An experimental study on rheological behavior of ethylene glycol based nanofluid: Proposing a new correlation as a function of silica concentration and temperature

Mohammad Akbari a, Masoud Afrand a,*, Ali Arshi b, Arash Karimipour a

a Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
b Department of Textile Engineering, Qaemshahr Branch, Islamic Azad University, Qaemshahr, Iran

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ABSTRACT

In this study, SiO2/EG nanofluids viscosity dependence on temperature and concentration was examined. The experiments were performed in the silica volume fraction range of 0.1–3.0% under the temperatures ranging from 30 °C to 50 °C. The experimental findings revealed that all nanofluid samples were Newtonian at all temperatures considered. The measurements also showed that the dynamic viscosity rises with growing the nanoparticles concentration and diminishes with rising temperature. The values of viscosity ratio indicated that with increasing the solid volume fraction from 0.1 to 3%, the dynamic viscosity increases up to 116%. Finally, using experimental data, in order to predict the dynamic viscosity of silica/ethylene glycol nanofluids, a new correlation has been suggested.

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1. Introduction

Ethylene glycol (EG) is the most important glycol commercially accessible, which is produced on a large scale in the world. It is the most common antifreeze fluid for heating and cooling applications. The most important use of EG is as a working fluid for convective heat transfer in thermal engineering applications including air conditioning systems, heat pumps, condensers, liquid-cooled computers, and solar collector that can be cooled to below water’s freezing point. According to the applications above mentioned, the thermophysical properties of EG play an important role in energy efficient of heat transfer equipment. However, EG has low thermal conductivity, which many researchers have tried to increase it. For this purpose, they reported that suspending nanoparticles (with size < 100 nm) in common fluids, called nanofluids, can lead to improve their thermal conductivity and heat transfer rate [1–10]. They revealed that material and size of nanoparticles, concentration and temperature affect the thermal conductivity of the nanofluids.

By adding nanoparticles into the common fluids to improve the thermal conductivity, the viscosity also changes, which influences the flow and heat transfer characteristics. Accordingly, many studies revealed that the viscosity of fluids affected by dispersing the additive to them.

Here, a brief review of studies on the effects of temperature and concentration of nanoparticles on the viscosity of nanofluids is conducted. Duangthongsuk and Wongwises [11] investigated the viscosity of TiO2/water nanofluid employing the Bohlin rotational rheometer (Malvern Instrument) in volume concentrations ranging from 0.2 to 2 vol% and temperatures ranging from 15 °C to 35 °C. Their experiments showed that the viscosity of nanofluids decreased with the rising temperature, and increased as the particle concentrations augmented. They also found that the measured viscosity of nanofluids were different from the predicted values from the previous correlations; thus, they proposed new correlations for predicting the viscosity of nanofluids. The viscosity of TiO2/water nanofluids also is investigated by Tseng and Lin [12], Turgut et al. [13], and Nambrro et al. [14].

Lee et al. [15] examined the viscosity of Al2O3/water nanofluid in the solid fraction range of 0.01%–0.3% under temperatures ranging from 21 °C to 39 °C. Their results showed that the viscosity of the nanofluids meaningfully decreases with increasing temperature. They reported that the viscosity of the nanofluid show a nonlinear relation with the concentration and exceed the Einstein model predictions. Putra et al. [16], Nguyen et al. [17], and Rea et al. [18] also investigated the viscosity of Al2O3/water nanofluid at different concentrations and temperatures.

Pastoriza-Gallego et al. [19] examined the influence of particle size, solid weight fraction and temperature on the viscosity of CuO/water nanofluids. Their experiments were performed in the weight fractions up to 10% and the temperatures ranging from 10 °C to 50 °C. They reported that the viscosity of the nanofluids increases with an increase in solid weight fraction, while decreases with an increase in temperature and size of nanoparticles. The viscosity of CuO/water nanofluid also was investigated by Heris et al. [20], Kulkarni et al. [21] and Nguyen et al. [22].
Azmi et al. [23] measured the viscosity of SiO2/water nano fluid in the solid volume fractions ranging from 0.5% to 4% at temperature of 30 °C. They showed that the viscosity increases up to 50%, when the nanoparticles volume fraction was 4%. The viscosity of SiO2/water nano fluid also was examined by Tayman et al. [24] and Masuda et al. [25].

Many studies have been conducted on the viscosity of nanofluids containing EG. A literature review of the available studies on the viscosity of nanofluids containing EG is presented in Table 1. In these works, the researchers reported that the viscosity increases with increasing the concentration of particles, resulting in the increase pumping power. These studies also revealed that the viscosity of nanofluids is a function of temperature, concentration, and type of nano-sized materials.

Review of the aforementioned articles showed that the thermophysical properties of various nanoparticles into the different base fluids were investigated in different studies. From each work, different results were obtained and each of which could be useful in its position. However, a few works have been performed on the viscosity of the EG-based nanofluids. Because of the important applications of ethylene glycol in thermal engineering, for the first time, the viscosity of is examined in this study. The nanofluid samples were prepared in volume concentrations ranging from 0.1% to 3%. Moreover, for engineering applications, a new correlation is proposed to predict the viscosity of SiO2/EG nano fluid for the temperatures ranging from 30 °C to 50 °C.

2. Nanofluid preparation

In this study EG, that its properties are presented in Table 2, has been used as base fluid. Silica nanoparticles, that their properties are presented in Table 3, have been used as additives. In order to ensure the size of nanoparticles, the structural properties of the dry SiO2 nanoparticles were measured using X-ray diffraction, which is displayed in Fig. 1. The average size of silica nanoparticles was obtained approximately 25 nm by employing the Debye–Scherrer equation [40] on XRD image (bruker-D8 Germany). Debye–Scherrer equation is as follows:

$$d = \frac{0.9\lambda}{\beta\cos\theta}$$  \hspace{1cm} (1)

in which d is nanoparticles diameter, λ is X-ray wavelength, β is peak width, and θ is Bragg’s angle.

Based on our past experience [6–9], silica nanoparticles should be dispersed in EG (Merck product, Germany) by a two-step method. For preparing sustainable samples, after magnetic stirring for 2 h, each sample was subjected to an ultrasonic processor for optimal duration of 4 h. This instrument was made in Hilscher Company and had the power of 400 W and frequency of 24 kHz.

SiO2/EG nano fluid samples with solid volume fractions of 0.1%, 0.25%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3% were prepared. The amount of silica nanoparticles needed for several samples can be calculated from the standard formula [41].

$$\varphi = \left[\frac{\rho_{SiO2} m_{SiO2} + \rho_{EG} m_{EG}}{\rho_{SiO2}}\right]$$  \hspace{1cm} (2)

where ϕ is the solid volume fraction, ρ is the density and m is the mass.

The images of silica nanoparticles, EG and nano fluid sample with solid volume fraction of 3% are displayed in Fig. 2. It should be noted that all samples have a good stability and no sedimentation was observed in the long time before the experiments.

3. Measuring dynamic viscosity

The viscosity of the nano fluid samples was measured in the temperatures ranging from 30 °C to 50 °C using DVI-Prime model of Brookfield Viscometer. This instrument is provided by Brookfield engineering laboratories of USA and associated with a temperature bath. The accuracy and repeatability of Brookfield Viscometer is respectively 1% and 0.2%. The Viscometer was verified with EG at various temperature before the measurement of dynamic viscosity of all samples. All trials were repeated at different rotational speed for all samples to recognize the Newtonian or non-Newtonian behavior of nano fluid samples.

4. Results and discussion

4.1. Comparison between theoretical models and experimental data

In Fig. 3, the ratio of viscosity of nano fluid is displayed against solid volume fraction in comparison of that values from Batchelor [42] and Wang [43] models. It can be observed that both classical models are incapable to predict the viscosity of SiO2/EG nanofluids. In addition, the experimental data for the viscosity of nano fluids are significantly greater than Batchelor and Wang models.
4.2. Rheological behavior

Since the viscosity affects the Reynolds and Prandtl number, it is a vital property for the pumping power and convective heat transfer rate. To assess the rheological behavior of SiO2/EG nanofluid, the viscosity of nanofluid samples has been measured at several shear rates (rotational speeds). The equation of Newtonian behavior of a fluid is known as [44],

$$\tau = \mu \dot{\gamma}$$

where $\tau$ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (1/s) and $\mu$ is the dynamic viscosity (Pa·s).

Based on this equation, when shear stress-shear rate dependency is linear, fluid has Newtonian behavior. Fig. 4 shows the dynamic viscosity versus shear rate for the samples at nanoparticles volume fractions of 0, 1%, 2% and 3% for different temperatures. This figure showed that the nanofluid samples were Newtonian.

4.3. Viscosity dependence on temperature and concentration

Fig. 5 depicts the dynamic viscosity of nanofluid as a function of silica volume fraction at different temperatures. It is obvious that the nanofluid viscosity enhances with increasing silica volume fraction at all temperatures considered with a parallel trend. This is maybe due to the numerous interactions between silica nanoparticles and EG molecules. It can also be understood that the augmentation of dynamic viscosity for samples with $\phi > 2\%$ is higher than that for samples at with $\phi < 2\%$. In fact, for more diluted samples ($\phi < 2\%$), the nanoparticles are away from each other, which consequently reduced the possibility of accumulation of nanoparticles. However, in more concentrated samples $\phi > 2\%$, this phenomenon is more probable due to the short distance between the nanoparticles. Accumulation of nanoparticles may lead to a higher viscosity.

Fig. 6 illustrates the dynamic viscosity of various nanofluid samples as a function of temperature. It can be found that the dynamic viscosity diminishes with enhancing temperature. The reason may be related to the fact that at higher temperatures, the energy of molecules and intermolecular distance becomes more, resulting in the lower effects of molecules on each other. In fact, with increasing temperature the Van der Waals forces between the molecules become weaker, which leads to less resistance against the movement of the fluid. Moreover, the results reveal that for samples of 2.5% and 3% the effect of temperature on the viscosity of nanofluid is more obvious. With increasing the number of nanoparticles in EG, accumulation of nanoparticles may be occurred.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purity</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>Color</td>
<td>White</td>
</tr>
<tr>
<td>APS</td>
<td>20–30/nm</td>
</tr>
<tr>
<td>SSA</td>
<td>180–600/m²·g⁻¹</td>
</tr>
<tr>
<td>Bulk density</td>
<td>&lt;0.10/g·cm⁻³</td>
</tr>
<tr>
<td>True density</td>
<td>2.4/g·cm⁻³</td>
</tr>
</tbody>
</table>

Fig. 1. XRD pattern for SiO₂ nanoparticles.

Fig. 2. Images of silica nanoparticles, EG and nanofluid sample with solid volume fraction of 3%.

Fig. 3. Comparison between theoretical models and experimental data.
Augmentation of temperature can lead to break down the agglomeration of nanoparticles. Therefore, the effect of temperature in more concentrated samples is more evident.

To determine the viscosity sensitivity to temperature and concentration, viscosity ratio is demonstrated as a function of temperature and concentration in Fig. 7. The viscosity ratio was obtained by dividing the viscosity of the samples to the viscosity of EG. It is found that the maximum viscosity enhancement of SiO₂/EG nanofluid is 116%. This occurred at the nanoparticles volume fraction of 3.0% and temperature of 40 °C.

**Fig. 4.** Dynamic viscosity versus shear rate for various nanofluid samples at different temperatures.

**Fig. 5.** Variations of dynamic viscosity with nanoparticles volume fraction at different temperatures.

**Fig. 6.** Variations of dynamic viscosity with temperature at different nanoparticles volume fractions.

**Fig. 7.** Viscosity ratio as a function of temperature and concentration.
4.4. Suggestion of new correlation

As mentioned above, previous existing models cannot predict the dynamic viscosity of SiO₂/EG nanofluids. Consequently, an empirical correlation is suggested for predicting the dynamic viscosity ratio for this nanofluid. The correlation as a function of temperature (T) and volume fraction (φ) can be expressed as follows:

\[
\frac{\mu_{nf}}{\mu_{bf}} = -24.81 + 3.23T^{0.0014} \exp(1.838\phi^{0.00234}) - 0.000679T^2 + 0.024\phi^3
\]  

(4)

This correlation is valid for volume fractions < 3% and the temperature range between 30 and 50 °C.

Fig. 7. Variations of relative viscosity with nanoparticles volume fraction at different temperatures (left), with temperature at different nanoparticles volume fraction (right).

Fig. 8. Comparison between experimental data and correlation outputs for relative viscosity at different temperatures.
In order to assess the precision of the new proposed correlation, and for representing the deviation at each experimental measurement, the comparisons between experimental findings and correlation outputs at different temperatures are shown in Fig. 8. As can be seen, in most measurement data, the points related to the experiments and correlation overlap each other and show a small deviation. This presentation indicates that the proposed correlation has an adequate accuracy.

5. Conclusion

In the present work, SiO2/EG nanofluids viscosity dependence on temperature and concentration was shown. The viscosity of several nanofluid samples at volume concentrations of 0.1%, 0.25%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3% was measured in the temperature range of 30–50 °C. The experiments performed at the shear rate range of 6.115–24.46 (1/s). The measurements at various shear rates showed that the SiO2/EG nanofluid has a Newtonian behavior at all temperatures considered. The evaluations also indicated that the dynamic viscosity rises with growing the silica volume fraction and reduces with rising temperature. Moreover, the values of viscosity ratio showed that when the silica volume fraction augments from 0 to 3%, the dynamic viscosity increases up to 116%. Eventually, using experimental findings, a new correlation was suggested to predict the dynamic viscosity of SiO2/EG nanofluids. The comparisons between the results obtained by the correlation and those of obtained by experiments revealed that the suggested correlation has an adequate accuracy.

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