



Research Article

Experimental study of the Heat Transfer Coefficient of an Automobile Radiator Using Alumina & Titania based Nanofluids as Coolants

Salman Basha SHEIK^{1,2,*} , Praveena Devi NAGIREDDY¹ , Kiran Kumar KUPIREDDI³ 

¹Department of Mechanical Engineering, SR University, Warangal, 506371, India

²Department of Mechanical Engineering, Sasi Institute of Technology & Engineering, Tadepalligudem, 534101, India

³Department of Mechanical Engineering, National Institute of Technology Warangal, 506371, India

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ABSTRACT

Better engine cooling capability remains a desperate challenge in automotive heat management, as traditional water–ethylene glycol coolants regularly manifest limited heat transfer potential. This work investigates the improvement of radiator operation using alumina and titania-based nanofluids as a progressive heat-transfer approach. Nanofluids were produced by ultrasonic dispersion of nanoparticles (0.02–0.08 vol%) in water–ethylene glycol mixtures, followed by experimental testing in a customized automobile radiator test rig at an inlet temperature of 65°C and flow rates of 7–14 L min⁻¹. The specific-heat equation was employed to determine the rate of heat transfer, and differential surface-fluid temperature analyses were used to obtain convective heat-transfer coefficients. The results show that adding alumina and titania nanoparticles notably enhances heat transfer. The hybrid nanofluid (0.06 vol% alumina + 0.02 vol% titania) achieved a highest heat transfer coefficient of nearly 6400 W m⁻² K⁻¹, depicting a 155.6% increase over distilled water and about 60% advancement compared to the base water–ethylene glycol mixture. Radiator efficacy improved by 25–47%, while specific heat capacity was reduced by up to 73%, specifying a faster heating–cooling reaction. The results proposed that nanoparticle-induced micro-convection and improved thermal conduction govern the observed enhancements. The novelty of this work lies in experimentally quantifying the integrated thermal impact of alumina–titania nanofluids under practical automotive conditions, extending existing literature focused primarily on single nanoparticles. These results provide design insights for developing high-efficiency cooling systems in electronic thermal management, automobiles, and renewable-energy heat exchangers.

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*Corresponding author.

*E-mail address: sheiksalmanbasha@gmail.com

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INTRODUCTION

A cooling system is an essential part of performance because it allows the necessary temperature ranges for operation in the engine. The management of temperature in a thermal management system helps to improve engine efficiency and to reduce engine wear and overheating, which will directly affect performance in the vehicle. Therefore, since radiators are compact heat exchangers and important parts of the cooling system, they stand to benefit a lot from the use of modern automotive coolants. Choi introduced the term “nanofluids” in 1995, and they are fluids engineered with nanometer-sized solid particles, which are suspended in a base fluid and form a solid-liquid composite material. Over the past 2-3 decades, nanofluids have received a tremendous amount of research. A primary use of nanofluids is to argue their applicability in automotive, industrial, and other technology sectors, and often as coolants and friction-reducing agents. The present experimental comparison focuses on the performance of nanofluids in comparison to traditional coolants, i.e., pure water.

Shriram Sonawane et al. [1] studied the capacity of nanofluids in increasing the functioning of automotive cooling bodies and contributed to the development of automotive thermal management. Since designing these nanofluids for practical applications would be beneficial, including some potential advantages when implementing them in automotive cooling systems. Kundan Kumar et al. [2] expressed that improving heat transfer performance through nanofluids provides great advancements in the application of nanofluids as potential replacements in the automobile cooling system. The study cites nanofluids as a key component for radiator innovation that enhances automotive performance while also being environmentally friendly. The engine heat transfer ability is improved when utilizing nanofluids, since colloidal suspensions of nanoparticles have favorable thermal properties when properly formulated in traditional engine coolants. Chandan Kumar, et al. [3] investigated that paraffin wax in sustained-centigrade nanofluids works with phase change materials to improve thermal management by efficiently regulating temperatures and actively absorbing heat during high-load situations in a vehicle, which improves the sustainability of radiator performance in internal combustion engines.

Atul Bhattad et al. [4] investigated the preparation and use of nanofluids in IC engines. Amr M Hassaan et al. [5] investigated the application of hybrid nanofluids, specifically MWCNTs-Al, to an automobile radiator. The results indicate that hybrid nanofluids can provide better performance of radiators and improve thermal management in vehicles. Najmul Hidayat et al. [6] investigated the heat transfer capability of hybrid Al_2O_3 - TiO_2 nanofluid in an automobile radiator. Chandan Kumar et al. [3] examined the thermal efficiency of pure coolant and hybrid nanofluid with various concentrations for cooling fluids (0.25%, 0.30%, and 0.35% wt. of nanoparticles) and fluid flow rates (20, 24, and 28 L min^{-1}) at inlet temperatures of 70, 80, and 90 °C respectively.

Kundan Kumar et al. [7] investigation explores the orientations and use of nanofluids with Al_2O_3 and TiO_2 -based suspensions to improve heat transfer coefficient air performance related to automotive/alternator radiators. The addition of nanoparticles to any coolant, including traditional engine coolants, will improve heat capacity and thermal conductivity characteristics. Experimental results confirmed that radiator systems that included nanofluids increased their heat transfer performance effectiveness, which supported sustainability and operational performance improvements. Budi Kristiawan et al. [8] studied the thermal properties of hybrid nanofluids in a cooling system, which implements a helically twisted tube inside a brushless direct electric motor. The data collected were for Nusselt number and dropped stator temperatures; however, an assessment of the automobile radiator heat transfer coefficient was not present in the data. The hybrid nanofluids tested were noted to have significant heat transfer capability over water-based fluids according to the research, although there was no research focused on automotive applications. The experimental data of the Al_2O_3 -water showed superior performance, and then the TiO_2 -water, with hybrid nanofluids showing better thermal performance especially at the higher concentration and best ratios of the nanoparticles, which gave better overall and convective heat transfer coefficients [9].

The CFD investigation was completed using inlet temperatures at 60, 70, and 80 °C. Overall, and while CuO nanofluid represented the best-performing nanofluid in terms of temperature reductions and pressure drops, the performance parameters calculated for Al_2O_3 and TiO_2 show their potential use as coolants in radiator applications [10]. The authors address hybrid nanofluid thermal performance in a car radiator. They show that AlTi (Al_2O_3 + TiO_2) leads to the greatest increase in the overall performance while CuTi (CuO + TiO_2) showed decreased performance. The papers support the use of THNF(Al_2O_3 + CuO + TiO_2) hybrid coolant as it leads to lower entropy generation and offers moderate thermal performance improvements that demonstrate its potential for improving the heat transfer characteristics for an automobile radiator [11]. Research on Al_2O_3 and TiO_2 -nanofluids utilization in automotive radiators showed significant improvement in radiator cooling performance. Research reports that Al_2O_3 -nanofluid with a 0.3% vol. fraction showed the highest radiator effectiveness improvement of 24.21%. The use of TiO_2 -water nanofluid indicated a radiator effectiveness improvement of 47% when operating with its best volume concentration. The heat transfer rates for both nanofluids were improved under a specific volume concentration at a specific Reynolds number, resulting in better operation of the vehicle cooling system [12].

A.T. Akinshilo et al. (2020) [13] investigated heat transfer and fluid flow of an electrically conducting magnetohydrodynamic (MHD) nanofluid in diverging or converging channels made from a porous medium of internally generated heat. The governing equations in this problem are high order and nonlinear, the homotopy perturbation approach

was considered an appropriate tool of analysis for obtaining approximate solutions. Researchers then studied the nonlinear influence of heat radiation in Casson nanofluid, which is entrapped between a porous medium and the flow over a narrow needle, including the internal heat generation [14]. The homotopy perturbation method (HPM) has also been employed to examine the fluctuating flow and heat transfer of a nanofluid being injected by an expanding or retracting porous channel, with the system being exposed to a constant magnetic flux [15]. The study investigates the flow and thermal transfer of magneto-hydrodynamic nanofluid inside a rotating system, using more complex, non-linear ordinary differentials and the homotopy perturbation method (HPM) to obtain analytical solutions [16].

Recently, multiple studies have been focusing on the development of nanofluids as useful alternatives for traditional heat-transfer fluids due to their better thermal conductivity and energy efficiency. Kiaei et al. (2023) [17] evaluated the performance of an Al₂O₃ and CuO nanofluid compared with mono-disperse nanoparticles and pure water-based fluids,

showing that radiator thermal performance was increased with higher Reynolds numbers and nanoparticle volume fractions. Ukueje et al. (2022) [18] aligns with the conventional opinion that hybrid nanofluid takes advantage of the synergistic effect of the disparate nanoparticles, thus making it a more effective heat-transfer medium. Dai et al. (2024) [19] proved that optimization of mixing ratios can significantly increase the thermal conductivity of Cu-Al hybrid suspensions, which in turn allowed increasing the overall heat-transfer performance. Nanoparticle agglomeration, viscosity modulation, and flow turbulence are the phenomena that have been significantly sensitive to the performance of radiators, which is supported by recent numerical simulations. Such studies emphasize how essential nanofluids are in improving the heat-transfer capacity of radiator systems [20]. The results demonstrated that there is a notable enhancement in heat transfer rate in the existence of a typical inserted perverted tape [21].

Table 1 presents the notable enhancement of heat transfer properties, such as the Nusselt number, convective heat transfer coefficient, heat transfer rate, overall U, etc., of

Table 1. Details of percentage improvement of heat transfer properties of hybrid nanofluids

Hybrid composition	Metric reported	Concentration reported	Key experimental conditions	Reference
MWCNT–CuO hybrid (aqueous)	Convective heat transfer coefficient enhanced by 295%	Reported concentrations varied 0.05–0.15 wt% (highest effects at ~0.1 wt%)	Coolant flow 7 L min ⁻¹ , inlet 80 °C (automotive radiator test rig)	[22]
CNC (cellulose nanocrystal) + CuO hybrid (CNC/CuO)	Heat transfer efficiency improved by 92.43%	Fixed volume fraction 0.01 vol% (hybrid)	Scaled-down and commercial radiator tests; flowrates 0.75–1.25 L min ⁻¹ , radiator inlet 80 °C	[23]
Graphene nanoplatelets (GnP) + cellulose nanocrystals (CNC)	Convective heat transfer coefficient +51.91%	Reported test used 0.01% hybrid in optimized tube (base fluid DW:EG 40:60)	Counterflow radiator test rig (laboratory)	[24]
GnP + CNC hybrid	Overall heat transfer coefficient +46.72%	Same as above (reported optimized concentration 0.01% in tube study)	Counterflow radiator test rig	
CuO–MgO–TiO ₂ ternary hybrid	Coolant-side heat transfer coefficient +46%	0.5 vol% (hybrid)	Flat-tube car radiator tests (varied flow rate, frontal air velocity)	[25]
Al ₂ O ₃ –TiO ₂ –SiO ₂ tri-hybrid	Coolant-side heat transfer coefficient +39.7%	0.3 vol% (maximum reported)	Coolant flow 2–12 LPM, working temperature 70 °C, air velocity ~4 m/s	[26]
MWCNT + Al ₂ O ₃ hybrid (EG + DW base 1:1)	Heat transfer increase +35%	Volume concentrations tested 0.03–0.12%	Inlet temperatures 40–75 °C; flow rate 0.6–0.96 m ³ /h (as reported)	[27]
SiC + MWCNT hybrid	Reported heat-transfer boost (approx.)	Concentrations discussed in paper (see source)	Automotive radiator system experiments (paper reports thermophysical tests and radiator performance)	[28]
Glycerin/Al ₂ O ₃	Enhanced heat transfer coefficient is 62%	0.05, 0.1 and 0.15% volume fractions of nanofluids	Engine model and a car radiator test rig	[29]
CuO/Water	Improved heat transfer characteristics from 16% - 31%	Cu based water nanofluid of 0.025, 0.05 and 0.075% volume concentration	Tractor engine radiator test rig	[30]

hybrid nanofluids in radiator or radiator-like tests, together with the composition, concentration, and experimental circumstances specified by the authors.

The difficulties involving stability, erosion, and corrosion came when the volume fraction of nanoparticles increased in nanofluid. Hence, the optimum concentration of nanofluids plays an important role [31].

Despite these advances, limited experimental studies have examined the condensed thermal and hydrodynamic performance of hybrid nanofluids under actual automobile radiator operating conditions. Addressing this gap, the present study provides an experimental evaluation of alumina–titania nanofluids to establish reliable heat-transfer correlations for automotive and energy-system cooling applications.

The research aims to provide comprehensive experimental details on the heat transfer and flow properties of specific alumina and titania nanofluids in automotive radiators, with a novel focus on confirming stable dispersions to specifically assess the effect of nanoparticle type and volume fraction on cooling system efficiency. The originality of the current research work lies in the experimental investigation of the hybrid nanofluids between alumina and titania under the real-life conditions of an automotive radiator. Contrary to the antecedent studies, which have mainly focused on individual formulations of nanofluid solely dependent upon numerical modeling. The present research work provides experimental support for the synergistic effect of combined nanoparticle effect on important thermophysical parameters, including specific heat, thermal conductivity, and convective heat-transfer coefficient. The results demonstrate a direct relation between nanoparticle composition and efficiency of radiator, thereby contributing new experimental evidence to guide future automotive and energy-system cooling design.

CHARACTERIZATION AND SYNTHESIS

This section presents the characterization of Al_2O_3 (CAS: 1344-28-1) and TiO_2 (CAS: 13463-67-7) fine

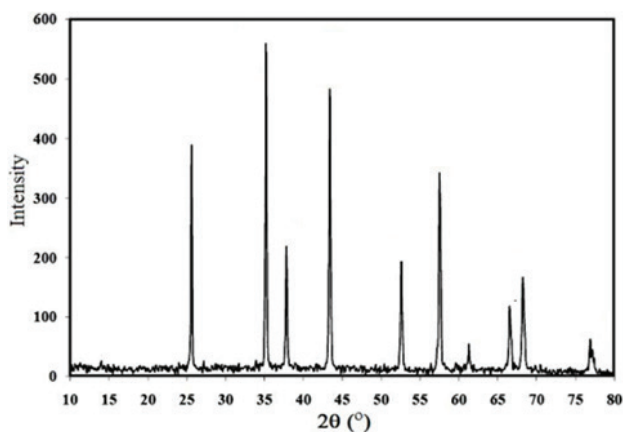


Figure 1. XRD data for Alumina nanoparticles.

metal oxides purchased from Nano Research Lab (NRL), Jharkhand, and also the synthesis of nanofluids.

Analysis of Al_2O_3 Nanoparticles

Nanoparticles of aluminum oxide (Al_2O_3) are well known for their excellent thermal properties, which makes them an optimal addition to nanofluids for heat transfer applications. The aluminum oxide nanoparticles in this study are high purity (99.9%), therefore consistent with a low level of impurities. The X-ray diffraction (XRD) patterns in Figure 1 suggest an average particle size of 30–50 nm, which creates a large surface area to volume ratio and enhances thermal conductivity and stability of the nanofluid. Al_2O_3 nanoparticles with a specific surface area of 130–140 m^2/g are efficient in the dispersion rate of the base fluid while avoiding aggregation to create uniform suspensions.

Figure 2 shows the spherical shape in co-occurrence with the crystallographic structure evaluated using TEM characterization, represents that the Al_2O_3 nanoparticles reveal isotropic electrical and thermal properties under a steady dispersion state. However, in experimental nanofluid systems, particle accumulation and settling may affect the reliability of electrical conductivity.

The nanoparticles have a bulk density of 1.5 g/cm^3 and a true density of 3.97 g/cm^3 , demonstrating the highly compact and dense nature of the material used. The density values of Al_2O_3 nanoparticles (CAS: 1344-28-1) were opted from supplier specifications (Nano Research Lab, Jharkhand, India), which are established on standardized measurements (ASTM D1895B and helium pycnometry methods). The XRD and TEM analysis was conducted in this research to validate the consistency of particle size and structural morphology with the collected data.

The substrate is prevalent in automotive radiators, as it is highly stable to 2055°C melting, ensuring system dependability in hot systems. The atomic weight of the

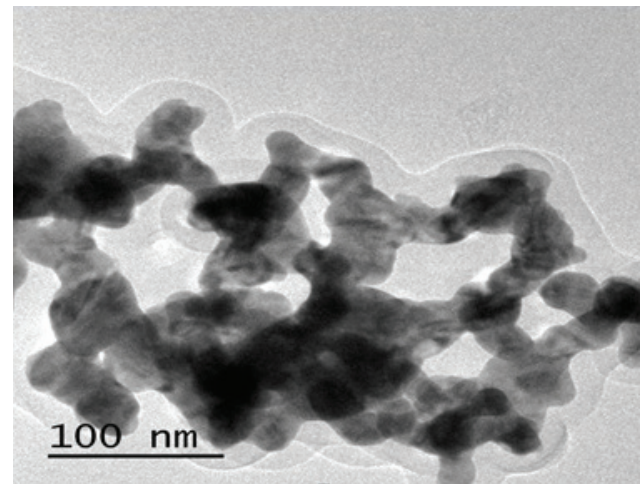


Figure 2. TEM analysis of Al_2O_3 nanoparticles.

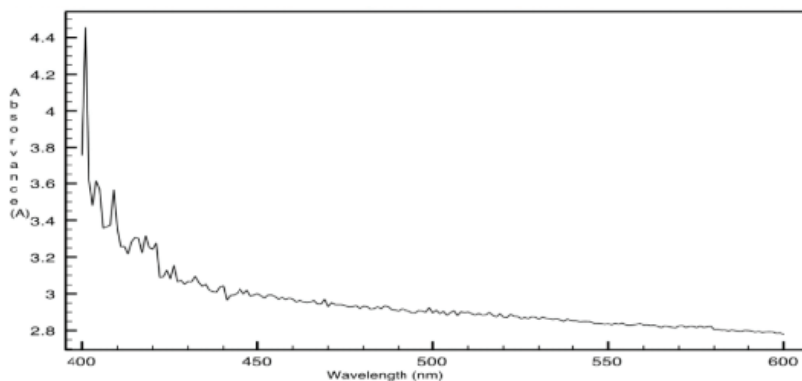


Figure 3. UV-Vis spectrometer reading of Al₂O₃ nanoparticles.

Al₂O₃ nanoparticles is 101.95 g/mol, which indicates the fast interactions within the fluid matrix. There is significant absorption below 400 nanometers; this is used with Figure 3, and the UV-Vis absorption spectra of the Al₂O₃ nanoparticles demonstrate the wide band gap for Al₂O₃ nanoparticles. The atomic and nanoscale properties of Al₂O₃ establish a unique optical behavior suitable for optical and electronic applications.

Combining these properties makes Al₂O₃ nanoparticles an attractive medium for enhancing the thermal behavior of nanofluids. Specifically, incorporating these nanoparticles in the coolant fluid blend with water can enhance the thermal efficiencies of the overall automotive cooling system. This phenomenon was examined in this study.

Analysis of TiO₂ Nanoparticles

The titanium oxide (TiO₂) nanoparticles (CAS: 13463–67–7) have a purity of 99.9% with a spherical morphology. XRD analysis, shown in Figure 4, shows that the TiO₂ nanoparticles do have a crystalline structure, and indicating

the peak position at 25.3° (101), indicating to the anatase phase (2θ = 25.3°, 37.8°, 48.0°, and 54.0°), is clearly noticeable and aligns with standard JCPDS card no. 21-1272.

The size of the crystallites calculated using the Scherrer equation indicates that the approximated size of the nanoparticles is ~10 nm. The SEM image shown in Figure 5 confirmed that the average crystalline sizes of TiO₂ nanoparticles are in the range of ~10-20 nm. They also have a very high specific surface area (SSA) of between 200 and 220 m²/g, suggesting that they have a large reactive surface area. They are white in colour with a bulk density of between 0.15 and 0.25 g/cm³ and a true density of 4.23 g/cm³, indicating they are compact and light weight when in bulk, and are in accordance with a spherical morphology with its crystallographic structure.

The bulk and true density values of TiO₂ nanoparticles were taken from the supplier’s technical specifications sheet (Nano Research Lab, Jharkhand, India) and measured using standard laboratory procedures. An identical structural morphology has been observed in the literature

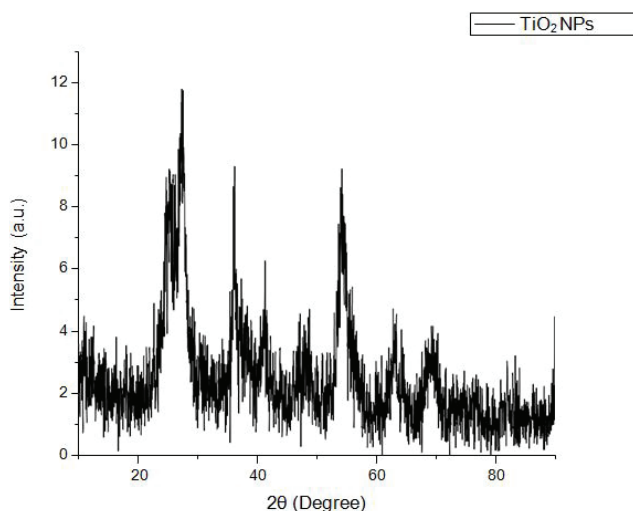


Figure 4. XRD analysis of TiO₂ nanoparticles.

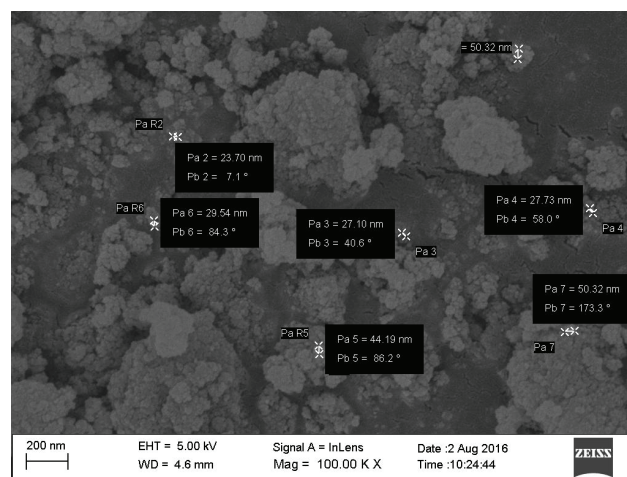


Figure 5. SEM image of TiO₂ nanoparticles (analysis report provided by Nano Research Lab, Jharkhand).

[32]. The stability of particle size and structural morphology with these data was validated through the XRD and SEM analyses provided by the supplier in the present study. Furthermore, the atomic weight of TiO_2 is 79.8658 g/mol, which corroborates their expected chemical composition. With these properties, TiO_2 nanoparticles are suitable for various applications such as photocatalysis, coatings, and biomedical applications.

Synthesis of Alumina & Titania-based nanofluids

Al_2O_3 and TiO_2 -based nanofluids were produced using the ultrasonic processor shown in Figure 6 to achieve stable dispersion and retention of the nanoparticles within the base fluids. The production process of the nanofluids was via the ultrasonication technique, where the duration was 12 hours of ultrasonication at varying volume concentrations. Six formulations were created, including distilled water, distilled water along with ethylene glycol (EG), 0.02 vol% TiO_2 , 0.06 vol% TiO_2 , 0.08 vol% Al_2O_3 , and 0.06 vol% Al_2O_3 and 0.02 vol% TiO_2 in both distilled water and ethylene glycol. The extended duration of ultrasonication produced stable nanofluids due to the particles not yielding any large clusters. This allows for clearer systematic investigation of the thermal and physical behaviour of nanofluids when finding the effects of types of nanoparticles and concentrations of the nanoparticles.

EXPERIMENTATION

A test setup for a vehicle radiator was experimentally tested to evaluate the potential of applying Alumina (Al_2O_3) and Titania (TiO_2)-based nanofluids as cooling fluids during the performance evaluation. The experimental testing setup was shown in Figure 7, while the working of the radiator was represented in Figure 8. The detailed features of the test rig used in this research are represented in Table 2.

The experimental testing involved filling the tank with coolant until it reached the specified measurement mark

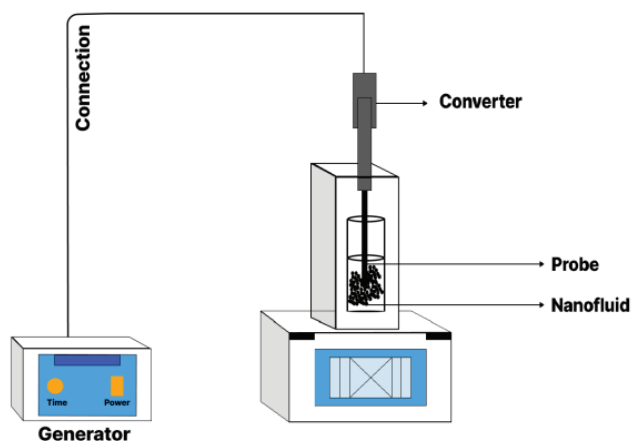
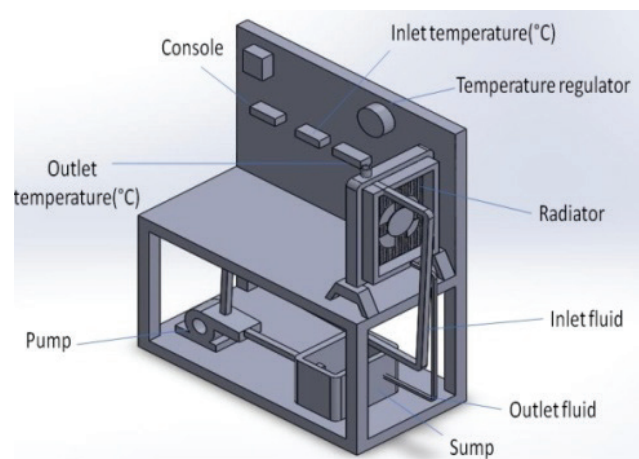


Figure 6. Probe sonication of Nanofluids.

before turning on the power supply and heater. The temperature control was established at 75°C prior to starting the process. The flow rate was then adjusted based on the flow meter measurement before the fan and the pumps were turned on to initiate circulation. It was the aim of the process to measure outlet coolant flow rate and temperature differential across the inlet, outlet, and surface at varying pump discharge rates. Thus, this process was an effective method for accurately measuring data to characterize the thermal behavior and flow characteristics of nanofluids under specified operating conditions.

The radiator system consisted of a half-horsepower pump that circulated Al_2O_3 and TiO_2 nanofluids through the radiator system managed by a flow control valve. The heating coil used with thermostat controls maintains the nanofluids in a range from 50 to 75°C , as indicated by the Cengel et al. study [33]. There were a number of



(a)



(b)

Figure 7. (a) 3D Model of an Automobile Radiator Test Setup. (b) Experimental setup of an Automobile radiator Test Setup.

Table 2. Specifications of the Automobile Radiator Test Rig

Component / Parameter	Specification / Description
Type of Apparatus	Automobile Radiator Testing Setup (Heat Transfer Laboratory Setup)
Radiator Fan Speed	1500 RPM
Water Pump Capacity	0.25 HP centrifugal pump
Pump Head Range	4 m – 15 m
Heater Capacity	2000 W (Electrical immersion heater)
Working Fluid	Water / Water–Ethylene Glycol / Nanofluids (Alumina, Titania, Hybrid)
Flow Measurement	Rotameter calibrated for 0 – 20 L min ⁻¹
Temperature Measurement	K-type thermocouples (±0.5 °C) connected to NI-9213 DAQ
Cooling Air Flow	Axial fan coupled with variable-speed motor
Power Source	230 V AC, 50 Hz
Make	SASI Institute of Technology & Engineering
Test Performed	Determination of Rate of Heat Transfer and Convective Heat Transfer Coefficient
Safety & Monitoring	Thermostat control with over-temperature cutoff and cooling-system inspection provision

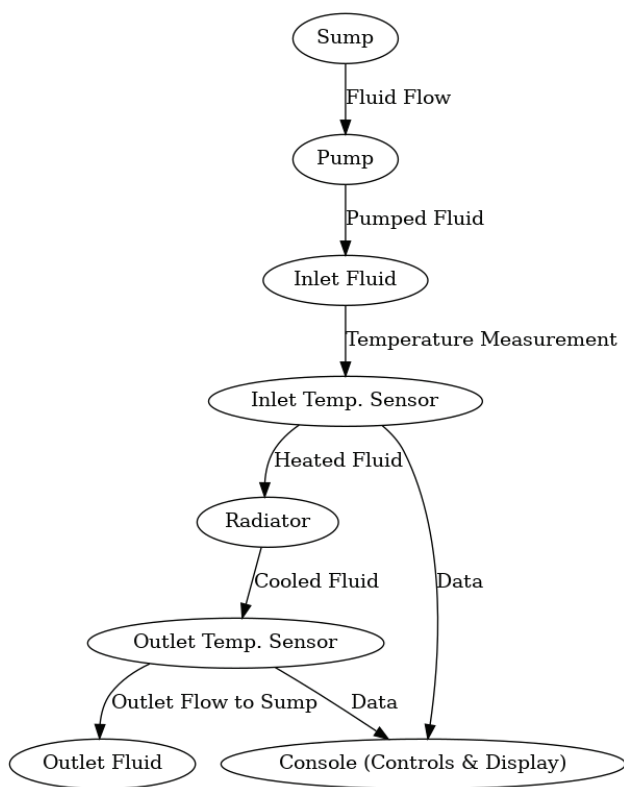


Figure 8. Flowchart of working of automobile radiator test rig.

thermocouple instruments to ensure the system was measured accurately along many points in the system. For the radiator performance measurements, there were two thermocouples used to log inlet temperature and outlet temperature from the flow line, and four other thermocouples monitored the radiator wall temperatures. There was a fan system mounted next to the radiator to enhance the cooling

system. Researchers used the conceived system to provide further heat transfer and flow investigations on nanofluids at different operational conditions. The nanofluid formulation was employed to obtain the specific heat capacity (C_p) values while the team obtained flow rate (m°) and temperature measurement. The formula would then be used to calculate radiator heat dissipation, which made it possible to assess Al_2O_3 and TiO_2 -based nanofluids’ thermal performance.

$$Q = m^\circ_{nf} C_{p_{nf}} \Delta T \tag{1}$$

Heat Transfer Measurement

The rate of heat transfer (Q) of the nanofluid was calculated using the measured mass flow rate of nanofluid (m°_{nf}), specific heat of nanofluid ($C_{p_{nf}}$), and temperature difference between the inlet and outlet of the radiator using the relation

$$Q = m^\circ_{nf} C_{p_{nf}} (T_{in} - T_{out}) \tag{2}$$

The inlet, outlet, and surface temperatures were reported using K-type thermocouples attached to a data acquisition system.

The heat transfer coefficient (h) of the nanofluid was then acquired from the calculated heat transfer rate (Q) and the measured radiator surface temperature difference using:

$$h = \frac{Q}{A_s(T_s - T_m)} \tag{3}$$

where A_s is the effective heat transfer area of the radiator, T_s is the average surface temperature (measured by wall-mounted thermocouples), and T_m is the average fluid temperature.

All temperature values were steadily monitored using K-type thermocouples (accuracy $\pm 0.5^\circ\text{C}$) connected to a calibrated data acquisition system. They are positioned at the radiator inlet, outlet, and four wall locations to track coolant and surface temperatures. The method ensures accuracy and repeatability consistent with standards for radiator performance testing.

All thermocouples were attached to a digital data acquisition system with automatic cold-junction compensation for specific temperature recording. Prior to testing, all thermocouples were calibrated using a certified laboratory mercury thermometer in a constant-temperature bath to minimize systematic error. These temperature readings were subsequently used to find the mean fluid and surface temperatures need to compute the convective heat-transfer coefficient.

Density Measurement

The density of the nanofluid was measured by using the correlation established by Das et al. [34]. The correlation is empirical, meaning that it relies on the volume concentration of the nanoparticle and the base fluid to predict the effective density of the nanofluid. The equation is as follows:

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_p \quad (4)$$

The correlation from Xuan et al. [35] is utilized to define the specific heat of the nanofluid. This correlation classifies a mathematical formulation for nanofluid effective specific heat to include the characteristics of the base fluid and nanoparticle volume fraction. The relationship is as follows:

$$Cp_{nf} = \frac{(1-\phi)(\rho Cp)_f + \phi(\rho Cp)_p}{\rho_{nf}} \quad (5)$$

Where ϕ represents the nanoparticle volume fraction, ρ and C_p represent the density and specific heat capacity of the base fluid (f) and nanoparticles (p). The equation takes into consideration nanoparticle dispersion, which strongly affects heat transfer performance during cooling system operations and electronic cooler and industrial heat transfer applications.

RESULTS AND DISCUSSION

Thermal efficiency testing for an automotive radiator was carried out at a constant inlet temperature of 65°C and volumetric flow rates of 7, 10, and 14 L min^{-1} . The outcome of nanoparticle addition on thermo-physical and thermal-hydraulic functioning was investigated in terms of both engineering trends and the fundamental physical phenomena governing energy transport in nanofluids.

The improvement in thermal conductivity and convective performance can be explained through several nanoparticle-scale mechanisms as reported in contemporary literature [14], [15]. When nanoparticles are suspended in the base fluid, rapid Brownian motion of particles generates localized micro-convection currents, promoting better energy exchange between the fluid molecules and solid particles. In addition, the formation of ordered liquid layers at the solid-liquid interface provides an interfacial thermal bridge, which enhances the effective thermal conductivity beyond simple mixture models.

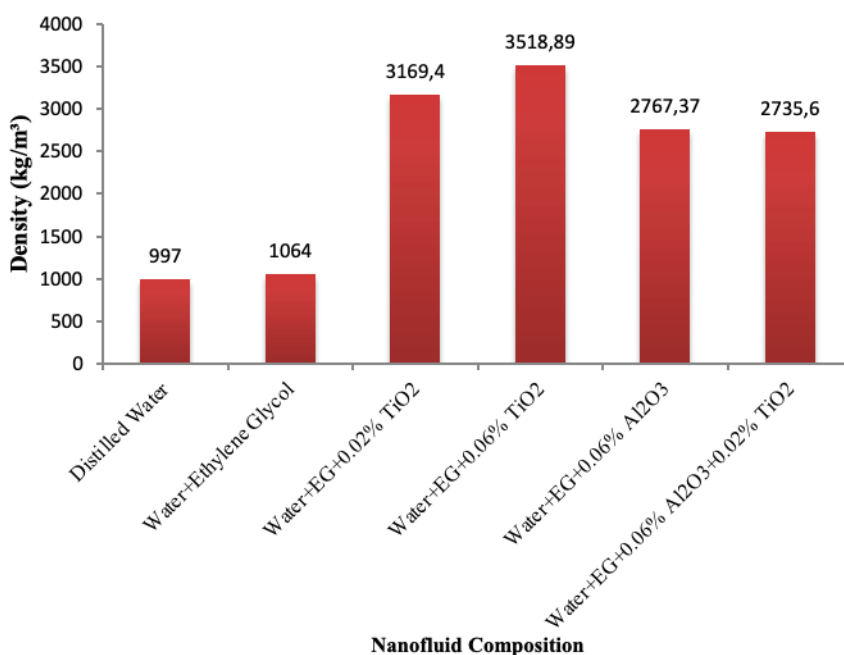


Figure 9. Density of nanofluids.

The properties of the nanofluids changed slightly from the properties of the base fluid. Density increased, thermal conductivity increased, but the specific heat value decreased slowly compared to the base fluid. Viscosity increased in the volumetric fraction more than heat transfer efficiency would possibly want. Additional evidence showed the heat transfer coefficient was probably biased to increase exponentially as the volumetric fractions of Al_2O_3 and TiO_2 nanoparticle-based fluids were increased.

Density

The broad effects of the increase in density were seen in Figure 9, wherein the densities of all of the prepared nanofluids were greatly opposed to distilled water (997 kg/m^3). While that of the Water and Ethylene Glycol mixture is increased by 6.72%, 1064 kg/m^3 . This was reflected by the 217.89% and 252.95% respectively, when 0.02% and 0.06% TiO_2 were added, with a total air content of 3518.89 kg/m^3 . For the 0.08% Al_2O_3 nanofluid this enhancement

was 177.57%, and for the 0.06% $Al_2O_3 + 0.02\% TiO_2$ mixture this was relatively similar at 174.38%. The increase in density at these higher concentrations and its effect on flow behavior indicate that optimization will be required when incorporating these nanofluids in automotive cooling applications.

Specific Heat

The specific heat capacity of various nanofluid compositions was considered to determine the potential for application in automobile cooling applications. The specific heat of conventional nanofluid compositions was decreased compared to that of distilled water (4180 J/kg-K). For example, the water + ethylene glycol treatment was 19.38% less, the 0.02% TiO_2 treatment was 73.03% less, and the 0.06% TiO_2 treatment was 71.81% less. The 0.08% Al_2O_3 treatment decreased specific heat by 68.98%, and the $Al_2O_3 + TiO_2$ decreased 68.74%; both would decrease thermal performances.

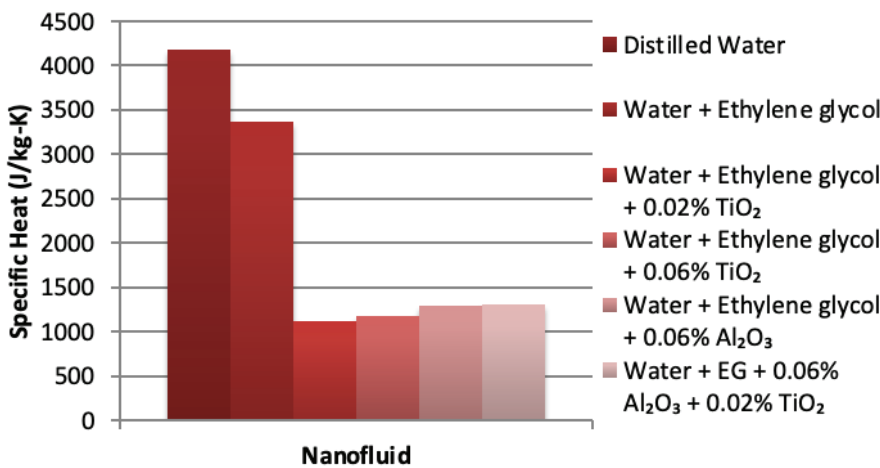


Figure 10. Specific heat of nanofluids.

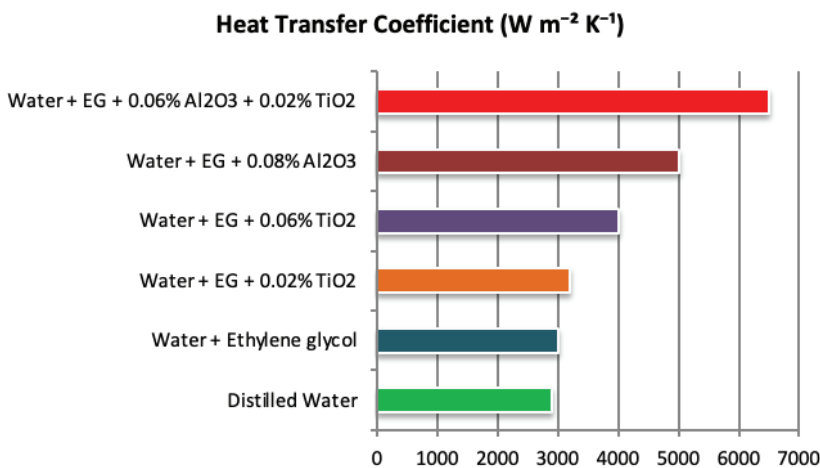


Figure 11. Heat transfer coefficients of nanofluids.

As presented in Figure 10, the addition of TiO_2 and Al_2O_3 nanoparticles noticeably lowers the specific heat capacity when compared to distilled water and water-ethylene glycol mixtures. Specific heat capacity is important because a lower specific heat capacity means that the nanofluid will heat quicker and release heat quicker, which would lead to heating at a greater rate. This reduction of specific heat capacity should also be paired with other thermal properties like thermal conductivity and convective heat transfer coefficient to ensure that nanofluids could be used for cooling without changing temperatures too quickly or too often. The results also indicated that Al_2O_3 nanofluids have a greater potential for heat transfer, meaning they would be good candidates for further research on enhanced automotive radiators.

Heat Transfer Coefficient

An automobile radiator test rig was used to compare the heat-transfer coefficients of the mixtures. The coefficient for distilled water was $\approx 2645 \text{ W m}^{-2} \text{ K}^{-1}$; all nanofluids exhibited higher values, as shown in Figure 11. The increment on the heat transfer coefficient ranged from 2.83% for the water and ethylene Glycol mixture to 155.64% for the combination of water, ethylene glycol, 0.06% Al_2O_3 , and 0.02% TiO_2 .

The increase is attributed to the combination of (i) enhanced thermal conductivity from solid inclusions, (ii) Brownian-motion-induced micro-convection within the boundary layer, and (iii) thinning of the thermal boundary layer due to disturbance of the near-wall region by nanoparticles. These mechanisms collectively accelerate heat diffusion from the wall to the fluid.

An empirical equation has been used to generalize the effect of working parameters on the convective heat transfer coefficient (h) through the experimental data. The correlation amongst the Nusselt number (Nu), Reynolds

number (Re), and nanoparticle concentration (ϕ) proposed by Hussein et al. (2014) [36] and Said et al. (2015) [37] can be expressed as:

$$Nu = 0.328 \times Re^{0.62} \times \phi^{0.18} \quad (6)$$

This generalized correlation suggests that the convective heat transfer coefficient improves depending on nanoparticle concentration and flow velocity. The trend corresponds to previous research studies, confirming the robustness of the current results and indicating that nanofluid concentration and volumetric flow rate are important in improving heat transmission.

This improvement offers better heat transfer from the surface to the fluid, thus demonstrating the promise of nanofluids for high-end heat transfer applications, including automotive radiators. At concentrations over 0.08 vol % Al_2O_3 or 0.06 vol % TiO_2 , viscous drag and particle agglomeration begin to offset these benefits, producing a saturation or slight decline in heat transfer coefficient.

Flow Rate

Heat transfer coefficients of the various fluid combinations for the three different flow rates (7, 10, and 14 L min^{-1}) are displayed in Figure 12. The study demonstrates that water offers the highest heat transfer coefficient at all the study's flow rates and that water managed to offer a coefficient of approximately $7200 \text{ W/m}^2\text{-K}$ at a 14 L min^{-1} flow rate. However, for systems that need to do better, notably (i.e., carrying a full level transition at near $0\text{--}14 \text{ L min}^{-1}$), the water + EG + 0.08 vol% Al_2O_3 improved to approximately $6400 \text{ W/m}^2\text{-K}$.

Moreover, the mixture of additives with both TiO_2 and Al_2O_3 has benefits over water and ethylene glycol as well, and they can cater to better usage. In Addition of ethylene glycol (EG) results in reducing the heat transfer coefficient,

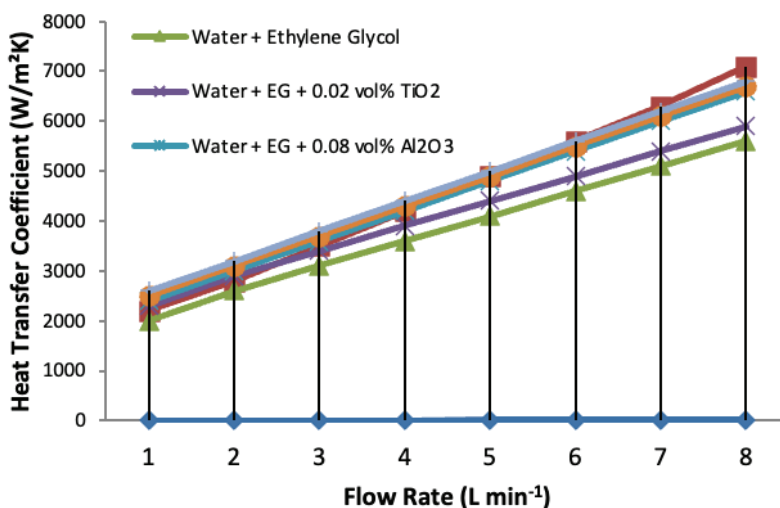


Figure 12. Heat transfer coefficient vs flow rate of nanofluids.

and among the mixtures tested, the lowest coefficients are provided by the water + EG mixture. On the other hand, the addition of nanoparticles like TiO_2 and Al_2O_3 enhances heat transfer ability.

The present study demonstrated an enhancement in the convective heat-transfer coefficient corresponds to previous studies. Shankara R. P., et al. (2020) [22] reported a 295% enhancement in convective heat transfer coefficient was observed for aqueous MWCNT–CuO hybrid (at 0.05–0.15 wt%, with peak effects near 0.1 wt%) at 7 L min^{-1} coolant flow and 80°C inlet in the radiator experiments. The 92.43% improvement in heat transfer efficiency was reported for a CNC+CuO hybrid at 0.01 vol% in scaled-down and commercial radiator tests using an 80°C inlet and flow rates of $0.75\text{--}1.25 \text{ L min}^{-1}$. Ganesan T. et al. (2018) [25] and Kumar A. et al. (2023) [26] reported hybrid fluids (CuO-MgO-TiO_2 , $\text{Al}_2\text{O}_3\text{-TiO}_2\text{-SiO}_2$) coolant-side HTC gains in the ~40% range at concentrations of 0.3–0.5 vol% under the test conditions described in those studies. Similarly, K. G. Sundari et al. (2020) [29] reported nanofluids with 0.05, 0.1, and 0.15 vol. % of TiO_2 nano-material in glycerine and the increase in the heat transfer coefficient is 62% at 0.15 vol. %. Ravi Sankar R. et al. (2018) [30]. The Reported experimental and numerical study for the enhanced heat transfer properties of a radiator with Cu/water nanofluid of 0.025, 0.05, and 0.075 vol. % concentration is finished with an inlet temperature of $50\text{--}60^\circ\text{C}$ under the unstable flow system.

The current research finds up to 155% enhancement of the total heat-transfer coefficient and 25–47% enhancement of the radiator effectiveness, which is within the bounds of published data [22–30]. Such similarities prove the fact that the thermal enhancement is due to the nanoparticle-induced micro-convection and interfacial energy transportation processes, which are always highlighted in the literature.

It is noted that the final thermal performance of an automobile radiator can be controlled by the combined heat transfer coefficients on both the coolant and air sides. The effective heat transfer coefficient of the radiator is restricted by the lower of the two values, commonly the air-side coefficient. Therefore, the present research demonstrates substantial improvement in liquid-side heat transfer using Al_2O_3 and TiO_2 nanofluids; the overall system performance must also account for air-side resistance. Further performance enhancement can be achieved through concurrent optimization of airflow conditions and fin geometry.

CONCLUSION

Combining alumina and titania nanoparticles with the water–ethylene glycol (EG) solution resulted in a notable improvement in thermal transfer efficiency of the automobile radiator. The hybrid nanofluid (0.06 vol% Al_2O_3 + 0.02 vol% TiO_2) achieved a maximum heat transfer coefficient of nearly $6,400 \text{ W/m}^2\cdot\text{K}$, representing a 155.6% enhancement

compared to distilled water and about a 60% improvement over the base water and ethylene glycol mixture. The radiator effectiveness also increased by nearly 25–47%, consistent with previously reported studies.

At nanoscale particle concentrations of 0.06 vol% Al_2O_3 and 0.02 vol% TiO_2 , the hybrid nanofluid demonstrated an overall heat transfer improvement of nearly 60% in comparison with deionized water. Additionally, the specific heat capacity of the nanofluids decreased by up to 73% relative to water, indicating faster heat absorption and dissipation, which is beneficial for dynamic thermal management applications.

The rate of heat transfer improved substantially by 27% when the volume fraction of TiO_2 changed from 0.02% to 0.06%. The heat transfer rates of the 0.08 vol% Al_2O_3 nanofluid were greater than those of the TiO_2 nanofluids at volume fractions of 0.02% and 0.06% by 27% and 49.6%, respectively. If the flow rate was enhanced to 14 L min^{-1} , there are considerable increases in the heat transfer coefficients related to both the water–ethylene glycol solutions and the nanofluids. This substantial increase in performance is beyond what would be expected from changes in both a change in physical properties and a change in thermal conductivity separately. The improvement in heat transfer is most likely due to the Brownian motion of the nanoparticles. The experimental and analytical results were comparable, and the heat transfer coefficients were similar for both Al_2O_3 and TiO_2 -based nanofluids. The rate of heat transfer in the case of hybrid nanofluids is greater when compared with mono nanofluids.

These improvements can be applied to reduce the required radiator surface area, increase cooling system compactness, and improve fuel economy through better thermal efficiency and reduced vehicle weight. The present results not only demonstrate the technical feasibility of using alumina–titania nanofluids in automobile radiators but also indicate potential applications in broader heat-exchange and energy systems. These include waste-heat recovery, electronic cooling, and renewable-energy devices where enhanced convective performance can lead to reduced energy consumption and improved operational reliability. Thus, the study offers practical relevance to both academic researchers and practicing heat engineers working on sustainable thermal management technologies.

This study presents an experimental evaluation of alumina–titania nanofluids in a real automobile radiator system, providing quantitative insights into hybrid nanoparticle interactions that enhance convective heat transfer and efficiency of the radiator in addition to the levels reported for conventional or mono nanofluids.

NOMENCLATURE

A_s	Effective surface area of the radiator, m^2
C_p	Specific heat capacity of fluid, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
d_p	Average nanoparticle diameter, nm

h	Convective heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
k	Thermal conductivity, $W \cdot m^{-2} \cdot K^{-1}$
\dot{m}	Mass flow rate of coolant, $kg \cdot s^{-1}$
Q	Rate of heat transfer, W
Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number
T_s	Average surface temperature of radiator, $^{\circ}C$ or K
T_m	Mean fluid temperature, $^{\circ}C$ or K
T_{in}	Inlet fluid temperature, $^{\circ}C$ or K
T_{out}	Outlet fluid temperature, $^{\circ}C$ or K
ΔT	Temperature difference between inlet and outlet, $^{\circ}C$ or K
ρ	Density of fluid, $kg \cdot m^{-3}$
μ	Dynamic viscosity, $Pa \cdot s$
φ	Volume fraction of nanoparticles
η	Thermal efficiency of radiator, %
ε	Radiator effectiveness
θ	Temperature difference ratio

Abbreviations

EG	Ethylene Glycol
Al_2O_3	Alumina
TiO_2	Titania
CAS	Chemical Abstracts Service
THNF	Ternary Hybrid Nanofluid
CFD	Computational Fluid Dynamics
DAQ	Data Acquisition System
XRD	X-ray Diffraction
TEM	Transmission Electron Microscopy
SEM	Scanning Electron Microscopy
UV-Vis	Ultraviolet-Visible Spectroscopy

Subscripts

f	Refers to fluid
m	Refers to medium
p	Refers to nanoparticle
nf	Refers to nanofluid

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

Authors confirm that the data that supports the findings of this study are available within the article. The raw data that supports the findings of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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