Journal of Mines, Metals and Fuels, *72(11): 1187-1202; 2024. DOI: 10.18311/jmmf/2024/46001*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Experimental Investigation of the Enhancement of Heat Transfer Rate in Automobile Radiator Using Low Concentration Hybrid Nanofluids

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Abstract

Engine coolant, also called antifreeze, is essential to a vehicle's performance since it controls engine temperature, keeps the cooling system from freezing in cold weather and prevents corrosion. To increase engine cooling efficiency, this study looks into using low-concentration hybrid nanofluids to accelerate heat transfer rates in automobile radiators. To maximise heat dissipation within the radiator system, the project focuses on the synthesis, characterisation and practical applications of these nanofluids. Through an extensive literature review, various nanoparticles, including metallic and oxide-based particles, were evaluated for their compatibility and effectiveness in enhancing heat transfer. The chosen nanoparticles underwent thorough characterisation for size, shape and surface properties to determine their suitability for dispersion in a base coolant. Reduced Graphene is known for its good thermal conductivity, making it an ideal candidate for enhancing cooling rates in various applications hence keeping this in mind, this experiment compares and investigates the heat transfer rate in the radiator of an automobile with a hybrid combination of Reduced Graphene Oxide (RGO) + Copper Oxide (CuO) with ethylene glycol and distilled water, at volume fractions of 0.001%, 0.005% and 0.01%. The results show a notable increase in the efficiency of the radiator both in terms of pressure drop and effectiveness. A maximum of 9.2 and 1.5 times increase in temperature drop is recorded at 0.001%, a maximum of 12.3 and 2.08 times increase in temperature drop is noted at 0.005% and the highest of 17.9 and 3.03 times increase in temperature drop is tabulated at 0.01% volume fraction of copper oxide and 0.01% the volume fraction of RGO hybrid nanofluid. It can safely be concluded that compared to the sixty experiments conducted, the recommended nanofluid among them would be Ethylene Glycol and Distilled Water + 0.01% concentration of RGO and CuO hybrid as they have exhibited higher pressure drop, effectiveness and reduction in temperature.

Keywords: *CuO, Ethelene Glycol, Heat Transfer Rate, Hybrid Nanofluid, Low Concentration*

1.0 Introduction

The equipment used for power conversion, particularly automotive engines with internal combustion, has improved technologically many times due to the increasing growth of technology and power consumption. Over time, the equipment's capacity to handle power has also steadily decreased by a couple of magnitudes. Consequently, there is now an exponential increase in the necessity for cooling this equipment's essential components. In the end, the liquid-cooled systems transferred heat to the outside world using a radiator-based cooling system.

These days, the majority of electronic devices, encompassing high-power semiconductor apparatus and sophisticated computing processors, use the "liquid-air radiator" cooling system. Thanks to developments in semiconductor process technologies, processor performance has increased exponentially in terms of

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flops per second while processor size has decreased. The liquid coolant's ability to transmit heat is required by all the previously mentioned factors. For numerous years, this liquid coolant has comprised a mixture of deionised water and an organic solvent, typically ethylene glycol.

Nonetheless, this may be achieved using the invention of new kinds of heat transfer fluids. The thermal conductivity of densely packed metallic solids with small crystallite sizes is at least two orders of magnitude greater than that of heat transfer fluids. The thermal conductivity of copper surpasses that of any coolant by a minimum of three orders of magnitude. Researchers are trying to enhance the conductivity of solids in thermal transfer applications by incorporating low or high-scale Solid particulates into the coolant fluid.

The conductivity of solids such as copper significantly exceeds that of liquid coolants. The metallic particles would improve the thermal conductivity of the base fluid. Maintaining such metallic systems in a liquid state is unfeasible and hence, this phenomenon has never been seen in the industry. Extensive research has been conducted on the application of low-concentration hybrid nanofluids to enhance the heat transfer rate in vehicle radiators. Studies indicate that the use of nanofluids as coolants in radiators significantly increases the heat transfer efficiency.

Studies by Suresh *et al.*,[1] and Sultan *et al*[2]. The utilisation of nanofluids, especially hybrid nanofluids, is crucial for enhancing heat transfer in automobile radiators. Hybrid nanofluids, including those composed of CuO-TiO_2[3] or Al_2O_3-TiO_2-SiO_2[4], were discovered to enhance the heat transfer coefficient by a substantial percentage, leading to improved overall performance. Furthermore, the research by Zanzote[5] and Chaurasia *et al.*[6] studies the incorporation of nanoparticles in nanofluids resulting in a higher overall thermal conductivity coefficient compared to traditional coolants like water. This enhancement facilitates a reduction in the total heat transfer area of the radiator, thereby increasing system efficiency. Additionally, studies by Maisuria *et al.*[7] Chougule and Sahu[8] have highlighted that nanofluids can enhance convective heat transfer, allowing for a reduction in radiator size while preserving optimal performance. Furthermore, inquiries by Ullah *et al.*[9] and Farooq *et al.*[10] have shown that hybrid nanofluids offer increased heat transfer rates due to higher solid volume fractions of nanoparticles, resulting in enhanced thermal performance. The use of nanofluids in radiators has been efficient in enhancing heat transfer efficiency, with potential applications in reducing the size of radiators while maintaining or even enhancing their cooling capabilities. In conclusion, the utilisation of low-concentration hybrid nanofluids in automobile radiators presents a promising approach to increasing heat transfer phenomenon, improving cooling efficiency and potentially optimising the design of automotive cooling systems.

2.0 Literature Survey

Elankathiravan Mathivanan *et al.*,[15] assessed the impact of several nanofluids on convective heat transfer efficiency in an automobile radiator based on the observed parameters of the nanofluids. B. Rajesh Babu *et al.*,[16] examined the impact of varying volumetric concentrations of nanofluids on the heat transfer rate and was examined experimentally. The readings were recorded at a set of temperatures and by changing the rate of flow also the readings of inlet and outlet temperatures were recorded. Ekadewi Anggraini Handoyo *et al.*,[17] discuss the impact of employing Zinc Oxide (ZnO) nanofluid as the cooling fluid in the motorbike Vixion 2012 radiator. During the experiment, the surrounding air temperature ranged from 29.2 to 32.1°C. A larger concentration of ZnO in the nanofluid causes the cooling fluid going through the radiator to reduce in temperature. Mohd Muzammil Zubair *et al.*,[18] mentioned that in this work, Titanium Dioxide (TiO_2) nanoparticles were combined with water and ethylene glycol (75:25 by volume) as a base fluid to create various concentrations of nano coolants. In comparison to other coolants, the nano coolant with a 0.03% TiO_2 volume fraction demonstrates the greatest enhancement in heat transfer and the highest heat transfer coefficient.

Firlianda *et al.*,[19] did an experimental investigation on the augmentation of heat transfer utilising Manganese Iron Oxide ($MnFe_2O_4$) and ethylene glycol within a compact shell and tube heat exchanger. The researchers examined the impact of incorporating $MnFe_2O_4$ into ethylene glycol as the base fluid; the heat transfer outcomes were evaluated using the Log Mean Temperature Difference (LMTD) method, with the maximum value achieved at a concentration of 0.075% $MnFe_2O_4$ nanoparticles. Dattatraya G. *et al.*,[20] have

conducted a study of Aluminium Oxide (Al_2O_3) water-mono Ethylene Glycol nanofluid in heat transfer as a coolant in automobile radiators experimentally. The study examined the utilisation of nanoparticle volume fraction, the coolant flow rate at the inlet temperature and the probability of a radiator's area diminishing upon transitioning from base fluid to nanofluids. This made the cooling system lighter, reduced drag and saved fuel. The research by Alhassan Salami Tijani and Ahmad Suhail Bin[21] employed a base fluid consisting of a 50% concentration of water and ethylene glycol. Nano-sized particles of Al_2O_3 and CuO at Concentrations of 0.05%, 0.15% and 0.3% were incorporated into the base fluid to assess the thermal transfer properties of the nanofluid. This research seeks to improve the efficacy of automotive cooling systems, with a specific focus on the radiator and coolant fluid. They ultimately evaluated the thermal transfer efficiency of both H_2O_3 and CuO nanofluids. by conducting a comparative analysis and identifying the most suitable nanofluid for application as a coolant in automotive radiators. The research paper employed a base fluid consisting of a 50% mixture of water and ethylene glycol. Nanoparticles of Al_2O_3 and CuO at concentrations of 0.05%, 0.15%, and 0.3% were integrated into the base fluid to evaluate the thermal transfer characteristics of the nanofluid. This research seeks to improve the effectiveness of automotive cooling systems, specifically the radiator and coolant fluid. They ultimately assessed the heat transfer efficiency of both H_2O_3 and CuO nanofluids by conducting a comparative analysis and identifying the most suitable nanofluid for application as a coolant in automotive radiators.

J.A. Ranga Babu K *et al.*,[22] formulated hybrid nanofluids by dispersing individual nanoparticles as discrete components or by integrating nanocomposite particles into the base fluid. This hybrid nanofluid may demonstrate improved thermal conductivity and rheological properties owing to a synergistic effect. This review summarises contemporary research on the behavioural traits of these hybrid nanofluids. Nor Azwadi Che Sidika *et al.*,[23] determined that hybrid nanofluids are promising substances that provide superior heat transfer efficiency and thermo-physical characteristics compared to traditional heat transfer fluids. Their inquiry into recent developments in the preparation methods of hybrid nanofluids. Nonetheless, they employed an excessive amount of surfactant, which affects the viscosity, thermal conductivity and stability of the hybrid nanofluid. H.W. Chiama *et al.*,[24] illustrates that the thermal transfer efficiency of a system can be improved by incorporating passive techniques, particularly nanofluids and various tube geometries, which enhances the heat transfer coefficient and subsequently diminishes the system's weight. This paper examines the influence of tube geometry and nanofluids on heat transfer efficiency in a numerical framework. The different tube geometries in the simulation are analysed, demonstrating that the flat tube displays a higher heat transfer coefficient and an increased friction factor relative to the circular tube. K. Goudarzi[25] employed Al_2O_3 in Ethylene Glycol (EG) as a nanofluid to improve heat transfer in automotive radiators, alongside wire coil inserts. Two wire coil inserts with different geometries were employed and nanofluids with volume concentrations of 0.08%, 0.05% and 1% were analysed. The results indicated that the incorporation of coil inserts enhanced heat transfer rates by up to 9%. The coil wire inserts with diverse configurations and Al_2O_3 nanofluid at varying volume concentrations was assessed.

R.B. Ganvir *et al.*,[26] noted that the thermal conductivity of nanofluids is markedly improved by the incorporation of nano-sized solid particles, making them advantageous working fluids for diverse applications. This study investigates the convective heat transfer efficacy of nanofluids and their thermophysical characteristics. Furthermore, the preponderance of their research has been executed utilising metal oxides. The augmentation method of heat transfer is markedly superior with metallic nanoparticles, even at low-volume fractions. G. Najafid *et al.*,[27] collected and examined extensive literature on the synthesis of hybrid nanofluids. The difficulties and prospective developments in the utilisation of hybrid nanofluids for thermal transfer are analysed. The paper by Paison Napon *et al.*,[28] examines the thermal transfer and flow dynamics of nanofluids in horizontally coiled spiral tubes. In this configuration, an 8.50mm inner diameter straight copper tube is bent into a five-turn spiral coil, resulting in spirally coiled tubes. assessed three different curvature ratios of 0.035, 0.043 and 0.06. He evaluates the influence of curvature, nanofluid concentration and hot water temperature on the thermal transfer properties and pressure drop of nanofluids. The Nusselt numbers he

acquired are approximately 21.29%, 29.02%, and 34.07% for volume concentrations of 0.01%, 0.025% and 0.05%, respectively, exceeding the Nusselt number documented for water as the working fluid. The friction factor for the working fluid exhibits a slight increase relative to that of water as the working fluid. Furthermore, he suggested two correlations for the Nusselt number and the friction factor. Rahul A. Bhogare *et al.*,[29] analysed the applications and difficulties of nanofluids as cooling agents in automotive radiators. They analysed the latest literature concerning the applications and challenges related to PhD and master's theses, journal articles, conference proceedings, reports, and online resources. Recent studies indicate that substituting traditional coolants with nanofluids demonstrates potential in automotive radiators. Nanofluids have considerable potential to augment cooling rates in automotive and heavy-duty engines by enhancing efficiency, reducing weight and streamlining thermal management.

3.0 Particle Morphology Analysis and Chemical Composition Analysis

Knowing the microstructure and chemical composition of the nanoparticles purchased is crucial to determining the quality of the nanoparticles before using them in experimental experiments. The nanoparticles are characterised through Scanning Electron Microscopy (SEM) for microstructural examination, Energy Dispersive X-Ray Spectroscopy (EDXS) for compositional analysis and X-Ray Diffraction Analysis (XRD) for evaluation of physical properties.

3.1 Examination of Scanning Electron Microscopy (SEM)

Figure 1 presents SEM images of CuO nanoparticles, illustrating the internal structure of the sample at a

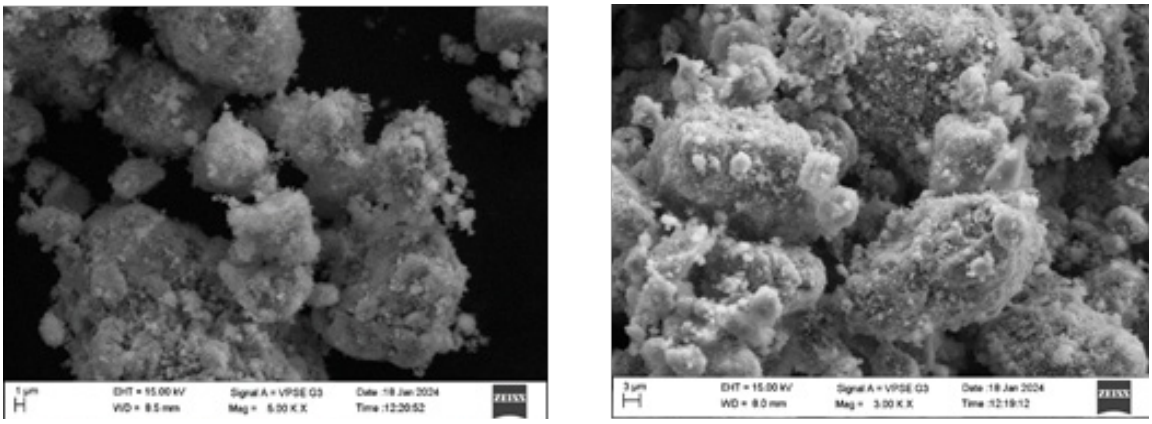
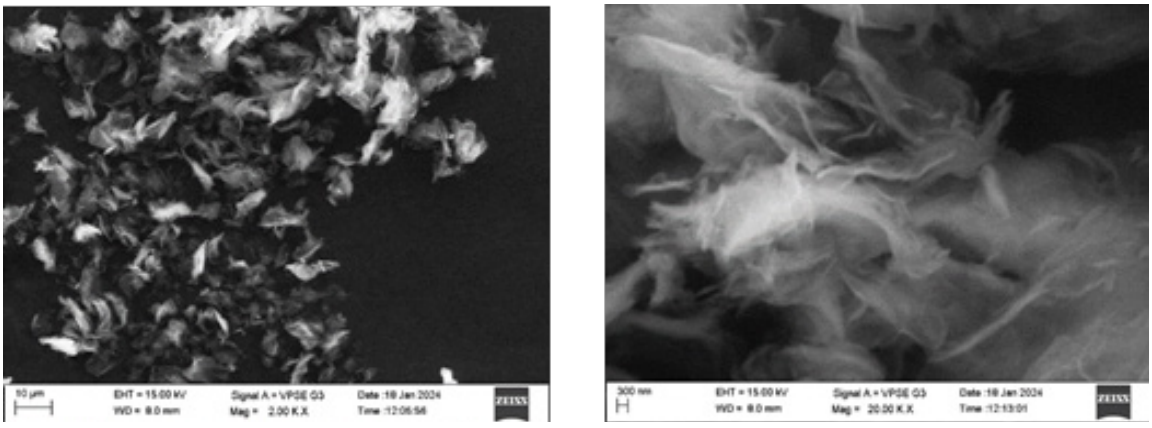


Figure 1. Copper oxide (CuO) nanoparticles SEM images.



(a) (b)

Figure 2. Reduced Graphene Oxide (RGO) nanoparticles SEM images.

microscopic scale. SEM images possess higher resolution, allowing for significant magnification of closely spaced specimens. To check the purity of the sample, SEM testing must be conducted prior to experimentation. (B)

RGO nanoparticles are obtained by reducing Graphene Oxide (GO) nanoparticles using chemical exfoliation. RGO nanoparticles at 2.00 kX resolution [Figure 2 (A)], with an average flake size of fewer than 10 microns, resemble the flaky structure with wavy edges. Figure 2 (B) at 20 kX resolution shows that the RGO is a stacked layer and contains many fragmentations. Oxygen atoms may be pulled out of the free edge of the GO nanoparticles during chemical exfoliation. The wavy edges help create micro-convection and increase the heat transfer rate during its moment.

3.2 Examination of Energy-Dispersive X-Ray Spectroscopy (EDX)

EDX testing of nanoparticles is necessary for checking the purity of nanoparticles. Copper oxide nanoparticles are typically synthesised using various chemical methods. These include chemical precipitation, where copper salts react with a precipitating agent to yield nanoparticles and the sol-gel approach, which transforms a solution into a gel before heating to produce nanoparticles. Thermal decomposition involves breaking down copper-containing compounds at high temperatures, while the microemulsion method employs a unique liquid system for nanoparticle formation. Hydrothermal synthesis entails heating copper precursors in a sealed container under high pressure. Each method provides different

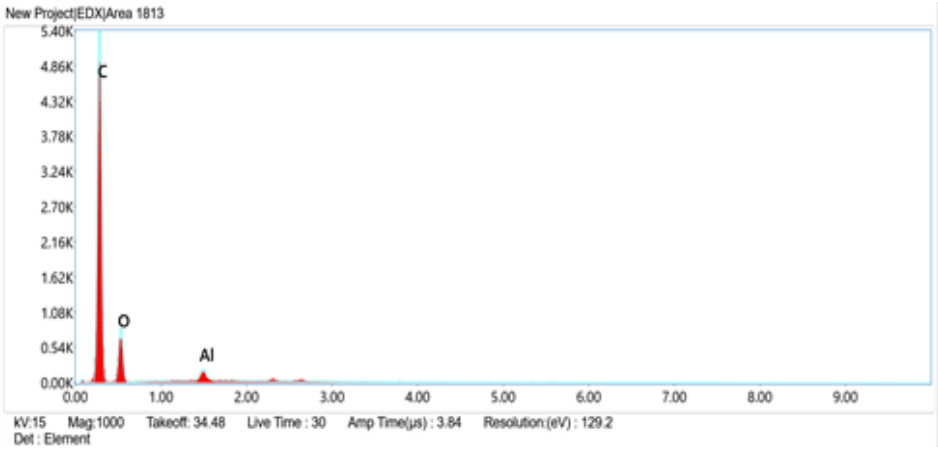


Figure 3. Copper oxide (CuO) nanoparticles EDX analysis.

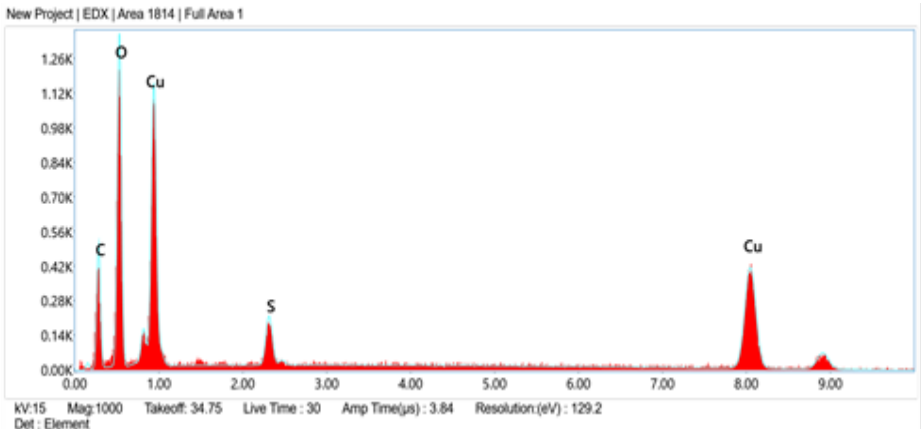


Figure 4. Reduced graphene oxide (RGO) nanoparticles EDX analysis.

Table 1. Nanoparticles EDX analysis

Nanoparticle	Cu (K)	O (K)	C (K)	Al (K)	S (K)
Copper Oxide (CuO) **Elements by weight %**	61.3	18.2	18.1	-	2.4
Reduced Graphene Oxide (RGO) **Elements by weight %**	-	23.9	74.7	1.4	-
Copper Oxide (CuO) **Elements by atomic %**	26.2	30.8	40.9	-	2.1
Reduced Graphene Oxide (RGO) **Elements by atomic %**	-	9.3	80.1	0.6	-

degrees of control over nanoparticle characteristics, such as size and shape, to meet specific application requirements. Figure 3 shows the EDX analysis of Copper Oxide.

RGO is produced using BT-Corp's proprietary chemical exfoliation reduction process from graphene oxide. Figure 4 illustrates the EDX analysis results for RGO.

Table 1 presents the elemental compositions of CuO and RGO, in both weight and atomic percentages. The reduction of oxygen content is substantial in RGO, decreasing from approximately 27% to 3.66% when compared to GO.

The chemical composition of CuO and RGO, as presented in Table 1, aligns with the manufacturer's datasheet, confirming that the nanoparticle's purity exceeds 99%.

3.3 Examination of X-Ray Diffraction (XRD)

X-ray Diffraction Analysis (XRD) is a technique utilised in materials science to ascertain the crystallographic structure in accordance with Bragg's law. Bragg's law states that when X-rays impinge upon a crystal surface, the angle of incidence, θ, is equivalent to the angle of scattering, θ. Constructive interference occurs when the path difference, d, is an integer multiple, n, of the wavelength. The interlayer spacing (d-spacing) between two nanoparticle layers is calculated using Equation 1.

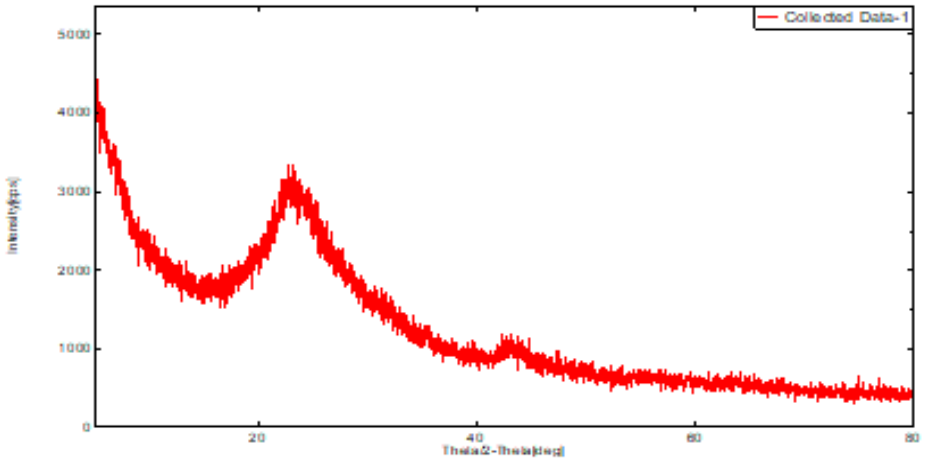


Figure 5. Copper oxide (CuO) nanoparticles XRD analysis.

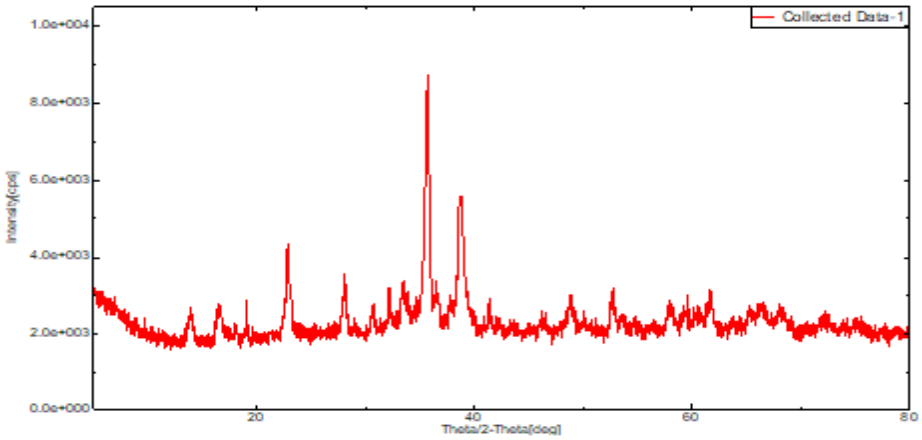


Figure 8. Reduced graphene oxide (RGO) nanoparticles XRD analysis.

$$n\lambda=2d\sin\theta \quad (1)$$

where,
X-ray wavelength is 'λ'
Crystal layers spacing is 'd'
The incident angle is 'θ' and
'n' is an integer

Figure 5 represents the XRD analysis of copper oxide. In Figure 5, There exists a pronounced peak at 2θ=66.16° for copper oxide. it signifies the crystallographic planes of the material. Specifically, in CuO nanoparticles, this peak corresponds to the plane of the cubic phase, known as cuprite (Cu_2O). The intensity and position of this peak offer insights into the crystalline structure and orientation of the nanoparticles, facilitating their characterisation and recognition.

In reduced GO (Figure 6), the initial peak appears at 2θ=26.51°, indicating an interlayer distance of 0.35nm, which signifies the removal of oxygen functional groups during the reduction process.

4.0 Methodology

4.1 Preparation of Nanofluids

Nanofluids can typically be produced through either a one-step or a two-step process. The one-step method



(a) (b)

Figure 7. Preparation of nanofluid.

provides enhanced stability and dispersion characteristics compared to the two-step method; however, it is impractical for producing large volumes of nanofluids. As a result, most researchers favour the two-step method. This is likewise executed in the present study. The two-step method entails the initial synthesis or procurement of nanoparticles, succeeded by their dispersion in the base fluid using mechanical or ultrasonic agitators[11]. In the two-step preparation method, nanoparticles are first synthesised or extracted independently from the base fluid. In this phase, nanoparticles are generated via multiple methods, including chemical synthesis, the sol-gel technique and physical processes such as grinding or laser ablation. The intended uses and characteristics of the nanofluid dictate the kind of nanoparticles that are employed. To make the nanofluid, the nanoparticles must first be obtained and then dispersed throughout the base fluid. This dispersion technique requires careful monitoring to produce consistent and

stable suspensions. An electronic scale is used to weigh the nanoparticles as shown in Figure 7(A) The least count is 0.01mg, and the particles are subsequently distributed uniformly within the base fluid (EG + Water = 6 litres). For the acquisition of a stable nanofluid, the nanofluid is put through to an ultrasonic bath-type sonicator, as illustrated in Figure 7(b) 45 litres, 480 watts of power, 37kHz frequency and 230 volts at 50Hz of input supply AC. To improve stability, the fluid is sonicated for almost three hours.

The volume concentration for the proportion of nanoparticles to be added to prepare the nanofluid was calculated using the below relationship[11].

$$\varphi = \left[\frac{W_{np}/\rho_{np}}{\frac{W_{np}}{\rho_{np}} + \frac{W_{bf}}{\rho_{bf}}}\right] X\ 100 \quad (1)$$

4.1.1 Hybrid Nanofluid

The mathematical modelling for different properties of hybrid nanofluids is based on the study of Sahoo and Sarkar[12]

- Effective Density of Nanofluid:

$$\rho_{hnf} = (1-\phi)\rho_{bf} + \phi_1\rho_{np1} + \phi_2\rho_{np2} \quad (2)$$

- Specific Heat of the Nanofluid:

$$(C_p\rho)_{hnf} = \left((1-\phi)C_{p_{bf}} * \rho_{bf}\right) + \phi_1(C_{p_{np1}} * \phi_2(C_{p_{np2}} * \rho_{np2}\right) \quad (3)$$

- Dynamic Viscosity of the Nanofluid[11]

$$\mu_{hnf} = \mu_{bf} * (1 + 7.3\phi + 123\phi^2) \quad (4)$$

- Thermal Conductivity of Hybrid Nanofluids[13]

$$\frac{k_{hnf}}{k_{bf}} = \left(\frac{\frac{\varphi_{np1}k_{np1} + \varphi_{np2}k_{np2}}{\varphi} + 2k_{bf} + 2(\varphi_{np1}k_{np1} + \varphi_{np2}k_{np2}) - 2\varphi k_{bf}}{\frac{\varphi_{np1}k_{np1} + \varphi_{np2}k_{np2}}{\varphi} + 2k_{bf} - (\varphi_{np1}k_{np1} + \varphi_{np2}k_{np2}) - \varphi k_{bf}}\right) \quad (5)$$

where k_{hnf}, k_{bf}, k_{np1}, k_{np2} are the thermal conductivities of the hybrid nanofluid, base fluid, Copper Oxide, and Reduced Graphene Oxide φ_{np1}, φ_{np2} and φ are the volume concentrations of CuO, RGO and the hybrid nanofluid.

4.1.2 Mathematic Modelling

Reynolds Number of Nanofluid:

$$Re_{nf} = \left(\frac{\rho * v * D_h}{\mu}\right) \quad (6)$$

Prandtl Number of Nanofluid:

$$Pr_{nf} = \left(\frac{\mu * C_p}{K}\right) \quad (7)$$

Experimental Nusselt Number of Nanofluid[14]

$$Nu_{nf} = \left(\frac{h * D_h}{K}\right) \quad (8)$$

Normalized Nusselt Number of Nanofluid:

$$Nu_{normalized} = \left(\frac{Nu_{nf}}{Nu_{bf}}\right) \quad (9)$$

Heat Transfer Rate:

$$Q_h = m_h C_{ph}(T_i - T_o) \quad (10)$$

Effectiveness of Compact Heat Exchanger:

$$\varepsilon_h = \left(\frac{Q_h}{(mC_p)_{min}(T_i - T_o)} \right) \quad (11)$$

4.2 Experimental Set-Up

Figure 8 depicts the experimental test apparatus utilised to assess the efficacy of a compact heat exchanger. The study employs a compact heat exchanger, specifically a Honda VFR400 89-92 RVF400 radiator, with its geometric specifications detailed in Table 1. The test rig depicted in Figure 8 has a maximum reservoir capacity of 15 litres and is outfitted with a 2-kW heater and a thermostat to control the inlet temperature of the heated fluid. A pump transports hot fluid from the reservoir to the compact heat exchanger, employing a rotameter to gauge the flow rate. A bypass valve is positioned after the pump to control the flow rate and avert excessive pressure buildup in the system. A U-tube manometer using mercury as the working fluid is utilised to measure the differential pressure between the inlet and outlet of the heat exchanger. Furthermore, two thermocouples are utilised at the inlet and outlet of the heat exchanger to measure the bulk mean temperatures of the hot fluid stream. The heated fluid exits the heat exchanger and is redirected to the reservoir via a secondary reservoir that contains an additional 2-kW heater, serving as a pre-heater in a closed-loop system. A suction fan is installed to improve airflow rate and is housed within a duct to enable flow rate measurement using an anemometer.



Figure 5. Experimental setup.

Table 2. Geometrical parameters of compact heat exchanger

Parts	Dimension	Units
Pipe Diameter Inlet/Outlet	17	mm
Thickness of 1 Fin	0.8	mm
Width of Fin	25.5	mm
Number of Fins in Single Column	157	-
Number of Fin Columns	13	-
Total Number of Fins	2040	-
Diameter of Cooling Tube	2	mm
Radiator Core Height	160	mm
Radiator Core Length	210	mm
Total Number Tube	12	-

One k-type thermocouple is situated at the air inlet to measure the inlet temperature, while four supplementary thermocouples are strategically placed at Gaussian positions on the exit side to ascertain the average exit temperature of the air.

5.0 Results and Discussion

The hybrid nanofluid was utilised in the test rig to assess the performance of the compact heat exchanger. A series of concentrations were replicated after three and six months to evaluate the reliability of the results. Notwithstanding two trials, the fluctuation in results persists below 5%. The performance of a heat exchanger is measured by the Nusselt number, friction factor and pressure drop.

5.1 Convective Heat Transfer Coefficient (CHTC)

The CHTC quantifies the efficacy of heat transfer by a fluid via convection. Figure 9 depicts the effect of the Reynolds number of nanoparticles and their volume concentration on the CHTC.

The graphs depict the relationship between the Reynolds Number (Re) and the CHTC for a fluid mixture (DW+EG) with various additives.

The x-axis represents the Re, characterising fluid flow behaviour, while the y-axis represents the CHTC, indicating heat transfer efficiency. The baseline (black square line) shows the CHTC for the base fluid without additives, with increasing Re leading to improved heat transfer efficiency.

The red diamond line (+0.001% Hybrid) and the blue triangle line (+0.005% Hybrid) indicate slightly and significantly higher CHTC, respectively, suggesting additive enhancement of heat transfer. The magenta inverted triangle line (+0.01% Hybrid) is presumably another additive level with potential further enhancement. In summary, the graph illustrates how Re influences convective heat transfer and demonstrates the potential of additives to enhance this process.

5.2 Heat Transfer Rate (Q)

Figure 10 depicts the influence of the Re of nanoparticles and their volumetric concentration on Q. The graph illustrates the relationship between Re and Heat Transfer rate (Q) across various fluid conditions. The baseline (black square line) depicts the heat transfer rate for the base fluid (DW+EG) devoid of any additives. showing increased efficiency with rising Re. The red circle line (Q for BF + 0.001% Hybrid) mirrors this trend but with a slightly lower slope. The blue triangle line (Q for BF + 0.005% Hybrid) exhibits a steeper slope, indicating

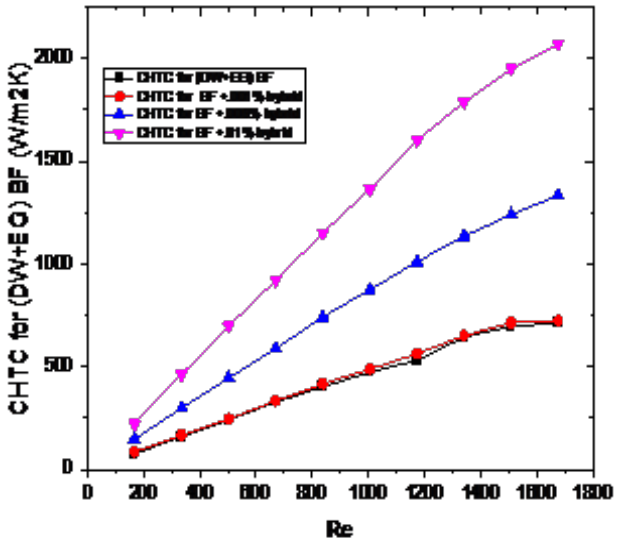


Figure 9. Reynolds o. v/s CHTC.

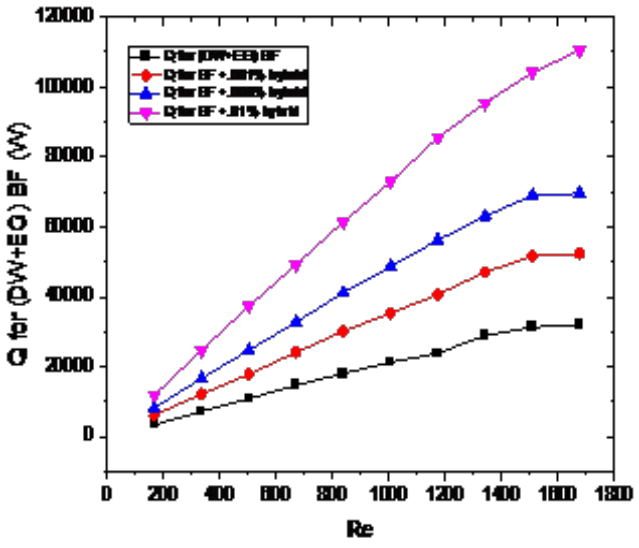


Figure 10. Reynolds no. v/s heat transfer.

substantial enhancement in heat transfer with a 0.05% hybrid additive. The magenta diamond line (Q for BF + 0.01% Hybrid) exhibits the best Q per unit rise in Re among the conditions tested. In essence, the graph underscores how Re influences Q and highlights the significant efficiency boost achievable with small percentages of hybrid additives

5.3 Nusselt Number (Nu)

Increasing Re and volume concentration enhanced Nu, as shown in Figure 11. The graph illustrates the relationship between the Nusselt Number (Nu) and the Re, essential variables in the analysis of convective heat transfer. The Nusselt Number signifies the efficacy of heat transfer. while the Re indicates fluid flow characteristics. The baseline (black circles) shows increasing Nu values with rising Re for the base fluid (DW=0% BF), signifying improved heat transfer.

Efficiency. The red squares (Nu for BF + 0.001% Hybrid) suggest enhanced heat transfer compared to the baseline, with a slightly steeper slope. The blue triangles (Nu for BF + 0.005% Hybrid) exhibit even better heat transfer performance, as indicated by their steeper slope. The pink triangles (Nu for BF + 0.01% Hybrid) illustrate the maximum rate of heat transfer per unit increment in Re across the evaluated conditions. In essence, the graph illustrates how Re influences heat transfer efficiency, with small percentages of the hybrid additive notably improving performance.

5.4 Normalised Nusselt Number ($Nu_{normalised}$)

Figure 12 illustrates the impact of nanoparticle Re and concentration volume on the normalised Nu. Increasing the concentration of nanoparticles enhances the normalised Nu. The impact of Re air is more pronounced than that of Re hot fluid regarding normalised Nu.

The graph demonstrates the relationship between the Normalised Nu and the Re, highlighting the influence of fluid flow behaviour on convective heat transfer efficiency. The y-axis denotes the normalised Nu, which contrasts the actual Nu with a reference condition (Nu(0)), whereas the x-axis indicates the Re that characterizes fluid flow. As the Re increases, the flow transitions from laminar to turbulent, affecting heat transfer. The graph data sets are characterised by varying percentages of a hybrid additive red square (0.001%), blue triangles (0.005%) and pink triangles (0.01%). These sets demonstrate differing levels of improvement in heat transfer efficiency relative to the baseline. With higher percentages of the hybrid additive exhibit steeper slopes, indicating more significant improvements. In essence, the graph highlights how Re influences heat transfer efficiency and demonstrates the substantial enhancement provided by small percentages

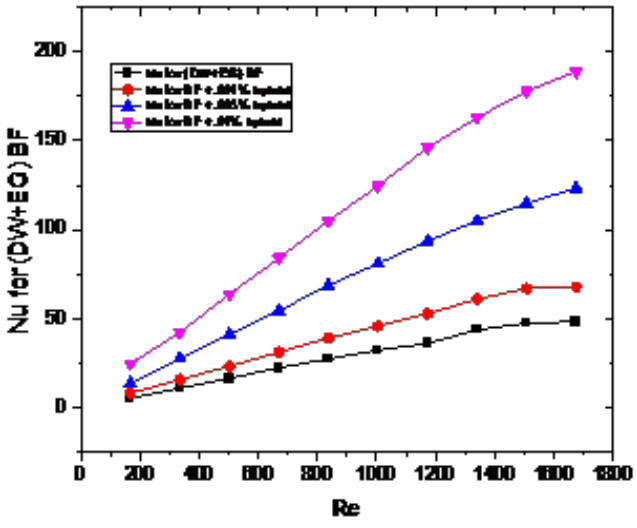


Figure 11. Reynolds no. v/s Nusselt no.

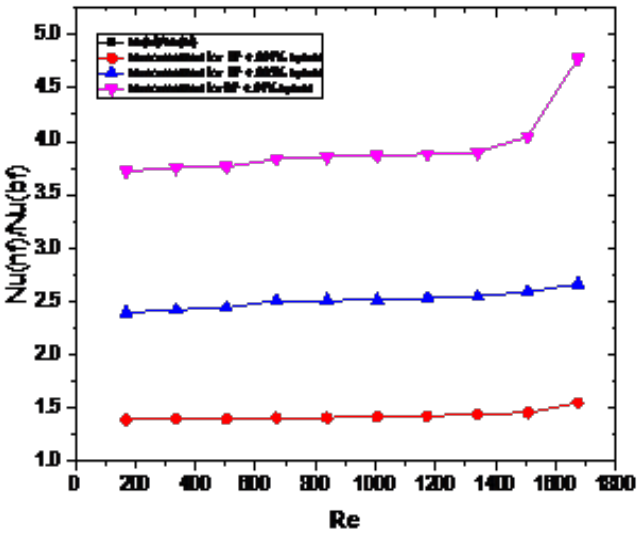


Figure 12. Reynolds no. v/s Nusselt no. normalized.

of the hybrid additive, with steeper slopes indicating stronger effects on heat transfer.

5.5 Pressure Drop

Figure 13 illustrates the influence of the volumetric flow rate of hot fluid (Qhf), Re of air, type of nanoparticles and volume concentration on ΔP. Augmenting Qhf from 3 to 6 LPM amplifies the ΔP, while reair exerts a partial influence on it.

The graph depicts the correlation between Pressure Drop (Pa) and Re, showing how fluid flow behaviour impacts pressure within a system. Pa is represented on the y-axis, reflecting that Figure 13 depicts the impact of the Qhf, the Re of air, the type of nanoparticles and their volume concentration on ΔP. Augmenting Qhf from 3 to 6 LPM amplifies the ΔP, while Reair exerts a partial influence on it. Pressure decreases across the fluid system, resulting from friction and other factors during flow. Re on the x-axis characterises flow behaviour, Low values indicate laminar flow, while high values signify turbulent flow. A data set includes red squares (0.001% hybrid additive), blue triangles (0.005% hybrid additive), pink diamonds (0.01% hybrid additive) and black squares (pure base fluid). Each series illustrates a similar trend: as the Reynolds Number increases, pressure drop also rises. This suggests that hybrid additives affect flow resistance, The base liquid also undergoes an increased drop in pressure with high Reynolds numbers. The graph depicts the influence of the Reynolds Number on pressure drop and emphasises the influence of hybrid additives on flow resistance within the system.

5.6 Effectiveness

Figure 14, The graph depicts the relationship between Effectiveness and Re, focusing on Boundary Layer Flow (BF) performance. Effectiveness, on the y-axis, denotes how well the fluid boundary layer achieves its purpose, such as heat transfer, mass transfer, or drag reduction. Re, The x-axis delineates fluid flow behaviour, with lower values signifying laminar flow and higher values denoting turbulent flow. The data series includes red squares (0.001% hybrid additive), blue triangles (0.005% hybrid additive), pink diamonds (0.01% hybrid additive) and a black square (pure base fluid). Each series demonstrates a consistent trend: as the Re increases, effectiveness also improves, suggesting that hybrid additives positively influence the intended purpose, such as enhancing heat transfer or reducing drag. Even the base fluid exhibits increased effectiveness with higher Re. In essence, the graph highlights how Re impacts boundary layer flow effectiveness and emphasises the potential enhancement provided by hybrid additives, with steeper slopes indicating stronger additive effects.

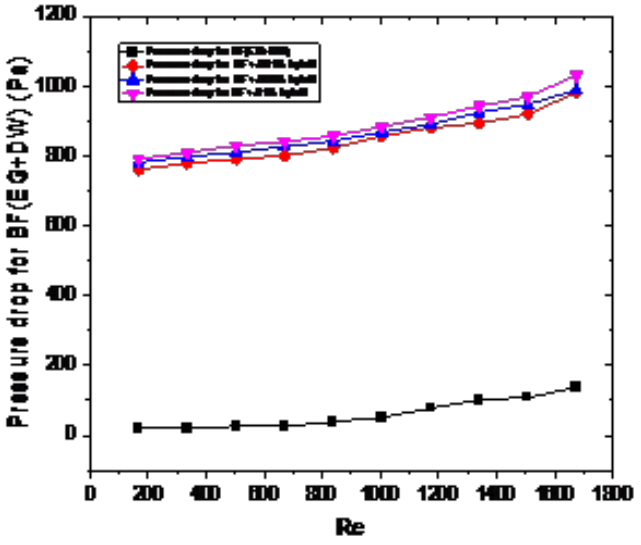


Figure 11. Reynolds no. v/s Nusselt no.

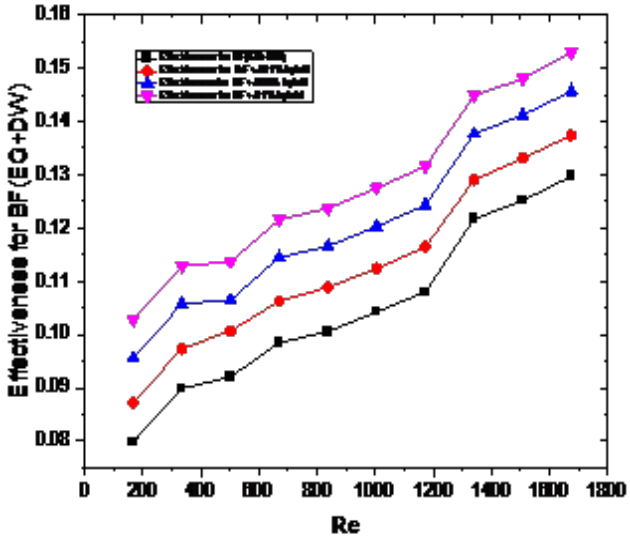


Figure 12. Reynolds no. v/s Nusselt no. normalized.

5.7 Temperature Difference

Figure 15 analyses the relationship between Temperature Difference and Re, focusing on heat transfer efficiency within a fluid system or boundary layer. Temperature Difference (Δt) is represented on the y-axis in degrees Celsius, indicating the change in temperature across the system. Re, on the x-axis, characterises fluid flow behaviour, Low values signify laminar flow, while high values denote turbulent flow. The data series includes red circles (0.001% hybrid additive), blue triangles (0.005% hybrid additive), pink triangles (0.01% hybrid additive) and black squares (pure base fluid). Each series shows a consistent pattern: as the Re increases, the temperature difference also rises, suggesting that hybrid additives positively influence heat transfer efficiency. Even the base fluid experiences increased temperature differences with higher Re. In essence, the graph highlights how the Re affects temperature differences and underscores the potential enhancement provided by hybrid additives, with steeper slopes indicating stronger additive effects.

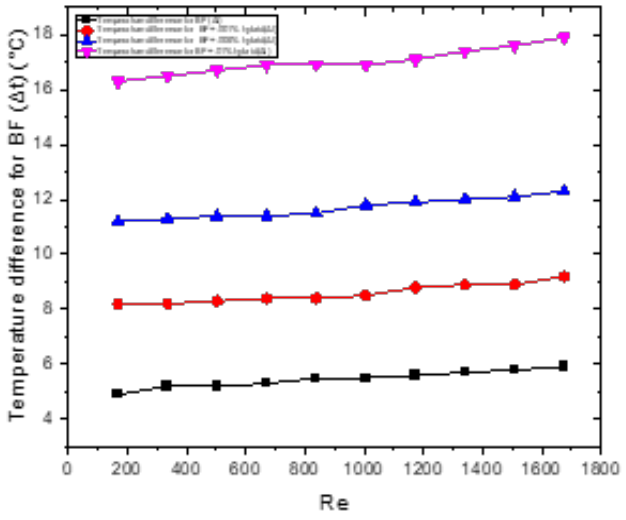


Figure 15. Reynolds no. v/s temperature difference.

6.0 Conclusion

This study investigates the effects of metallic and non-metallic nanoparticles, RGO and CuO at low concentrations on the efficacy of an automobile radiator. A hybrid nanofluid is created by integrating copper oxide and reduced graphene oxide nanoparticles at three concentrations: 0.001%, 0.005% and 0.01 vol% into a 50:50 mixture of ethylene glycol and water (1:1 by volume). The flow rate, Re of the fluid, and volume concentrations have been modified, leading to the conduction of 60 experiments.

The efficacy of a compact heat exchanger employing nanofluids is assessed according to seven parameters: convective heat transfer coefficient, overall Q, Nu, normalised Nu, PD, temperature differential and effectiveness.

- The application of hybrid nanofluids leads to a notable improvement in the Nu and efficiency compared to mono-nanofluids.
- The incorporation of nanoparticles at minimal concentrations results in a reduction of PD.
- The utilisation of hybrid nanoparticles reduces the size of the radiator for a specific heat load.
- A maximum increase of 9.2 and 1.5 times in temperature reduction is noted at 0.001%, a maximum increase of 12.3 and 2.08 times at 0.005%, and a maximum increase of 17.9 and 3.03 times at 0.01% volume of copper oxide and 0.01% volume of RGO hybrid nanofluid, respectively.
- A maximum enhancement of 88.82 and 9.48 times in the Nu is recorded at 0.01 vol% of copper oxide and 0.01 vol% of RGO hybrid nanofluid, respectively.
- The maximum decrease in PD for hybrid nanofluid is 60%.
- An enhancement in effectiveness of up to 80% is observed at 0.01 volume % of RGO and 0.01 volume % of copper oxide hybrid nanofluid.
- The employment of hybrid nanofluids as a coolant in automotive radiators is highly recommended.
- It can safely be concluded that compared to the sixty experiments conducted, the recommended nanofluid among them would be Ethylene Glycol and Distilled Water + 0.01% concentration of RGO and CuO hybrid as they have exhibited higher PD, effectiveness and reduction in temperature.

7.0 Acknowledgements

The authors wish to extend their heartfelt gratitude to the management of Vidyavardhaka College of Engineering,

Mysuru, for facilitating the research resources necessary for this research.

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Nomenclature

W - Weight, grams

T - Temperature, K

SEM - Scanning Electron Microscope

Re - Reynolds Number

Q - Heat transfer rate, Watts

Pr - Prandtl Number

Nu - Nusselt Number

K - Thermal Conductivity, Watts per meter-Kelvin

H - Convective heat transfer coefficient, W/m^2-K

Cp - Specific heat at constant pressure, J/kg·K

EDX - Energy Dispersive X-ray Analysis

Dh - Hydraulic diameter

Super-script and sub-script

Np - nano-particle

np_1 - nano-particle 1, Copper Oxide

np_2 - nano-particle 2, Reduced Graphene-oxide

bf - base-fluid

nf - nanofluid

hnf - hybrid-nanofluid

Greek letters

Φ - Volume concentration ($\phi 1 + \phi 2$)

$\phi 1$ - Volume concentration of nanoparticle 1 (copper oxide)

$\phi 2$ - Volume concentration of nanoparticle 2 (reduced graphene oxide)

ρ - Density, kg/m^3

μ - Dynamic viscosity, kg/ms

ε - Effectiveness

η - Efficiency

η_o - Surface efficiency of finned tube.