Assessing thermophysical properties of Nanostructured Cellulose Nano Crystal (CNC) and Graphene Nanoplatelets (GNP) Additives in Palm Oil-Based Heat Transfer Fluid

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Abstract. This study explores the examination of the thermophysical characteristics of eco-friendly CNC-Palm oil, GNP-Palm oil and CNC/GNP-palm oil mono and hybrid nanofluids. The stability assessment involves a comprehensive analysis, incorporating visual observations and thermal conductivity assessments. Notably, it was observed that an elevated proportion of hybrid mixture contributed to the enhanced stability of the nanosuspension, ensuring the uniform dispersion of nanomaterials within the base liquid for an extended period. The results indicate that hybrid nanofluids containing CNC/GNP and formulated with palm oil exhibit substantial stability. A comprehensive visual examination over an impressive 30-day duration reveals minimal accumulation, underscoring the enduring stability of these nanofluids. The study also examines crucial thermal and physical properties, including thermal conductivity and viscosity about temperature. The most significant enhancement was witnessed in thermal conductivity, achieving a noteworthy 100% increase in the 0.1w/v% concentrated CNC/GNP/Palm Oil hybrid nanofluid at 70°C, demonstrating a significant improvement compared to the base fluid. Furthermore, there are noticeable increments in viscosity, albeit with a more modest enhancement compared to thermal conductivity. These outcomes suggest a direct relationship between the increased concentrations can improve stability and thermal conductivity. This study contributes valuable insights into utilizing CNC/GNP in nanofluid applications, with implications for fields requiring enhanced thermal performance and fluid stability.

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1 Introduction

In response to the urgent environmental crisis and energy shortages, governments and industries are increasingly shifting towards sustainable, renewable, and clean energy solutions, focusing on developing and utilizing hybrid heat transfer nanofluids [1][2]. In the last few years, there has been a rising interest in nanofluids, which are viscid suspensions of nano enhancers in a carrier fluid. Nanosuspensions attract the attention for their unique thermophysical properties and for enhancing heat transfer in various applications [3]. Nanofluids have been recognized to be remarkably well-suited for use as working fluids in countless heat transfer utilizations, mainly caused by their outstanding thermophysical characteristics. The deep-rooted stability of nanosuspensions portrays key responsibility in determining the extent of improvement in their thermophysical properties [4,5]. Nanofluids innovate heat transfer with tailored suspension properties. Despite attractive features like tunability, unique surface attributes, and remarkable thermal conductivity, challenges remain, especially in nanofluid stability and productivity [6].

Over the past two decades, scientists and engineers have held extreme expectations for the rapid advancement of nanotechnology. Nanofluids with suspended nanoparticles under 100 nm in size offer significant benefits over conventional fluids in heat transfer applications. The presence of firmly suspended and uniformly dispersed nanomaterials in the base fluids manages notable improvements in the thermal properties of the host fluids [7]. Traditional coolants like water, ethylene glycol, and propylene glycol have not fully met the desired thermophysical criteria set by the United States Department of Energy (DoE). In opposition to this, nanofluids have showcased their ability to boost thermal transport efficacy and increase whole performance significantly [8].

The rapid progression of technology has led to increased heat generation in various miniature thermal systems. To tackle this issue, small heat sinks, such as mini-channels and micro-channels, coupled with the utilization of nanofluids, are being implemented to enhance cooling effectiveness [9]. In response to the growing demand for green energy and environmental protection, numerous researchers have explored the introduction of alternative oil types to investigate their diverse characteristics as insulating oils [10]. In the case of vegetable oil, researchers have conducted studies on its thermophysical properties, including thermal conduction and viscosity. These investigations encompassed many volume strengths and a broad temperature limit. The investigational findings consistently indicated improvements in thermal conductivity across all scenarios, alongside an observed increase in viscosity [11]. Enhancing the thermal efficiency of a composite thermal energy storage system involves integrating even wasted food oil with wax [12]. Vegetable-based oils are known for their excellent biodegradability, eco-friendliness concerning the environment and human health, and widespread availability. However, they have limitations, such as low thermal and chemical stability, inadequate corrosion protection, and relatively high freezing points. It is worth noting that when used as a base fluid, vegetable oil-based nanofluids exhibit favorable heat transfer characteristics [4][13].

In real-world applications, the stability of nanofluids can be adversely affected by cyclic heating and exposure to high temperatures [14]. The heat transport properties of the carrier fluid are influenced by several key parameters, including nano enhancers Concentration, magnitude, configuration, thermal conductivity, type of base liquid, nanosuspensions temperature, and the method of preparation. Among these factors, nanoparticle concentration was found to have the most significant impact [15]. Numerous researchers have directed their studies toward nanomaterial concentration due to the remarkable enhancement in thermal conduction observed at low concentrations of nanoparticles [16]. The impact on viscosity varies significantly in specific instances, with elements like the particular nanofluid type, shape and size of the nanoparticle, volume intensity, and base liquid playing distinct roles in influencing viscosity. Therefore, solely examining viscosity effects may not be productive without determining these parameters. To maximize heat transfer enhancement and achieve optimal results, it is advisable to study nanofluids in conjunction with other passive methods simultaneously [17].

Addressing the increasing global concerns surrounding environmental sustainability, this paper explores the viability of Palm oil and nanofluids derived from palm oil in the context of potential alternatives for transformer oils. Palm oil is a cornerstone of Malaysia's primary industries, with over half of its production concentrated in Peninsular Malaysia. Due to its environmentally friendly, biodegradable, and renewable attributes, palm oil is a promising candidate to replace petroleum-based mineral oil [18]. Nanofluids with impressive stability, lasting up to 6 months without any signs of aggregation, were successfully created by incorporating nanoparticles into waste palm oil. Notably, The assessment of thermal properties in these nanofluids showed a significant rise in thermal conductivity when the concentration of nanoparticles was increased in waste palm oil [19]. While there is a wealth of information available on water-based nanofluids, it's important to note that the literature on oil-based nanofluids is comparatively sparse [20].

Hybrid nanofluids have gained favor due to their favorable thermophysical properties, enhanced heat transfer rates, and improved stability. Consequently, there has been a growing emphasis on research focused on hybrid nanofluids, surpassing the attention given to mono-type nanofluids [21]. Novel results have been reported in developing a palm oil-based hybrid heat transfer fluid. This fluid exhibits enhanced thermal conductivity, improved viscosity, and increased solar absorption capacity. These improvements contribute to the reduction of photovoltaic temperature, resulting in higher thermal efficiency and superior heat transfer performance.

Additionally, this fluid's enhanced photo-thermal conversion properties represent a noteworthy advancement in the field [22]. Hybrid nanofluids composed of nanocomposites mixed with palm oil were carefully fabricated using the two-step process. These nanofluids are currently investigated as promising candidates for enhancing heat transfer in various applications [23]. This results from the remarkably excessive thermal conduction exhibited by graphene nanoplatelets [24]. The interest in employing carbon-based nanomaterials, which encompass carbon nanotubes, graphene, carbon nanofibers, and nano-diamonds, has surged because of the superior thermal conductivity and lower density properties these carbon materials offer in comparison to other nanoparticle varieties [25]. Nanofluids containing graphene nanoplatelets (GNP) demonstrate exceptional thermal performance attributes along with excellent stability. Moreover, they are relatively cost-effective and can be conveniently prepared using a straightforward two-step method [26][27]. GNP-nanofluids have been observed to yield a superior heat transport coefficient, and GNP concentration increases significantly enhance the thermal conduction of the nanosuspension. Notably, the increase in GNP concentration does not notably impact the viscosity of the nanofluid [28]. It was observed that adding nanomaterials to the carrier liquid led to a significant increase in viscosity. Specifically, when graphene nanoparticles (GNPs) were introduced into vegetable oil nanofluid, the viscosity increased by approximately 19% compared to the base liquid [29]. Graphene nanoparticles (GNPs) and cellulose nanocrystals (CNC) combined in an ethylene glycol base exhibit promising nanofluid performance, with 0.1% volume demonstrating excellent stability in the core fluid [30]. The addition of graphene nanoplatelets (GNPs) to silicone oil has raised thermal conduction. Notably, as the intensity of GNPs remained rising to 0.1% and 0.15%, changes in thermal conductivity became noticeable for various ultrasonication times, with the maximum thermal conductivity achieved after 3 hours of ultrasonication. Additionally, it's worth mentioning that the silicone oil’s viscosity tends to upsurge after introducing nano-enhancers, but this viscosity declines with an elevation in temperature [31].

Impressively, the highest improvement of thermal conduction exceeding 25% was noticed for cellulose nanocrystal (CNC) nanofluids. These CNC nanofluids exhibited a decreasing trend in dynamic viscosity across all volume concentrations as the temperature reached 70°C. Additionally, it's noteworthy that CNC displayed negative specific heat capacity, indicating mechanical uncertainty. This condition implies that the isothermal compressibility remains denied or equal in nature [32]. The CNC with 2D MXene nano lubricants exhibited excellent dispersion, indicating a favorable distribution of the components within the lubricant mixture. This dispersion is a positive attribute as it can lead to improved lubrication and performance in various applications [33]. The connection amid thermal conductivity, dynamic viscosity, CNC volume intensity, and temperature in CNC nanofluids is noteworthy. Thermal conductivity tends to rise with an increase in both CNC volume strength and temperature.

Conversely, dynamic viscosity tends to increase when CNC volume concentration increases but decreases as the temperature rises. It's particularly interesting that the 0.5% CNC volume concentration nanosuspension demonstrated optimal stability and viscosity. These attributes render it a relevant preference for utilization in machining operations [34]. A limited number of researchers have explored the incorporation of nanoparticles to improve thermal properties [35,36].

Carbon-based nanomaterials, specifically nanotubes and graphene, present a promising avenue for superior thermal conductivity. Notably, incorporating graphene nanoplatelets in nanofluids has demonstrated exceptional thermal performance. However, when introduced into vegetable oil, a notable increase in viscosity is observed. Conversely, stability is maintained in ethylene glycol nanofluids containing graphene nanoplatelets and cellulose nanocrystals.

Despite the improved thermal properties, introducing nanoparticles leads to an elevation in carrier liquid viscosity. When combined with graphene nanoplatelets, this effect is observed differently in vegetable and silicone oil. In the case of cellulose nanocrystals (CNC) nanofluids, viscosity exhibits intricate trends concerning concentration and temperature, introducing an additional layer of complexity to the study.

The underlying hypothesis driving this research posits that incorporating graphene and cellulose nanocrystals in nanofluids aims to strike a delicate balance between thermal enhancement and viscosity. This delicate equilibrium is essential for achieving enhanced overall efficiency across diverse applications. The primary objective of this investigation is to advance thermal performance in cooling fluids by introducing highly conductive nanoparticles.

This study meticulously explores various concentrations (ranging from 0.02 to 0.1 w/v %) of CNC/GNP in palm oil. The goal is to optimize heat transfer rates for superior cooling applications. The novelty of this research lies in its nuanced approach to addressing the intricate interplay between thermal enhancement and viscosity in the context of diverse nanoparticle-infused cooling fluids, thereby contributing significantly to the field.

2 Experimental section

This section encompasses an assessment of the materials used in the study, the methodology for nanoparticle characterization, the creation of a hybrid nanofluid, and the assessment of nanofluid steadiness. Furthermore, this section outlines the approach employed in this research for viscosity and thermal conductivity determination.

2.1 Materials

The meticulous documentation of materials and sources utilized in synthesizing CNC/GNP/Palm oil nanofluid is systematically presented in Table 1.

Table 1. Material sources used.

Materials	Sources
Palm oil	commercially available
Graphene Nanoplatelets	Sigma Aldrich
Cellulose Nanopowder	Nanoshel

2.2 Methodology

The preparation of nanofluids remains a crucial stage in this process. The single-step approach and the two-step approach are regularly used [14]. Nanoparticles play a pivotal role as essential components within nanofluids, considerably in modifying the thermal transport properties of these fluids. It's worth highlighting that specified experiments have developed nanofluid formulations that do not rely on adding surfactants [37]. The researchers used a two-step method [38] for nanofluid preparation primarily.

The preparation procedure involves the two-step method of creating nanofluids, utilizing nanoparticles measured at varying weights over volume percentages. These nanoparticles generate nanofluids with low volume concentrations, specifically at 0.02, 0.04, 0.06, 0.08, and 0.1 w/v% for CNC and GNP when blended with palm oil. A 50:50 blend of these specified percentages is employed to create hybrid nanomaterials incorporating CNC and GNP. These hybrid nanomaterials are mixed with 100 ml of commercially available palm oil, as detailed in Table 2. The primary intention of this examination is to research the influence of nanocomposite volume concentrations on nanofluid effectiveness. In this research, the mass of nano additives is calculated using an equation grounded on the principle of the law of mixtures.

$$\varnothing = \frac{\frac{[W_p/\rho_p]}{\rho_p}}{[(W_p/\rho_p)+(W_{bf}/\rho_{bf})]} \qquad (1)$$

Nanoparticles, specifically Cellulose Nanocrystals (CNC) and Graphene Nanoplatelets (GNP), in their dry powder form, were utilized to formulate a nanofluid consisting of CNC, GNP, and palm oil. Table 2 furnishes information on the properties of palm oil under atmospheric pressure conditions. In contrast, Table 3 presents a comprehensive overview of the properties of the nanoparticles used in this study and the Prepared nanofluid concentrations listed in Table 4. After the monodisperse and hybrid nanofluids were prepared, a comprehensive set of characterization studies was conducted. These investigations included assessing dispersion stability through visual inspection and thermal performance by thermal conductivity measurements. The significance of thermal conductivity cannot be overstated as a crucial thermophysical attribute of any liquid, especially in applicability related to heat transfer.

Table 2. Palm oil properties.

Palm oil	Properties
Appearance	solid/white/yellow
Flash point	> 110 °C
Relative density Purity	0.897 g/cm^3 99.99%
Melting point and freezing point	20°C

Table 3. Nanoparticle properties.

Nanoparticle	CNC	GNP
Farm	powder	powder
Color	off white	Black
Particle Size	80 – 100 nm	5 nm
Purity	99.9%	100%
structure	linear chain [39]	pore
Bulk Density	0.3 – 0.5 g/l	0.2 – 0.4 g/cm^3

Table 3. Prepared nanofluid concentrations.

Palm oil volume %	Nanocomposite w/v %	Palm oil+CNC+GNP total %
99.98	0.02	100
99.96	0.04	100
99.94	0.06	100
99.92	0.08	100
99.90	0.10	100

The assessment of dynamic viscosity holds significant importance as a pivotal thermophysical parameter for evaluating the stability and efficacy of nanofluids within thermal systems. The experimental determination of these attributes was conducted using a TEMPOS thermal properties analyzer sourced from Meter Environment, USA. The measurement of heat conduction was executed employing the transient hot-wire principle, wherein susceptible sensor needles, precisely the KS-3 TEMPOS variety, were manipulated by a dedicated controller. These sensor needles, crafted from stainless steel, exhibit dimensions of 60 mm in length and 1.3 mm in diameter. The KS-3 sensor boasts a measurement range from 0.1 to 4.0 W/m-K tailored for fluid thermal conductivity measurements, ensuring comprehensive data capture. Furthermore, the dynamic viscosity was ascertained using the Brookfield viscometer DV-III ultra, a state-of-the-art instrument from Brookfield Engineering Laboratories, Inc., MA, USA. The measurements were conducted at a fixed shear rate or shear stress, providing a nuanced understanding of the fluid's rheological behavior in the experimental context.

3 Results and discussion

3.1 Base fluid

Thermal conductivity and viscosity measurements were systematically conducted on palm oil, with heat as the variable parameter. The experimental methodology encompassed the meticulous acquisition of readings through ten trials to ensure robust reliability. The ensuing comparative analysis juxtaposed empirically determined thermal conductivity and viscosity against established reference data. These findings unequivocally substantiate the dependability and efficacy of the investigational technique for evaluating nano-enhanced fluids' thermal and physical attributes.

3.2 Visual Inspection

The evaluation of sedimentation, commonly known as visual inspection, is a widely adopted and uncomplicated methodology for appraising the dispersion stability of nanoparticles in a base fluid. This approach is frequently employed in assessing nanomaterials, as it provides a facile means of gauging their propensity to settle within a fluid medium. Visual inspection as a technique is emblematic of its practicality and prevalence in nanoparticle research, where a discerning eye can discern the nuances of sedimentation behaviors, thereby contributing valuable insights into the overall stability of nanoparticulate dispersions.

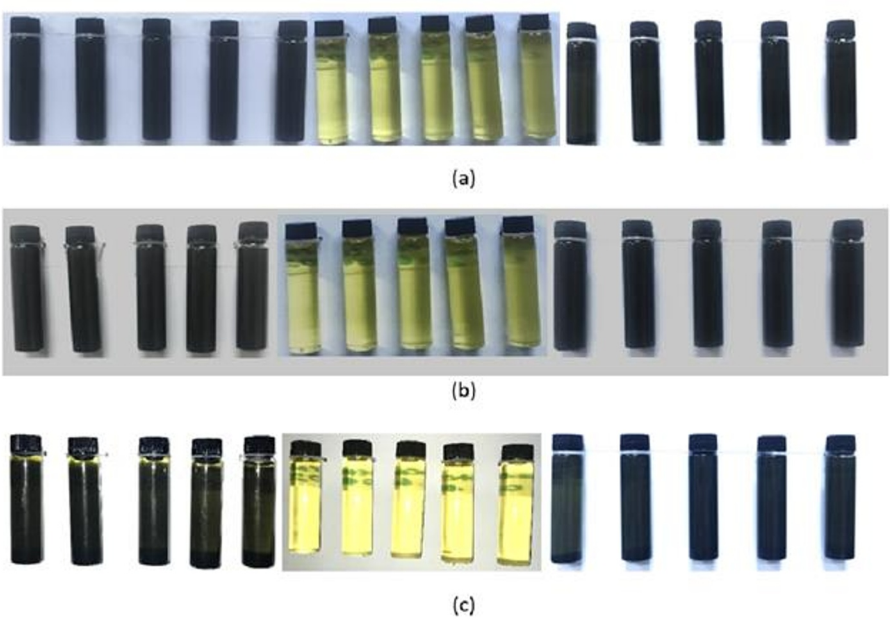


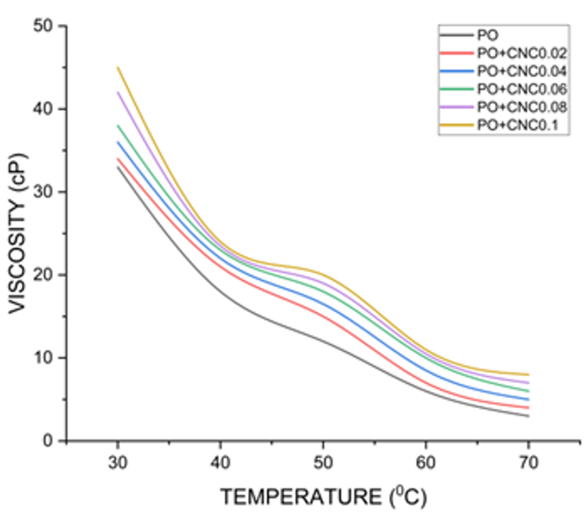
Fig. 1. Palm Oil/CNC (Cellulose Nano Crystal) nanofluid, Palm Oil/ GNP(Graphene nanoplatelets) nanofluid, Palm Oil/CNC/GNP hybrid nanofluid. (a) Day 1, (b) Day 15, (c) Day 30.

During this study, the sedimentation assessment involved capturing photographic images of the prepared nanofluid, which was stored in sealed containers under varying conditions for 30 days, with 15-day intervals between observations. Figure 1. visually illustrates the quality of nanoparticle dispersion within palm oil—notably, the diffusion of nanoparticles is moderately stable throughout the entire observation period. Nanofluids formulated with Palm oil were visually monitored without troubling the samples. The sedimentation was observed visually for 30 days; the monofluids samples showed moderate agglomeration than hybrid nanosuspensions, whereas hybrid showed very little sedimentation. Therefore, further characterization was carried out. No significant nanomaterial accumulation has been found in palm oil as a core oil with CNC/GNP nanosuspension.

3.3 Rheological examination of prepared nanofluid

In theory, fluid behavior can be classified into three categories: shear-thickening, shear-thinning, and ideal Newtonian behavior. As per Newton's Law, an ideal Newtonian fluid maintains a stable viscosity regardless of changes in shear rate, whereas non-Newtonian fluids, such as shear-thickening and shear-thinning liquids, exhibit variations in viscidness as the shear rate increases [40]. The viscosity of novel nanofluid, measured using an Ultra DV-III rheometer, consistently increased while concentration increased. Figure 2 illustrates the temperature-to-viscosity relationship. In contrast, the viscosity of pure palm oil exhibited a significant decrease when measured at elevated temperatures within the temperature range of 30 to 70 °C. Notably, the nanofluid revealed a gradual and consistent rise in viscidness when checked with the core fluid.

Nonetheless, in elevated temperatures, there remained a decrease in the nanosuspension's viscosity. Furthermore, with an increase in concentration, the nanofluid's viscosity showed a corresponding rise in comparison to the lower-concentration mixture. But at the maximum temperature, viscosity decreases in all attention, and very close readings are observed. The viscosity of nanofluid decreases at elevated temperatures due to the enhanced thermal motion and reduced viscosity of the base fluid. The increased kinetic energy at higher temperatures leads to a decrease in intermolecular forces, allowing nanoparticles to move more freely and reducing overall fluid viscosity [41].



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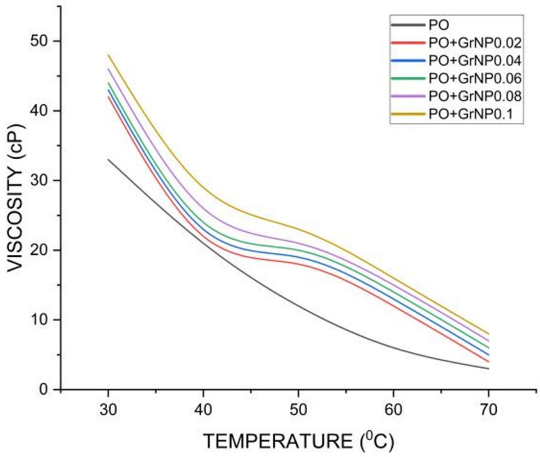

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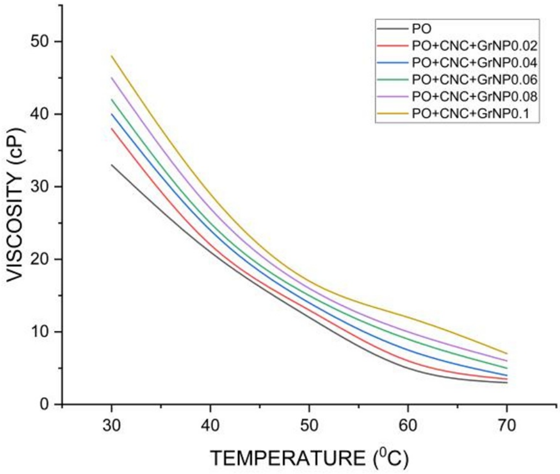

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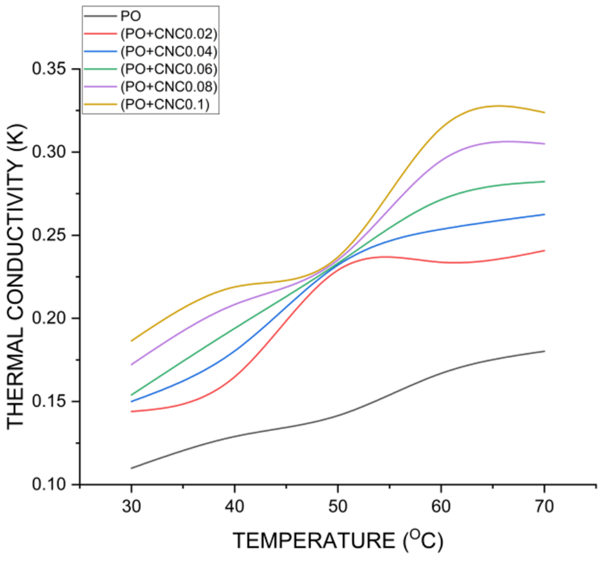
Fig. 2. Viscosity study of (a) Palm Oil/CNC (Cellulose Nano Crystal) nanofluid, (b) Palm Oil/ GNP (Graphen nanoplatelets) nanofluid, (c) Palm Oil/CNC/GNP nanofluid.

3.4 Thermal conductivity

The thermal conduction of a nano-enhanced fluid improves with an increase in volume fraction [42]. This study found the maximum heat conductivity at 0.3605 W/m-K when the volume fraction was 0.1 w/v %. This value was notably 100 % higher than the thermal conduction of pure palm oil, which measured 0.1802 at a temperature of 70 °C. Furthermore, it was observed that as the intensity of nanomaterials in the liquid increased, the heat conduction also increased.

Consequently, the nanofluid's thermal conductive ability remained enhanced compared to the base fluid. The Brownian motion that principals from the relations of solid nano-enhancers dispersed in the core fluid produces heat transport via spreading matrix by elementary excitation transmutation in an unsystematic path. This mechanism triggers a substantial heat transport enrichment if the ballistic phonons [43] induced in individual particles can endure in the core fluid and extend to nearer elements. Brownian motion results from the movement of solid particles mixed in a core fluid. It plays a crucial role in enhancing heat transfer by carrying energy through the random motion of these particles. Molecular layer development occurs at the interfaces among solid particles and the liquid-phase carrier fluids. This phenomenon facilitates thermal energy transfer from the solid particles to the base fluid.

The improvements in thermal conduction behavior of all formulated nano-enhanced fluids at a temperature range of 30-70 °C are illustrated in Figure 3 to make comparisons. The graph shows that nanofluid ought to be 0.02 w/v % CNC/GNP, which also collectively showed below-average thermal conductivity. In the meantime, the maximum thermal conductivity improvement of 100 % is attained by newly formulated nanosuspension with a concentration of 0.1 w/v % CNC/GNP nanocomposite. This notable improvement in thermal transport performance of formulated 0.10 w/v % CNC/GNP/palm oil nano suspensions remains influence by the higher percentage of CNC/GNP nanomaterials and their dispersal in the Palm oil. Each nanofluid sample is tested ten times to measure the thermal conductivity using TEMPOS with a KS 3 sensor.



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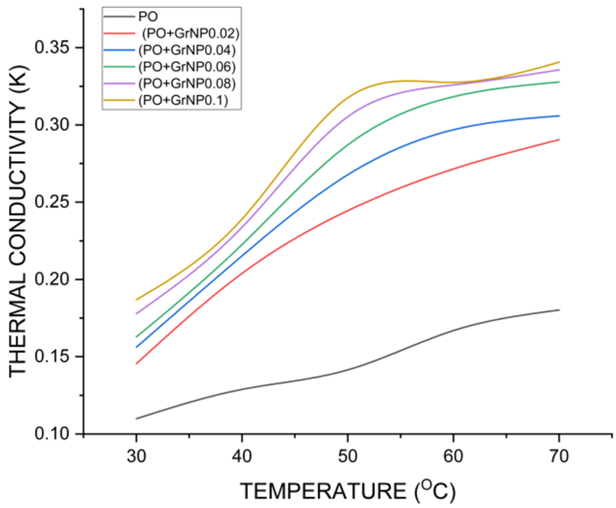

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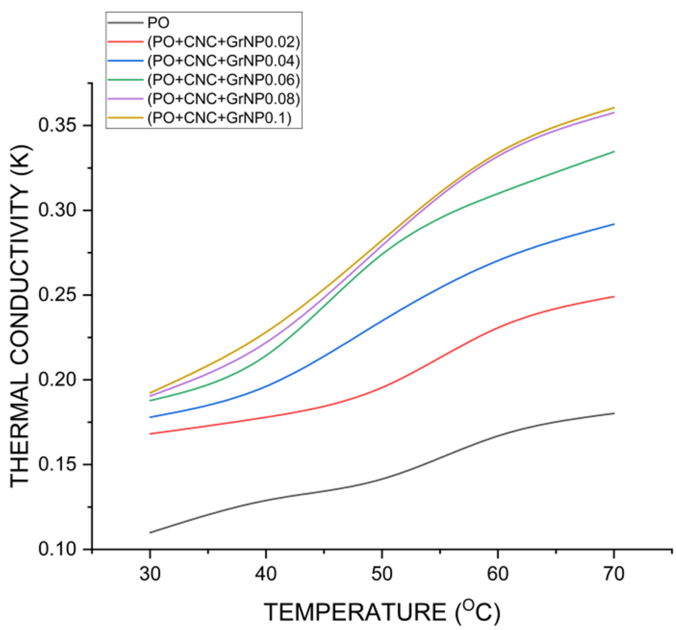

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Fig. 3. Thermal Conductivity analysis of (a) Palm Oil/CNC (Cellulose Nano Crystal) nanofluid, (b) Palm Oil/ GNP (Graphen nanoplatelets) nanofluid, (c) Palm Oil/CNC/GNP nanofluid.

The graphical representation in Figure 3 illustrates a uniform temperature distribution across different plots, forming a continuous and cohesive line. This observation underscores the general distribution of values and the appropriate positioning of standard deviations. Notably, mixtures with higher volume concentrations consistently exhibit superior thermal conductivity compared to those with lower volume concentrations of nano additives. The investigation highlights a noteworthy finding—the maximum thermal conductivity is achieved at 100%, specifically at 0.1 w/v %. This underscores the pivotal role of the thermal conductivity of the heat transfer fluid in influencing heat transfer performance. Such findings accentuate the reliability of the formulated nanofluid and its potential implications for enhancing heat transfer processes.

4 Conclusion

In conclusion, the CNC-palm oil nanofluid has demonstrated commendable dispersion stability, which is evident in the minimal sedimentation of nanoparticles during visual inspection. This characteristic underscores its suitability for practical applications, affirming its high-quality dispersion. Moreover, the GNP-palm oil nanofluid exhibits superior dispersion stability, showcasing minimal sedimentation upon visual examination. This heightened stability substantially enhances GNP-palm oil nanofluids' overall reliability and effectiveness across various applications.

Notably, the hybrid CNC/GNP-palm oil nanofluid surpasses expectations in dispersion stability, revealing minimal sedimentation during visual inspection. A noteworthy outcome of this hybrid nanofluid is the remarkable 100% increase in thermal conductivity, indicating enhanced heat transfer capabilities. Despite the concentration-dependent viscosity increase and the manifestation of non-Newtonian behavior, it is pivotal to acknowledge that, at elevated temperatures, all concentrations exhibit a uniform viscosity reduction, indicative of Newtonian behavior.

This crucial observation further underscores the potential for achieving controlled and optimized thermal performance in practical applications. It affirms the versatility and efficacy of the CNC/GNP-palm oil nanofluid, positioning it as a promising candidate for various industrial and technological applications where superior dispersion stability and enhanced thermal conductivity are paramount.

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