



Temperature-Dependent Thermophysical Behaviour of Bio-Based CNC Nanolubricants for Engine Applications

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Abstract

The thermal management capability of engine oils is increasingly important under modern engine operating conditions characterised by high thermal loads. In this study, the effects of cellulose nanocrystals (CNC) on the specific heat capacity and density of SAE 40 engine oil were experimentally investigated over a range of temperatures and CNC volume concentrations. The results show that the specific heat capacity of CNC-enhanced engine oil increased with temperature for all samples, indicating improved thermal energy storage behaviour. Among the investigated concentrations, 0.5 vol.% CNC exhibited the highest specific heat capacity, demonstrating an optimal balance between particle–fluid interactions and dispersion quality. Density was observed to increase gradually with CNC concentration due to the contribution of solid nanoparticles; however, the magnitude of increase remained moderate and within an acceptable range for engine lubrication applications, particularly up to 0.7 vol.% CNC. The combined results indicate that the enhancement in thermal energy storage capability is not offset by adverse mass-related effects. These findings highlight the potential of renewable CNC-based nanolubricants as sustainable alternatives for improving the thermophysical performance of conventional engine oils. The findings provide new insights into the thermophysical optimisation of bio-based nanolubricants for engine thermal management applications.

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1. Introduction

Engine oils are multifunctional fluids that play a critical role in ensuring the reliable operation of internal combustion engines by reducing friction, minimising wear, sealing combustion chambers, and dissipating heat generated during operation. With the continuous demand for higher power output, improved fuel efficiency, and reduced emissions, modern engines are subjected to increasingly severe thermal and mechanical loads. Under such conditions, the thermal management capability of lubricants

becomes a decisive factor influencing engine durability and operational stability (Mang & Dresel, 2017). Traditionally, engine oil performance has been predominantly evaluated based on rheological parameters such as viscosity and viscosity index. While these properties remain essential for hydrodynamic lubrication, they do not fully describe the thermal behaviour of lubricants under transient and high-temperature operating conditions. In many practical scenarios, lubricant failure is initiated not by viscosity breakdown alone but by inadequate thermal buffering and unstable heat absorption characteristics (Totten, 2014).

Specific heat capacity is a basic thermophysical characteristic defining the amount of thermal energy the lubricant can absorb before the temperature increases. The higher the specific heat capacity of a lubricant, the better its thermal regulation abilities, ensuring a buffer zone of temperatures during dynamic loading and stop-and-go driving operations (Rudnick, 2013). Density, despite being a second-order parameter, exerts a significant influence directly impacting the mass flow rate, hydrodynamic thickness of the lubricant film, and the efficiency of oil circulation pumps. Dependence of density values on temperature can significantly affect the behavior of oil circulation and loading capacity during high-temperature operation of engines, where the expansion process of matter is more pronounced (Mang & Dresel, 2017). Even a minimal variation of density can result in changes of lubrication regimes, calling for a comprehensive study.

In recent years, nanolubricants have attracted considerable academic attention as an emerging approach for the potential upgrade of lubricant properties by the incorporation of nanoparticles into base oils. A great deal of literature has documented the improved properties based on the incorporation of metal oxide nanoparticles, carbon nanomaterials, or hybrid nanoparticles with regard to the reduction of friction coefficients, improvement of wear resistance, and increased thermal conductivities (Suganthi & Rajan, 2014; Khorasani et al., 2021). These properties are generally attributed to the increased heat transfer current paths, the micro-bearing mechanism, or the improved lubricant layer strength. Nevertheless, the emphasis on most of the nanolubricant-related works remains on the enhancement of the heat dissipation properties, with the main performance index occasionally fixed on the improvement of thermal conductivity as the core property. On the other hand, the number of works conducted on the study of the thermal energy storage capacity of lubricants, depending on the specific heat capacity, remains much fewer than those on the heat dissipation properties.

Recent investigations on nanofluids indicate that the effect of nanoparticles on specific heat capacity is complex and often non-linear. Although classical mixture models predict a reduction in specific heat capacity due to the lower heat capacity of solid particles, experimental studies have demonstrated that interfacial energy storage, surface functional groups, and temperature-dependent particle dynamics can lead to enhanced specific heat capacity at low to moderate nanoparticle concentrations (Mahmoud et al., 2023). These findings suggest that particle–fluid interactions play a more significant role than previously assumed. Density behaviour in nanolubricants is influenced by both nanoparticle loading and operating temperature. While nanoparticle addition generally increases density due to the added solid mass, increasing temperature results in density reduction due to thermal expansion (Khorasani et al., 2021). Although these changes are often modest, their combined effect can influence lubricant circulation stability, pumping losses, and film formation, particularly in high-speed and high-temperature engine applications.

From the viewpoint of sustainability, the major concern with traditional inorganic nanoparticles is their persistence, toxicity, and recyclability properties. Therefore, there is an ever-increasing focus on the search for renewable or bio-based nanoparticles. Cellulose nanocrystals (CNCs), which are derived from cellulose materials, are advantageous because they are low-density materials that are biodegradable with ample surface groups, which are potentially useful for the stabilization of the interactions between the base oils (Kargarzadeh et al., 2018). Due to these properties, CNCs are potential candidates found suitable for the development of environmentally compatible nanolubricants. While there is an increased focus on the potential use of CNCs as nanolubricants, the major concern is that past works have been dominated by the study of their effects on the tribological properties and the enhancement of thermal conductivity properties alone. Moreover, most reported studies involve polar base fluids or short-term evaluations, leaving uncertainty regarding the thermophysical behaviour of CNC-enhanced mineral engine oils under temperature-varying conditions.

To synthesise the current state of research and highlight the identified knowledge gap, a summary of selected previous studies on nano-additive-enhanced lubricants is presented in Table 1. As summarised in Table 1, investigations focusing on the effects of renewable nano-additives on specific heat capacity and density in conventional SAE 40 engine oil remain scarce, underscoring the need for a focused thermophysical evaluation. The use of nanomaterials as additives in base oils has been experimentally shown to improve thermal and lubricity performance. For example, Gulzar et al. (2016) found that Al_2O_3 in SAE 40 oil improved heat dissipation, but its effectiveness was limited by caking issues at high concentrations. For rheological improvements, Ali et al. (2016) showed that TiO_2 improved the viscosity stability of engine oils, although the study did not comprehensively evaluate density and heat capacity parameters.

Carbon-based materials such as Graphene and CNT offer very high thermal enhancement in synthetic and mineral oils, respectively, as reported by Selvam et al. (2021) and Etefaghi et al. (2013), but both face challenges of cost and dispersion stability. Meanwhile, the use of more sustainable Cellulose Nanocrystal (CNC) shows potential in water/glycol mixtures (Samyalingam et al., 2020) and bio-based oils (Awang et al., 2019), providing a green alternative for future cooling and lubrication systems. Therefore, the present study aims to investigate the effects of cellulose nanocrystals on the specific heat capacity and density of SAE 40 engine oil over a range of temperatures and CNC concentrations. By addressing the identified knowledge gap, this study provides a more comprehensive understanding of the thermal energy storage behaviour and mass-related characteristics of CNC-enhanced nanolubricants. The findings are expected to contribute to the development of thermally efficient, environmentally sustainable lubrication systems suitable for modern engine applications.

Table 1. Summary of previous studies on nano-additive-enhanced lubricants with emphasis on thermophysical properties

Nano-additive	Base oil / fluid	Properties investigated	Key findings	Identified limitation	Reference
Al_2O_3	SAE 40	Thermal conductivity, viscosity	Improved heat dissipation and lubrication performance	Agglomeration at higher concentrations	Gulzar et al. (2016)
TiO_2	Engine oil	Viscosity stability	Enhanced rheological behaviour	C_p and density not evaluated	Ali et al. (2016)
Graphene	Synthetic oil	Thermal conductivity	Superior thermal enhancement	High cost and stability issues	Selvam et al. (2021)
CNT	Mineral oil	Heat transfer, friction	Significant thermal improvement	Dispersion difficulty	Etefaghi et al. (2013)
CNC	ethylene glycol + Water	Thermal conductivity, stability	Improved thermal performance	Not representative of engine oil	Samyalingam et al. (2020)
CNC	Bio-based oil	Thermophysical behaviour	Moderate enhancement observed	Short-term evaluation only	Awang et al. (2019)

2. Methodology

2.1 Materials

SAE 40 commercial oil was chosen as the primary lubricant based on its common use in internal combustion engines. Cellulose nanocrystals (CNCs), which are lightweight, environmentally friendly, and possess favorable thermal properties, were used as the renewable nano additive in this investigation. All materials were utilized without any additional chemical modification to maintain their default characteristics.

2.2 Preparation of CNC–SAE40 Nanolubricants

The CNC-based nanolubricants were prepared using a two-step dispersion technique to ensure uniform particle distribution and stable suspension. Predetermined amounts of CNC powder were gradually added to the SAE 40 engine oil to obtain the desired CNC volume concentrations. The mixtures were initially homogenised using magnetic stirring to promote preliminary dispersion. This was followed by ultrasonic agitation to reduce the likelihood of particle agglomeration and to improve the dispersion stability. This preparation method was adopted to ensure the production of nanolubricants with sufficient dispersion stability for accurate thermophysical characterization. The preparation of the nanolubricants is shown in Figure 1.

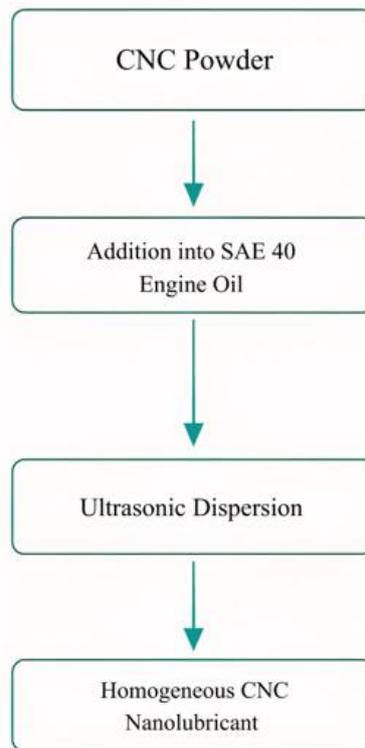


Figure 1. Schematic flow diagram of the preparation process of CNC-based nanolubricants.

2.3 Specific Heat Capacity Measurement

The specific heat capacity (C_p) of the CNC-enhanced SAE 40 engine oil was measured using a Differential Scanning Calorimeter (DSC), model DSC1000-/C from Linseis Messgeräte GmbH, Germany. The measurement procedure followed the ASTM E1269-01 standard to ensure accuracy in exploring how the heat capacity changes over temperature. Samples were placed in aluminum crucibles and heated from 30 °C to 90 °C under a dynamic nitrogen atmosphere with a constant heating rate of 5 °C/min. Prior to measurement, each sample was conditioned to reach thermal equilibrium to ensure consistent and repeatable energy storage data.

2.4 Density Measurement

Density investigations were conducted in accordance with the ASTM D1298 standard using a DA-130 Portable Density / Specific Gravity meter. To check the device's functionality, a water density was measured, to prove the testing of the nanolubricant samples would have a deviation of the measured and theoretical values of density not greater than $\pm 0.001 \text{ g/cm}^3$. The nanolubricants were loaded into the measuring cell to avoid the creation of air pockets, and a value was taken when the indicator stabilized. Each measurement was repeated three times to calculate an averaged final result, ensuring high repeatability across all volume concentrations.

2.5 Experimental Scope

The experimental scope of the present study focused on evaluating the combined effects of CNC concentration and temperature on the specific heat capacity and density of SAE 40 engine oil. This approach allows for a comprehensive assessment of the thermophysical behaviour of CNC-enhanced nanolubricants, with particular emphasis on thermal energy storage capability and mass transport characteristics.

3. Result and Discussion

3.1 Specific Heat Capacity of CNC-Based Nanolubricants

Figure 2 shows the variation of specific heat capacity of CNC-enhanced SAE 40 engine oil as a function of temperature at different CNC volume concentrations. For all samples, the specific heat capacity increased with temperature up to approximately 60–70 °C, followed by a slight reduction at higher temperatures. This trend reflects the typical thermal behaviour of liquid lubricants, where increased molecular mobility at elevated temperatures enhances thermal energy absorption until thermal saturation effects become dominant (Mahmoud et al., 2023). Compared to the base oil, the addition of CNC significantly modified the specific heat capacity behaviour.

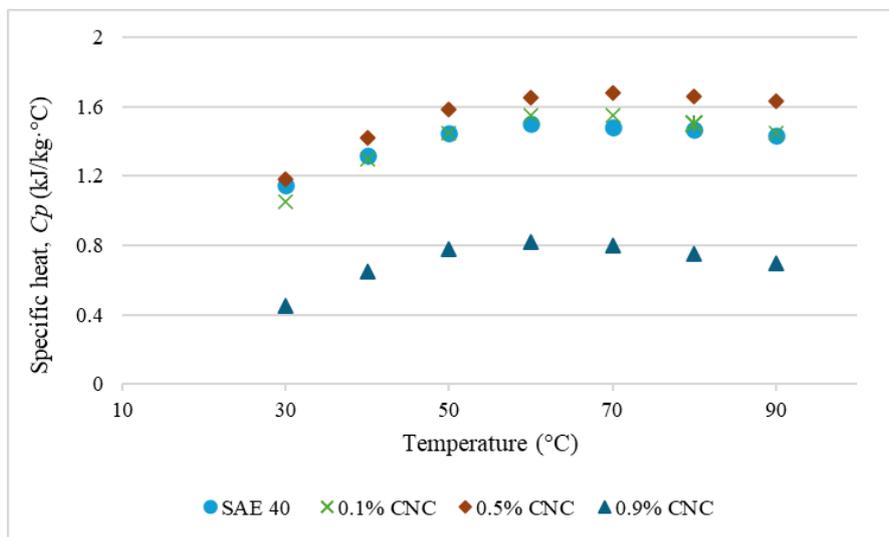


Figure 2. Specific heat capacity of CNC-based SAE 40 engine oil at different temperatures and CNC concentrations.

Among the investigated concentrations, the nanolubricant containing 0.5 vol.% CNC consistently exhibited the highest specific heat capacity across the entire temperature range. This indicates that moderate CNC loading provides an optimal balance between particle–fluid interactions and dispersion

quality, leading to enhanced thermal energy storage capability. Similar optimal concentration effects have been reported in recent nanofluid studies, where specific heat capacity enhancement was maximised at intermediate nanoparticle concentrations rather than at the highest loading levels (Induranga, 2025).

At lower CNC concentration (0.1 vol.%), the specific heat capacity showed a modest improvement compared to the base oil, suggesting that limited nanoparticle content provides insufficient interfacial surface area to significantly enhance thermal energy storage. In contrast, at higher CNC concentration (0.9 vol.%), the specific heat capacity was noticeably lower than both the base oil and other CNC-enhanced samples. This reduction can be attributed to increased particle–particle interactions and partial agglomeration, which reduce the effective surface area available for energy exchange and weaken the contribution of interfacial thermal storage (Ghosh, 2024).

The non-linear dependence of specific heat capacity on CNC concentration highlights the limitations of classical mixture models in describing the thermal behaviour of nanolubricants. Recent studies have emphasised that interfacial nanolayers and surface functional groups play a critical role in determining the heat capacity of nanoparticle-enhanced fluids, particularly for renewable nanoparticles such as CNCs with abundant hydroxyl groups (Mahmoud et al., 2023). Among the concentrations investigated, 0.5 vol.% CNC demonstrated the most favourable specific heat capacity behaviour, indicating an optimal balance between thermal energy storage and dispersion stability.

From an application perspective, the enhanced specific heat capacity observed at optimal CNC concentration implies improved thermal buffering capability for engine lubrication systems. Lubricants with higher specific heat capacity can absorb greater thermal loads without excessive temperature rise, which may help reduce thermal degradation and extend lubricant service life under transient and high-temperature engine operating conditions. The results demonstrate that renewable CNC nanoparticles can effectively enhance the thermal energy storage behaviour of conventional SAE 40 engine oil when used at appropriate concentrations.

3.2 Density Behaviour of CNC-Based Nanolubricants

Density is an important thermophysical property that influences lubricant flow behaviour, hydrodynamic film formation, and pumping efficiency in engine lubrication systems. As shown in Figure 3, the density of CNC-enhanced SAE 40 engine oil increased gradually with increasing CNC volume concentration. This trend is expected, as the incorporation of solid nanoparticles with higher intrinsic density than the base oil increases the overall mass per unit volume of the suspension. Similar density behaviour has been widely reported for nanofluids and nanolubricants and is consistent with classical mixture theory (Pak & Cho, 1998; Vajjha et al., 2009).

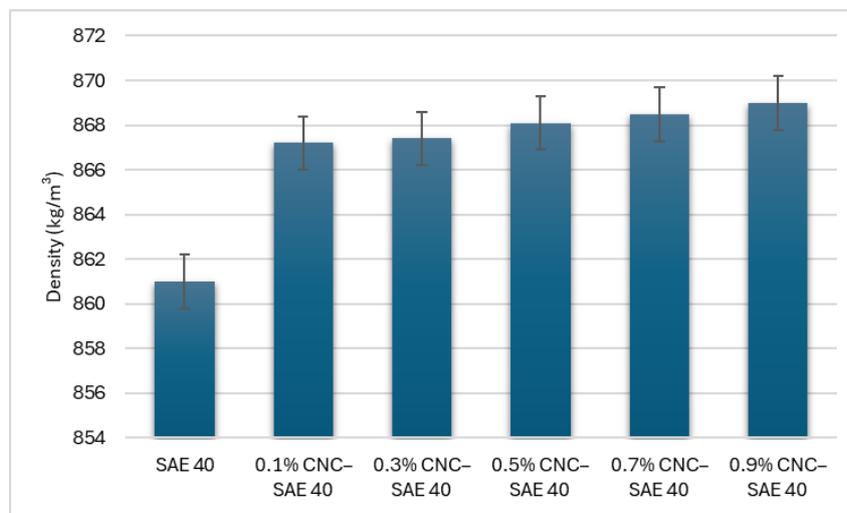


Figure 3. Density of CNC-based SAE 40 engine oil at 20 °C for different volume concentrations

The observed density increase remained relatively small and exhibited an almost linear trend across the investigated CNC concentration range. Such moderate density variation suggests that the CNC particles were well dispersed within the base oil without causing abrupt changes in mass-related properties. Recent studies have reported that nanolubricants exhibiting gradual and limited density increases are generally associated with stable dispersion and acceptable flow characteristics, particularly when nanoparticle concentrations are maintained at low to moderate levels (Ghosh, 2024; Induranga, 2025). The higher the concentration of the CNC resulted in slightly higher density values. The values were still within the applicable range of an engine lubrication application. However, recent literature suggests that increased particle–particle interactions and decreased dispersion stability may explain the greater variation in density at the greater mass fractions of the nanoparticles (Kotia et al., 2017; Ghosh, 2024). It is therefore necessary to concentrate on the CNC to balance the improvement to thermophysical performance and the stability of the lubricant behaviour.

Overall, the density results demonstrate that the incorporation of CNCs as renewable nano-additives does not impose a significant mass penalty on SAE 40 engine oil. When considered together with the enhanced specific heat capacity observed at optimal CNC concentrations, the slight increase in density does not offset the benefits in thermal energy storage capability. These findings support the potential of CNC-based nanolubricants as sustainable alternatives for improving thermophysical performance while maintaining suitable flow characteristics for modern engine applications (Induranga, 2025).

3.2 Optimum Concentration

Based on a combined evaluation of specific heat capacity and density, an integrated thermophysical assessment was performed to identify the optimal CNC concentration. The results indicate that **0.5 vol.% CNC** represents the optimum concentration for thermal energy storage, as it consistently exhibits the highest specific heat capacity across the investigated temperature range. This behaviour suggests an optimal balance between particle–fluid interactions and dispersion quality, enabling enhanced interfacial energy storage without excessive particle–particle interactions.

Although density increases progressively with CNC concentration, the magnitude of increase remains moderate up to 0.7 vol.%, indicating acceptable mass-related behaviour and flow characteristics for engine lubrication applications. At higher concentrations, the marginal gains in density are accompanied by diminishing benefits in specific heat capacity, likely due to increased agglomeration tendencies. Therefore, 0.5 vol.% CNC is identified as optimal for maximising thermal energy storage, while 0.7 vol.% represents the upper practical limit where density remains within an acceptable range without significantly compromising stability.

4. Conclusion

This study investigated the effects of cellulose nanocrystals on the specific heat capacity and density of SAE 40 engine oil over a range of temperatures and CNC concentrations. The results demonstrate that the incorporation of CNC significantly modifies the thermophysical behaviour of the base oil. Specific heat capacity increased with temperature for all samples, with 0.5 vol.% CNC exhibiting the highest thermal energy storage capability across the investigated temperature range.

Density was found to increase gradually with CNC concentration, reflecting the contribution of solid nanoparticles to the overall mass of the lubricant. However, the density variation remained moderate and within an acceptable range for engine lubrication applications, particularly up to 0.7 vol.% CNC. The combined analysis indicates that the enhancement in specific heat capacity at optimal CNC loading is not offset by adverse density effects.

Overall, the findings confirm that renewable CNC can serve as effective nano-additives for improving the thermal energy storage behaviour of conventional engine oils. The use of CNC offers a sustainable approach to enhancing thermophysical performance while maintaining suitable mass transport characteristics, supporting their potential application in advanced and environmentally responsible lubrication systems.

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