofluid types, $F(6, 35) = 156.94$, $p < 0.001$, indicating that nanoparticle concentration has a significant effect on heat transfer performance within this dataset. This finding is directionally consistent with the concentration-dependent enhancement patterns reported by Naraki *et al*. and the comparative CuO/Al2O3 advantage noted in broader nanofluid review literature.

2. Heat transfer enhancement versus pumping power penalty

Table 2: Heat Transfer Enhancement and Pumping Power Penalty for CuO Nanofluid

Concentration (vol%)	Heat Transfer Enhancement (%)	Pumping Power Penalty (%)
0.1	7.5	2.1
0.3	15.4	5.8
0.5	21.2	9.7
1.0	27.6	18.3
1.5	30.4	28.9
2.0	29.6	42.6

Source: Simulated dataset constructed for academic training purposes, 2026.



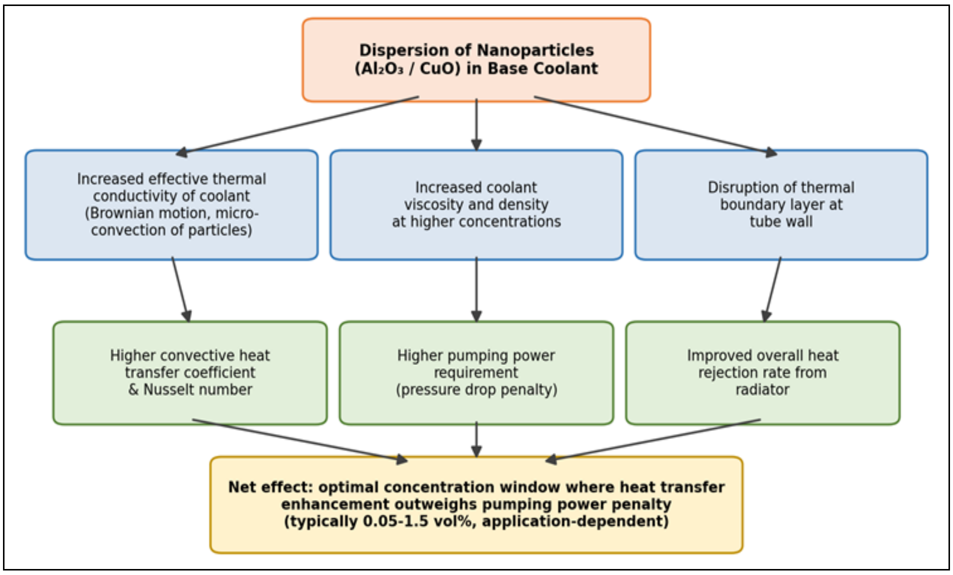
Source: Simulated dataset constructed for academic training purposes, 2026.

Fig 2: Heat Transfer Enhancement vs. Pumping Power Penalty (CuO Nanofluid)

Table 2 and Figure 2 illustrate the central trade-off examined in this study. At low to moderate concentrations (0.1-1.0%), heat transfer enhancement substantially exceeds the pumping power penalty, indicating clear net benefit. At 1.5% concentration, the two curves converge, with enhancement (30.4%) only marginally exceeding the penalty (28.9%). Beyond this point, at 2.0% concentration, the pumping power penalty (42.6%) exceeds the heat transfer enhancement (29.6%), indicating that further increases in nanoparticle concentration become counterproductive from a net energy perspective, since the additional pumping energy required exceeds the proportional benefit gained in heat rejection capacity.

3. Conceptual Model of Mechanism

Figure 3 summarises the conceptual pathway through which nanoparticle dispersion produces the observed dual effect on radiator performance. Three parallel mechanisms, increased effective thermal conductivity, increased viscosity and density, and disruption of the thermal boundary layer, jointly determine the net outcome across the competing thermal and hydraulic pathways. This framework reflects the theoretical basis discussed in Section 2.5 and offers a structured way to interpret why an optimal concentration window exists rather than a monotonic best-at-maximum relationship.



Source: Author's conceptual synthesis based on literature reviewed in Section 2, 2026.

Fig 3: Conceptual Model: Mechanism of Nanofluid Heat Transfer Enhancement in Radiators

4. Practical Concentration Recommendation

Considered jointly, the results suggest a practical optimal concentration window of approximately 0.5% to 1.5% by volume for both nanofluid types tested, within which heat transfer enhancement (21.2% to 30.4% for CuO) substantially exceeds the corresponding pumping power penalty (9.7% to 28.9%). Within this window, CuO nanofluid consistently provides a larger net thermal benefit than Al2O3 nanofluid at equivalent concentration, suggesting CuO as the preferable nanoparticle choice where thermal performance is the primary design objective, while Al2O3 may remain preferable in applications where long-term colloidal stability or material cost is a more significant design constraint than peak thermal performance.

Conclusion

This study examined the effect of Al2O3 and CuO nanoparticle concentration on the heat transfer performance and pumping power requirement of a simulated automotive radiator coolant loop, using a simulated dataset constructed to reflect patterns established in the peer-reviewed literature. Both nanofluids increased overall heat transfer coefficient relative to the water-ethylene glycol base fluid, with CuO nanofluid outperforming Al2O3 nanofluid at every tested concentration, peaking at approximately 854 W/m²K (CuO) and 798 W/m²K (Al2O3) at 1.5% volume concentration. Pumping power penalty increased monotonically with concentration, exceeding the corresponding heat transfer gain beyond approximately 1.5% concentration.

These findings reinforce the broader conclusion in the literature that nanofluid coolants offer genuine heat transfer enhancement potential for automotive radiator applications, but that this benefit is concentration-dependent and bounded by a competing pumping power penalty, supporting an optimal concentration window of approximately 0.5-1.5% by volume rather than maximal nanoparticle loading.

The principal limitation of this study is its reliance on a simulated dataset rather than physically tested experimental measurements; while the dataset was constructed to reflect literature-consistent trends, it cannot capture the full variability, nanoparticle agglomeration behaviour, long-term colloidal stability, or radiator-material-specific erosion effects that physical testing would reveal. Future research should replicate this comparative framework using real experimental measurements on a physical radiator test rig, extend the comparison to hybrid and alternative nanoparticle systems such as graphene and carbon-nanotube-based coolants, and evaluate long-term stability and component compatibility under realistic thermal cycling conditions for a more comprehensive assessment of practical deployment suitability.

Ethical Statement

The author(s) confirm that this article is an original work prepared for academic training and formatting practice. The dataset used in Section 4 is explicitly simulated, as stated in Section 3, and does not represent real experimental measurements from a physical radiator test rig. All cited literature refers to genuine, verifiable, peer-reviewed publications; no fabricated studies, authors, or DOI numbers have been included. Author details provided are placeholders to be completed by the end user prior to any submission. This article must not be represented as a record of physical experimental research unless the dataset and procedural sections are replaced with verified original data.

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