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Effect of Mechanical Technique on the Stability and Thermal Conductivity of MgO/Commercial Coolant-Based Nanofluid

Nurul Izzati Akmal Muhamed Rafaizul[1,2], Mohd Afzanizam Mohd Rosli[2], Mohd Nurazzi Norizan[3], Noor Aisyah Ahmad Shah[1], Ong Keat Khim[1], Intan Juliana Shamsudin[1], Norherdawati Kasim[1], Mohd Haizal Mohd Husin[2], Norli Abdullah[1,*]

[1]*Center for Defence Foundation Studies, National Defence University of Malaysia, Sungai Besi Camp, 57000 Kuala Lumpur, Malaysia*
[2]*Faculty of Mechanical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia*
[3]*Bioresource Technology Division, School of Industrial Technology, Universiti Sains Malaysia, Penang 11800, Malaysia*

**Corresponding author (email: norli.abdullah@upnm.edu.my)*

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ABSTRACT

In recent years, nanofluid coolants enhanced with nanoparticles have attracted significant attention as promising alternatives because of their superior thermal properties. Magnesium oxide (MgO) nanoparticles, known for their high thermal conductivity, chemical stability, and environmental safety, offer a promising material for developing advanced automotive cooling fluids. This study investigates the influence of mechanical dispersion methods on the stability, thermal conductivity, and viscosity of MgO nanoparticles dispersed in a commercial automotive coolant. Nanofluids were prepared using a two-step method with variations in homogenization and sonication durations, and with or without polyvinylpyrrolidone (PVP) as a surfactant. Stability was assessed through visual observation, while thermal and rheological properties were analyzed across different temperatures and shear rates. The results show that PVP significantly improves nanoparticle suspension by delaying agglomeration and sedimentation. CNP-1 (with PVP and 60 min of sonication) exhibited the highest thermal conductivity at 60 °C (0.3157 W/mK), while maintaining moderate viscosity with shear-thinning behavior. CN-1, lacking PVP, showed poor dispersion and higher viscosity. CNP-4 demonstrated unusually high thermal conductivity at 40 °C, but instability at 60 °C, highlighting the delicate balance between dispersion and performance. Overall, the findings reveal that both surfactant usage and sonication duration are critical for enhancing the performance and long-term stability of MgO-based nanofluids for automotive cooling applications.

Keywords: chemical stability; mechanical dispersion; sedimentation; shear rate; viscosity

INTRODUCTION

Nanofluids, consisting of nanoparticles suspended in base fluids, have gained significant attention in heat transfer applications for their superior thermal conductivity and heat transfer efficiency. Compared to traditional coolants, nanofluids exhibit enhanced thermal conductivity, heat capacity, and convective heat transfer coefficients [1]. These characteristics make them particularly promising for automotive cooling systems, where efficient heat transfer is crucial for engine performance and longevity [2]. However, the practical application of nanofluids remains limited due to stability issues, as nanoparticles tend to agglomerate and sediment over time, reducing their effectiveness [3].

Several studies have investigated the use of commercial car engine coolants enhanced with metal oxide nanoparticles to improve heat transfer and cooling efficiency. Magnesium oxide (MgO) nanoparticles have been widely studied due to their high thermal conductivity, chemical stability, and cost-effectiveness [4]. Compared to metal-based nanoparticles such as copper (Cu) or aluminum oxide (Al_2O_3), MgO shows promise for automotive applications where it offers better oxidation resistance and is more compatible with conventional cooling fluids [5]. Studies have demonstrated that the incorporation of MgO nanoparticles in commercial coolants can significantly enhance heat transfer in automotive radiators and industrial heat exchangers [6]. However, stability remains a major challenge, as MgO nanoparticles tend to aggregate due to their high surface energy, leading to rapid sedimentation and loss of thermal performance over time [7].

Sun et al., [8] used commercially data center coolant as fluids with the addition CuO (40 nm) and Al_2O_3 (80 nm). The results showed an average increase in thermal conductivity of up to 20 – 25%. The dispersion technique used in nanofluid preparation plays a critical role in preventing agglomeration and improving stability. Various methods, such as magnetic stirring, ultrasonication, and surfactant-assisted dispersion, have been explored to enhance the uniformity and longevity of nanofluids [9]. Among these, ultrasonication has been widely recognized as an effective method for breaking nanoparticle clusters and achieving homogeneous dispersion [10]. An experimental investigation on the thermal conductivity of commercial engine coolant based SiO_2 nanofluids has been presented by Mukherjee et al. [11]. The process involves the direct dispersion of SiO_2 nanoparticles into engine coolant using 1 h of magnetic stirring followed by 3 h of sonication. The sedimentation in the samples of SiO_2 nanofluids has occurred in the samples after 15 days. Whereas, with 1% concentration at 65 °C showed a maximum enhancement in thermal conductivity value of 21.083%. In another work, the effects of 0.5 wt.% Al_2O_3 nanoparticles (13 nm) to an engine coolant were investigated and the results show the cooling power of the radiator has increased up to 17.46%. The nanoparticles were dispersed in a base fluid using probe type ultrasonic homogenize for 30 min without any dispersant agent [12].

Additionally, the use of stabilizing agents like polyvinylpyrrolidone (PVP) has shown promising results in improving nanoparticle stability by modifying the surface properties and reducing van der Waals attractions [13–15]. Despite these advancements, an optimized preparation strategy that ensures long-term dispersion stability of MgO nanofluids in commercial coolants remains an active area of research.

This study aims to systematically investigate the effect of mechanical technique and their impact on the stability of MgO nanoparticles in a commercial coolant. The stability of the

nanofluids will be evaluated using visual observation to monitor sedimentation trends over time. The use of homogenization and sonication in the preparation of nanofluids was adapted from our previous work [16]. These mechanical processes were employed due to their effectiveness in breaking down particle agglomeration and enhancing the homogeneity of the solution, thereby contributing to improved long-term stability and dispersion sustainability. This study seeks to identify the most effective preparation method to enhance the long-term stability of MgO-based nanofluids. The findings will provide valuable insights into the practical implementation of nanofluids in automotive cooling systems and other heat transfer applications.

MATERIALS AND METHODS

Magnesium oxide (MgO) nanoparticles were synthesized using magnesium nitrate salt ($MgNO_3.6H_2O$) as precursor with sodium hydroxide (NaOH) using the sol-gel method. The coolant used as the base fluid in this study was purchased commercially, while the surfactant, polyvinylpyrrolidone (PVP) was purchased from Sigma Aldrich.

Preparation of MgO Nanoparticles

The concentration of 0.5M $MgNO_3.6H_2O$ and 0.5M NaOH solutions were prepared using deionized water from Millipore water purification system. Precipitation was induced by drop-wise addition of NaOH into the magnesium nitrate solution under continuous stirring for 1 h at room temperature. During the sol-gel process, the initial clear solution turns to cloudy slurry represent hydrolysis reaction occurs. The white slurry was washed with copious amount of high purity water and methanol three times for effective removal of impurities. The final product was dried at 500 ˚C for 12 h. The MgO nanoparticles was grinded using mortar and pestle to get the fine nanoparticles prior to usage. Figure 1 represent schematic diagram for the preparation of nanoparticles.

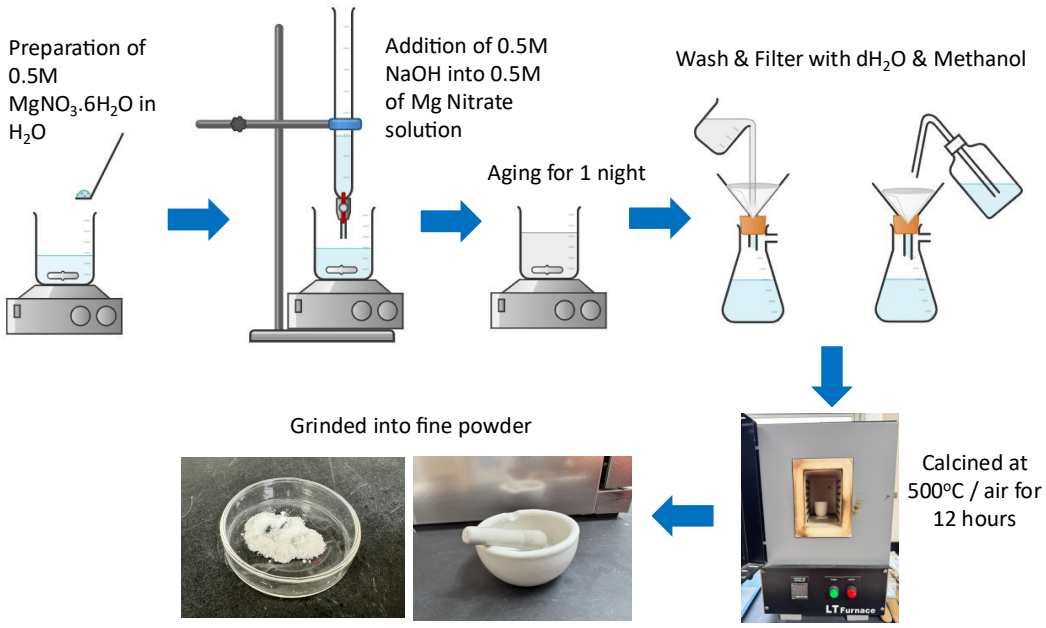


Figure 1. Schematic diagram for the preparation of magnesium oxide nanoparticles using sol-gel method

Characterization Analysis

The Fourier Transform Infrared (FTIR) spectroscopy was analyzed using Attenuated Total Reflectance (ATR) method. The sample is placed in direct contact with the crystal surface. Infrared light enters the crystal and undergoes total internal reflection at the crystal-sample interface. A small portion of the light, called the evanescent wave, penetrates a few microns into the sample. The sample absorbs specific wavelengths of light based on its molecular composition. The MgO nanoparticle was characterized by X-ray diffraction (XRD) analysis to obtain the average size of the MgO nanoparticle [17]. Scherrer equation is used to calculate the crystallite size of the particle as shown in Eq. (1):

$$D = \frac{K\lambda}{\beta cos\theta}, \tag{1}$$

where D is the crystallite size, K is the Scherrer constant (0.9), λ is the wavelength of the X-rays used, β is the full width at half maximum, and θ is the peak position.

Nanofluids Formulation

The nanofluids were formulated using the two-step method with the weight concentration of 0.06 wt.% MgO NPs are used. The density of the commercial coolant was obtained by using Eq. (2):

$$\rho = \frac{m}{V}. \tag{2}$$

The details of the commercial coolant are presented in Table 1. The durations of both homogenization and sonication were varied as presented in Table 3 to identify the most optimal time required to achieve a stable and uniform dispersion of the nanofluid. Figure 2 represent the process involve during preparation of nanofluids. The mass required for each materials used are listed in Table 2. This investigation aimed to optimize the dispersion process, ensuring that the nanoparticles remain evenly distributed throughout the base fluid for an extended period, thereby enhancing the overall stability and performance of the nanofluid.

Table 1. Details of commercial coolant used as base fluids

Basic Parameters	Value
Mass of commercial coolant	10.9156 g
Volume of commercial coolant	10 ml
Density	1091.56 kg/m^3
Appearance	Green

Table 2.Details of formulated nanofluid using MgO and commercial coolant

Weight percentage of MgO (wt.%)	Mass of MgO (g)	Mass of 10% PVP from MgO (g)	Mass of commercial coolant (g)	Total volume of nanofluid (ml)

0.06	0.089	0.0089	44.9021	45

Table 3. Duration for homogenization and sonication process

Sample code		Homogenization (min)	Sonication (min)	Homogenization (min)
PVP	No PVP			
CNP-1	CN-1	5	60	5
CNP-2	-	5	30	5
CNP-3	-	10	60	10
CNP-4	-	10	30	10

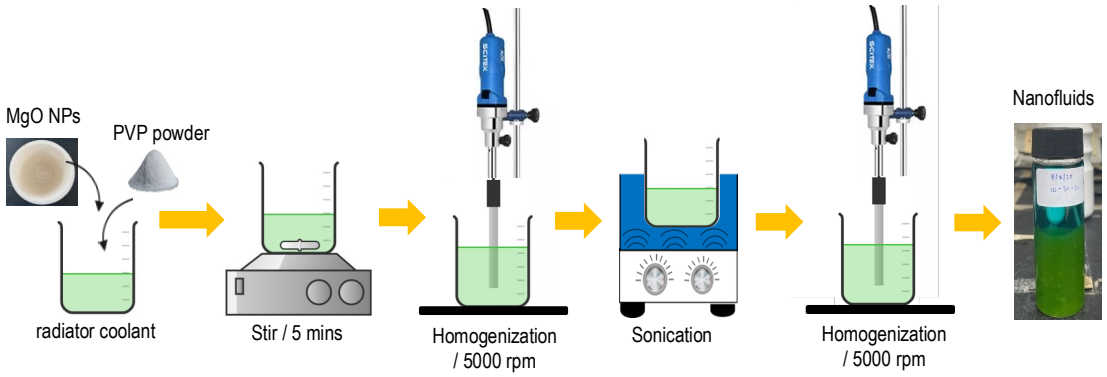


Figure 2. Preparation of nanofluids

Visual observation is a simple yet effective method for assessing the long-term stability of nanofluids by monitoring sedimentation behavior. This technique helps determine the extent of nanoparticle aggregation and settling over time. In this study, sedimentation was evaluated qualitatively at two-time intervals, which are when it was freshly formulated (0 h) and one week after nanofluid preparation. Thermal conductivity is a key parameter in evaluating the heat transfer performance of nanofluids. This study examines the effect of different preparation methods on the thermal conductivity of MgO/commercial coolant-based nanofluids to determine the relationship between dispersion stability and heat transfer enhancement. The thermal conductivity of the nanofluid samples was measured using TEMPOS Thermal Analyzer with KS-3 sensor. Measurements were conducted at room temperature (25 °C), 40 °C, and 60 °C to simulate engine operating conditions. The baseline thermal conductivity of the pure commercial coolant was also measured for comparison. The thermal conductivity enhancement is calculated using Eq. (3) as follows:

$$\%\, TC\ Enhancement = \frac{k_{nf} - k_{bf}}{k_{bf}} \times 100\%. \quad (3)$$

The viscosity of the MgO/commercial coolant-based nanofluid was measured using Brookfield R/S Plus Rheometer equipped with DG3 DIN spindles for low to moderate viscosity fluids. Each measurement was performed in triplicate under steady shear conditions to ensure reproducibility and accuracy. The viscometer was calibrated with standard fluid

before use. All experiments were conducted in accordance with ASTM D2196-18 for the determination of rheological properties of non-Newtonian fluids [18].

RESULTS AND DISCUSSION

FTIR Spectrum of Commercial Coolant

The Fourier-Transform Infrared (FTIR) spectroscopy of the commercial radiator coolant, as shown in Figure 3, reveals characteristic vibrational bands associated with its major chemical constituents. The spectrum was recorded in the wavenumber range of 4000 – 500 cm^{-1} and displays several prominent absorption bands that enable the identification of functional groups present in the coolant formulation.

A broad and intense band observed at approximately 3420 cm^{-1} corresponds to the O-H stretching vibrations of hydrogen-bonded hydroxyl groups. This feature is typical of polyhydric alcohols such as ethylene glycol (EG) or propylene glycol (PG), which are widely used as base fluids in commercial coolant formulations due to their excellent antifreeze properties [19,20]. This absorption also suggests the presence of water, which is typically mixed with glycols in a 1:1 volume ratio in standard formulations [21].

In the regions between 2950 and 2850 cm^{-1}, peaks are observed that correspond to the asymmetric and symmetric stretching vibrations of aliphatic C-H bonds (-CH_2 and -CH_3 groups). These features further confirm the presence of glycol-based organic compounds. Notably, ethylene glycol exhibits strong C-H stretching in this region due to its two methylene groups [22].

A noticeable absorption near 1630 – 1650 cm^{-1} is attributed to the H-O-H bending vibration of molecular water and potentially C=O stretching from carboxylate groups. The bands located at 1450 and 1380 cm^{-1} are characteristic of C-H bending which are scissoring and wagging vibrations, further confirming the presence of aliphatic hydrocarbons. In particular, these peaks are consistent with the structural units of mono- or dihydric alcohols. A strong, complex absorption band around 1100 – 1000 cm^{-1} is indicative of C-O stretching vibrations, which are typically strong in polyhydroxy compounds such as glycols. Ethylene glycol, for instance, exhibits an intense C-O stretch around 1070 – 1040 cm^{-1}, which often appears as a sharp or broad peak depending on hydrogen bonding interactions [8]. In the fingerprint region (950 – 500 cm^{-1}), several sharp peaks are visible. While specific assignments in this region are more complex due to overlapping vibrations, peaks in this range are often linked to phosphate, silicate, and borate additives, all of which may be present in coolants as corrosion inhibitors or pH buffers. The presence of such additives supports the identification of a formulated coolant product rather than a pure glycol solution.

Taken together, the FTIR spectral features strongly suggest that the coolant sample is based on a glycol-water matrix and contains a mixture of corrosion inhibitors, which may include carboxylates and inorganic salts. These observations are consistent with the typical composition of commercial radiator coolants currently used in automotive applications [11].

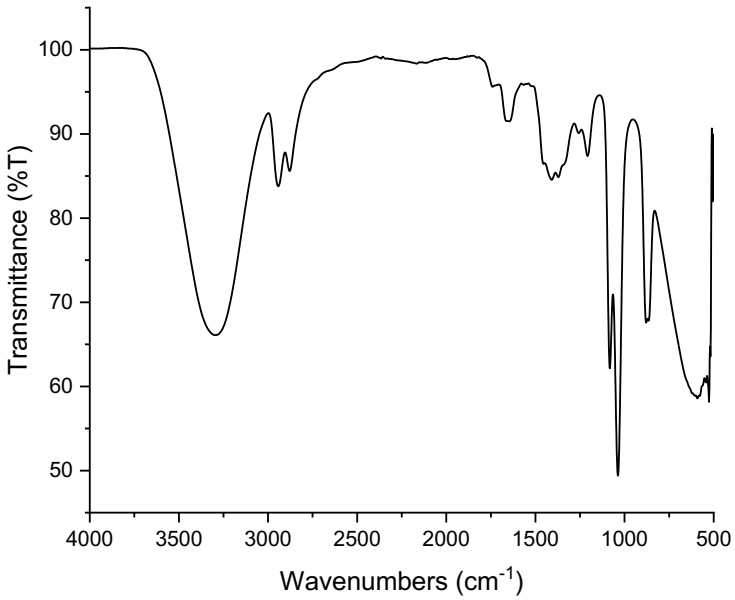


Figure 3. FTIR spectrum of commercial coolant

XRD Analysis on MgO Nanoparticles

The observed XRD diffraction peaks in Figure 4 were indexed and matched to the standard MgO pattern in the JCPDS file (Card No. 45-0946). The analysis in Figure 4 clearly shows the presence of a periclase, which is the only crystalline form of magnesium oxide. The broadening of diffraction lines is clearly seen. The peaks at 36.84223°, 42.8363°, 62.02234°, 74.41176°, and 78.24897° correspond to the (111), (200), (220), (311), and (222) planes of MgO, respectively [23]. This confirms the presence of a single-phase MgO with a face-centered cubic (FCC) crystal structure and space group Fm-3m. The XRD peaks observed for the MgO sample were recorded at the following 2θ values in Table 4.

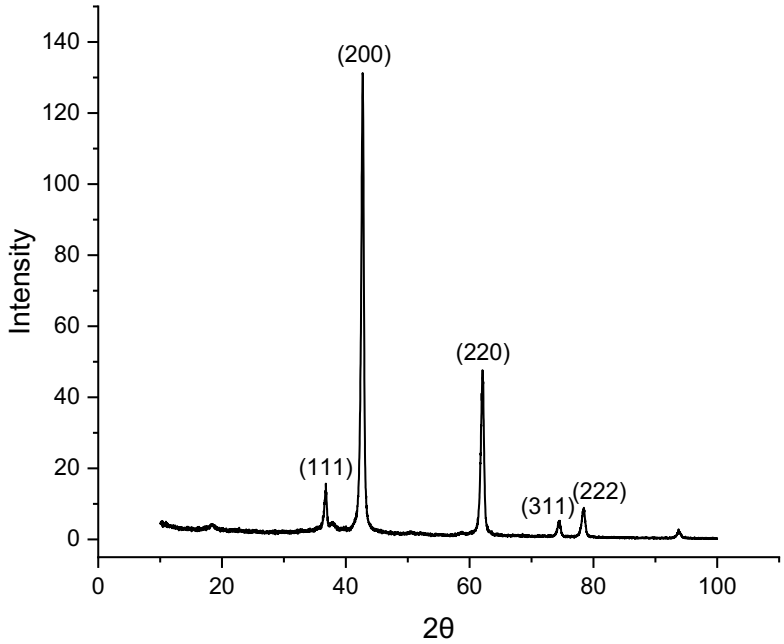


Figure 4. XRD pattern of MgO nanoparticles

Table 4. XRD analysis data

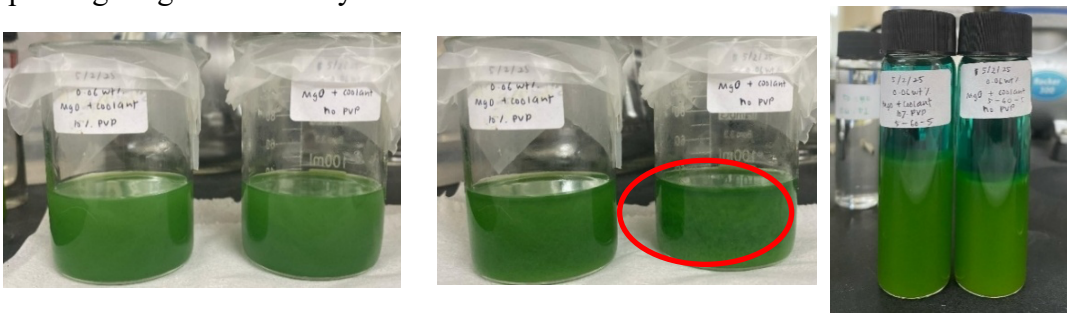
Peak position (2θ)	Crystallographic plane	Full width at half maximum (FWHM)	Particle size (nm)
36.84	(111)	1.03694	8.44
42.84	(200)	0.68254	13.06
62.02	(220)	0.62528	15.49
74.41	(311)	0.621	16.79
78.25	(222)	0.6468	16.55
Average size			14.07

The average crystallite size of the MgO nanoparticles is approximately 14.07 nm, confirming the nanocrystalline nature of the sample. The absence of additional peaks in the XRD pattern indicates the high phase purity of the MgO sample. No secondary phases or impurities were detected within the detection limits of XRD, indicating the purity of the synthesized powder. The (200) intense and sharp peak of periclase phase in the diffraction spectrum shows the high crystallinity of the product.

Visual Observation of Nanofluid Stability

Sample code: CNP-1 and CN-1

At the initial stage, the nanofluid was formulated both with and without PVP to evaluate the time required for agglomeration to begin. The visual stability test compared CNP-1 (with PVP) and CN-1 (without PVP) under identical mechanical processing conditions (5 min homogenization – 60 min sonication – 5 min homogenization). As shown in Figure 5(a), immediately after formulation, both samples appeared stable with no signs of agglomeration. However, after 30 min, CN-1 began to show visible particle aggregation, while CNP-1 remained homogenous as shown in Figure 5(b). By the end of one week, CN-1 exhibited complete sedimentation with a dense layer at the bottom, indicating poor dispersion stability due to the absence of a surfactant as presented in Figure 5(c). This emphasizes the importance of PVP in providing steric stabilization, thereby delaying sedimentation and improving long-term stability.



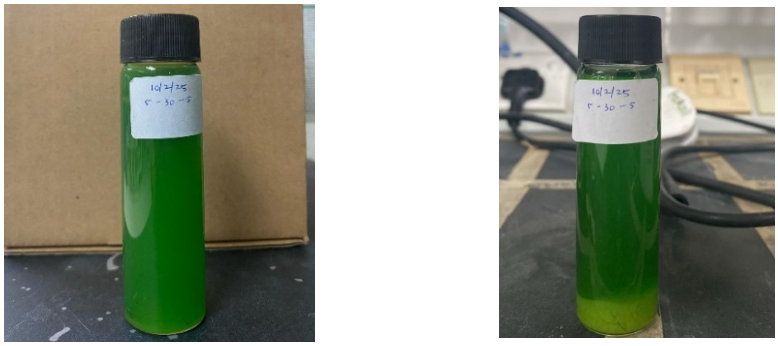
(a) Freshly formulated (b) After 30 mins (c) After one week

Figure 5. Observation of MgO-commercial coolant using parameter 5-60-5 min

Sample code: CNP-2

CNP-2, which utilized a shorter sonication time (30 min) but included PVP, initially exhibited good dispersion as presented in Figure 6 (a). However, agglomeration signs became noticeable within 30 min. Complete sedimentation was observed by the second day as shown in Figure 6 (b), with particles forming a uniform gel-like deposit at the container's

base. This suggests that while PVP aids initial dispersion, the reduced sonication energy in CNP-2 was insufficient to achieve lasting nanoparticle deagglomeration, leading to reduced colloidal stability over time.

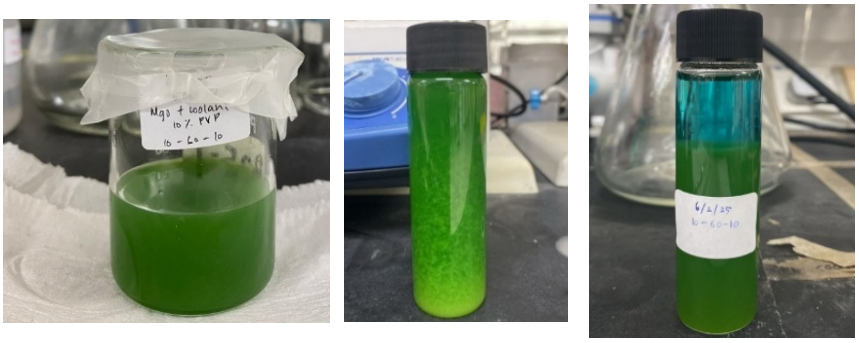


(a) Freshly formulated (b) After two days

Figure 6. Observation of MgO-commercial coolant using parameter 5-30-5 min

Sample code: CNP-3

Initially, the nanofluid displays a uniform and well-dispersed state, with nanoparticles evenly distributed throughout the base fluid. However, as time progresses, the stability of the dispersion begins to decline, and signs of agglomeration become noticeable after approximately 10 min, as shown in Figure 7. During this stage, the nanoparticles start to cluster together, reducing the overall uniformity of the suspension and indicating the onset of instability in the nanofluid system. Over time, the extent of agglomeration increases, leading to gradual sedimentation. After approximately a week, complete settling of the nanoparticles is observed, resulting in the formation of a sediment layer at the bottom of the container. This outcome implies that although longer homogenization assists initial mixing, sonication duration remains the more critical factor for long-term stability.



(a) Freshly formulated (b) After 10 min (c) After 1 week

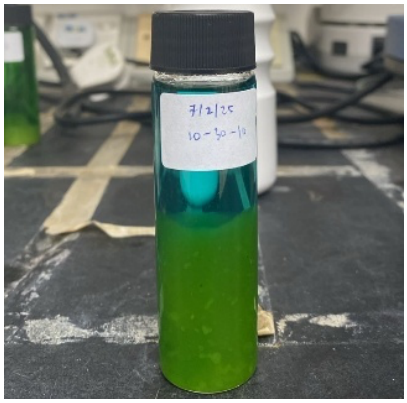
Figure 7. Observation of MgO-commercial coolant using parameter 10-60-10 min

Sample code: CNP-4

CNP-4, as shown in Figure 8 was prepared with the same homogenization duration as CNP-3 but shorter sonication (30 min), initially exhibited uniform dispersion. However, visible agglomerates appeared within a few minutes. After one week, complete sedimentation occurred, with nanoparticles forming a thick semi-solid deposit. The faster onset of

instability compared to CNP-3 further supports the hypothesis that prolonged sonication is essential for breaking down agglomerates and maintaining suspension.

(a) Freshly formulated



(b) After one week

Figure 8. The gel-like settled nanoparticles

For all tested parameters, it was observed that once the nanofluid undergoes complete sedimentation, the settled nanoparticles do not form a loose or powdery layer at the bottom. Instead, the sediment exhibits a distinctive jelly-like texture, indicating potential interactions between the nanoparticles and the base fluid. This gel-like consistency suggests the presence of interparticle forces or possible weak bonding mechanisms that contribute to the formation of a semi-solid structure rather than a simple precipitate. These findings highlight the importance of sonication energy and surfactant presence in delaying agglomeration and preserving nanofluid stability [24,25]. The visual representation of this phenomenon is provided in the Figure 9 below and the summary of the nanofluid's stability is presented in Table 5.

Figure 9. The gel-like sediment

Table 5. Summary of nanofluid's stability

Sample code	Observation
CNP-1	No agglomeration after freshly formulated Agglomeration occurs after one week
CNP-2	Nanoparticles begin to cluster after 30 min Complete sedimentation after two days
CNP-3	Agglomeration occurs after 10 min Complete sedimentation after one week
CNP-4	Starts to agglomerate after few min Complete sedimentation after one week
CN-1	Start to agglomerate after 30 min Settled faster than CNP-1 after one week

Effect of homogenization and ultrasonication on sedimentation rate

MgO nanoparticles have a relatively high density of 3580 kg/m³, making them prone to rapid sedimentation, especially when suspended in a low-viscosity fluid such as commercial coolant. The tendency of nanoparticles to settle is influenced by gravitational forces, which act more significantly on higher-density particles, leading to phase separation over time. Additionally, the composition of the commercial coolant plays a crucial role in dispersion stability, as factors such as viscosity, pH, and chemical interactions with the nanoparticles determine how well the MgO remains suspended. If the base fluid has a low viscosity, the nanoparticles experience minimal resistance to settling, reducing their effective dispersion time.

Thermal Conductivity of MgO/Commercial Coolant-Based Nanofluid

Table 6 and Figure 10 presents the thermal conductivity of MgO/commercial coolant nanofluids synthesized under different homogenization and sonication conditions and were compared with the base commercial coolant. The experimental conditions varied based on processing time and the presence of PVP as a surfactant. The analysis considers temperature-dependent behavior and improvements or reductions in thermal conductivity compared to the base commercial coolant.

Table 6. Thermal conductivity of MgO-commercial coolant under different parameters

Temperature (°C)	Thermal Conductivity (W/mK)					
Sample code	Commercial coolant	CNP-1	CN-1	CNP-2	CNP-3	CNP-4
25	0.2850	0.2885	0.2815	0.289	0.2854	0.2901
40	0.2878	0.2923	0.283	0.2926	0.2885	0.3987
60	0.3042	0.3157	0.2943	0.3118	0.2938	0.2607

In general, all nanofluid samples demonstrated a temperature-dependent increase in thermal conductivity, a trend consistent with existing literature on nanofluids. This enhancement is attributed to the increased Brownian motion of nanoparticles at elevated temperatures, which facilitates greater thermal energy transport within the fluid medium. Among the samples, CNP-1, prepared with 60 min of sonication and the inclusion of PVP, exhibited the highest thermal conductivity at 60 °C (0.3157 W/mK), indicating the positive impact of prolonged sonication on nanoparticle dispersion. This result suggests that adequate

sonication allows for effective deagglomeration of nanoparticles, thereby increasing the surface area available for thermal conduction. The presence of PVP further stabilizes the suspension, preventing re-agglomeration and contributing to sustained enhancement in thermal properties [26]. In contrast, CN-1, which was processed under similar sonication conditions but without PVP, showed inferior performance across all temperatures. This comparison underscores the critical role of surfactants in improving the colloidal stability of nanofluids. PVP likely forms steric barriers around the nanoparticles, minimizing van der Waals forces and enhancing the suspension stability, which directly correlates with improved thermal conductivity [27].

Interestingly, CNP-4 exhibited the most notable thermal conductivity enhancement at 40 °C (0.3987 W/mK), representing a 38.53% increase compared to the base commercial coolant. This sample, which employed shorter sonication (30 min) but longer homogenization (10 min before and after sonication), appears to have benefited from a synergistic effect between homogenization and the PVP dispersant. However, a significant decline in thermal conductivity at 60 °C (0.2607 W/mK) was observed for CNP-4. This anomaly may be indicative of thermal instability at higher temperatures, potentially caused by PVP degradation, re-agglomeration of nanoparticles, or phase separation within the suspension [28]. CNP-2, subjected to shorter sonication (30 min) while retaining PVP, showed comparatively lower thermal conductivity, reinforcing the hypothesis that extended sonication is vital for effective nanoparticle dispersion. Meanwhile, CNP-3, which underwent both extended sonication and longer homogenization without any evident instability, yielded moderate thermal enhancement, suggesting that while homogenization improves dispersion to an extent, sonication duration remains the more influential parameter [29].

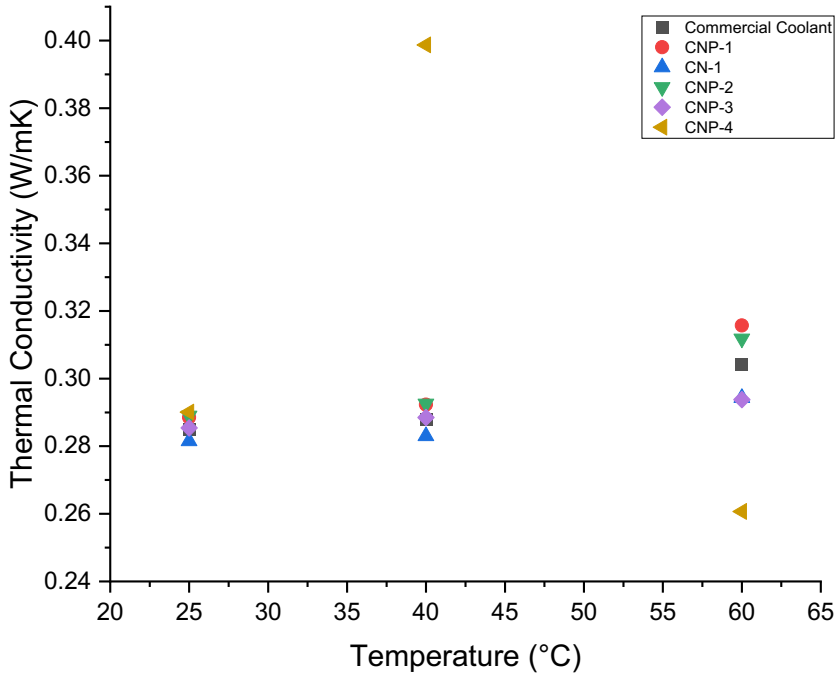


Figure 10. Thermal conductivity of MgO/commercial coolant-based nanofluids

Overall, the results demonstrate that both processing parameters and surfactant use significantly affect the thermal conductivity of MgO-based nanofluids. The combination of prolonged sonication and PVP integration, as demonstrated in CNP-1, yielded the most stable and consistently enhanced thermal performance across the tested temperature range. The thermal conductivity enhancement of each nanofluid compared to the commercial coolant is calculated as follows in Table 7.

Table 7. Thermal conductivity enhancement of MgO-commercial coolant nanofluid

Temperature (°C)	Thermal conductivity enhancement (%)				
Sample code	CNP-1	CN-1	CNP-2	CNP-3	CNP-4
25	1.23	-1.23	1.40	0.14	1.79
40	1.56	-1.67	1.67	0.24	38.53
60	3.78	-3.25	2.5	-3.42	-14.3

Viscosity of MgO/Commercial Coolant-Based Nanofluid

The viscosity of the MgO/commercial coolant nanofluids, plotted against varying shear rates, reveal key insights into the rheological behavior of these fluids and their dependence on preparation parameters. Unlike the base commercial coolant, which exhibited Newtonian behavior with nearly constant viscosity, all nanofluid samples displayed non-Newtonian shear-thinning behavior, wherein viscosity decreased as shear rate increased. This behavior is commonly observed in nanofluids and is attributed to the disruption of nanoparticle networks, alignment of suspended particles with the flow, and reduced inter-particle interactions under shear. As shown in Figure 11, among the nanofluids, CN-1 which was prepared without PVP exhibited the highest viscosity at low shear rates, indicating the formation of stronger nanoparticle agglomerates in the absence of dispersants. The elevated viscosity can be attributed to increased internal resistance caused by larger, less-stabilized particle clusters. In contrast, samples incorporating PVP (CNP-series) showed reduced viscosities, confirming the efficiency of PVP in stabilizing nanoparticles through steric repulsion, which in turn minimizes agglomeration and enhances fluidity [30].

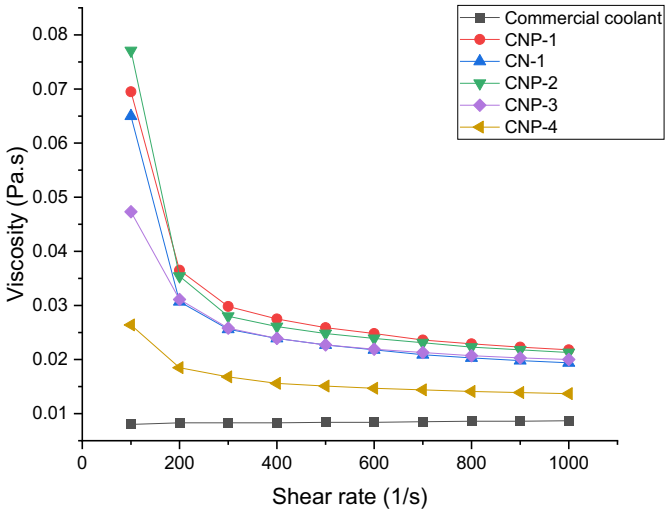


Figure 11. Viscosity of MgO/commercial coolant-based nanofluids

CNP-1, which underwent prolonged sonication (60 min) and used PVP, demonstrated a moderate and stable viscosity profile, suggesting an optimal balance between particle dispersion and fluid structure [31]. This formulation offers a desirable compromise between thermal conductivity enhancement and manageable flow resistance, making it suitable for heat transfer applications requiring both high performance and energy efficiency. CNP-2 and CNP-3, prepared with varying combinations of sonication and homogenization times, exhibited intermediate viscosity behaviors. These results indicate that although longer homogenization may contribute to improved dispersion, sonication time has a more pronounced effect on breaking down agglomerates and reducing viscosity [32]. Of particular interest is CNP-4, which displayed the lowest viscosity among all nanofluids, approaching that of the base fluid. While this characteristic may seem advantageous for reducing pumping power in flow systems, it should be interpreted with caution. As seen in the previous thermal conductivity analysis, CNP-4 exhibited significant performance degradation at elevated temperatures, likely due to poor nanoparticle stability. Therefore, low viscosity in this case may be symptomatic of insufficient dispersion or weak nanoparticle-fluid interaction, rather than an optimized formulation [33]. The combined analysis of thermal conductivity and viscosity underscores the trade-off between heat transfer efficiency and flow resistance in nanofluid systems. While high thermal conductivity is desirable, excessively high viscosity can impede flow and increase operational costs. Conversely, very low viscosity, as seen in CNP-4, may signal inadequate nanoparticle stabilization, compromising thermal performance. In summary, CNP-1 emerges as the most promising formulation, offering a well-balanced combination of high thermal conductivity and moderate viscosity. This reinforces the importance of optimizing dispersion techniques and the use of surfactants to develop effective, stable, and energy-efficient nanofluids.

CONCLUSIONS

This study explored the impact of mechanical dispersion methods on the stability and thermophysical performance of MgO nanoparticles suspended in a commercial coolant. Our results showed that:

- The use of PVP as a surfactant significantly improves dispersion stability and prevents early sedimentation.
- Sonication duration is a more influential factor than homogenization in achieving stable and high-performing nanofluids.
- CNP-1, prepared with 60 min of sonication and PVP, demonstrated the most balanced profile, which enhances the thermal conductivity while maintaining manageable viscosity and long-term stability.
- Samples without PVP or with shorter sonication durations showed early agglomeration, reduced thermal conductivity, and greater viscosity.

The formation of slurry sediments across all samples suggests complex interactions between MgO nanoparticles and coolant constituents, warranting further exploration into the chemical compatibility and surface modifications. For industrial applications, the optimized formulation (CNP-1) offers a promising solution for automotive thermal management systems where both heat transfer efficiency and flow characteristics are critical.

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AUTHORS' CONTRIBUTIONS STATEMENT

The manuscript was written through the contributions of all authors. N.A and N.I.A.M.F designed and organized this work. M.A.M.R writing-review and editing. M.N.N drafts the main ideas of the work. O.K.K, I.J.S, N.K and M.H.H supervising. N.A.A.S review and editing of the manuscript. All authors have approved the final version of the manuscript.

CONFLICT OF INTEREST

All authors declare no competing interests that could have influenced the work reported in this paper.

REFERENCES

1. Choi S, Eastman JA. Enhancing thermal conductivity of fluids with nanoparticles. Argonne (IL): Argonne National Laboratory; 1995. Report No.: ANL/MSD/CP-84938; CONF-951135-29.
2. Wang XQ, Mujumdar AS. Heat transfer characteristics of nanofluids: a review. *International Journal of Thermal Sciences.* 2007;46(1):1–19.
3. Das SK, Choi SU, Patel HE. Heat transfer in nanofluids: a review. *Heat Transfer Engineering*. 2006;27(10):3–19.
4. Mahbubul IM, Saidur R, Amalina MA. Latest developments on the viscosity of nanofluids. *International Journal of Heat and Mass Transfer.* 2012;55(4):874–885.
5. Noorzadeh S, Moghanlou FS, Vajdi M, Ataei M. Thermal conductivity, viscosity, and heat transfer process in nanofluids: a critical review. *Journal of Composites and Compounds*. 2020;2(5):175–192.
6. Choudhary S, Sachdeva A, Kumar P. Investigation of the stability of MgO nanofluid and its effect on the thermal performance of flat plate solar collector. *Renewable Energy*. 2020;147:1801–1814.
7. Rahman MA, Hasnain SMM, Pandey S, Tapalova A, Akylbekov N, Zairov R. Review on nanofluids: preparation, properties, stability, and thermal performance augmentation in heat transfer applications. *ACS Omega.* 2024;9(30):32328–32349.
8. Sun L, Geng J, Dong K, Sun Q. An experimental study on the effect of nanofluids on the thermal conductivity and rheological properties of a coolant for liquids. *Energies*. 2024;17(6):1313.
9. Jehhef KA, Siba MAAA. Effect of surfactant addition on the nanofluids properties: a review. *Acta Mechanica Malaysia.* 2019;2(2):1–19.
10. Afzal A, Nawfal I, Mahbubul IM, Kumbar SS. An overview on the effect of ultrasonication duration on different properties of nanofluids. *Journal of Thermal Analysis and Calorimetry.* 2019;135(1):393–418.

11. Mukherjee S, Halder T, Ranjan S, Bose K, Mishra PC, Chakrabarty S. Effects of SiO_2 nanoparticle addition on performance of commercial engine coolant. *Energy.* 2021;231:120913.
12. Mert S, Yasar H, Durmaz U, Topuz A, Yeter A, Engin T. Cooling performance of a car radiator using Al_2O_3–ethylene glycol/water nanofluid. *Thermal Science.* 2021;25(1B):801–809.
13. Seoudi R, Al-Salem L, Said D. Effects of PVP stabilizing agent on ZnO nanoparticles morphology and properties. *Research Square* [preprint]. 2022.
14. Zainal Abidin S, Mohamad IS, Bani Hashim AY, Abdullah N, Md Isa MH, Masripan NA, Abdullah A. Thermal characteristics of CNF-based nanofluids for electronic cooling. *Journal of Mechanical Engineering and Sciences.* 2016:2336–2349.
15. Mohd Saidi N, Norizan MN, Abdullah N, Janudin N, Mohd Kasim NA, Osman MJ, Mohamad IS. Characterizations of MWCNT nanofluids with surface oxidative treatments. *Nanomaterials.* 2022;12(7):1071.
16. Mohd Saidi N, Abdullah N, Norizan MN, Janudin N, Mohd Kasim NA, Osman MJ, Mohamad IS, Mohd Rosli MA. Surface-oxidised carbon nanofibre-based nanofluids. *Nanomaterials.* 2022;12(21):3922.
17. Ahmad A, Pervaiz M, Ramzan S, Kiyani MZ, Khan A, Ahmad I, Asiri AM. Role of XRD for nanomaterial analysis. In: *Nanomedicine Manufacturing and Applications*. Elsevier; 2021. p.149–161.
18. Patra AK, Nayak MK, Misra A. Viscosity of nanofluids: a review. *International Journal of Thermofluid Science and Technology.* 2020;7(2):070202.
19. Stuart BH. *Infrared Spectroscopy: Fundamentals and Applications*. Chichester: John Wiley & Sons; 2004.
20. Katsu S, Ito S, Yoshimura N, Takayanagi M. Variation in near-infrared spectra of water with polyhydric alcohol. *Journal of Solution Chemistry*. 2019;48:1564–1575.
21. Zykova VA, Surovtsev NV. Structural properties of glass-forming ethanol and glycerol. *Journal of Structural Chemistry*. 2018;59:321–327.
22. Yang B, Ren P, Xing L, Sun C, Men Z. Hydrogen-bond dynamics in ethylene glycol solutions. *Journal of Physical Chemistry Letters.* 2023;14(6):1641–1649.
23. Herng SY, Mohd Rosli MA, Salimen N, Herawan SG, Hussain F. Performance evaluation of photovoltaic thermal using MgO nanofluid. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences.* 2023;109:184–209.
24. Ali N, Teixeira JA, Addali A. Nanofluids: fabrication, stability, and thermophysical properties. *Journal of Nanomaterials*. 2018;2018:6978130.
25. Wang J, Yang X, Klemeš JJ, Tian K, Ma T, Sunden B. Nanofluid stability: preparation and application. *Renewable and Sustainable Energy Reviews.* 2023;188:113854.
26. Yasmin H, Giwa SO, Noor S, Sharifpur M. *Thermal conductivity enhancement of metal oxide nanofluids. Nanomaterials.* 2023;13(3):597.
27. Kaggwa A, Atkins M, Tarighaleslami A, Walmsley M, Carson JK. Thermal performance of nanofluids with surfactants. *International Journal of Thermophysics*. 2023;44(11):160.
28. Xuan Y, Li Q, Tie P. Effect of surfactants on heat transfer features of nanofluids. *Experimental Thermal and Fluid Science.* 2013;46:259–262.

29. Esfe MH, Afrand M, Karimipour A, Yan WM, Sina N. Thermal conductivity of MgO nanofluids. *International Communications in Heat and Mass Transfer.* 2015;67:173–175.
30. Mishra PC, Mukherjee S, Nayak SK, Panda A. A brief review on viscosity of nanofluids. *International Nano Letters*. 2014;4:109–120.
31. Zhou M, Xia G, Li J, Chai L, Zhou L. Factors influencing thermal conductivity and viscosity in surfactant solutions. *Experimental Thermal and Fluid Science.* 2012;36:22–29.
32. Sajid MU, Bicer Y. Ultrasonication and surfactant effects on nanofluid stability. *Ultrasonics Sonochemistry.* 2022;88:106079.
33. Abdullah A, Mohamad IS, Bani Hashim AY, Abdullah N, Poh BW, Md Isa MH, Zainal Abidin S. Thermal conductivity and viscosity of water and ethylene glycol nanofluids. *Journal of Mechanical Engineering and Sciences.* 2016;10:2249–2261.