An experimental study on the thermophysical properties of Al_2O_3-TiO_2/ Ethylene Glycol-Water hybrid nanofluid at different concentrations and temperatures

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A nanofluid is a fluid in which particles with a size between 1 and 100 nm are permanently suspended in the base fluid. The addition of nanoparticles affects the thermophysical properties of the liquid. In this study, the effect of temperature and concentration of alumina and titanium dioxide nanoparticles on the thermal conductivity and dynamic viscosity of a base fluid comprised of water and ethylene glycol was investigated. The volume fraction of the nanoparticles was 0.05, 0.1, 0.5, and 1 %vol. and the test temperatures were chosen to be between 260 and 305 K. SEM and TEM were used to examine the nanoparticles' morphology and microstructure. XRD analysis was used to detect phases in nanoparticles. BET analysis was also used to determine the specific area and porosity of the nanoparticles. The hybrid nanofluids' thermal conductivity and dynamic viscosity were measured and compared to the base fluid. The results showed that the thermal conductivity of the Al_2O_3-TiO_2/ethylene glycol-water hybrid nanofluid depended on the concentration of nanoparticles and temperature. The findings revealed that the thermal conductivity of hybrid nanofluids increases with temperature and nano-additive concentration. Moreover, the viscosity increases with the increasing volume fraction of nanoparticles. As the results show, the viscosity changes with temperature are more pronounced at higher concentrations. [DOI: 10.22034/ASAS.2022.163105]

Keywords: Al_2O_3 and TiO_2 nanoparticles; hybrid nanofluid; Dynamic viscosity; Thermal conductivity; Hybrid nano-additives concentration

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Introduction

A liquid that transfers heat from one component to another is called a heat transfer fluid. These fluids are used in processes where cooling or heating is required to reach and maintain a specific temperature. In heat transfer of fluids, temperature difference, cross-sectional area, and heat transfer coefficient are the parameters that affect the heat transfer rate in heat exchangers[1]. If the heat transfer rate is to be increased, this can be achieved by increasing the heat transfer coefficient of the fluid. One of the factors that affect the heat transfer coefficient is viscosity, which plays a vital role in the relationships that govern heat transfer[1], [2]. In some applications, nanofluid is used to improve the heat transfer properties of the fluid. Nanofluids are a new type of heat transfer agent resulting from the uniform and stable dispersion of nanoparticles (usually less than 100 nanometers) in a base fluid. Common base fluids are water, ethylene glycol, propylene glycol, and motor oil. The ability to lower the freezing point of water, the low vapor pressure, and the relatively low corrosion of ethylene glycol make it a suitable fluid for use as a freezing point depressant of water and as a heat transfer fluid in refrigeration systems[2]–[6].

Nanofluids can be divided into two main categories: Single nanofluids and hybrid nanofluids[7]. Owing to their excellent heat transfer properties, nanofluids have attracted researchers' attention recently[8]–[12]. Studies show that the thermal conductivity of nanofluids is significantly higher than that of conventional liquids. This behavior depends on factors such as the shape of the nanoparticles, their size distribution and volume fraction, temperature, the thermal conductivity of the nanoparticles, and the base fluid. Various studies show that the smaller the nanoparticles, the higher the effective thermal conductivity[11], [13]–[15]. It has also been reported that the effective thermal conductivity of nanofluids increases as the number of nanoparticles increases. The effective thermal conductivity of nanofluids and their Brownian motion increase with increasing temperature[16], [17].

In the last decade, the heat transfer properties of nano-

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fluids have been extensively studied. Consideration has been given to using nanofluid systems for various applications. In the context of heat transfer, the viscosity of nanofluids is critical. However, most research has been done specifically to increase the heat transfer rate in heating applications at medium and high temperatures[18]–[20]. Due to the lack of studies on the application of nanofluids at low temperatures (below zero), the application and commercialization of the use of nanofluids at low temperatures have not progressed[17].

Because the particles in nanofluids are so small, there are fewer problems with corrosion, contamination, and pressure drop, and the stability of the fluids against sedimentation is critical. Surfactants and the physical or chemical bonding of polymer chains on the surface of nanostructures are two techniques that can be used to increase the stability of nanofluid suspensions and consequently improve thermal conductivity[1], [3], [21].

Among the factors affecting the properties of nanofluids, the nanoparticle concentration parameter can be considered a crucial factor because properties such as viscosity, density, pH, heat capacity, thermal conductivity, heat transfer coefficient, and stability of nanofluids are directly affected by the concentration of nanoparticles. It has also been shown that increasing the concentration of nanoparticles leads to greater instability of the nanofluid[3], [18], [22], [23]. On the other hand, it should be considered that increasing the concentration of nanoparticles increases the cost of production and industrial application of nanofluids. In general, nanoparticles with concentrations ranging from 0.1 to 10% by weight are used to produce various nanofluids[6].

In this study, the influence of nanoparticle concentration and temperature on the thermophysical properties and rheological behaviour of a hybrid Al_2O_3-TiO_2/ethylene glycol-water nanofluid was experimentally studied. In order to achieve this, nanofluid samples with various solid volume fractions were prepared and examined at various shear rates and temperatures. Currently, the hybrid nanofluids are prepared with a water-ethylene glycol mixture (WEG 50:50 vol% at 25oC) and surfactants such as oleic acid (OA) and sodium dodecyl sulfonate (SDS). Nanoparticle concentrations of 0.05, 0.1, 0.5 and 1 volume % were investigated. In addition, the properties of the hybrid nanofluids were experimentally evaluated in the temperature range of 260 to 305 K to confirm their performance at low temperatures and demonstrate their potential applications.

Materials and methods

The first step in the present study is the preparation of the stable nanofluid. The stability of nanofluids is of great importance in maintaining their thermophysical properties. The use of surfactants is one of the most effective solutions to improve the stability of nanofluids, as they prevent the agglomeration of nanoparticles by reducing the surface tension of the base fluid.

The TiO_2 and Al_2O_3 nanoparticles used in this study were obtained from US research nanomaterials (USA) with the properties tabulated in Tables 1 and 2.

Table 1- Specifications of TiO_2 nanoparticles used in this study

Parameter	Value
Purity	99+%
Color	white
Size	21 nm
Morphology	nearly spherical
Specific surface area (SSA)	220 m^2/g
Density	3900 kg/m^3

Table 2- Specifications of Al_2O_3 nanoparticles used in this study

Parameter	Value
Purity	99+%
Color	white
Size	15 nm
Morphology	nearly spherical
Specific surface area (SSA)	138 m^2/g
Density	3890 Kg/m^3
Specific heat capacity	880 J/(Kg-K)

In this study, a combination of ethylene glycol and distilled water with a ratio of 50:50 vol. % at 298 K was considered as the base fluid, 0.2 vol. % of oleic acid (OA) and 0.2 wt% of sodium dodecyl sulfonate (SDS) were added to the base fluid as a surfactant to stabilize and disperse the nanoparticles. Tables 3 and 4 show the physical and chemical properties of ethylene glycol and oleic acid.

Nanoparticles have been dispersed into base fluid with fractions of the solid volume of 0.05, 0.1, and 1 %. In the base fluid, equal volumes of Al_2O_3 and TiO_2 nanoparticles have been dispersed. Equation (1) was used to calculate the amount of nanoparticles needed to prepare the hybrid nanofluid samples:

$$\varphi = \left[\frac{\left(\frac{W}{\rho}\right)_{Al2O3} + \left(\frac{W}{\rho}\right)_{TiO2}}{\left(\frac{W}{\rho}\right)_{Al2O3} + \left(\frac{W}{\rho}\right)_{TiO2} + \left(\frac{W}{\rho}\right)_{EG} + \left(\frac{W}{\rho}\right)_{Water}}\right] \times 100 \qquad (1)$$

Where φ is the nanoparticle volume fraction, ρ is the density in kg/m3, and W is the mass in kg.

The amounts of nanoparticles, ethylene glycol (EG),

Table 3- Characteristics of Ethylene Glycol used in this study

Characteristic	Value
Chemical formula	$C_2H_6O_2$
Appearance	Clear, colorless liquid
Odor	Odorless
Molar mass	62.07 g/mol
Density	1113.20 kg/m^3
Boiling point	197.3 °C
Thermal conductivity	0.244 W/m K (at 20 °C)
Viscosity	16.1 cP (at 20 °C)

Table 4- Characteristics of oleic acid[24]–[26].

Characteristic	Value
Chemical formula	$C_{18}H_{34}O_2$
Appearance	Clear, Pale yellow
Viscosity(@293.15K)	38.80 mPa.s
Melting point	286.15K
Freezing point	277.15K
Cloud point (CP)	283.15K±1
Pour point (PP)	273.15K±1

and water used to prepare 400 ml of hybrid nanofluid are listed in Table 5. The concentration of surfactant was constant in all samples. In this study, the nanofluids are prepared in two steps. A magnetic stirrer (IKA, model RCT basic) was utilized for 181 minutes to break up particle aggregation and achieve a uniform suspension. The nanoparticles were dispersed in the base fluid for 4 hours, and the agglomeration was broken up by continuous ultrasonication.

The viscosity of hybrid nanofluids was measured with solid volume fractions from 0.05 to 1% in the temperature range from 260 to 305 K. A Brookfield viscometer with a temperature bath was used to measure the viscosities of nanofluids in the shear rate range from 0.3 rpm to 70 rpm. The amplitude and accuracy of the viscometer are 0.2 and 0.1, respectively. Before measuring the dynamic viscosity of hybrid nanofluids, the viscometer was calibrated with a mixture of pure water and ethylene glycol (50:50) at various temperatures. Figure 1 depicts a logical correlation between the measured data and the ASHRAE handbook data [27]. The mean absolute deviation between the ASHRAE data and the experimental data in this study is less than 2%. The thermal conductivity of the nanofluid was calculated using a thermal analyzer (Decagon Devices, Inc., model KD2 Pro). Over a temperature range of 260 to 305 K, the sensor›s accuracy was 5%. The thermal conductivity of the base fluid (a mixture of pure water and ethylene glycol (50:50)) at various temperatures was compared with data from the ASHRAE handbook [27] before measuring the thermal conductivity of the hybrid nanofluids with the KD2 Pro. As shown in Figure 2, with a tiny (0.5%) variance in the given temperature range, the base fluid›s experimentally determined thermal conductivity is in good agreement with the data.

A thermal analyzer was used to calculate the thermal conductivity of the nanofluid (Decagon Devices, Inc., model KD2 Pro). The accuracy of the sensor was 5% over a temperature range of 260 to 305 K. Before measuring the thermal conductivity of the hybrid nanofluids with the KD2 Pro, the thermal conductivity of a mixture of pure water and ethylene glycol (50:50) at various temperatures was compared to information from the ASHRAE handbook [27]. The experimentally determined thermal conductivity of the base fluid agrees well with the available data, as shown in Figure 2, with a small deviation (0.5%) in the temperature range mentioned.

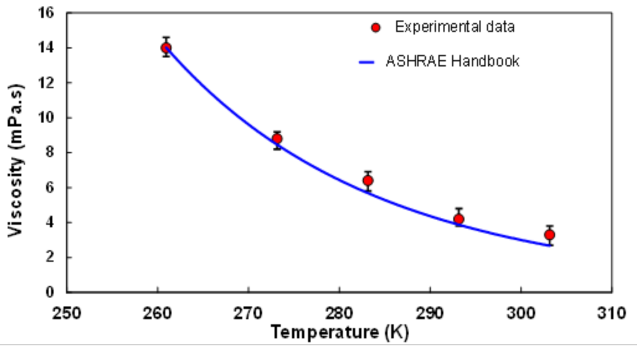

Figure 1- Comparison of experimental findings with ASHRAE data [27] on the viscosity of a water-ethylene glycol mixture (50-50) at various temperatures.

Table 5- Mass of nanoparticles, ethylene glycol (EG), and water used for the preparing a volume of 400 ml of hybrid nanofluid

Solid volume fraction (%)	Mass [±0.001] (g)			
	TiO_2	Al_2O_3	Ethylene glycol	Water
0	0.000	0.000	199.642	222.640
0.05	0.390	0.389	199.542	222.529
0.1	0.780	0.778	199.442	222.417
0.5	3.900	3.890	198.644	221.52687
1	7.800	7.780	197.646	220.414

Results and discussion

Zeta potential analysis was used to confirm the stability of hybrid nanofluids. The zeta potential index, which is related to the electrostatic repulsive forces between nanoparticles, is used to evaluate the stability of nanoparticles. The zeta potential of stable nanofluids is above 30 mV. Zeta potential values below 15 mV indicate instability of the nanofluid [12], [28], [29]. Hybrid nanofluids have zeta potential values between -31 and -55 mV, which is sufficient for the stability of the nanofluid.

The X-ray diffraction pattern of Al_2O_3 nanoparticles is shown in Figure 3(a). The diffraction peaks of γ-Al_2O_3 nanoparticles at 32.81 °, 36.72 °, 45.38 °, 66.59 °, and 67.24 ° at intervals of 2.726, 2.446, 1.996, 1.403, and 1.391 can be seen. These peaks correspond to crystallographic plates (220), (311), (400), (422) and (440) [30]–[32]. No peaks of impurities were observed in the X-ray diffraction pattern of the alumina powder nanoparticles.

The X-ray diffraction pattern of TiO_2 nanoparticles is shown in Figure 3(b). Diffraction peaks of TiO_2 nanoparticles were viewed at 27.42°, 36.08°, 41.25°, 54.33°, and 63.44°. These peaks correspond to crystallographic plates (110), (101), (111), (211), and (002), respectively [33]. No impurity peaks were observed in the X-ray diffraction pattern of the nanoparticles of titanium oxide powder.

The morphology of the nanoparticles was studied using SEM. Figure 4(a) shows the SEM image of γ-Al_2O_3 nanoparticles. The morphology of alumina nanoparticles is relatively spherical, as shown in this figure. As can be seen in Figure 4(a), the nanopowders are somewhat agglomerated. The aggregation of the particles is due to the huge surface area and volume ratio of the nanoparticles. SEM images of TiO_2 nanoparticles are shown in Figure 4(b). According to these images, quasi-spherical particles were observed. As shown in Figure 4(b), the nanopowders are somewhat agglomerated.

Further investigation into the size and shape of nanoparticles was conducted using TEM images. TEM Images of γ-Al_2O_3 and TiO_2 nanoparticles are shown in Figure 5. All particles exhibit a spherical shape.

The hydrophobicity of nanoparticles depends on their surface area. The active surface area of the nanoparticles was determined using the BET analysis. According to Figure 6, the BET surface area, pore volume, and average pore size of Al_2O_3 nanoparticles were determined to be 15.178 cm²/g, 0.78 cm³/g, and 58.174 Å, respectively.

The BET surface area of TiO_2 nanoparticles is shown in Figure 7. From Figure 7, the BET surface area, pore volume, and average pore size of titanium dioxide

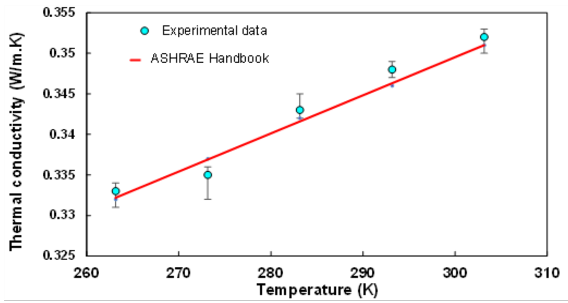

Figure 2- comparison of experimental findings with ASHRAE data[27] on the thermal conductivity of a mixture of water and ethylene glycol (W:EG/50:50 Concentrations in Volume Percent) at various temperatures.

nanoparticles are 79.49 cm²/g, 0.21 cm³/g, and 108.38 Å, respectively.

Figure 8 shows the dynamic viscosity of the Al_2O_3-TiO_2/ethylene glycol-water hybrid nanofluid per shear rate at 273.15 K for different values of solid volume fraction. It is observed that the viscosity of nanofluids increases with increasing volume fraction of nanoparticles at a constant temperature. This is because that the random movement of nanoparticles in the base fluid and constant collision between nanoparticles and molecules of the base fluid is one of the factors affecting viscosity. When nanoparticles are added to the base fluid, these nanomaterials are dispersed in the base fluid, and symmetrical and larger nanoclusters are formed due to the Van der Waals force between the nanoparticles and the base fluid[16], [17], [23]. These nanoclusters prevent ethylene glycols from moving on top of each other, resulting in increased viscosity.

At all temperatures studied, Al_2O_3-TiO_2/ethylene glycol-water hybrid nanofluid samples with high concentrations (φ = 0.5 - 1) exhibit non-Newtonian behavior. Non-Newtonian fluids follow Equation 2:

$$\tau = m\dot{\gamma}^n \tag{2}$$

Where τ is the shear stress, $\dot{\gamma}$ is the shear rate, m is the consistency index, and n is the power law index.

Temperature is the most critical and influential factor for viscosity[2]. As shown in Figure 9, the viscosity of the Al_2O_3-TiO_2/ethylene glycol-water hybrid nanofluid decreases with increasing temperature. This is because that as the temperature increases, the intermolecular attraction between the nanoparticles and their base fluids decreases[2]. Most studies have shown a decreasing trend in viscosity as temperature rises [34]–[37].

The thermal conductivity of Al_2O_3-TiO_2/ethylene glycol-water hybrid nanofluid in the temperature range of 260 to 305 K was carried out for suspensions with solid volume fractions of 0.05, 0.1, 0.5, and 1%. Figure 10 shows the thermal conductivity of Al_2O_3-TiO_2/

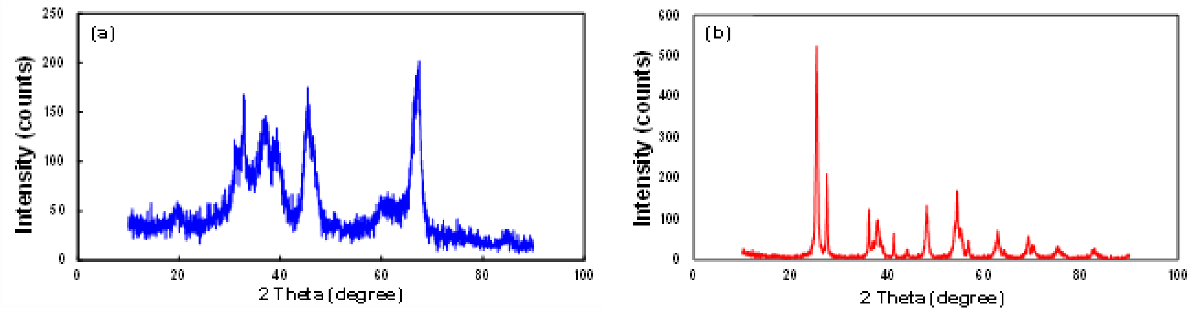

Figure 3- XRD patterns of a) nanosized γ-Al_2O_3 and b) TiO_2 nanoparticles.

ethylene glycol-water hybrid nanofluid as a function of solid volume fraction at different temperatures. As can be seen in this figure, the thermal conductivity of the Al_2O_3-TiO_2/ethylene glycol-water hybrid nanofluid increases with the volume fraction of nanoparticles. Assuming a uniform suspension, the number of particles in a given volume is larger at high volume fractions than for the hybrid nanofluid, and the distance between the solid particles in the base fluid is more minor than at lower concentrations. The thermal conductivity of nanofluids is significantly improved due to their high stability, particle size, and inherent thermal conductivity of solids. Therefore, the application of nanofluids in heat exchangers is very suitable. Nanofluids, which have better heat transfer properties and higher thermal conductivity, are more ideal for increasing the heat transfer coefficient of the base fluid[11], [38].

As the temperature increases, the kinetic energy of the particles increases, and the number of random collisions between the particles increases, the more collisions between the nanoparticles, the more energy is exchanged between the particles. This increases the thermal conductivity of the base fluid[16], [38], [39]. This increase is more pronounced in hybrid nanofluids

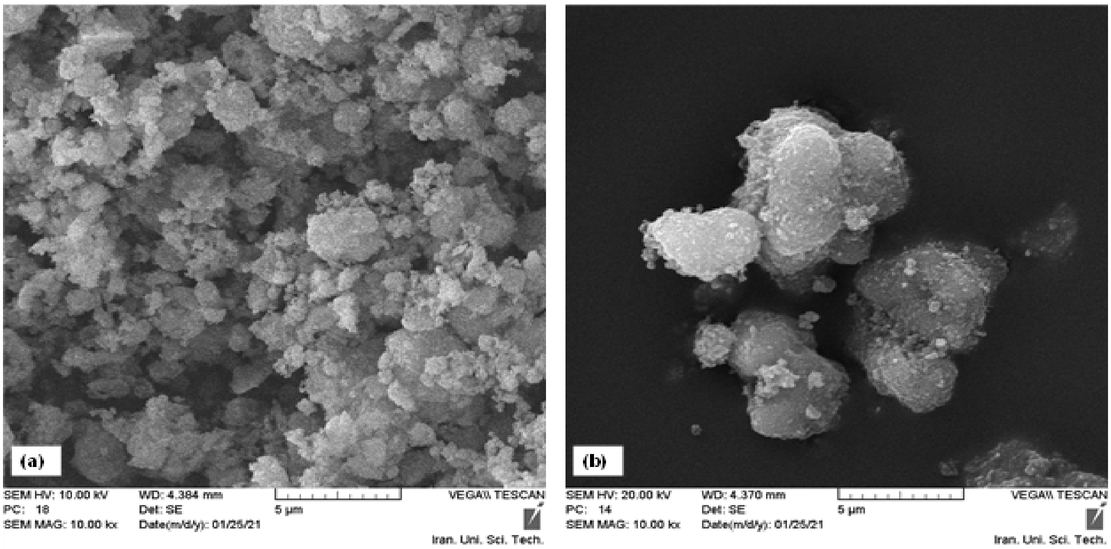

Figure 4- Scanning Electron Microscopy images of a) γ-Al_2O_3 and b) TiO_2 nanoparticles.

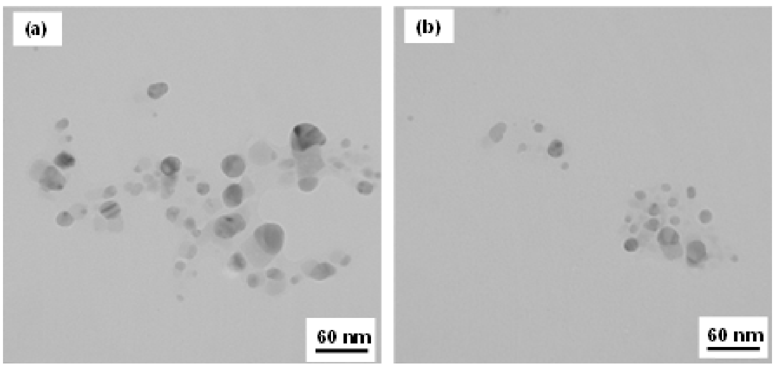

Figure 5- TEM images of a) γ-Al_2O_3 nanoparticles and b) TiO_2 nanoparticles.

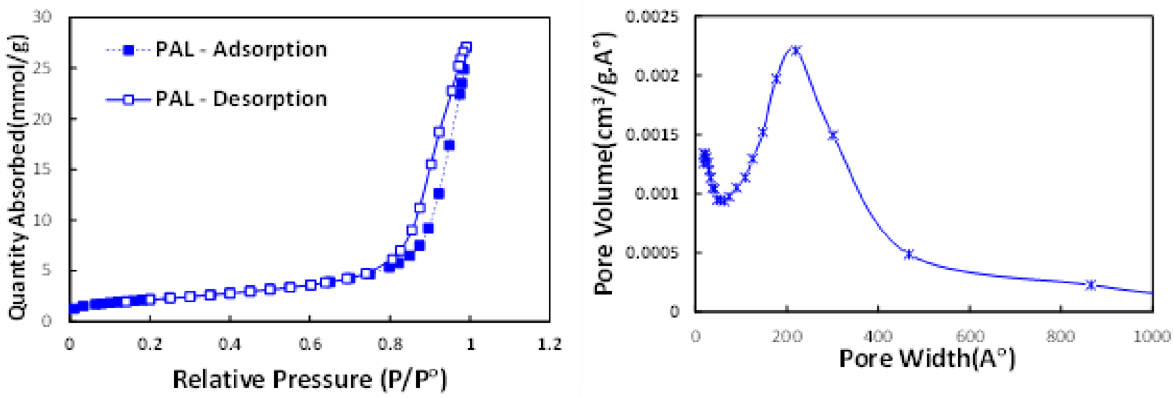

Figure 6- N_2 adsorption/desorption isotherms and pore diameter distribution of Al_2O_3 nanoparticles.

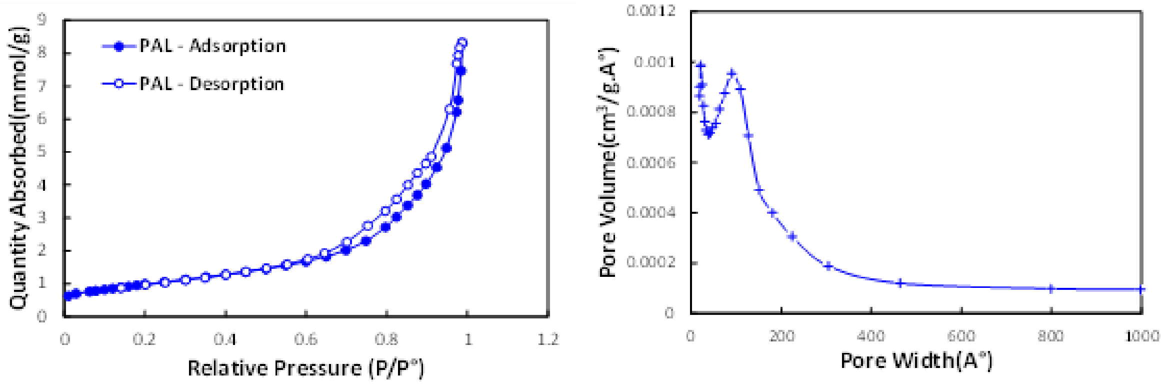

Figure 7- N_2 adsorption/desorption isotherms and pore diameter distribution of TiO_2 nanoparticles.

with higher concentrations. The considerable distance between particles prevents a significant increase in thermal conductivity at low concentrations. Increasing the concentration of nanoparticles increases the thermal conductivity, but on the other hand, can increase the probability of nanoparticle agglomeration. Agglomeration of nanoparticles decreases the surface area to volume ratio and reduces thermal conductivity[39]. As shown in Figure 10, the thermal conductivity increases with increasing temperature. At higher temperatures, the slope of these positive changes is more significant. This means that the thermal efficiency of the hybrid nanofluid is improved at higher temperatures. As shown in Figure 10, the effect of temperature on the thermal conductivity of the hybrid nanofluid is more significant at higher solid volume fractions (0.5-1 vol%). The thermal conductivity is based on Brownian motion and collision between nanoparticles. At high concentrations, the effect of temperature is more noticeable.

TiO_2 and Al_2O_3 nanoparticles have thermal conductivities of about 11.7 W/m.K [40] and 46 W/m.K [41],

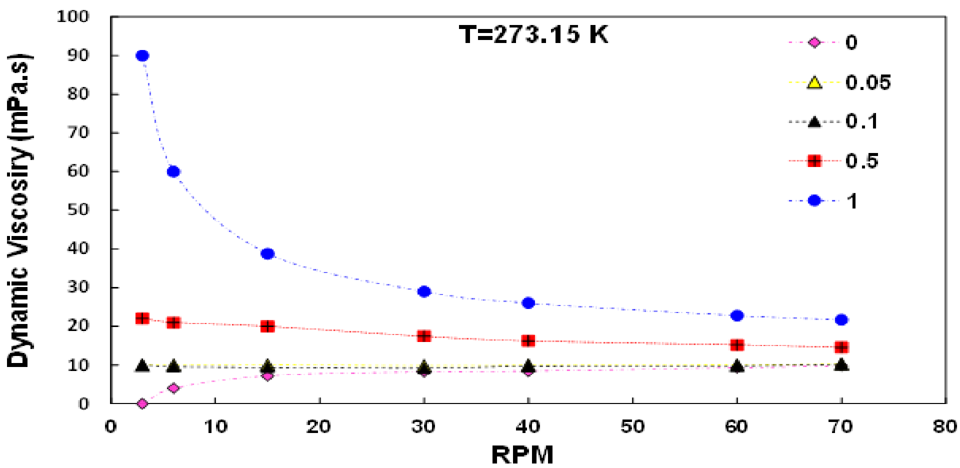

Figure 8- The viscosity of hybrid nanofluids versus the shear rate for various solid volume fractions at a temperature equal to 273.15 K.

respectively, while ethylene glycol has a thermal conductivity of 0.244 W/m.K and water has a thermal conductivity of 0.6 W/m.K [42]. As a result, adding nano-additives to the base fluid improves its thermal conductivity. As mentioned earlier, as the concentration of nanoparticles increases, the number of suspended nanoparticles also increases. This improves the heat transfer rate and, at the same time, increases the viscosity of the nanofluid. On the other hand, the stability of the nanofluid decreases at high concentrations, leading to agglomeration and accumulation of nanoparticles[3]. Therefore, the rate of increase in thermal conductivity is relatively low at a higher solid volume fraction.

To illustrate the improved thermal conductivity, Figure 11 shows the change in the thermal conductivity ratio of the hybrid nanofluid as a function of solid volume fraction and temperature. This figure clearly shows how the nanoparticle content and temperature affect the increase in the thermal conductivity of nanofluids. The increase in thermal conductivity ratio corresponds to approximately 24.5% and 15.2% at the highest and lowest test temperatures for the highest volume fraction (1% by volume). The results of the thermal conductivity measurements of the hybrid nanofluid at low temperatures show an acceptable improvement in thermal conductivity compared to the base fluid. It was concluded that its application might be helpful in low-temperature environments. These results are promising for using hybrid nanofluids in low-temperature applications.

Conclusion

The dynamic viscosity and thermal conductivity of the TiO_2-Al_2O_3/Ethylene Glycol-Water hybrid nanofluid at low temperature were investigated. Hybrid nanofluids were prepared using a water-ethylene glycol mixture (W: EG/50:50 %vol. at 298.15 K) and surfactants containing SDS (sodium dodecyl sulfonate) and oleic acid. The thermal conductivity and density of the TiO_2-Al_2O_3/Ethylene Glycol-Water hybrid nanofluid were measured at temperatures of 260 to 305K and various volume fractions of nanoparticles including 0.05%,

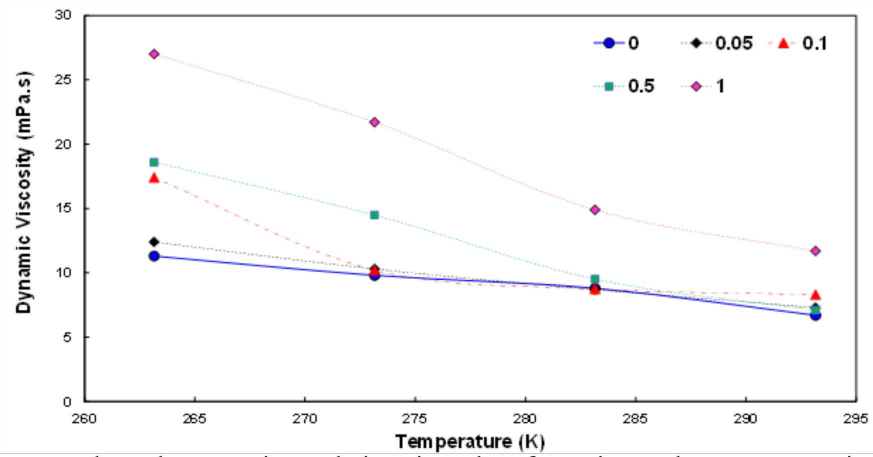

Figure 9- Temperature-dependent experimental viscosity values for various volume concentrations of nanofluids.

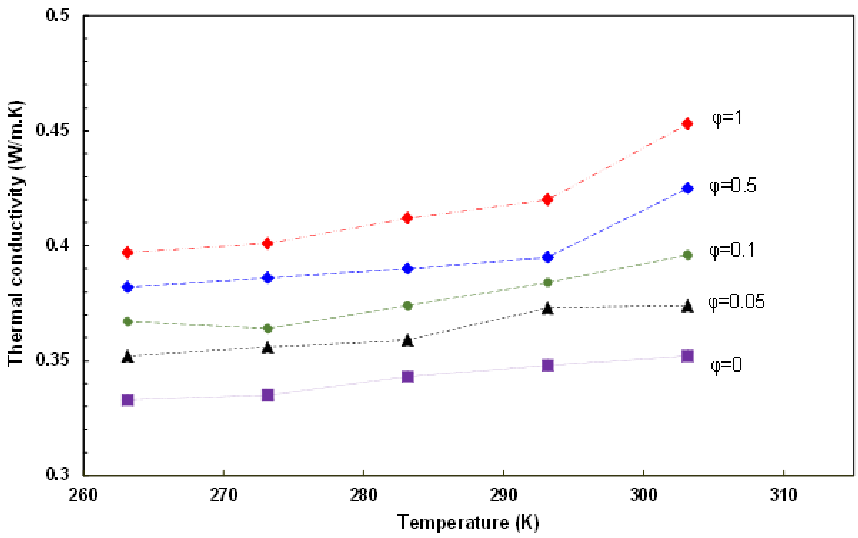

Figure 10- Variations in hybrid nanofluids thermal conductivity versus temperature for different solid volume concentrations.

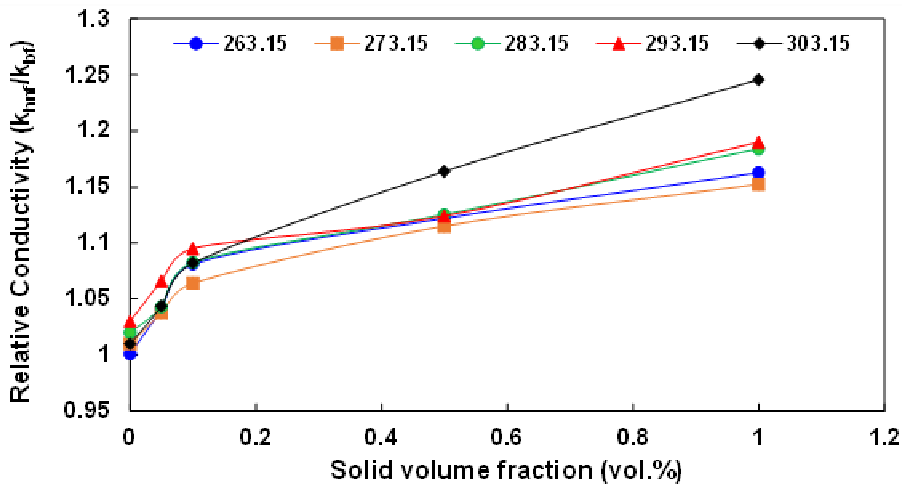

Figure 11- Dependence of the relative thermal conductivity of the hybrid nanofluid on the solid volume fraction of the base fluid at different temperatures.

0.1%, 0.5%, and 1%, respectively. The major conclusions from this work are summarized below:

1. Hybrid nanofluids (ϕ=0.05-1) have zeta potential values between -31 and -55 mV, which is sufficient for the stability of the nanofluid.
2. The results showed that the thermal conductivity and rheological properties of Al_2O_3-TiO_2/ Ethylene Glycol-Water hybrid nanofluid depend heavily on the temperature and concentration of nanoparticles, particularly at low temperatures.
3. Adding nanoparticles to the base fluid increases the viscosity considerably. The viscosity of the hybrid nanoliquid also declines as the temperature increases.
4. The thermal conductivity of hybrid nanofluids was a function of temperature and nanoparticle concentration. The results showed improved thermal conductivity of hybrid nanofluids with increased temperature and volumetric concentration of nanoparticles. The maximum increase in the thermal conductivity of the hybrid nanofluid was 38.09% and was obtained at a solid volume fraction of 1% and temperature of 305.15 K.

Referrences

[1] R. B. Ganvir, P. V. Walke, and V. M. Kriplani, "Heat transfer characteristics in nanofluid—A review," Renew. Sustain. Energy Rev., vol. 75, no. November 2016, pp. 451–460, 2017, doi: 10.1016/j.rser.2016.11.010.

[2] A. K. Patra, M. K. Nayak, and A. Misra, "Viscosity of nanofluids-A Review," Int. J. Thermofluid Sci. Technol., vol. 7, no. 2, 2020, doi: 10.36963/ijtst.2020070202.

[3] W. Yu and H. Xie, "A review on nanofluids: Preparation, stability mechanisms, and applications," J. Nanomater., vol. 2012, 2012, doi: 10.1155/2012/435873.

[4] M. U. Sajid and H. M. Ali, "Thermal conductivity of hybrid nanofluids: A critical review," Int. J. Heat Mass Transf., vol. 126, pp. 211–234, 2018, doi: 10.1016/j.ijheatmasstransfer.2018.05.021.

[5] J. Sarkar, P. Ghosh, and A. Adil, "A review on hybrid nanofluids: Recent research, development and applications," Renew. Sustain. Energy Rev., vol. 43, pp. 164–177, 2015, doi: 10.1016/j.rser.2014.11.023.

[6] L. S. Sundar, K. V. Sharma, M. K. Singh, and A. C. M. Sousa, "Hybrid nanofluids preparation, thermal properties, heat transfer and friction factor – A review," Renew. Sustain. Energy Rev., vol. 68, no. August 2016, pp. 185–198, 2017, doi: 10.1016/j.rser.2016.09.108.

[7] A. Jan, B. Mir, and A. A. Mir, "Hybrid nanofluids: An overview of their synthesis and thermophysical properties," arXiv, no. 3, 2019.

[8] A. K. Yasuri and E. Soleimani, "An Experimental Study on the Simultaneous Effect of Nanofluid and Tube Insert on the Thermal Performance of an Automobile Cooling System," J. Appl. Fluid Mech., vol. 14, no. 5, pp. 1559–1566, 2021, doi: 10.47176/JAFM.14.05.32421.

[9] S.-R. Yan, D. Toghraie, L. A. Abdulkareem, A. Alizadeh, P. Barnoon, and M. Afrand, "The rheological behavior of MWCNTs–ZnO/Water–Ethylene glycol hybrid non-Newtonian nanofluid by using of an experimental investigation," J. Mater. Res. Technol., vol. 9, no. 4, pp. 8401–8406, 2020, doi: 10.1016/j.jmrt.2020.05.018.

[10] V. Nair, A. D. Parekh, and P. R. Tailor, "Experimental investigation of thermophysical properties of R718 based nanofluids at low temperatures," Heat Mass Transf. und Stoffuebertragung, vol. 55, no. 10, pp. 2769–2784, 2019, doi: 10.1007/s00231-019-02624-y.

[11] A. S. Dalkılıç et al., "Experimental study on the thermal conductivity of water-based CNT-SiO2 hybrid nanofluids," Int. Commun. Heat Mass Transf., vol. 99, pp. 18–25, 2018, doi: 10.1016/j.icheatmasstransfer.2018.10.002.

[12] S. N. M. Zainon and W. H. Azmi, "Recent progress on stability and thermo-physical properties of

mono and hybrid towards green nanofluids," Micromachines, vol. 12, no. 2, pp. 1–35, 2021, doi: 10.3390/mi12020176.
[13] S. Nallusamy, "Thermal conductivity analysis and characterization of copper oxide nanofluids through different techniques," J. Nano Res., vol. 40, pp. 102–112, 2015, doi: 10.4028/www.scientific.net/JNanoR.40.105.
[14] T. Le Ba et al., "Experimental investigation of rheological properties and thermal conductivity of SiO2–P25 TiO2 hybrid nanofluids," J. Therm. Anal. Calorim., no. 0123456789, 2020, doi: 10.1007/s10973-020-10022-4.
[15] P. Sharma, I. H. Baek, T. Cho, S. Park, and K. B. Lee, "Enhancement of thermal conductivity of ethylene glycol based silver nanofluids," Powder Technol., vol. 208, no. 1, pp. 7–19, 2011, doi: 10.1016/j.powtec.2010.11.016.
[16] N. A. Usri, W. H. Azmi, R. Mamat, K. A. Hamid, and G. Najafi, Thermal Conductivity Enhancement of Al2O3 Nanofluid in Ethylene Glycol and Water Mixture, vol. 79. Elsevier B.V., 2015.
[17] N. Nayebpashaee and S. M. M. Hadavi, "Thermal Conductivity and Rheological Studies for Graphene-Al2O3 / Ethylene Glycol-Water Hybrid Nanofluid at Low Temperatures," J. Nano Res., vol. 73, pp. 139–160, 2022, doi: 10.4028/p-h9do2u.
[18] Y. Li, S. Tung, E. Schneider, and S. Xi, "A review on development of nano fl uid preparation and characterization," vol. 196, pp. 89–101, 2009, doi: 10.1016/j.powtec.2009.07.025.
[19] D. P. Kulkarni, D. K. Das, and R. S. Vajjha, "Application of nanofluids in heating buildings and reducing pollution," Appl. Energy, vol. 86, no. 12, pp. 2566–2573, 2009, doi: 10.1016/j.apenergy.2009.03.021.
[20] K. V. Wong and O. De Leon, "Applications of nanofluids: Current and future," Adv. Mech. Eng., vol. 2010, 2010, doi: 10.1155/2010/519659.
[21] S. Chakraborty and P. K. Panigrahi, "Stability of nanofluid: A review," Appl. Therm. Eng., vol. 174, no. March, 2020, doi: 10.1016/j.applthermaleng.2020.115259.
[22] B. Aladag, S. Halelfadl, N. Doner, T. Maré, S. Duret, and P. Estellé, "Experimental investigations of the viscosity of nanofluids at low temperatures," Appl. Energy, vol. 97, pp. 876–880, 2012, doi: 10.1016/j.apenergy.2011.12.101.
[23] M. T. Naik, G. Ranga Janardhana, K. Vijaya Kumar Reddy, and B. Subba Reddy, "Experimental investigation into rheological property of copper oxide nanoparticles suspended in propylene glycol-water based fluids," J. Eng. Appl. Sci., vol. 5, no. 6, pp. 29–34, 2010.
[24] N. Salih, J. Salimon, and E. Yousif, "The physicochemical and tribological properties of oleic acid based triester biolubricants," Ind. Crops Prod., vol. 34, no. 1, pp. 1089–1096, 2011, doi: 10.1016/j.indcrop.2011.03.025.
[25] D. R. Lide, "Hardness of Minerals and Ceramics," CRC Handb. Chem. Phys., pp. 2313–2314, 2005, [Online]. Available: http://www.hbcpnetbase.com.
[26] A. Banisharif, M. Aghajani, S. Van Vaerenbergh, P. Estellé, and A. Rashidi, "Thermophysical properties of water ethylene glycol (WEG) mixture-based Fe3O4 nanofluids at low concentration and temperature," J. Mol. Liq., vol. 302, p. 112606, 2020, doi: 10.1016/j.molliq.2020.112606.
[27] M. S. Owen, 2009 ASHRAE Handbook: Fundamentals, vol. 30329, no. 404. 2009.
[28] H. W. Xian, N. A. C. Sidik, and R. Saidur, "Impact of different surfactants and ultrasonication time on the stability and thermophysical properties of hybrid nanofluids," Int. Commun. Heat Mass Transf., vol. 110, 2020, doi: 10.1016/j.icheatmasstransfer.2019.104389.
[29] F. Rubbi, L. Das, K. Habib, N. Aslfattahi, R. Saidur, and M. T. Rahman, "State-of-the-art review on water-based nanofluids for low temperature solar thermal collector application," Sol. Energy Mater. Sol. Cells, vol. 230, p. 111220, Sep. 2021, doi: 10.1016/J.SOLMAT.2021.111220.
[30] P. D. Shelke, A. S. Rajbhoj, M. S. Nimase, G. A. Tikone, B. H. Zaware, and S. S. Jadhav, "An efficient, solvent free one pot synthesis of tetrasubstitued imidazoles catalyzed by nanocrystalline γ-alumina," Orient. J. Chem., vol. 32, no. 4, pp. 2007–2014, 2016, doi: 10.13005/ojc/320427.
[31] Á. B. Sifontes et al., "Preparation of functionalized porous nano-γ-Al2O3 powders employing colophony extract," Biotechnol. Reports, vol. 4, no. 1, pp. 21–29, 2014, doi: 10.1016/j.btre.2014.07.001.
[32] A. Khodadadi Darban, Y. Kianinia, and E. Taheri-Nassaj, "Synthesis of nano- alumina powder from impure kaolin and its application for arsenite removal from aqueous solutions," J. Environ. Heal. Sci. Eng., vol. 11, no. 1, 2013, doi: 10.1186/2052-336x-11-19.
[33] Z. Chen et al., "Characteristics of TiO 2 particles prepared by simple solution method using TiCl 3 precursor Characteristics of TiO 2 particles prepared by simple solution method using TiCl 3 precursor."
[34] V. Y. Rudyak, "Viscosity of Nanofluids. Why It Is Not Described by the Classical Theories," Adv. Nanoparticles, vol. 02, no. 03, pp. 266–279, 2013, doi: 10.4236/anp.2013.23037.
[35] I. M. Mahbubul, R. Saidur, and M. A. Amalina, "Latest developments on the viscosity of nanofluids," Int. J. Heat Mass Transf., vol. 55, no. 4, pp. 874–885, 2012, doi: 10.1016/j.ijheatmasstransfer.2011.10.021.
[36] A. Malekzadeh, A. R. Pouranfard, N. Hatami, A. Kazemnejad Banari, and M. R. Rahimi, "Experimental

Investigations on the Viscosity of Magnetic Nanofluids under the Influence of Temperature, Volume Fractions of Nanoparticles and External Magnetic Field," J. Appl. Fluid Mech., vol. 9, no. 2, pp. 693–697, 2016, doi: 10.18869/acadpub.jafm.68.225.24022.
[37] W. Yu, H. Xie, L. Chen, and Y. Li, "Investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid," Thermochim. Acta, vol. 491, no. 1–2, pp. 92–96, 2009, doi: 10.1016/j.tca.2009.03.007.
[38] R. K. Shukla and V. K. Dhir, "Effect of Brownian motion on thermal conductivity of nanofluids," J. Heat Transfer, vol. 130, no. 4, pp. 1–13, 2008, doi: 10.1115/1.2818768.
[39] I. Palabiyik, Z. Musina, S. Witharana, and Y. Ding, "Dispersion stability and thermal conductivity of propylene glycol-based nanofluids," J. Nanoparticle Res., vol. 13, no. 10, pp. 5049–5055, 2011, doi: 10.1007/s11051-011-0485-x.
[40] A. Subramaniyan and R. Ilangovan, "Thermal Conductivity of Cu2O-TiO2 Composite -Nanofluid Based on Maxwell model," Int. J. Nanosci. Nanotechnol., vol. 11, no. 1, pp. 59–62, 2015.
[41] A. H. Zamzamian and M. T. Jamal-Abadi, "Factor effect estimation in the convective heat transfer coefficient enhancement of Al2O3/EG nanofluid in a double-pipe heat exchanger," Int. J. Eng. Trans. B Appl., vol. 26, no. 8, pp. 837–844, 2013, doi: 10.5829/idosi.ije.2013.26.08b.05.
[42] J. R. Satti, D. K. Das, and D. Ray, "Investigation of the thermal conductivity of propylene glycol nanofluids and comparison with correlations," Int. J. Heat Mass Transf., vol. 107, pp. 871–881, 2017, doi: 10.1016/j.ijheatmasstransfer.2016.10.121.