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# Dynamic Viscosity of Aluminum Oxide–Ethylene Glycol ($Al_2O_3$–EG) Nanofluids

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The paper presents the results of measurements of rheological properties of ethylene glycol (EG) based aluminum oxide ($Al_2O_3$) nanofluids. The nanofluids have been produced by two-step method with the use of commercially available nanoparticles. Dynamic viscosity curves and dependence of viscosity on temperature for these materials have been measured. It has shown that with higher concentration of nanoparticles in the suspension, these nanofluids exhibit the non-Newtonian flow and it can be considered as shear-thinning liquids. The effect of temperature on the dynamic viscosity in $Al_2O_3$–EG nanofluids can be modelled with the use of Vogel–Fulcher–Tammann expression.

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## 1. Introduction

Nanofluids are relatively a new group of engineering materials in a form of suspensions of nanoparticles in a liquid base. Due to the increase of the thermal conductivity of nanosuspensions, in relation to the pure liquid base, nanofluids have a large number of potential applications in industry [1].

There are two basic methods of preparation of nanofluids. The one-step method, which involves the preparation of the nanoparticles directly within a volume of liquid and the two-step method, which involves a dispersion of dry nanoparticles in a liquid base [2].

Basic thermophysical and rheological properties of nanofluids depend mainly on type of particles, their concentration, size, and the type of base fluid.

One of the most researched group of nanofluids are suspensions of $Al_2O_3$ particles. There are numerous reports describing the increase of thermal conductivity in these materials [3–7]. There are papers that describe the rheological properties of nanosuspensions of $Al_2O_3$, however, they are concentrated around the water-based nanofluids [6–9]. Pastoriza-Gallego et al. [10] presented the results of rheological studies, which show the dependence of the viscosity in $Al_2O_3$–EG nanofluids on particles sizes. Results acquired from our research complement these studies with the dynamic viscosity curves and confirm the idea, included in this study, that the temperature dependence of the viscosity of these materials can be described with the use of the Vogel–Fulcher–Tammann (VFT) expression.

In view of the potential use of nanofluids in heat exchange processes [11, 12] in the industry, the theoretical model of mechanical properties of these materials would be extremely valuable. Unfortunately, there is no coherent theoretical model invented at the moment, describing the rheological behavior of nanofluids. It is, therefore, necessary to provide high-quality experimental data in this field.

## 2. Materials and methods

### *2.3. Characterization of $Al_2O_3$ nanoparticles*

Nanoparticles used in the studies were commercially available $\alpha$–$Al_2O_3$ from Taimei Chemicals (Japan). The density of the dry nanoparticles is 3.8 g/cm$^3$. The characteristics of the average size of the nanoparticles is based on measurements of the average particle size in suspension with use of Zetasizer Nano ZS (Malvern Instruments Ltd, Worcestershire, UK) for diluted suspensions of particles in ethylene glycol, which underwent ultrasonication (VibraCell VCX130, Sonics & Materials, Inc., Newtown, USA) prior measurement and the scanning electron microscopy (SEM) Nova NanoSEM 200 (FEI, Hillsboro, USA) pictures.

Results of Zetasizer Nano ZS measurement are shown in Fig. 1. The average particle size can be determined as 230 nm.

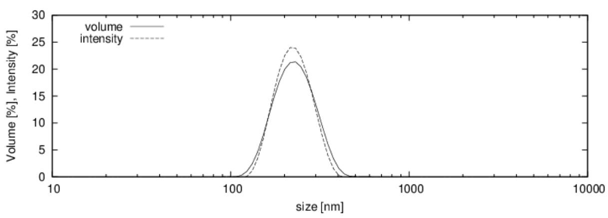


Fig. 1. Size distribution of $Al_2O_3$ nanoparticles in ethylene glycol.

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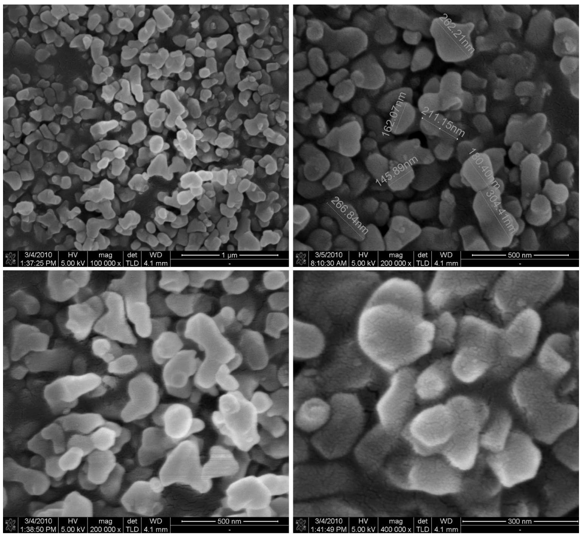

Fig. 2. Scanning Electron Microscope pictures of dry $Al_2O_3$ nanoparticles.

Figure 2 presents SEM pictures of dry $Al_2O_3$ nanoparticles used to produce nanofluids and corroborate the results obtained using Zetasizer Nano ZS.

*2.2. Sample preparation*

Nanofluids were prepared with the use of two-step method as a various mass concentration suspensions of $Al_2O_3$ nanopowder in ethylene glycol (pure p.a., Chempur, Poland). Analytical balance AS 220/X (Radwag, Radom, Poland) with accuracy of measurement of 0.1 mg was used for mass measurements. For preliminary mechanical mixing Genius 3 Vortex (IKA, Staufen, Germany) was used for 30 min. The process of breaking up of the agglomerates was achieved with use of the ultrasonic device Emmi-60HC (EMAG, Moerfelden-Walldorf, Germany) for further 200 min. Ultrasonication bath as a method of dispersing of nanoparticles in the base fluid is commonly used [2, 13–15].

All samples were prepared at a controlled temperature below 25 °C. $Al_2O_3$-EG nanofluids prepared with this method were stable for several hours.

*2.3. Measuring system*

Experiments were performed on the HAAKE MARS 2 rheometer (Thermo Fisher Scientific, Karlsruhe, Germany), which enables the adjustment of torque up to 200 mNm with the minimum measurable torque of 0.5 $\mu$N m. The cone–plate geometry with diameter of 60 mm and 2° cone angle was used. Constant temperature inside was controlled with use of a Peltier system connected to a Phoenix 2 (Thermo Fisher Scientific, Karlsruhe, Germany) thermostat. Measurement geometry was further isolated from the environment by using the solvent trap. The aims of the use of solvent trap were (a) to restrict the evaporation of base liquid during the measurements, (b) to assist in controlling the temperature of the entire volume of the sample.

Dynamic viscosity curves were determined in rotational measurement at a constant temperature of 20 °C (293.15 K). Measurements were planned on a logarithmic scale, each data point was collected after 20 s of shearing with a constant shear rate in range from 1 $s^{-1}$ to 1000 $s^{-1}$.

The dependence of dynamic viscosity on temperature measurements were performed with constant shear rate of 50 $s^{-1}$ in temperature range from −10 °C (263.15 K) to 50 °C (323.15 K) with 1 °C/20 s step.

## 3. Results and discussion

*3.1. Dynamic viscosity*

Measurements of the dynamic viscosity curves of various mass concentration of particles in $Al_2O_3$–EG nanofluids were performed with the use of HAAKE MARS 2 rheometer. Due to the non-Newtonian nature of the examined materials the cone–plate measurement geometry was used.

The results of the measurements are shown in Fig. 3. Research shows that for low mass concentration of nanoparticles, nanofluid can be considered as a Newtonian liquid. With increase of mass concentration of the particles, material changes its rheological properties, and exhibits shear-thinning non-Newtonian flow.

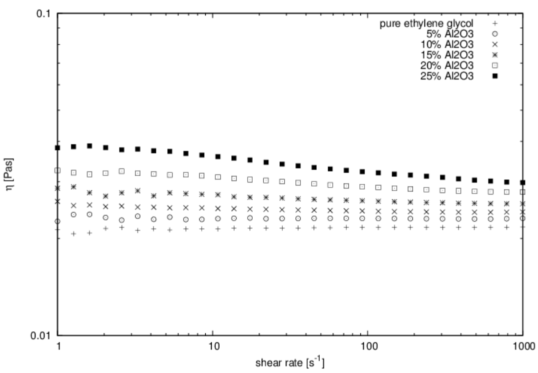


Fig. 3. Dynamic viscosity curves of various mass concentrations of $Al_2O_3$ nanoparticles suspensions in ethylene glycol at 20 °C (293.15K).

*3.2. Viscosity on temperature dependence*

Dependence of viscosity on temperature studies were carried out on a sample which was previously used to study the viscosity curves. This results with the fact that the sample was examined, wherein the condition is established (by the high shear rate measurements in the previous stage of the study).

The results of the study have been collected in Fig. 4.

It can be seen that the temperature dependence of the viscosity can be modeled with use of a Vogel–Fulcher–Tammann expression

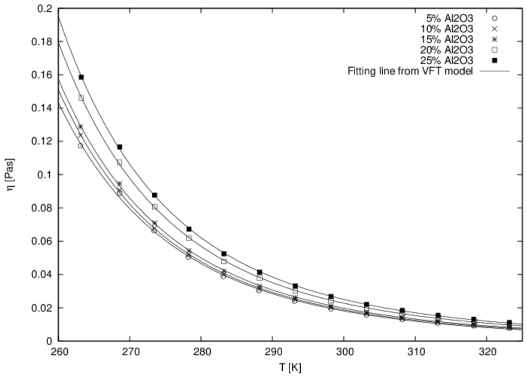


Fig. 4. Dependence of dynamic viscosity of different mass concentration of $Al_2O_3$ nanoparticles suspension in ethylene glycol on temperature at range from -10 °C (263.15 K) to 50 °C (323.15K) at constant shear rate 50 $s^{-1}$. Points represent measuring results, lines – the VTF model fit.

$$\ln(\eta) = A + \frac{B}{T - T_0}, \quad (1)$$

where $A$, $B$ and $T_0$ are the fitting coefficients. This model has already been used to describe the dependence of viscosity on temperature by Pastoriza-Gallego et al. for $Al_2O_3$–EG [10] and ZnO–EG [16] nanofluids.

For the $Al_2O_3$–EG nanofluids described in present paper, it was possible to fit the VFT expression to the experimental data. The fitting parameters are summarized in Table, whereas Fig. 4 shows the result of fitting.

TABLE

VFT expression parameters for viscosity on temperature dependence in $Al_2O_3$–EG nanofluids.

| Concentration | $A$ | $B$ [K] | $T_0$ [K] |
|---|---|---|---|
| 5 wt% | –14.9166 | 2732.01 | 49.423 |
| 10 wt% | –12.9641 | 1907.66 | 87.741 |
| 15 wt% | –12.7635 | 1858.38 | 89.732 |
| 20 wt% | –12.0009 | 1634.61 | 101.063 |
| 25 wt% | –11.5721 | 1526.45 | 106.399 |

## 4. Conclusions

The paper presents the results of experimental studies on the dynamic viscosity of $Al_2O_3$–EG nanofluids. It is shown that the increase in mass concentration of nanoparticles causes a change in the nature of nanofluid from Newtonian to shear-thinning non-Newtonian.

In addition, the effect of temperature on the viscosity of nanofluids was measured. It was confirmed that the temperature dependence of the viscosity can be described using a Vogel–Fulcher–Tammann expression.

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