══════ MECHANICS ══════

Experimental Data on the Dependence of the Viscosity of Water- and Ethylene Glycol-Based Nanofluids on the Size and Material of Particles

V. Ya. Rudyak[a], A. V. Minakov[b], M. S. Smetanina[a], and M. I. Pryazhnikov[a]

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Abstract—The viscosities of all nanofluids considered are shown to be dependent on the size of nanoparticles. It has been established that the greater the nanofluid viscosity, the smaller the size of particles. The measurements carried out in this study make it possible for the first time to fix experimentally the fact of the dependence of the viscosity of nanofluids on the particle material.

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Today it is already clear that nanofluids, i.e., two-phase fluids with disperse nanoparticles, have unusual thermophysical properties. In particular, contrary to coarse dispersed fluids, their viscosity is not described by universal relations of the type of the formulas of Einstein, Batchelor, etc. The viscosity of nanofluids considerably exceeds that of the usual disperse fluids with an identical volume concentration of disperse particles (see [1−4]). In [5, 6], the method of molecular dynamics with the potential of solid spheres showed that the effective viscosity of a nanofluid depends also on nanoparticle size instead of only on their volume concentration. The corresponding experimental data [1−4], however, which was quite contradictory, appeared simultaneously.

To remove these contradictions, a special series of measurements was carried with ethylene glycol−based nanofluids and silicon-dioxide particles, which made it possible to assert unambiguously that the viscosity of nanofluids increases with decreasing size of particles [7, 8].

In [9], it was established by the molecular-dynamics method for nanofluids with small particles that the viscosity of nanofluids depends also on the material of nanoparticles. Nevertheless, the nonuniversality of the existing experimental data requires further regular measurements of the viscosity of nanofluids. This is the purpose of this study. It was necessary to clarify the

following problems: how the viscosity depends on the size of nanoparticles, their material, and the viscosity of the carrier fluid. We investigated more than twenty various distilled water−based and ethylene glycol−based nanofluids with SiO_2, Al_2O_3, TiO_2, and ZrO_2 particles. The sizes of nanoparticles varied from 11.5 to 150 nm, and their volume concentrations varied from zero to 6%. All nanopowders were purchased from OAO Plazmoterm (Moscow).

The viscosity of nanofluids was measured by a rotational viscosimeter Brookfield DV2T with the adapter ULA(0) for a low viscosity. The accuracy of the measurement of viscosity was not lower than 2%. All the data below are obtained at the temperature of 25°C.

The conventional two-step method was used for the preparation of nanofluids. The necessary quantity of powder was added to the fluid after which the obtained suspension was carefully mixed mechanically.

To destroy conglomerates of nanoparticles, the suspension was treated in a Sapphire TTs-10338 ultrasonic bath for 45 min.

The first series of experiments was performed for determining the dependence of viscosity on the nanoparticle size. As the base fluid in this series of experiments, we used distilled water. Three nanofluids were with SiO_2 particles with a size of 11.5, 25, and 100 nm; four fluids were with Al_2O_3 particles (48, 75, 100, and 151 nm); three fluids were with TiO_2 particles (70, 100, 150 nm); and two fluids were with ZrO_2 particles (44 and 105 nm). In all cases, the volume concentration of particles amounted to 2%. The data obtained are shown in Fig. 1; here we present the values of relative

[a] *Novosibirsk State Architecture and Civil Engineering University, Novosibirsk, 630008 Russia*
[b] *Siberian Federal University, Krasnoyarsk, 660041 Russia*
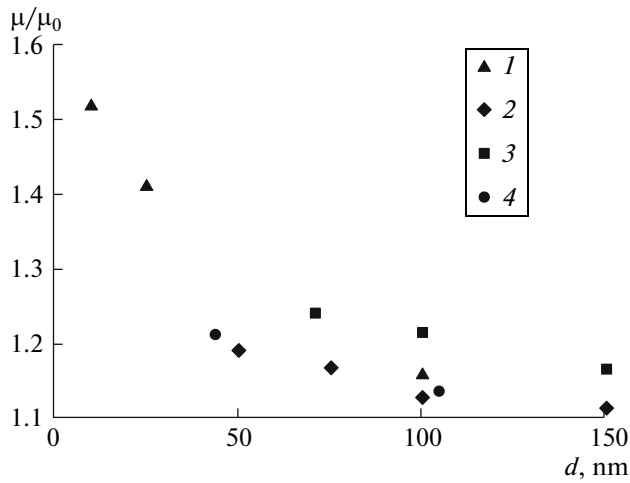*e-mail: valery.rudyak@mail.ru*

Fig. 1. Dependence of the coefficient of the dynamic viscosity of the water-based nanofluids on the particle sizes at a concentration of 2%: the nanoparticles of (*1*) SiO_2, (*2*) Al_2O_3, (*3*) TiO_2, and (*4*) ZrO_2.
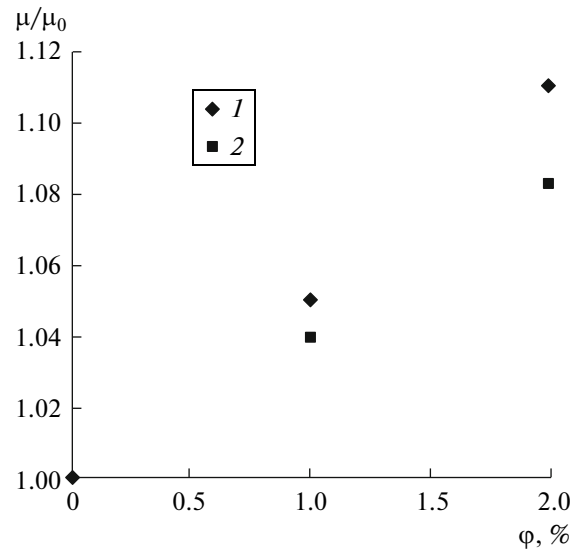

Fig. 2. Dependence of the relative viscosity on the volume concentration of nanoparticles at the size of particles of 100 nm. The base fluid is water: nanoparticles of (*1*) SiO_2 and (*2*) Al_2O_3.

viscosity $\mu_r = \dfrac{\mu}{\mu_0}$, where μ_0 is the viscosity of the base fluid. All data presented testify to the fact that, first, the viscosities of all considered nanofluids depend on the size of nanoparticles and, second, the viscosity of a nanofluid is the higher, the smaller the size of the particles. In addition, neither Einstein's theory $\mu = \mu_0\left(1 + \dfrac{5}{2}\varphi\right)$ [10], nor the Batchelor theory [11]

$$\frac{\mu}{\mu_0} = 1 + 2.5\varphi + 6.2\varphi^2, \qquad (1)$$

as well as no other classical theories describe the experimental data for nanoparticles smaller than 100 nm (formula (1) gives a value equal to 1.051).

As was already noted in [9] the method of molecular dynamics was used for establishing the dependence of the viscosity of nanofluids on the nanoparticle material. The measurements carried out in this study for the first time confirm this conclusion experimentally. At the fixed concentration of nanoparticles, it can already be seen in Fig. 1 for nanofluids with 100-nm particles. A more complete picture is presented in Fig. 2 for water-based nanofluids with Al_2O_3 and SiO_2 particles. In both cases, the nanoparticles had an average size of 100 nm. The distinction in the measured viscosities proves to be significant, and they are not described by the classical theories.

The second important point consists in the fact that the viscosity of disperse fluids with coarse particles (150 nm), which actually are not nanoparticles (by definition), proves to be different (see Fig. 1). It points to the fact that the viscosity of disperse fluids with sub-

micron particles depends on the nanoparticle material just as with nanoparticles.

Figure 3 illustrates the last fact well. Here we present the data for the dependence of viscosity of water-based disperse fluids with Al_2O_3 and TiO_2 particles. The measured values of the viscosities are described well by the correlations: in the first case,
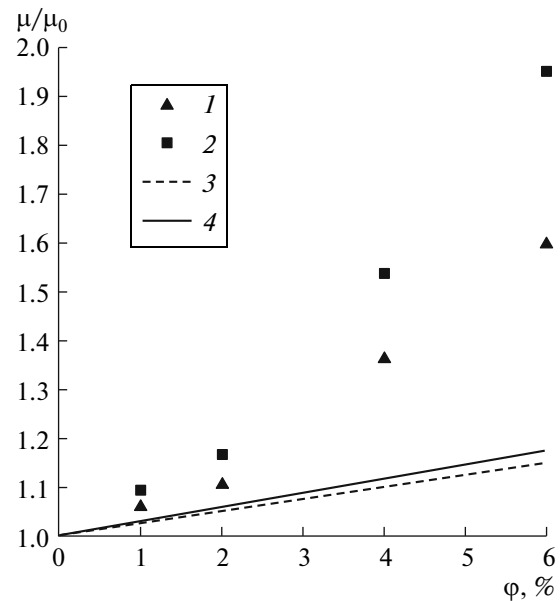

Fig. 3. Dependence of the relative viscosity on the concentration at the size of particles of 150 nm. The base fluid is water: nanoparticle of (*1*) Al_2O_3, (*2*) TiO_2; (*3*) Einstein's theory, and (*4*) the Batchelor theory.
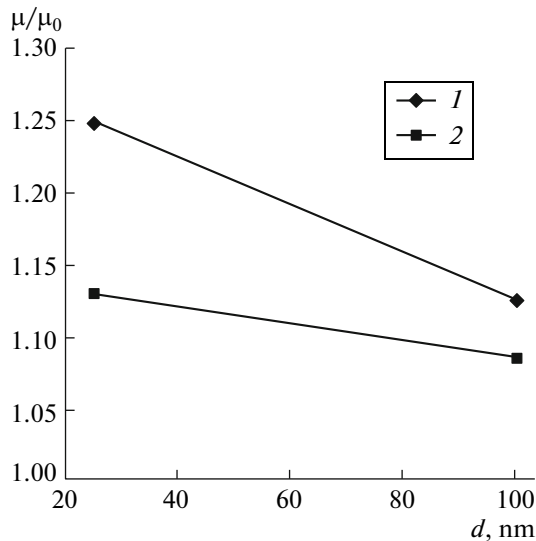
μ/μ_0

Fig. 4. Dependence of the relative viscosity of the nano-fluid on the properties of the base fluid. The concentration of SiO$_2$ particles is 1%; (*1*) the base fluid is ethylene glycol, and (*2*) the base fluid is water.

$$\frac{\mu}{\mu_0} = 1 + 6\varphi + 72\varphi^2, \qquad (2)$$

in the second case,

$$\frac{\mu}{\mu_0} = 1 + 7.1\varphi + 148\varphi^2. \qquad (3)$$

According to Eqs. (2) and (3), the viscosity exceeds the corresponding Einstein value two-and-half-to-three times even at a low particle concentration.

The viscosity for all classical disperse fluids is described by the relation $\dfrac{\mu}{\mu_0} = 1 + 2.5\varphi + b\varphi^2$, where the factor b varies from 4.3 to 7.6 [4]. In particular, it means that the relative viscosity μ_r for all disperse fluids is universal and independent of the viscosity of the base fluid. With a nanofluid, it is not so. The relative viscosity of the nanofluid with a higher viscosity of the base fluid also has a higher relative viscosity. It is illustrated in Fig. 4. Here we present the data for two water-based and ethylene glycol–based nanofluids with SiO$_2$ nanoparticles of identical sizes of 25 and 100 nm. The viscosity of the base fluids at this temperature differs by approximately 17 times. The relative viscosities of nanofluids also prove to be different. An excess of the relative viscosity of the ethylene glycol–based nanofluid above the corresponding value for the water-based nanofluid depends on the size of nanoparticles and decreases with its increase.

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