Exploring Surfactant-Enhanced Stability and Thermophysical Characteristics of Water-Ethylene Glycol-Based Al_2O_3-TiO_2 Hybrid Nanofluids

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Abstract: - This study presents an empirical investigation into the impact of surfactant's enhanced stability and thermophysical characteristics of water-ethylene glycol (60:40) based Al_2O_3-TiO_2 hybrid nanofluids. It aims to shed light on the nanofluid's behavior, mainly how surfactants affect its stability and thermal performance, thus contributing to advancements in heat transfer technology and engineering applications. The growing interest in nanofluids, which involves blending nanoparticles with conventional base fluids, spans diverse sectors like solar energy, heat transfer, biomedicine, and aerospace. In this study, Al_2O_3 and TiO_2 nanoparticles are evenly dispersed in a DI-water and ethylene glycol mixture using a 50:50 ratio with a 0.1 % volume concentration. Three surfactants (SDS, SDBS, and PVP) are utilized to investigate the effect of the surfactants on hybrid nanofluids. The study examines the thermophysical characteristics of these hybrid nanofluids across a temperature range of 30 to 70 ^{0}C in 20 ^{0}C intervals to understand their potential in various industrial applications. The results show the highest stability period for nanofluids with PVP compared to nanofluids with surfactant-free and other surfactants (SDS, SDBS). The thermal conductivity is slightly decreased (max 4.61%) due to PVP surfactant addition compared to other conditions. However, the nanofluids with PVP still exhibit more excellent thermal conductivity value than the base-fluid and significantly reduced viscosity (max 55%). Hence, the enhanced thermal conductivity and reduced viscosity with improved stability due to PVP addition significantly impact heat transfer performance. However, the maximum thermal conductivity was obtained for surfactant-free Al_2O_3-TiO_2/Water-EG-based hybrid nanofluids that reveal a thermal conductivity that is 17.05 % higher than the based fluid. Instead, the lower viscosity of hybrid nanofluids was obtained at 70 ^{0}C with the addition of PVP surfactant. Therefore, adding surfactants positively impacts Al_2O_3-TiO_2/Water-EG-based hybrid nanofluids with higher stability, enhancing thermal conductivity and reducing viscosity compared to the based fluids. The results show that adding surfactants at a fixed volume concentration affects thermal conductivity at low temperatures and viscosity at high temperatures, suggesting that these fluids might be used as cooling agents to increase pumping power in industrial applications.

Key-Words: - Thermal conductivity; viscosity; TiO_2; Al_2O_3; surfactant; stability; temperature; volume concentration.

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1 Introduction

Heat transfer devices play a role in our lives as their efficiency is essential for minimizing energy consumption and maintaining a compact design. The heat transfer fluid used can influence these devices' efficiency in operations, [1]. Boosting heat transfer efficiency can impact a system's performance, leading to lower operating costs and improved energy efficiency. However, traditional methods of heat transfer often face difficulties in achieving optimal heat transfer performance. The researchers introduced metals and metal oxides with heat transfer properties into the liquids to overcome the difficulties. This enabled the fluids to employ methods of heat transfer, [2]. The remarkable thermal properties of nanofluids have attracted attention as fluids for heat transfer purposes. Nanofluid consists of a base fluid such as water, ethylene glycol, and mineral oil that contains nanoparticles ranging in size from 1 to 100 nm, [3]. Because nanofluids possess improved thermal conductivity, enhanced heat convective coefficients, and increased thermal stability, they have gained significant importance in various heat transfer applications, [4]. Scientists and researchers have been conducting extensive research on nanofluids. They encountered a sheared obstacle that needed to be addressed. However, nanofluids are considered fluids that pose challenges in their synthesis, characterization, and applications. Models do not adequately describe these aspects, [5], [6]. In contrast, nanofluids have gained attention across fields. They are extensively utilized in sectors including cosmetics, [7], manufacturing [8], [9], solar energy applications [10], [11], biomedicine [12], and various heat transfer devices [13], [14]. Therefore, it has become crucial to investigate types of nanofluids to establish commercially viable nanofluid formulations. However, it is quite challenging to summarise all the research conducted on the characteristics and sensitivity of nanofluids in the introduction. Nanoparticles have caught the attention of researchers because of their size, surface area, and surface-to-volume ratio, and they exhibit enhanced thermal conductivity. Nanoparticles are made of metal and metal oxides [15], carbon nanotubes [16], and graphene-based nanofluids in the fields of heat transfer, [17]. Choosing the type of nanoparticle base fluids and their concentration is vital when preparing nanofluids with thermal properties that can be utilized in different heat transfer applications, [18]. The preparation methods significantly affect the thermal properties. Nanoparticles in suspended nanofluids tend to cluster when they are not well dispersed. This clustering phenomenon significantly influences the nanofluids' stability and performance, reducing thermal conductivity and enhanced viscosity, [1]. It is vital to maintain the thermal characteristics of the base fluid to ensure long-term stability that enables nanofluids to be consistently used in heat transfer applications. The nanoparticles can be affected by gravity even though they are tiny, which eventually causes the nanoparticle to settle and cluster. In a study conducted using ZnO nanofluids based on water-ED, a heat transfer enhancement of 9.8 % was achieved at a volume concentration of 1.5 %, [19]. However, this improvement came with the weakness of increased pressure drop. The exergetic and energetic efficiencies can also be boosted with the rising weight and mass fraction of MWCNT while analyzing the exergy and energy of solar collectors using nanofluid, [20]. In another study, a quantum dot nanofluid was prepared to explore a customized electronic system's cooling capability when graphene-silver quantum dots were synthesized using silver nitrate and citric acid, [21]. The prepared 1200 ppm nanofluid revealed excellent stability in terms of higher zeta potential value (-49 mV), maintaining a neutral pH value while the thermal conductivity improved significantly (46%). Besides, electronic system temperature declined by applying nanofluid, increasing nanofluid's Reynolds number and volume concentration. The results also concluded that compared to improved convective heat transfer capability, the pumping power needed for the nanofluid does not result in a substantial penalty (<5.12%). The study unveiled the highest 13% heat transfer along with 8% pressure drop enhancement while investigating the efficiency of graphene nanofluids in microchannel heat transfer devices, [22].

Nanofluids are relatively innovative in cooling mediums and frequently demonstrate improved cooling and lubrication properties compared to traditional coolants. Nevertheless, in the base fluid, nanoparticles are prone to agglomeration driven by Brownian motion and van der Waals forces. This agglomeration results in clusters that can settle and adversely affect performance. Therefore, it is crucial to adopt effective strategies to improve the dispersion stability of nanofluids significantly, thereby maintaining their optimal functionality, [23]. The surfactants are essential components, particularly in uses involving sustainable machining coolants, improving heat transfer, and vehicle cooling systems. Nanofluid stability and efficiency are of the most tremendous significance for these uses. While several studies have been performed on nanofluid properties, such as thermal conductivity, viscosity, stability, and heat transfer capacity, the effects of various surfactants used during synthesis have yet to be explored. Usually, various kinds of dispersants or surfactants are used to achieve homogeneity of nanofluids, which is the most crucial challenge in the study of nanofluids, [24]. For example, while preparing a stable nanofluid, treated TiO_2 particles with CTAB and SDS and finally found stability for over two weeks, [25]. The research also revealed an enhancement of 15% and 10% in thermal conductivity at a volume concentration of 1.25%. After sufficient sonication with SDS surfactant addition, Al_2O_3/distilled water nanofluid behaved as a homogeneous nanofluid with nearly 30 mV zeta potential value, [26]. Another study suggested using [BMIM] PF6 ionic liquid to prepare a stable Al_2O_3 nanofluid, [27]. However, the effect of various kinds of dispersants or surfactants on nanofluids, a crucial issue, is discussed in a limited number of scientific studies. However, there is a lack of research investigating the impacts of surfactants on the thermal conductivity, viscosity, and stability of TiO_2-Al_2O_3 hybrid nanofluids based on 60: 40 Water-EG. Hence, the present research focuses on the impacts of various surfactants on the stability and thermophysical properties of TiO_2-Al_2O_3 hybrid nanofluid. Besides, the sensitivity analysis of thermophysical properties is also discussed in this study. This is an extension of our previous research where the reason for choosing TiO_2 and Al_2O_3 nanoparticles is mentioned due to their excellent properties, [28]. Following the previous study, one scientific report is published on the thermophysical properties of the 80:20 ratio of TiO_2-Al_2O_3 hybrid nanofluids, [19]. Therefore, this study chooses a 50:50 ratio of TiO_2-Al_2O_3 nanoparticles as it is proved that an increasing percentage of Al_2O_3 nanoparticles enhances thermal conductivity with the formidable challenge of achieving stability. So, the present study is about accepting the stability challenge of applying surfactants, analyzing the effects of surfactants on stability and thermal properties, and exploring the sensitivity of thermal properties.

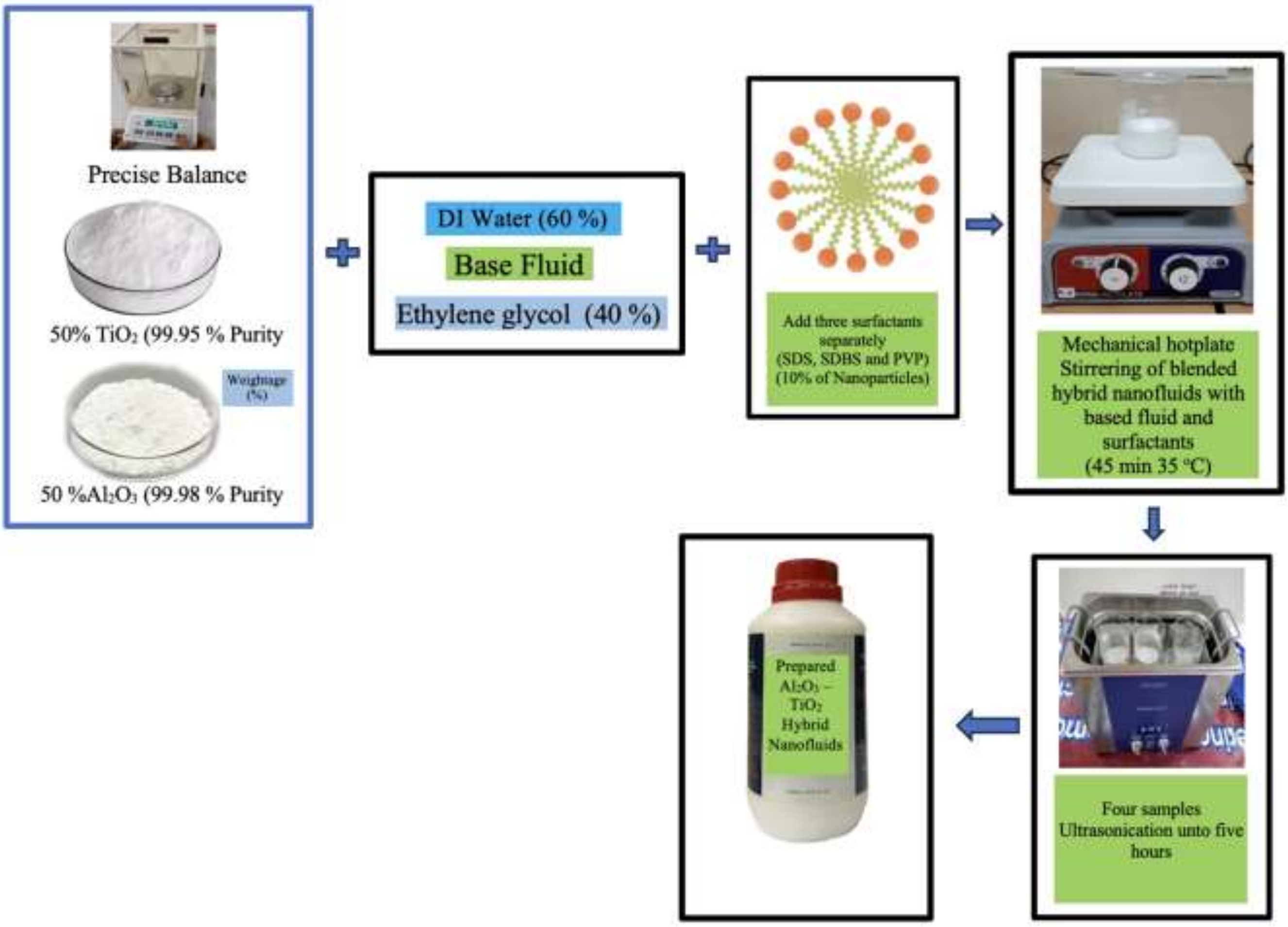


Fig. 1: A two-step technique employed to prepare the hybrid nanofluids utilizing the chosen based fluid and nanoparticles

2 Materials and Methods

2.1 Preparation of Hybrid Nanofluids and Their Stability

Table 1 presents the thermophysical properties of selected base fluids, including DI-water and ethylene glycol, alongside nanoparticles such as Al_2O_3 and TiO_2. This research utilizes the widely recognized two-step synthesis technique for preparing Al_2O_3- TiO_2 hybrid nanofluids in water-ethylene glycol as the base fluid. Figure 1 illustrates a two-step technique to prepare the hybrid nanofluids utilizing the chosen based fluid and nanoparticles. Utilizing individual beakers, the Al_2O_3 and TiO_2 nanoparticles mixed in a 50:50 proportion were blended with the base fluid (DI-water and EG) at a weighting ratio of (60:40) and three different surfactants. Eq. (1) was utilized to calculate the volume concentration of the nanoparticles. Four hybrid nanofluids samples were synthesized with a 0.1 % volume concentration of the nanofluids. These surfactants were polyvinylpyrrolidone (PVP), sodium dodecyl sulfonate (SDBS), and sodium dodecyl sulfate (SDS). Information on a selection of surfactants is presented in Table 2.

Table 1. Thermal properties of base fluids (DI Water and ethylene glycol) and nanoparticles (Al_2O_3 and TiO_2)

Description	DI Water (volume %)	Ethylene glycol (volume %)	Nanoparticles in weightage %	
			Al2O3	TiO2
Proposition ratio	60	40	50	50
Colour	-	-	White	White
Average particle size	-	-	> 30 nm	5-10 nm
Molecular mass (g.mol^{-1})	18.02	62.07	101.96	79.86
Thermal conductivity (W.m^{-1}.K^{-1})	0.60	0.22	40	8.40
Density (kg.m^{-3})	998.21	1113.20	4000	4230

Table 2. Surfactants used in this study

Surfactants	Abbreviation	Chemical formula	Purity (%)
Sodium Dodecyl Sulfate	SDS	$CH_3(CH_2)_{11}OSO_3Na$	> 99 %
Sodium dodecyl benzene sulfonate	SDBS	$CH_3(CH_2)_{11}C_6H_4SO_3Na$	>99.93 %
Polyvinylpyrrolidone	PVP	$C_6H_9NO)_n$	-

The SDS, SDBS, and PVP surfactants were individually synthesized at volume concentrations of 10% for each of these three samples. The fourth sample was prepared uniquely and did not include any surfactant to provide a surfactant-free variant for comparison analysis. To begin, we first used nanoparticle-based liquids with surfactants. Afterwards, we used a hotplate stirrer to stir the mixture for 45 minutes at 35 ^{0}C. The duration of sonification noticeably impacted the stability of the nanofluids. The increase of stability of nanofluids with increasing sonication time while decreasing has a reverse force effect. The sonication time also affects the viscosity of the nanofluids due to breaking the larger particles. It reduces the viscosity and lowers the flow resistance, [1]. Therefore, the optimum sonification time is necessary for good stability. In this study, samples were ultrasonicated for five hours at a temperature that ranged from 30 to 70 degrees Celsius. The transmission electron micrographs (TEM) are used to determine the dimensions and shapes of the nanoparticles. TEM images revealed that the typical diameters of TiO_2 and Al_2O_3 are between 5 and 10 nanometers and between 20 and 30 nanometers, respectively. The TiO_2 particles have a spherical shape in their appearance. However, the micrographs of Al_2O_3 nanoparticles do not contain any varieties that have been specifically identified.

$$Volume\ Concentration\ (\varphi) = \frac{\left(\frac{m_{Al_2O_3}}{\rho_{Al_2O_3}}\right)+\left(\frac{m_{TiO_2}}{\rho_{TiO_2}}\right)}{\left(\frac{m_{Al_2O_3}}{\rho_{Al_2O_3}}\right)+\left(\frac{m_{TiO_2}}{\rho_{TiO_2}}\right)+\left(\frac{m_{Water}}{\rho_{Water}}\right)+\left(\frac{m_{EG}}{\rho_{EG}}\right)} \times 100\ \% \qquad (1)$$

where m and ρ represent the mass and density of nanoparticles and base fluid.

The repulsive force that prevents nanoparticles from settling in suspension is known as stability, [28]. This study follows the most straightforward quantitative technique of the zeta potential test to depict the stability of samples. Several previous investigations also applied this method to state fluid homogeneity, [29]. Finally, the visual inspection also confirms the uniformity of nanofluids.

2.2 Thermophysical Properties Measurement

Understanding the properties of nanofluids requires consideration of the thermal conductivity and viscosity of the hybrid nanofluids. These factors impact the pumping power of the system, making them incredibly important. The research examines the thermal conductivity and viscosity are essential properties of Al_2O_3 and TiO_2 hybrid nanofluids. The KD2 Pro analyzer is equipped with a temperature-controlled water bath to analyze thermal conductivity. The method it employs involves using a heat source and interchangeable sensors to measure thermal properties such as thermal conductivity. The KD2 Pro utilizes an approach to identify the heat source for either single or dual-needles. The KD2 Pro analyzer sensor, which is thin and needle-shaped, is inserted vertically into the sample without making contact with the container walls. It ensures that the sample remains undisturbed while measurements are taken. Three different temperatures, 30, 50, and 70 degrees, are being examined to assess their properties. Ten readings are collected for each sample and temperature, with a 15-minute delay between each reading, and the average results are finally considered during the procedure.

The viscosity measurement was conducted using the Brookfield LVDV III Ultra Rheometer equipped with an oil bath. Its purpose is to analyze the properties of the viscosity of the fluids. The LVDV III Ultra employs a shaft powered by a motor and connected to a calibrated spiral spring. The motor's drive shaft powers a spindle immersed in the tested fluid. We measured the resistance of the flow movement by observing the increasing torque values. When the LVDV III Ultra motor rotates, we measured the fluid's ability to resist movement by monitoring the increasing torque values. The experiments included the viscosity changes at 30 to 70 ^{0}C with 20 ^{0}C intervals using a designed Rheocal Program. Similarly, we gathered ten readings for each sample and temperature, keeping a consistent time interval of 15 minutes. The final dataset is then determined by calculating the average values obtained from these readings.

3 Results and Discussion

3.1 Stability Analysis of Hybrid Nanofluids

One way to determine the consistency of the colloidal mixture is by the zeta potential method. This indicates the repulsive force between the suspension mixture and the stationary fluid layer when the nanoparticles are present. The zeta potential absolute value can provide insight into the stability of the hybrid nanofluids. However, it is essential to note that this approach has limitations when dealing with highly viscous fluids, [30]. However, the colloidal suspension with a zeta potential absolute value of 15 mV exhibits minimum stability. On the other hand, when the zeta potential absolute value reaches 30 mV, 45 mV, and 60 mV, it demonstrates good, very good, and excellent stability, respectively, [26]. Table 3 presents the zeta potential absolute value changes for hybrid nanofluids at a 0.1 % volume concentration with and without surfactants. According to the information presented in Table 3, it can be observed that the sample without surfactant exhibited a level of moderate stability (28 mV). However, the PVP surfactant sample demonstrated good stability, as indicated by the highest zeta potential absolute value of 39.8 mV. The samples with SDS and SDBS surfactant represented minimal stability. Hybrid nanofluid samples containing PVP exhibit fluctuations in zeta potential values because changes in solution modify the surface charge density [2]. Visual inspection was also employed in this study to conclude the stability period of the samples. The visual inspection results presented that the samples with SDS and SDBS surfactants started to sediment after 2-3 hours, and the sample with SDS also created some foam during sonication. However, the sample without surfactant showed the beginning of nanoparticle sedimentation after three days, while the sample with PVP showed uniformity until eight days. Hence, the sample with PVP stars showed little apparent sedimentation around one week. Finally, the study concluded that the sample without any dispersant and with PVP dispersant had uniformity until 3 and 8 days, respectively. Hence, these two samples are considered for thermophysical properties analysis. In contrast, the samples with SDS and SDBS did not undergo properties analysis because of minimal stability for a few hours.

Table 3. Zeta potential absolute value of Al_2O_3-TiO_2 (50:50) hybrid nanofluids

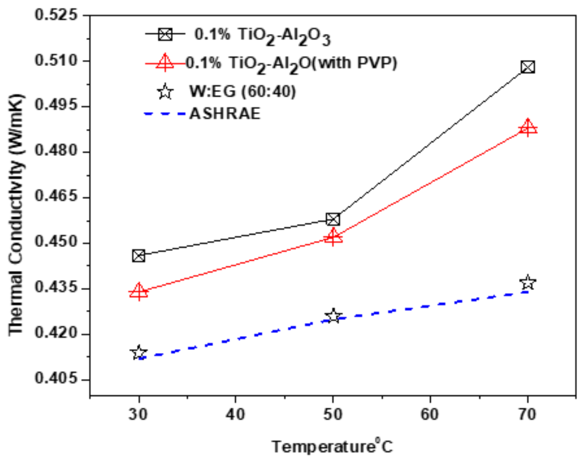
Samples (0.1% Volume concentration)	**Value of Zeta Potential (±mV)**
0.1% Al_2O_3-TiO_2 (Without surfactant)	Moderate stability (28 mV)
0.1% Al_2O_3-TiO_2 (SDS)	Slight stability (16 mV)
0.1% Al_2O_3-TiO_2 (SDBS)	Slight stability (22 mV)
0.1% Al_2O_3-TiO_2 (PVP)	Good stability (39.8mV)

3.2 Thermophysical Properties Behaviour

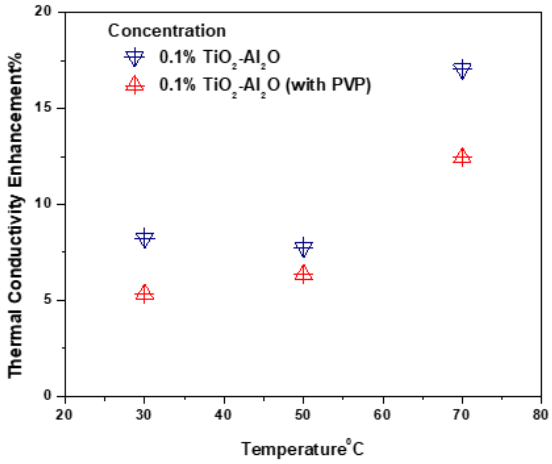
It is crucial to analyze the various factors and their effects to understand the thermal conductivity of hybrid nanofluids. It enhances thermal conductivity in industrial applications, and there is a need for minor changes. We utilized the KD2 Pro Analyzer to perform experiments on hybrid nanofluids containing water-EG and Al_2O_3-TiO_2 and to investigate their thermal conductivity. These studies aimed to evaluate the impact of adding surfactants and temperature variation in hybrid nanofluids. The thermal conductivity is evaluated for two samples of Al_2O_3 -TiO_2 (without surfactant, with 0.01% PVP) at three different temperatures, as the other two samples (with SDS and SDBS) showed limited stability or instability. Figure 2 demonstrates the intricate interplay between temperature and the percentage enhancement of thermal conductivity for Al_2O_3-TiO_2 hybrid nanofluids, providing valuable insights into their complex thermal behavior. Based on the information in Figure 2(a), the thermal conductivity of samples with and without surfactants surpasses that of the base fluid (water; EG) as the ASHRAE reference value. A noticeable increase in the thermal conductivity of tested hybrid nanofluids as temperature rises. The noticeable increase in thermal conductivity is mainly attributed to the interaction between protons and the interface between solid and liquid walls as nanoparticles' unpredictable movement within the uniformly dispersed hybrid nanofluid, [31]. Two factors contribute to the increase in thermal conductivity. The first factor is the nanoparticles' random motion, which leads to collisions. The second factor is the composition of the nanoparticles and the type of surfactants employed. In addition, the increasing kinetic energy of the nanoparticles and the repetitive collisions of the nanoparticles with the increasing temperature are additional factors that contribute to improving thermal conductivity, [31], [32]. The highest thermal conductivity is achieved for the sample without surfactant at 70 °C, while the lowest value is revealed for the sample with PVP at 30 °C. From the result, it is also clear that adding nanoparticles significantly improves thermal conductivity. However, the thermal conductivity slightly decreases due to surfactant addition, showing noticeable enhancement to base fluid. The thermal conductivity enhancement is expressed in Eq. (2).

$$\text{Thermal Conductivity Enhancement } (\%) = \left(\frac{TC_{nf}}{TC_{bf}} - 1\right) \times 100\ \% \qquad (2)$$

The thermal conductivity of nanofluid was assessed with and without surfactant, as well as with 0.1 % of the volume concentration of nanoparticles. Figure 2(b) illustrates the percentage of improvement observed in samples without surfactant and those that included PVP surfactant when subjected to different temperatures. A maximum of 17.05% enhancement of thermal conductivity is observed for the sample without surfactant at 70 °C, while a minimum of 5.33% enhancement is derived for the Al_2O_3-TiO_2 with PVP at 30 °C. In addition, the thermal conductivity is reduced by 2.92%, 1.41%, and 4.61% at 30 °C, 50 °C, and 70 °C, respectively, due to PVP addition compared to the Al_2O_3-TiO_2 hybrid nanofluid without surfactant. The increasing specific surface area that results from the mixing of nanoparticles is a factor that contributes to the enhancement of thermal interactions inside the hybrid nanofluids. It is accomplished by Brownian motion and the agglomeration of particles, [33]. Additionally, PVP surfactant enhances the synthesized fluid's stability, prevents particle agglomeration and sedimentation, and demonstrates a more excellent Brownian motion and thermo-migration effect, ultimately improving the synthesized fluid's thermal conductivity.



(a) Thermal conductivity versus temperature



(b) Thermal conductivity enhancement (%)

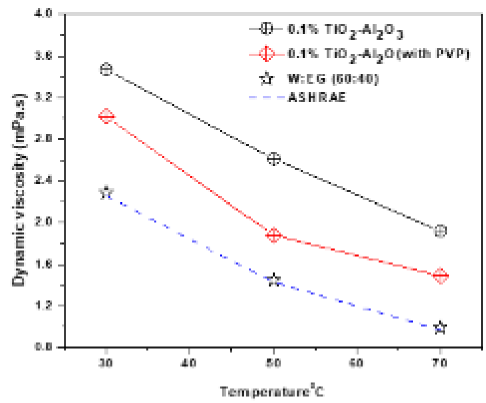
Fig. 2: The thermal conductivity trends exhibited by 0.1% Al_2O_3 -TiO_2 (50:50) hybrid nanofluids

3.3 Viscosity Analysis of Hybrid Nanofluids

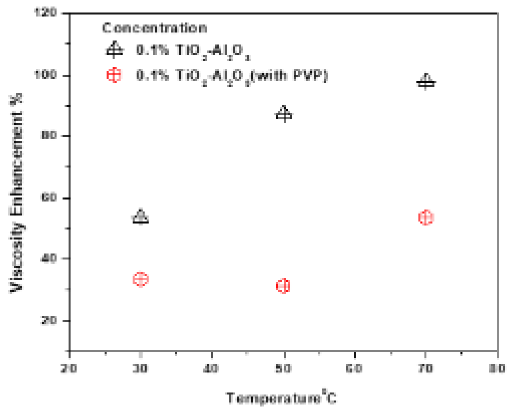
Viscosity was measured for the samples without surfactant and with PVP for 30 °C, 50 °C, and 70 °C. Figure 3(a) represents the samples' viscosity values for various temperatures. Figure 3(a) reveals that the viscosity of both samples is higher than the viscosity of the base fluid (W: EG). The viscosity of the sample without surfactant is comparatively higher than that of PVP surfactant. For both samples of Al_2O_3 -TiO_2, the viscosity decreases with increasing temperature due to the higher movement of nanoparticles into the medium at a higher temperature which retards the sedimentation of particles. This is because the attraction interactions between the nanoparticles are reduced, resulting in wider gaps between the molecules in the fluid, [2]. As a consequence of this,

The nanofluid undergoes a decrease in resistance to the fluid flow, decreasing its viscosity. Furthermore, the fluid molecules increase energy when the temperature rises. This increased energy enables them to overcome the forces within the nanofluid medium, resulting in a decrease in viscosity [32]. Figure 3(b) shows the enhancement percentage of viscosity of the hybrid nanofluid against temperature, which can be derived using Eq. (3).

$$Enhancement\ of\ Viscosity = \left(\frac{\mu_{nf}}{\mu_{bf}} - 1\right) \times 100\ \% \qquad (3)$$



(a) Viscosity versus temperature



(b) Viscosity enhancement (%)

Fig. 3: The viscosity variation of 0.1% Al_2O_3-TiO_2 (50:50) hybrid nanofluids

Al_2O_3 -TiO_2 hybrid nanofluid without surfactant presented the highest viscosity enhancement at 70 °C by 97.93%, while the lowest enhancement by 33.62% was found for the sample with PVP surfactant at 30 °C. The enhancement rate with temperature for the sample without surfactant is steeper than that with PVP. Adding PVP surfactant significantly reduces the sample's viscosity by 19.91 %, 55.95 % and 44.33 % at 30 ^{0}C, 50 ^{0}C and 70 ^{0}C, respectively, compared to the sample without surfactant. Hence, it can be concluded that the sample with PVP has comparatively significantly lower viscosity with improved thermal conductivity and stability, which can potentially affect various heat transfer applications. The nanoparticles start moving randomly and dispersing throughout the fluids when the temperature increases. In addition, the nanofluid's molecular activity becomes stronger, making the molecules more distinct from one another as the temperature increases, [33], [34]. Consequently, the interactions between the nanoparticles and the molecules in the base fluids are expected to weaken, potentially reducing the fluid's viscosity.

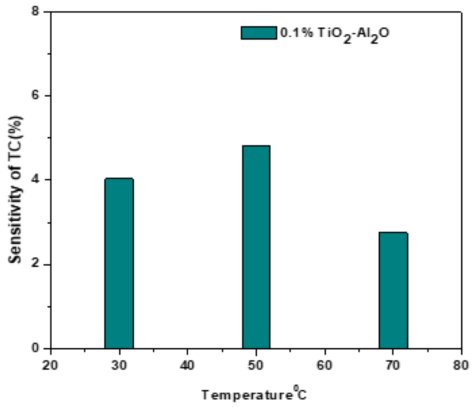
3.4 Sensitivity Analysis

Conducting a sensitivity analysis on nanofluids to design energy systems helps gain insights into the primary parameters' contributions to thermal conductivity. We added a 10% proportion of surfactants with a nanoparticle mixture (based on the nanoparticle content) to the nanofluid to study how the thermal conductivity and viscosity of Al_2O_3-TiO_2-based hybrid nanofluids are affected when adding the different surfactants at various temperatures. Afterwards, we measured the thermal conductivity and viscosity values, covering a range of selected temperatures using the methods described in the methodology section. Equations (4-5) are used to evaluate the sensitivity of thermal conductivity and viscosity of the hybrid fluids, respectively.

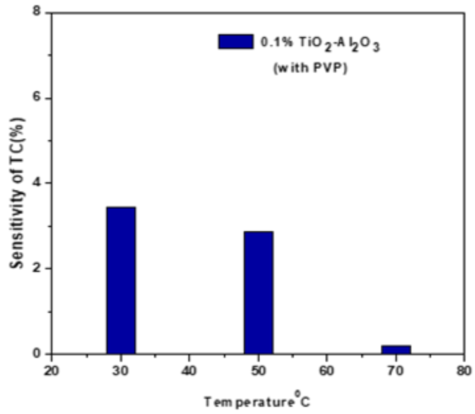
$$\text{Sensitivity of Thermal Conductivity (\%)} = \left(\frac{K_{nf\,(After\ Change)}}{K_{nf\,(Before\ Change)}} - 1\right) \times 100\ \% \qquad (4)$$

$$\text{Sensitivity of Viscosity (\%)} = \left(\frac{\mu_{nf\,(After\ Change)}}{\mu_{nf\,(Before\ Change)}} - 1\right) \times 100\ \% \qquad (5)$$

Figure 4 and Figure 5 comprehensively portray the sensitivity analysis for thermal conductivity and viscosity, showcasing the impact of volume fraction variations across different temperature ranges. Figure 4 illustrates the diminishing thermal conductivity sensitivity with volume concentration as temperatures increase for both samples. According to the findings of the sensitivity analysis, the hybrid nanofluid that did not contain the surfactant exhibited the highest sensitivity at a temperature of 50 ^{0}C and a volume fraction of 0.1 %. However, the hybrid nanofluid containing 0.1 % volume concentration and a PVP surfactant exhibited significant sensitivity regarding thermal conductivity at a temperature of 30 ^{0}C. This implies that after introducing a specific quantity of nanoparticles into the nanofluid suspension, the thermal conductivity exhibits reduced efficiency at higher temperatures in contrast to lower temperatures.



(a) Sensitivity analysis for 0.1% Al_2O_3-TiO_2 (without surfactant)



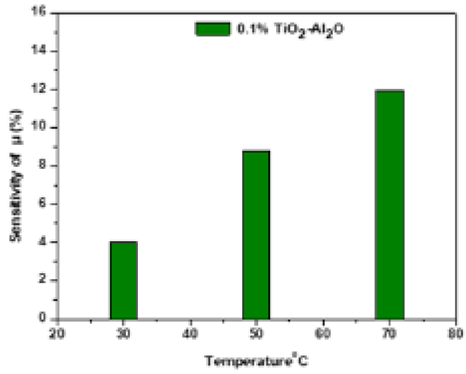
(b) Sensitivity analysis for 0.1% Al_2O_3-TiO_2 (with PVP surfactant)

Fig. 4: Sensitivity analysis of thermal conductivity versus temperature for Al_2O_3-TiO_2 (50:50) hybrid nanofluids

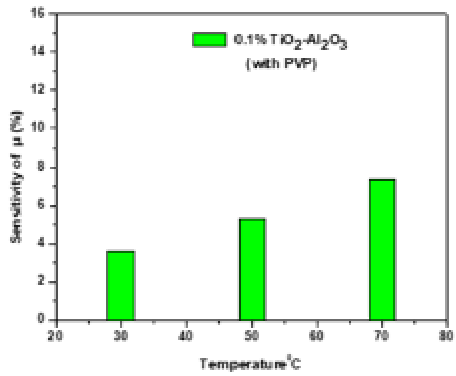
According to the findings in Figure 5, the viscosity of the hybrid nanofluid, both with and without the surfactant, exhibited the maximum level of sensitivity at a temperature of 70 degrees Celsius and a volume concentration of 0.1 %. On the contrary, in case the sensitivity of viscosity of TiO_2-Al_2O_3 hybrid nanofluid to the volume concentration increases with rising temperature, and the increasing rate of sensitivity is comparatively higher for the sample without surfactant, which means the sample with PVP shows less viscosity even after adding a meaningful amount of nanoparticles into the nanofluid. This feature can help design a heat transfer system. The strategic integration of surfactants, such as PVP, into Al_2O_3-TiO_2 hybrid nanofluids marks a significant advancement in optimizing their viscosity and thermal conductivity for superior heat transfer applications. This approach strikingly balances reduced viscosity with sustained thermal efficiency, highlighting the transformative potential of these nanofluids in advancing heat transfer technologies. Ongoing research in this domain is imperative to unlock the full spectrum of nanofluids' capabilities in industrial settings.

$$Sensitivity\ of\ Thermal\ Conductivity\ (\%) = \left(\frac{K_{nf_{(After\ Change)}}}{K_{nf_{(Before\ Change)}}} - 1\right) \times 100\ \% \quad (4)$$

$$Sensitivity\ of\ Viscosity\ (\%) = \left(\frac{\mu_{nf_{(After\ Change)}}}{\mu_{nf_{(Before\ Change)}}} - 1\right) \times 100\ \% \quad (5)$$



(a) Sensitivity analysis for 0.1% Al_2O_3-TiO_2 (without surfactant)



(b) Sensitivity analysis for 0.1% Al_2O_3-TiO_2 (with PVP)

Fig. 5: Sensitivity analysis of viscosity versus temperature for Al_2O_3-TiO_2 (50:50) hybrid nanofluids.

4 Conclusions

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The present study has successfully synthesized water-EG-based Al_2O_3-TiO_2 (50:50) hybrid nanofluid employing the most widely recommended two-step technique. This study investigates hybrid nanofluids' stability and thermophysical properties with various temperature ranges. It has also explored the impact of three distinct surfactants on these properties, including SDS, SDBS, and PVP. The sensitivity of thermophysical properties to the volume concentration at various temperatures was evaluated. The findings of this study are detailed as follows:

i) The Al_2O_3-TiO_2 hybrid nanofluid, in the absence of any surfactant, demonstrated moderate stability, as indicated by a zeta potential value of 28 mV. Conversely, including PVP significantly enhanced stability, evidenced by a notable zeta potential of 39.8 mV. Samples with SDS and SDBS exhibited only marginal stability improvements. The surfactant-free and PVP-enhanced samples maintained stability for three days, while those with SDS and SDBS remained stable for merely a few hours.
ii) The surfactant-free Al_2O_3-TiO_2 nanofluid exhibited superior thermal behavior compared to its PVP-containing counterpart. However, the PVP-infused sample demonstrated a significant increase in thermal conductivity relative to the base fluid, with the highest enhancement (17.05%) observed at 70 °C.
iii) An inverse relationship was observed between viscosity and temperature. The surfactant-free sample exhibited a notably higher viscosity compared to the PVP-treated sample. The most pronounced increase in viscosity (97.93%) was recorded at 70 °C for the surfactant-free sample. Notably, applying PVP resulted in a substantial viscosity reduction, with a maximum decrease of 55.95% at 50 °C compared to the surfactant-free sample. This marked viscosity reduction and improved thermal conductivity are anticipated to influence heat transfer applications significantly. The behavior of the nanofluid at elevated temperatures offers a promising avenue for future exploration.
iv) The study uncovered that thermal conductivity is more responsive at lower temperatures, while viscosity exhibits greater sensitivity at higher temperatures, particularly when adjusting the nanoparticle concentration.

The ramifications of these findings are extensive, especially in machining and automotive cooling. Al_2O_3-TiO_2 hybrid nanofluids are revolutionizing these sectors by enhancing heat dissipation and improving tool life and precision in machining operations. In automotive contexts, these nanofluids surpass traditional coolants in efficiently cooling engines, which is crucial for high-performance vehicles. This leads to optimal engine temperature regulation, heightened fuel efficiency, diminished wear and tear, and prolonged component longevity, fostering sustainable automotive technologies. In summary, the Al_2O_3-TiO_2 hybrid nanofluids developed in this study exhibit significant promise for elevating heat transfer efficiency in various industrial applications, heralding a new era of more sustainable and effective cooling solutions.

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NOMENCLATURE

Al_2O_3	Aluminium oxide
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CTAB	Cetyl trimethylammonium bromide
E.G.	Ethylene glycol
TiO_2	Titanium oxide
MWCNT	Multiwalled carbon nanotube
PVP	Polyvinylpyrrolidone
SDS	Sodium dodecyl sulfate
SDBS	Sodium dodecyl benzene sulfonate
TC[W/mK]	Thermal conductivity
ZnO	Zinc oxide
M [gm]	Mass

Subscripts

np	Nanoparticles
nf	Nanofluid
bf	Base fluid

Greek Symbols

ρ [Kg/m^3]	Density
ø	Volume concentration (%)

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