EXPERIMENTAL STUDY ON HEAT TRANSFER ENHANCEMENT USING MGO-ZNO/WATER HYBRID NANOFLUIDS IN AN AUTOMOTIVE RADIATOR

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Abstract
An ongoing demand for enhanced thermal management in modern car engines means that new coolants should be developed. Nanofluids exhibit superior thermal characteristics; however, the optimal concentration for hybrid systems that strike a balance between the benefits of enhanced heat transfer and the drawbacks of higher viscosity and increased pumping power remains unknown. This work tackles this issue by experimentally examining the thermo-hydraulic performance of MgO-ZnO/water hybrid nanofluids at low volumetric concentrations (0.02%, 0.04%, and 0.06%) within the automotive radiator. At a concentration of 0.06%, the most significant increase in the convective heat transfer coefficient was 42.3%. However, the 0.04% concentration represents the best compromise between thermal performance and operational cost. Higher concentrations result in a disproportionately significant increase in viscosity and pumping power penalties for only minor improvements in heat transfer, which reduces the net practical advantage. The 0.04% concentration, which yields a 32.5% improvement, nonetheless outperforms the individual mono-nanofluids, which require significantly higher concentrations to achieve the same results.
Keywords: Nano-particles, Nanofluid, Thermal performance, Base fluid, Heat transfer, Radiator.

1. INTRODUCTION

Nanofluids with their superior thermal and hydrodynamic properties have proven effective in automotive thermal management. They enhance radiator performance by improving heat transfer and reducing vehicle weight. Recent studies have shown that hybrid nanofluids outperform mono-nanoparticle-based fluids, especially when used with water–ethylene glycol mixtures. This chapter reviews recent advancements in using hybrid nanofluids for automotive radiator applications (Malika et al., 2025). A cooling system is used to remove this excess heat. Most automotive cooling system consists of the following components: radiator, water pump, electric cooling fan, radiator pressure cap, and thermostat (Peyghambarzadeh et al., 2011). As coolant travels through the engine's cylinder block, it accumulates heat. Once the coolant temperature exceeds a certain threshold value, the vehicle's thermostat activates a valve that forces the coolant to flow through the radiator. As the coolant flows through the radiator's tubes, heat is transferred through the fins and tube walls to the air by conduction and convection. Rapid heat transfer has become a growing engineering discipline over the years. Researchers are working tirelessly to improve heat transfer rate and thermal conductivity while also reducing frictional loss, pressure drop, and pumping power for heat transfer

fluid. In recent years, conventional heat transfer fluids, such as water, mineral oils, and ethylene glycol, have been widely used as coolants in automotive radiators. A new type of heat transfer fluid has been engineered, providing improved thermal properties for enhanced heat transfer, known as nanofluid (A. R. I. Ali & Salam, 2020). Vidhya et al. (2021) prepared hybrid nanofluids (ZnO-MgO/ethylene glycol (EG)-water) at various concentrations (0%, 0.0125%, 0.025%, 0.05%, 0.075%, and 0.1%). The thermal resistance of nanofluids was reduced by 4.07 %, while the heat transfer coefficient improved by 28.9 %. Bargal et al. (2025) investigated recent advancements in using nanofluids as coolants in automotive radiators to enhance engine performance and reduce emissions. It covers nanofluid mechanisms, synthesis methods, and thermohydraulic performance, based on factors such as particle type, size, concentration, and flow rate. Results show that hybrid nanofluids (e.g., Al_2O_3/TiO_2, SiC/MWCNTs) can improve thermal performance by 6.3–124%, with optimal results achieved at volume concentrations of 0.05–2%. While nanofluids show great potential, further research is necessary to overcome the current challenges for their widespread application. Khan et al. (2019) analyzed the effect of a 0.04% volume concentration of ZnO/EG-water nanofluid, finding a maximum rise in heat transfer rate of up to 36%. They also found that the heat transfer

rate is greater at low flow rates (such as 4 LPM and 6 LPM) than at higher flow rates. Abbas et al. (2021) tested three hybrid nanoparticle (Fe_2O_3-TiO_2/water) concentrations (0.005 vol.%, 0.007 vol.%, and 0.009 vol.%). The effect of intake temperature and fluid velocity on the heat transfer rate was investigated by adjusting the inlet temperature from 48°C to 56°C and the flow rate from 11 L/min(LPM) to 15 L/min. The heat transfer rate increased by a maximum of 26.7% at an inlet temperature of 56 °C, a flow rate of 15 LPM, and a nanoparticle concentration of 0.009 vol. percent. Under the aforementioned operating conditions, the Nusselt number increased by 20.03%. Li et al. (2021) utilized a SiC-MWCNTs (multi-walled carbon nanotubes)/EG hybrid nanofluid with varying volume concentrations. The maximum enhancement in the hybrid nanofluids at 0.4 vol. percent was determined to be 32.01%. The viscosity rose as particle loading increased, but decreased as temperature increased. Under the same circumstances, the maximum convective heat transfer coefficient of SiC-MWCNTs nanofluids was 26% higher than that of pure EG. Ramadhan et al. (2020) experimentally investigated the heat transfer properties of Al2O3-TiO2-SiO2-based water/ethylene glycol mixtures and compared them to a water/ethylene glycol mixture. They created four distinct nanofluid concentrations by dispersing tri-hybrid nanofluid nanoparticles in a water/ethylene glycol combination at concentrations ranging from 0.05 to 0.3 vol.%. At a volume concentration of 0.3%, the greatest enhancement of the heat transfer coefficient for the coolant side is 39.7%. Okello et al. (2020) investigated three different types of ethylene glycol-based hybrid nanofluids (Cu-Al_2O_3), (Cu-TiO_2), and (TiO_2-Al_2O_3) to determine their cooling capacities for industrial cooling purposes. According to the findings, the (Cu-Al_2O_3)/EG hybrid nano-coolant causes a quick decrease in temperature at the boundary layer. Benedict et al. (2020) evaluate the performance of mono- or hybrid metal oxides, such as Al2O3 and TiO2, with or without plant-based-extracted nanocellulose at varying concentrations as a better heat transfer nanofluid for distilled water as a radiator coolant. The maximum absorption peak was seen at 0.9% volume concentration of TiO_2, Al_2O_3, Al_2O_3/TiO_2, and Al_2O_3 nanofluids, indicating improved suspension stability. They found that the thermal conductivity of Al_2O_3 hybrid nanofluids with 0.9% volume concentration was higher than that of Al_2O_3/TiO_2 hybrid nanofluids. Sahoo et al. (2017) analyzed the thermal performance of a louvered fin vehicle radiator employing a water-based (50/50) volume proportion of Fe_2O_3, CuO, TiO_2, Ag, and Cu in Al_2O_3 hybrid nanofluids as coolants. They found that Al_2O_3-Ag/water hybrid nanofluid has greater effectiveness, heat transfer rate, pumping power, and pressure drop than water by 0.8%, 3%, 6%, and 5.6%, respectively, and is followed by (50/50) volume fraction

of Cu, CuO, Fe_2O_3, TiO_2 hybrid nanofluids as radiator coolant. Hassaan, (2024) tested MWCNT–Al_2O_3/water hybrid nanofluid in a Honda radiator and found up to 28.5% improvement in heat transfer, with increases of 22.54% in effectiveness and 23.74% in Nusselt number. Pressure drop rose by up to 24%. The results matched those of previous studies, and a correlation was established for predicting the Nusselt number. Naiman et al. (2019) analyzed radiator performance at high coolant temperatures below 80°C, as well as comparative data from experimental and one-dimensional analytic data. They found the thermal conductivity values were maximal at 0.9% concentrations. Ahmed et al. (2018) used TiO_2 nanofluids with volume concentrations of 0.1%, 0.2%, and 0.3% in trials conducted at flow rates ranging from 0.097 to 0.68 m³/h, with Reynolds numbers varying from 560 to 1650. They found that the effectiveness of a car radiator may be increased by 47% when using a 0.2% concentration of TiO_2-water nanofluid compared to 0.1 and 0.3% concentrations of TiO_2-water nanofluid and pure water as a coolant. Ramadhan et al. (2022) used tri-hybrid nanofluids mixed in a water/ethylene glycol (60:40) solution to create four distinct nanofluid concentrations ranging from 0.05 to 0.3 vol.%. To investigate the impact of coolant flow rate on heat transfer, they conducted experiments with flow rates ranging from 2 to 12 LPM at a working temperature of 70°C, while maintaining an average airflow velocity of 4 m/s. They found the greatest improvement in the heat transfer coefficient for the air side to be up to 23.8% at a 0.05% volume fraction and 39.7% at a 0.3% volume fraction. Rashidi et al. (2024) examined a graphene oxide–silicon oxide hybrid nanofluid in a water-ethylene glycol base for car radiators. Tests with volume fractions of 0.1–1.0% and flow rates of 3–7 LPM demonstrated improved heat transfer and Nusselt numbers with increased flow and concentration. Karana & Sahoo, (2018) used coolants for an automotive Thermoelectric Generator (TEG) waste heat recovery system found that nanofluid provides the highest performance enhancement over nanofluid and specifically nanofluid (at volume fraction) increased power output by and conversion efficiency by compared to. This is because nanofluid achieves a lower cold-side temperature, resulting in a higher temperature gradient across the TEGs. Crucially, using nanofluid allows the optimal total area of TEGs to be reduced by up to, leading to lower system cost and easier arrangement. Performance metrics consistently improved with increasing concentration, Reynolds number, and exhaust inlet temperature. Giwa et al. (2021) conducted experiments with hybrid nanofluids containing MgO and ZnO nanoparticles in water, demonstrating a significant improvement in heat transfer performance compared to traditional fluids. Their enhanced thermal conductivity and convective

heat transfer properties make them suitable for applications such as automotive radiators. Optimizing nanoparticle concentration and size can improve efficiency by up to 40%. However, managing the increased viscosity and pressure drop requires careful attention. Stability and dispersion techniques are crucial for maintaining effectiveness in practical use. These nanofluids hold promise for advanced thermal systems, but further research is needed for their widespread application. Nazir et al. (2024) incorporated ZnO–MgO nanoparticles into base fluids to create hybrid nanofluids (HNFs), which have been demonstrated to significantly enhance thermal conductivity. Research indicates that the thermal conductivity of these HNFs increases with temperature, nanoparticle size reduction, and optimized mixing ratios, particularly around a 40:60 ratio of MgO to ZnO. Experimental results report improvements up to 31% over the base fluid at elevated temperatures (~50°C). These enhancements result from improved nanoparticle dispersion, increased Brownian motion, and synergistic effects between the metallic oxides. Consequently, ZnO–MgO-based HNFs represent a promising advancement for high-efficiency heat transfer applications in various industrial thermal systems.

Most previous studies on hybrid nanofluids have focused on higher concentrations or different nanoparticle combinations, often overlooking the practical challenges of cost, stability, and availability. In Bangladesh, the high cost and limited availability of nanoparticles hinder their large-scale implementation, necessitating the investigation of low concentrations for economic feasibility. Furthermore, issues such as ensuring the long-term stability of nanofluids, as their thermophysical properties may vary over time, and the time-consuming preparation process have not been adequately addressed in earlier works. Experimental challenges, including inevitable heat loss through insulation, difficulty in maintaining a constant flow rate, and the inability to obtain absolute experimental data due to practical constraints, further highlight the gap between theoretical studies and real-world applications. MgO and ZnO are both metal oxides renowned for their robust thermal conductivity, chemical stability, and ability to enhance heat transfer in nanofluid applications (H. Ali et al., 2015). Studies have demonstrated that both materials exhibit enhanced dispersion stability in water compared to denser metallic nanoparticles, a quality crucial for practical applications (Nazir et al., 2024). Research into the synergistic thermal effects of this particular combination is in its early stages, although adjacent domains have demonstrated encouraging connections. For example, when creating piezoelectric materials, it has been demonstrated that combining MgO with ZnO exhibits a synergistic effect, meaning that the two materials work more effectively together than they do individually (Bodhi T K et al., 2025). This study was thus formulated to examine the potential for a comparable synergistic increase of the thermophysical parameters associated with convective heat transfer.

Our experiment primarily focused on synthesizing stable MgO-ZnO/water hybrid nanofluids at low volumetric concentrations using the ball milling method and investigating how to enhance the heat transfer process by adding hybrid nanoparticles to the conventional coolant in the radiator case. Three volumetric concentrations (0.02%, 0.04%, and 0.06%) of hybrid nano fluid were implemented in an experimental setup consisting of a radiator to analyze the impact of different concentrations of nano fluid on convective heat transfer coefficient, Nusselt number, friction factor, pressure drop, and heat transfer rate. By focusing on specific low concentrations of MgO-ZnO/water hybrid nanofluid in radiator systems, this study directly addresses these overlooked aspects, aiming to identify an optimum concentration that balances enhanced heat transfer performance with cost-effectiveness and practical applicability.

2. MATERIALS AND METHODOLOGY
2.1 Preparation of Hybrid Nanofluid
Commercially available MgO and ZnO micro-sized (purity 99.9%) powders were sourced from the Research lab in India. To achieve a nano-sized powder from a micro-sized one, we followed a top-down approach, such as ball milling. In this study, planetary ball milling was performed at ambient temperature and pressure. Two identical containers were used to ensure proper balance during high-speed rotation, and 10g of the powder sample was placed in each container. Ball milling parameters for both powder samples are tabulated in Table 1. Prommalikit et al. and many others followed these parameters of ball milling to reduce the particle size of MgO and ZnO micro-sized powder to less than 100nm (Prommalikit et al., 2019). After ball milling, the milled powder was dried in an oven at 100°C for 12 hours to remove moisture. Then, MgO and ZnO were calcined in a muffle furnace to get better crystallinity at 650 °C and 450 °C, respectively, for 2 hours. The calcined nanoparticles of MgO and ZnO were weighed to make the desired concentration of hybrid nanofluid. Initially, nanoparticles were mixed with the distilled water using a magnetic stirrer. To achieve enhanced dispersion and stability of nanoparticles in the base fluid, ultrasonication was performed using an ultrasonicator (Joanlab UC20D, 60W) with an operating frequency of 40kHz.

TABLE 1: Parameters of Ball Millin

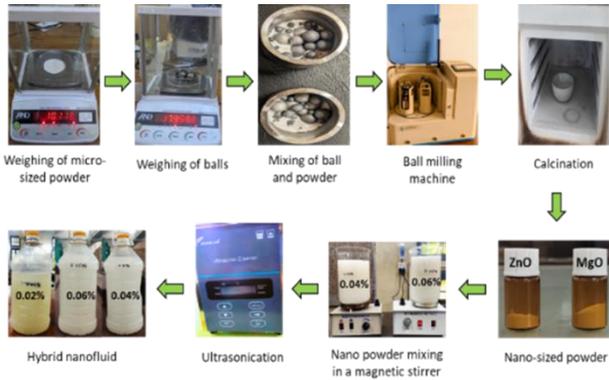| Parameter	Value	Remarks
Container material	-	Stainless steel
Ball material	-	Stainless steel
Ball size (mm)	4, 6, 8, 12, 16	-
Ball to powder weight ratio	15:1	-
Rotational speed (rpm)	400	-

Fig. 1. Preparation of hybrid nanofluid

Abbas et al. (2021) employed the following equation for the volume concentration of nanofluids.

$$\varphi_{p1} = \left[\frac{\frac{m_{p1}}{\rho_{p1}}}{\frac{m_{p1}}{\rho_{p1}} + \frac{m_{bf}}{\rho_{bf}}} \right] \times 100 \qquad (1)$$

$$\varphi_{p2} = \left[\frac{\frac{m_{p2}}{\rho_{p2}}}{\frac{m_{p2}}{\rho_{p2}} + \frac{m_{bf}}{\rho_{bf}}} \right] \qquad (2)$$

Here, φ_{p1} = Volume concentration of MgO nanoparticle, φ_{p2} = Volume concentration of ZnO nanoparticle, m_{p1} = Mass of MgO nanoparticle, m_{p2} = Mass of ZnO nanoparticle, m_{bf} = Mass of base fluid, ρ_{p1} = Density of MgO nanoparticle, ρ_{p2} = Density of MgO nanoparticle, ρ_{bf} = Density of the base fluid

Sahoo et al. (2017) used the following equation to calculate the overall volume concentration of hybrid nanofluid.

$$\varphi_p = \varphi_{p1} + \varphi_{p2} \qquad (3)$$

Here, φ_p=Overall volume concentration of hybrid nanofluid

To prepare MgO-ZnO (1:1)/water hybrid nanofluids, MgO and ZnO nanofluids were first synthesized separately in equal volumes at half of the desired final concentration, and then mixed. Accordingly, 0.01 vol% MgO and ZnO nanofluids were combined to obtain 0.02 vol% hybrid nanofluid, 0.02 vol%. MgO and ZnO nanofluids were mixed to prepare 0.04 vol% hybrid nanofluid, and 0.03 vol% MgO and ZnO nanofluids were blended to achieve 0.06 vol% hybrid nanofluid.

2.1.1 Density of hybrid nanofluid

For the density, the equation is collected from Takabi & Salehi, (2014).

TABLE 2: Thermophysical Properties of Nanofluid used in the Experiment

Parameters	Values
Radiator length	0.40 m
Radiator height	0.37 m
Radiator width	0.015 m
Tube length	0.37 m
Tube height	0.003 m
Tube width	0.015 m
Tube thickness	0.0001 m
Number of tubes	37

$$\rho_{hnf} = (1 - \varphi_p)\rho_{bf} + \varphi_{p1}\rho_{p1} + \varphi_{p2}\rho_{p2} \qquad (4)$$

2.1.2 Specific heat capacity of hybrid nanofluid

Abbas et al. (2021) used the following equation to calculate the Specific heat capacity of the hybrid nanofluid.

TABLE 3: Measured Parameters of Radiator

Properties	Base fluid	0.02% MgO-ZnO/water	0.04% MgO-ZnO/water	0.06% MgO-ZnO/water
Density, ρ (kg/m³)	978	1050.34	1122.68	1195.02
Specific heat, Cp (J/kg.K)	4200	3896.68	3632.55	3400.21
Dynamic viscosity, μ (Pa.s)	4.035×10^{-4}	4.056×10^{-4}	4.062×10^{-4}	4.067×10^{-4}
Thermal conductivity, K (W/m·K)	0.6100	0.646	0.684	0.723

$$(C_p)_{hnf} = \frac{(1-\varphi_p)(C_p)_{bf}\rho_{bf} + \varphi_{p1}C_{p1}\rho_{p1} + \varphi_{p2}C_{p2}\rho_{p2}}{\rho_{hnf}} \qquad (5)$$

2.1.3 Thermal conductivity of hybrid nanofluid

The thermal conductivity of the hybrid nanofluid was calculated by the equation given by Hamilton et al. (Hamilton & Crosser, 1962) .

$$k_{hnf} = \left[\frac{\frac{\varphi_{p1}k_{p1} + \varphi_{p2}k_{p2}}{\varphi_p} + (n-1)(\varphi_{p1}k_{p1} + \varphi_{p2}k_{p2}) - (n-1)\varphi_p k_{bf}}{\frac{\varphi_{p1}k_{p1} + \varphi_{p2}k_{p2}}{\varphi_p} + (n-1)\varphi_p k_{bf} - (\varphi_{p1}k_{p1} + \varphi_{p2}k_{p2}) + \varphi_p k_{bf}} \right] \times k_{bf} \quad (6)$$

2.1.4 Dynamic viscosity of hybrid nanofluid

The following correlation was given by Akilu et al. (2018) to find the dynamic viscosity of a hybrid nanofluid.

$$\frac{\mu_{hnf}}{\mu_{bf}} = 0.9894 \left[1 + \frac{\varphi_p}{100} \right]^{6.6301} \times \left[\frac{T_{hnf}}{T_o} \right]^{0.064} \quad (7)$$

Here,
T_{hnf} = Temperature of hybrid nanofluid

2.2 Block Diagram
Figure 2 shows the schematic layout of the experimental setup of this study. On the bottom side of the setup, the working fluid is sucked by a centrifugal pump, which adds kinetic energy to the fluid to ensure proper circulation and pressure. It is a closed-loop system. The fluid enters the radiator at the inlet temperature T_{in}, where heat is dissipated to the atmosphere. The radiator wall temperature, T_{wall}, is measured to evaluate thermal performance, whereas the outlet fluid temperature, T_{out}, is recorded after heat rejection through the radiator.

2.3 Experimental Setup
Figure 3 illustrates the actual experimental setup, which is used to investigate the thermal performance of the radiator system. The working fluid is stored in a collection tank equipped with an electric heater to maintain the desired fluid inlet temperature of the radiator and pumped by a centrifugal pump. The flow rate of the fluid is measured using a rotameter installed after the pump and a ball valve is just before rotameter to regulate the flow rate of the system. Heat is rejected from the heated fluid in the radiator through forced convection. A fan mounted behind the radiator provides forced air across the radiator surface to enhance convective heat transfer. After dissipation of heat, the cooled working fluid is returned to the collection tank.
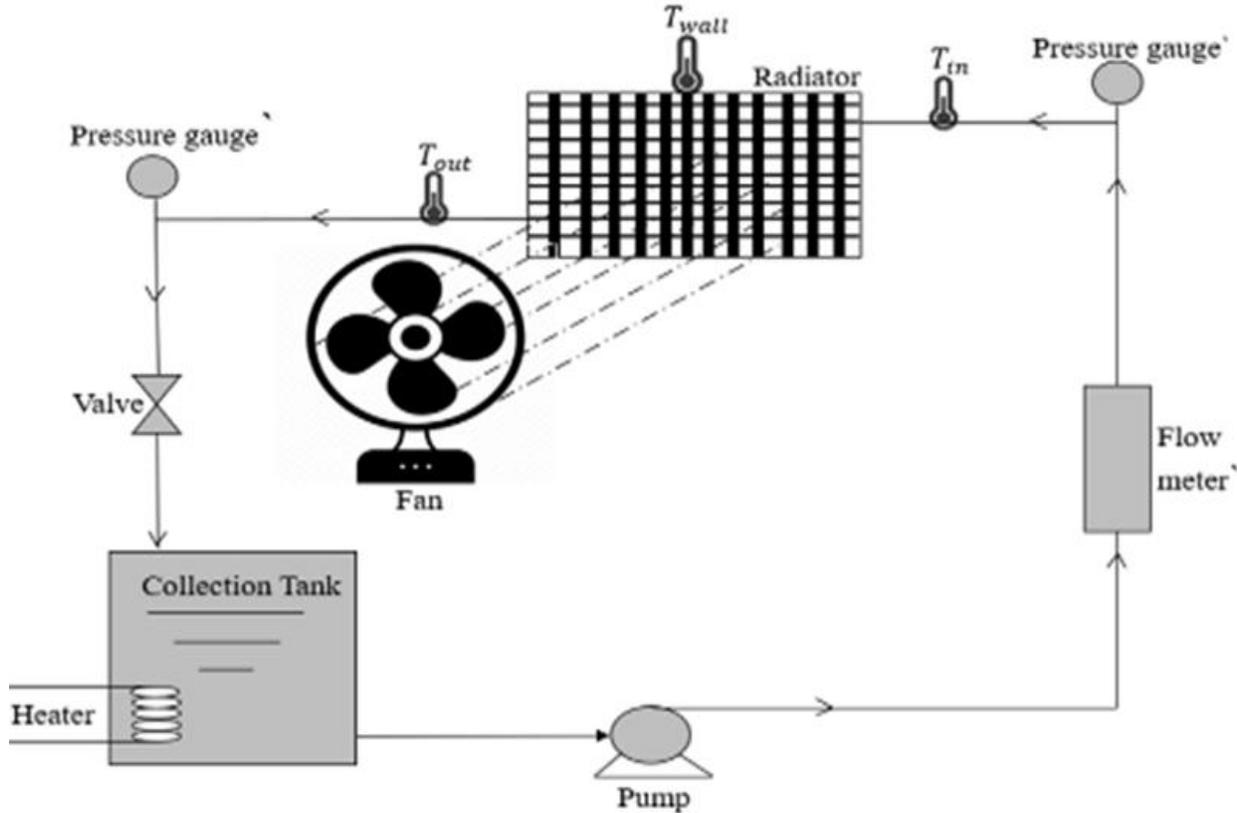

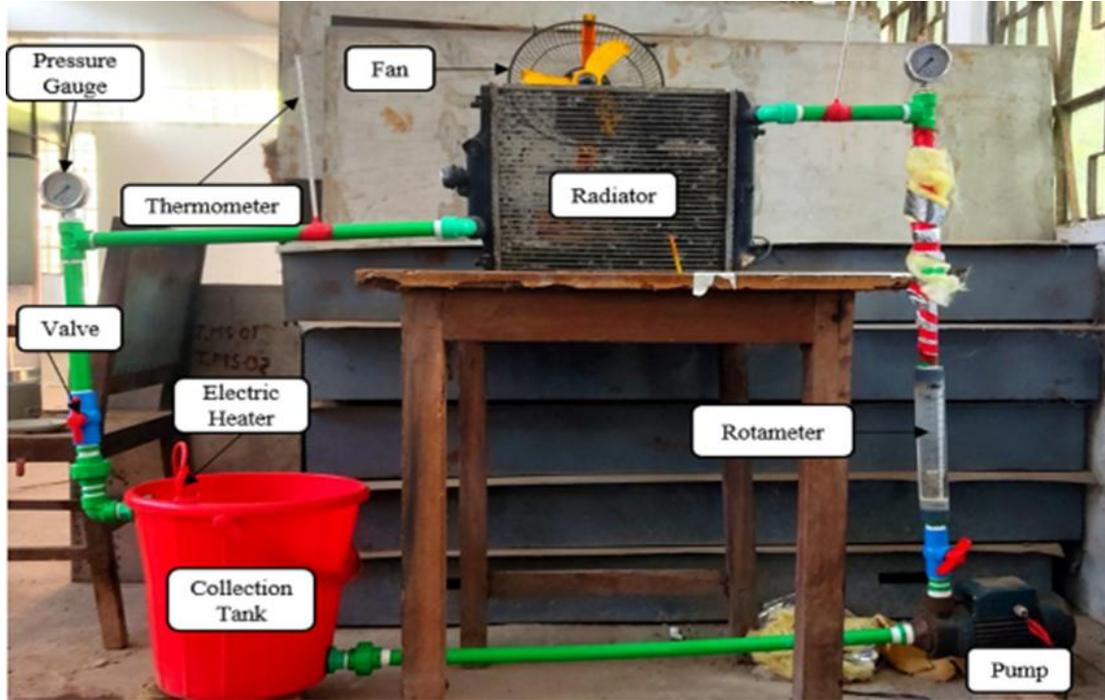**Fig. 2.** Flow chart of the experiment

Fig. 3. Front view of the experimental setup

2.4 Mathematical Equation

From the cooling law (Newton's cooling law), the Heat transfer rate was given by,

$$Q_{hnf} = h_{in} A_{in} \Delta T = h_{in} A_{in} \left((T_b)_{hnf} - (T_w)_{hnf} \right) \quad (8)$$

$(T_b)_{hnf}$ = Bulk fluid temperature = $\dfrac{(T_{in})_{hnf} + (T_{out})_{hnf}}{2}$ (9)

$(T_w)_{hnf}$ = Average surface temperature of radiator wall
$= \dfrac{T_1 + T_2 + \cdots + T_6}{6}$ (10)

The heat transfer coefficient of the hybrid nanofluid was calculated from,

$$\dot{Q}_{hnf} = m_{hnf} (C_p)_{hnf} \Delta T = \dot{m}_{hnf} (C_p)_{hnf} \left((T_{in})_{hnf} - (T_{out})_{hnf} \right) \quad (11)$$

The heat transfer coefficient of air was calculated from,

$$\dot{Q}_a = m_{air} (C_p)_{air} \Delta T = \dot{m}_{air} (C_p)_{air} \left((T_{in})_{air} - (T_{out})_{air} \right) \quad (12)$$

Now, for the calculation of Nusselt no, the equation given by:

$$Nu_{exp} = \frac{(h_{in})_{exp} D_h}{k_{hnf}} = \frac{\dot{m}_{hnf}(C_p)_{hnf} \left((T_{in})_{hnf} - (T_{out})_{hnf} \right)}{A_{in} \left((T_b)_{hnf} - (T_w)_{hnf} \right)} \quad (13)$$

The calculation for the Reynolds number was given by,

$$(R_e)_{hnf} = \frac{\rho_{hnf} V_{hnf} D_h}{\mu_{hnf}} \quad (14)$$

For the Friction factor, the equation was given by:

$$C_f = \frac{2 D_h \, \Delta P}{L \, \rho_{hnf} V_{hnf}^2} \quad (15)$$

And Prandtl number, $P_r = \dfrac{\mu_{hnf} (C_p)_{hnf}}{k_{hnf}}$ (16)

All the properties were measured at bulk temperature. For the validation, the experimental setups "Dittus-Boelter correlation" and "Gnielinsky correlation" are given below: (Dittus & Boelter, 1985)

$$Nu = 0.0236 \, Re^{0.8} Pr^{0.3}$$

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000) Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{0.5} \left(Pr^{\frac{2}{3}} - 1\right)} \quad (17)$$

$$f = (0.79 \, lnRe - 1.69)^{-2} \quad (18)$$

3. RESULTS AND DISCUSSION

3.1 Graphical Representation

Properties of the heat transfer coefficient, Nusselt number, pressure drop, and pumping power have been observed. The change in these parameters has been graphically demonstrated. The variation in the heat transfer coefficient is illustrated in Figure 5. It has been found that as the Reynolds number increases, the heat transfer coefficient also increases. The convective heat transfer coefficient significantly increases with the increase in volume concentration (%) of MgO-ZnO in water.

Figure 5 shows the validation between the experimental setup and the Dittus-Boelter correlation. The experimental Nusselt numbers for water closely follow the Dittus-Boelter correlation with nearly parallel slopes, which is reasonable for a heat exchanger given minor heat losses and property evaluation. In the present study, three different volume concentrations (0.02%, 0.04%, 0.06%) of MgO-ZnO/Water hybrid nanofluid were investigated, showing progressive heat transfer coefficient enhancements of 23.4%, 32.5%, and 42.3% respectively, attributed to increased surface area, higher thermal conductivity, and Brownian motion effects of nanoparticles.

Figure 6 plots the convective heat-transfer coefficient h against the Reynolds number and shows an apparent rise in h as the flow rate (Re) increases for all fluids; the nanofluids always sit above water, with the following order: 0.06% > 0.04% > 0.02% > water. This occurs because a faster flow creates stronger turbulence, which thins the thermal layer at the wall and transfers heat away more quickly. Nanoparticles lift h further by raising the effective thermal conductivity and slightly disturbing the near-wall region. The trade-off is that higher particle loading also raises viscosity, so at the same velocity, Re falls, friction and pressure drop rise, and pumping power and operating costs increase. Additionally, it increases the risk of settling, which results in fouling and extra maintenance. Because the gain from 0.06% to 0.04% is small, while these penalties increase, 0.04% offers a better balance of substantial heat-transfer improvement with more acceptable pressure drop, energy use, and reliability for long-term operation.

Figure 7 shows that the experimental Nusselt number increases with Reynolds number for all fluids, and the nanofluids sit above water in the order 0.06% > 0.04% > 0.02% > water. The rise with Re occurs because the flow becomes faster.
Turbulence, thins the thermal boundary layer, and moves heat away from the wall more quickly. Nanoparticles lift Nu further by raising the effective

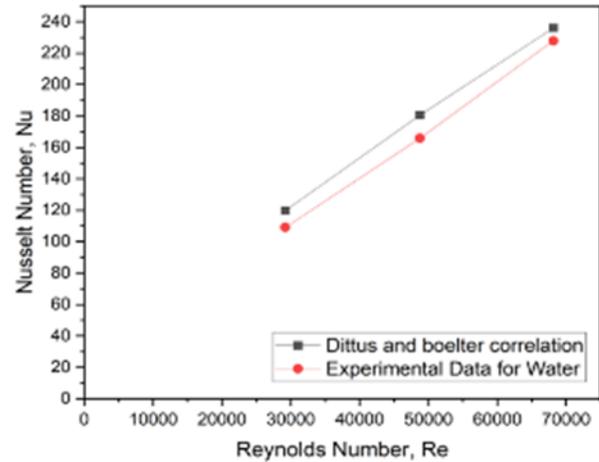thermal conductivity and slightly disturbing the near-wall region.

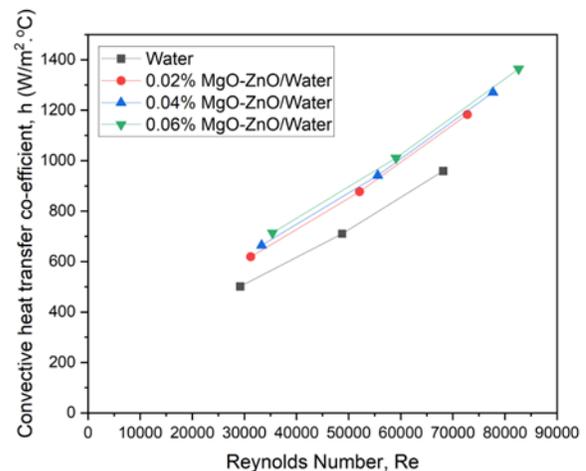**Fig. 5.** Comparison of experimental results with the correlation of Dittus and Boelter.

Fig. 6. Variation of the Convective heat transfer coefficient with Reynolds number

suspensions in water exhibit the friction factor f drops as the Reynolds number rises, and that all nanofluids have higher than water in the order 0.06% > 0.04% > 0.02% > water. The fall of f with Re is typical of turbulent pipe flow. The higher f for nanofluids primarily stems from their higher viscosity and additional momentum loss near the wall. Particles thicken the near-wall layer, acting like very fine roughness, which increases drag even at the same Re. As a result, the pressure drop increases and the pumping power rises. These hydraulic penalties increase with concentration: 0.06% exhibits the largest drag, while 0.04% yields a smaller penalty and still provides substantial heat-transfer gains. Thus, for practical heat exchangers, 0.04% offers a better trade-off between higher heat transfer and acceptable pressure drop/energy use.
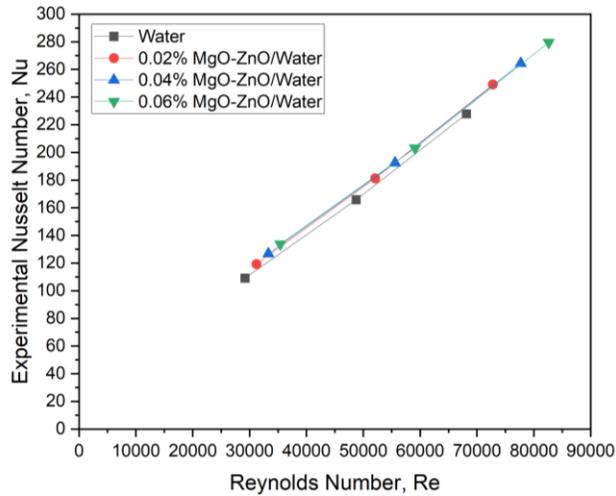
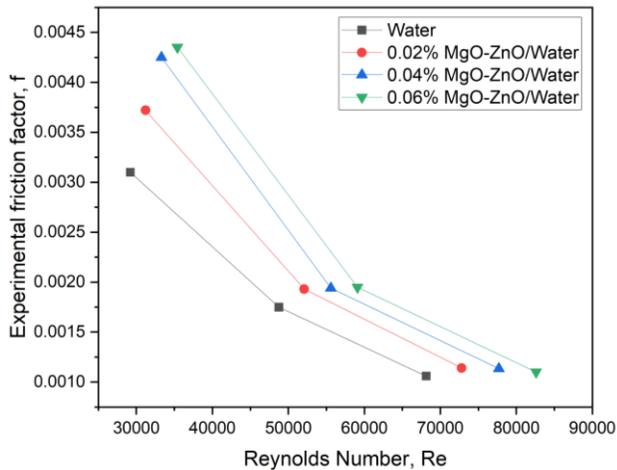**Fig. 7.** Variation of Nusselt number with Reynolds number

Fig. 8. Variation of friction factor with Reynolds number

The variation of pressure drops with Reynolds number, as shown in Figure 9, reveals critical trade-offs in nanofluid applications. Pressure drop increases linearly with the Reynolds number for all fluids; however, the introduction of nanoparticles significantly amplifies this effect due to increased fluid viscosity and altered flow characteristics. Pure water exhibits the lowest pressure drop, while the 0.06% MgO-ZnO/Water hybrid nanofluid shows the highest-pressure penalty, representing approximately a 65-26% increase over water across the Reynolds range of 30,000-80,000. The intermediate concentrations (0.02% and 0.04%) demonstrate proportional pressure penalties, creating a critical engineering trade-off. While higher nanoparticle concentrations provide superior heat transfer enhancement (42.3% for 0.06%), they

simultaneously impose substantial pumping power penalties that can offset thermal benefits. Since pumping power rises almost cubically with pressure drop, the 0.06% concentration requires significantly more energy to maintain the same flow rate. This extra energy requirement can offset its substantial heat transfer benefits, making it less practical in real applications. For this reason, the ideal nanofluid concentration must strike a balance—boosting thermal performance without imposing excessive hydraulic costs. At a concentration of 0.04%, this balance is achieved, delivering approximately a 32.5% improvement in heat transfer while keeping the rise in pressure drop within reasonable limits.
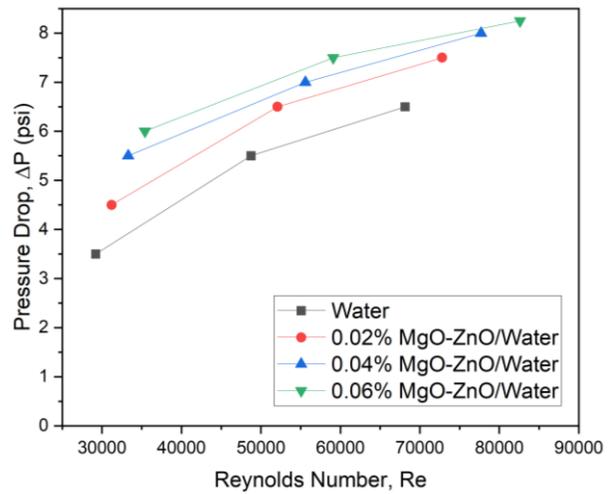

Fig.9. Variation of pressure drop with Reynolds number

This makes it the most practical choice, ensuring an optimal trade-off between heat transfer efficiency and pumping power requirements. As the flow speed increases, the dynamic pressure term grows rapidly, while the friction factor decreases only mildly with Re. Therefore, the pressure difference increases with Reynolds number (Re). Nanofluids sit above water because particles increase viscosity, which requires a higher velocity to achieve the same Reynolds number (Re); they also require a higher velocity, both effects pushing the pressure difference higher. Figure 10 demonstrates the relationship between pumping power and heat transfer rate for pure water and three MgO–ZnO nanofluid concentrations. The results show a clear, near-linear increase in heat-transfer rate with pumping power for all fluids, with nanofluids consistently outperforming water. The 0.06% mixture achieves the highest rate compared to water, while the 0.02% and 0.04% mixtures yield intermediate gains. Higher pumping power means higher flow velocity, which in turn increases the Reynolds number; this strengthens turbulence, thins the thermal layer at the

wall, raises the convective heat transfer coefficient (h), and therefore enhances heat transfer adding nanoparticles further lifts Q because they increase the effective thermal conductivity and slightly disturb the near-wall region, which boosts h at the same pumping power. At very high loading, viscosity increases, and the additional power cost rises, so the performance gains can start to level off. Overall, the trend confirms that MgO–ZnO nanofluids deliver more heat per watt of pumping than water across the tested range.
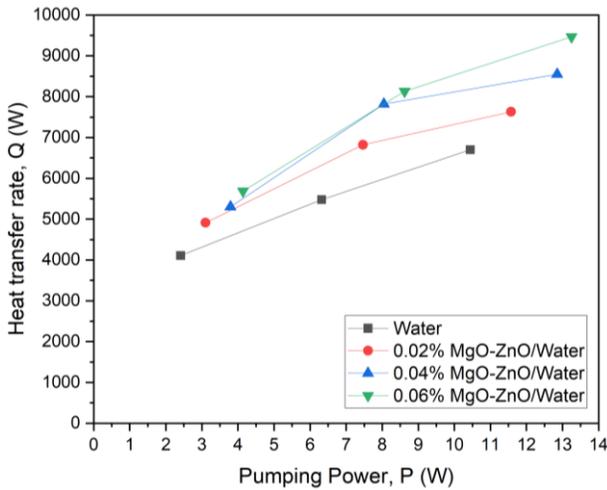

Fig. 10. Variation of heat transfer rate with pumping power

Figure 11 quantifies the increase in heat-transfer coefficient resulting from the addition of MgO–ZnO particles compared to water, with gains of approximately 23.4% (0.02%), 32.5% (0.04%), and 42.3% (0.06%). This increase with concentration occurs because nanoparticles raise the effective thermal conductivity and disturb the near-wall region, which boosts the convective coefficient h and, therefore, the Nusselt number. In our tests, the only operating parameter varied was the flow rate.

Figure 12 shows that for 0.02%, 0.04%, and 0.06% MgO-ZnO/Water hybrid nanofluid compared to water, the Nusselt number increases by 9.3%, 16.1%, and 22.5%, respectively. The Nusselt number is a dimensionless parameter that represents the ratio of convective to conductive heat transfer, so these increases directly indicate improved convective heat transfer performance of the nanofluids. The progressive enhancement pattern indicates that adding MgO-ZnO nanoparticles significantly enhances the fluid's ability to transfer heat through convection, likely due to improved thermal conductivity, increased surface area for heat exchange, and enhanced fluid mixing caused by the motion of nanoparticles. The substantial 22.5% improvement at the highest concentration demonstrates the effectiveness of MgO-

ZnO nanofluids in enhancing heat transfer systems, making them highly valuable for thermal management applications where improved heat transfer efficiency is critical. Adding MgO–ZnO raises the fluid's effective thermal conductivity and slightly disturbs the thin thermal layer at the wall, so heat is carried away faster. The moving particles also promote tiny mixing effects near the wall, which further help heat transfer. At the same time, higher loading increases viscosity, which can lower Re at a given velocity and damp some turbulence. As we add more particles, the benefits continue to grow but level off, reaching a maximum of about 22.5% at a concentration of 0.06%.
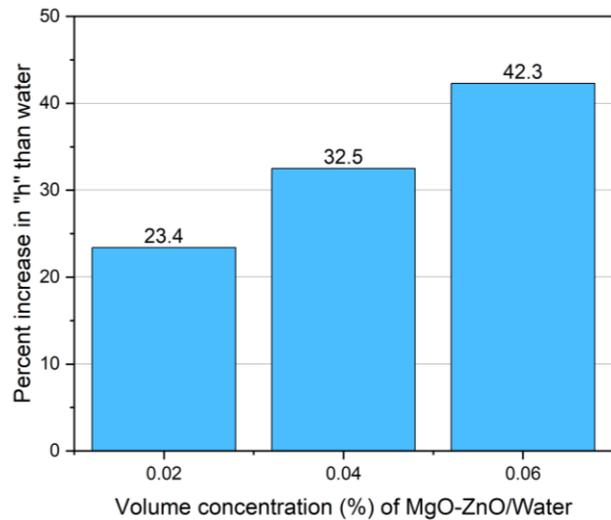

Fig. 11. Percent increase in heat transfer coefficient

The study primarily presents initial performance results showing enhancement in heat transfer coefficients and Nusselt numbers at various nanoparticle concentrations. However, it acknowledges that the addressed scientific knowledge gap lacks comprehensive long-term durability and practical operational data. The thermophysical characteristics and performance over prolonged use periods remain unexplored, which limits immediate confidence in engineering applications. The long-term stability and clogging risk of nanofluids, while a challenge, can be framed positively as a driver for innovation and progress in the field. The recognition of these hurdles has led to the development of advanced preparation and stabilization techniques, such as the use of surfactants and high-pressure homogenization, which significantly improve nanoparticle dispersion and prevent aggregation or sedimentation. These methods have already demonstrated the ability to extend nanofluid stability for months under optimal conditions, making practical application increasingly feasible. Importantly, this study has already implemented

ultrasonication during the nanofluid preparation step. Ultrasonication is a proven, highly effective method for breaking up nanoparticle agglomerates and achieving a uniform, stable suspension. By applying ultrasonic energy, the nanoparticles are dispersed more evenly throughout the base fluid, which not only enhances initial stability but also improves the thermal performance of the nanofluid.
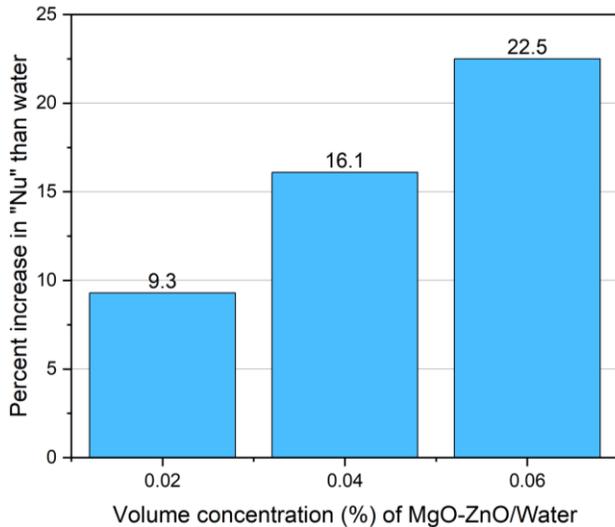

Fig. 12. Percent increase in Nusselt number

For future research, several recommendations can be made to enhance experimental reliability and expand the study's scope. The use of thermocouples with higher accuracy is advised to ensure precise temperature measurements. Further investigation could include the application of other nanofluids as well as tri-hybrid nanofluids to explore their comparative performance. Moreover, incorporating surfactants is suggested to enhance the stability and uniform dispersion of nanoparticles within the base fluid, resulting in more consistent and efficient heat transfer behavior.

4. CONCLUSION

The study's findings reveal several key trends in the heat transfer performance of MgO-ZnO/water hybrid nanofluids. Firstly, both the Nusselt number and the convective heat transfer coefficient were found to increase with rising Reynolds number, highlighting enhanced thermal performance at higher flow rates. When comparing different volume concentrations—0.02%, 0.04%, and 0.06%—of the MgO-ZnO/water hybrid nanofluid, all demonstrated superior heat transfer characteristics over pure water. Among them, the 0.06% concentration achieved the highest enhancement, with a remarkable 42.3% increase in the convective heat transfer coefficient and a 22.5%

increase in the Nusselt number at a flow rate of 14 L/min. On the fluid dynamics side, the friction factor decreased as the Reynolds number increased, while the pressure drops exhibited an upward trend with rising Reynolds numbers. Additionally, the overall heat transfer rate was found to improve with an increase in pumping power. Importantly, for a given pumping power, a higher volumetric concentration of hybrid nanofluid yielded a significantly better heat transfer rate, emphasizing the effectiveness of nanofluids in thermal systems.

However, 0.04% volume concentration of MgO-ZnO/water hybrid nanofluid represents the optimal balance between enhanced heat transfer performance and manageable hydraulic penalties. While higher concentrations, such as 0.06%, provide slightly greater heat transfer improvements, they also cause disproportionately higher increases in viscosity, pressure drop, and pumping power, which in turn raise energy consumption and operational costs. Conversely, lower concentrations yield less thermal benefit. Therefore, 0.04% achieves the best trade-off by delivering significant heat transfer enhancement with acceptable increases in pressure drop and energy use, making it the most practical and efficient choice for real-world radiator applications.

The research is designed to identify the concentration that maximizes heat transfer while minimizing adverse hydraulic effects, such as increased viscosity, pressure drop, and pumping power. This technical trade-off is essential for laboratory validation and provides a clear, data-driven recommendation for immediate engineering performance. Practical engineering adoption requires more than just technical optimization. Real-world applications must consider cost-effectiveness, long-term operational stability, maintenance, and overall system efficiency. Factors such as nanoparticle cost, preparation complexity, risk of clogging, and the energy required for pumping at higher viscosities all influence whether the technical gains translate into tangible benefits for industry. Without a cost-benefit or performance-per-cost analysis, the conclusion remains limited to technical feasibility and does not fully address the economic or practical considerations needed for widespread adoption. The results of this study suggest that MgO–ZnO hybrid nanofluids could help automotive radiators achieve higher efficiency and more compact designs, thereby supporting future innovations in vehicle design. However, for these benefits to be realized in industry, long-term stability and practical integration challenges—such as maintaining nanoparticle dispersion and managing system maintenance—must be addressed. The findings encourage further research into durable, cost-effective nanofluid solutions that can

be reliably integrated into real-world automotive cooling systems.

Compliance with ethical standards

Ethical Statement: This work does not harm humans and Society in any way

Conflict of interest: The author declares no conflict of interest

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