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Viscosity, thermal and electrical conductivity of silicon dioxide–ethylene glycol transparent nanofluids: An experimental studies

Gaweł Żyła*, Jacek Fal

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

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ABSTRACT

Nanofluids are novel engineering materials with many potential industrial applications, particularly in the processes of heat exchange. The paper presents the results of experimental investigation of viscosity, thermal and electrical conductivity of transparent suspensions of silicon dioxide (SiO_2) nanoparticles in ethylene glycol (EG). Dynamic viscosity of samples was measured in shear rate range from $100\,s^{-1}$ to $1000\,s^{-1}$. Thermal and electrical conductivity of nanosuspensions with various fractions of particles was measured. All measurements were conducted at constant temperature 298.15 K. It was presented that with increasing concentrations of nanoparticles in nanofluids all investigated properties increase linearly in examined volume fraction range. Finally evaluation of the heat transfers performance, and thermo-electrical conductivity (TEC) ratio based on obtained results was presented.

1. Introduction

In 1995, S. Choi presented a paper in which he demonstrated an increase of the thermal conductivity in the suspensions of nanoparticles, which he described as "nanofluids" [1]. From that moment, the thermal properties of such materials are intensively explored all around the world, leading to the development of numerous industrial applications [2–4]. Some of the main areas of potential use of the nanofluids are the heat exchange process in the buildings [5], the machinery industry [6] and the nuclear power engineering [7]. Another advantage of the nanofluids is a possibility to use them in the alternative energy sources [8] and solar systems [9–12], the significance of which can not be overestimated in our era of an increasing need of the, "clean" energy. A separate group of nanofluids are the ferrofluids, which also have a lot of sophisticated applications [13] due to their unique properties.

There are two types of the methods of nanofluid preparations: the one-step and the two-step [14] ones. The one-step methods consist in the preparation of nanoparticles directly in the base fluid, and are used most often in the case of metallic nanoparticles. The two-step methods rely on the preparation of nanoparticles (first step), and then their dispersion in a liquid base (second step). In the case of two-step methods it is necessary to use mechanical methods to break up agglomerates. The mechanical mixing and sonication are the most common used techniques.

The mainstream of research of the characteristics of nanofluid is its thermal conductivity. Numerous studies are conducted in both experimental and theoretical fields on the thermal conductivity enhancement in nanofluids [15]. This leads to formation of new complex theoretical models of this issue [16]. Unfortunately, we still do not have a coherent theoretical model describing the mechanism of thermal conductivity of nanosuspensions. Certain models may describe some of materials correctly but can not be entirely applicable to others.

However, one should keep in mind that the practical application of nanofluids is not be possible without deep knowledge of their mechanical properties and, in particular, the viscosity. This is another area of intensive studies of the nanofluids. As in the case of thermal conductivity, theoretical [17] and experimental [18] studies of the rheological properties of nanosuspensions are conducted now. Great efforts have been made to develop a coherent theoretical model describing the viscosity of nanofluids but at the moment there are only models [19] which can be applied only to some individual cases.

One of the areas of study of the physical properties of nanofluids is their electrical properties, which are equally important but prob-

* Corresponding author.
E-mail address: gzyla@prz.edu.pl (G. Żyła).

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Nomenclature

c_p	specific heat (const. pressure) [J kg^{-1} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
p	pressure [Pa]
T	temperature [K]
u	uncertainty
$\dot{\gamma}$	shear rate [s^{-1}]
η	viscosity [Pa s]
τ	shear stress [Pa]
σ	electrical conductivity [μS cm^{-1}]
ρ	density [kg m^{-3}]
φ	fraction [–]

Subscripts

bf	base fluid
m	mass
nf	nanofluid
p	particle
r	relative
v	volume

ably underestimated by researchers as compare to their thermal or rheological properties. Among the electric properties, the electrical conductivity is most frequently studied. The electric conductivity of nanofluids tends to increase, like thermal conductivity, with an increasing volume concentration of nanoparticles in the base fluid. However, such studies are rather scarce, and the further work in this area is still needed.

Some studies of the thermophysical properties of nanofluids containing SiO_2 nanoparticles have been already performed. For example, Kulkarni et al. [20] described the heat transfer properties of ethylene glycol/water mix based nanofluids. The dependence of viscosity on the particle diameter and an increase of the heat transfer coefficient were reported. Dutta and De [21] presented the results of experimental studies of electrical properties of polypyrrole (PPY–SiO_2) nanocomposites at various temperatures and concentrations of the nanoparticles. Konakanchi et al. [22] measured pH of the suspension of SiO_2 in the mixture of propylene glycol with water. They observed that the pH of nanofluid increases with an increase of the volume fraction of particles. Talib et al. [23] presented the results of thermophysical measurements of dispersions of SiO_2 nanoparticles in ethylene glycol/water mixture, and described the potential use of this materials in the proton exchange membrane fuel cell cooling. Shahrul et al. [24] and Anoop et al. [25] evaluated the possibility of using SiO_2–water nanofluids in heat exchange processes and compared the properties of this material with the other water based nanofluids. Sharifpur et al. [26] carried out studies of an effect of the ultrasound energy densities on the electrical conductivity SiO_2–EG nanofluids with various volume concentrations in temperature range from 20 to 70 °C. They showed that an increase of the energy density causes the decrease in electrical conductivity of SiO_2–EG nanofluids. Haghtalab et al. [27] present the results of experiments on absorption of the carbon dioxide in the water-based nanofluids of spherical SiO_2 nanoparticles.

This paper presents the results of experimental studies of viscosity and thermal and electrical conductivity of SiO_2–EG.

2. Materials and methods

2.1. SiO_2 nanoparticles

The nanoparticles used in the studies are commercially available They were produced by PlasmaChem GmbH (Berlin, Germany) with >99.8% purity, catalog number PL-SiOF-25g. The particle size distribution declared by the manufacturer is 7—14 nm, and the specific surface over 200 m^2 g^{-1}. The thermal conductivity of SiO_2 is 1.38 W m^{-1} K^{-1}, the electrical conductivity 10^{-21} μS cm^{-1}, and the value of density 2220 kg m^{-3}, as presented in [23]. According to available literature, the specific heat of silicon dioxide is 745 J kg^{-1} K^{-1} at 300 K [28]. Dry SiO_2 nanoparticles were observed with VEGA3 (TESCAN Brno, s.r.o., Brno, Czech Republic) scanning electron microscope (SEM). Fig. 1 presents the SEM image of used nanoparticles and shows that the size of particles is in correspondence to the supplier information.

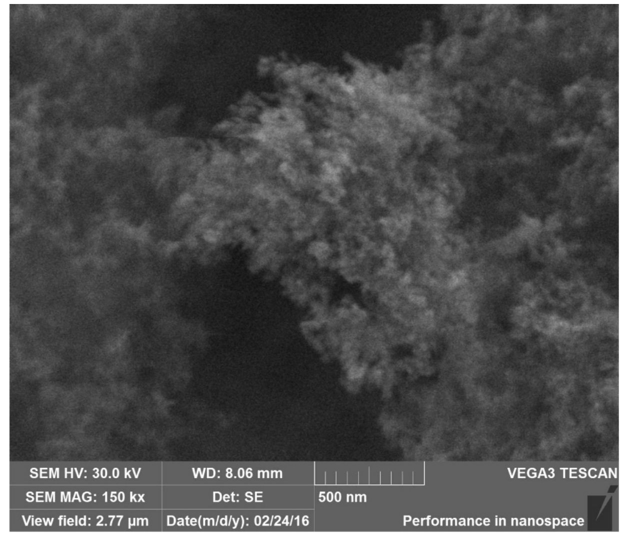

Fig. 1. SEM image of dry SiO_2 nanoparticles.

Table 1
Provenance and purity of the used materials.

Product	Provenance	Mass fraction purity
Ethylene glycol	Avantor Performance Materials Poland	>0.99
SiO_2 nanopowder	PlasmaChem GmbH	>0.998

2.2. Sample preparation

The samples were prepared by using the two-step method. This method is based on the dispersion of prepared nanoparticles in a base fluid. As a base fluid we use the ethylene glycol (POCH, Avantor Performance Materials Poland, Gliwice, Poland). The density of ethylene glycol is 1113.7 kg m^{-3} at 293.15 K [29], and the heat capacity is 2384.9 J kg^{-1} K^{-1} at 298.15 K as presented in Ref. [30]. The provenance and purity of the used materials are listed in Table 1. The samples were prepared in mass concentrations from 1% to 5%, and the mass concentrations were recalculated to the volumetric fractions by using the equation:

$$\varphi_v = \frac{\varphi_m}{\rho_p\left(\frac{\varphi_m}{\rho_p} + \frac{1-\varphi_m}{\rho_{bf}}\right)}. \quad (1)$$

The uncertainty of volume and mass fraction were calculated as a complex uncertainty, taking into account the accuracy of used analytical balance, uncertainty of density of nanofluids and base fluid, buoyancy corrections, and is found to be less than 1%.

Mechanical stirring for 30 min in Genius 3 Vortex (IKA, Staufen, Germany) and the sonication for 200 min in ultrasound wave bath Emmi 60 HC (EMAG, Moerfelden-Walldorf, Germany) were used to break agglomerates. After this preparation, all the samples were transparent as presented in Fig. 2. All measurements of thermo-