Hybrid Nanofluids: Exploring Their Thermal Properties and Mechanisms – A Literature Review

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Abstract. There are significant challenges nowadays in improving thermal systems for greater energy efficiency, compactness, and reduced weight. In this context, extensive research has focused on hybrid nanofluids, an advanced type of thermal transmission fluid. This combination has the potential to offer improved thermal properties of the fluid, leading to improved heat transfer performance. This review examines recent experimental studies investigating the thermal properties of hybrid nanofluids, focusing on the factors and mechanisms contributing to their superior heat transfer capabilities. The findings reveal that most significant factors influencing these properties include nanoparticle concentration, temperature, nanoparticle material combinations, and the use of surfactants. The superior performance of hybrid nanofluids is attributed to mechanisms such as enhanced Brownian motion and synergistic interactions between different nanoparticle type. By elucidating these factors and mechanisms, this review enhances the knowledge of the thermal properties of hybrid nanofluids, which can be applied in more efficient and compact thermal systems.

Keywords. hybrid nanofluids, thermal properties, heat transfer, thermal engineering.

1. Introduction

The field of thermal engineering faces some significant challenges in the search to improve thermal systems for higher energy efficiency, along with the demands for compactness and reduced weight. In the past, extensive research has focused on enhancing heat transfer rates through various active and passive techniques [1]. Recently, attention has shifted towards hybrid nanofluids, which represent an advanced class of thermal transmission fluids which can significantly enhance the thermal properties of the fluid, leading to improved heat transfer performance.

By definition, a nanofluid is a colloidal mixture in which nanoparticles, typically ranging from 1 to 100 nm in size, are suspended in a base fluid [2]. The introduction of two or more types of nanoparticles into the base fluid results in hybrid nanofluids, which offer the possibility of superior thermal properties. These properties—such as thermal conductivity, viscosity, specific heat, and density, play an important role in determining their effectiveness in heat transfer applications [3].

However, while empirical studies have demonstrated that hybrid nanofluids can outperform conventional nanofluids, the underlying mechanisms responsible for these enhancements are still not fully understood [4]. Thus, the goal of this study is to review the latest experimental findings on the thermal properties of hybrid nanofluids and explore the mechanisms that contribute to their superior heat transfer capabilities.

2. Methodology

In this review, was adopted a narrative literature review methodology. The selection of the studies was made through advanced searches using Google Scholar. Advanced searches were conducted using terms such as “hybrid nanofluids” AND ”thermal properties” AND “experimental study". The focus was mainly on studies published after 2022, ensuring the inclusion of the most recent findings.

Following a preliminary search of titles and abstracts, irrelevant studies that did not align with the search terms were excluded. Initially, approximately 240 documents were identified across the database. In the final step, only those articles that directly addressed the research goals and to the specified publication date criteria were selected for review.

As a result, 14 articles remained for reading and analysis in this review study. The subsequent sections of this review are structured as follows: the results section presents an overview of the experimental findings of the hybrid nanofluids from each selected study; the discussion section synthesizes insights from the review, aiming to provide a perspective on the thermal properties and the underlying mechanisms responsible for their superior performance; and finally, the conclusion section will make a recapitulation of all the work.

3. Results

This section presents an overview of the experimental findings investigated in these studies. Table 1 summarizes the experimental findings.

Syam Sundar at al., 2024 [5] investigated the thermophysical properties of Fe_3O_4-TiO_2 magnetic hybrid nanofluids, including thermal conductivity, viscosity, density, and specific heat, in a heat sink under a magnetic field. Thermal conductivity increased with both temperature and volume fraction, showing enhancements of 9.46%-22.26% at 20°C and 20.67%-46.55% at 60°C compared to the base fluid. Both Brownian motion and nanoparticle migration contribute to the increase in heat transfer. Viscosity displayed a strong dependence on concentration, particularly at lower temperatures, with increases of 59.49%-113.92% at 20°C and 26.67%-73.33% at 60°C compared to water. Density increased with both temperature and nanoparticle concentration, while specific heat decreased with higher nanoparticle concentration but slightly increased with temperature.

Shaik AH, et al., 2024 [6] examined the thermophysical properties of Cu-graphene hybrid nanofluids. The thermal conductivity showed an increase (~35%) at high particle loading (~0.14 vol%). Viscosity increased significantly (~65%) compared to water, attributed to the interaction between base fluid molecules and the nanoparticles. Specific heat was calculated using theoretical equations and found to decrease with higher concentrations of hybrid nanostructures, likely due to the lower specific heat of Cu and graphene compared to the base fluid.

Dai J et al. 2024, [7] investigated the effects of nanoparticle volume fraction (0.5–2.0 vol%) and the Cu volume mixing ratio (20:80, 40:60, 50:50, 60:40, and 80:20) in Cu-Al/Ar hybrid nanofluids using non-equilibrium molecular dynamics (NEMD) simulations at a temperature of 85 K. The results showed that the thermal conductivities of Cu-Al/Ar hybrid nanofluids with a mixing ratio of 20:80 was lower than those of the corresponding Cu/Ar mono nanofluids with volume fraction below 1.3 vol% due to the low quantity of Cu nanoparticles. However, increasing the Cu content through mixing ratios from 40:60 to 80:20 resulted in higher thermal conductivity across all volume fractions. The highest thermal conductivity was observed at 0.166 W/m·K with an 80:20 ratio at 2.0 vol%, a 14.48% improvement over Cu/Ar mono nanofluids.

Borode A. et al., 2023, [8] investigated the impact of concentration and temperature on the electrical conductivity (σHNF), viscosity (μHNF), and thermal conductivity (λHNF) of GNP/Fe_2O_3 hybrid nanofluids with a 50:50 mixing ratio. The electrical conductivity and thermal conductivity increase linearly with concentration for a constant temperature. Viscosity also increased with nanoparticle addition but decreased with temperature due to enhanced Brownian motion. Another explanation is that when the temperature rises, the distance between molecules in the base fluid and the nanoparticles shortens, thus, reducing μHNF and flow resistance. Thermal conductivity was maximized with increased nanoparticle loading, though higher temperatures led to agglomeration and reduced conductivity.

Rehman A, et al., 2023 [9] explores the influence of eight distinct surfactants on the stability, rheological characteristics, and thermophysical properties of hybrid nanofluids (NFs) composed of Water-EG (60:40) based Al2O3-TiO2 (20:80) hybrid NFs at a concentration of 0.02 vol%. Thermophysical properties were determined at a temperature range of 30°C to 80°C, polyvinylpyrrolidone (PVP) showed the highest stability among all surfactants, enhancing the viscosity by 50% and thermal conductivity (TC) by 3.6% at 80°C. The addition of surfactants increased the overall viscosity of the nanofluids, with polyethylene glycol (PEG) providing the highest enhancement at 37.2% at 30°C. However, as the temperature increased, the viscosity decreased, showing minimal changes at 80°C.

Borode A, et al., 2023 [10] explores the thermophysical properties and heat transfer performance of a hybrid nanofluid made from graphene nanoplatelets (GNP) and γ-Al_2O_3 nanoparticles dispersed in deionized water. It examines how varying nanoparticle concentrations (0.1–0.4 vol%) and temperatures (15–40 °C) affect viscosity (μ), thermal conductivity (λ), and electrical conductivity (σ). The results show that viscosity increases with higher nanoparticle concentration but decreases with rising temperatures, while both thermal and electrical conductivities improve with higher concentrations and temperatures. The viscosity increased by 21.74% at 0.4 vol%, but decreased by 34.68% when the temperature rose from 15 °C to 40 °C. The study also noted a peak thermal conductivity enhancement of 17.82% at 40 °C and 0.4 vol%, with a 50:50 GNP and Al_2O_3 mixture showing superior performance.

Sofiah A. G. N. et al., 2023 [11] presents the synthesis of copper oxide-polyaniline (CuO/PANI). nanocomposites blended dispersed in ecologically friendly palm oil to develop hybrid nanofluids and investigated as potential heat transfer hybrid nanofluids for the first time. The formulated CuO/PANI-palm oil hybrid nanofluids are prepared

Tab. 1 – Resume of key findings

Ref	Nps	Base fluid	Variables	Thermal conductivity enhancement	Viscosity enhancement	Key findings
[5]	Fe_3O_4-TiO_2	Water	20 °C to 60°C, 0.2% to 1.0%	9.46%-22.26% at 20°C, 20.67%-46.55% at 60°C	59.49%-113.92% at 20°C, 26.67%-73.33% at 60°C	Enhancement increases with temperature and concentration; magnetic field influence
[6]	Cu-Graphene	Water	0.14 vol%	35%	65%	Significant viscosity increase; specific heat decreases with concentration
[7]	Cu-Al	Argon	0.5–2.0 vol%, 85K, (various ratios)	2.76%-14.48%	-	Mixing ratio and volume fraction significantly affect thermal conductivity
[8]	GNP/Fe_2O_3	Water	0.1% to 0.4%, 15°C and 40°C, 50:50	Linear increase with concentration	Increases with concentration, decreases with temperature	Electrical conductivity also investigated; temperature significantly affects viscosity
[9]	Al_2O_3-TiO_2	Water-EG (60:40)	0.02 vol%, 30°C to 80°C, Surfactant	Up to 3.6% at 80°C (with PVP)	Up to 37.2% at 30°C (with PEG)	Surfactants influence stability and thermophysical properties
[10]	GNP/γ-Al_2O_3	Water	0.1–0.4 vol%, 15°C –40°C	Peak: 17.82% at 40°C and 0.4 vol%	Peak: 21.74% at 0.4 vol%	Both thermal conductivity and viscosity improved significantly; 50:50 mixture shows superior performance
[11]	CuO/PANI	Palm Oil	0.01% to 0.5%, 1,5 and 10wt%, 30°C-600°C	31.34% at 10 wt%	Increases with concentration	Density increases with concentration, decreases with temperature; eco-friendly base fluid
[12]	ZnO–MgO	Coolant, Engine oil, Deionized water, Coconut oil	Various base fluids, 20°C - 60°C	7.29%-19.04% (depending on base fluid)	-	Enhancement depends on base fluid and temperature sensitivity
[13]	MXene/C-Dot	Water	0.01 wt%-0.2 wt%, 25-65°C	42.2%	-	Significant enhancement above 0.05 wt%; volumetric heat capacity decreases with temperature
[14]	Fe_3O_4/CNT, Fe_3O_4/Graphene	Water	5 wt%, 24°C, with and without magnetic field	Up to 12% (CNT) and 51% (Graphene) with magnetic field	-	Magnetic field influence enhances thermal conductivity, especially with Fe_3O_4/Graphene
[15]	Al_2O_3-GO	Water	0.25-1.0%,30°C to 50°C, (80:20)	4.30%-4.34% igher than mono nanofluids at 1.0%	Decreases with concentration, up to 4.6% reduction	Hybrid nanofluid shows better thermal conductivity and lower viscosity reduction compared to mono nanofluids
[16]	Al_2O_3-MWCNT	Water	(60:40), 0.3 vol%, 10-30°C, (5 nm, 20 nm, <7 nm, 30-50 nm)	Best: Al_2O_3 (20nm)-MWCNT (<7nm)	Highest: 1.13 mPa·s, Lowest: 0.6 mPa·s	Particle size significantly affected heat transfer performance, hybrid nanofluid with smaller Al_2O_3 and MWCNT showed the best performance
[17]	SiC-ZnO	EG	(50:50), (20, 55, 90 nm), 0.2-1.0%, 25-50°C	Max 15.91% at 50°C, 1 vol%, 20 nm	-	Volume fraction has the highest influence, followed by temperature and particle size
[18]	Cu-Doped ZnO	EG	0.01–0.08 wt%, 298-328 K	Increases with concentration and temperature	Increases with concentration, decreases with temperature	Viscosity and thermal conductivity analyzed for cooling systems
[19]	ZrO_2-SiC	water	0.025-0.1 vol%, 20-60°C	4.36% (20°C, 0.025 vol%) to 25.75% (60°C, 0.1 vol%)	Increases with concentration	Higher concentrations increase both thermal conductivity and viscosity

by varying the weight percentage of CuO nanoparticles (1, 5, and 10 wt%).

and stabilized using an ultrasonication process without any surfactant. Density evaluation of formulated nanofluids shows a linear relationship between density and volume concentration of nanocomposites but decreased with increasing temperature. Results showed that thermal conductivity increased

with the concentration of nanocomposites, with the highest enhancement (31.34%) observed in the nanofluid containing 10 wt% CuO/PANI. Meanwhile, nanofluid having 1 wt% CuO/PANI exhibited the least improvement in thermal conductivity (25.82%). The density of formulated nanofluids is directly proportional to the volume concentration of nano additives but decreased at ramping temperature. The highest viscosity was observed for nanofluid dispersed with the highest weight percentage of CuO NP (10 wt% CuO/PANI nanocomposites) than others.

Nazir A, et al., 2024 [12] investigates the enhanced thermal conductivity of plasma-generated ZnO–MgO-based hybrid nanofluids (HNFs) and their temperature-dependent behavior. The thermal conductivity of these HNFs was analyzed in the temperature range of 20–60°C, showing a significant improvement compared to base fluids (BFs). The results indicated that the thermal conductivity increased with rising temperature, with improvements ranging from 9.2% to 19.04% in coolant-based HNFs and 7.29% to 16.28% in engine oil-based HNFs. The enhancement of 11.94 %– 17.77 % and 8.88 %–17.65 % were observed in DW and coconut oil-based HNFs.

Sreekumar S, et al., 2024 [13] introduces an energy-efficient and environmentally friendly synthesis method for producing carbon quantum dot (C-dot), MXene, and hybrid MXene/C-dot nanofluids for heat transfer applications. Characterizations were performed on all the nanofluids of five different concentrations (0.01–0.2 wt %). Thermal conductivity was found to increase with both nanofluid concentration and temperature, with the hybrid nanofluids showing a 42.2% enhancement. Notably, thermal conductivity increased significantly at concentrations above 0.05 wt%. For hybrid nanofluids, volumetric heat capacity decreased by about 0.47 $MJ/m^3 \cdot K$ when the temperature increased by 40 °C, consistent with prior studies (Zhou and Ni, 2008). The decrease in specific heat with higher nanoparticle concentration can be attributed to the lower specific heat of nanomaterials compared to the base fluid they are dispersed in.

Alsangur R, et al., 2024 [14] investigates the magnetic field-dependent thermal conductivity of Fe_3O_4/CNT-water and Fe_3O_4/Graphene-water magnetic hybrid nanofluids. The results reveal that the thermal conductivity of both samples increases with the magnetic field and particle concentration, with Fe_3O_4/Graphene-water showing up to 3 times higher thermal conductivity enhancement than Fe_3O_4/CNT-water. The maximum thermal conductivity enhancements were observed as ~12% and ~9% for Fe_3O_4/CNT-water, and ~51% and ~21% for Fe_3O_4/Graphene-water under the application of an external magnetic field in parallel and perpendicular directions, respectively. Measurements at room temperature (24°C) without a magnetic field showed enhancements of 6.7% (0.64 W/mK) for Fe_3O_4/CNT-water and 14.6% (0.69 W/mK) for Fe3O4/Graphene-water at 5 wt%. The study highlights that the magnetic field significantly boosts thermal conductivity, with a more pronounced effect in the parallel direction. The observed difference in conductivity between the two fluids is attributed to the aspect ratio differences, with graphene's two-dimensional plate-like structure offering a higher surface area than CNT's one-dimensional structure. This effect can be explained by the chain-like aggregation of magnetic nanoparticles in the presence of a magnetic field, where particles align due to magnetic dipole-dipole interactions. The potential for creating magnetic hybrid nanofluids with enhanced thermal conductivity and mobility under magnetic fields could address various thermal management challenges.

Selvarajoo K, et al., 2024 [15] explores the thermophysical properties of aluminum oxide (Al_2O_3) and graphene oxide (GO)-based mono and hybrid nanofluids at varying volume concentrations for heat transfer applications. The hybrid Al_2O_3-GO nanofluid (80:20) was tested at concentrations of 0.25%, 0.5%, 0.75%, and 1.0%, with viscosity and thermal conductivity measured between 30°C and 50°C. The findings reveal that at 1.0% concentration, the Al_2O_3-GO hybrid nanofluid improves thermal conductivity by 4.30% and 4.34% over the Al_2O_3 and GO mono nanofluids, respectively. Additionally, this hybrid nanofluid exhibits the least viscosity reduction (4.6%), outperforming the mono nanofluids. As volume concentration increases, the viscosity drop diminishes, while thermal conductivity rises significantly with increasing temperature, peaking at 0.968 W/m.K at 50°C for the 1.0% hybrid nanofluid.

Ibrahim I. U, et al., 2024 [16] investigates the effects of nanoparticle size on the heat transfer characteristics of Al_2O_3 and MWCNT-based hybrid nanofluids in transitional flow regimes. Four particle sizes were used: 5 nm and 20 nm for Al_2O_3 and <7 nm and 30–50 nm for MWCNT, and three different hybrid nanofluid combinations: (Al_2O_3 (5 nm) – MWCNT (<7 nm), Al_2O_3 (20 nm) – MWCNT (<7 nm), and Al2O3(20 nm) – MWCNT (30–50 nm)) with a 60:40 ratio and 0.3% volume concentration were prepared. The thermal conductivity and viscosity were measured across temperatures between 10°C and 30°C, the results revealed that particle size significantly impacts convective heat transfer characteristics. the tested shows coefficient of thermal performance (COP) was better than that of Al_2O_3 (20 nm) – MWCNT (30–50 nm) and Al_2O_3 (5 nm) – MWCNT (<7 nm) with 43.53 % and 21.89 %, respectively. Additionally, this hybrid nanofluid displayed the lowest friction factor and pressure drop. The viscosity of the hybrid nanofluids, measured using the Sv–10 Vibro Viscometer, shows a decreasing trend as the particle size increases and with a rise in temperature. The highest viscosity value was observed for the Al_2O_3 (20 nm) – MWCNT (<7 nm) combination, reaching 1.13 mPa·s, while the lowest value was recorded for the Al_2O_3 (5 nm) – MWCNT (<7 nm) combination, at approximately 0.6 mPa·s.

Ghafouri A. et al., 2023 [17] investigate the thermal conductivity of hybrid nanofluids composed of SiC and ZnO nanoparticles in an ethylene glycol (EG) base fluid, focusing on the effects of nanoparticle size (20, 55, and 90 nm), volume fraction (0.2% to 1%), and temperature (25–50 °C). Results showed that thermal conductivity increased with higher volume fractions, smaller nanoparticle sizes, and elevated temperatures, with a maximum enhancement of 15.91% at 50 °C, a 1% volume fraction, and a 20 nm nanoparticle size. The study underscores the importance of optimizing these parameters to improve the heat transfer properties of hybrid nanofluids and the importance of the parameters as: volume fraction > temperature > nanoparticle size.

Kiruba R, et al., 2023 [18] explores the synthesis and thermo-physical properties of Cu-doped ZnO–EG hybrid nanofluids based on ethylene glycol (EG) for improved viscosity and thermal efficiency in cooling systems. Viscosity and thermal conductivity were analyzed at varying nanoparticle concentrations (0.01 wt% to 0.08 wt%) and temperatures (298 K to 328 K). The experimental data revealed that the viscosity of nanofluid systems increases as the particle concentration rises, while it decreases with higher temperatures.

Ajeena A. M. et al., 2023 [19] explores the thermal properties of ZrO2-SiC/DW hybrid nanofluid recorded at various solid volume fractions and temperatures, revealing notable enhancements in thermal conductivity, influenced by both properties. A significant increase of 25.75% in thermal conductivity was observed at a 0.1% volume fraction and 60°C, with improvements starting as low as 4.36% at 20°C and 0.025% volume fraction, and reaching 20.8% at higher concentrations. The nanofluid's ability to transfer heat more efficiently is attributed to the increased kinetic energy and clustering of nanoparticles at elevated temperatures, which facilitate rapid heat transfer. Interestingly, while higher nanoparticle concentrations boost thermal conductivity, they also lead to increased viscosity, demanding more pumping power.

4. Discussion

As observed in the findings from the studies, the performance of hybrid nanofluids is influenced by several factors, including nanoparticle concentration, type, mixing ratio, temperature, surfactants, as well as the composition and morphology of the nanoparticles.

It was found that thermal conductivity generally increases with nanoparticle concentration such as Cu-graphene, GNP/Fe_2O_3, CuO/PANI, C-dot/MXene, Fe_3O_4/CNT, and Fe_3O_4/Graphene. However, as indicated in some studies, the relationship between nanoparticle concentration and thermal conductivity is not always linear, at higher concentrations, agglomeration of nanoparticles may occur, which can lead to a reduction in the effective surface area for heat transfer and, consequently, a decrease in thermal conductivity, as observed in studies involving ZnO-MgO hybrid nanofluids. Furthermore, thermal conductivity typically increases with temperature, as seen in Fe_3O_4-TiO_2, GNP/Fe_2O_3, CuO/PANI, ZnO–MgO, and C-dot/MXene hybrid nanofluids.

The findings also underscore the complex interplay between concentration, temperature, and viscosity conductivity, which can negatively impact fluid flow characteristics. Viscosity generally increases with increasing nanoparticle concentration (Fe_3O_4-TiO_2, Cu-graphene, GNP/ Fe_3O_4, CuO/PANI, GNP/γ-Al_2O_3) and decreases with increasing temperature (Fe_3O_4-TiO_2, GNP/Fe2O3, GNP/γ-Al_2O_3). This increase in viscosity is particularly pronounced at lower temperatures, where fluid mobility is already reduced. Higher viscosity increases the pumping power required for fluid circulation, leading to higher energy consumption in thermal systems. Surfactants can contribute by stabilizing the nanoparticles and optimizing their dispersion.

Specific heat capacity tends to decrease with rising nanoparticle concentration but may increase slightly with temperature. Density greatly influences various heat transfer characteristics, including Reynolds number, pumping power, frictional factor, and stability.

Mechanistically, the superior thermal performance of hybrid nanofluids can be attributed to several factors. Brownian motion enhances thermal dispersion, with interactions between diverse nanoparticles amplifying this effect. Nanoparticle migration towards regions with higher temperature gradients facilitates heat dissipation, while reduced interfacial thermal resistance between nanoparticles and the base fluid promotes efficient heat transfer. Synergistic effects improve dispersion stability and reduce agglomeration, leading to thermal conductivity surpassing the weighted average of individual components. and enhanced interfacial interactions. Additionally, thermophoresis—the movement of nanoparticles from hotter to colder regions due to temperature gradients—can also contributes to enhanced heat transfer.

5. Conclusion

In this paper, a literature review was conducted through an analysis of experimental findings. First, after evaluating the studies, 14 primary studies from 2018 to 2023 were identified. Second, the main findings of each proposed article were summarized. Third, a discussion section was presented, in which insights from all the articles was write. Numerous studies have demonstrated a huge improvement in thermal properties of hybrid nanofluids. The enhancement in thermal conductivity observed across different studies is influenced by factors such as nanoparticle type, concentration, temperature. Furthermore, the main mechanisms responsible for this enhancement are reported, which is important for understanding the behavior of hybrid nanofluids.

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