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Comparative Evaluation of Thermophysical Properties of Copper-Water and Graphene-Water Nanofluids

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Abstract:

Nanofluids have emerged as promising heat transfer media because of their enhanced thermophysical properties compared with conventional working fluids. Among the various nanoparticles investigated for thermal applications, copper and graphene have attracted significant attention owing to their excellent thermal characteristics. The present study provides a theoretical comparison of the thermophysical properties of copper-water (Cu-W) and graphene-water (Gr-W) nanofluids over a nanoparticle mass concentration range of 0-5%. Density, thermal conductivity, specific heat, and dynamic viscosity were evaluated using established theoretical models. The calculated results reveal that thermal conductivity increases continuously with nanoparticle concentration for both nanofluids, while graphene-water consistently exhibits slightly higher thermal conductivity than copper-water. The density of Cu-W nanofluids increases significantly with concentration because of the higher density of copper nanoparticles, whereas Gr-W nanofluids demonstrate only a moderate increase. The specific heat decreases for both nanofluids with increasing concentration; however, graphene-water retains comparatively higher values throughout the investigated range. The adopted viscosity model predicts identical viscosity variations for both nanofluids as a function of concentration. Based on the theoretical analysis, graphene-water nanofluids demonstrate more favorable thermophysical characteristics for advanced heat transfer applications owing to their superior thermal conductivity combined with lower density. The findings of the present work provide useful guidance for selecting suitable nanofluids for thermal management systems and heat exchanger applications.

Keyword: - Copper-Water nanofluid; Graphene-Water nanofluid; Thermophysical properties; Thermal conductivity; Density; Specific heat; Viscosity

1. INTRODUCTION

1.1 Heat Exchangers and Their Importance

Heat exchangers are essential thermal devices designed to transfer heat between two or more fluids at different temperatures without direct mixing. They are extensively employed in power plants, chemical processing industries, refrigeration and air-conditioning systems, automotive radiators, petroleum refineries, food processing, and electronic cooling [1]. The primary objective of a heat exchanger is to maximize heat transfer while minimizing energy consumption and operational cost [2].

The performance of a heat exchanger is influenced by several factors, including its geometry, flow configuration, operating conditions, and most importantly, the thermophysical properties of the working fluid. Conventional heat transfer fluids such as water, ethylene glycol, and thermal oils are commonly used because of their availability and low cost. However, these fluids possess relatively low thermal conductivity, which limits the overall heat transfer rate and restricts the efficiency of thermal systems [3]. Consequently, considerable research has focused on developing advanced working fluids capable of enhancing heat transfer without requiring major modifications to existing heat exchanger designs.

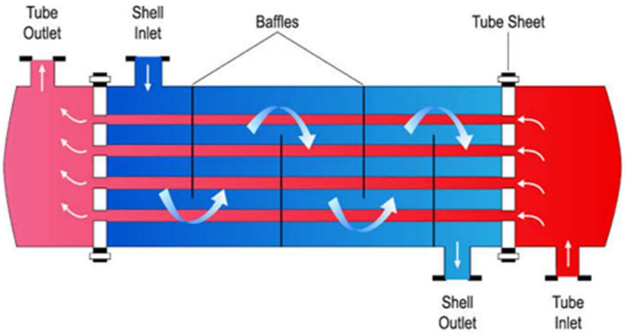


Figure 1. Schematic representation of a shell & tube heat exchanger.

1.2 Nanofluids and Their Significance

Nanofluids are engineered suspensions formed by dispersing nanoparticles, typically smaller than 100 nm, into conventional base fluids. Since their introduction of nanofluids, they have attracted widespread attention because they offer enhanced thermal conductivity, improved convective heat transfer characteristics, and better thermal stability compared with conventional fluids [4].

The incorporation of nanoparticles increases the effective thermophysical properties of the base fluid, resulting in improved heat transfer capability. Depending on the type of nanoparticles used, nanofluids can significantly enhance thermal conductivity while maintaining acceptable viscosity and stability [5]. Metallic nanoparticles, metal oxide nanoparticles, and carbon-based nanomaterials are among the most extensively investigated materials for nanofluid preparation.

Figure 2. *Schematic illustration of nanoparticle dispersion in a base fluid.*

Thermophysical Properties of Nanofluids

The thermal performance of any nanofluid is primarily governed by its thermophysical properties. Among these, thermal conductivity, density, specific heat, and dynamic viscosity play the most significant roles in determining heat transfer behaviour and practical applicability [6].

Thermal conductivity governs the rate of heat conduction through the nanofluid, while density influences the fluid inertia and pumping requirements. Specific heat determines the heat storage capability of the working fluid, whereas viscosity affects the ease of fluid circulation through thermal equipment [7]. Since these properties vary with nanoparticle concentration, an accurate evaluation of their behaviour is essential for selecting suitable nanofluids for engineering applications.

Research Gap and Objectives

Although numerous studies have independently investigated the thermophysical behaviour of copper-water and graphene-water nanofluids, direct comparative theoretical analyses employing identical nanoparticle concentration ranges remain limited. Most available investigations primarily focus on experimental heat transfer performance, whereas comparative evaluation of the fundamental thermophysical properties receives comparatively less attention.

Therefore, the present work aims to perform a theoretical comparison of Cu-W and Gr-W nanofluids over a nanoparticle mass concentration range of 0-5%. The investigation evaluates the variation of thermal conductivity, density, specific heat, and dynamic viscosity using established theoretical models. The obtained results provide a comprehensive comparison of both nanofluids and assist in identifying the most suitable working fluid for future thermal management applications [8].

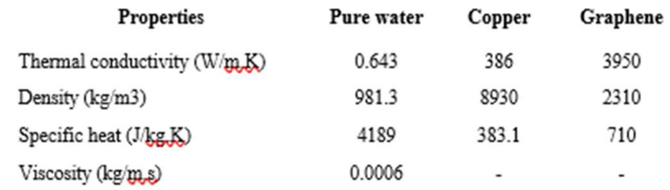
2. MATERIAL AND METHODOLOGY

2.1 Selection of Nanoparticles

Copper (Cu) and Graphene (Gr) nanoparticles were selected for the present investigation owing to their superior thermal characteristics and widespread application in heat transfer enhancement. Copper nanoparticles are well known for their high thermal conductivity and have been extensively investigated for nanofluid applications. Graphene, on the other hand, possesses exceptionally high intrinsic thermal conductivity, excellent mechanical strength, and comparatively lower density, making it one of the most promising carbon-based nanomaterials for advanced cooling systems.

Water was considered as the base fluid because of its favourable thermophysical properties, wide industrial acceptance, and ease of comparison with previous investigations. The thermophysical properties of the nanoparticles and the base fluid used in the present theoretical analysis were obtained from standard literature.

Table 1. *Thermophysical properties of water, copper nanoparticles, and graphene nanoparticles.*



Properties	Pure water	Copper	Graphene
Thermal conductivity (W/m.K)	0.643	386	3950
Density (kg/m3)	981.3	8930	2310
Specific heat (J/kg.K)	4189	383.1	710
Viscosity (kg/m.s)	0.0006	-	-

2.2 Assumptions

The following assumptions were considered during the theoretical evaluation of nanofluid properties:

- Nanoparticles are uniformly dispersed throughout the base fluid.
- The nanofluids behave as single-phase homogeneous fluids.
- Nanoparticle agglomeration and sedimentation are neglected.
- Thermophysical properties of the nanoparticles remain constant throughout the analysis.
- The effect of Brownian motion on thermophysical properties is neglected.
- Heat losses to the surroundings are ignored.
- All calculations are carried out under steady-state conditions.

These assumptions simplify the mathematical analysis while providing reliable theoretical predictions of nanofluid behaviour.

2.3 Nanoparticle Concentration

The thermophysical properties of both Cu-Water and Gr-Water nanofluids were evaluated over a nanoparticle mass concentration range of 0-5%. Calculations were performed at concentration intervals of 1%, namely 0%, 1%, 2%, 3%, 4%, and 5%.

This concentration range was selected because it represents the range most employed in nanofluid research, where noticeable enhancement in thermophysical properties can be achieved without causing excessive particle agglomeration or instability [9].

2.4 Methodology

The present work adopts a theoretical analytical approach for evaluating the thermophysical properties of Cu-Water and Gr-Water nanofluids. Standard mathematical models available in the literature were employed to estimate the effective thermal conductivity, density, specific heat, and dynamic viscosity of the nanofluids at different nanoparticle concentrations.

Initially, the thermophysical properties of water and the selected nanoparticles were collected from published literature. These values were then substituted into the corresponding theoretical equations to determine the effective properties of each nanofluid [10-11].

The obtained results were plotted graphically to examine the influence of nanoparticle concentration on each thermophysical property. A comparative assessment was subsequently carried out to identify the relative performance of Cu-Water and Gr-Water nanofluids for potential heat transfer applications.

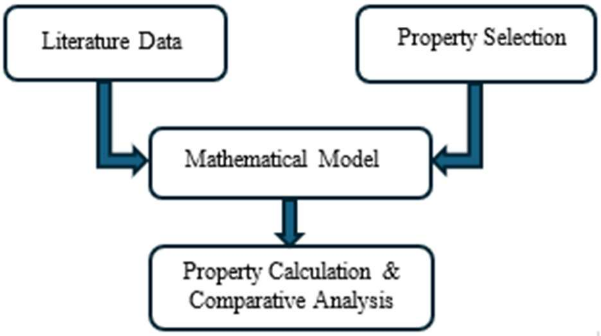


Figure 3. *Flowchart illustrating the methodology adopted for the theoretical analysis.*

2.5 Scope of the Present Study

The present investigation is limited to the theoretical evaluation of thermophysical properties of Cu-Water and Gr-Water nanofluids. The study focuses on four important properties:

- Thermal Conductivity
- Density
- Specific Heat
- Dynamic Viscosity

No experimental investigation or computational fluid dynamics (CFD) analysis has been performed. Furthermore, flow characteristics such as Reynolds number, Nusselt number, friction factor, pressure drop, and pumping power are beyond the scope of the present work.

The comparative analysis is intended to provide a preliminary understanding of the influence of nanoparticle type and concentration on the effective thermophysical behaviour of nanofluids, which may assist future experimental and numerical investigations.

3. MATHEMATICAL FORMULATION

The thermophysical properties of Cu-Water and Gr-Water nanofluids were theoretically evaluated using well-established mathematical models available in the literature [12]. Four important properties, namely density, specific heat capacity, thermal conductivity, and dynamic viscosity, were determined as functions of nanoparticle mass concentration. These analytical models provide a convenient approach for estimating the effective properties of nanofluids without performing experimental measurements.

The calculations were carried out for nanoparticle mass concentrations ranging from **0% to 5%** while maintaining water as the base fluid. The properties of copper and graphene nanoparticles were assumed to remain constant throughout the analysis.

3.1 Effective Density

The effective density of the nanofluid was determined using the classical mixture relation, which considers the weighted contribution of the base fluid and nanoparticles according to their respective mass concentrations [13-14].

Equation (1)

$$\rho_{nf} = c\rho_p + (1 - c)\rho_f \tag{1}$$

Where,

ρ_{nf} = Density of nanofluid (kg/m³)
ρ_f = Density of base fluid (kg/m³)
ρ_p = Density of nanoparticle (kg/m³)
c = Mass concentration of nanoparticles (%)

The density increases with increasing nanoparticle concentration because nanoparticles generally possess higher density than the base fluid. The extent of this increase depends primarily on the intrinsic density of the selected nanoparticles [15].

3.2 Effective Specific Heat Capacity

The effective specific heat capacity was evaluated using the volumetric heat capacity model, which considers the combined thermal storage capability of the nanoparticles and the base fluid [16].

$$C_{pnf} = cC_{pp} + (1 - c)C_{pf} \tag{2}$$

Where,

C_{pnf} = Specific heat capacity of nanofluid (J/kg·K)
C_{pf} = Specific heat capacity of base fluid (J/kg·K)
C_{pp} = Specific heat capacity of nanoparticle (J/kg·K)

The effective specific heat generally decreases with increasing nanoparticle concentration because the specific heat capacities of solid nanoparticles are lower than that of water [17].

3.3 Effective Thermal Conductivity

Thermal conductivity is one of the most important thermophysical properties governing heat transfer enhancement. In the present work, the effective thermal conductivity of the nanofluids was estimated using the Maxwell model [18].

$$\mathrm{k}_{nf} = k_f\left[\frac{k_p + (SH - 1)k_f - (SH - 1)c\left(k_f - k\right.}{k_p + (SH - 1)k_f + c\left(k_f - k_p\right)}\right. \tag{3}$$

Where,

k_{nf} = Thermal conductivity of nanofluid (W/m·K)
k_f = Thermal conductivity of base fluid (W/m·K)
k_p = Thermal conductivity of nanoparticle (W/m·K)
SH = solid particle shape factor and its value is taken as 3 for spherical shaped particles.

An increase in nanoparticle concentration results in improved thermal conductivity due to the significantly higher thermal conductivity of copper and graphene compared with water [19-20].

3.4 Dynamic Viscosity

The effective viscosity of the nanofluid was estimated using Einstein's theoretical equation, which correlates viscosity with nanoparticle concentration [21-22].

$$\mu_{nf} = \mu_f(1 + 2.5c) \tag{4}$$

Where,

μ_{nf} = Dynamic viscosity of nanofluid (Pa·s)
μ_f = Dynamic viscosity of base fluid (Pa·s)

The viscosity of nanofluids generally increases with increasing nanoparticle concentration because the suspended particles increase internal resistance to flow.

3.5 Calculation Procedure

The calculation procedure adopted in the present investigation is summarized as follows:

- The thermophysical properties of water, copper nanoparticles, and graphene nanoparticles were collected from published literature.
- Nanoparticle mass concentrations ranging from **0% to 5%** were selected for the analysis.
- The mathematical models presented in Equations 1-4 were used to calculate the effective density, specific heat capacity, thermal conductivity, and dynamic viscosity.
- The calculated values were tabulated and subsequently represented graphically for comparative analysis.
- The variation of each thermophysical property with nanoparticle concentration was examined to identify the relative

performance of Cu-Water and Gr-Water nanofluids.

3.6 Validation of the Mathematical Model

The mathematical formulations adopted in the present study have been widely reported in previous investigations for predicting the effective thermophysical properties of nanofluids [23]. These models are commonly employed for preliminary analytical evaluations and provide satisfactory agreement with experimental trends within low nanoparticle concentration ranges. Therefore, the present theoretical approach offers a reliable basis for comparing the thermophysical behaviour of Cu-Water and Gr-Water nanofluids under identical operating conditions.

4. RESULTS AND DISCUSSION

The thermophysical properties of Cu-Water and Gr-Water nanofluids were theoretically evaluated over a nanoparticle mass concentration range of **0-5%**. The calculated values were analysed to understand the influence of nanoparticle concentration on thermal conductivity, density, specific heat, and dynamic viscosity. The results are presented graphically and discussed in the following subsections.

4.1 Thermal Conductivity

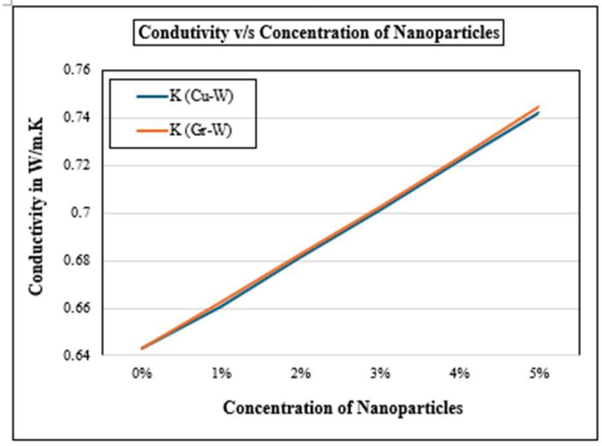


Figure 4. *Variation of thermal conductivity with nanoparticle mass concentration.*

Figure 4 illustrates the variation of thermal conductivity with nanoparticle mass concentration for both Cu-Water and Gr-Water nanofluids. As expected, the thermal conductivity increases continuously with increasing nanoparticle concentration owing to the substantially higher thermal conductivity of the dispersed nanoparticles compared with water. The enhancement becomes more pronounced as the concentration increases from 0% to 5% [24].

The calculated results indicate that both nanofluids exhibit nearly linear improvement in thermal conductivity with concentration. However, the Gr-Water nanofluid consistently demonstrates slightly higher thermal conductivity than the Cu-Water nanofluid throughout the investigated concentration range. At 5% concentration, the thermal conductivity reaches approximately 0.74447 W/m·K for Gr-Water nanofluid compared with 0.74199 W/m·K for Cu-Water nanofluid. Although the numerical difference is relatively small in the adopted theoretical model, graphene exhibits a consistently superior trend because of its exceptionally high intrinsic thermal conductivity.

The increase in thermal conductivity directly improves the heat conduction capability of the working fluid and enhances the overall heat transfer potential in thermal systems [25]. Therefore, among the two nanofluids investigated, graphene-water nanofluid demonstrates comparatively better thermal transport characteristics and appears more suitable for advanced cooling applications.

4.2 Density

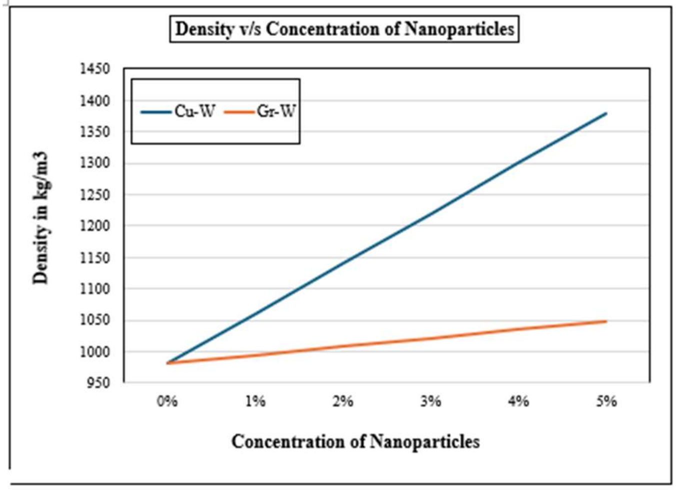


Figure 5. *Variation of density with nanoparticle mass concentration.*

The variation in nanofluid density with nanoparticle concentration is presented in Figure 5. The density of both nanofluids increases progressively with increasing nanoparticle concentration because the density of the dispersed solid particles is considerably higher than that of water [26].

The Cu-Water nanofluid exhibits a significantly larger increase in density than the Gr-Water nanofluid owing to the much higher density of copper nanoparticles (8933 kg/m³) compared with graphene (2250 kg/m³). At 5% concentration, the density of Cu-Water nanofluid increases to approximately 1378.74 kg/m³, whereas the density of Gr-Water nanofluid reaches only 1047.74 kg/m³. Lower density is generally advantageous because it reduces the inertia of the working fluid and minimizes pumping energy requirements during circulation. Consequently, Gr-Water nanofluids provide a better balance between enhanced thermal conductivity and acceptable density, making them more attractive for practical heat transfer systems [28].

4.3 Specific Heat Capacity

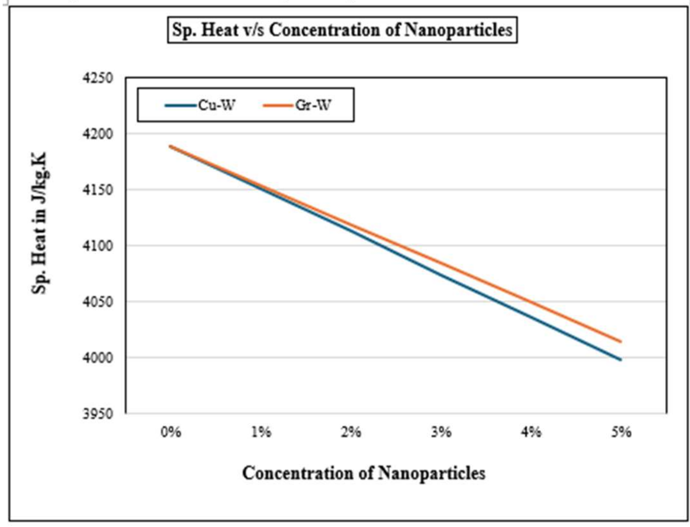


Figure 6. *Variation of specific heat with nanoparticle mass concentration.*

Figure 6 shows the influence of nanoparticle concentration on the effective specific heat capacity of the nanofluids. The specific heat decreases gradually with increasing nanoparticle concentration because the specific heat capacities of both copper and graphene nanoparticles are lower than that of water [29, 32].

Although both nanofluids exhibit a reduction in specific heat, the Gr-Water nanofluid consistently maintains slightly higher values than the Cu-Water nanofluid over the entire concentration range. At 5% concentration, the specific heat of Cu-Water nanofluid decreases to approximately 3998.71 J/kg·K, whereas the corresponding value for Gr-Water nanofluid remains approximately 4015.05 J/kg·K.

The comparatively higher specific heat of Gr-Water nanofluid indicates greater thermal energy storage capability, which is beneficial for applications involving continuous heat absorption and thermal energy transport.

4.4 Dynamic Viscosity

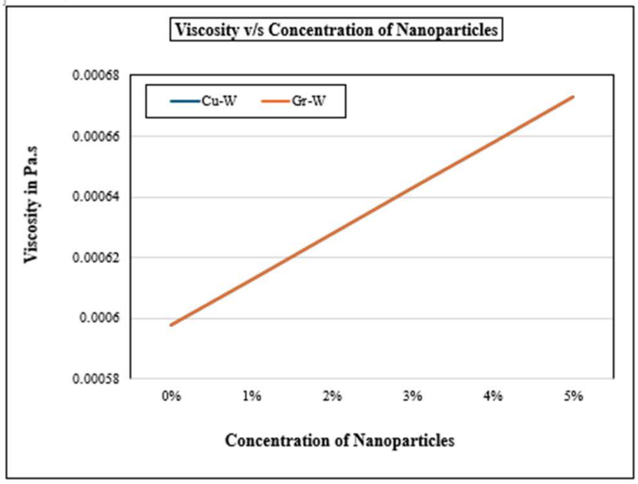


Figure 7. *Variation of dynamic viscosity with nanoparticle mass concentration.*

The variation of dynamic viscosity with nanoparticle concentration is presented in Figure 7. The theoretical calculations indicate that the viscosity increases gradually with increasing nanoparticle concentration because the suspended nanoparticles increase the internal resistance to fluid motion [31].

Interestingly, both Cu-Water and Gr-Water nanofluids exhibit identical viscosity values throughout the investigated concentration range. This behaviour is attributed to the theoretical viscosity model employed in the present study, which considers viscosity as a function of nanoparticle concentration alone and does not account for particle morphology or material-specific interactions.

Although practical experimental investigations may report slight differences in viscosity owing to particle shape, agglomeration, and Brownian motion, the adopted analytical model provides a consistent basis for comparing the influence of concentration on nanofluid viscosity.

4.5 Comparative Assessment of Thermophysical Properties

Table 2. *Comparative evaluation of thermophysical properties of Cu-Water and Gr-Water nanofluids.*

Property	Better Performer	Remarks
Thermal Conductivity	Gr-Water	Slightly higher thermal conductivity
Density	Gr-Water	Lower density reduces pumping requirements
Specific Heat	Gr-Water	Higher heat storage capacity
Dynamic Viscosity	Almost Equal	Almost same values predicted by the adopted theoretical model

A comparative assessment of the calculated thermophysical properties reveals distinct advantages and limitations of both nanofluids. Copper nanoparticles contribute to a substantial increase in density while providing noticeable enhancement in thermal conductivity. Conversely, graphene nanoparticles offer superior thermal conductivity enhancement with only a moderate increase in density.

Furthermore, graphene-water nanofluids maintain comparatively higher specific heat throughout the investigated concentration range, indicating better thermal energy storage capability. Both nanofluids exhibit identical viscosity behaviour under the adopted theoretical model, suggesting that nanoparticle concentration is the dominant parameter influencing viscosity in the present analysis.

Overall, graphene-water nanofluids demonstrate more favourable thermophysical characteristics because they combine enhanced thermal conductivity with lower density and higher specific heat. These characteristics make graphene-water nanofluids promising candidates for future thermal management applications, including compact heat exchangers, electronic cooling systems, automotive radiators, and renewable energy systems.

5. Conclusions

The present study carried out a theoretical comparative analysis of the thermophysical properties of Copper-Water (Cu-W) and Graphene-Water (Gr-W) nanofluids over a nanoparticle mass concentration range of 0-5%. The effective thermal conductivity, density, specific heat capacity, and dynamic viscosity were evaluated using established theoretical models. Based on the obtained results, the following conclusions can be drawn:

- The thermal conductivity of both Cu-Water and Gr-Water nanofluids increased continuously with increasing nanoparticle concentration. However, Gr-Water nanofluids consistently exhibited slightly higher thermal conductivity than Cu-Water nanofluids due to the superior intrinsic thermal conductivity of graphene nanoparticles.
- The density of both nanofluids increased with increasing nanoparticle concentration. The increase was significantly higher for Cu-Water nanofluids because of the considerably higher density of copper nanoparticles. In contrast, Gr-Water nanofluids exhibited only a moderate increase in density, making them comparatively advantageous for applications requiring lower hydraulic loading.
- The effective specific heat capacity of both nanofluids decreased with increasing nanoparticle concentration. Nevertheless, Graphene-Water nanofluids maintained comparatively higher specific heat values than Copper-Water nanofluids throughout the investigated concentration range, indicating improved thermal energy storage capability.
- The theoretical viscosity model predicted identical viscosity variations for both nanofluids. The viscosity increased gradually with increasing nanoparticle concentration, reflecting the influence of suspended nanoparticles on the flow characteristics of the base fluid.
- A comparative assessment of all thermophysical properties indicated that Graphene-Water nanofluids provide a better balance between enhanced thermal conductivity, lower density, and higher specific heat capacity. Therefore, graphene-based nanofluids appear to be more suitable for advanced heat transfer and thermal management applications.

Overall, the present analytical investigation provides a useful comparison of Cu-Water and Gr-Water nanofluids and may serve as a reference for selecting appropriate working fluids in heat transfer systems where thermophysical properties play a critical role.

6. FUTURE SCOPE

The present study is limited to the theoretical evaluation of thermophysical properties of Cu-Water and Gr-Water nanofluids. Future research may be directed towards the following aspects:

- Experimental validation of the theoretical thermophysical properties presented in this study.
- Investigation of the heat transfer performance of Cu-Water and Gr-Water nanofluids in practical heat exchanger systems.

- Comparative Computational Fluid Dynamics (CFD) analysis of nanofluid flow and thermal characteristics.
- Evaluation of long-term stability, sedimentation behaviour, and dispersion characteristics of nanofluids under different operating conditions.
- Investigation of hybrid nanofluids combining metallic and carbon-based nanoparticles to achieve further enhancement in thermal performance.
- Techno-economic and environmental assessment of nanofluid applications for large-scale industrial heat transfer systems.

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