The effect of nanoparticles additives in the drilling fluid on pressure loss and cutting transport efficiency in the vertical boreholes

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The effect of nanoparticles of various chemical components and sizes on the rheological behaviour of drilling fluids, pressure loss and cuttings transport in the vertical borehole for a laminar flow regime is considered in the paper. The results of numerical and experimental studies are presented. Silicon, aluminium and titanium oxides nanoparticles are considered. A drilling fluid is Bentonite-water solution with a mass fraction of 5%. The particles concentration in the solution was varied from 0.25 to 2 weight percentages and the particles sizes ranged from 5 to 50 nm. The dependences of the effective viscosity and rheological parameters of the solutions on the nanoparticles concentrations, sizes and materials were obtained. It was shown that nanoparticles in drilling fluid increase cuttings transport by 17% and decrease the average slip velocity of the sludge particles in 1.7 to 2.0 times, but the pressure losses when pumping the drilling fluid increase in 2.5 times.

Key words: non-Newtonian fluids, drilling fluid, nanoparticles, rheology, annular channel, pressure loss, Herschel-Bulkley model, cutting transport, vertical borehole, laminar flow.

Introduction

Active interest in the suspensions with nanoparticles (nanofluids) has been appeared a quarter of a century ago and still continues to grow up. The number of publications devoted to the study of nanofluids properties and applications is increasing exponentially. Nanoparticles have a number of unusual properties that are absent in the macroscopic dispersed particles due to their small size. Unusual properties of nanoparticles make the properties of nanofluids (in which they are an integral part) unconventional too, that lead to the widest range of nanofluids applications [1-7]. The influence of nanoparticles additives on heat transfer has been studied in a large number of works. As it was shown in the experimental investigations of laminar and turbulent forced convection of water-based nanofluids, the CNT-nanofluids can increase the heat transfer coefficient within the range from a few percents up to 350%. Also, it was found, that the nanoparticles adding to a fluid increase the boiling critical heat flux by several times. Many investigations of nanoparticles applications in the medical technologies were carried out. Nanoparticles are used for localized drug delivery and cancer therapy. Nanoparticles are also employed for improvement of strength properties of materials, especially applying the coatings, the lubricants, and the adhesives. There are many other applications.

At present possible applications of nanofluids are very actively investigated [8-19]. Nanofluids are used to control the mud filtration process, to reduce the friction factors of a drill string and a borehole wall, and to prevent sidewall sticking of a drilling rod. It makes such solutions competitive compared to the hydrocarbon-based solutions, whose usage is limited by environmental requirements.

Modern drilling muds have different properties, which can be influenced by nanoparticles additives in a varying degree. The most important of these are viscosity and rheology because they influence the pressure loss during flushing-out of the well, the efficiency of the cutting transport, the borehole stability, etc. In this regard, a large number of investigations of the nanoparticles effect on the viscosity and rheological behaviour of the drilling muds have been carried out in the last few years [8-18]. It was found that nanoparticles significantly increase the viscosity of drilling fluids, and change the rheological properties of these solutions. It is an undesirable feature because it leads to the increase in the pressure loss. Thus, it was shown in [8], that TiO_2 nanoparticles increase the plastic viscosity of the water-based drilling fluid thirteenfold, and the yield point in 2.9 times. It was found in [9], that SiO_2 nanoparticles of 10% concentration in water-based drilling mud increase the plastic viscosity in 2.9 times and the yield point fivefold. Belayneh et al. [10] showed that nanoparticles affect the rheology of not only the pure clay mud but also the drilling fluid with polymer additives. It was found by them, that nanoparticles of silicon dioxide (SiO_2) increase the yield point of a polymer solution in 1.5 times. Rajat et al. [11] also reported that the polyacrylamide-grafted-polyethylene glycol/SiO_2 nanocomposite shows a significant increase in rheological parameters of drilling fluid, namely the plastic viscosity increased in 1.5 times and the yield point increased in 1.8 times. However, a non-monotonic behaviour of the rheological characteristics with an increase in nanoparticle concentration was observed by many authors. The rheological properties begin to change at a very low concentration of nanoparticles.

At the same time, it was established in some other investigations a much weaker effect of nanoparticles on the rheology of drilling fluid. It was found in [12], that the nanoparticles of CuO and ZnO with sizes less than 50 nm have almost no effect on the plastic viscosity and the yield point of the mud at atmospheric pressure and room temperature, but as the pressure increases the effect becomes noticeable. Slight impact of SiO_2 and TiO_2 nanoparticles on the rheology of the bentonitic drilling fluid was also found in [13]. In addition, even some decrease in the yield point at 50°C was observed for all considered types of nanoparticles. The decrease in the yield point and the increase in the plastic viscosity after adding the nanoparticles to the drilling fluid was also reported in [14]. It was concluded, that nanoparticles do not significantly effect on the rheological properties in general.

Finally, it was shown in some investigations, that nanoparticles significantly reduce the rheological properties of drilling fluids. It was shown in [15], that silicon dioxide nanoparticles in the clay mud with barite particles reduce both the plastic viscosity and the yield point twofold as under normal conditions, as under an elevated temperature and pressure. Moreover, such decrease becomes stronger with the increase in temperature.

The effect of nanoparticles sizes on the rheology of drilling fluid was also observed by many researchers, in addition to the effect of nanoparticles concentration. A significantly higher increase in the rheological properties of the clay mud with Fe2O3 nanoparticles of 3 nm average size in comparison with the nanoparticles of 30 nm average size at the same concentration was found in [16]. For silicon dioxide particles [17] were obtained similar conclusions.

Thus, despite a large amount of data and research in this field, a complete understanding of the nanoparticles influence on the viscosity and the rheology of the drilling fluids still absent, so the additional systematic study is needed. In spite of existing disagreements, most researchers concluded, that the effect of nanoparticles on the properties of drilling fluids is much stronger than that caused by microscopic particles. Such an effect is observed at very low concentrations and depends on the sizes and materials of nanoparticles, that provides an opportunity to manage properties of drilling fluid.

On the one hand, the influence of nanosuspension on the rheology of drilling fluids has a negative effect in terms of practical applications. The increase in the viscosity, which is observed after the addition of nanoparticles in most cases, leads to higher pressure losses when pumping muds. On the other hand, the increase in the viscosity and the yield point provides better removal of the sludge from the borehole and improves its stability. Therefore, it is necessary to find the optimum between the pressure losses and the cutting transport while choosing nanoparticles additives. So the aim of the presented study is a systematic investigation of the nanoparticles effect on the pressure losses, because, nowadays, among a large number of studies of the nanosuspension rheology, there are no scientific works devoted to it. The effect of varying of the nanoparticles materials on the pressure drop in the borehole was also investigated. The numerical simulation on the basis of experimentally measured rheological properties of the drilling fluids was conducted in the study.

1. Experimental apparatus and procedures

First, an experimental study of the nanoparticles effect on the rheological properties of the drilling fluids was carried out. An aqueous suspension of clay mud was used as a basic model of drilling fluid. Weight concentration of the clay was equal to 5%. The Malvern Zetasizer Nano ZS analyser was used to determine the sizes of nanoparticles. The clay mud was prepared by adding particles to distilled water, then that mixture was intensely stirred for 30 minutes with the use of "OFITE 152-18 - Prince Castle" high-speed stirrer (20000 rpm). The clay suspension was kept for two days after preparation for the purpose of the final swelling of the clay and to obtain the stable properties of it. The colloidal stability of the suspensions was monitored by using the "TURBISCAN LAB" optical stability analyzer (http://www.formulaction.com). Turbiscan LAB analyzes sample stability without dilution or mechanical stress and provides fast and sensitive identification of destabilization mechanisms (creaming, sedimentation, flocculation, coalescence) of suspensions. Then, the necessary amount of pre-made nanosuspension was added to the prepared by the described above method clay suspension. The same amount of the distilled water was poured into the sample of the basic clay suspension to provide an equal mass concentration of clay particles in all investigated solutions. A standard two-step method was used to prepare the nanosuspension. The required amount of nanopowder was added to the fluid, and the resulting suspension was subjected of a thoroughly mechanical stir. The suspension was treated in "Sapphire SC-10338" ultrasonic bath to destroy the nanoparticle conglomerates [20-21].

The silicon, aluminium and titanium oxides nanoparticles were used in the study. The densities of the alumina, the silica and the titania particles were 3950 kg/m^3, 2650 kg/m^3 and 4230 kg/m^3, respectively. These particles were stable and chemically inert. The particles concentration in the solution was varied from 0.25 to 2 weight percentages and the particles sizes ranged from 5 to 50 nm.

Study of the rheological properties of the prepared nanosuspensions was undertaken with the use of the "OFITE Model 1100" rotational viscometer (http://www.ofite.com), which rotation speed varied between 0.01 and 600 rpm with the speed accuracy of 0.001 rpm and shear rate ranged from 0.01702 to 1021 s^{-1}. The ranges of the shear rate in the carried out measurements were from 5.1 to 1021 s^{-1}, which correspond to the ranges of the rotation speed from 3 to 600 rpm. The measurement error of the viscometer was 2%. All measurements were conducted at the atmospheric pressure and the room temperature (298 K).

In terms of rheological properties, the basic clay mud was treated as a non-Newtonian fluid. Its effective viscosity μ_f was well described by Herschel–Bulkley model [22]:

$$\mu_f = (\tau_0 + k_v \cdot \dot{\gamma}^n) \cdot \dot{\gamma}^{-1},$$

where $\tau_0 = 0.34$ Pa is the yield stress of viscoplastic fluid, $k_v = 0.038$ Pa·s^n is the plastic viscosity, $n = 0.72$ is the flow index and $\dot{\gamma}$ is the shear rate in s^{-1}.

Analyzing the Fig. 1 it was found, that rheological parameters of the clay suspension with silicon dioxide nanoparticles depend on their sizes and weight concentrations φ (even at very low values). As the nanoparticles concentration increases, the plastic viscosity and the yield point increase too, and, in contrast, the flow index decreases significantly. It is clear that the rheological properties of the studied suspensions essentially depend also on the nanoparticles sizes, namely, as the size decreases, this effect enhances. Thus, similar to the previous case, it was found that as the nanoparticles size increases, the plastic viscosity and the yield point increase, and the flow index decreases. Moreover, nanoparticles of an average sizes larger 50 nm have almost no effect on the rheological properties of suspensions.

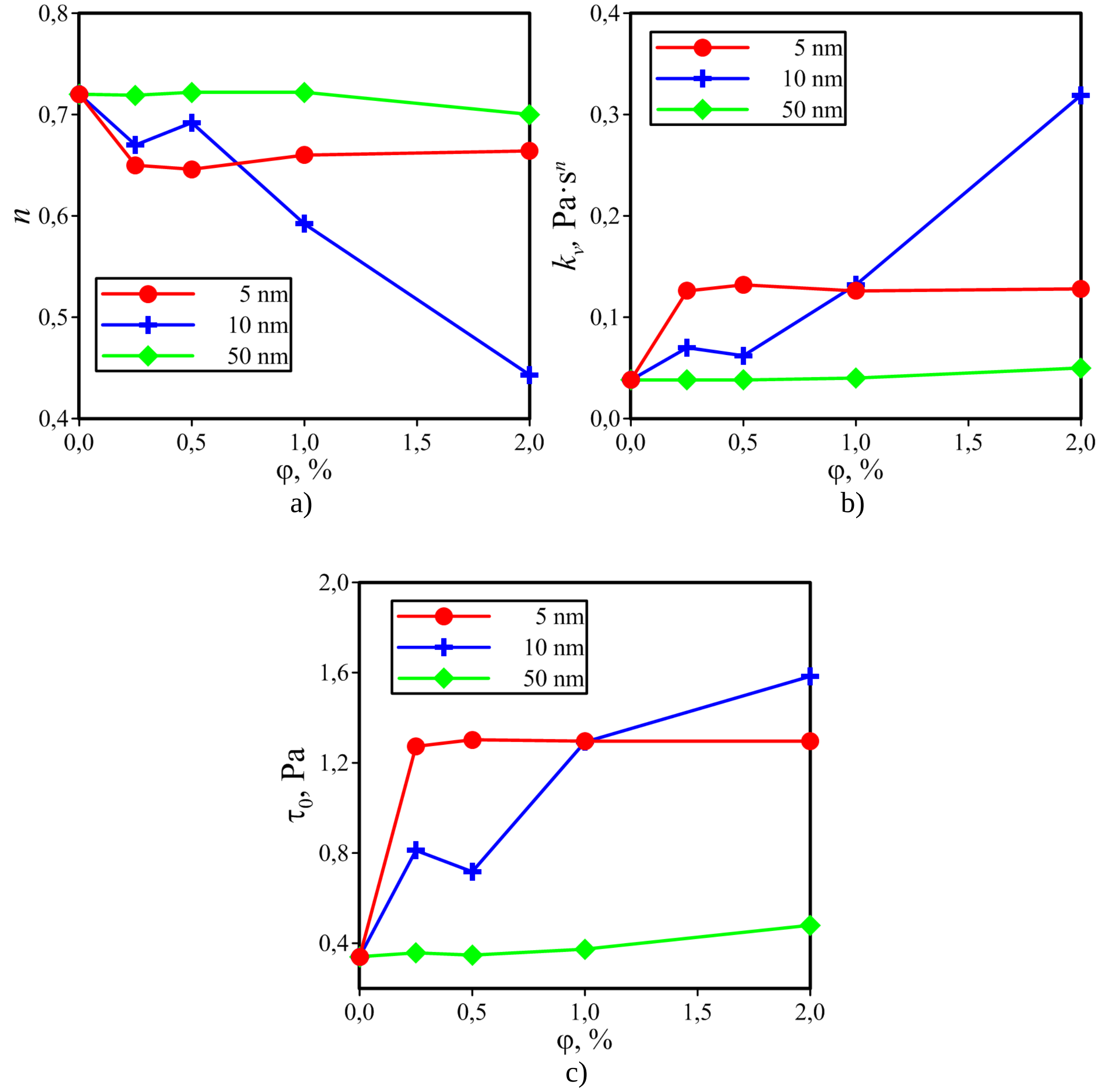


Fig. 1. The dependences of the suspensions rheological parameters on the concentrations and sizes of the silicon dioxide nanoparticles: flow index *n* (a); plastic viscosity (b); yield point (c)

The effect of the nanoparticles materials on the rheological characteristics of clay muds was also studied. The nanosuspensions with closest average sizes of nanoparticles, such as the silicon dioxide of 50 nm average size, the aluminium oxide of 43 nm average size and the titanium dioxide of 47 nm average size, were selected.

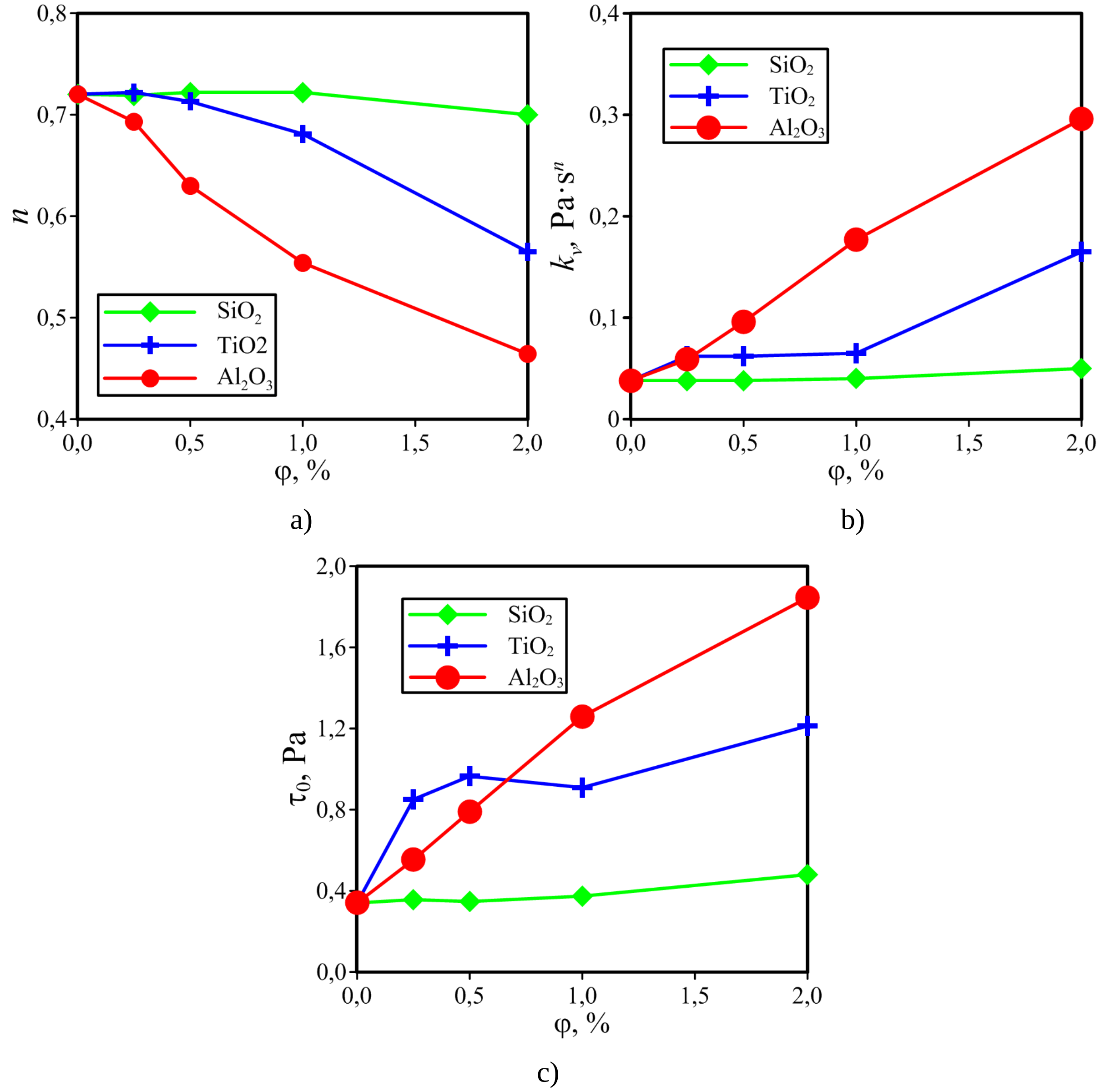


Fig. 2. The dependences of the suspensions rheological parameters on the concentrations and chemical composition of the nanoparticles: flow index n (a); plastic viscosity (b); yield point (c)

The obtained results shown in Fig. 2 allow one to draw some conclusions about the effect of the nanoparticles material on the rheology of suspensions. Despite the fact that nanoparticles of the oxides of the silicon, the titanium and the aluminium have similar average particle sizes, rheology of drilling fluid based on them significantly differs from each other even at the same concentration. The aluminium oxide nanoparticles have the most significant effect on the rheology at all other conditions being equal. The dependence of the viscosity on sizes and materials of the nanoparticles is not peculiar to the classical suspensions, and it is a specific feature of nanosuspensions (see [5, 23]). The rheological parameters obtained in the experiments were used to calculate the pressure losses in the borehole.

2. Mathematical model

The isothermal, laminar, fully developed and steady flow of an incompressible fluid with constant density was considered in the study. The Eulerian-Eulerian two-phase flow model was used to study the flow behaviour of cuttings and drilling fluid in an annulus [24-35]. The Eulerian model assumes that the sludge flow consists of solid «*s*» and fluid «*f*» phases, which are separate, yet they form interpenetrating continua, so that $\alpha_f + \alpha_s = 1.0$, where α_f and α_s are the volume concentrations of the fluid phase and the solid phase, respectively. The basic equations of the Eulerian model have the next form:

1) Continuity equations:

$$\nabla \cdot (\alpha_s \rho_s \vec{v}_s) = 0,$$
$$\nabla \cdot (\alpha_f \rho_f \vec{v}_f) = 0. \qquad 1)$$

2) Momentum equations

for fluid phase:

$$\nabla \cdot (\alpha_f \rho_f \vec{v}_f \vec{v}_f) = -\alpha_f \nabla P + \nabla \cdot \bar{\bar{\tau}}_f + \alpha_f \rho_f \vec{g} + K_{sf}(\vec{v}_s - \vec{v}_f). \qquad (2)$$

for solid phase:

$$\nabla \cdot (\alpha_s \rho_s \vec{v}_s \vec{v}_s) = -\alpha_s \nabla P - \nabla P_s + \nabla \cdot \bar{\bar{\tau}}_s + \alpha_s \rho_s \vec{g} + K_{fs}(\vec{v}_f - \vec{v}_s). \qquad (3)$$

where $\bar{\bar{\tau}}_s$ and $\bar{\bar{\tau}}_f$ are the stress tensors for solid and fluid, respectively. They are expressed as:

$$\bar{\bar{\tau}}_s = \alpha_s \mu_s (\nabla \vec{v}_s + \nabla \vec{v}_s^{\,tr}) + \alpha_s \left(\lambda_s - \frac{2}{3}\mu_s\right) \nabla \cdot \vec{v}_s \bar{\bar{I}} \qquad (4)$$

and

$$\bar{\bar{\tau}}_f = \alpha_f \mu_f \left(\nabla \vec{v}_f + \nabla \vec{v}_f^{\,tr}\right). \qquad (5)$$

where $\bar{\bar{I}}$ is the identity tensor, μ_f is the shear viscosity of the fluid.

The drilling fluid is considered as non-Newtonian fluid, so a well-known approach to simulate the non-Newtonian flows was used. The medium is considered as a non-linear viscous fluid that characterized by effective viscosity $\mu_f(\dot{\gamma})$. That viscosity in general case depends on the shear rate, which is the second invariant of the strain rate tensor:

$$\dot{\gamma} = \sqrt{\frac{1}{2}\mathbf{D} \cdot \mathbf{D}}. \qquad (6)$$

The drilling fluid can be considered as both viscous Newtonian fluid and non-Newtonian viscoplastic fluid in such approach. The Herschel–Bulkley model was used in this study:

$$\mu_f(\dot{\gamma}) = \frac{k_v \dot{\gamma}^n + \tau_0}{\dot{\gamma}}, \tag{7}$$

where τ_0 is the yield point of the viscoplastic fluid, k_v is the plastic viscosity, n is the flow index.

λ_s is the bulk viscosity of the solids [25]:

$$\lambda_s = \frac{4}{3}\alpha_s \rho_s d_s \mathbf{g}_{o,ss}(1 + e_{ss})\left(\frac{\Theta_s}{\pi}\right)^{\frac{1}{2}}, \tag{8}$$

where d_s is the particles diameter.

The $\mathbf{g}_{o,ss}$ is the radial distribution function, which is interpreted as the probability of a particle to touch another particle [26]:

$$\mathbf{g}_{o,ss} = \left[1 - \left(\frac{\alpha_s}{\alpha_{s,\max}}\right)^{\frac{1}{3}}\right]^{-1}, \tag{9}$$

$\alpha_{s,\max} = 0.63$ is the packing limit.

Variable $\mathbf{P}_s$ is the solid pressure given by [25]:

$$P_s = \alpha_s \rho_s \Theta_s + 2\rho_s(1 + e_{ss})\alpha_s^2 \mathbf{g}_{o,ss}\Theta_s, \tag{10}$$

where e_{ss} is the restitution coefficient, taken as 0.9.

The granular temperature for solid phase Θ_s describes the kinetic energy of the random motion of solid particles. The transport equation derived from the kinetic theory [27-28]:

$$\frac{3}{2}\nabla \cdot (\rho_s \alpha_s \vec{v}_s \Theta_s) = \left(-P_s \bar{\bar{I}} + \bar{\bar{\tau}}_s\right) : \nabla \vec{v}_s + \nabla \cdot \left(k_{\Theta_s} \nabla \Theta_s\right) - \gamma_{\Theta_s} + \varphi_{fs}, \tag{11}$$

where k_{Θ_s} is the diffusion coefficient given by [29]:

$$k_{\Theta_s} = \frac{15 d_s \rho_s \alpha_s \sqrt{\Theta_s \pi}}{4(41 - 33\eta)}\left[1 + \frac{12}{5}\eta^2(4\eta - 3)\alpha_s \mathbf{g}_{o,ss} + \frac{16}{15\pi}(41 - 33\eta)\eta \alpha_s \mathbf{g}_{o,ss}\right], \tag{12}$$

$$\eta = \frac{1}{2}(1 + e_{ss}), \tag{13}$$

γ_{Θ_s} is the collisional dissipation energy, which represents the energy dissipation rate within the solid phase due to the collision between particles:

$$\gamma_{\Theta_s} = \frac{12(1 - e_{ss}^2)\mathbf{g}_{o,ss}}{d_s \sqrt{\pi}} \rho_s \alpha_s^2 \Theta_s^{\frac{3}{2}}, \tag{14}$$

and φ_{fs} is the transfer of the kinetic energy of random fluctuation in particle velocity from solid phase «*s*» to the fluid phase «*f*», given by:

$$\varphi_{fs} = -3K_{fs}\Theta_s. \tag{15}$$

μ_s is the shear viscosity of solids, defined as:

$$\mu_s = \mu_{s,col} + \mu_{s,kin}\,, \tag{16}$$

where $\mu_{s,col}$ and $\mu_{s,kin}$ are collisional and kinetic viscosities, that calculated using following expressions:

$$\mu_{s,col} = \frac{4}{5}\alpha_s\rho_s d_s \mathrm{g}_{o,ss}(1 + e_{ss})\left(\frac{\Theta_s}{\pi}\right)^{\frac{1}{2}} \tag{17}$$

and

$$\mu_{s,kin} = \frac{\alpha_s d_s \rho_s \sqrt{\Theta_s \pi}}{6(3 - e_{ss})}\left[1 + \frac{2}{5}(1 + e_{ss})(3e_{ss} - 1)\alpha_s \mathrm{g}_{o,ss}\right]. \tag{18}$$

$K_{sf} = K_{fs}$ is the interphasial momentum exchange coefficient, given by Gidaspow model [28], which is a combination of the Wen and Yu model [30] and the Ergun equation [31].

When $\alpha_f > 0.8$, the fluid-solid exchange coefficient K_{sf} has the following form:

$$K_{sf} = \frac{3}{4}C_D\frac{\alpha_s\alpha_f\rho_f|\vec{v}_s - \vec{v}_f|}{d_s}\alpha_f^{-2.65}, \tag{19}$$

where

$$C_D = \frac{24}{\alpha_f Re_s}\left[1 + 0.15(\alpha_f Re_s)^{0.687}\right]. \tag{20}$$

When $\alpha_f < 0.8$,

$$K_{sf} = 150\frac{\alpha_s(1 - \alpha_f)\mu_f}{\alpha_f d_s^2} + 1.75\frac{\rho_f\alpha_s|\vec{v}_s - \vec{v}_f|}{d_s}. \tag{21}$$

Parameter Re_s is the relative Reynolds number between phases «*f*» and «*s*», given by

$$Re_s = \frac{\rho_f d_s|\vec{v}_s - \vec{v}_f|}{\mu_f}. \tag{22}$$

The computational domain is an annular channel formed by two smooth straight pipes of circular cross-sections. The diameter of the inner pipe is D_1, and the diameter of the outer pipe is D_2. The inner pipe rotates around its axis with a constant angular velocity ω. The constant mass flow *G* is set at the inlet of the annular channel. The no-slip conditions are set on the walls of the pipes.

The commercial code ANSYS Fluent (academic version) was used for calculation of cuttings transport. Here will be noted the main points of numerical technique. The difference analogue of the convective–diffusion equations is determined using the finite volume method for unstructured grids. In this case, the resulting scheme is automatically conservative. The method consists in splitting the computational domain into control volumes and integrating the original conservation equations for each control volume to obtain finite–difference equations. Approximation of convective terms of the transfer equations is carried out using a second order upwind QUICK scheme. Diffusion fluxes and source terms were approximated by finite-volume analogues of the central-difference correlations with the second order of accuracy. The connection between the velocity and pressure fields, ensuring the fulfilment of the continuity equation, was implemented by means of the SIMPLEC procedure for aligned grids. Rhi-Chow approach consisting in the introduction of monotonizator into the equation for the pressure correction was used to eliminate the pressure field oscillations. The difference equations obtained after discretization of the original system of differential equations were solved by an iterative method with the use of the algebraic multigrid solver.

3. Verification of the numerical algorithm

To test the numerical algorithm the steady laminar flow of non-Newtonian fluid in an annular channel without eccentricity with a rotation of the inner tube was considered. The numerical results were compared to the experimental data [36-38]. A 3% solution of carboxymethyl cellulose (CMC) was considered as the operating fluid in Case 1, while 0.25% solution of peracetic acid (PAA) was tested in Case 2. The rheology of these solutions are described by the Power Law model $\tau = k\dot{\gamma}^n$ with parameters presented in Table 1. Values of the other parameters are also given in Table 1.

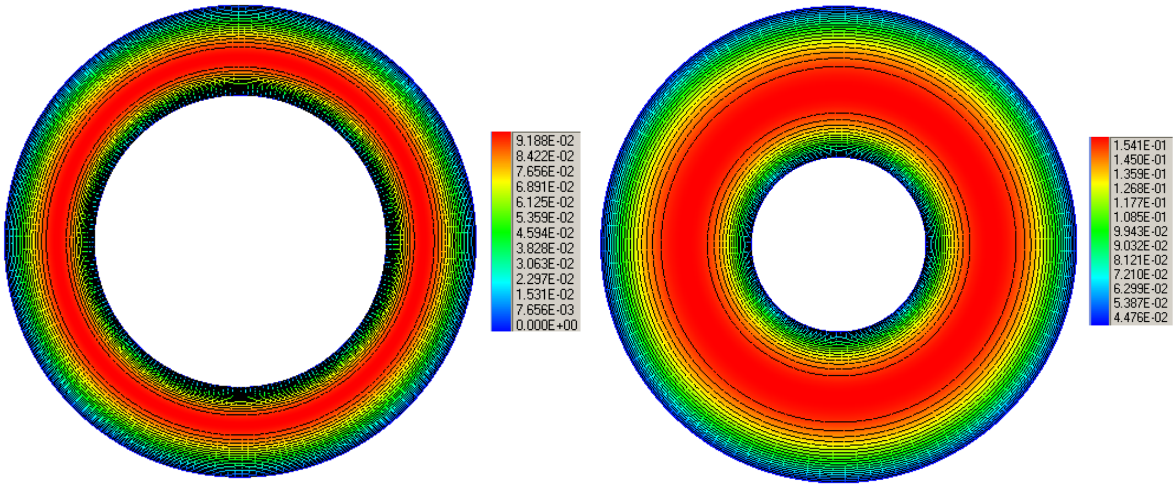
Table 1. The experimental parameters

	Case 1	Case 2
D_1,m	0.04	0.048
D_2, m	0.065	0.1319
G, kg/s	0.1198	1.93
ω, rad/s	70.1	4.4
n	0.56	0.62
k,Pa×s^n	2.9	0.175
ρ, kg/m^3	1000	1000

Taking into account the presence of rotational motion, the Reynolds and the Taylor numbers were 3.04 and 789 in case 1 and 108 and 2134 in case 2, respectively.

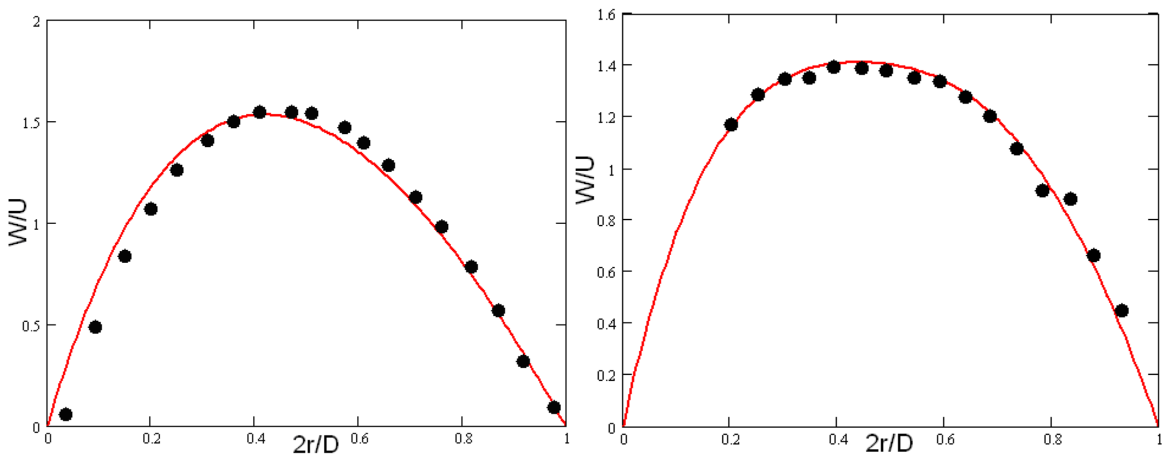
A grid consisting of 40×140×3 nodes was used for the numerical simulation (40 nodes along the radius, 140 nodes around the circumference, and 3 nodes along the channel length). The fully developed flow along the channel length was considered for verifying the numerical algorithm. In such case, the velocity field is the same in each cross-section of the channel and the number of mesh nodes along the channel is not of great importance. A special algorithm [24] was used to specify the boundary conditions for such fully developed flows. The procedure of correcting the fluxes enables us to construct a fully developed flow on a short fragment of the channel without having to simulate long channels with a zone of flow stabilization.

The distribution of axial velocity in the channel section for the both considered cases is shown in Fig. 3. Fig. 4 represents the comparison of the calculating dimensionless axial velocity profile in the channel section to the experimental data. Conversion into dimensionless form was carried out through dividing the relevant values by the average velocity U = 0.06 m/s (Case 1) and U = 0.163 m/s (Case 2). The x-axis corresponds to the distance between the cylinders, which was converted into dimensionless form through dividing by the width of the annular gap.



a) b)

Fig.3. The isolines of the axial velocity for Case 1 (a) and Case 2 (b).



a) b)

Fig. 4. The comparison of the calculated (solid curves) results and the experimental (filled circles) data [36-38] of the profile of the axial velocity for Case 1 (a) and Case 2 (b).

As one can see, there is a good agreement between numerical results and experimental data of the axial velocity profile in all cases. Numerical results of the pressure drop in the annular channel obtained by the use of the power law fluid model were presented in [39]. Three solutions with close to real mud properties were investigated in this paper. It was also presented experimental data of the pressure drop there. The obtained experimental data were used to verify the numerical method. The calculated pressure drop were in a good agreement with the experimental data. Thus, it has been shown that used numerical algorithm correctly describes both the velocity profiles and pressure drop for non-Newtonian flows in annular channels. Further, that algorithm was applied to calculate the pressure drop for the mud with nanoparticles.

4. Simulation results

The drilling process parameters were chosen for calculation the pressure loss in the borehole while pumping drilling fluid. The inner pipe diameter was D_1 = 0.08895 m, the outer pipe diameter was D_2 = 0.1463 m, the rotation speed of a drill string was 100 rpm, the mud flow rate was 11.61 kg/s, and the density of the mud was 1050 kg/m^3. The rheological properties of the drilling fluids were set on the basis of the experimental data shown in Figs. 1 and 2. In this case, the calculations were performed with the use of the Herschel–Bulkley model. The described above computational grid, which consisted of 40×140×3 nodes (40 nodes along the radius, 140 nodes around the circumference, and 3 nodes along the channel length) was used for the numerical simulation. A steady laminar flow was investigated. The maximum Reynolds number was equal to 895. The pressure drop and velocity profiles for various concentrations, sizes and materials of nanoparticles were obtained in the calculations. The dependence of the pressure drop in the annular channel on the nanoparticles sizes and materials is shown in Fig. 5.

It is obvious that nanoparticles significantly affects the pressure drop in the borehole. In the suspension with 2% concentration of nanoparticles, the pressure loss increases more than twice. It can be quite critical when implementing the drilling process. Nonetheless, the strongest effect is observed for the nanoparticles of the smallest size. Thus, silicon oxide nanoparticles increase the pressure loss even at very low concentrations of 0.25%. Further increase in concentration of these nanoparticles has practically no effect on the pressure loss. Large nanoparticles (50 nm) of silicon oxide have a little effect on the pressure loss even at high concentrations. In addition to the nanoparticles concentrations and sizes, the pressure loss is affected by nanoparticles materials. It can be clearly seen in Fig. 5b. Nanoparticles of various materials, but with the similar average sizes of about 50 nm reveal the completely different effect on the pressure loss in the channel. As was mentioned above, the silicon dioxide nanoparticles have almost no effect on the pressure loss, while that loss increases more than twice with the monotonously increasing in the aluminium oxide nanoparticles concentration. Undoubtedly, that effect is completely related to the rheology of the studying drilling fluids.

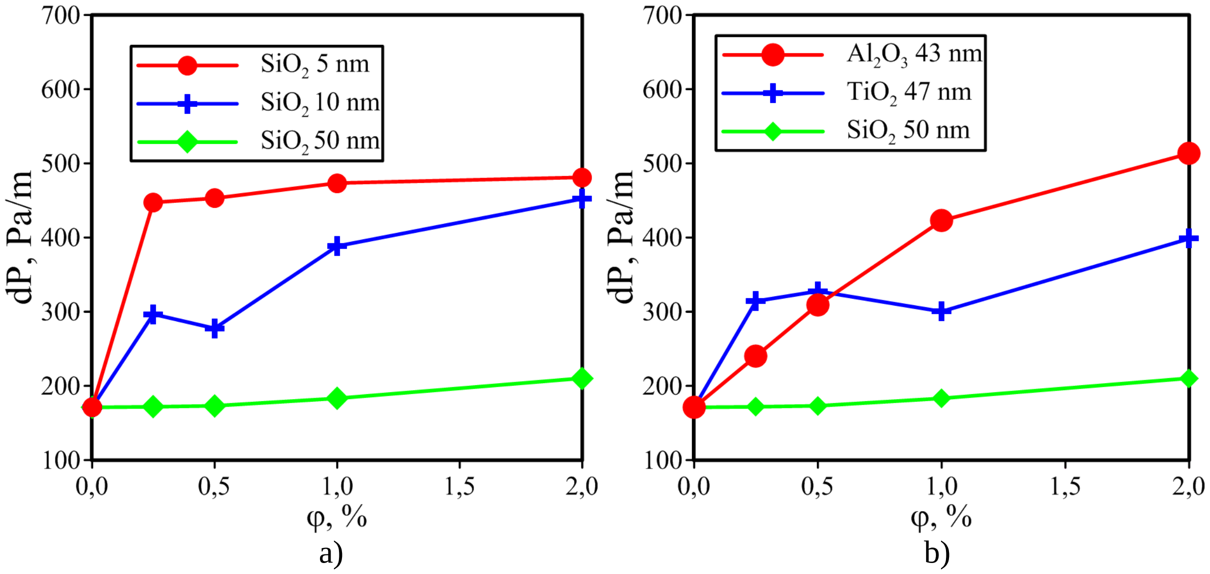


Fig. 5. The dependences of the pressure drop in the annular channel on the concentration of the nanoparticles of different sizes and materials

The effect of nanoparticles on the shape of the axial velocity profile in the annular gap is shown in Figs. 6 and 7. As one can see, that effect is also quite significant. As the nanoparticles concentration at a given flow rate of drilling fluid increases, monotonic broadening of the shape of the velocity profile occurs, because the flow index *n* decreases in such a case. The decrease in the size of nanoparticles results in the same effect on the shape of the velocity profile. A decrease in the nanoparticles average size has the same effect on the shape of the velocity profile, which becomes a bit flatter due to the decreasing in the flow index *n*. The influence of nanoparticles material on the shape of the velocity profile also explains by the rheology. The use of aluminium oxide nanoparticles makes the velocity profile in the channel more uniform at all the other factors being equal.

Thus, it was shown that the velocity profile in the channel becomes more uniform due to adding the nanoparticles and reducing their sizes that lead to better cutting transport during a drilling process. Currently, there are some experimental studies which confirm such conclusions. It was shown in [40], that adding of 0.01% carbon nanotubes in the working fluid increase the well clean-up efficiency by more than 10-15%. However, at the moment there are no systematic studies of the nanoparticles effect on the cutting transport. For this reason, the numerical investigation of the influence of the nanoparticles on the cutting transport with the use of the Eulerian model for granular media was carried out in this work. Parameters of the borehole and drilling process, which were used for the calculations, were described at the beginning of this section (D_1=0.08895 m, D_2=0.1463 m, G=11.61 kg/s, ω=100 rpm).

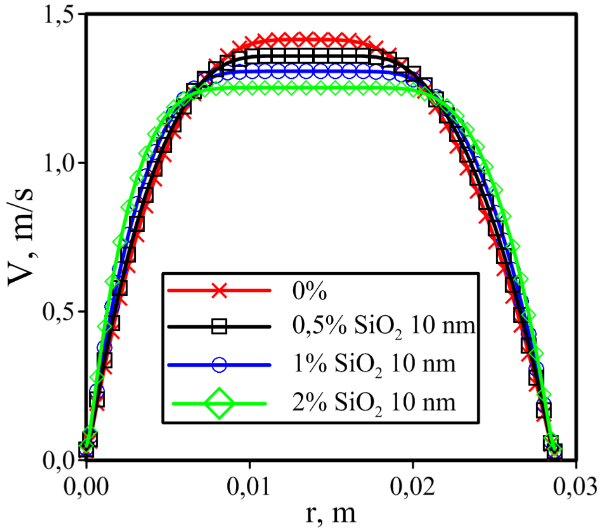


Fig. 6. The distribution of the velocity profile in the annular gap for different concentrations of the silicon dioxide nanoparticles of 10 nm average size

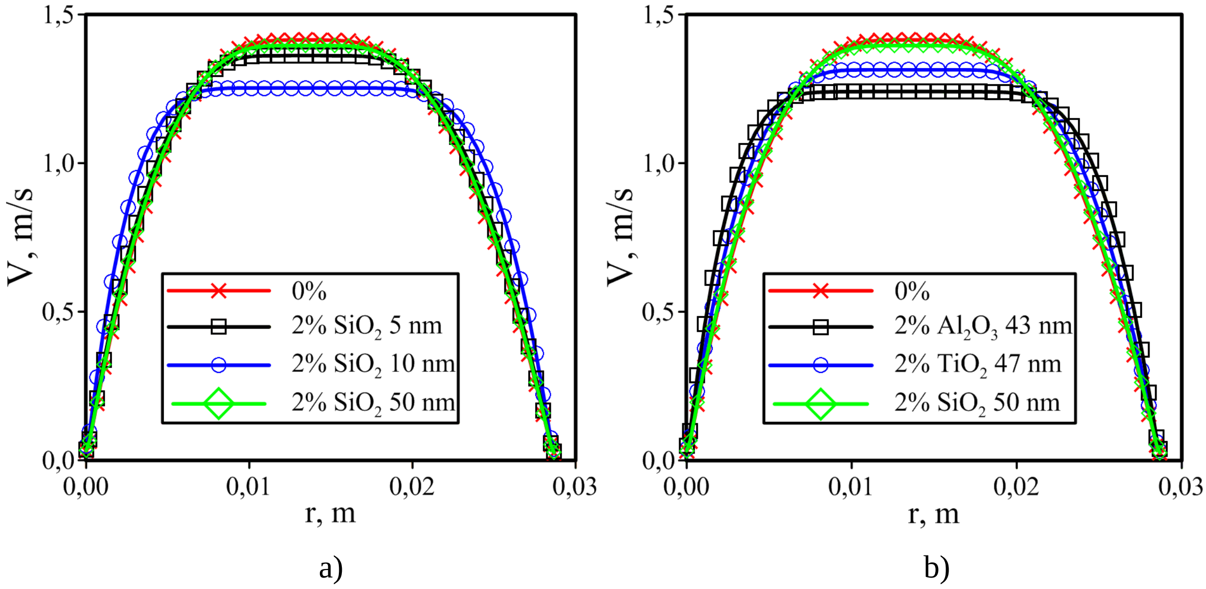


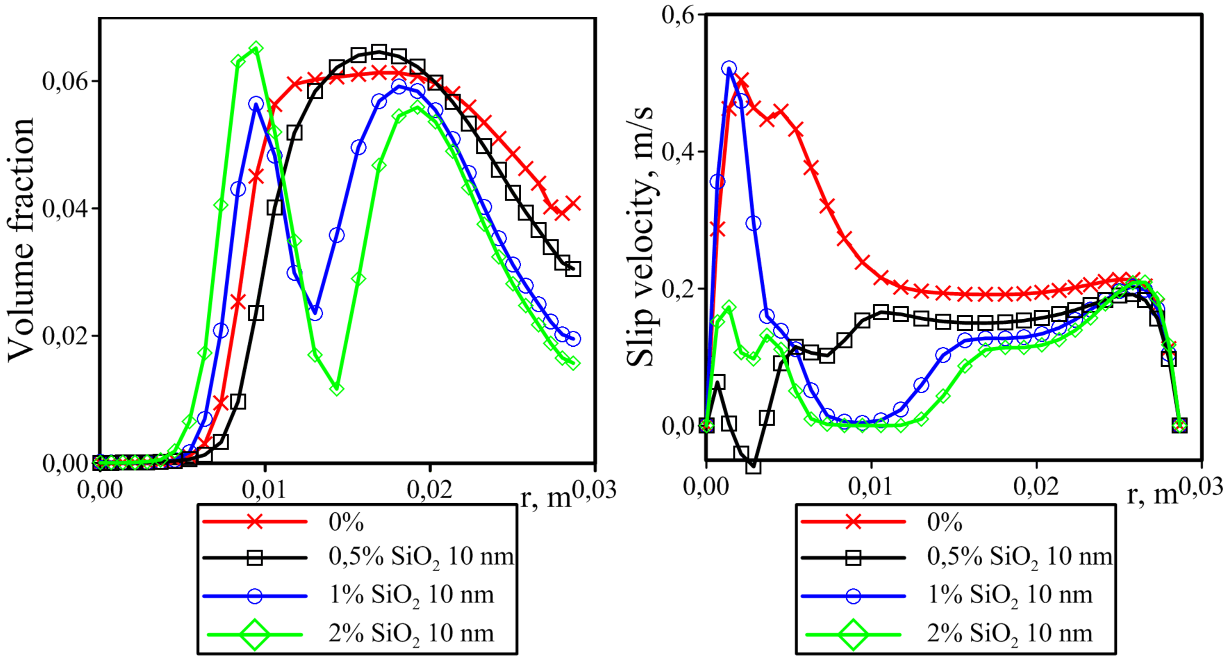
Fig. 7. The distribution of the velocity profile in the annular gap for different average sizes of the silicon dioxide nanoparticles of 2% concentration (a) and for 2% nanoparticles concentration of different materials, but with the similar average sizes of about 50 nm (b)

Spherical particles of 3 mm with the density of 2600 kg/m^3 were taken as sludge particles. The sludge concentration at the channel inlet was equal to 3 vol.%. The vertical borehole was considered. The length of the computational domain of the annular channel was equal to 10 m. Such length was enough to set the flow steady and the sludge concentration uniform along the channel. The uniform sludge concentration profile at the inlet of the borehole was set. The sludge particles velocity and the drilling fluid velocity at the inlet of the borehole were equal. The grid consisting of 40×140×3 nodes was used for the numerical simulation (40 nodes along the radius, 140 nodes around the circumference, and 3 nodes along the channel length). The simulation results of the cutting transport by drilling fluids with nanoparticles, namely, the steady concentration and slip velocity profiles of cutting particles, were shown in Fig. 8-10. In the absence of rotation of the drill string, the sludge is transported well along the centre of the channel, where the velocity profile is flat. The slip velocity of the sludge particles reaches a maximum near the wall of the borehole. The particle concentration is maximal near the outer wall of the annular channel where it is increased by 6-7% due to the action of the centrifugal force acting on particles. Analysis of the simulation results shows that the nanoparticles significantly reduce the slip velocity both in the flow core and in the boundary layers. That effect enhances with the increase in the nanoparticles concentration. The nanoparticles sizes, in addition to their concentration, also has a significant impact on the slip velocity. The decrease in the size of nanoparticles results in a reduction of the slip velocity of the sludge particles throughout the channel section. The maximum influence on the slip velocity is provided by aluminium oxide nanoparticles at all other factors being equal. The effect of nanoparticles on the slip velocity leads to the change in concentration of sludge particles. The maximum concentration of sludge particles is decreased that provides more efficient flushing-out of the well.

To define the efficiency of flushing-out of the well usually used such parameter as the cutting transport performance (CTP), which is the ratio of the vertical velocity of the sludge particles averaged by volume of the borehole to the mud velocity averaged in the same manner. A similar definition was used before in [34, 41]. In this case, CTP = 1 means that the sludge is moving on average at the velocity of drilling fluid, and the efficiency of flushing-out of the well is maximal, while CTP = 0 means that the sludge particles are not transported.

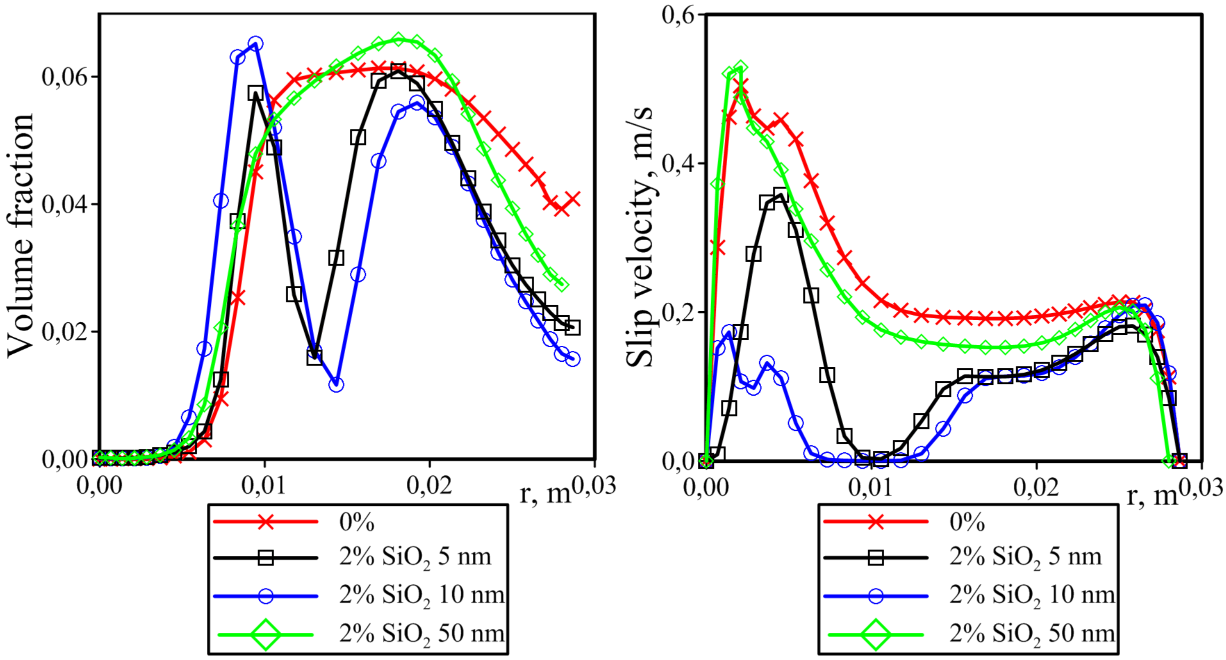
Besides, such parameter as the average slip velocity (ASV), i.e. the slip velocity of sludge particles (the difference between drilling fluid velocity and the sludge velocity) averaged over the volume, was also used to assess the cuttings transport performance. High ASV means poor cutting transport performance.

Quantitative characteristics of the cutting transport are shown in Fig. 10-11. As one can see, the nanoparticles significantly affect the efficiency of the cutting transport, namely, the presence of the nanoparticles of 2 wt.% concentration in drilling fluid leads to increase in the cuttings transport performance by 16.5% and to decrease in the average slip velocity by 2.08 times.



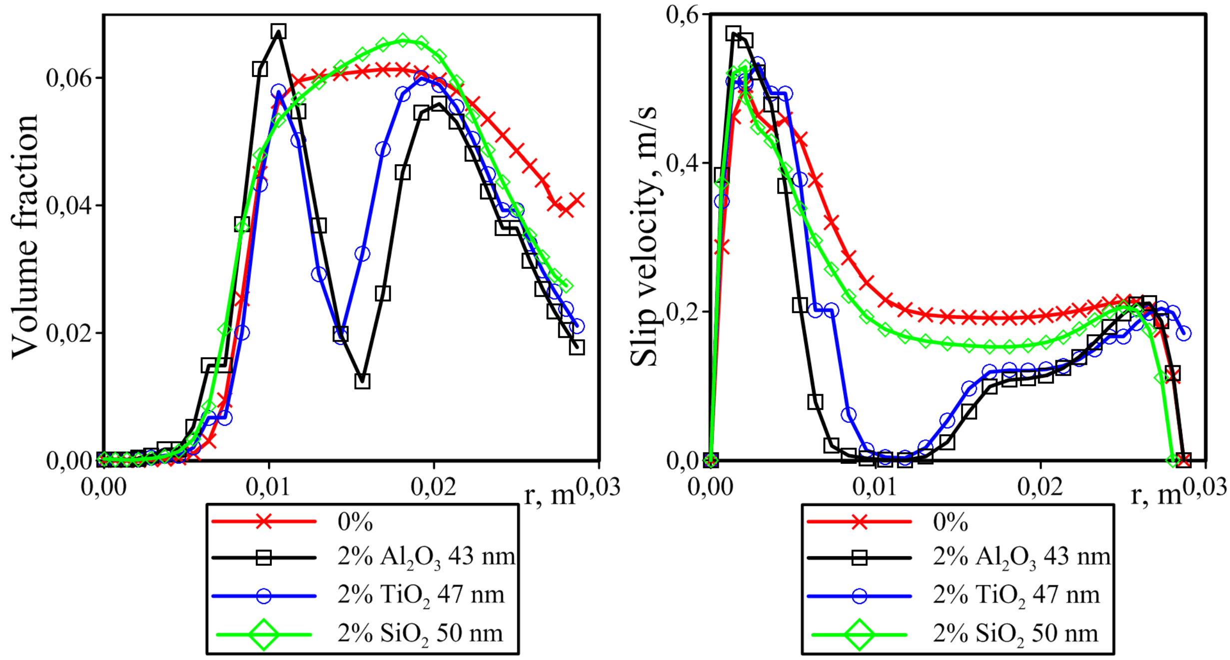
a) b)

Fig. 8. The distribution of the sludge particles concentration (a) and slip velocity (b) in the annular gap for different concentrations of the silicon dioxide nanoparticles of 10 nm size



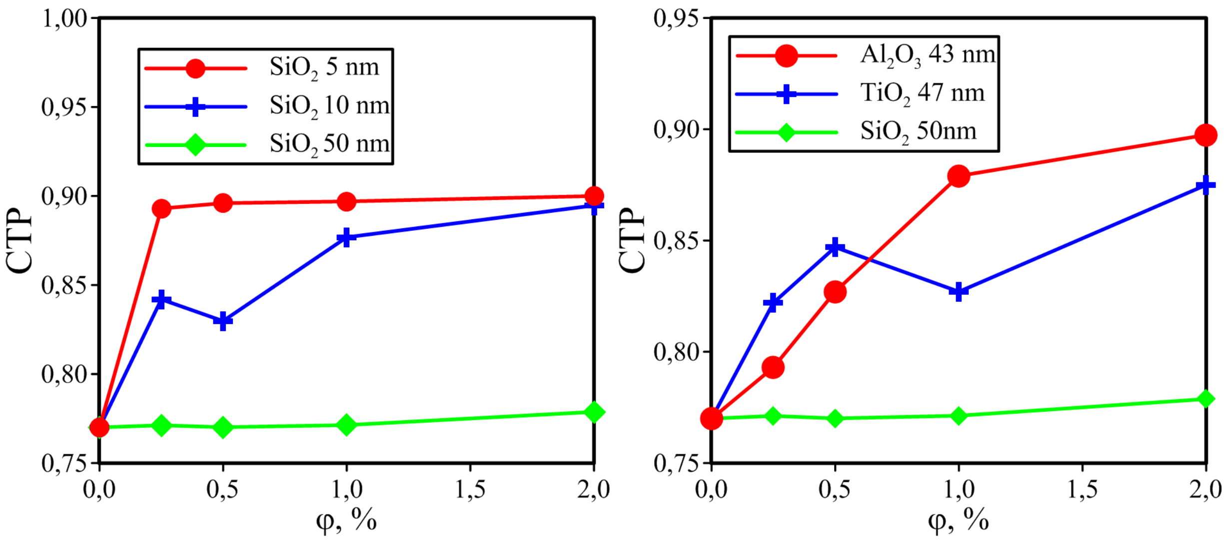
a) b)

Fig. 9. The distribution of the sludge particles concentration (a) and slip velocity (b) in the annular gap for different average sizes of the silicon dioxide nanoparticles of 2% concentration



a) b)

Fig. 10. The distribution of the sludge particles concentration (a) and slip velocity (b) in the annular gap for 2% nanoparticles concentration of different materials, but with the similar average sizes of about 50 nm.



a) b)

Fig. 11. The dependences of the cutting transport performance in the annular channel on the concentration of the nanoparticles of different sizes and materials

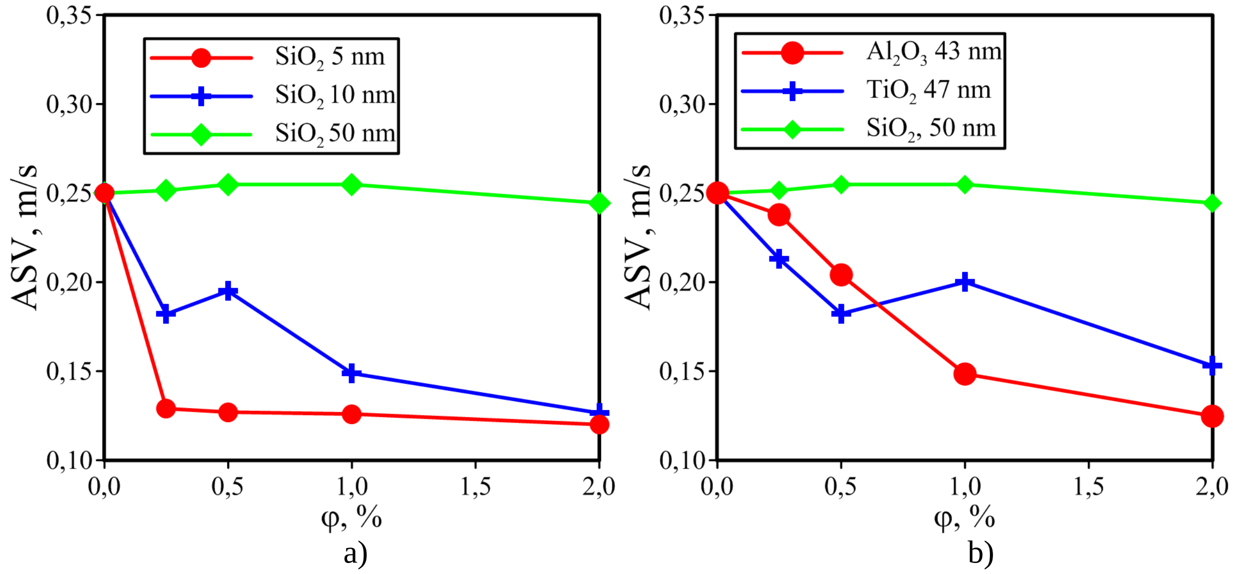


Fig. 12. The dependences of the average slip velocity in the annular channel on the concentration of the nanoparticles of different sizes and materials

However, as it has been repeatedly noted before, this effect also depends on the sizes and the materials of nanoparticles. Silicon dioxide nanoparticles of 5 and 10 nm average sizes, as well as aluminium oxide nanoparticles of 47 nm average size, have the most significant effect on the cutting transport. At the same time, these nanoparticles most strongly increase the pressure drop in the borehole (see Fig. 5).

Conclusions

The effect of nanoparticles of various chemical components and sizes on the rheological behaviour of drilling fluids, pressure loss and cuttings transport in the vertical borehole for a laminar flow regime was considered. The results of the experimental study of the rheological properties of the suspensions made from the clay particles with silicon, aluminium and titanium oxides nanoparticles were presented. The effects of the nanoparticles concentrations, sizes and materials on the effective viscosity and the rheological parameters of the solutions were studied experimentally. The effect of the presence of the nanoparticles on the pressure drop and cuttings transport performance in a vertical borehole was studied numerically. Experimentally measured rheological properties of the solutions were used in the calculations.

It was shown experimentally that the nanoparticles can significantly change the rheological properties of the drilling fluids. Furthermore, the rheological parameters of nanosuspensions depend on the nanoparticles sizes and materials in contrast to the suspensions with macro- and microscopic particles. An important feature of the nanoparticles in term of their influence on the effective viscosity is that that effect begins manifesting itself at very small weight concentrations. At the same time, the measurements show that the density of the drilling fluid stays almost unchanged because it depends on the volume concentration of nanoparticles. The same increase in the viscosity of macroparticles-based suspensions requires more than a tenfold increase in their concentration, which inevitably leads to an increase in the mud density, but that is not always possible because of the borehole stability.

It is found that the nanoparticles significantly affects the pressure drop in the borehole. In particular, it was shown that the presence of SiO_2 nanoparticles of 2% concentration and of 10 nm average size increases the pressure loss in the borehole twofold. At the same time, such increase essentially depends on the nanoparticles sizes and materials. The strongest effect is observed for nanoparticles of the smallest size. The increase of the pressure loss in the borehole due to the presence of the nanoparticles is observed in most cases. It can be explained by the increase in the effective viscosity of mud.

On the other hand, it was shown by means of numerical simulation that the presence of the nanoparticles in the drilling fluid significantly affect the quality of flushing-out of the well from the sludge. The increase of cuttings transport performance by means of nanoparticles at given flow rate of mud is mainly due to the broadening of the velocity profile shape in the channel because of the decrease in flow index n, that takes place with the increase in the concentration of nanoparticles and the decrease in their size. The effect of the nanoparticles materials on the cuttings transport performance could also be explained by the rheological properties. As a result, it was demonstrated that the presence of silicon (10 nm) or aluminium oxides (47 nm) nanoparticles of 2 wt.% concentration in the drilling fluid leads to the increase of CTP by 17% and to the decrease of the average slip velocity of sludge particles by 1.7-2.08 times. It is certainly a positive factor. Obviously, this is far from the best result, and certainly, it is possible to choose the nanoparticles which would essentially improve that result. In contrast to the suspensions with a macro- and microscopic particles, the rheological parameters of the nanosuspensions, the pressure loss and the cuttings transport performance depend on the nanoparticles sizes and materials. They are changed considerably even at small concentrations. This opens up the prospects for the application of nanoparticles to control the drilling fluids operating characteristics.

Despite a large number of laboratory studies of nanoparticles in drilling fluids the use of nanoparticles in real drilling is not common. Nevertheless, such works have already been started. Very good results were obtained in real wells with the use of drilling fluids containing the nanoparticles [42-43]. Four successful examples of the actual application of the nanoparticles in the drilling and operation of the oil wells were mentioned in [44]. The application of nanoparticles will be developed in future. Of course, the additional questions such as processing and utilization of these drilling fluids will arise. These problems are to be solved in future.

In addition, it should be noted that the results presented in the paper were obtained for the Bentonite-water base solutions. The influence of nanoparticles on the other types of the drilling fluids (oil-based and polymer-based) can be different. It also requires the additional research. It should be noted that all the obtained results refer to the atmospheric pressure and the room temperature. The behaviour of the drilling fluids with nanoparticles under HPHT conditions requires the further study.

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