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Thermophysical properties of ethylene glycol based yttrium aluminum garnet ($Y_3Al_5O_{12}$–EG) nanofluids

Gaweł Żyła

Department of Physics and Medical Engineering, Rzeszow University of Technology, Rzeszow 35-905, Poland

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ABSTRACT

The paper presents results of measurements of basic thermophysical properties of ethylene glycol based yttrium aluminum garnet ($Y_3Al_5O_{12}$–EG) nanofluids. Nanofluids used in presented experiments were prepared with two-step method based on commercial nanoparticles. Basic rheological properties were investigated on HAAKE MARS 2 rheometer (Thermo Electron Corporation, Karlsruhe, Germany). Dynamic viscosity curves in the range of shear rates from 10 to 1000 s^{-1} at a constant temperature of 298.15 K were determined. Additionally, the temperature dependence of the viscosity in the range from 273.15 K to 333.15 K was measured. To determinate thermal conductivity of nanofluids a KD2 Pro Thermal Properties Analyzer (Decagon Devices Inc., Pullman, Washington, USA) was used. The dependence of thermal conductivity of $Y_3Al_5O_{12}$–EG nanofluids on the concentration of nanoparticles was measured at constant temperature of 298.15 K.

1. Introduction

Nanofluids are an innovative engineering materials which have numerous applications in technology, medicine and industry [1–3]. It has been found experimentally that thermal conductivity of nanofluids increases with the concentration of nanoparticles in suspension. Because of such properties, one of the most common uses of these processes are nanofluids heat exchange [4–6].

In view of the possible uses of nanofluids, one of the most commonly used base fluid is ethylene glycol. For example Pastoriza-Gallego et al. shows that thermal conductivity of Al_2O_3–EG [7], and ZnO–EG [8] increases with the concentration of nanoparticles. The same trend was presented for other nanosuspensions in ethylene glycol, for example by Wang et al. [9] for graphite–EG, Yu et al. [10] for Zno–EG, Mariano et al. [11] for Co_3O_4–EG, and Esfe et al. [12] for Al_2O_3–EG. High values of thermal conductivity for nanofluids were presented for nanodiamond (ND)–EG by Yu et al. [13] and for ND-Ni:EG by Sundar et al. [14].

Not only the thermal conductivity of nanofluids is an interesting matter, but these materials exhibit a number of interesting rheological properties. The viscosity of nanofluids increases with the concentration of nanoparticles, however, different materials have different flow character. The most commonly reported nature of nanofluids based on ethylene glycol is the non-Newtonian behavior. Chen et al. [15] presented non-Newtonian flow of titanate nanotube–EG nanofluids. Pastoriza-Gallego et al. [16] shows complex rheological properties of Fe_2O_3–EG nanofluids. There was also presented a complex rheological structure of BN–EG [17] nanofluids, while indicating that classical models can be employed to describe the viscosity properties of these nanofluids. Shear thinning was also shown by Cabaleiro et al. [18] for TiO_2–EG, Mariano et al. [19] for SnO_2–EG, and Li et al. [20] for SiC–EG. However, some of the nanofluids exhibit Newtonian fluid nature, for example results presented by Pastoriza-Gallego et al. [8] for ZnO–EG, and Mariano et al. [11] for Co_3O_4–EG.

Presented examples show that the thermo-physical properties depend on the type of suspended nanoparticles, its' size and concentration. Unfortunately, the theoretical models describing the thermo-physical properties of fluids do not always apply to the nanofluids. Many researchers stress the need to provide detailed experimental data in this field. This would allow to prepare new models, and this paper is also a possible contribution to this case.

2. Materials and methods

2.1. $Y_3Al_5O_{12}$ nanoparticles

Nanoparticles were manufactured by Baikowski (Annecy, France), ID LOT: 18513. The average size of the nanoparticles measured by X-ray Diffraction (XRD) was 100 nm. The average size of hydrodynamic diameter of nanoparticles in suspension in ethylene glycol measured with Cilas Nano DS (Cilas, Orleans, France) device

E-mail address: gzyla@prz.edu.pl

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was 185.6 nm. This size was confirmed on the basis of images from scanning electron microscope Nova NanoSEM 200 (FEI, Hillsboro, USA), results are presented in Fig. 1.

2.2. Sample preparation

Samples were prepared in the mass concentration (5–20 wt.%) with the use of an analytical balance WAS 220/X (Radwag, Radom, Poland) with the accuracy of 0.1 mg. In order to break up the agglomerates of nanoparticles, a mechanical stirring in mechanical shaker Genius 3 Vortex (IKA, Staufen, Germany) for 30 min, and the subsequent ultrasound for a period of 200 min in ultrasoundwave bath Emmi 60 HC (EMAG, Moerfelden-Walldorf, Germany) were conducted.

All samples were prepared at room temperature not exceeding 298.15 K, and due to the possibility of agglomeration and sedimentation of nanoparticles in suspension, thermophysical properties of samples were measured immediately after sonication.

The volumetric concentrations of nanofluids were calculated based on the mass concentration with the equation:

$$\varphi_v = \frac{\varphi_m}{\rho_p\left(\frac{\varphi_m}{\rho_p} + \frac{1-\varphi_m}{\rho_0}\right)}, \tag{1}$$

where φ_v and φ_m are respectively a volume and a mass concentration, ρ_p and ρ_0 stands for density of solid particles and base fluid.

2.3. Measuring system

Basic rheological properties were investigated on HAAKE MARS 2 rheometer (Thermo Electron Corporation, Karlsruhe, Germany), with the minimum measurable torque of 0.5 μNm. The double cone measurement geometry with 60 mm diameter and cone angle of 1° was used. Flow and viscosity curves in the range of shear rates from 10 to 1000 s^{-1} at a constant temperature of 298.15 K were determined. To maintain a constant temperature, a Peltier system coupled with a Phoenix 2 thermostat (Thermo Electron Corporation, Karlsruhe, Germany) was used. The temperature dependence of the viscosity in the range from 273.15 K to 333.15 K was measured at constant shear rate of 100 s^{-1}. The rate of temperature change in the sample during this measurement was 1 K/min. In addition, measurement geometry was isolated from the environment by glass rings.

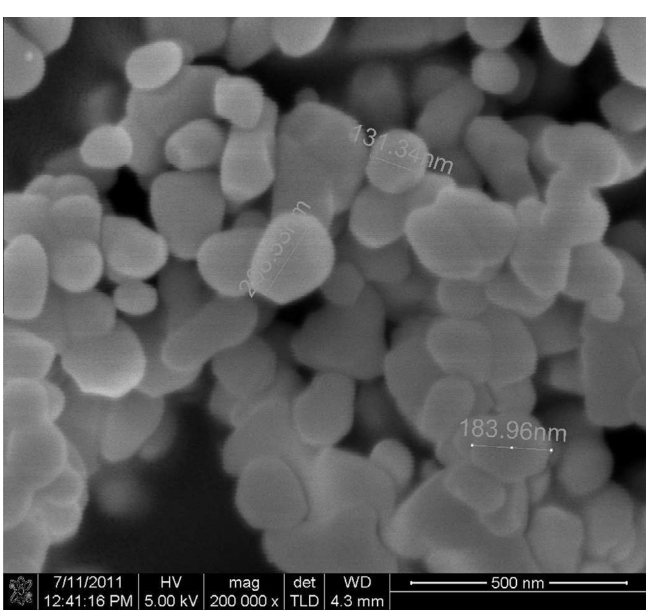

Fig. 1. Scanning electron microscope pictures of $Y_3Al_5O_{12}$ nanoparticles.

To determinate thermal conductivity of nanofluids, a KD2 Pro Thermal Properties Analyzer (Decagon Devices Inc., Pullman, Washington, USA) was used. The dependence of thermal conductivity of $Y_3Al_5O_{12}$–EG nanofluids on the concentration of nanoparticles was measured at constant temperature of 298.15 K, and the temperature was stabilized in a water bath MLL 547 (AJL Electronic, Cracow, Poland).

The thermal conductivity values were determined as the average of five measurements and the time between successive measurements was at least 15 min, which corresponds to the recommendations of the manufacturer of equipment.

The KD2 Pro Thermal Properties Analyzer meets the standards of ASTM D5334 and IEEE 442-1981 regulations. Before measurements of thermal conductivity of nanofluids samples, a series of ten calibration measurements with pure glycerol were made. The average result obtained during the calibration measurements of glycerol in 20 °C differed from the literature by 1.7%. The standard deviation for the ten calibration measurements did not exceed 1.1%. Thus, it can be stated that the uncertainty of the thermal conductivity measurement, with the use of this measuring station is lower than 2%. The manufacturer's instruction manual predicts the inaccuracy of 5%, while the actual uncertainty of this equipment evaluated by Pastoriza-Gallego et al. [7,8] is 3%. This kind of measuring system (using KD2 Pro) is popular, and was previously used by many researchers to study the physical properties of nanofluids [7,8,21–25].

3. Results and discussion

3.1. Flow curves

Fig. 2 shows the flow curves for different concentrations of nanoparticles in $Y_3Al_5O_{12}$–EG nanofluids. It can be seen that the shear stress increases linearly with increasing shear rate. Therefore, the material might be classified as a Newtonian liquid which can be modeled using the Newton equation:

$$\sigma = \eta\dot{\gamma}, \tag{2}$$

where σ is shear stress, η is dynamic viscosity, and $\dot{\gamma}$ is shear rate. Fig. 2 presents both experimental results and the theoretical model fit.

3.2. Dynamic viscosity curves

One of the basic curves determining the rheological properties of the material is the viscosity curve which shows the dependence of the viscosity on shear rate. Viscosity curves are presented in Fig. 3, and it shows the experimental results and the Newton model fit. Studies have shown that nanofluids viscosity is not dependent on shear rate, so that material definitely can be classified as Newtonian.

3.3. Viscosity enhancement

As expected, the viscosity of the nanofluids increases with increasing concentration of nanoparticles in suspension. Table 1 summarizes calculated values of dynamic viscosity and η_{nf}/η_0 ratio.

One of the first models describing the viscosity of suspensions was presented by Einstein [26] in form of:

$$\eta_{nf}/\eta_0 = 1 + 2.5\varphi_v \tag{3}$$

This model refers to a suspension of spherical particles in low concentrations. Chow [27] proposed variable degree volume fraction polynomial to model the η_{nf}/η_0 ratio in form of:

$$\eta_{nf}/\eta_0 = 1 + \sum_{i=1}^{N} C_i\varphi_v^i \tag{4}$$