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Enhancing Thermal Conductivity of Water-Ethylene Glycol Mixtures: A Study on TiO_2-Al_2O_3 Hybrid Nanofluids with Surfactants

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ABSTRACT

This analysis examines the thermal behaviour of 40% ethylene glycol-based TiO_2-Al_2O_3 hybrid nanofluids by synthesizing them and assessing their thermal conductivity as a function of volume concentration and temperature. These hybrid nanofluids, emerging as a promising new class of advanced operating fluids, offer remarkable potential for enhancing heat transfer performance in various thermal engineering applications. Using a two-stage synthesis method, TiO_2-Al_2O_3/40% ethylene glycol nanofluids were prepared across five distinct volume focuses (varying from 0.02% to 0.1%), incorporating Polyvinylpyrrolidone (PVP) as a stabilizing emulsifier. Precise thermal conductivity measurements were conducted over 30 °C to 80 °C, with incremental steps of 10 °C, ensuring comprehensive data collection. The investigation yielded significant findings, notably a substantial maximum thermal conductivity enhancement of 37.44%, observed at 80 °C with a 0.1% volume concentration, demonstrating pronounced sensitivity to elevated temperatures and concentrations. The strategic addition of PVP surfactant resulted in a remarkable 125% improvement in the nanofluid's stability period, although a maximum 5.33% reduction in thermal conductivity. Considering the inadequacy of existing predictive models to capture the observed data accurately, this study proposed developing a high-precision predictive model, achieving an impressive maximum deviation of less than 3%. The research concludes that these hybrid nanofluids, characterized by their exceptional stability and significantly enhanced thermal conductivity, hold immense potential to revolutionize heat transfer applications across various domains of practical thermal engineering. This breakthrough paves the way for developing more efficient, high-performance heat transfer systems, potentially catalysing energy efficiency and thermal management advancements across diverse industrial sectors.

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1. Introduction

Nanofluids, an innovative class of engineering materials, consist of base fluids enhanced with nanometre-sized additives. Pioneered initially by Maxwell [1], who reported enhanced thermal conductivity in such fluids, nanofluids have gained significant attention for their potential to improve thermal characteristics and facilitate heat conversion [2]. Nanofluids promise to enhance heat transfer, but no clear understanding of their formulation and behaviour exists. Dilute nanoparticle suspensions can also exhibit exceptionally improved thermal properties with extensive applications [3]. Specifically, we showcase tuneable conduction properties deploying nanofluids, which have a vital assemblage of products extending from manufacturing to nuclear power facilities and transportation or electronics/medicine/food processing. Much research continues to secure nanofluids' fluid dynamics to enable customized utilization across utilities. However, most nanofluids minorly enhance specific heat capacity and fluid conductivity even with trace amounts of metal or carbon-based nanoparticle inclusions. These are sufficient to elevate a base fluid to reactive coolant status—and allow for tailoring performance characteristics. Recent studies have further confirmed their remarkable heat transfer capabilities, with Wang *et al.,* [4] reporting up to 27% enhancement in thermal conductivity of TiO_2 nanofluids under magnetic fields. However, their behaviour often deviates substantially from predictions based on conventional macroscopic theories, highlighting the urgent need for new theoretical frameworks. While nanofluids offer promising applications in heat transfer, they also present challenges such as erosion, clogging and sedimentation in flow paths. The stability of nanofluids depends on the balance between Brownian motion and gravitational settling, which is primarily influenced by particle size [5,6]. A new insight into nanoparticle aggregation dynamics using in-situ synchrotron X-ray scattering, offering potential solutions to stability issues. The primary challenge in nanofluid research is understanding heat propagation at atomic and microscale levels. This comprehension is crucial for fully harnessing the potential of nanofluids as advanced heat transfer fluids and for developing accurate theoretical models that can account for their unique properties. Although efforts have been made to theoretically explore potential heat transfer mechanisms [7], recent advancements in molecular dynamics have shed new light on the mechanisms of thermal conductivity enhancement in graphene-based nanofluids [8,9]. Bridging the gap between observed behaviour and theoretical predictions, particularly at the microscale level, remains a crucial objective for unlocking the full potential of these emerging engineering materials [9]. Recent applications, such as using hybrid Al_2O_3-Cu nanofluids in data centre cooling, demonstrating a 17% reduction in energy consumption, highlight the practical impact of ongoing nanofluid research [10].

Improving heat transfer appropriation in the applicable field of thermal engineering is a severe issue because traditional conventional heat removal fluids such as water propylene glycol, ethylene glycol or other oils are structurally restrained due to physical defects [11]. Nanotechnologies are to offer a possible solution in terms of heat transfer beyond the limit related to typical working fluids. At the same time, as advances have been made concerning nanomaterial construction, an interest has developed in how these can be used for dispersal within base oils, which function as coolant carriers. These new classes are called nanofluids and simply refer to engineered colloidal suspensions consisting of nanoparticles, nanopowders or nanotubes suspended in a commercial fluid; this formulation may have considerably improved both conductive as well convective thermal properties when compared with conventional coolants that were possible only by other approaches like the addition doping methods within customary matrices [12]. These temperature-dependent properties follow the nanostructured materials used in most cases. They can be categorized as nanofluids, which are a type of colloidal suspension consisting of solid particles suspended in base fluids with typical sizes ranging from 1–100 nm, significantly influencing thermos-physical properties for uncertainties associated with those found in traditional-liquids-based fluid applications [13]. Because adding nanoparticles with more excellent thermal conductivity into conventional fluid improves the thermal behaviour of fluids [14], this attractive feature has drawn the attention of recent researchers to explore new working fluids with enhanced thermal properties. Among various properties of nanofluids, thermal conductivity and viscosity are more significant.

Several researchers [15-17] examined the effects of various kinds of nanoparticles on different traditional fluids on thermophysical properties. The property of viscosity has a significant influence on energy consumption and pumping power [18]. Most studies reported that viscosity increases with the growing volume fraction of nanoparticles and declines with rising temperature [19]. Moreover, the fraction of solid particles, the temperature, the size of the particle, and the types of base fluids also influence thermal conductivity. Growing concentration and reduced size of nanoparticles with rising temperature can augment the thermal conductivity of nanofluid. Research in nanofluids has seen significant developments in pushing boundaries to enhance thermal conductivity and seek new applications. These latest findings have expanded knowledge of the underlying mechanisms governing nanofluid performance and diversified their potential applications in various thermal management systems. Rabby *et al.,* [20] provided an overview of recent developments with nanofluids for thermal systems, which are critically reviewed, focusing on preparation strategies, characterization techniques and applications. Hemmat Esfe *et al.,* [21] found a 20.1% enhancement of thermal conductivity for EG-based SiO_2- multi-walled carbon nanotubes (MWCNT) (70:30). From this study, the authors also ensured the higher efficiency of composite nanofluids in terms of heat transfer and price compared to single nanofluid. Moreover, in another study, a comparison of the thermal properties of three base fluids such as paraffin oil, vegetable oil and SAE oil, was conducted while adding a 50:50 ratio of Cu-Zn nanoparticles at volume concentrations of 0.1, 0.1 and 0.5% [22]. From this experiment, vegetable oil-based Cu-Zn nanofluid shows maximum thermal conductivity, followed by paraffin oil and SAE oil-based nanofluids. The researchers reported that the higher thermal conductivity and internal repellent force to flow of vegetable oil is responsible for showing the highest thermal conductivity of vegetable oil-based nanofluid. Another study explored that changes in thermal conductivity are more sensitive to temperature at high temperatures during the investigation of water-EG-based MWCNT- SiC for concentrations ranging from 0 to 0.755 and temperatures 25-50 ^{o}C [23]. Results also revealed that thermal conductivity improved by 33 % compared to base fluid for 0.75% volume fraction at 50 oC. Moreover, for water-EG-based TiO_2-SiO_2 (20:80) nanofluids, thermal conductivity improved by 13.85 at 70 ^{o}C [24]. However, several researchers are trying to discover novel class nanofluid and finally implement nanofluid in the practical field. Based on the literature review, TiO_2-Al_2O_3/40% EG's thermal conductivity has not yet been investigated.

Bao *et al.,* [24] introduced a novel hybrid aqueous nanofluid containing multi-walled carbon nanotubes and SiC nanoparticles, designed to enhance photothermal conversion in solar collectors by leveraging the complementary optical properties of its components and overcoming the limitations of single-component nanofluids. The hydroxyl-functionalized MWCNT/SiC hybrid nanofluid demonstrates excellent stability and enhanced thermal conductivity. It achieves a remarkably high photothermal conversion efficiency of 64.7% after 1-hour irradiation, significantly outperforming previously reported MWCNT-based aqueous nanofluids and thus promoting its potential application as a light-absorbing working fluid in solar collectors. Azman *et al.,* [25] evaluated the performance of a hybrid nanofluid (0.5% Al_2O_3-CuO/water, 80:20 by volume) in sawtooth-shaped corrugated pipes with varying pitch heights and distances, demonstrating improved heat transfer efficiency (8-74% increase in Nusselt number) at higher Reynolds numbers due to increased flow turbulence and mixing, despite increased friction and pressure drops, thus providing insights for optimizing heat transfer systems in industries using condensers, solar collectors and thermal machines. Alfellag *et al.,* [26] explored green synthesis of hybrid nanofluids, focusing on optimizing the mixing ratio of clove-treated MWCNTs and TiO_2 nanomaterials in water-based samples. Testing various ratios at 0.1 wt% concentration and temperatures of 30-50 °C, the research found a 60:40 (clove-treated-MWCNTs:TiO_2) ratio to be optimal, balancing high thermal conductivity with low viscosity. The study concludes that these environmentally-friendly hybrid nanofluids outperform mono nanofluids, offering potential improvements in thermal system efficiency. Rezman *et al.,* [27] investigated the thermal conductivity of coconut, soybean and palm oil-based nanofluids containing Al_2O_3-TiO_2 nanoparticles (50:50 ratio) with 10 % CTAB surfactant. Testing concentrations from 0-0.6% and temperatures from 30-60 °C, results showed thermal conductivity increases of 1.77 % to 27.1 %. Palm oil-based nanofluid with 0.2 % nanoparticle concentration proved the most stable, while palm oil-based hybrid nanofluid achieved the highest thermal conductivity with 0.6 % Al_2O_3-TiO_2 concentration at 30 °C.

Advancements in characterization and modelling techniques have played a crucial role in deepening our understanding of nanofluid behaviour. This study addresses a research gap in hybrid nanofluid technology by investigating the thermal conductivity of TiO_2-Al_2O_3 nanoparticles suspended in a 40% ethylene glycol-water solution, a composition yet unexplored in the literature. The novelty of this research is multifaceted, encompassing both material synthesis and characterization aspects. Firstly, the unique 80:20 weight ratio of TiO_2 to Al_2O_3 in a 40% EG base fluid leverages the high thermal conductivity of Al_2O_3 and the excellent stability of TiO_2 suspensions, offering a synergistic enhancement previously unexamined. This base fluid composition bridges pure water and pure EG studies, providing insights into a practically relevant coolant for various industrial applications. Furthermore, unlike many studies focusing solely on thermal properties, this research presents a comprehensive stability analysis over an extended period (>40 days), correlating long-term stability with thermal performance, a crucial factor for real-world applications. The study's examination of thermal conductivity across a wide temperature range (30-80 °C) addresses the absence of data on the temperature-dependent behaviour of hybrid nanofluids. Developing a high-accuracy predictive model for thermal conductivity, accounting for both nanoparticle concentration and temperature effects, also fills a significant gap in design tools for thermal management systems. This application-oriented approach expands the fundamental knowledge base of hybrid nanofluid thermal properties. It provides critical insights for optimizing heat transfer fluids in the automotive, electronics and renewable energy sectors. By bridging the gap between fundamental research and practical implementation, this study contributes valuable data and methodologies for developing next-generation coolants, potentially revolutionizing thermal management strategies across multiple industries. Thus, the present research should focus on leveraging cutting-edge methods to investigate the thermal conductivity behaviour of TiO_2-Al_2O_3/40% EG nanofluids, potentially uncovering novel properties and applications for this specific formulation.

2. Methodology

2.1 Preparation of Hybrid Nanofluids

Figure 1 illustrates the schematic synthesis protocol for hybrid nanofluids comprising titanium dioxide (TiO_2) and aluminium oxide (Al_2O_3) nanoparticles. The diagram describes the stepwise preparation process, including the initial dispersion of nanoparticles in the base fluid, followed by mechanical agitation, homogenization, ultrasonication and stability assessment procedures.

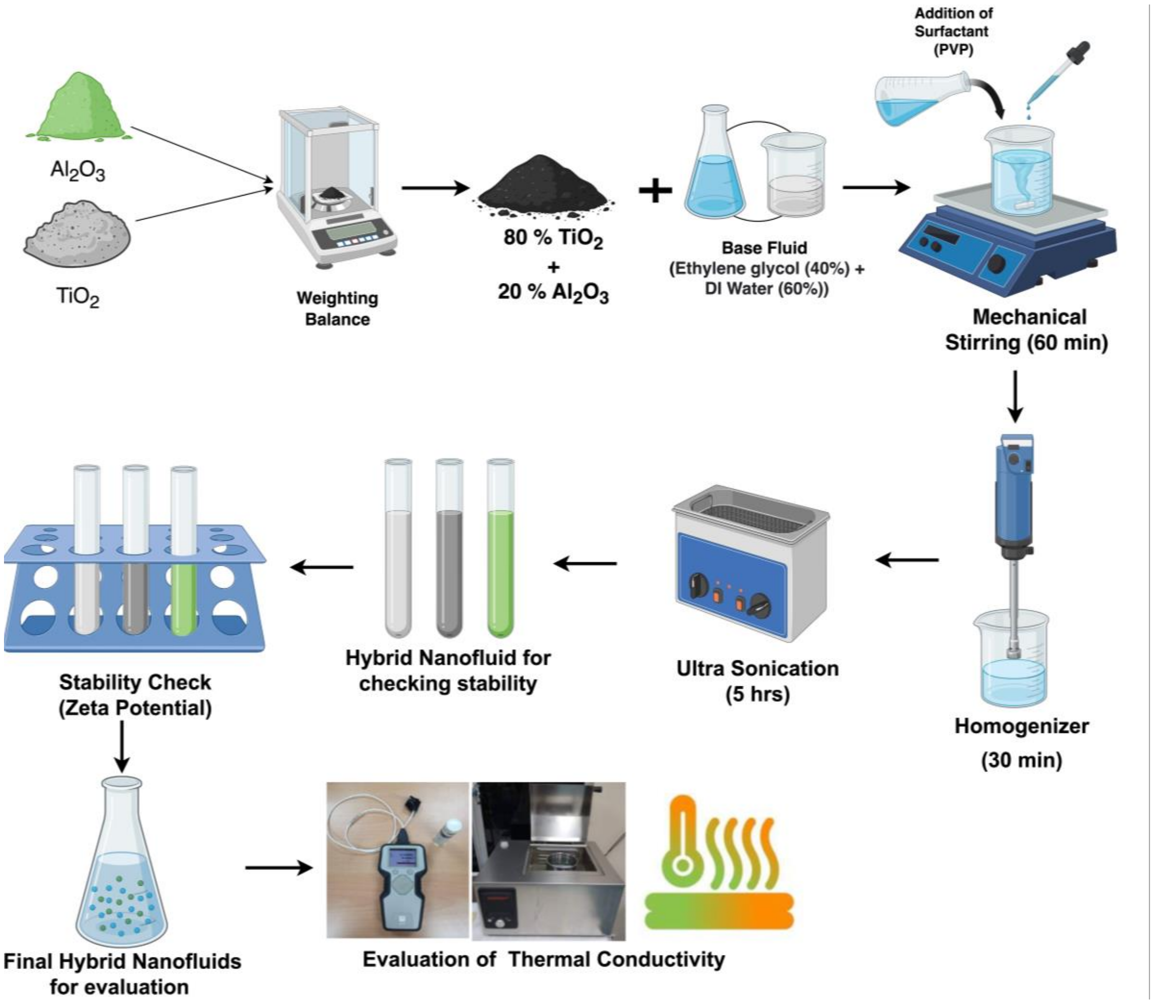


Fig. 1. Preparation of hybrid nanofluids and thermal conductivity measurement

This figure provides a visual overview of the critical stages of producing a stable colloidal suspension of the binary nanoparticle system, highlighting the essential steps that ensure the hybrid nanofluid's uniform dispersion and long-term stability. Hybrid nanofluids were synthesized employing a two-step method. Titanium oxide (TIO_2, below 30 nm, 99.5 % purity, US research nanomaterials) and aluminium oxide (Al_2O_3, >20 nm, 99.8 % purity, US research nanomaterials) nanoparticles were dispersed in a 40 % (v/v ethylene glycol solution (99.8 % purity, Sigma-Aldrich) at an 80:20 weight ratio (TiO_2: Al_2O_3), respectively. The selection of the 80:20 weight ratio of TiO_2 to Al_2O_3 nanoparticles was predicated on its superior colloidal stability characteristics, as elucidated in a comprehensive previous investigation [28]. This study conducted a comparative analysis of various TiO_2:Al_2O_3 ratios, including 60:40, 50:50, 40:60 and 20:80. By Eq. (1), this study investigates hybrid nanofluids at five distinct volume concentrations: 0.02%, 0.04%, 0.06%, 0.08% and 0.1%. The nanofluid preparation protocol consisted of a two-step process to ensure colloidal stability. Initially, the suspension underwent magnetic stirring for 60 minutes, followed by high-shear homogenization for 30 minutes to break down agglomerates and then bath sonication for 5 hours. Polyvinylpyrrolidone was incorporated as a surfactant at a concentration of 0.1% w/v to enhance dispersion stability. This optimized preparation methodology resulted in hybrid nanofluids exhibiting excellent stability, with no significant sedimentation observed for a duration exceeding five weeks (>1 month). The prolonged stability period indicates enhanced interfacial interactions and reduced agglomeration tendencies, factors that have been correlated with improved thermal conductivity in hybrid nanofluids [18]. This observed stability provided a strong foundation for the subsequent thermal conductivity investigations. The physicochemical properties of the constituent nanoparticles and base fluids are comprehensively detailed in Table 1 and Table 2, respectively, providing essential data for the characterization and analysis of the prepared nanofluids [29].

$$\phi\ (\%) = \frac{\left(\frac{m}{\rho}\right)_{TiO_2} + \left(\frac{m}{\rho}\right)_{Al_2O_3}}{\left(\frac{m}{\rho}\right)_{TiO_2} + \left(\frac{m}{\rho}\right)_{Al_2O_3} + \left(\frac{m}{\rho}\right)_{Water} + \left(\frac{m}{\rho}\right)_{EG}} \times 100\% \tag{1}$$

where m and ρ represent the mass and density and ϕ denote nanoparticle volume concentration in percentage.

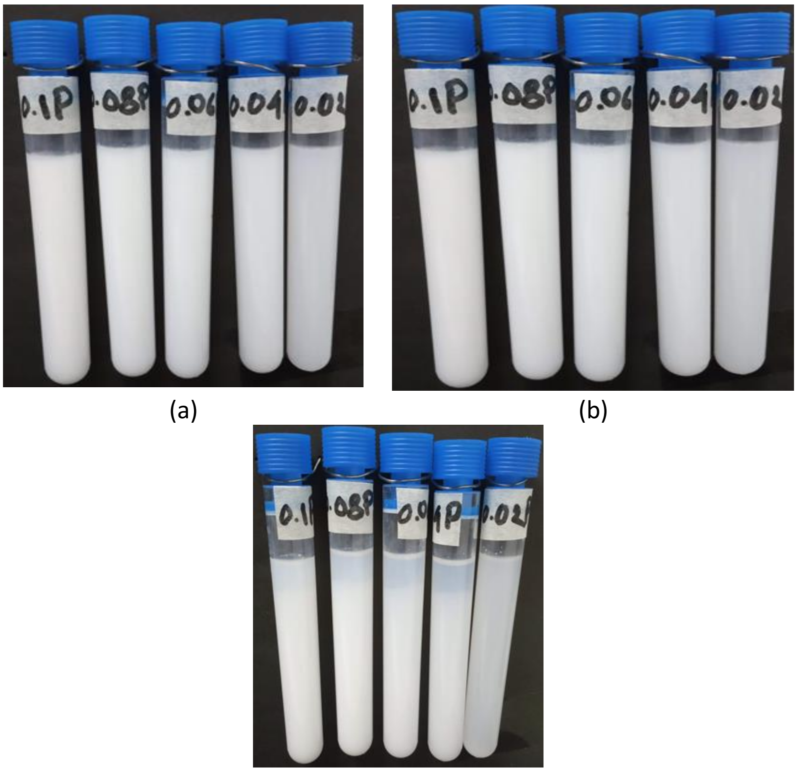
Table 1
Properties of TiO_2 and Al_2O_3 nanoparticles [29]

Characteristics	TiO_2	Al_2O_3
Purity (%)	>99	99.8
Colour	White	White
Average particle diameter (nm)	5-6	30
Molecular Mass (g mol^{-1})	79.86	101.96
Density (Kg m^{-3})	4230	4000
Thermal conductivity (W m^{-1} K^{-1})	8.4	40
Specific heat (J Kg^{-1} K^{-1})	692	773

Table 2
Properties of base fluids [29]

Characteristics	Water	Ethylene Glycol
Ratio	60	40
Colour	Colourless and clear	Colourless and clear
Smell	Odourless	Odourless
Chemical formula	H_2O	C_2H_6O
Molecular Mass (g mol^{-1})	18.02	62.07
Density (Kgm^{-3})	998.21	1113.20
Melting point (^{o}C)	0.00	-12.9
Boiling point (^{o}C)	100	197.3
Thermal conductivity (W/ mK)	0.6	0.224

Visual stability assessment of the TiO_2-Al_2O_3 hybrid nanofluid was conducted through periodic photographic documentation, as illustrated in Figure 2. The images reveal no discernible sedimentation up to 21 days post-synthesis, with minimal precipitate formation observed only after approximately 45 days. This observation indicates excellent colloidal stability of the hybrid nanofluid for one month. Incorporating a dispersant in the present formulation has extended the stability period from approximately two weeks to six weeks. This marked enhancement in long-term stability presents a substantial advantage for potential applications in practical fields. The prolonged stability ensures consistent thermophysical properties over extended periods and mitigates concerns related to nanoparticle agglomeration and settling during storage or operational use. These findings underscore the critical role of dispersants in optimizing the colloidal stability of hybrid nanofluids and highlight the potential for their sustained efficacy in various thermal management applications.



(a) (b)

(c)

Fig. 2. Time-dependent sedimentation analysis of TiO_2-Al_2O_3 hybrid nanofluids. Photographic documentation of 40% ethylene glycol-based nanofluids (0.1 vol% total nanoparticle concentration, 80:20 TiO_2:Al_2O_3 weight ratio) at (a) 0 days (b) 21 days (c) 45 days post-synthesis, (a) Immediately after preparation, (b) After 21 days, (c) After 45 days

2.2 Thermal Conductivity Assessment

Thermal conductivity measurements of the TiO_2-Al_2O_3/40% ethylene glycol (EG) hybrid nanofluids were conducted using a KD2 Pro thermal property analyser with a KS-1 sensor (Decagon Devices Inc., USA). The apparatus was calibrated according to the manufacturer to ensure measurement accuracy. Thermal conductivity was assessed at six discrete temperatures (30, 40, 50, 60, 70 and 80 °C) using a temperature-controlled water bath, covering a range relevant to potential applications. The KS-1 sensor was immersed vertically in the nanofluid sample, maintaining a minimum distance from the container walls to mitigate boundary effects. Strict protocols were implemented to minimize fluid disturbance and sensor movement during measurements. Five independent measurements were performed at 15-minute intervals for each temperature point and nanofluid concentration to ensure thermal equilibrium and measurement stability. The arithmetic mean of these readings was calculated to determine the representative thermal conductivity value for each condition. This rigorous methodology aims to enhance measurement reliability and reduce systematic errors. Figure 3 provides a schematic representation of the experimental setup for thermal conductivity assessment, illustrating the key components and their spatial arrangement.

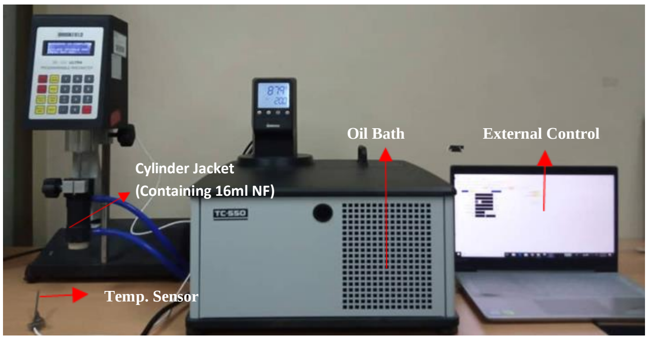


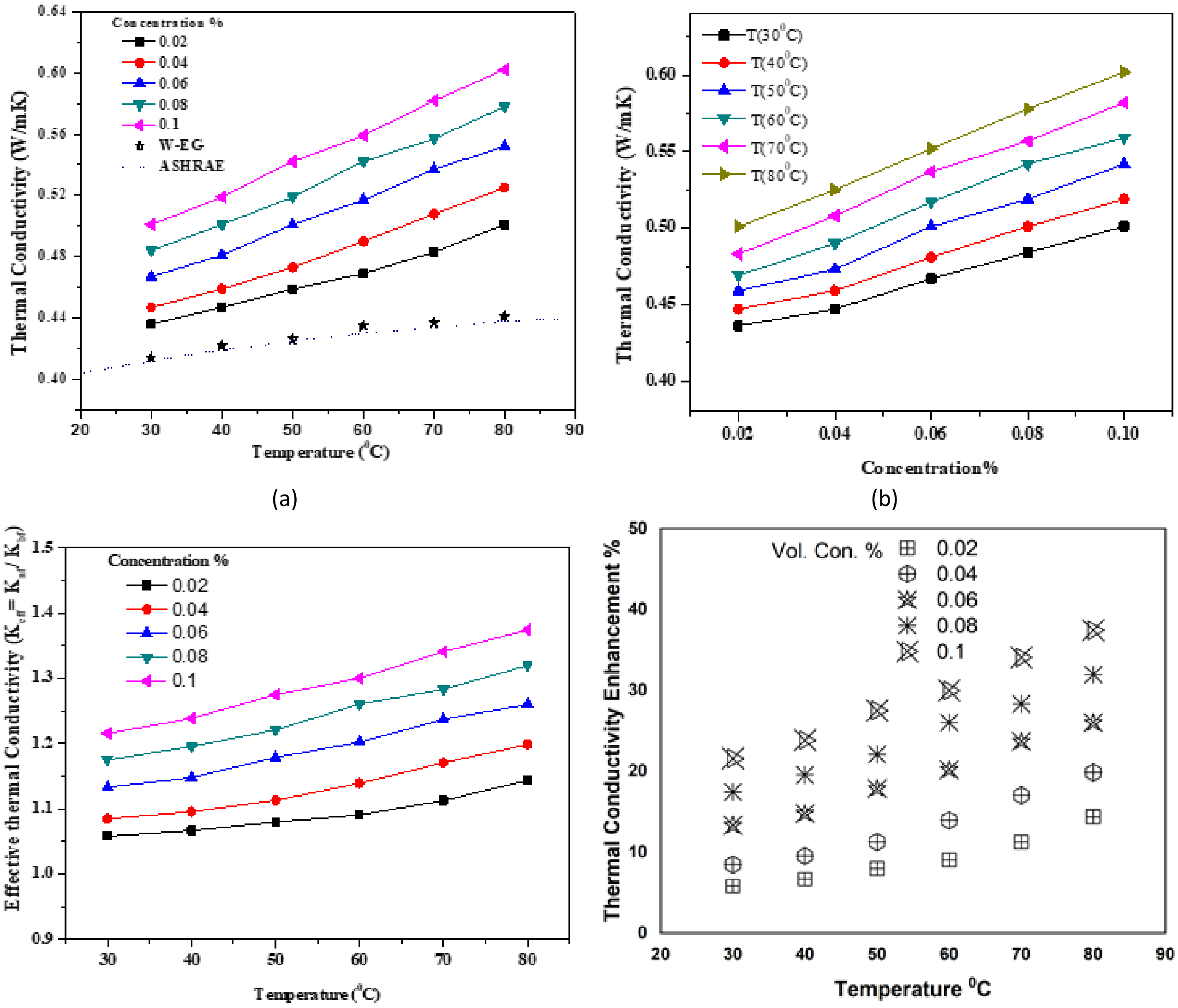
Fig. 3. Set up of LVDV III Ultra Rheometer

3. Results and Discussion

3.1 Thermal Conductivity Behaviour

The thermal conductivity of TiO_2-Al_2O_3 hybrid nanofluids exhibits dependencies on temperature and nanoparticle volume concentration as illustrated in Figure 4(a) to 4(b). Across all investigated volume fractions, thermal conductivity consistently exceeds that of the base fluid (40% ethylene glycol-water mixture), with a positive correlation observed between k and temperature. This temperature-dependent enhancement, attributed to intensified Brownian motion, is more pronounced at higher volume concentration values, suggesting a synergistic interaction between thermal energy and nanoparticle concentration. Concurrently, thermal conductivity demonstrates a monotonic increase with rising volume concentration at constant temperatures. This concentration-dependent augmentation is ascribed to the increased presence of high-conductivity nanoparticles and subsequent inter-particle collisions [30]. The observed thermal conductivity enhancement can be attributed to multiple mechanisms, including increased thermal energy carriers, Brownian motion-induced localized convection currents, potential percolation network formation at higher concentrations and modification of liquid layering at solid-liquid interfaces. These results underscore the intricate interplay between nanoparticle concentration, temperature and thermal conductivity in hybrid nanofluid systems, providing crucial insights for optimizing their performance in various heat transfer applications.

Figure 4(c) to (d) elucidates the effective thermal conductivity and its relative enhancement, respectively, for the TiO_2-Al_2O_3 hybrid nanofluid system as functions of temperature and nanoparticle volume concentration. A maximum thermal conductivity enhancement of 37.44 % is achieved at $\phi = 0.1$ vol% and T = 80 °C, while the minimum enhancement occurs at $\phi = 0.02$ vol% and T = 30 °C. This trend of increasing enhancement with temperature and concentration can be attributed to main mechanisms, including increased thermal energy carriers and potential percolation pathways at higher nanoparticle loadings and intensified Brownian motion and micro-convection at elevated temperatures [23,28]. The substantial enhancement observed in this 40% ethylene glycol-based hybrid nanofluid presents promising implications for practical applications, particularly as a high-performance alternative to water-based coolants in machining processes. The enhanced thermal properties suggest potential improvements in heat dissipation during machining operations, which could lead to reduced tool wear, enhanced surface finish quality and increased machining speeds. However, further investigations are necessary to assess the practical efficacy of this nanofluid in machining applications, considering factors such as viscosity, long-term stability and potential interactions with workpiece materials.



(a) (b)

(c) (d)

Fig. 4. Variation of thermal conductivity of TiO_2-Al_2O_3 hybrid nanofluids (a) Thermal conductivity versus temperature, (b) Thermal conductivity versus volume concentration, (c) Effective thermal conductivity, (d) Thermal conductivity enhancement (%)

3.2 Comparison with Other Models

Figure 5 presents a comparative analysis of the effective thermal conductivity (K_{eff}) of the current TiO_2-Al_2O_3/40% ethylene glycol hybrid nanofluid system with several established models from the literature [23,31,32]. The comparison encompasses three distinct temperatures (30 °C, 50 °C and 70 °C) and primarily focuses on a 0.1 vol% nanoparticle concentration, with an additional data point at 0.5 vol% from Nabil *et al.,* [32]. Notably, the studies by Hemmat Esfe *et al.,* [16,21] employed identical base fluids (EG) but different nanoparticle compositions (MWCNT-SiO_2 and SWCNT-MgO, respectively), providing insight into the impact of nanoparticle type on thermal conductivity enhancement. At lower temperatures (30 °C and 50 °C), a discernible difference in thermal conductivity ratios is observed between these two nanofluid systems, with the SWCNT-MgO/EG nanofluid exhibiting superior thermal conductivity compared to its MWCNT-SiO_2/EG counterpart. The present TiO_2-Al_2O_3/40% EG hybrid nanofluid demonstrates remarkable thermal performance, with K_{eff} ranging from 1.21 to 1.34 times that of the base fluid across the investigated temperature range [32]. This enhancement surpasses the performance of several previously reported nanofluid systems, underscoring the potential synergistic effects of the TiO_2-Al_2O_3 nanoparticle combination in enhancing thermal transport properties. The observed variations in thermal conductivity enhancement across different nanofluid compositions highlight the critical role of nanoparticle material selection and the potential for tailoring nanofluid properties for specific thermal management applications.

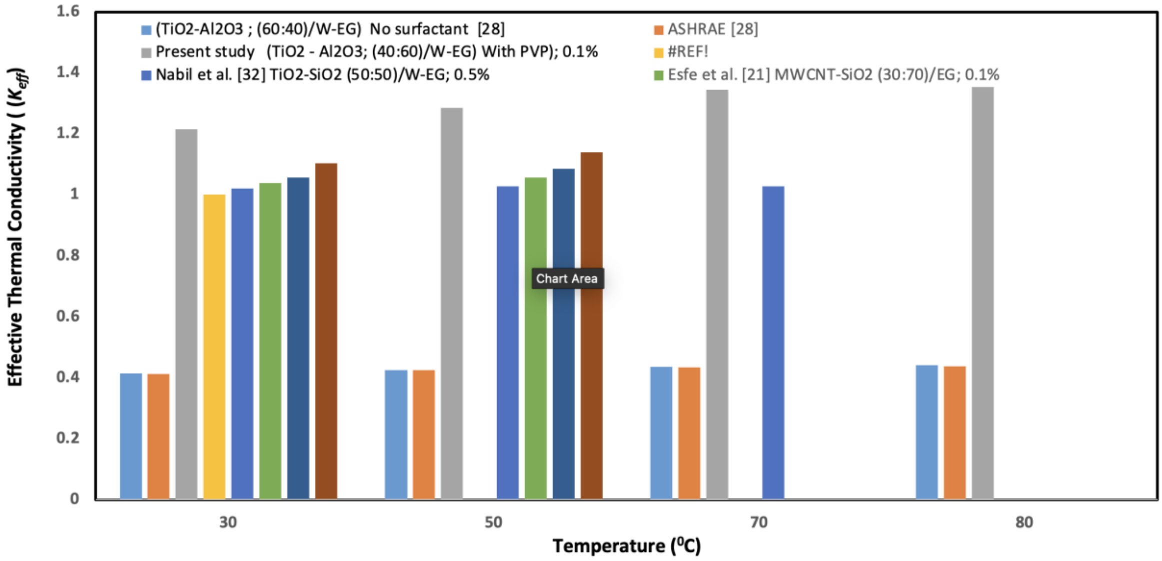


Fig. 5. Comparison of effective thermal conductivity of the present study with other literature

Comparative analysis reveals significant disparities in effective thermal conductivity between the present TiO_2-Al_2O_3 hybrid nanofluid and previously reported systems. Notably, the model proposed by Nabil *et al.,* [32] for a water-EG (60:40) based nanofluid exhibits K_{eff} ratios ranging from 1.02 to 1.03 across the investigated temperature range, despite a higher nanoparticle concentration (0.5 vol% vs. 0.1 vol% in the present study. The superior thermal performance of the current TiO_2-Al_2O_3 system, even at lower concentrations, can be attributed to the inherently higher thermal conductivity of Al_2O_3 nanoparticles, potential synergistic effects between TiO_2 and Al_2O_3 and differences in nanoparticle size and mixing ratios. These observations align with Sundar *et al.,* [34] conclusion that nanoparticle characteristics and base fluid composition strongly influence nanofluid thermal properties. The discrepancies observed between various models, including Zadkhast *et al.,* [31], highlight the system-specific nature of nanofluid thermal behaviour. The inability of existing models to accurately predict the thermal conductivity of the present TiO_2-Al_2O_3 hybrid nanofluid highlights the need for a tailored predictive model. This necessity is further emphasized by the unique thermal signature of each nanofluid system, which is intricately linked to its specific composition and preparation methods. Consequently, the development of a new, system-specific model for TiO_2-Al_2O_3 nanofluids is imperative to accurately capture and predict their thermal behaviour, thereby facilitating the optimization and application of these advanced heat transfer fluids in various thermal management scenarios.

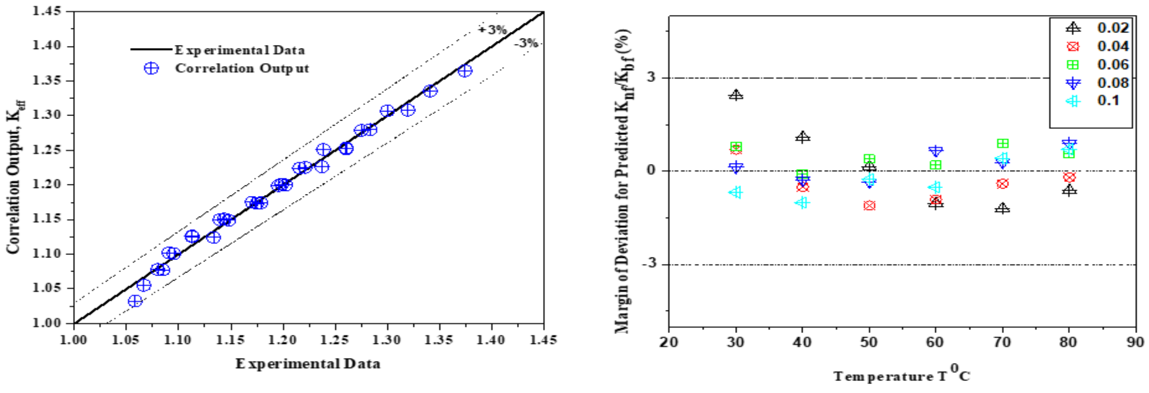
3.3 New Model of Thermal Conductivity

This investigation has yielded a new empirical correlation for predicting the thermal conductivity of TiO_2-Al_2O_3/40% ethylene glycol hybrid nanofluids as a function of nanoparticle volume concentration and temperature. The correlation, presented in Eq. (2), was derived through regression analysis of comprehensive experimental data covering the studied parametric range. The predictive efficacy of this newly developed correlation was rigorously assessed through statistical comparison with experimentally measured thermal conductivity values. Figure 6(a) illustrates the correspondence plot comparing the correlation outputs against the experimental data. The graphical analysis reveals high concordance between predicted and measured values, with most data points aligning closely with the ideal correlation line ($y = x$). The observed deviations are minimal, with a calculated mean absolute percentage error and a coefficient of determination (R^2), indicating the robust predictive capability of the proposed correlation. This statistical congruence emphasizes the reliability of the developed model in accurately estimating the thermal conductivity of the hybrid nanofluid system within the investigated range of volume concentrations and temperatures.

$$K_{eff} = \frac{K_{nf}}{K_{bf}} = 0.927e^{(2.13\phi+0.00217T)} \tag{2}$$

$$\text{Percentage of Deviation} = \left[\frac{(K_{nf})_{Exp} - (K_{nf})_{Pred}}{(K_{nf})_{Exp}}\right] \times 100\% \tag{3}$$

The newly developed thermal conductivity correlation for TiO_2-Al_2O_3/40% ethylene glycol hybrid nanofluids experienced statistical validation across the experimental range of 0.02-0.1 vol% nanoparticle concentration and 30-80 °C. Deviation analysis, visualized in Figure 6(b), employed the percentage of deviation (relative error) formula (Eq. (3)), yielding a maximum deviation of 2.43 %, a minimum of 0.08 % and a mean absolute deviation (*MAD*) of 0.65 %. The root mean square error (*RMSE*) and coefficient of determination (R^2) were calculated as 0.00142 W/m·K and 0.9987, respectively, further corroborating the model's accuracy. The observed maximum deviation of <3% and high R^2 value indicate exceptional concordance between predictions and experimental data.



(a) (b)

Fig. 6. Performance analysis of a newly developed model, (a) Correlation output and experimental data, (b) The margin of deviation for a new model

Figure 7 illustrates the model's consistent performance across the parametric space, with error bars representing the standard deviation of replicate measurements. The low *MAD* and narrow deviation range (2.35 percentage points) suggest minimal systematic bias and high precision. A two-tailed paired t-test between predicted and experimental values yielded p > 0.05, confirming no statistically significant difference. These comprehensive statistical indicators collectively affirm the model's high fidelity within the studied ranges, rendering it a reliable tool for predicting the thermal behaviour of this hybrid nanofluid system. The model's robustness is particularly valuable for computational fluid dynamics simulations and the design optimization of heat transfer systems employing these advanced nanofluids.

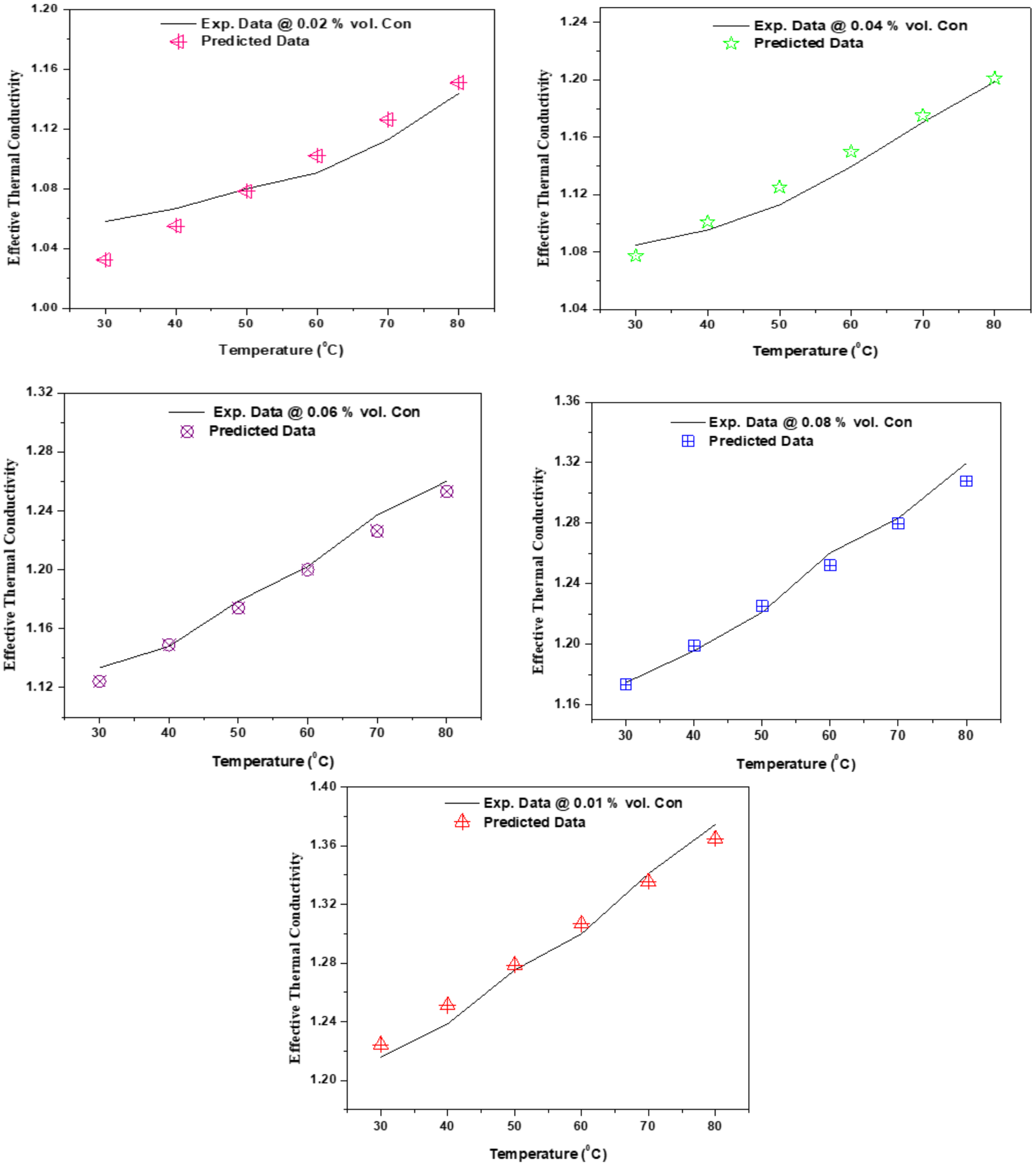


Fig. 7. Proof of the accuracy of a new model for all studied concentrations and temperatures

3.4 Effect of Surfactant on TiO$_2$-Al$_2$O$_3$ Hybrid Nanofluids Properties

The discussion of the effect of surfactant on the stability period and thermal conductivity of TiO$_2$-Al$_2$O$_3$ hybrid nanofluids is presented in this section briefly. The present study achieved a stability period of about five weeks, indicating about 125% improvement in the stability period of the surfactant-free same hybrid nanofluid in the previous study by Urmi *et al.,* [33]. Besides, the thermal conductivity of TiO_2-Al_2O_3 hybrid nanofluids of this current study is also compared with the previous study by Urmi *et al.,* [33]. The comparison shows that the thermal conductivity slightly decreases while the surfactant is added. The result is aligned with another study by Corumlu *et al.,* [35]. Figure 8 shows the percentage of changes in thermal conductivity enhancement for using surfactant, which is achieved from the difference of the thermal conductivity enhancement (%) value between with and without surfactant hybrid nanofluid of TiO_2-Al_2O_3.

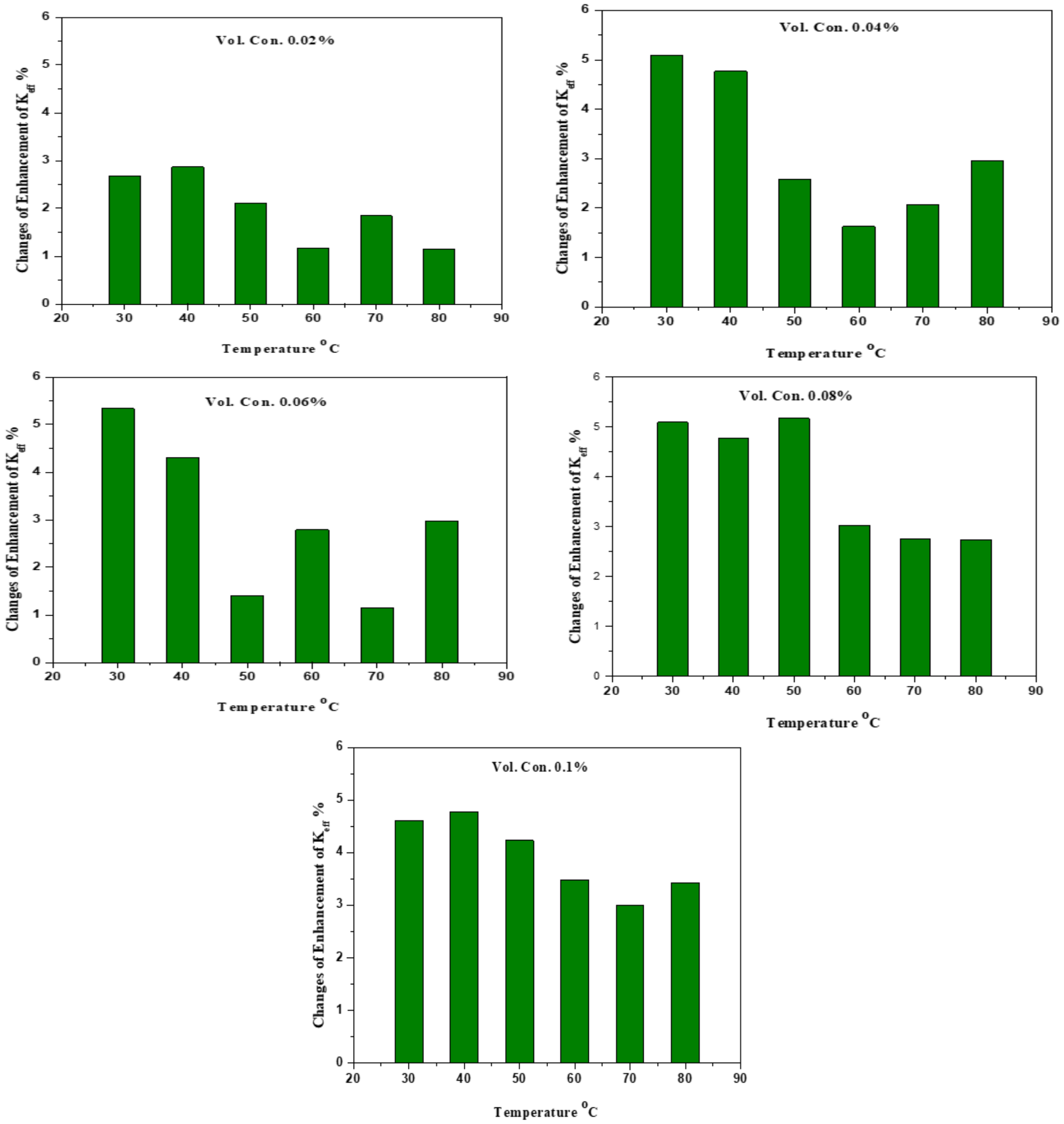


Fig. 8. The percentage of changes in thermal conductivity enhancement for using surfactant of hybrid nanofluids of TiO_2-Al2O_3

Figure 8 elucidates the complex influence of polyvinylpyrrolidone surfactant on the thermal conductivity enhancement (TCE) of TiO_2-Al_2O_3 hybrid nanofluids as a function of nanoparticle concentration and temperature. The data reveal a non-linear relationship, with more pronounced effects at higher concentrations and lower temperatures. Quantitative analysis yields a maximum TCE reduction of 5.33 % at 0.06 vol% and 30 °C and a minimum decrease of 1.14 % at 0.02 vol% and

80 °C, indicating a temperature-dependent interaction between PVP and nanoparticles. Notably, while PVP addition results in this thermal conductivity reduction, it concurrently enhances colloidal stability by 125% compared to the surfactant-free system. This trade-off is attributed to potential mechanisms such as forming a thermal barrier layer by PVP, alteration of nanoparticle aggregation affecting heat conduction pathways and modification of interfacial thermal resistance. The inverse relationship between temperature and surfactant impact suggests changes in PVP's conformation or adsorption characteristics at elevated temperatures. These findings underscore the critical balance between thermal performance and stability in surfactant-stabilized hybrid nanofluids, emphasizing the need for careful optimization in nanofluid formulation for specific heat transfer applications.

4. Conclusions

This research investigated the thermal conductivity of 40% EG-based TiO_2-Al_2O_3 (80:20) nanofluids for different temperatures and concentrations. A new correlation of thermal conductivity is proposed through regression analysis, which possesses excellent accuracy. Moreover, the sensitivity of the thermal behaviour of TiO_2-Al_2O_3 nanofluids is also analysed, considering the studied temperatures and concentrations. From the investigations, the following results are achieved:

i. The thermal conductivity of 40% EG-based TiO_2-Al_2O_3 is increased with rising temperatures and concentrations. Moreover, the effect of temperature is more at higher concentrations.
ii. The most significant improvement in thermal conductivity was 37.44%, which happened at 0.1% volume concentration and 80 ^{0}C temperature. The minimum improvement of thermal conductivity has occurred for 0.02% volume concentration at 30 ^{0}C.
iii. The percentage of improvement of thermal conductivity is comparatively higher at high temperatures and volume concentrations.
iv. As the previous model cannot predict the thermal conductivity data of studied nanofluids, this study proposes a new model for predicting thermal conductivity with excellent accuracy within the studied range of temperature and concentrations.
v. As the standard deviation for the new model is very limited (less than 3%), this model can predict the thermal conductivity of nanofluids with high precision for the considered temperatures and concentrations.
vi. Adding 0.1%, PVP prolongs the stability period by 125%, while the thermal conductivity is slightly reduced for all temperatures and concentrations. The highest and lowest reduction of thermal conductivity is found at 5.33% and 1.14%, respectively, due to PVP addition.

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