Viscosity and acoustic parameters of suspension based on ethylene glycol with aluminum nanoparticles

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Abstract. The study of suspensions with aluminum nanoparticles was carried out. Ethylene glycol was used as the base fluid. The mass concentration of Al nanoparticles varied from 2.5 to 20%. The viscosity coefficient of the suspension at different shear rates was measured. The dependence of the viscosity on the concentration of Al nanoparticles in ethylene glycol was obtained. The attenuation of the suspensions was measured. The dependence of the sound speed in suspension on the nanoparticle concentration was obtained. The acoustic parameters of the suspension, such as adiabatic compressibility, acoustic impedance, intermolecular free length, viscous relaxation time, are calculated.

1. Introduction
Nanofluids are the two-phase systems consisting of base fluid (water, ethylene glycol, etc.) and solid nanoparticles, usually metallic or oxide [1]. Quite a lot of studies have been conducted on the thermophysical properties of nanofluids, such as viscosity and thermal conductivity (see review [2-3]). However, very few studies on the acoustic properties of nanoparticle suspensions are available.

The study of suspensions using ultrasound technique (based on ultrasonic attenuation in medium) allows you to obtain useful information, such as particle size distribution, concentration, mechanical properties (for example, adiabatic compressibility and storage modulus) and some information about intermolecular interactions. The study of intermolecular interactions in suspensions can provide information about the interacting properties of molecules.

In this work, the study of suspensions based on ethylene glycol with aluminum nanoparticles was conducted. The acoustic parameters of the suspension, such as adiabatic compressibility, acoustic impedance, intermolecular free length, and viscous relaxation time, are calculated.

2. Materials and methods

2.1. Aluminum nanoparticles and suspension preparation
Aluminum nanopowder L-ALEX\textsuperscript{TM} was used. Aluminum powder was obtained by spraying a metallic conductor in an argon atmosphere, and then passivating by a slow stream of dry air. The powder contains about 99.5% active aluminum. The specific surface area measured by the BET (Brunauer–
Emmett–Teller [4] method is 24.5 m$^2$g$^{-1}$. The average particle size calculated using a specific surface area is 91 nm. A high-resolution transmission electron microscope photo of Aluminum powder is shown in figure 1.

The standard two-step method was used to prepare suspensions. The required amount of Al powder was added to ethylene glycol. After that, the suspension was thoroughly mechanically mixed. Ultrasonic sonication (“Volna” model UZTA-0.4/22-OM) was also used to destroy nanoparticle conglomerates. The sonication time was 20 minutes.

Volume concentration was calculated by mass concentration:

$$\phi = \frac{\rho_f \omega}{\rho_f \omega + \rho_p (1 - \omega)}$$  \hspace{1cm} (1)

where $\rho_f$, $\rho_p$ are densities of ethylene glycol and aluminum nanoparticles, respectively. The density of aluminum is 2700 kg m$^{-3}$, and the density of ethylene glycol is 1110 kg m$^{-3}$.

The density of suspensions was determined using the nanoparticle concentration (see table 1):

$$\rho = \rho_f \phi + \rho_p (1 - \phi)$$  \hspace{1cm} (2)

2.2. Viscosity

The Brookfield DV2T rotational viscometer was used to measure the viscosity coefficient of suspension. The range of shear rates is from 0.4 to 78 s$^{-1}$. The accuracy of viscosity measurements was not lower than 2%. All measurements were carried out at a suspension temperature of 25°C.

2.3. Attenuation and sound speed in suspension

Attenuation in suspensions was measured using a DT1202 acoustic and electroacoustic spectrometer (Dispersion Technologies). A detailed description of the spectrometer is described in [5]. The frequency range is from 3 to 100 MHz. The sound speed was also measured. Measurements of attenuation and sound speed were carried out several times, and then the average value was calculated. All measurements were performed at a suspension temperature of 25 °C.

3. Results and discussion

A study of suspension viscosity on shear rate was carried out (see figure 2a). Ethylene glycol and four mass concentrations of nanoparticles in ethylene glycol were investigated: 2.5%, 5.0%, 10%, and 20% (the corresponding volume concentrations are shown in table 1). It was found that the viscosity is constant at different shear rates at concentrations $w \leq 10\%$. This suggests that the suspension is Newtonian at $w \leq 10\%$, and the suspension becomes non-Newtonian at high concentrations [6]. Thus, suspensions based on ethylene glycol with aluminum nanoparticles exhibit both Newtonian and non-Newtonian nature. The suspension rheology ($w = 20\%$) is well described by the Power-law:
\[ \mu(\dot{\gamma}) = K\dot{\gamma}^n \]  

(3)

where \( K \) is flow consistency index, mPa s\(^n\); \( n \) is flow behavior index. Flow consistency index is 269.4 mPa s\(^n\), and flow behavior index is 0.662 for 20wt\% suspension.

The dependence of the relative viscosity coefficient of suspension on the Al nanoparticle concentration was obtained (see figure 2b). Figure 2b shows that the suspension viscosity increases with increasing Al nanoparticle concentration. A comparison with Batchelor's theory [7] is also given (figure 2b):

\[ \frac{\mu}{\mu_f} = 1 + (5/2)\phi + 6.2\phi^2 \]  

(4)

where \( \mu \), \( \mu_f \) are viscosity coefficients of suspension and base fluid (ethylene glycol), respectively. The viscosity of ethylene glycol is 17.12 mPa s. The measured viscosity values are higher than those obtained by the Batchelor's theory. The relative viscosity coefficient according to the theory of Batchelor is 1.12, and the experimental value is 1.298. The viscosities of suspensions at different nanoparticle concentrations are shown in table 1.

**Figure 2.** The dependence of suspensions viscosity coefficient on the shear rate (left) and relative viscosity on volume concentration (right).

Attenuation of the suspension at different nanoparticle concentrations is presented in figure 3. The attenuation coefficient is 2.780 and 4.559 at a frequency of 100MHz for concentration of 10\% and 20\%, respectively. For pure ethylene glycol, this attenuation coefficient is 0.950.
In addition, the sound speed on nanoparticle concentrations in suspension was measured, the data are presented in table 1. The sound speed in ethylene glycol is 1658.5 m s$^{-1}$, and it decreases with increasing nanoparticle concentrations.

Adiabatic compressibility is calculated by the formula based on the assumption that the Newton-Laplace [8]:

$$\beta = \frac{1}{\rho c^2}$$

A decrease in adiabatic compressibility is observed with increasing concentration (table 2).

**Table 1.** Volume concentration, density, viscosity, sound speed, and attenuation for suspension.

| Concentration $w$, wt% | Volume concentration $\phi$, vol% | Density $\rho$, kg m$^{-3}$ | Viscosity $\mu$, mPa s | Sound speed $c$, m s$^{-1}$ | Attenuation at 100 MHz $\alpha$, dB cm$^{-1}$ MHz$^{-1}$ |
|------------------------|----------------------------------|-----------------------------|-------------------------|----------------------------|-----------------------------------------------------|
| 0                      | 0                                | 1111.0                      | 17.12                   | 1658.5                    | 0.950                                               |
| 2.50                   | 1.04                             | 1127.6                      | 17.74                   | 1654.6                    | 1.410                                               |
| 5.00                   | 2.12                             | 1144.7                      | 18.82                   | 1650.8                    | 1.861                                               |
| 10.0                   | 4.37                             | 1180.5                      | 22.23                   | 1643.7                    | 2.780                                               |
| 20.0                   | 9.33                             | 1259.2                      | -                       | 1632.5                    | 4.559                                               |

Acoustic impedance can be calculated from Eq. 6:

$$Z = \rho c$$

The dependence of acoustic impedance on concentration is similar to the dependence of density. Intermolecular free length is determined according to Jacobson [9]:

$$L = k_j \sqrt{\beta}$$

where $k_j$ is Jacobson constant ($k_j = 2.0568 \times 10^{-6}$ [9]). Intermolecular free length decreases.
The viscous relaxation time can be calculated as follows [10]:

$$\tau = \frac{4}{3} \beta \eta$$  \hspace{1cm} (8)

An increase in the relaxation time is observed with increasing concentration. The relaxation time of 20 wt% suspension is not determined since it is a non-Newtonian fluid.

The results of the acoustic measurements are presented in Table 2.

| Concentration $w$, wt% | Adiabatic compressibility $\beta$, $10^{10}$ Pa$^{-1}$ | Acoustic impedance $Z$, $10^{6}$ N s m$^{-3}$ | Intermolecular free length $L$, $10^{11}$ m | Viscous relaxation time $\tau$, $10^{12}$ s |
|------------------------|---------------------------------|---------------------------------|----------------------|---------------------------------|
| 0                      | 3.272                           | 1.843                           | 3.582                | 7.461                           |
| 2.50                   | 3.239                           | 1.866                           | 3.564                | 7.662                           |
| 5.00                   | 3.206                           | 1.890                           | 3.545                | 8.044                           |
| 10.0                   | 3.135                           | 1.940                           | 3.506                | 9.293                           |
| 20.0                   | 2.980                           | 2.056                           | 3.418                | -                               |

4. Conclusion
The study of suspension based on ethylene glycol with aluminum nanoparticles was carried out. The dependence of suspension viscosity on the concentration of aluminum nanoparticles was obtained. When the concentration of nanoparticles is less than 10%, the suspensions are Newtonian, above this concentration, a change in rheology to non-Newtonian is observed.

The attenuation in the suspension was measured. The attenuation coefficient was 2.780 and 4.559 at frequency of 100 MHz for concentrations of 10% and 20%, respectively.

The sound speed decreases with increasing nanoparticle concentration. The sound speed in ethylene glycol is 1658.5 m s$^{-1}$, and in 20 wt% suspension it is 1632.5 m s$^{-1}$. The acoustic parameters such as adiabatic compressibility, acoustic impedance, absorption coefficient, intermolecular free length, and relaxation time were calculated.

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