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An experimental investigation on the thermophysical properties of 40% ethylene glycol based TiO_2-Al_2O_3 hybrid nanofluids

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ABSTRACT

This paper presents an experimental study on the thermophysical properties of 40% ethylene glycol-based TiO_2-Al_2O_3 hybrid nanofluids. The hybrid nanofluids were prepared for concentrations of 0.02 to 0.1% and temperature of 30 to 80 °C. Nanofluid stability is studied using visual observation, spectral UV–Vis, zeta potential, and results obtained excellent stability. The rheological test was conducted to determine the Newtonian behaviour. The viscosity and thermal conductivity were investigated. Viscosity and thermal conductivity of hybrid nanofluids boost as opposed to the base fluid. The thermal conductivity is improved by 40.86% at 0.1% volume concentration and 80 °C. The hybrid nanofluids have higher thermal conductivity than single TiO_2 and Al_2O_3 and better heat transfer efficiency with a concentration greater than 0.04%. The newly developed models of viscosity and thermal conductivity are defined with good accuracy from the experimental data. The performance enhancement ratio shows that hybrid nanofluids with a concentration greater than 0.04% are advantageous due to having better efficiency in heat transfer. The combined effects of TiO_2 and Al_2O_3 nanoparticles on thermal behaviour, compared to viscosity, are more significant. Therefore, the practical application of hybrid nanofluids in heat transfer systems could have a potential influence for its increased thermal conductivity and low viscosity.

1. Introduction

The efficient heat transfer process remains one of the significant challenges in the energy sectors of industry. Conventional fluids such as water, oil and ethylene glycol have an essential role to play in heat transfer. The thermal properties of fluids suggest the effectiveness of heat transfer in this situation. A number of researchers have tried to improve these liquids thermophysical characteristics. Various studies of the past decades have shown evidence to affect the efficiency of heat transfer by introducing nanoparticles to fluids [1–6]. Thus, nanofluids have developed which include the immersion of nanometer-sized particles, tubes bars or fibres into the base fluid [7], and have attracted the attention of engineers in fluid mechanics and fluid flow [8–11], machining [12–16], electronics [17,18], solar and nuclear energy [19–21], biomedicine [22,23], process of treatment of water [24], transportation [25], and heat exchangers [2,26] and especially in various cooling and lubrication purpose experiments and devices [6,27]. The two most common methods of nanofluid synthesis are one and two-step method [28,29]. In the one-step method, the synthesization and dispersion of nanoparticles into the base fluid co-occurs [30,31] while in the two-step method, this occurs separately [32]. Although it is comparatively beneficial in terms of getting the stability of nanofluids while one-step synthesis process is occupied, it is not recommended [30] due to its high expense and applicability of fluids with only lower vapour pressure [33,34].

On the contrary, compared to one-step method, two-step synthesis process is widely used in industries and research areas at a large scale because of its simplicity and lower production cost [29] despite having difficulties of agglomeration of nanoparticles [28]. Most of the researchers use this two-step synthesis process of nanofluids [1,4,35]. In addition, this method is primarily proposed by Choi and Eastman [7] for the synthesis of oxide-based nanofluids, perhaps metallic particles based nanofluids. It influences the thermophysical properties of base fluids such as viscosity, thermal conductivity, density and thus plays an essential role after introducing nanoparticles into the base fluids. For instance, the viscosity suggests that the pumping power or energy use and thermal conductivity contribute to the efficiency of heat transfer [3]. The thermal properties of the nanofluids influence various parameters such as the type of particles and base fluid, particle size, shape, concentration, temperature and so on [36–40]. In addition, the thermal conductivity of nanofluid was more affected by the thermal conductivity of the base fluids in conjunction with the temperature,

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Nomenclature

Abbreviations

A	Absorbency
Al_2O_3	Aluminium oxide
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
ASTM	American Society for Testing and Materials
Conc.	Concentration
Co_3O_4	Cobalt oxide
Cu	Copper
EG	Ethylene glycol
Fe_3O_4	Ferrosoferric oxide
IEEE	Institute of Electrical and Electronics Engineers
K	Thermal conductivity
MWCNT	Multi-walled carbon nanotubes
ND	Nanodaimond
PER	Properties enhancement ratio
SAE	Society of Automotive Engineers
SiO_2	Silicon dioxide
SWCNT	Single walled carbon nanotubes
T	Temperature (°C)
TEM	Transmission electron microscopy
TiO_2	Titanium dioxide
UV–Vis	Ultraviolet–visible spectrophotometry
Vol.	Volume
W	Water
Zn	Zinc

Greek symbols

Ø	Volume concentration
ρ	Density
T	Shear stress
μ	Viscosity
Y	Shear strain

Subscripts

o	Initial
bf	Base fluid
Exp.	Experimental
nf	Nanofluid
np	Nanoparticles
Pred.	Predicted
r	ratio

concentration and dimension of nanoparticles [40].

Many experiments were carried out on different nanofluids. Philip, Shima and Raj [41] reported 300% enhancement of thermal conductivity when applying Fe_3O_4 nanoparticles (oleic acid-coated) to kerosene with 82 G magnetic field inclusion. In another study, Choi, Zhang, Yu, Lockwood and Grulke [42] found that thermal conductivity improved by 150% for synthetic poly oil (α-olefin) based MWCNT nanofluid. The addition of composite nanoparticles to a basic fluid is expected to achieve better thermophysical properties than single nanoparticles by the combined physical and chemical effects of nanoparticles. Hamid, Azmi, Nabil, Mamat and Sharma [4] examined the thermal conductivity and viscosity of water-EG based TiO_2-SiO_2 nanofluids and found 13.8% improvement of thermal conductivity at 70^{0}C for the mixing ratio of 20:80 and highest viscosity has been found for 50:50 mixing ratio of TiO_2-SiO_2. Kumar, Vasu and Gopal [43] analyzed the efficiency of various base fluids (vegetable oil, SAE oil and paraffin oil) using Cu−Zn (50:50 ratio) nanoparticles into the base oil for 0.1, 0.3 and 0.5% volume concentrations. Highest thermal conductivity was observed for Cu-Zn/vegetable oil hybrid nanofluid trailed by paraffin oil and SAE oil. This study concluded that the highest thermal conductivity of Cu-Zn/ vegetable oil nanofluid is responsible for the internal repellent fluid force to flow and a comparatively higher thermal conductivity of vegetable oil. An improved thermal conductivity with low viscosity could be attained at high temperature while studying ND- Co_3O_4 /water nanofluid [44]. In another study, used EG-based 70: 30 ratio of SiO_2-MWCNT hybrid nanofluid revealed that an improvement in thermal conductivity of 20.1% at 50 °C [45]. This study also established a correlation for thermal conductivity ratio. Besides, the author also concluded from the price-performance analysis that the hybrid nanofluids are more economical and efficient than single nanofluids in terms of heat transfer efficiency. The thermal oil-based Al_2O_3- MWCNT hybrid nanofluid at a temperature between 25 and 50 °C and concentrations between 0.125 and 1.5% was studied and revealed 45% improvement in thermal conductivity (50 °C, 1.5% volume concentration) and 81% improvement in viscosity (40 °C, 1.5% volume concentration) [3]. In addition, this study proposed a new correlation for both thermal conductivity and viscosity. The rising solid concentration of particles and temperature is responsible for higher thermal conductivity. However, in the case of viscosity, shows an increasing trend with increasing fractions of particles but a decreasing trend with increasing temperature. The viscosity enhancement for water-based SWCNT at a volume fraction of 0.73% and 25 ^{0}C is 320% [46]. In this study, the result of dynamic viscosity is also compared with Einstein [47], Brinkman [48] and Batchelor models [49]. Finally, it concluded that the dynamic viscosity of SWCNT / water could not be accomplished using these three models. Moreover, the dynamic viscosity of 30% EG-based MWCNT-TiO_2 (20: 80) is explored for volume concentrations ranging from 0.05 to 0.85% at 10, 30 and 50 °C [50]. Highest viscosity enhancement (83%) was observed at 10 °C for the volume fraction of 0.85% whereas 0.05, 0.45% solid fraction of MWCNT-TiO_2 behaved as Newtonian fluid and 0.85% as non-Newtonian fluid. The study also showed that changes in viscosity with concentration are more incredible at low temperature due to the number of particles and collisions among them.

Some studies have shown that Brownian motion has the effect of modifying nanofluid viscosity [11,51]. The rate of heat transfer also increases with the Brownian parameters, thermophoresis and Biot number [52]. The viscosity of the magneto-hydrodynamic nanofluid radial flow over a stretch plate is related to convective boundary conditions, the temperature and the radiation effect [53]. This study has observed that an increase in viscosity with concentration and temperature profiles increases but the nanofluids velocity decreases. The viscosity variations in nanofluid are due to the brownian motion and interactive force of nanoparticle ions when assessing the effect of ions in the brine solution on salt and silica nanoparticles. The variation of viscosity of nanofluid is related to Brownian motion and interaction force of the ions of nanoparticles while evaluating the impact of various

Table 1
Properties of the nanoparticles TiO_2 and Al_2O_3.

Characteristics	TiO_2	Al_2O_3
Purity (%)	> 99	99.8
Colour	White	White
Average particle diameter (nm)	5-6	13
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 the base fluids.

Characteristics	Water(H_20)	Ethylene Glycol (C_2H_6O)
Ratio	60%	40%
Colour	Colourless and clear	Colourless and clear
Molecular mass (g mol-1)	18.02	62.07
Density (Kgm^{-3})	998.21	1113.20
Melting point(^0C)	0.00	−12.9
Boiling point(^0C)	100	197.3
Thermal conductivity (W m-1 K-1)	0.6	0.224

ions in the brine solution on the salt and silica nanoparticles [51]. The heat transfer coefficients increase by almost 7% and 20%, and the thermal efficiencies increase by 8% and 15% for inlet temperature of 500 K and 600 K when evaluating the effects of a new parabolic trough collector using Al_2O_3-synthetic oil nanofluids [21]. Nonetheless, the thermal efficiency, pressure drop, heat transfer enhances insignificantly by adding nanoparticles to synthetic oil; however, these properties decrease clearly with an increasing inlet temperature of heat transfer fluid. In the field of heat transfer, however, from an extensive literary analysis, the rheological and thermophysical properties of nanofluids play a vital role.

Although various types of research work on nanofluid properties exist, the thermophysical properties of the new hybrid nanofluids, including rheological properties, are yet to be explored. The rheological aspect of the fluids, which is a critical issue for the study of nanofluids, is included with the limited number of studies. Nevertheless, there is no study to predict the thermal conductivity, viscosity and heat transfer efficiency for TiO_2-Al_2O_3 with 40% EG-based hybrid nanofluids. Therefore, the present study focuses on rheology, viscosity and thermal conductivity and their enhancement ratio for different temperatures and concentrations. Hybrid nanofluids thermophysical properties are also compared with single nanofluids properties. In addition, two new models are developed for viscosity and thermal conductivity in concentration and temperature for the studied range. However, for their superior properties, TiO_2 and Al_2O_3 nanoparticles are selected in this investigation. There are therefore supposed to be good stability with enhanced thermal properties and heat transfer performance with the 40% EG-based TiO_2-Al_2O_3 hybrid nanofluids. The superior thermal properties and the potential and widespread use of various nanofluids in industries and research areas, however, motivate authors to pursue the study. In the field of heat transportation and nanotechnology, the new study of 40% EG-based TiO_2-Al_2O_3 nanofluids might add substantial value.

2. Methods and materials

2.1. Synthesization of hybrid nanofluids

The first and foremost process of experimental research in the area of nanofluids is nanofluid synthesization. Two types of TiO_2 and Al_2O_3 nanoparticles have been used to synthesize the hybrid nanofluids. Table 1 shows the properties of the single nanoparticles of TiO_2 and Al_2O_3. In this study, 40% aquatic solution of EG or the 60:40 (W: EG) combination of ethylene glycol and water (W) is used as base fluid. Table 2 reveals the properties of the base fluid. Eq. (1) has been used to determine the volume concentration of TiO_2-Al_2O_3 hybrid nanofluids. This analysis is related to the mixture ratio of nanoparticles of 80:20 (TiO_2: Al_2O_3). The ratio of 80:20 (4:1) is chosen for its excellent fluid uniformity in 40% EG. It is explained extensively in the previously published article [54]. The previous study shows that the ratio of 80:20 shows the best stability in terms of the zeta potential and absorption, with no long exhibition of sedimentation, among all the ratios of 20:80, 40:60, 50:50, 60:40, and 80:20 of TiO_2:Al_2O_3 nanoparticles. Finally, TiO_2-Al_2O_3 hybrid nanofluids (80:20) are synthesized with an interval of 0.02% to 0.1% at five different volume concentrations (0.02, 0.04, 0.06, 0.08, 0.1). The 40% EG-based TiO_2-Al_2O_3 hybrid nanofluids are prepared using the common two-step synthesis method. First, both measured nanoparticles are mixed with base fluid using a 45-min magnetic stirrer. The solution is then inserted into the ultrasonic bath

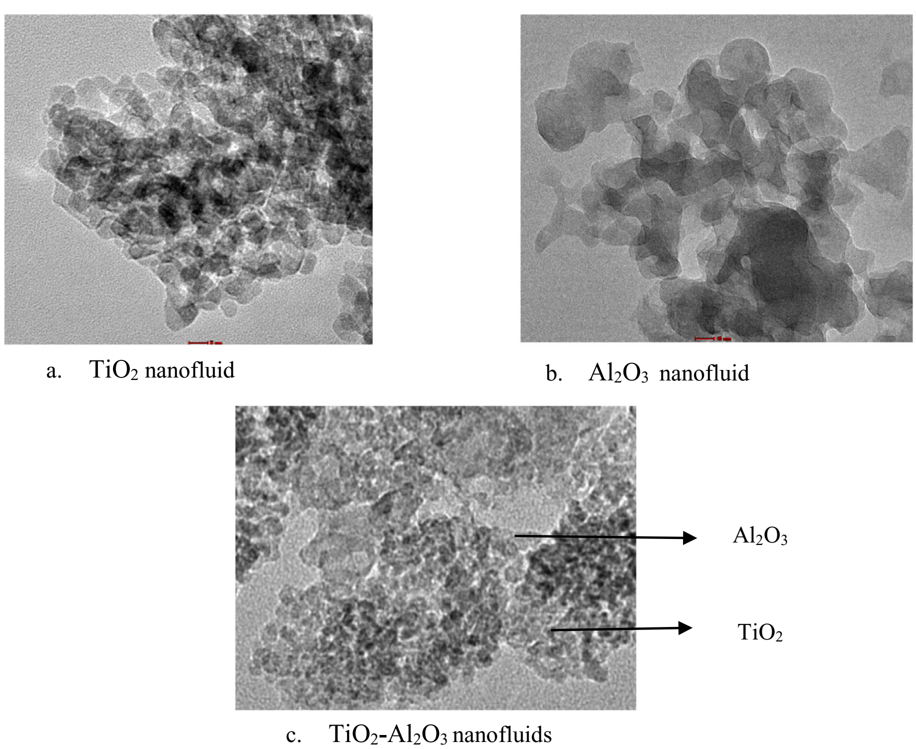
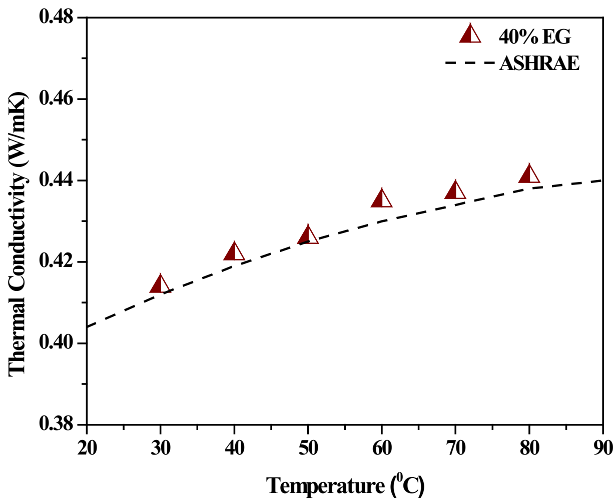
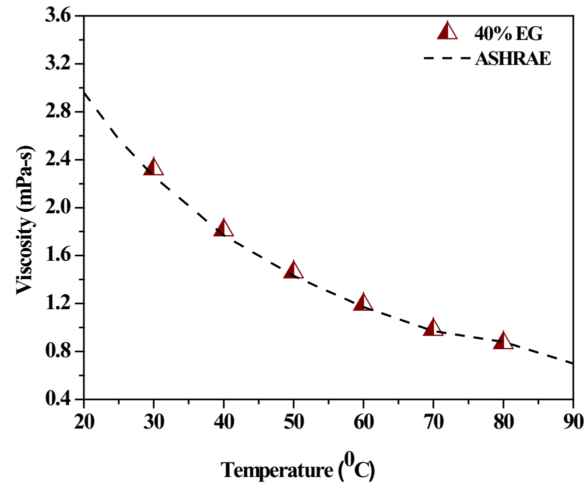


Fig. 1. TEM images of 40% EG based single TiO_2, Al_2O_3 and TiO_2-Al_2O_3 hybrid nanofluids.



a. Thermal conductivity of 40% EG



b. Viscosity of 40% EG

Fig. 2. The validity of the measurement of thermal conductivity and viscosity using KD2 pro and LVDV III Ultra Rheometer.

Table 3
Condition of stability for various zeta potential value [62].

± Value of Zeta Potential (mV)	Stability condition
60	Excellent
45	Good
30	Moderate
15	Light
0	Unstable

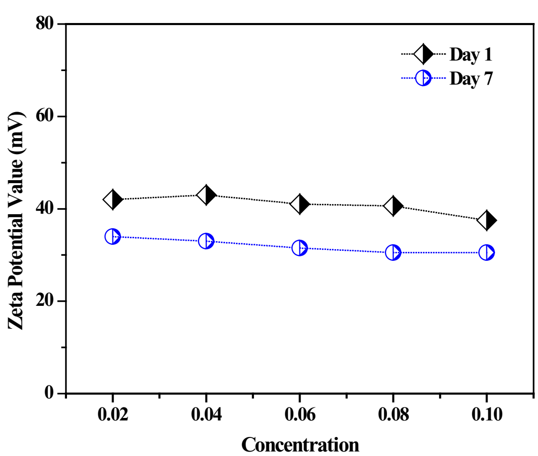


Fig. 3. Zeta potential value of the various concentration of 40% EG based on TiO_2-Al_2O_3 nanofluids.

for 7 h (Section 3.1 UV–Vis Spectral Analysis) to enhance stability without surfactant. Transmission electron microscopy technique (TEM) is used for the size characterization of TiO_2-Al_2O_3 nanofluids. The TEM images of single TiO_2, Al_2O_3 and TiO_2-Al_2O_3 hybrid nanofluids are presented in Fig. 1

$$ø = \frac{\frac{m_{np}}{\rho_{np}}}{\frac{m_{np}}{\rho_{np}} + \frac{m_{bf}}{\rho_{bf}}} * 100 \quad (1)$$

2.2. Stability analysis

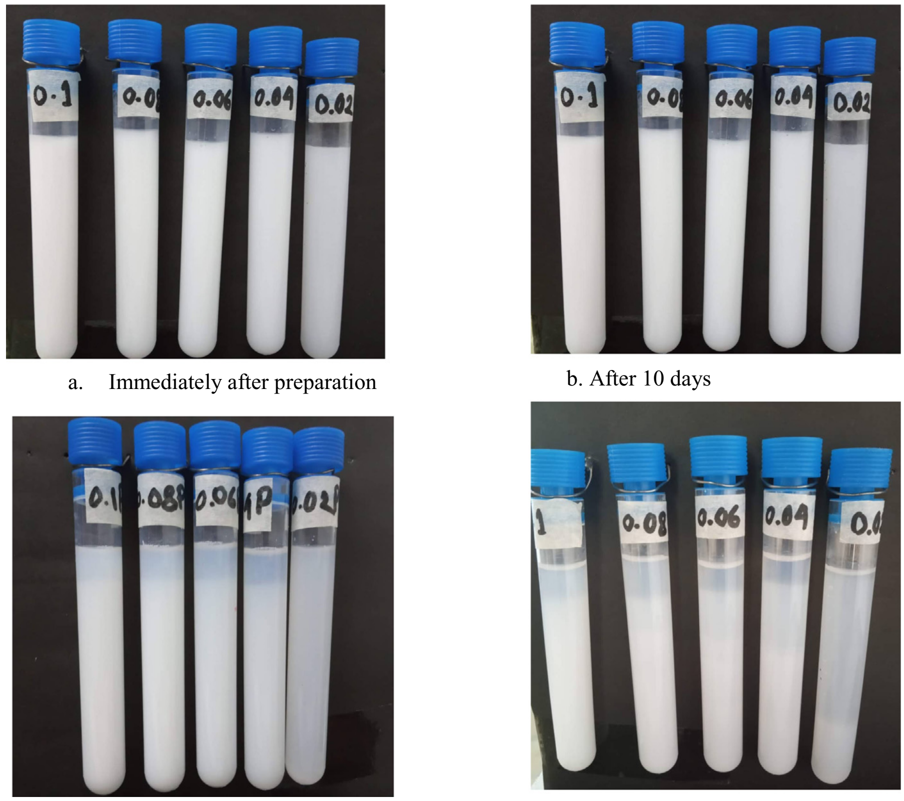
The stability of hybrid nanofluids is assessed by zeta potential test using particle size analyzer (Malvern Zetasizer Ultra- DKSH), absorbency analysis from UV visible spectrophotometer (Genesys 50) and also visual observation. Several researchers have used these methods for stability analysis. [2], Hamid, Azmi, Nabil, Mamat and Sharma [4], for example, used the method of visual sedimentation and UV–Vis spectrophotometry. In addition, the zeta-potential estimation is another method for stability analysis [55]. Numerous researchers used this test to comment on colloidal suspension uniformity [3,56]. All of these three approaches are followed for a specific time in this analysis. Consequently, the results of the stability study become more authentic.

2.3. Thermal conductivity measurement

In order to evaluate the thermal conductivity of TiO_2-Al_2O_3 hybrid nanofluids, KD2 pro thermal property analyzer (Decagon) has been used with the addition of a water bath to maintain the nanofluids consistent temperature. The KD2 pro analyzer fulfils IEEE 442–1981 and ASTM D5334 standards. The KD2 pro sensor, used to evaluate the thermal conductivity, is vertically positioned in the sample with proper attention to prevent data errors [57]. Thermal conductivity is measured at six temperatures ranging from 30 to 80 °C with an interval of 10 ^{0}C. Ten measurements are obtained for each temperature and concentration, maintaining a time interval of 10–15 min, and the average values are eventually recorded.

2.4. Viscosity measurement

The viscosity analysis is carried out using the LVDV III Ultra Rheometer with the addition of a rotating water bath, and the precision of this system is ± 5%. Customized RheoCal program was used to measure the dynamic viscosity of nanofluids at different spindle speeds and temperatures. The analysis of the viscosity of nanofluids is carried out at temperatures between 30 and 80 °C with an interval of 10 °C. The range of viscosity measurements allowed is between 1 and 10 mPa-s. For measuring the viscosity, 16 ml of solution is poured into the cylinder jacket. The cylinder jacket is attached to the Rehometer and the rotating bath. Thus, the temperature of the nanofluid in the jacket is reached to the expected level through the circulating bath. The viscosity measurements are taken for at least five times at an interval of



a. Immediately after preparation

b. After 10 days

c. After 20 days

d. After one month

Fig. 4. Sedimentation Photograph of TiO_2-Al_2O_3 hybrid nanofluids.

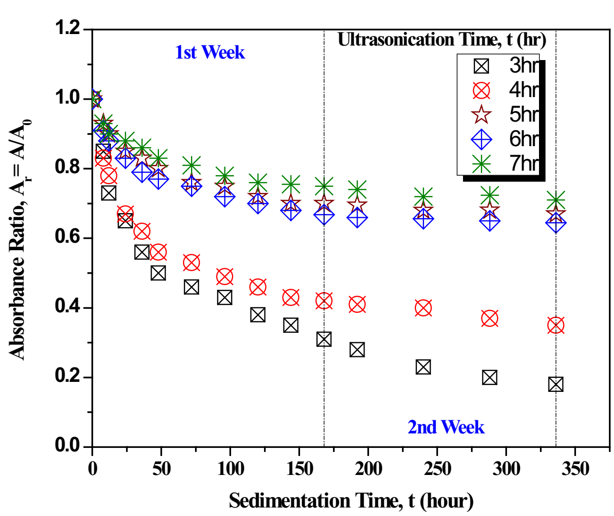


Fig. 5. Variation of the absorbance ratio and sedimentation time, apparently with specific ultrasound periods.

10 min for considered concentrations ($0.02 \le ø \le 0.1$; $\Delta ø = 0.02$), temperatures (30 °C $\le T \le$ 80 °C; ΔT = 10 °C) at different spindle speeds (10 rpm $\le$ V $\le$ 220 rpm; ΔV = 10 rpm) and the final data is then averaged.

2.5. Measurement validation

The reliability of KD2 pro and LVDV III Ultra Rheometer is validated by comparing the current thermal conductivity and viscosity data of 40% EG with the ASHRAE value [58] for the temperature range of 30–80 °C. This technique was also used for the validation purpose by several researchers. The maximum deviation of 2.5% and 1.6% was obtained from the Reddy and Rao [59] and Nabil, Azmi, Hamid, Mamat and Hagos [2] tests, respectively. Fig. 2 shows the validity of the measurement of thermal conductivity and viscosity with a maximum deviation of 0.5 and 2.5% respectively. Thus, it can be concluded that these devices with minimal variation are reliable and effective for measurement purposes. In comparison, in the case of thermal conductivity and viscosity, respectively, the properties of 40% EG accompanied the rising and decreasing pattern of temperature.

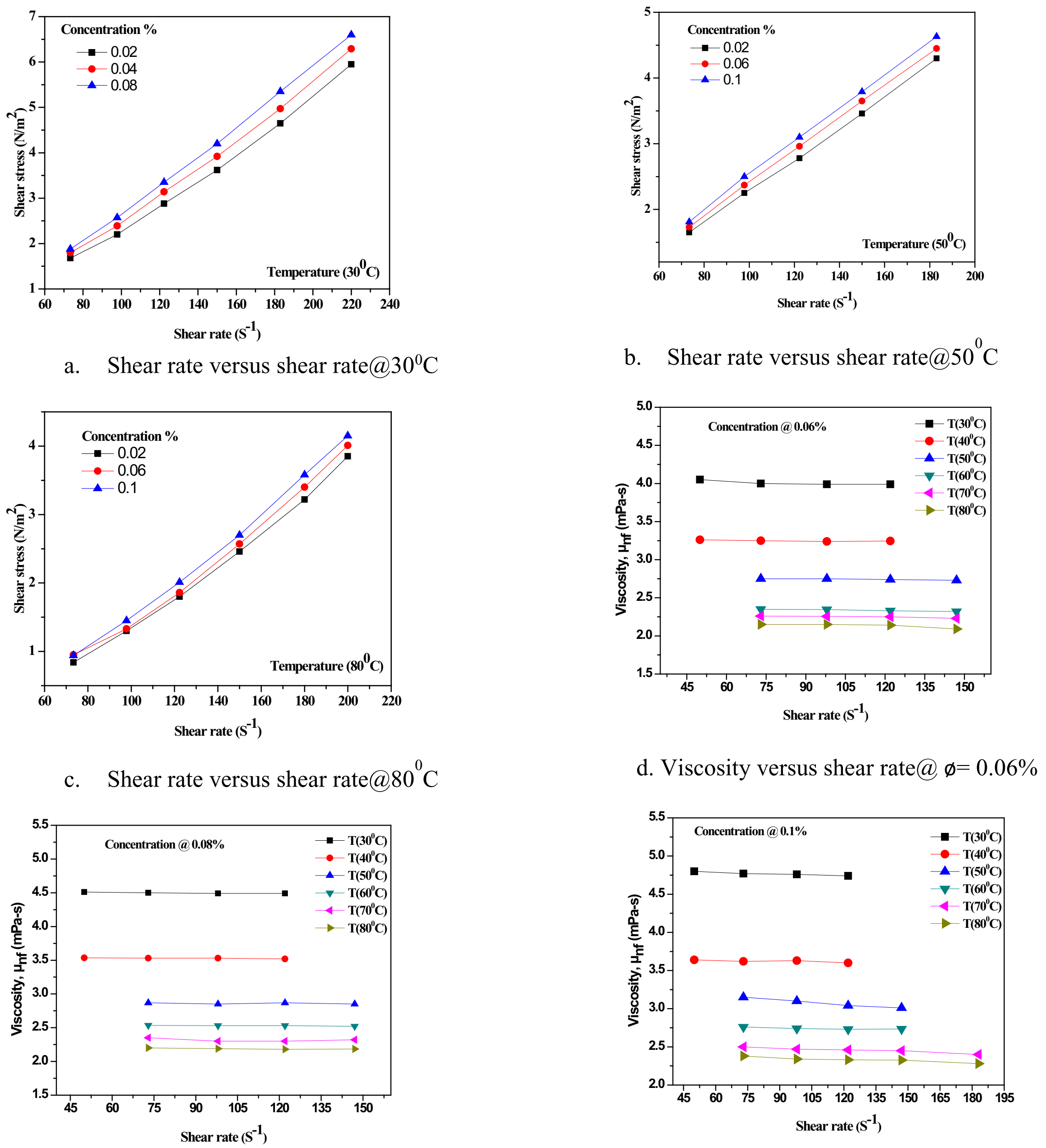
3. Results and discussion

3.1. Stability analysis

3.1.1. Zeta potential measurement

Zeta potential measurement is one of the essential quantitative methods for nanofluid stability assessment related to the electrophoretic behaviour of nanofluids [28,55]. The main benefit is that the test is simple and fast [60]. The higher the value of zeta, the higher repulsive forces among nanoparticles will lead to stability. Ghadimi, Saidur and Metselaar [61] state that zeta potential value of 30 mV or higher indicates good stability. The standard zeta potential value range is presented in Table 3.

In this analysis, this technique is used to depict the dispersibility of the nanoparticles in the base fluid. This test is performed immediately after nanofluid preparation and seven days later. The maximum value for zeta potential of 40% EG based TiO_2-Al_2O_3 hybrid nanofluids is obtained after preparation by 43 mV. The zeta potential value for different concentrations of nanofluids is shown in Fig. 3. As 30 mV zeta potential value implies good stability, and as the minimum zeta potential value is 37.5 mV in the present study, the present zeta potential



a. Shear rate versus shear rate@30⁰C

b. Shear rate versus shear rate@50⁰C

c. Shear rate versus shear rate@80⁰C

d. Viscosity versus shear rate@ ø= 0.06%

e. Viscosity versus shear rate@ ø= 0.08%

f. Viscosity versus shear rate@ ø= 0.1%

Fig. 6. Rheology of 40% EG-based TiO_2-Al_2O_3 hybrid nanofluids for various concentrations and temperatures.

value has shown excellent nanofluid stability. Although after a week, all nanofluid samples show good zeta stability.

3.1.2. Visual observation

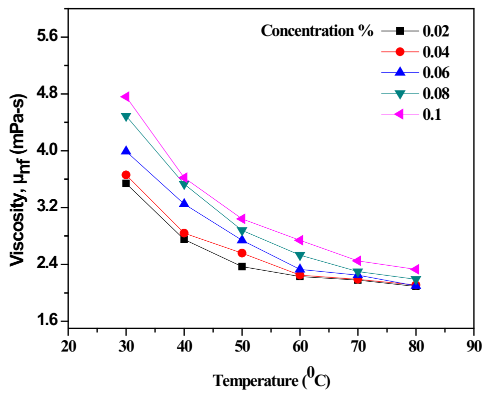
Samples of the nanofluids tested are analyzed for one month by taking time-to-time sedimentation photographs to assess the stability period. Other researchers have also used this method to describe the stability of suspensions [4,63]. Fig. 4 displays the sedimentation photographs of TiO_2-Al_2O_3 nanofluids at different periods. It is clear from the figure that all the samples are in good condition in terms of stability even after two weeks. Few nanoparticles start to sediment in the third week. It could be due to gravity and the strong force of van der Walls [64] among the particles. However, the TiO_2-Al_2O_3 nanofluids are stable for two weeks, and the spectral analysis of UV–Vis confirms the finding. In this analysis, a suspension homogeneity is only achieved through an ultrasonic period of 7 h. Additional methods, such as surfactant use and particle surface modification, may be used to achieve long term stability that can be potential scope for future research.

3.1.3. UV–Vis spectral analysis

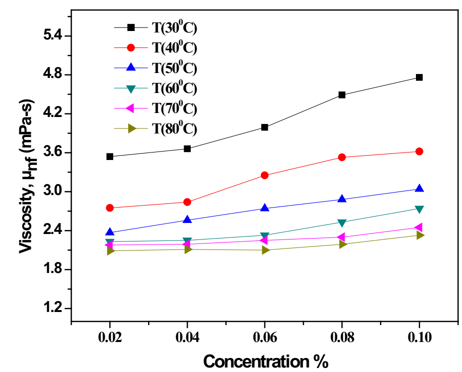
The UV–Vis spectral analysis is carried out through the Ultra Violet-Visible spectrophotometer (GENESYS 50) to assess the stability of nanofluids. In this analysis, the samples are examined to determine the wavelength. Furthermore, for this wavelength, 903 nm is chosen as the peak absorption value for every sample. Here, the nanofluid absorption is assessed by comparing the light intensity and base fluid [61].

Fig. 5 shows the absorbance ratio against sedimentation time for various ultrasonication time. Eq. (2) is used to measure the absorbance ratio of a sample.

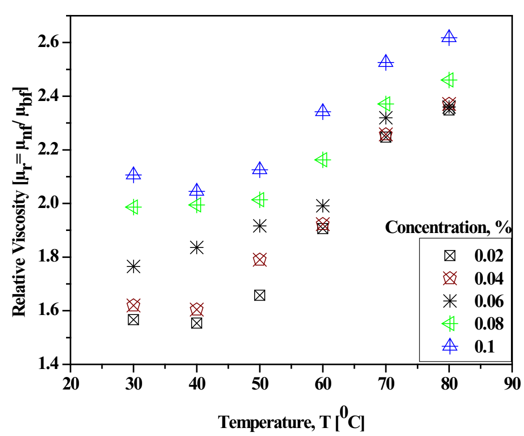
$$A_r = \frac{A}{A_0} \tag{2}$$



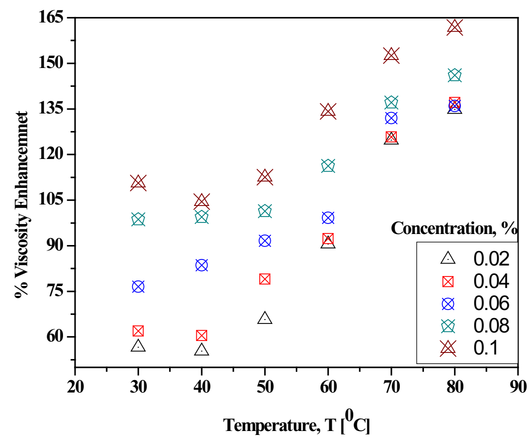
a. Viscosity versus temperature.



a. Viscosity versus concentration.



c. Relative viscosity versus temperature.



d. Percentage of viscosity enhancement for various temperatures and concentrations.

Fig. 7. Viscosity variation (a) (b), relative viscosity (c) and Percentage of viscosity enhancement for various concentrations and temperatures (d).

where A_r is the absorbance ratio, A is the final absorbance of a sample at a particular time, A_0 indicates the initial absorbance of the sample.

The absorbance ratio of 1 shows excellent suspension stability [4]. This approach has been proposed by many researchers for stability analysis [58,65,66]. From Fig. 5, it is evident that the absorbance ratio shows the highest value of more than 70% even after two weeks for 7 h of sonication time compared to other studied ultrasonic times (3, 4, 5, 6 h). Therefore, in this research, the preparation time of nanofluids requires 7 h of sonication time, and it can be inferred that the samples have excellent stability for more than two weeks.

3.2. Rheology of nanofluids

Research on the rheological behaviour of prepared samples after a stability analysis is the deciding step of this study. It is an important issue for researchers to discuss. In addition, this property is the main condition in order to study nanofluid viscosity. Newtonian behaviour of nanofluids can be explained by Eq. (3).

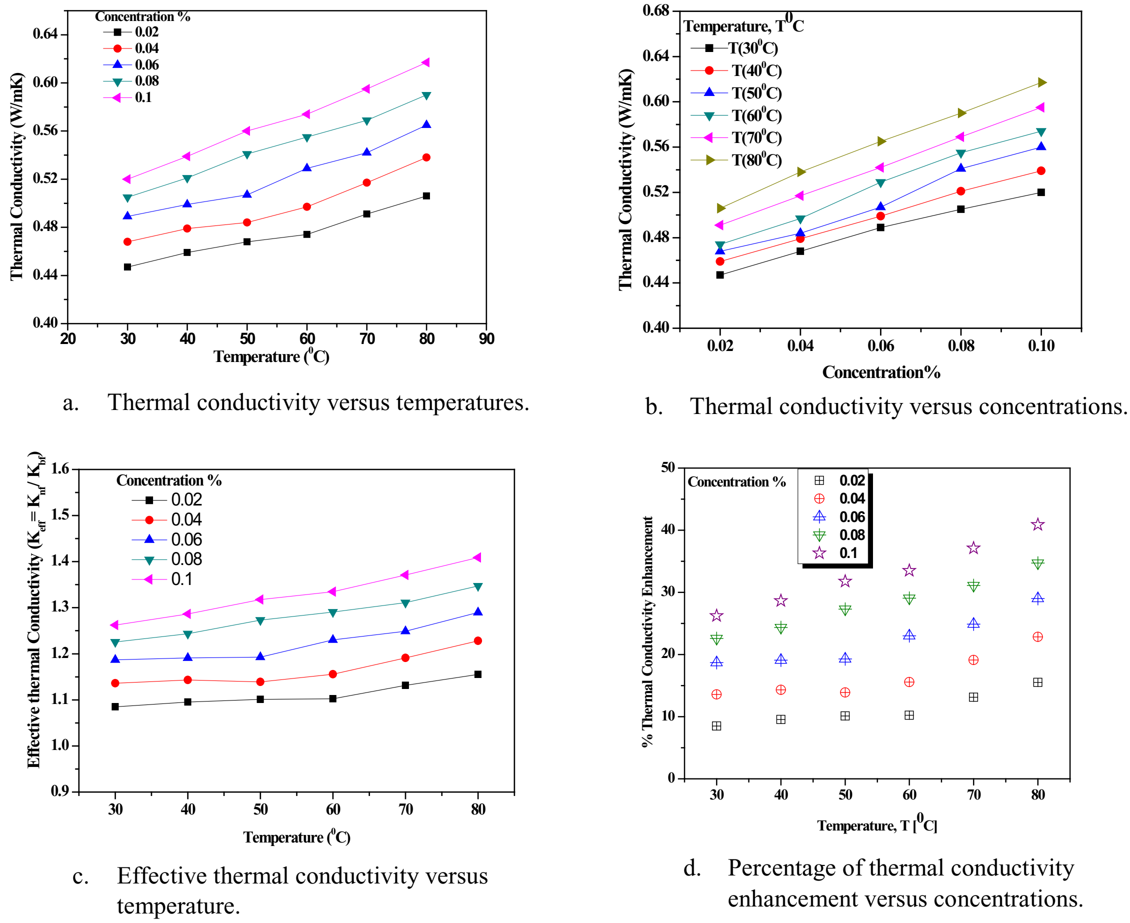
$$□ = \mu \gamma \qquad (3)$$

where T is the shear stress, μ represents the viscosity and γ represents shear strain.

Fig. 6(a-c) shows that the shear stress linearly increases with the shear rate for temperatures 30 °C (ø = 0.02, 0.04, 0.08%), 50 °C (ø = 0.02, 0.06, 0.1%) and 80 °C (ø = 0.02, 0.06, 0.1%) respectively. In the same way, other samples of TiO_2-Al_2O_3 with rest of the volume concentrations and temperatures behave like a Newtonian fluid. Moreover, Fig. 6 (d-f) represents the viscosity behaviour of studied samples for various shear rates at volume concentrtaions of 0.06, 0.08, 0.1% and temeratures ranging from 30 to 80 °C which confirms about the Newtonian behaviour of nanofluids again.

3.3. Viscosity of hybrid Nanofluid of TiO_2-Al_2O_3

The viscosity measurement of TiO_2-Al_2O_3 hybrid nanofluids is conducted at the range of temperature 30–80 °C. Fig. 7(a) and (b) display the value of viscosity for various temperatures and concentrations. From the figure, it is evident that the TiO_2-Al_2O_3 hybrid nanofluids exhibit higher viscosity than 40% EG and viscosity shows a rising trend with increasing concentration but a declining trend with increasing temperature. The internal shear stress is increased for a higher concentration solution, leading to increased viscosity [4]. However, the interactions between nanoparticles and base fluid are also responsible for viscosity improvements, according to Bahrami, Akbari, Karimipour and Afrand [67]. The addition of an increased amount of nanoparticles increases the likelihood of agglomeration, which delays the normal suspension movement, thereby increasing viscosity. The measurement of the percentage of viscosity enhancement can be expressed by Eq. (4). The enhancement is, however, more steeper at 30 and 40 °C but gradual at higher temperatures (50–80 °C) (Fig. 7(b)). When the temperature becomes higher, the Van der Walls force is weak between particles; therefore, the viscosity reduces [66,68]. The 0.1% concentration solution shows the highest viscosity value at 30 °C, whereas a 0.02% concentration solution shows the lowest viscosity at 80 °C. The viscosity



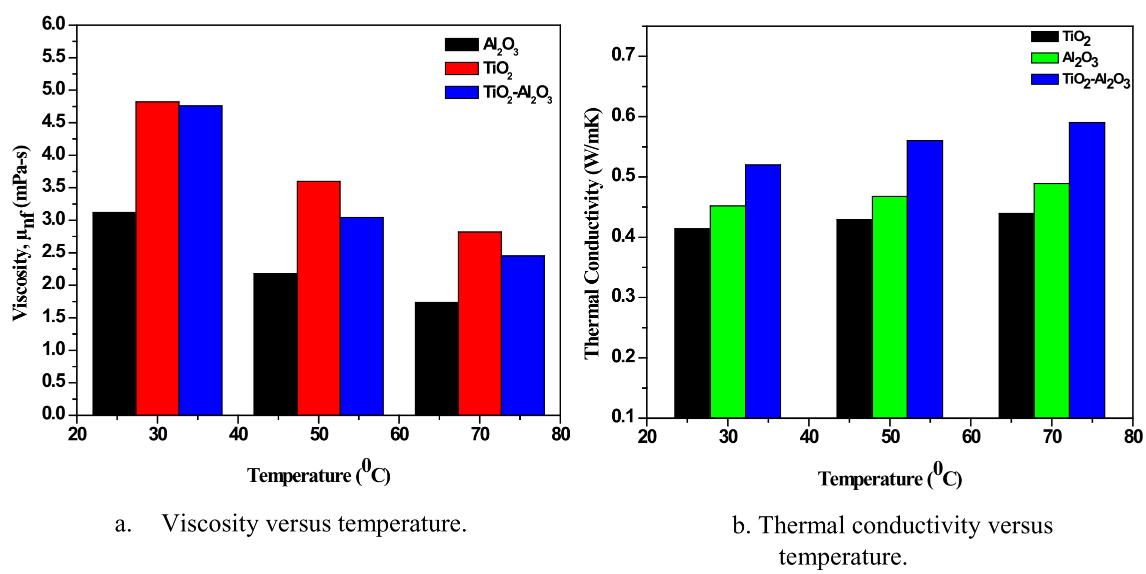
a. Thermal conductivity versus temperatures.

b. Thermal conductivity versus concentrations.

c. Effective thermal conductivity versus temperature.

d. Percentage of thermal conductivity enhancement versus concentrations.

Fig. 8. Thermal conductivity variation (a, b), effective thermal conductivity (c) and Percentage of thermal conductivity enhancement for various concentrations and temperatures (d).



a. Viscosity versus temperature.

b. Thermal conductivity versus temperature.

Fig. 9. Comparison of the thermal conductivity and viscosity of single (TiO_2, Al_2O_3) and hybrid nanofluids (TiO_2-Al_2O_3) with a volume concentration of 0.1%.

ratio and viscosity enhancement for various temperatures and concentrations are showed in Fig. 7(c) and (d) respectively. The maximum relative viscosity is found to be 161.80% enhancement for 0.1% concentration at 80 °C while the minimum value of relative viscosity is derived 56.64% enhancement for 0.0.2% concentration at 30 °C.

$$\text{Viscosity Enhancement } (\%) = \left(\frac{\mu_{nf}}{\mu_{bf}} - 1 \right) * 100 \tag{4}$$

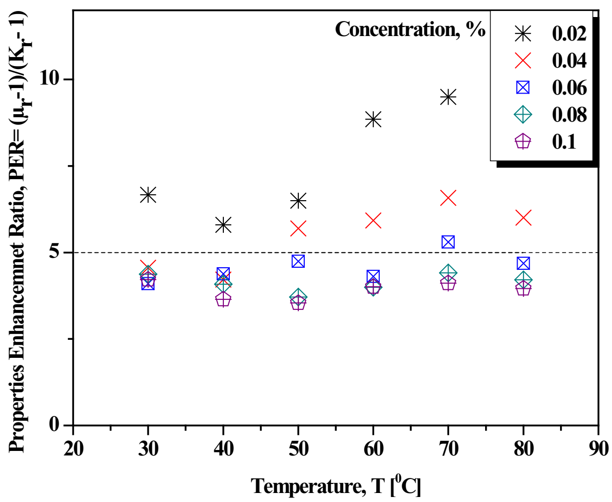


Fig. 10. Heat transfer efficiency of 40% EG-based TiO_2-Al_2O_3 hybrid nanofluids.

3.4. Thermal conductivity of TiO_2-Al_2O_3

The thermal conductivity of TiO_2-Al_2O_3 hybrid nanofluids is evaluated with a temperature range of 30–80 °C. Fig. 8(a) and (b) describe the variation of thermal conductivity of TiO_2-Al_2O_3 hybrid nanofluids for different concentrations and temperatures. From the Fig. 8(a) and (b), it is clear that for all the concentrations and temperatures, the thermal conductivity of TiO_2-Al_2O_3 hybrid nanofluids is greater than 40% EG due to the addition of nanoparticles and their superior properties while compared with the ASHRAE [58] value of 40% EG. In addition, due to the increasing number of nanoparticles, the actual value of thermal conductivity is significantly increased for the constant temperature. The increased number of nanoparticles means a larger nanoparticle interface, which leads to an increase in thermal conductivity [69]. Similarly, the rise in thermal conductivity with increasing temperatures represents an increasing number of collisions between particles due to Brownian movement [3,4]. This increased interaction between particles generates more kinetic energy, thus increasing thermal conductivity [4]. It is also observed (Fig. 8(a)) that temperature effects on thermal conductivity at high volume concentrations are relatively high compared to low volume concentrations. Eq. (5) is used to measure the percentage of thermal conductivity enhancement. The effective thermal conductivity and enhancement of thermal conductivity for various concentrations along with temperatures are shown in Fig. 8(c) and (d). The solution with concentration of 0.02% shows the lowest increase in thermal conductivity, while the solution with 0.1% provides the maximum improvement of up to 40.86% at 80 °C.

$$\textit{Thermal Conductivity Enhancement}\ (\%) = \left(\frac{K_{nf}}{K_{bf}} - 1\right) * 100 \tag{5}$$

3.5. Thermophysical properties comparison with TiO_2 and Al_2O_3

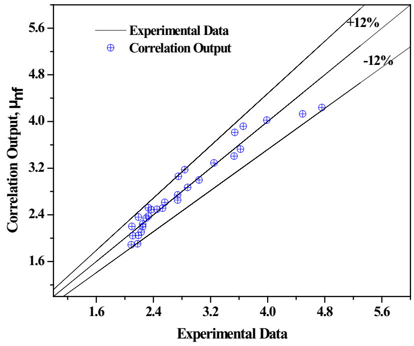
In this section, the thermophysical properties of TiO_2-Al_2O_3 hybrid nanofluids are compared to TiO_2 and Al_2O_3 single nanofluids. For this purpose, the single nanofluids of TiO_2 and Al_2O_3 based on 40% EG are synthesized using the two-step method at a volume concentration of 0.1%. The thermophysical properties of single nanofluids are measured for three different temperatures of 30, 50 and 70 °C. The comparison of the viscosity and thermal conductivity of hybrid (TiO_2-Al_2O_3) and single nanofluids (TiO_2 and Al_2O_3) is shown in Fig. 9(a) and (b) respectively. It is evident from Fig. 9(a) that the viscosity values of single and hybrid nanofluids are decreasing with temperatures, and the decreasing pattern of hybrid TiO_2-Al_2O_3 is slightly steeper than the single TiO_2 and Al_2O_3 nanofluids. The highest viscosity is found for TiO_2, while Al_2O_3 experiences the lowest viscosity. However, the hybrid TiO_2-Al_2O_3 nanofluid viscosity is less than TiO_2 but is greater than Al_2O_3, i.e. between TiO_2 and Al_2O_3 viscosity. Unlikely, the hybrid nanofluid shows the higher thermal conductivity than both TiO_2 and Al_2O_3 single nanofluids. It is clear from Fig. 9(b) that the TiO_2 has the lowest thermal conductivity while the TiO_2-Al_2O_3 hybrid nanofluids have the highest conductivity. It is due to the compounding of two nanoparticles that have improved the thermal behaviour of hybrid nanofluids. The combination of TiO_2 and Al_2O_3, on the contrary, does not geometrically increase viscosity. Therefore, the combined effect of nanoparticles TiO_2 and Al_2O_3 on thermal behaviour can also be inferred to be more significant compared to viscosity. However, this improved thermal conductivity and low viscosity may potentially influence the use of heat transfer systems in a practical way.

3.6. Heat transfer efficiency

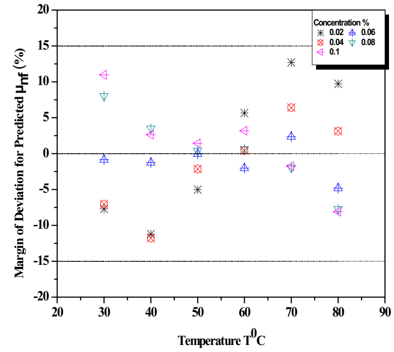
Another essential problem is the heat transfer efficiency prediction of the 40% EG-based TiO_2-Al_2O_3 hybrid nanofluids with the properties enhancement ratio (PER). The properties enhancement ratio reveals the fluid with optimum thermal conductivity and viscosity [70]. The PER is defined as the ratio of the increment of viscosity and thermal conductivity [71]. This ratio is also suggested in the case of internal laminar flow to show the fluid heat transfer efficiency. The PER value of less than five (PER < 5) is known as a more efficient heat transfer fluid than traditional fluids [70]. Fig. 10 reflects the PER value of TiO_2-Al_2O_3 for the range of temperatures and concentrations tested. The nanofluids with volume concentrations of 0.06, 0.08 and 01% indicate PER values of less than five except for 0.02 and 0.04% volume concentrations. The concentrations above 0.04 of TiO_2-Al_2O_3 hybrid nanofluids are an excellent fluid for the heat transfer. Since the low concentration PER value (0.02, 0.04%) exceeds 5, this concentration can be avoided for heat transfer. Subsequently, the nanoparticles have been incorporated into the base fluid; the thermal conductivity is enhanced significantly in contrast with viscosity, the PER values are lower than 5 for hybrid nanofluids with a greater concentration of 0.06, 0.08, and 0.1%. However, nanofluid with concentrations of 0.02 and 0.04% have a considerably higher PER value because it contains very few amounts of particles that have a comparatively lower increase in thermal conductivity. In addition, the rate of thermal conductivity improvement from temperature 60 to 80 °C, similar to the previous research [72,73], is comparatively higher. Because the collision between molecules or molecular movement in the fluid increases at the higher temperature. The molecules, therefore, achieve better energy together with vibration. Due to this molecular motion and vibration, these molecules transfer some energy to the nearby particles and thus increase thermal conductivity, which is similar to Brownian motion [72]. Similarly, due to the impact of Brownian motion, viscosity behaviour is also varied [11]. Therefore, the combined effects of increased thermal conductivity and lower viscosity improve the heat transfer capacity [74]. In addition, Sheikholeslami, Gerdroodbary, Moradi, Shafee and Li [5] also reported that using nanoparticles into the base fluid can enhance the heat transfer rate. Nevertheless, 40% EG-based TiO_2-Al_2O_3 hybrid nanofluids can be used as coolant and lubricant in machining and energy management in the automotive section. The flow can be called laminar in a variety of moving parts. Thus, in specific thermal applications with a higher viscosity than the base fluid, the enhanced heat transfer characteristics of the TiO_2-Al_2O_3 hybrid nanofluids can therefore play a beneficial role. To confirm the anticipation of this finding, further heat transfer experimental research is needed.

3.7. Regression analysis

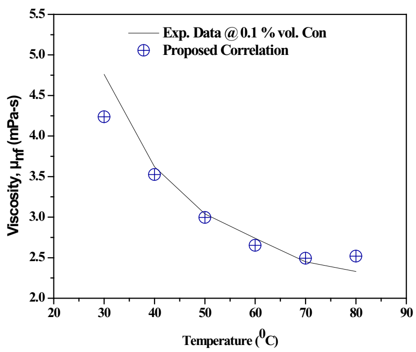
Experimental data are used to estimate the viscosity and effective



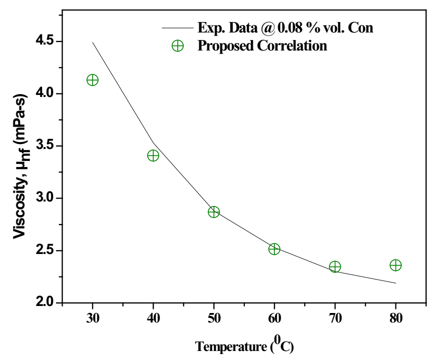
a. Experimental data versus correlation output.



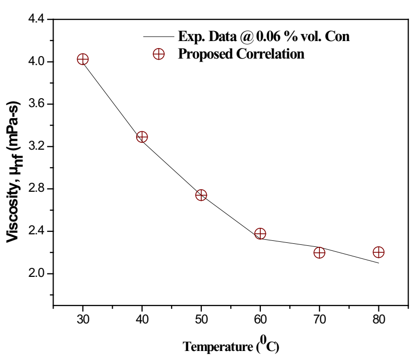
b. Margin of deviation for the proposed equation of viscosity.



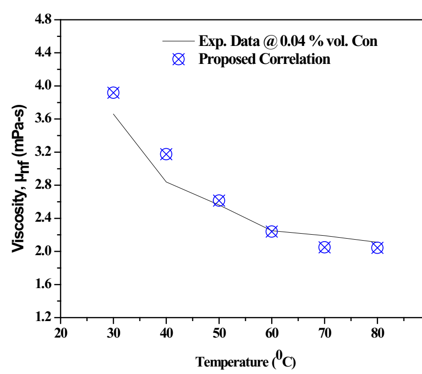
(c) Viscosity variation between measured and predicted data from proposed model at 0.1% vol. conc.



(d) Viscosity variation between measured and predicted data from proposed model at 0.08% vol. conc.



(e) Viscosity variation between measured and predicted data from proposed model at 0.06% vol. conc.



(f) Viscosity variation between measured and predicted data from proposed model at 0.06% vol. conc.

Fig. 11. Accuracy of the proposed model of viscosity.

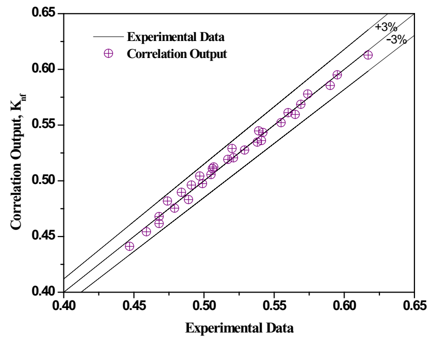
thermal conductivity of TiO_2-Al_2O_3 hybrid nanofluids through regression analysis. It is evident from the statistical analysis that Eq. (6) and Eq. (7) represent the viscosity and thermal conductivity that are suitable for 80:20 mixture ratio of TiO_2-Al_2O_3 in 40% EG for temperatures ranging from 30 to 80 °C and concentration from 0.02 to 0.1%.

$$\mu_{nf} = 7.1074 + 3.65ø - 0.14097T + 0.05176øT + 0.907ø^2 + 0.00092T^2 \quad (6)$$

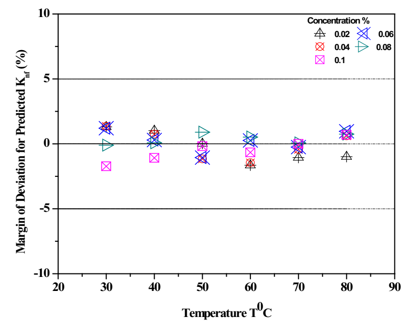
$$K_{nf} = 0.386\ \exp(2.27ø + 0.002939T) \quad (7)$$

The predicted results from both these viscosity and thermal conductivity equations show significant agreement with the measured data shown in Figs. 11 and 12. Furthermore, for both equations, the variance analysis is performed to calculate the accuracy of the proposed model. For evaluating the percentage deviation, Eqs. (8) and (9) are used. The average, minimum and maximum deviation for thermal conductivity equation are 0.75, 0.0005 and 1.73% respectively. Similarly, for the viscosity are 4.82, 0.053 and 12.70% respectively. It is therefore clear that, for thermal conductivity and viscosity equations, the highest margin of deviation (MOD) between the measured and predicted value is less than 2 and 15% respectively which indicate the high accuracy of the proposed thermal conductivity model and good accuracy of the proposed viscosity model.

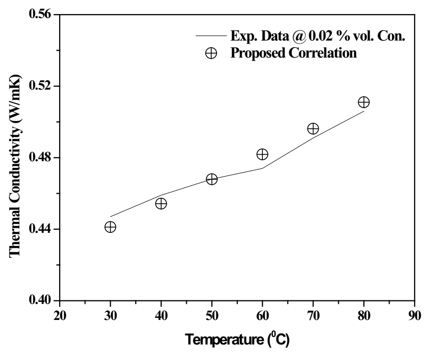
$$\%of\ Deviation = \left[\frac{(\mu_{nf})_{Exp.} - (\mu_{nf})_{Pred.}}{(\mu_{nf})_{Exp.}}\right] * 100 \quad (8)$$



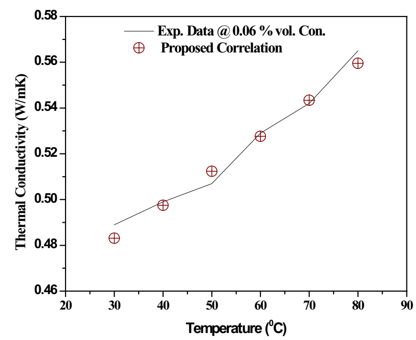
a. Experimental data versus correlation output.



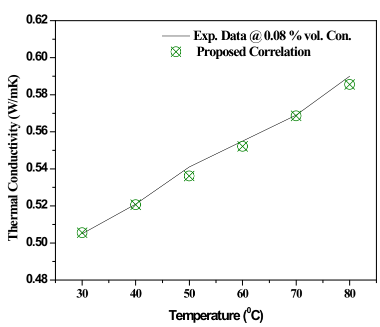
b. Margin of deviation for the proposed equation of thermal conductivity.



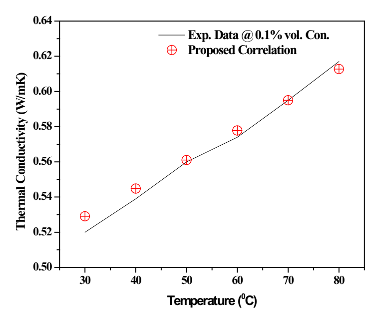
(c) Thermal conductivity variation between measured and predicted data from proposed model at 0.02% vol. conc.



(d) Thermal conductivity variation between measured and predicted data from proposed model at 0.06% vol. conc.



(e) Thermal conductivity variation between measured and predicted data from proposed model at 0.08% vol. conc.



(f) Thermal conductivity variation between measured and predicted data from proposed model at 0.1% vol. conc.

Fig. 12. Accuracy of the proposed model of thermal conductivity.

$$\%of\,Deviation = \left[\frac{(K_{nf})_{Exp.} - (K_{nf})_{Pred.}}{(K_{nf})_{Exp.}}\right] * 100 \quad (9)$$

4. Conclusion

In this analysis, 40% EG-based TiO_2-Al_2O_3 (80:20) hybrid nanofluid is synthesized using the most common and suggested two-step process, a new heat transfer fluid for its superior properties. The stability of 40% EG based TiO_2-Al_2O_3 hybrid nanofluid is analyzed using visual sedimentation photograph, UV- Vis spectral analysis and zeta potential test. The findings of the three methods have shown that the prepared nanofluids have excellent stability for over more than two weeks. The thermophysical characteristics of nanofluids including the rheology were explored for specific concentrations ($0.02 \le ø \le 0.1$; $\Delta ø = 0.02$) and temperatures (30^0C $\le T \le 80^0$; $\Delta T = 10$ °C). TiO_2-Al_2O_3 nanofluids also established to be Newtonian fluid for the ranges of temperatures and concentrations tested by measuring shear stress, shear rate and viscosity. In comparison, the nanofluid viscosity is found to be increased with increasing solid concentration of nanoparticles, while viscosity value decreases with increasing temperature. The viscosity variations are more at lower temperature with a constant volume concentration than at higher temperature. On the contrary, experimental thermal conductivity results show a rising trend for both increasing particle concentration and temperature. Maximum improvement in thermal conductivity of 40.86% at 0.1% concentration and 80 °C is observed, and the effect of temperature on the thermal conductivity of TiO_2-Al_2O_3 is greater for nanofluids with higher concentrations than for lower concentrations. The thermal conductivity of TiO_2-Al_2O_3 hybrid nanofluid is higher than that of TiO_2 and Al_2O_3 single nanofluids while the hybrid nanofluid viscosity is in between TiO_2 and Al_2O_3 single nanofluids. In addition, the performance enhancement ratio of nanofluids has been investigated by the study of viscosity and thermal conductivity improvement, suggesting optimal viscosity and thermal conductivity of nanofluids for heat transfer applications. The findings recommended a better heat transfer efficiency of the nanofluids with a concentration of above 0.04%. In addition, two new models for the viscosity and thermal conductivity of hybrid nanofluids with experimental data are also established, and both viscosity and thermal conductivity models show good accuracy for the concentrations and temperatures studied. Eventually, it can be concluded that the latest 40% EG-based TiO_2-Al_2O_3 hybrid nanofluids can be used as a possible coolant in machining as coolant performance depends on these thermophysical properties and can also be used in automotive industries.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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