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Study of transport coefficients of nanodiamond nanofluids

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Abstract. Experimental data on the thermal conductivity coefficient and viscosity coefficient of nanodiamond nanofluids are presented. Distilled water and ethylene glycol were used as the base fluid. Dependences of transport coefficients on concentration are obtained. It was shown that the thermal conductivity coefficient increases with increasing nanodiamonds concentration. It was shown that base fluids properties and nanodiamonds concentration affect on the rheology of nanofluids.

1. Introduction

Nanoparticle colloidal suspensions, referred to as ‘nanofluids’ [1], have potential application in many heat transfer areas because of their intriguing properties such as a considerable increase in thermal conductivity, long-term stability and prevention of clogging in micro-channels [2–3]. Recently extensive efforts have been made to prepare thermal performance enhanced nanofluids [4–5]. Diamond is one of the materials with very high thermal conductivity, and diamond particles are often used as filler in mixtures for upgrading the performance of a matrix [6]. In some studies nanodiamonds are used as particles that improve the thermal conductivity of heat-transfer liquids, such as water, oil and ethylene glycol just as particles of metals (gold, copper), metal oxides (aluminum and copper oxides) and silicon carbide [7-11]. It is reasonable to expect that the addition of diamond nanoparticles would lead to thermal performance enhancement in a base fluid. However, available information about them in the open literature is very scant.

Torii et al. [12] conducted experiments in nanodiamond-water nanofluids. The authors of work [12] investigated the coefficients of viscosity and thermal conductivity of nanodiamond-water nanofluids. Particle size ranged from 2 to 10 nm were used. Viscosity coefficient of nanofluid with a particle volume concentration of 2% is 55% higher the viscosity coefficient of water. Thermal conductivity coefficient of nanofluid with a particle volume concentration of 5% is 15% higher the thermal conductivity of water.

In work [13], nanodiamonds were chosen to form nanofluids with mixture base fluid composed of distilled water with a volume fraction of 0.55 and ethylene glycol with a volume fraction of 0.45. The thermal transport properties, including the thermal conductivity, the viscosity and the convective heat transfer coefficient, were investigated. The thermal conductivity enhancement of nanodiamond nanofluids increases with nanodiamonds loading and the thermal conductivity enhancement is more than 18.0% for a nanofluid at a nanodiamonds volume fraction of 0.02. Viscosity measurements show that the nanodiamond nanofluids demonstrate Newtonian behaviour, and the viscosity significantly decreases with temperature.



Yeganeh et al. [14] measured thermal conductivity enhancements of nanodiamond particles suspended in pure deionized water with different volume fractions in the range from 0.8% to 3%. The highest observed enhancement in the thermal conductivity is 7.2% for a volume fraction of 3% at a temperature of 30°C. The thermal conductivity increases by about 9.8% as the temperature rises to 50°C.

This work presents an experimental study of thermal conductivity coefficient and viscosity coefficient of nanodiamond nanofluids. Distilled water and ethylene glycol were used as the base fluid.

2. Preparation of nanofluids

The powder of nanodiamonds was produced by Joint Stock Company Federal Research & Production Center ALTAI.

Properties of nanodiamonds. The size of primary particles is 4-6 nm, it was defined by X-ray phase analysis. The aggregate size is 20-2500 nm and it is obtained by using a scanning electron microscope (see figure 1). Density $3.0 \pm 0.1 \text{ g/cm}^3$ was measured by the pycnometric method. The specific surface is $280 \pm 60 \text{ m}^2/\text{g}$ and is measured by the BET method. The chemical analysis showed a diamond phase content not less than 91.0%. The mass fraction of non-combustible impurities in the solid phase which was defined by the burning method is not more than 5.0%. Chemical impurities are O, N, H (elemental analysis).

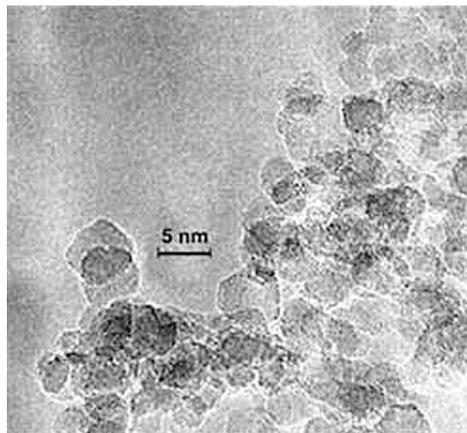


Figure 1. SEM image of nanodiamonds.

The volume concentration of nanoparticles varied from 0.25 to 2%. Preparation of nanofluids was based on standard twostep process. At first we have added the required amount of nanopowder to the base fluid, then the nanofluid was carefully mixed mechanically, then it was placed into an ultrasonic disperser ‘Sapphire TC-10338’ for a half-hour to destruct conglomerates of particles.

3. Dependence of thermal conductivity on particle concentration

Thermal conductivity measurements were performed by nonstationary hot-wire method. Detailed description of the test bench and testing technique is given in [15]. The resultant relative measurement error of fluid thermal conductivity coefficient does not exceed 3%.

Two series of measurements of thermal conductivity were carried out. The first series was carried out for a nanofluid based on distilled water. In the second series, ethylene glycol was used as the base fluid. Dependences of relative coefficient of thermal conductivity of nanofluids (the ratio of thermal conductivity of nanofluid to coefficient of thermal conductivity of base fluid) on nanodiamonds concentration were obtained (see figure 2-3).

Figures 2-3 show that the coefficient of thermal conductivity of nanofluids increases with increasing nanodiamond volumetric concentration φ .

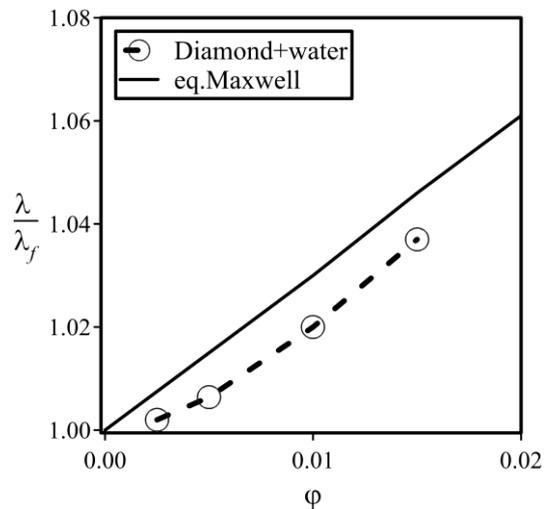


Figure 2. Relative thermal conductivity coefficient of water based nanofluids depending on diamond particle concentration.

Furthermore, figures 2-3 show the dependences of the thermal conductivity of nanofluids predicted by the Maxwell theory (solid line):

$$\lambda = \lambda_f \frac{\lambda_p + 2\lambda_f + 2\phi(\lambda_p - \lambda_f)}{\lambda_p + 2\lambda_f - \phi(\lambda_p - \lambda_f)} \tag{1}$$

where λ_p, λ_f are the thermal conductivity coefficient of particle material and base fluid.

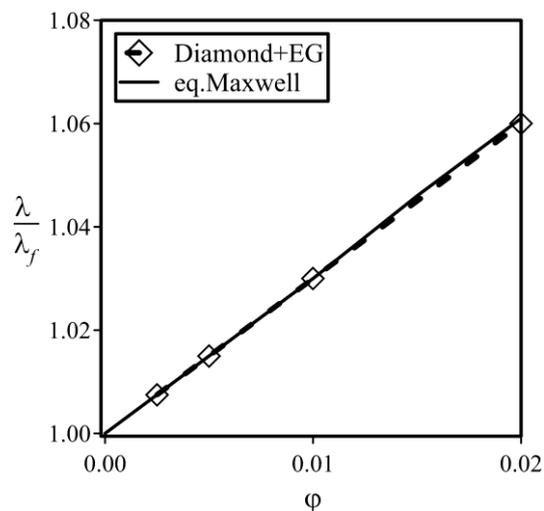


Figure 3. Relative thermal conductivity coefficient of ethylene glycol based nanofluids depending on diamond particle concentration.

It is seen that the experimental coefficient of thermal conductivity of ethylene glycol-based nanofluid is well described by Maxwell's theory. The experimental thermal conductivity coefficient of water-based nanofluid is slightly lower than the coefficient predicted by Maxwell's theory.

4. Dependence of viscosity on particle concentration

The viscosity of nanofluids was measured by a rotational viscosimeter Brookfield DV2T with the adapter ULA(0) for a low viscosity. The installations description and its approbation for the viscosity measurement of nanosuspensions are given in [16]. The accuracy of viscosity's measurement is not lower than 2 %. All the data below are obtained at the temperature of 25°C.

Two series of measurements were also carried out, as is the case with the study of the thermal conductivity of nanodiamond nanofluids. The first series of measurements was carried out for water-based nanofluids. Figure 4 shows the dependences of the relative viscosity coefficient on the spindle speed by different nanodiamond concentrations. It is seen that viscosity coefficient increases with increasing nanodiamond concentration. Furthermore, the dependence of viscosity on the spindle speed is well seen. This demonstrates the non-Newtonian properties of nanofluids. The obtained data are well described by a power law:

$$\frac{\mu}{\mu_f} = K \cdot \dot{\gamma}^{n-1} \tag{2}$$

where K is flow consistency index ($\text{Pa} \cdot \text{s}^{-n}$), $\dot{\gamma}$ is the shear rate (s^{-1}); n is the flow behavior index of nanofluids.

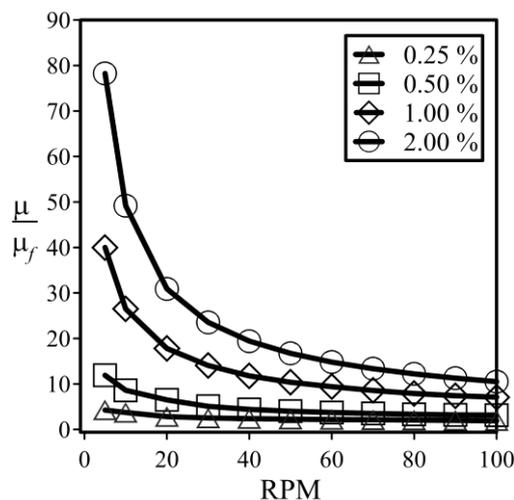


Figure 4. Relative viscosity coefficient of water based nanofluids depending on RPM.

The flow behavior index and the flow consistency index of investigated nanofluids are represented in table 1. It demonstrates that the flow behavior index decreased and the flow consistency index increased with increasing particle concentration. Thus, it was shown that non-Newtonian properties increase with increasing particle concentration.

Table 1. Flow behavior index and flow consistency index depending on particle concentration		
φ	n	K ($\text{mPa} \cdot \text{s}^{-n}$)
0.0025	0.84	6.37
0.0050	0.55	24.0
0.0100	0.42	101
0.0200	0.33	230

Similar studies of ethylene glycol-based nanofluids did not reveal non-Newtonian properties. The nanofluid remained Newtonian at all considered concentrations. The dependence of relative viscosity coefficient of ethylene glycol-based nanofluid on nanodiamond concentration is shown in figure 5. Figure 5 shows the dependence of the coefficient of viscosity on nanodiamond concentration predicted by Einstein's theory. Also figure 5 represent that the relative viscosity coefficient of nanofluid is much higher than the coefficient predicted by Einstein's formula:

$$\frac{\mu}{\mu_f} = 1 + \frac{5}{2}\phi \quad (3)$$

where μ_f is the viscosity coefficient of base fluids.

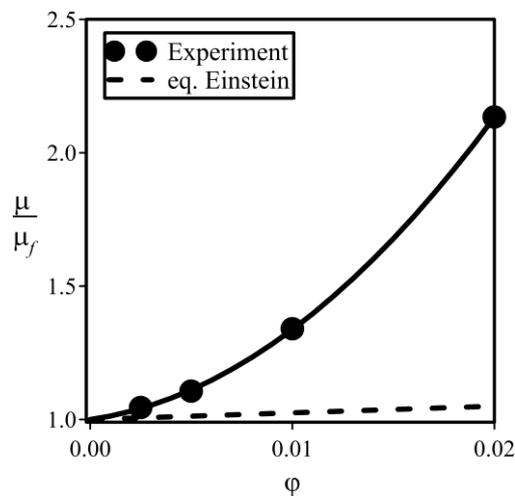


Figure 5. Relative viscosity coefficient of ethylene glycol based nanofluids depending on particle concentration.

5. Conclusion

Complex experimental study of the coefficient of thermal conductivity and the viscosity coefficient of nanodiamond nanofluids was carried out.

It was obtained that the coefficient of thermal conductivity of nanofluids increases with increasing nanodiamond concentration in all considered cases. It is shown that the increase in the thermal conductivity coefficient is greater for fluids with lower thermal conductivity. The experimental value of thermal conductivity of nanodiamond nanofluid is well described by the Maxwell formula (1).

It is shown that viscosity coefficient increases with increasing nanodiamond concentration. The experimental value is much higher than the value predicted by the Einstein formula. The strong influence of base fluid properties on the rheology of nanofluids is noteworthy. It is established that water-based nanofluids become non-Newtonian with increasing nanodiamonds concentration. The obtained data are well described by a power law (see formula (2)). The flow behavior index and the flow consistency index of the investigated nanofluids were determined (presented in table 1). However, the ethylene glycol-based nanofluids remain Newtonian.

Acknowledgments

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