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Enhanced Tribological and Thermal Performance of CNC–Al_2O_3 Hybrid Nanolubricant for Internal Combustion Engines: A Comprehensive Stability–Thermophysical–Tribological Assessment

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ABSTRACT

This experiment investigates the stability, thermophysical, and tribological characteristics of cellulose nanocrystal (CNC), aluminum oxide (Al_2O_3), and hybrid CNC-Al_2O_3 nanolubricants as additives in SAE 40 engine oil for internal combustion engine applications. Stability assessments were conducted through zeta potential analysis at various concentrations (0.01% to 0.05%) and temperatures (30°C to 90°C). The hybrid CNC-Al_2O_3 nanolubricants demonstrated excellent dispersion stability with zeta potential values exceeding 150 mV at optimal concentrations. Thermophysical property analysis revealed that dynamic viscosity increased significantly, with the hybrid system showing a 56% enhancement at 0.03% concentration and 30°C. The tribological testing revealed a remarkable 78.6% reduction in the coefficient of friction at a 0.01% concentration and an optimal specific wear rate of 0.016 mm^3/Nm at a 0.05% concentration. These synergistic improvements in stability, thermophysical, and tribological properties demonstrate the CNC–Al_2O_3 hybrid's significant potential to enhance efficiency, durability, and heat management in internal combustion engines, offering a novel, high-performance alternative to conventional lubricant additives.

Keywords: *Hybrid nanolubricant; cellulose nanocrystal; aluminum oxide; viscosity; thermal conductivity; tribological behavior; stability analysis; wear rate; coefficient of friction; engine oil*

1. INTRODUCTION

The development of advanced lubricants plays a crucial role in enhancing the performance and efficiency of mechanical systems, particularly in automotive and industrial applications. In recent years, the incorporation of nanoparticles into conventional lubricants has emerged as a promising approach to improve tribological properties and thermal characteristics. Nanolubricants have gained significant attention due to their potential to reduce friction, wear, and heat generation in various mechanical systems [1]. The addition of nanoparticles to base oils can lead to improved lubrication performance through several mechanisms, including the formation of protective tribofilms, the rolling effect between contact surfaces, and enhanced heat dissipation [2]. Cellulose nanocrystals (CNC) have attracted interest as a renewable and biodegradable nanomaterial with excellent mechanical properties and a high surface area [3]. When combined with metallic nanoparticles such as aluminum, CNC can potentially create a synergistic effect, enhancing both the tribological and thermal properties of the lubricant [4]. SAE 40 oil, a common monograde engine oil, serves as an excellent base fluid for this study due to its widespread use in various applications, including commercial diesel vehicles, stationary engines, and construction machinery. Previous studies have demonstrated the potential of nanoparticle additives in improving lubricant properties. For instance, the addition of copper (II) oxide nanoparticles to SAE 40 oil has been shown to reduce the coefficient of friction by up to 14% at an optimal concentration [5]. Similarly, research on graphene nanoparticles and cellulose nanocrystals blended with engine oils has indicated improvements in tribological behavior and thermal properties [6].

Aluminum oxide (Al_2O_3) nanoparticles have shown promising results as additives in engine lubricants, particularly in improving tribological properties and thermal characteristics. Recent studies have demonstrated their effectiveness in reducing friction and wear when added to base oils like SAE 40. A 2024 study by Singh, et al. [7] investigated the impact of oleic acid (OA)-capped Al_2O_3 nanoparticles on the tribological performance of conventional lube oil. They found that a nanolubricant containing 0.1 wt.% OA-Al_2O_3 nanoparticles exhibited the most significant improvement in tribological performance, achieving a 38.84% reduction in coefficient of friction (COF) and a 23.87% reduction in wear scar diameter (WSD) compared to the base lubricant. Ghalme, et al. [8] evaluated the effect of Al_2O_3 nanoparticles as additives in SAE 10W40 base oil using a four-ball tester. They observed that the addition of 0.5 wt% of Al_2O_3 nanoparticles resulted in a 20.75% reduction in wear scar diameter and a 22.67% reduction in coefficient of friction. The improved lubrication performance was attributed to the mending effect and ball bearing effect of Al_2O_3 nanoparticles, forming a self-protective film on the friction surface. The size of Al_2O_3 nanoparticles also plays a role in their effectiveness as lubricant additives.

Lin and Kedzierski [9] measured the specific heat of Al_2O_3 nanolubricants with two nominal surface-area-based diameter nanoparticles: 20 nm and 40 nm. The study found that the specific heat of the nanolubricant linearly increased with increasing temperature and linearly decreased with respect to increasing nanoparticle mass fraction. Interestingly, the size of the nanoparticle was shown to have no significant effect on the magnitude of the specific heat of the nanolubricant. These recent studies highlight the potential of Al_2O_3 nanoparticles as effective additives in engine lubricants, demonstrating improvements in friction reduction, wear resistance, and thermal properties. The optimal concentration of Al_2O_3 nanoparticles appears to be in the range of 0.1-0.5 wt%, depending on the specific application and base oil used.

Hybrid CNC nanolubricants, which combine CNC with other nanoparticles, have shown even more promising results in enhancing lubricant properties. For instance, a recent study investigated the use of hybrid CNC-MXene nanolubricants for tribological applications [10]. The researchers found that the combination of CNC and MXene nanoparticles dispersed in SAE 40 base oil led to improvements in both dynamic viscosity and thermal conductivity. The study utilized Response Surface Methodology (RSM) to develop robust empirical models for predicting the thermophysical properties of the nanolubricants, achieving high accuracy with more than 85% of output variations accounted for. Another example of a hybrid CNC nanolubricant is the combination of CNC with copper (II) oxide (CuO) nanoparticles. Hisham, et al. [11] investigated the tribological behavior and thermal properties of hybrid CNC-CuO nanolubricants using SAE 40 as the base fluid. Their results showed significant improvements in both tribological and thermal properties. The hybrid CNC-CuO nanolubricant at 0.1% concentration reduced the frictional force by 54% compared to the base oil. Additionally, the thermal conductivity increased by 4.2%, while the specific heat capacity improved by 2.1%. These findings demonstrate the potential of hybrid CNC nanolubricants in enhancing the performance of lubricating oils for various applications, including automotive and industrial uses [12]. Investigation on using CNC-Al_2O_3 nanoparticles as additives in lubricants is limited, and summarised in Table 1. Amirruddin [13] investigate the tribological viability of hybrid CNC-Al_2O_3 lubricants in improving the performance of the nano-lubricants. The nano-lubricant is prepared with multiple ratios: 0.3 %, 0.5 % and 0.7 % concentration, which were compared to base oil 10W-40 and tested for properties at 30 ºC, 50 ºC and 70 ºC. He discovered that as the temperature increases, thermal conductivity increases up to 18.09% while dynamic viscosity reduces up to 21.8%. The nano-lubricant also reduces COF and wear rate by 16% and 71%, respectively. He concluded that the use of CNC-Al_2O_3 has the potential to improve the lubricant for better durability of the actual internal combustion engine. Nabhan, et al. [14] studied CNC-Al_2O_3 nanoparticles to improve gear oil quality at concentrations of 0.25, 0.5, 0.75, and 1.0 wt.%. Finding reveals that the nanoparticles improve their chemical and physical properties, reducing both COF and wear rate by 26% and 36%, respectively. The author concludes that the effectiveness of the nanoparticles in improving efficiency and reducing mechanical wear and noise in gear systems.

Table 1 A comparison of CNC–Al_2O_3 nanoparticle additives used in lubricants from existing research

Lubricant	Findings	Ref.
Engine oil	Reduce 16% COF and 71% WR	[13]
Gear oil	Reduce 26% COF and 36% WR	[14]

Therefore, due to the limited number of studies using CNC-Al_2O_3 in lubricants, this study aims to investigate the effects of CNC-Al_2O_3 hybrid nanoparticles on the tribological and thermal properties of SAE 40 oil. Various concentrations of the nanoparticles will be examined to determine the optimal formulation for enhanced performance. The research will focus on key parameters such as friction reduction, wear resistance, thermal conductivity, and viscosity index. By developing this novel CNC-Al_2O_3 nanolubricant, a contribution to the growing body of knowledge on advanced lubricants is sought, and a potential solution for improving the efficiency and longevity of mechanical systems in automotive and industrial applications is provided, while the specific heat capacity is improved.

2. RESEARCH METHODOLOGY

This section will cover the study's materials, a method for characterising nanoparticles, the preparation of hybrid nanolubricants, and the evaluation of the nanolubricant's stability. In addition, this part will describe the process employed in this research to determine viscosity and thermal conductivity.

2.1. Nanolubricant Preparation

The preparation of nanolubricants for this study employed a two-step method to create nine distinct samples with concentrations ranging from 0.01% to 0.05% by volume. Single cellulose nanocrystals (CNC), single aluminum oxide (Al_2O_3), and hybrid CNC-Al_2O_3 nanoparticles were dispersed in SAE 40 base fluid to produce stable and homogeneous solutions [15, 16]. The process commenced with calculating the required volume for dilution using Equation 1:

$$\emptyset = \frac{\left[\frac{W_p}{\rho_p}\right]}{\left[\frac{W_p}{\rho_p} + \frac{W_{bf}}{\rho_{bf}}\right]} \tag{1}$$

CNC and Al_2O_3 powders were dry blended to create hybrid nanoparticles. In the second step, these nanoparticles were incorporated into the base fluid using a stirrer for 30 minutes, adhering to established protocols. Sonication was subsequently applied to enhance dispersion. The nanolubricants were formulated using 200 mL of SAE 40 base oil with volume fractions of 0.01%, 0.03%, and 0.05% for CNC, Al_2O_3, and CNC-Al_2O_3 compositions. Initial mixing was conducted using a hotplate magnetic stirrer for one hour at ambient temperature. Subsequently, each solution underwent ultrasonic bath treatment for approximately two hours to significantly improve stability [17]. This preparation methodology aligns with standard practices in nanolubricant research, utilizing a two-step approach that combines mechanical mixing and ultrasonic dispersion to ensure uniform distribution of nanoparticles within the base fluid. The combination of magnetic stirring and ultrasonication serves to break down agglomerates and enhance the overall stability of the nanolubricant suspensions [18, 19].

2.2. Nanolubricant Stability and Characterisation Evaluation

The stability and dispersibility of nanolubricants are critical factors influencing their effectiveness, particularly due to the high surface area and activity of suspended nanoparticles. Various methods have been developed to assess nanolubricant stability, including centrifugation, spectral absorbance analysis, zeta potential measurement, and sedimentation techniques. Among these, zeta potential measurements have proven to be particularly effective in evaluating the stability of solid additives in lubricants [20]. This study focuses on evaluating the dispersibility and stability of nanolubricants containing cellulose nanocrystals (CNC), aluminum oxide (Al_2O_3), and hybrid CNC-Al_2O_3 nanoparticles. The assessment employs a zeta potential measurement technique to quantify the electrostatic stability of the suspension [21].

The stability evaluation process typically involves preparing nanolubricant samples with varying concentrations (e.g., 0.01% to 0.05% by volume), performing zeta potential measurement to confirm stability, with values above 60 mV indicating excellent stability [22]. Recent studies have shown that for graphene-based nanolubricants, concentrations of 0.2 g/L demonstrated the highest stability, while for MWCNT-based nanolubricants, 0.65 g/L showed optimal performance.

These analyses provide valuable insights into the performance of CNC, Al_2O_3, and CNC-Al_2O_3 nanolubricants, particularly their stability and potential effectiveness in reducing friction and wear in lubrication applications. The results can help optimize preparation methods, such as sonication time and nanoparticle concentration, to achieve the most stable and effective nanolubricant formulation [23, 24].

2.2.1. Zeta Potential

Surface electric charge is estimated via zeta potential measurement. By monitoring the fluid's electrophoretic behaviour, the stability of the nanolubricant is assessed [25]. For this experiment, a particle analyzer from Anton Paar with the model number Litesizer 500 was used to measure the zeta potential. Table 2 displays the stability behaviour concerning the zeta potential value.

Table 2 Stability behaviour according to the zeta potential value

Zeta Potential Value	Stability Behaviour
0 to ±5	Swift aggregation or clumping
±10 to ±30	Emerging instability
±30 to ±40	Intermediate stability
±40 to ±60	Good stability
>61	Excellent stability

Source: Kumar and Dixit [26].

2.3. Thermophysical Properties Measurement

Advancements in modern equipment have led to the development of various measuring techniques that can operate under a wide range of temperatures and conditions. Many of these methods have resulted in standardized protocols that align with industry benchmarks or specific equipment manufacturer requirements. Among the most critical applications in tribology is the assessment of the rheological properties of lubricants. This section will focus on the standard techniques used to determine the viscosity, thermal conductivity, and tribological measurements of nanolubricants.

2.3.1. Viscosity Index Measurement

The viscosity index (VI) measures how the viscosity of a fluid changes with temperature. It is a dimensionless value that indicates the degree to which viscosity varies as a function of temperature. The reference values for VI are established based on kinematic viscosity measurements, following the standard procedure outlined in ASTM D-2270. The VI is calculated using the following equation:

$$VI = 100\frac{L-U}{L-H} \quad (2)$$

L and H are values taken from the ASTM D2270 table based on kinematic viscosity at 100 °C, and U is the kinematic viscosity at 40 °C.

2.3.2. Dynamic Viscosity Measurement

A commercial Brookfield DV-I Prime viscometer was employed to determine the rotational speed (rpm) for this study. This viscometer is suitable for both Newtonian and non-Newtonian fluids, with viscosity levels ranging from 1 to 600 cP. It demonstrates higher accuracy for low-viscosity liquids, specifically those between 1 and 5 cP. The viscometer utilizes a spindle that is immersed in the nanolubricant sample for measurement. For the testing procedure, a 25 mL volume of nanolubricant was introduced into the chamber. The chamber was then carefully connected to the rheometer spring, ensuring that the spring deflection remained within 2 to 3%. A circulating water bath was used to heat the nanolubricant sample to the desired temperature. Dynamic viscosity measurements were conducted over a temperature range of 30 °C to 90 °C, utilizing Rheocalc software for data analysis. The viscosity of the sample was assessed by varying the spindle's rotational speed. Each measurement was repeated three times, and the average values were recorded. To validate the system, viscosity measurements were also performed on SAE 40 base fluid within the same temperature range.

2.3.3. Thermal Conductivity Measurement

The thermal conductivity of CNC-Al_2O_3 nanolubricant was measured using a thermal property analyzer, specifically the Tempos. Before conducting the experimental measurements, the Tempos were calibrated with a glycerine verification standard provided by the manufacturer. The thermal conductivity was assessed using a TR-3 single needle sensor, which has a measurement range of 0.002 to 2.00 W/m·K for liquid thermal conductivity. The TR-3 sensor was vertically inserted into the centre of the sample bottle, which was then sealed with tape. Once the nanolubricants reached the desired temperature in the water bath, the sample bottle was submerged for approximately 10 minutes. The thermal conductivity experiments were conducted over a temperature range of 30 °C to 90 °C. Measurements were taken three times, and the average of these data sets was recorded. This procedure was essential for minimizing errors in thermal conductivity measurements caused by temperature fluctuations and the sensor's proximity to the nanolubricant sample. The current thermal conductivity measurements adhered to the standards set forth by IEEE 442-03 and ASTM D5332-08.

2.3.4. Tribological Measurement

Wear test involves making linear reciprocates movements similar to a cylinder piston ring pair operating under real conditions. The wear test was conducted under lubricated sliding conditions. Wear morphology that occurred at the surface of the specimen and during the linear reciprocating sliding motion against the outer surface of aluminium 6061 for 30 minutes. Normal loads are applied to the device by hanging weights on the bearing lever, where the piston ring sample is attached in order to produce the desired load. The load chosen was between 4 kg to 10 kg. Low engine-speed intervals (200 rpm to 500 rpm) were selected during testing because such conditions generate the greatest friction in engines, particularly during the first movement and at the top dead centre (TDC) [27]. The temperature was maintained at 30°C to 90°C, which is the regime temperature of the internal combustion engine, and the operating time was 30 minutes per specimen. The coefficient of friction was recorded automatically using NI-DAQ via the ratio of friction force to the normal load. Table 3 shows the tribology test conditions.

Table 3 Tribology test condition

Test specifications	Values
Load, kg	4.0 - 10.0 kg
Engine Speed, rpm	250 – 500 rpm
Operating Time	30 min
Temperature	30˚C-90˚C

The coefficient of friction was calculated as the following equation:

$$\mu_k = \frac{F_k}{N} \quad (3)$$

where

μ_k	Coefficient of kinetic friction
F_k	Applied force
N	Load

The specific wear rate was calculated as the following equation:

$$\Delta w = (w_1 - w_2) \quad (4)$$

where

Δw	Weight loss of the specimen
w_1	Weight of the specimen before the test
w_2	Weight of the specimen after the test

3. RESULTS AND DISCUSSION

The information in this section was obtained using CNC, Aluminum, and CNC-Al_2O_3 nanolubricants for the characterization of nanoparticles, stability analysis, physical properties assessment, and thermal properties evaluation. The initial phase of this study involved stability investigations that were conducted through zeta potential analyses. Subsequently, the physical parameters of the nanolubricants—such as dynamic viscosity and viscosity index—were evaluated at various composition ratios. Finally, the thermal characteristics, particularly thermal conductivity, were assessed based on the results obtained.

3.1. Stability Analysis

One of the crucial steps before undertaking additional research on the performance of nanolubricants is the stability analysis. It should be mentioned that there is currently no standardized method for assessing the stability of any nanofluid. Applying an appropriate method and parameter during the preparation of the nanolubricant will ensure its long-term stability. Controlling nanoparticle aggregation is an important step in the creation of nanolubricants. Particle aggregation significantly impacts the substance's overall behaviour when a nanolubricant is exposed to a shear or heat load. In the current investigation, the method of stability evaluations was zeta potential. In this part, each method was thoroughly covered with the necessary visualizations. Researchers have looked into similar ways [28-32].

3.1.1. Zeta Potential

The zeta potential analysis provides comprehensive insights into the stability characteristics of the nanolubricant formulations. At 0.01% concentration in Figure 1, the hybrid CNC-Al_2O_3 nanolubricant exhibits exceptional stability with a zeta potential value of approximately 175 mV, significantly higher than the individual components. The Al_2O_3 nanolubricant shows a value of around 130 mV, while CNC demonstrates approximately 85 mV. This superior performance of the hybrid formulation suggests effective synergistic interactions between CNC and Al_2O_3 nanoparticles, enhancing the electrostatic repulsion forces that prevent particle agglomeration [33].

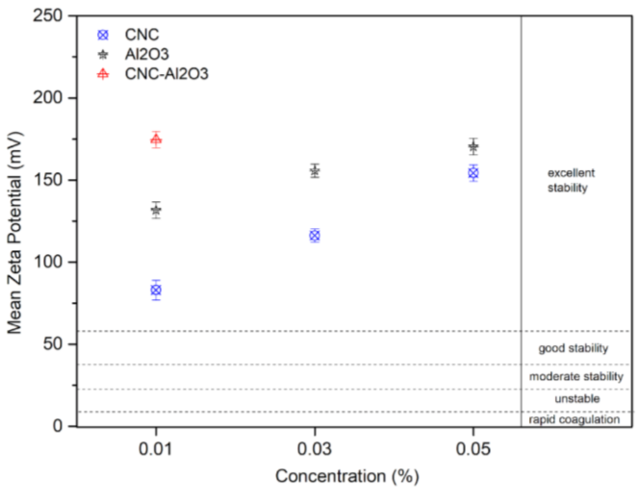

Figure 1. Zeta potential graph for single CNC, single Al_2O_3 and CNC-Al_2O_3.

At 0.03% concentration, all formulations maintain excellent stability but with interesting variations. The Al_2O_3 nanolubricant demonstrates improved stability with a zeta potential value reaching about 155 mV, while the CNC-Al_2O_3 hybrid shows a slight decrease to approximately 150 mV. The CNC formulation exhibits enhanced stability compared to its lower concentration, reaching about 115 mV. These values remain well above the 60-mV threshold that defines excellent stability, indicating robust colloidal systems. The trend continues at 0.05% concentration, where both Al_2O_3 and CNC formulations show further improvement in stability, reaching approximately 170 mV and 155 mV, respectively. These results demonstrated that Al_2O_3 nanoparticles exhibit optimal stability at moderate concentrations [34]. This suggests that higher concentrations particularly benefit the stability of single-component systems.

The error bars in the zeta potential measurements indicate high reproducibility and reliability of the data, with minimal variation between repeated measurements. The stability classification lines on the graph (ranging from rapid coagulation to excellent stability) provide context for interpreting these results, with all formulations falling well within the "excellent stability" region above 60 mV. This comprehensive stability across all concentrations and formulations suggests successful optimization of the preparation methodology, particularly the two-step process and ultrasonication parameters used in sample preparation. These findings align with recent research showing that hybrid nanolubricants often demonstrate enhanced stability characteristics compared to single-component systems, particularly at lower concentrations [35].

To better illustrate the combined stability and viscosity performance, Table 4 compares the zeta potential values and viscosity indices (VI) of all tested nanolubricant formulations against the base SAE 40 oil. A zeta potential value above ±60 mV is classified as "Excellent" stability, which was achieved by all nanoparticle-based lubricants in this study. The CNC–Al_2O_3 hybrid nanolubricant demonstrated particularly strong performance, achieving both high zeta potential (>150 mV) and improved viscosity indices (up to +19.2% over base oil). These results confirm the hybrid formulation's superior colloidal stability and temperature–viscosity resilience, both of which are critical for internal combustion engine lubrication.

3.2. Thermophysical Properties Analysis

The rheological behavior of engine oils is crucial for optimal engine performance and protection. The analysis of CNC, Al_2O_3, and hybrid CNC-Al_2O_3 nanolubricants' viscosity characteristics is essential as these additives can significantly influence the oil's performance across various operating conditions. The incorporation of these nanoparticles into engine oil aims to enhance lubrication efficiency and reduce wear between moving components. During cold engine starts, which account for approximately 80% of engine wear, the nanolubricant must maintain appropriate flow characteristics to reach critical components quickly. The addition of CNC, Al_2O_3, and CNC-Al_2O_3 nanoparticles to SAE 40 base oil has shown promising results in improving cold-start protection while maintaining stability at higher temperatures. Recent studies have demonstrated that these nanoadditives can enhance the viscosity index, ensuring better protection across a wide temperature range.

3.2.1. Viscosity Index

The viscosity index (VI) analysis reveals significant variations across different concentrations of CNC, Al_2O_3, and CNC-Al_2O_3 nanolubricants, as shown in Figure 2. The bar graph demonstrates that all formulations achieve relatively high viscosity indices, ranging from approximately 145 to 160, indicating good viscosity-temperature characteristics. For CNC nanolubricants, the VI values show a slight increasing trend with concentration, ranging from 150 at 0.01% to 155 at 0.05%. This suggests that higher concentrations of CNC particles contribute to better viscosity stability across temperature ranges. The Al_2O_3 nanolubricants exhibit similar behaviour, with VI values ranging from 148 to 153 across the concentration range. The hybrid CNC-Al_2O_3 formulations demonstrate particularly interesting behaviour.

Table 4 Zeta potential and viscosity index comparison for tested nanolubricants

Nanolubricant Type	Concentration (% vol)	Zeta Potential (mV)	Stability Classification	Viscosity Index (VI)	VI Improvement vs. Base Oil (%)
SAE 40 (Base Oil)	—	—	—	130*	—
CNC	0.01	~85	Excellent	150	+15.4%
CNC	0.05	~115	Excellent	155	+19.2%
Al_2O_3	0.01	~130	Excellent	148	+13.8%
Al_2O_3	0.05	~170	Excellent	153	+17.7%
CNC–Al_2O_3 (Hybrid)	0.01	~175	Excellent	155	+19.2%
CNC–Al_2O_3 (Hybrid)	0.03	~150	Excellent	155	+19.2%
CNC–Al_2O_3 (Hybrid)	0.05	~155	Excellent	150	+15.4%
*VI for base oil approximated from SAE 40 standard.					

At 0.05% concentration, the hybrid system achieves a VI of approximately 150, while at 0.03% and 0.01%, the values are slightly higher at around 155. This suggests that the synergistic effect of combining CNC and Al_2O_3 nanoparticles may be more pronounced at lower concentrations. The relatively high VI values across all formulations indicate enhanced temperature-viscosity stability compared to conventional engine oils. This improvement in viscosity index suggests better performance across a wide temperature range, which is crucial for maintaining adequate lubrication during both cold starts and high-temperature operations. The consistent VI values

above 145 for all samples indicate that these nanolubricants could provide reliable protection across various operating conditions.

3.2.2. Dynamic Viscosity

Dynamic viscosity plays a fundamental role in determining lubricant performance in tribological systems by characterizing the relationship between shear stress and shear rate. In liquid lubricants, viscosity exhibits a direct relationship with pressure while showing an inverse relationship with temperature - a behavior commonly observed in both synthetic and mineral oil formulations. In examining the viscosity characteristics of nanolubricants, our analysis focuses on three specific additives: CNC, Al_2O_3, and CNC-Al_2O_3. The data reveal distinct performance patterns across varying concentrations (0.01%, 0.03%, and 0.05%) and temperature conditions. These variations in viscosity characteristics highlight the significant influence of nanoparticle type and concentration on lubricant performance, with nano-crystalline structures showing particularly promising results in enhancing viscosity stability across operating conditions.

3.2.3. Dynamic Viscosity Across Various Operating Conditions

Figure 3 shows the pure CNC nanolubricant, which demonstrates unique viscosity characteristics when dispersed in SAE 40 base oil. At 30°C, all CNC concentrations (0.01%, 0.03%, and 0.05%) exhibit lower dynamic viscosity values compared to pure SAE 40 oil, with values ranging from 0.075 to 0.085 N·s/m². This reduction in viscosity suggests that CNC particles may act as friction modifiers, potentially improving the oil's flow characteristics. As the temperature increases from 30°C to 90°C, the viscosity decreases gradually, maintaining a more stable rate of reduction compared to other nanofluid compositions. This reduction in viscosity also aligns with findings that cellulose nanocrystals can act as effective friction modifiers in lubricating oils, potentially due to their unique rod-like morphology and surface chemistry [36].

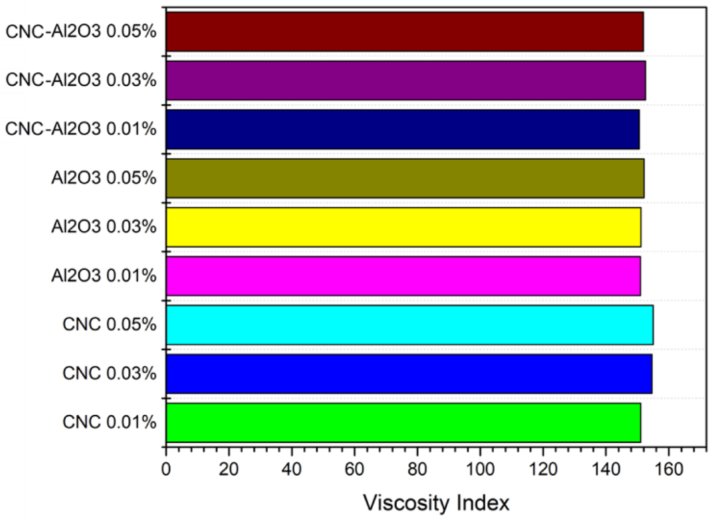

Figure 2. Viscosity index for nanolubricant at all concentrations.

Figure 4 shows the Al_2O_3 nanolubricant, which shows a marked increase in dynamic viscosity compared to the base oil, particularly at lower temperatures. The 0.05% Al_2O_3 concentration achieves the highest viscosity of 0.21 N·s/m² at 30°C, representing approximately a 31% increase over pure SAE 40. This enhancement can be attributed to the strong particle-particle and particle-fluid interactions of the Al_2O_3 nanoparticles. The viscosity decreases exponentially with temperature, following a typical non-Newtonian behaviour, with all concentrations converging towards similar values at 90°C. This significant increase can be attributed to the formation of three-dimensional networks of nanoparticles within the base fluid, as demonstrated in similar studies of metal oxide nanofluids. The exponential decrease in viscosity with temperature follows the established Arrhenius-type relationship, where particle-fluid interactions become progressively weaker at elevated temperatures [37].

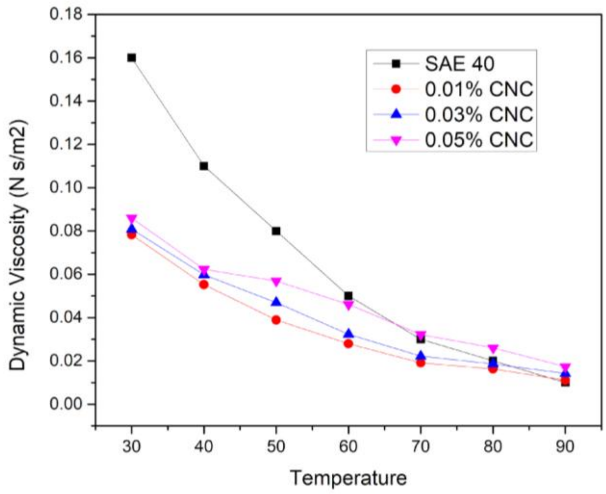

Figure 3. Dynamic viscosity of CNC nanolubricants at increasing temperature at different concentrations.

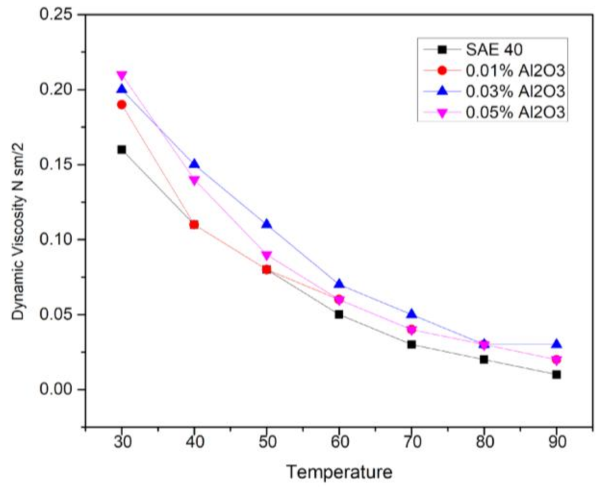

Figure 4. Dynamic viscosity of Al_2O_3 nanobricants at increasing concentration for different temperatures.

The hybrid CNC-Al_2O_3 nanofluids exhibit the most promising viscosity characteristics among all three compositions, as shown in Figure 5. At 30°C, the 0.03% CNC-Al_2O_3 concentration achieves the highest viscosity of 0.25 N·s/m², demonstrating a remarkable 56% enhancement over the base oil. This synergistic effect between CNC and Al_2O_3 nanoparticles creates a more stable suspension with superior thermophysical properties. The hybrid nanofluids maintain higher viscosity values throughout the temperature range, suggesting improved load-carrying capacity and better boundary lubrication properties for engine applications. The exponential decrease in viscosity with temperature follows the pattern $\mu = Ae - BT$, where the hybrid composition shows a more controlled rate of reduction compared to pure Al_2O_3 nanolubricant [38]. The optimal CNC–Al_2O_3 hybrid formulation (0.03% vol) achieved a 56% dynamic viscosity enhancement over base oil at 30 °C, indicating improved load-carrying capacity and boundary lubrication potential for internal combustion engine components.

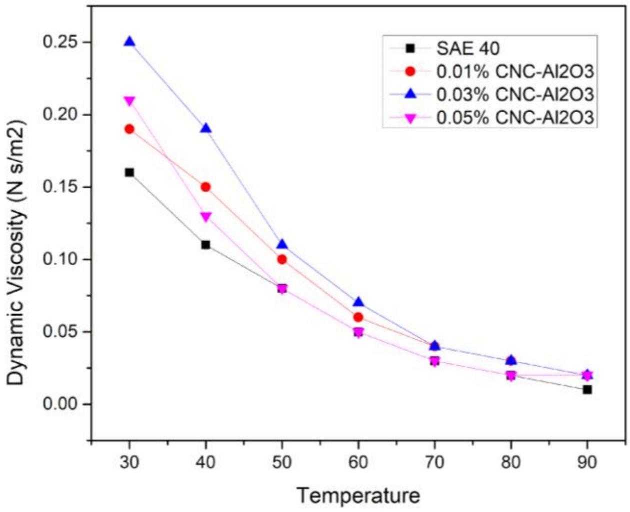

Figure 5. Dynamic viscosity of hybrid CNC-Al_2O_3 at different concentrations with increasing temperatures.

Interestingly, at temperatures below 50 °C, particularly at 30 °C, the dynamic viscosity at 0.03% CNC–Al_2O_3 concentration is higher than at 0.05%, indicating a non-linear relationship between concentration and viscosity enhancement. This behavior can be explained by the increased likelihood of nanoparticle agglomeration at higher concentrations. At 0.05%, stronger particle–particle interactions promote the formation of loose aggregates, which reduce the effective surface area in contact with the base oil molecules and disrupt the three-dimensional network structure responsible for viscosity improvement. In contrast, the 0.03% formulation maintains a more uniform dispersion, enabling more effective hydrodynamic resistance to flow and thus higher viscosity. Similar non-linear concentration–viscosity trends have been reported for other hybrid and metal oxide nanolubricants, where excessive loading leads to diminished viscosity gains due to clustering effects and reduced colloidal stability [39, 40]. The change of viscosity enhancement with temperature in various solid concentrations is shown in Figure 6. The following is a description of the viscosity enhancement calculation:

$$Viscosity\ enhancement, \% = \pm\left(\frac{\mu_{nl} - \mu_{bf}}{\mu_{bf}} \times 100\right) \quad (5)$$

The viscosity enhancement behaviour across different nanolubricant systems reveals interesting patterns with respect to temperature and concentration variations. At 40°C, Al_2O_3 nanolubricants show significant enhancement, with 0.01% concentration achieving approximately 37% improvement over base SAE 40 oil. The enhancement increases with concentration, reaching peak values of around 65% for 0.05% Al_2O_3 at 70°C, as demonstrated by the positive deviation above the reference line. Pure CNC nanolubricants exhibit a unique behaviour, showing negative enhancement at higher temperatures (60-90°C), particularly evident for 0.01% and 0.03% concentrations. This suggests that CNC particles act as friction modifiers rather than viscosity enhancers at elevated temperatures. The maximum negative enhancement reaches approximately -20% at 80°C for 0.01% CNC concentration. The hybrid CNC-Al_2O_3 system demonstrates the most remarkable enhancement characteristics at lower temperatures (40-50°C), with 0.03% concentration showing optimal performance. However, as temperature increases beyond 60°C, the enhancement effect diminishes significantly, converging with other concentrations around 90°C, where all systems show similar enhancement values near 100%.

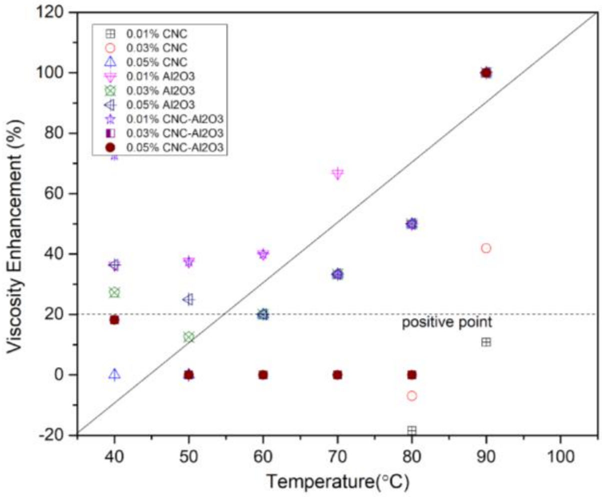

Figure 6. Viscosity enhancement at increasing temperature for different concentrations.

A notable "positive point" threshold is indicated at 20% enhancement on the graph, marking a critical reference for evaluating nanofluid performance. The Al_2O_3 nanofluids consistently maintain enhancement above this threshold until approximately 70°C, while hybrid and pure CNC nanolubricant show more variable behaviour around this reference point. This behaviour aligns with recent findings suggesting that metal oxide nanoparticles provide more stable viscosity enhancement at moderate temperatures compared to organic nanoparticles. The enhancement patterns follow different trends above and below the diagonal reference line, indicating temperature-dependent behaviours that vary significantly with both nanoparticle type and concentration. This complex relationship demonstrates the importance of selecting appropriate nanofluid compositions for specific operating temperature ranges in practical applications [41].

3.2.4. Thermal Conductivity

The thermal conductivity of engine lubricants plays a crucial role in heat transfer performance. In internal combustion engines, enhanced thermal properties of CNC, Al_2O_3, and CNC-Al_2O_3 nanolubricants enable the system to operate at peak efficiency [42-45]. Researchers have explored improving the inherently low thermal conductivity of conventional engine oils by dispersing these nanoparticles (CNC, Al_2O_3, and hybrid CNC-Al_2O_3) into the base fluid. The thermal conductivity enhancement of these nanolubricants was investigated under two key conditions: (i) varying nanoparticle concentrations in SAE 40 oil, and (ii) temperature-dependent behaviours at optimal concentration.

3.2.5. Thermal Conductivity at Different Temperatures and Solid Concentration

The thermal conductivity behavior of these nanofluid systems reveals distinctive characteristics across different temperatures and concentrations. For pure CNC nanolubricant as shown in Figure 7, the thermal conductivity demonstrates remarkable enhancement with increasing temperature and concentration. At 0.05% CNC concentration, the thermal conductivity shows the most significant improvement, starting from 0.32 W/mK at 30°C and reaching 0.90 W/mK at 80°C. This substantial enhancement can be attributed to CNC's unique rod-like morphology and high aspect ratio, which creates effective thermal networks within the base fluid.

Figure 8 shows the Al_2O_3 nanolubricant that exhibits contrasting behavior, where lower concentrations perform better than higher ones. The 0.01% Al_2O_3 concentration shows the highest thermal conductivity among Al_2O_3 samples, reaching 0.20 W/mK at 80°C. Interestingly, higher concentrations (0.03% and 0.05%) demonstrate reduced thermal conductivity, possibly due to particle agglomeration that impedes effective heat transfer. The thermal conductivity enhancement for Al_2O_3 nanolubricant follows a more modest linear increase with temperature compared to the CNC system nanolubricant.

For the hybrid CNC-Al_2O_3 nanolubricant as shown in Figure 9, it combines the advantages of both materials, demonstrating promising thermal characteristics. The thermal conductivity enhancement can be described by the relationship between effective thermal conductivity and particle volume fraction, taking into account the synergistic effects of both materials. The hybrid nanolubricant shows better stability and more consistent thermal conductivity enhancement across the temperature range, making it particularly suitable for engine applications where stable thermal properties are crucial. The temperature dependence of thermal conductivity follows different patterns for each system, with CNC showing the steepest increase with temperature, while Al_2O_3 demonstrates a more gradual enhancement.

This behavior suggests that the mechanism of heat transfer varies significantly between the different nanoparticle types, influenced by factors such as particle shape, size, and surface chemistry. Thermal conductivity enhancements were also notable, with pure CNC achieving up to a 181% increase at 0.05% and 80 °C, while the hybrid CNC–Al_2O_3 maintained consistent improvements across the full temperature range, demonstrating balanced heat transfer and stability characteristics suitable for engine operating conditions. All of the thermal conductivities follow the relationship:

$$k_{eff} = k_{bf}(1 + A\emptyset + B\emptyset^2) \quad (6)$$

where

k_{eff}	Effective thermal conductivity
k_{bf}	Base fluid thermal conductivity
$\emptyset$	Particle volume fraction
A, B	Empirical constant

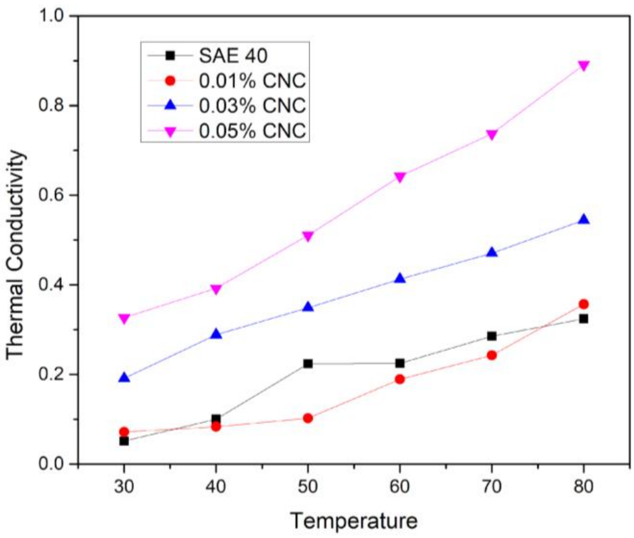

Figure 7. Thermal conductivity of CNC at different concentrations and increasing temperature.

3.2.6. Tribological Performance

Figure 10 shows the result of the coefficient of friction (COF) that demonstrates significant improvements in tribological performance with the addition of CNC-Al_2O_3 nanoparticles to SAE 40 base oil. The pure SAE 40 oil exhibits the highest coefficient of friction at 0.084, indicating considerable friction between the contact surfaces. This serves as the reference point for evaluating the effectiveness of nanoparticle additions in friction reduction. The addition of CNC-Al_2O_3 nanoparticles leads to dramatic improvements in friction reduction, with the 0.01% concentration showing the most significant impact. At this optimal concentration, the COF decreases to 0.018, representing a remarkable 78.6% reduction compared to the base oil. This substantial improvement can be attributed to the formation of a protective tribofilm on the contact surfaces and the synergistic effect between CNC and Al_2O_3 nanoparticles in reducing friction. As the concentration increases, there is a gradual rise in COF values. The 0.03% concentration shows a slight increase to 0.029, while the 0.05% concentration exhibits a further increase to 0.042. However, even at these higher concentrations, the COF values remain significantly lower than the base oil. This trend suggests that while all tested concentrations effectively reduce friction, higher concentrations may lead to increased particle accumulation at the contact interface, slightly diminishing the friction-reducing benefits. The results indicate that the 0.01% concentration provides the optimal balance for friction reduction, likely due to better particle distribution and more effective tribofilm formation at the contact surfaces.

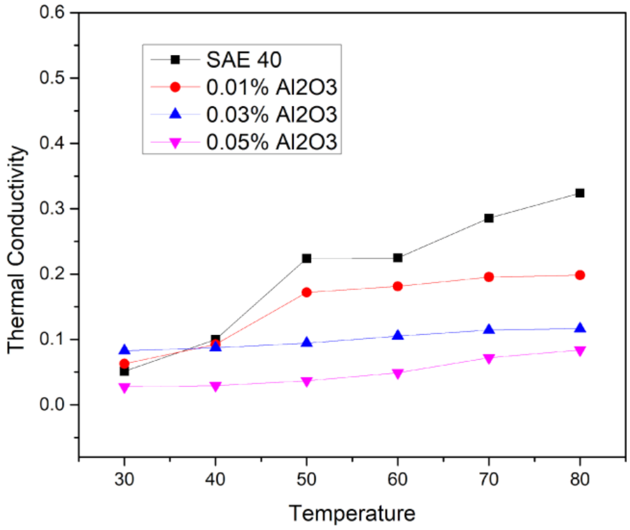

Figure 8. Thermal conductivity of Al_2O_3 at different concentrations at increasing temperature.

Figure 11 shows the specific wear rate analysis, which demonstrates significant improvements with the addition of CNC-Al_2O_3 nanoparticles to SAE 40 base oil. The pure SAE 40 oil exhibits the highest specific wear rate at approximately 0.030 mm^3/Nm, indicating substantial material loss during tribological contact. This baseline wear rate aligns with traditional observations of unmodified lubricating oils [46]. The addition of CNC-Al_2O_3 nanoparticles results in progressive wear rate reduction with increasing concentration. At 0.01% concentration, the specific wear rate decreases to 0.024 mm^3/Nm, representing a 20% improvement over the base oil. This reduction can be attributed to the formation of a protective tribofilm and the ball-bearing effect of nanoparticles [47]. Further improvements are observed at higher concentrations, with 0.03% showing a specific wear rate of 0.017 mm^3/Nm and 0.05% achieving the lowest rate of 0.016 mm^3/Nm. The minimal difference between 0.03% and 0.05% concentrations suggests an optimal concentration threshold, beyond which additional nanoparticles provide diminishing returns in wear protection.

CONCLUSIONS

The stability analysis confirms excellent dispersion characteristics of the hybrid CNC-Al_2O_3 nanolubricants, with zeta potential values exceeding 150 mV at optimal concentrations, indicating robust colloidal stability. The tribological performance demonstrates significant improvements with the addition of CNC-Al_2O_3 nanoparticles to SAE 40 base oil. At 0.01% concentration, the coefficient of friction (COF) shows a remarkable 78.6% reduction from 0.084 to 0.018, indicating superior friction reduction capabilities. The specific wear rate exhibits progressive improvement with increasing concentration, achieving optimal wear protection at 0.05% with a rate of 0.016 mm^3/Nm.

The thermophysical properties reveal distinct characteristics across different concentrations and temperatures. The dynamic viscosity shows optimal enhancement at 0.03% CNC-Al_2O_3 concentration, achieving a 56% improvement over the base oil at 30°C. The thermal conductivity demonstrates concentration-dependent behavior, with pure CNC showing the steepest temperature-dependent increase while Al_2O_3 exhibits more gradual enhancement.

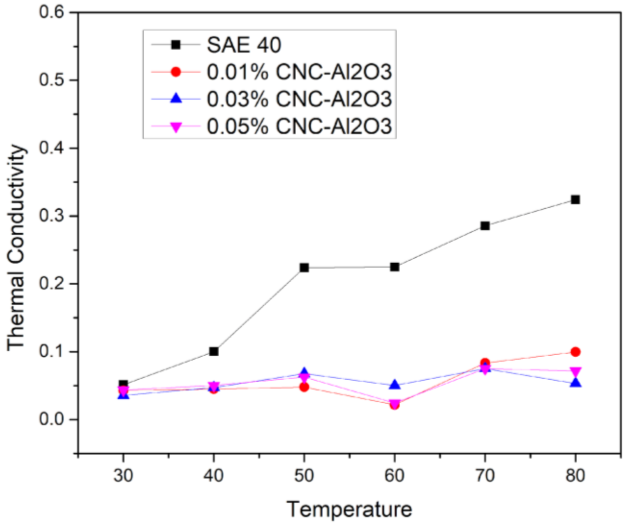

Figure 9. Thermal conductivity of CNC-Al_2O_3 at different concentrations at increasing temperature.

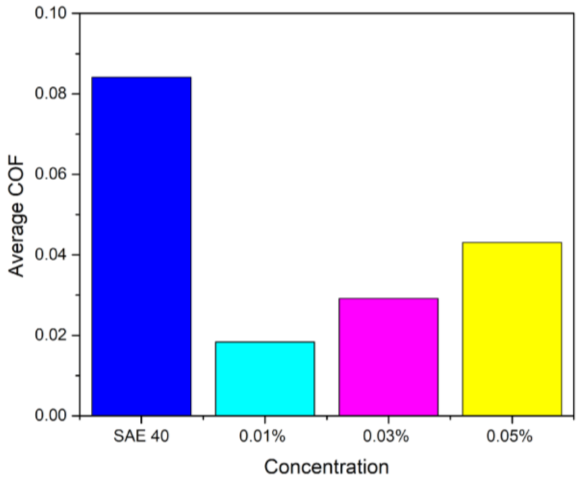

Figure 10. Average coefficient of friction (COF) for CNC-Al_2O_3 nanolubricant.

The tribological performance demonstrates significant improvements with the addition of CNC-Al_2O_3 nanoparticles to SAE 40 base oil. At 0.01% concentration, the coefficient of friction (COF) shows a remarkable 78.6% reduction from 0.084 to 0.018, indicating superior friction reduction capabilities. The specific wear rate exhibits progressive improvement with increasing concentration, achieving optimal wear protection at 0.05% with a rate of 0.016 mm^3/Nm.

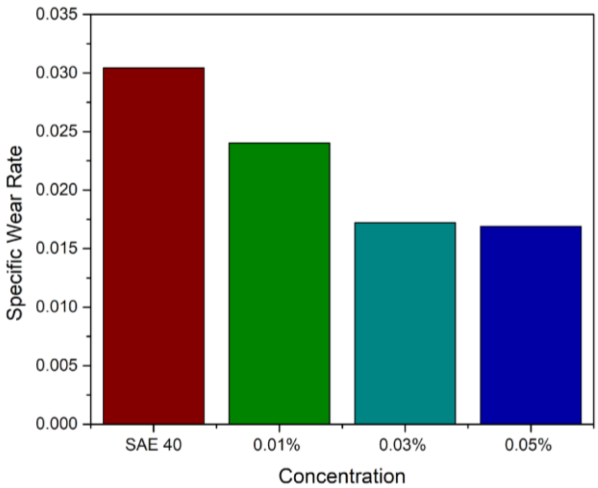

Figure 11. Specific wear rate for CNC-Al_2O_3 nanolubricant.

These findings indicate that the CNC-Al_2O_3 hybrid nanolubricant system offers a promising solution for enhanced tribological performance in internal combustion engines, with 0.01% concentration optimal for friction reduction and 0.05% concentration ideal for wear protection. The demonstrated improvements in both tribological and thermophysical properties suggest significant potential for practical applications requiring stable and efficient lubrication systems.

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REFERENCES

[1] S. Hisham *et al.*, "Hybrid Nanocellulose-Copper (II) Oxide as Engine Oil Additives for Tribological Behavior Improvement," (in eng), *Molecules,* vol. 25, no. 13, Jun 28 2020, doi: 10.3390/molecules25132975.

[2] M. Waqas, R. Zahid, M. U. Bhutta, Z. A. Khan, and A. Saeed, "A Review of Friction Performance of Lubricants with Nano Additives," (in eng), *Materials (Basel, Switzerland),* vol. 14, no. 21, Oct 22 2021, doi: 10.3390/ma14216310.

[3] G. Kadirgama *et al.*, "Graphene nanoplatelets (GNPs) - cellulose nanocrystal (CNC) blended in SAE 40 hybrid engine oil for automotive applications," *Green Materials,* vol. 11, pp. 1-9, 06/14 2022, doi: 10.1680/jgrma.21.00061.

[4] M. K. Kamarulzaman *et al.*, "Improving the thermophysical properties of hybrid nanocellulose-copper (II) oxide (CNC-CuO) as a lubricant additives: A novel nanolubricant for tribology application," *Fuel,* vol. 332, p. 126229, 2023.

[5] S. Hisham *et al.*, "Enhancing stability and tribological applications using hybrid nanocellulose-copper (II) oxide (CNC-CuO) nanolubricant: An approach towards environmental sustainability," *Tribology International,* vol. 194, p. 109506, 2024.

[6] M. K. Kamarulzaman *et al.*, "Improvement in stability and thermophysical properties of CNC-MXene nanolubricant for Tribology application," *Journal of Molecular Liquids,* vol. 381, p. 121695, 2023.

[7] A. P. Singh, R. K. Dwivedi, A. Suhane, K. S. Madhuri, and V. Shende, "Evaluation of the impact of oleic acid-capped Al2O3 nanoparticles on the tribological performance of conventional lube oil," *Industrial Lubrication and Tribology,* vol. ahead-of-print, no. ahead-of-print, 2024, doi: 10.1108/ILT-06-2024-0236.

[8] S. Ghalme, P. Koinkar, and Y. J. Bhalerao, "Effect of aluminium oxide (Al2O3) nanoparticles addition into lubricating oil on tribological performance," *Tribology in industry,* vol. 42, no. 3, pp. 494-502, 2020.

[9] L. Lin and M. A. Kedzierski, "Specific heat of aluminum-oxide nanolubricants," (in eng), *International journal of thermal sciences = Revue generale de thermique,* vol. 126 Pt B, no. Pt B, 2018, doi: 10.1016/j.ijheatmasstransfer.2018.06.077.

[10] S. M. Hisham *et al.*, "Hybrid CNC–MXene Nanolubricant for Tribological Application: Characterization, Prediction, and Optimization of Thermophysical Properties Evaluation," *Processes,* vol. 12, no. 10, p. 2146, 2024. [Online]. Available: https://www.mdpi.com/2227-9717/12/10/2146.

[11] S. M. Hisham, K. Kadirgama, D. Ramasamy, and S. Rahman, "Enhancement of Tribological behaviour and thermal properties of hybrid nanocellulose/copper (II) Oxide nanolubricant," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences,* vol. 72, no. 1, pp. 47-54, 2020.

[12] S. M. Hisham *et al.*, "Hybrid CNC–MXene Nanolubricant for Tribological Application: Characterization, Prediction, and Optimization of Thermophysical Properties Evaluation," *Processes,* vol. 12, no. 10, 2024.

[13] A. Amirruddin, "Tribological Performance Analysis of Nanocellulose-AL2O3-Engine Oil," Doctor of Philosophy, Universiti Malaysia Pahang Pahang, Malaysia, 2019. [Online]. Available: http://umpir.ump.edu.my/id/eprint/28000.

[14] A. Nabhan *et al.*, "Comparative Performance Analysis of Gear Oil Enhanced With Biomass-Derived Cellulose Nanocrystals and Al2O3 Nanoparticles," *International Journal of Polymer Science,* vol. 2025, no. 1, p. 8850107, 2025.

[15] L. Ma *et al.*, "Investigation of Anti-Friction Properties of MoS2 and SiO2 Nanolubricants Based on the Friction Pairs of Inconel 718 Superalloy and YG6 Carbide," *Lubricants,* vol. 13, no. 1, p. 4, 2025. [Online]. Available: https://www.mdpi.com/2075-4442/13/1/4.

[16] C. Vira, "Dispersion and Stability Behaviour of Graphene and MWCNT Based Nano-Lubricant for Vapour Compression Refrigeration (VCR) System," *Communications on Applied Nonlinear Analysis,* vol. 32, no. 1s.

[17] A. Ashraf, W. K. Shafi, M. I. Ul Haq, and A. Raina, "Dispersion stability of nano additives in lubricating oils–an overview of mechanisms, theories and methodologies," *Tribology-Materials, Surfaces & Interfaces,* vol. 16, no. 1, pp. 34-56, 2022.

[18] B. Zakani, S. Entezami, D. Grecov, H. Salem, and A. Sedaghat, "Effect of ultrasonication on lubrication performance of cellulose nano-crystalline (CNC) suspensions as green lubricants," *Carbohydrate Polymers,* vol. 282, p. 119084, 2022.

[19] A. Nurul Hani Noor, S. Siti Salmi, M. Mohd Shukry Abdul, J. Mohd Ridzuan Mohd, and O. Azlin Fazlina, "Physical, Mechanical and Thermal Properties of Hybrid Epoxy/ Multi-Walled Carbon Nanotubes/ Silicon Carbide Conductive Nanocomposites," *International Journal of Nanoelectronics and Materials (IJNeaM),* vol. 17, no. December, pp. 307-313, 12/27 2024, doi: 10.58915/ijneam.v17iDecember.1636.

[20] H. Piri, M. Renzi, and M. Bietresato, "Enhancing Performance and Sustainability of Engine Lubricants and Biolubricants by Dispersing SiO2 Nanoparticles Coated with KH570-Silane Coupling Agent," *Applied Sciences,* vol. 14, no. 17, p. 7943, 2024.

[21] M. Oprea and D. M. Panaitescu, "Nanocellulose Hybrids with Metal Oxides Nanoparticles for Biomedical Applications," (in eng), *Molecules,* vol. 25, no. 18, Sep 4 2020, doi: 10.3390/molecules25184045.

[22] F. Benedict *et al.*, "Nanocellulose as heat transfer liquid in heat exchanger," in *AIP Conference Proceedings*, 2019, vol. 2059, no. 1: AIP Publishing LLC, p. 020044.

[23] G. Kadirgama, M. K. Kamarulzaman, D. Ramasamy, K. Kadirgama, and S. Hisham, "Classification of Lubricants Base Oils for Nanolubricants Applications—A Review," in *International Conference on Mechanical Engineering Research*, 2023: Springer, pp. 205-213.

[24] R. Nurul Izzati Akmal Muhamed, R. Mohd Afzanizam Mohd, S. Nurfarhana, H. Ilham Akbar, P. Avita Ayu, and H. Safarudin Gazali, "Applications of Graphene Nanoplatelets as Working Fluids in Photovoltaic Thermal Systems: A Review," *International Journal of Nanoelectronics and Materials (IJNeaM),* vol. 17, no. 3, pp. 343-353, 08/13 2024, doi: 10.58915/ijneam.v17i3.1115.

[25] M. K. A. Ali and H. Xianjun, "Colloidal stability mechanism of copper nanomaterials modified by bis(2-ethylhexyl) phosphate dispersed in polyalphaolefin oil as green nanolubricants," *Journal of Colloid and Interface Science,* vol. 578, pp. 24-36, 2020/10/15/ 2020, doi: https://doi.org/10.1016/j.jcis.2020.05.092.

[26] A. Kumar and C. K. Dixit, "Methods for characterization of nanoparticles," in *Advances in nanomedicine for the delivery of therapeutic nucleic acids*: Elsevier, 2017, pp. 43-58.

[27] İ. Cesur, V. Ayhan, A. Parlak, Ö. Savaş, and Z. Aydin, "The effects of different fuels on wear between piston ring and cylinder," *Advances in Mechanical Engineering,* vol. 6, p. 503212, 2014.

[28] N. Sezer, M. A. Atieh, and M. Koç, "A comprehensive review on synthesis, stability, thermophysical properties, and characterization of nanofluids," *Powder Technology,* vol. 344, pp. 404-431, 2019/02/15/ 2019, doi: https://doi.org/10.1016/j.powtec.2018.12.016.

[29] M. Sharif, W. Azmi, A. Redhwan, and N. Zawawi, "Preparation and stability of silicone dioxide dispersed in polyalkylene glycol based nanolubricants," in *MATEC Web of Conferences*, 2017, vol. 90: EDP Sciences, p. 01049.

[30] L. Samylingam *et al.*, "Thermal analysis of cellulose nanocrystal-ethylene glycol nanofluid coolant," *International Journal of Heat and Mass Transfer,* vol. 127, pp. 173-181, 2018/12/01/ 2018, doi: https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.080.

[31] I. W. Almanassra, A. D. Manasrah, U. A. Al-Mubaiyedh, T. Al-Ansari, Z. O. Malaibari, and M. A. Atieh, "An experimental study on stability and thermal conductivity of water/CNTs nanofluids using different surfactants: A comparison study," *Journal of Molecular Liquids,* p. 111025, 2019/05/22/ 2019, doi: https://doi.org/10.1016/j.molliq.2019.111025.

[32] P. C. Mukesh Kumar, K. Palanisamy, and V. Vijayan, "Stability analysis of heat transfer hybrid/water nanofluids," *Materials Today: Proceedings,* 2019/08/26/ 2019, doi: https://doi.org/10.1016/j.matpr.2019.06.743.

[33] A. H. Hamisa, W. H. Azmi, M. F. Ismail, R. A. Rahim, and H. M. Ali, "Tribology Performance of Polyol-Ester Based TiO2, SiO2, and Their Hybrid Nanolubricants," *Lubricants,* vol. 11, no. 1, p. 18, 2023. [Online]. Available: https://www.mdpi.com/2075-4442/11/1/18.

[34] W. Azmi, M. Sharif, and N. Zawawi, "The tribology evaluation on a four-ball tribometer lubricated by Al2O3/PAG nanolubricants," *International Journal of Automotive and Mechanical Engineering,* vol. 21, no. 1, pp. 11055-11063, 2024.

[35] S. Yamini, S. Sekar, M. Sivakami Sundari, and K. Senthil Kumar, "Synergistic Enhancement of Tribological Performance and Thermal Stability in R-1234yf Refrigeration Systems Using Graphene Oxide-Silver Hybrid Nanolubricants," *Case Studies in Thermal Engineering,* p. 106430, 2025.

[36] F. S. Arockiasamy *et al.*, "Navigating the nano-world future: Harnessing cellulose nanocrystals from green sources for sustainable innovation," *Heliyon,* 2024.

[37] F. Wang, E. Fatunmbi, A. Adeosun, S. Salawu, I. Animasaun, and I. Sarris, "Comparative analysis between copper ethylene-glycol and copper-iron oxide ethylene-glycol nanoparticles both experiencing Coriolis force, velocity and temperature jump," *Case Studies in Thermal Engineering,* vol. 47, p. 103028, 2023.

[38] G. Sharma *et al.*, "Flow and heat transfer analysis of Couette and Poiseuille flow of a hybrid nanofluid with temperature-dependent viscosity and thermal conductivity," *Case Studies in Thermal Engineering,* vol. 51, p. 103550, 2023.

[39] H. P. Hirudayanathan, S. Debnath, M. Anwar, M. B. Johar, N. K. Elumalai, and U. Mohammed Iqbal, "A review on influence of nanoparticle parameters on viscosity of nanofluids and machining performance in minimum quantity lubrication," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering,* vol. 239, no. 2, pp. 1005-1024, 2025.

[40] W. Ahmed Abdalglil Mustafa, F. Dassenoy, M. Sarno, and A. Senatore, "A review on potentials and challenges of nanolubricants as promising lubricants for electric vehicles," *Lubrication Science,* vol. 34, no. 1, pp. 1-29, 2022.

[41] F. Khan *et al.*, "A hybrid MCDM optimization for utilization of novel set of biosynthesized nanofluids on thermal performance for solar thermal collectors," *International Journal of Thermofluids,* vol. 22, p. 100686, 2024.

[42] M. Afrand, K. N. Najafabadi, and M. Akbari, "Effects of temperature and solid volume fraction on viscosity of SiO2-MWCNTs/SAE40 hybrid nanofluid as a coolant and lubricant in heat engines," *Applied Thermal Engineering,* vol. 102, pp. 45-54, 2016.

[43] M. H. Esfe, M. Afrand, S. H. Rostamian, and D. Toghraie, "Examination of rheological behavior of MWCNTs/ZnO-SAE40 hybrid nano-lubricants under various temperatures and solid volume fractions," *Experimental Thermal and Fluid Science,* vol. 80, pp. 384-390, 2017.

[44] M. Hemmat Esfe, A. A. Abbasian Arani, and S. Esfandeh, "Improving engine oil lubrication in light-duty vehicles by using of dispersing MWCNT and ZnO nanoparticles in 5W50 as viscosity index improvers (VII)," *Applied Thermal Engineering,* vol. 143, pp. 493-506, 2018/10/01/ 2018, doi: https://doi.org/10.1016/j.applthermaleng.2018.07.034.

[45] H. Ahmadi, A. Rashidi, A. Nouralishahi, and S. S. Mohtasebi, "Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant," *International Communications in Heat and Mass Transfer,* vol. 46, pp. 142-147, 2013.

[46] Z. Ma, G. Zhang, L. Chen, Z. Geng, and F. Wang, "Tribological properties of diamond-like carbon films lubricated with water-emulsified engine oil," *Diamond and Related Materials,* vol. 148, p. 111516, 2024.

[47] S. Singh, A. S. Chauhan, and L. Prasad, "Nanolubrication Chemistry and Its Application," *Nanolubricants: Generation and Applications,* pp. 17-60, 2024.