The effect of the nanoparticles addition on the pressure drop in the annular channel

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Abstract. In this paper, the effect of nanoparticles addition to the drilling mud on the flow characteristics in an annular channel with a different ratio of diameters and eccentricity was studied, as well as the dependence of the pressure drop, velocity profiles, forces and torque on the concentration and size of silicon oxide nanoparticles at different ratio of pipe diameters and eccentricity.

1. Introduction

The development of the oil and gas industry, the build-up and stabilization of hydrocarbon raw stock at a level of Russia's energy security and the necessary budget earnings, should be accompanied by an increase in drilling operations. The use of effective drilling mud compositions and production technologies to prevent technological complications and reduce costs during drilling is one of the important areas to improve the quality of borehole construction. The nanoparticles addition is one of the methods for drilling muds improvement [1-5]. Nanoparticles addition can influence various properties of modern drilling muds. These properties include viscosity and rheology. Viscosity and rheology are very important in the drilling muds application, since they affect the pressure loss during flushing of borehole, cutting transport efficiency, borehole stability and many other factors in drilling. Many studies were carried out to investigate the effect of nanoparticles addition on the viscosity and rheology of drilling muds in the last few years [1-5].

Most studies noted that the nanoparticles addition to drilling muds leads to a significant increase in the viscosity and rheological properties of these solutions. On the one hand, the increase in viscosity and shear stress promotes better flushing of borehole from the slime and increases the borehole stability. On the other hand, the effect of nanosuspensions on the rheology of drilling muds can be negative. An increase in viscosity is often observed after adding the nanoparticles, which leads to an increase in pressure drop during drilling mud pumping. Therefore, it is necessary to find the optimum between pressure drop and cutting transport when selecting additives for nanoparticles.

There are many studies on the rheology of nanosuspensions. However, there are no systematic studies on the effect of nanoparticles addition on the pressure drop. The object of this paper was carrying out such studies. The influence of the addition of nanoparticles of various compositions on the pressure drop in the borehole with the rheological properties obtained in the experiment was studied using numerical simulation.

2. Mathematical model

In the general case, a viscous fluid flow is described by a system of Navier–Stokes equations consisting of the mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0$$

and the equations of motion or momentum conservation law:

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla(\rho \mathbf{v} \cdot \mathbf{v}) = -\nabla p - \nabla(\boldsymbol{\tau}) + \mathbf{F}$$

where $\mathbf{v}$ is the fluid velocity vector, $\boldsymbol{\tau}$ is the tensor of viscous stresses, $\mathbf{F}$ is the body forces vector, p is the static pressure, ρ s the fluid density. Since in most cases the drilling mud is non-Newtonian fluid, for simulating non-Newtonian flows we used well-known approach [6-7], in which the medium is considered as a nonlinear viscous fluid characterized by the effective fluid viscosity $\mu(\dot{\gamma})$, which in general is dependent on shear rate. At that, the tensor of viscous stresses $\boldsymbol{\tau}$ is determined as follows:

$$\boldsymbol{\tau} = \mu \mathbf{D}$$

The components of the strain velocity tensor $\mathbf{D}$ are of the form:

$$\mathbf{D}_{ij} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i},$$

shear rate $\dot{\gamma}$ is the second invariant of the strain velocity tensor:

$$\dot{\gamma} = \left(\frac{1}{2}\mathbf{D} \cdot \mathbf{D}\right)^{1/2}$$

Depending on the drilling fluid rheology, the effective viscosity is determined as $\mu(\dot{\gamma}) = K$ for Newtonian medium (K is the molecular viscosity of the fluid), $\mu(\dot{\gamma}) = K\dot{\gamma}^{n-1}$ for a power-law model, $\mu(\dot{\gamma}) = (K\dot{\gamma} + \tau_0)/\dot{\gamma}$ for Bingham Plastic model, $\mu(\dot{\gamma}) = (K\dot{\gamma}^n + \tau_0)/\dot{\gamma}$ for Herschel-Bulkley model, where n and K are the coefficients of the rheological models, τ_0 is the yield stress of viscoplastic fluid.

The typical parameters of drilling were selected to calculate the flow in a borehole during pumping a modified drilling mud. The diameter of the inner pipe was equal to: $D_1 = 0.05852$; 0.08895, and 0.11254 m, the outer pipe diameter was D_2=0.1463 m, the ratio of diameters D_1/D_2 was 0.40, 0.61, and 0.77, respectively. The rotation speed of the drill pipe was 100 rpm, the drilling mud rate was 11.61 kg·s^{-1}. The density of the drilling mud was 1050 kg·m^{-3}. We used the particles of silicon oxide in this work. The particles concentration φ in drilling muds varied within the range from 0.25 to 2wt.%. The particle size ranged from 5 to 50 nm. The rheology (the plastic viscosity K, yield stress τ_0, the flow index n) of drilling muds was determined from the experimental data obtained in [8] (table 1).

Table 1. The rheological parameters of the drilling mud as a function of concentration φ and the size d of the silica nanoparticles.

	d = 5 nm			d = 10 nm			d = 50 nm		
φ, %	n	K, mPa·s^n	τ_0, Pa	n	K, mPa·s^n	τ_0, Pa	n	K, mPa·s^n	τ_0, Pa
0	0.720	0.038	0.340	0.720	0.038	0.340	0.720	0.038	0.340
0.25	0.650	0.126	1.273	0.670	0.070	0.812	0.719	0.038	0.357
0.5	0.646	0.132	1.302	0.692	0.062	0.717	0.722	0.038	0.347
1	0.660	0.126	1.296	0.592	0.132	1.292	0.722	0.040	0.374
2	0.664	0.128	1.296	0.443	0.319	1.584	0.700	0.050	0.480

The Herschel-Bulkley model was used for numerical simulation. A computational grid consisted of 40×140×3 calculation nodes (40 nodes in radius, 140 nodes in circle, and 3 in channel length). The steady laminar flow was considered. The maximum Reynolds number for the least viscous mud was 895. The values of pressure drop, forces and torque acting on the borehole walls, and velocity profiles for different concentrations and sizes of nanoparticles were obtained in the calculations. Figure 1 shows the isolines of the axial velocity in the cross section of the borehole for a various ratio of the inner and outer pipes diameters for the mud modified by 2 wt.% silicon oxide nanoparticles 5 nm in size. Figures 2-3 show dependence of the pressure drops in the annular channel and the torque on the inner pipe on the nanoparticles concentration and size .

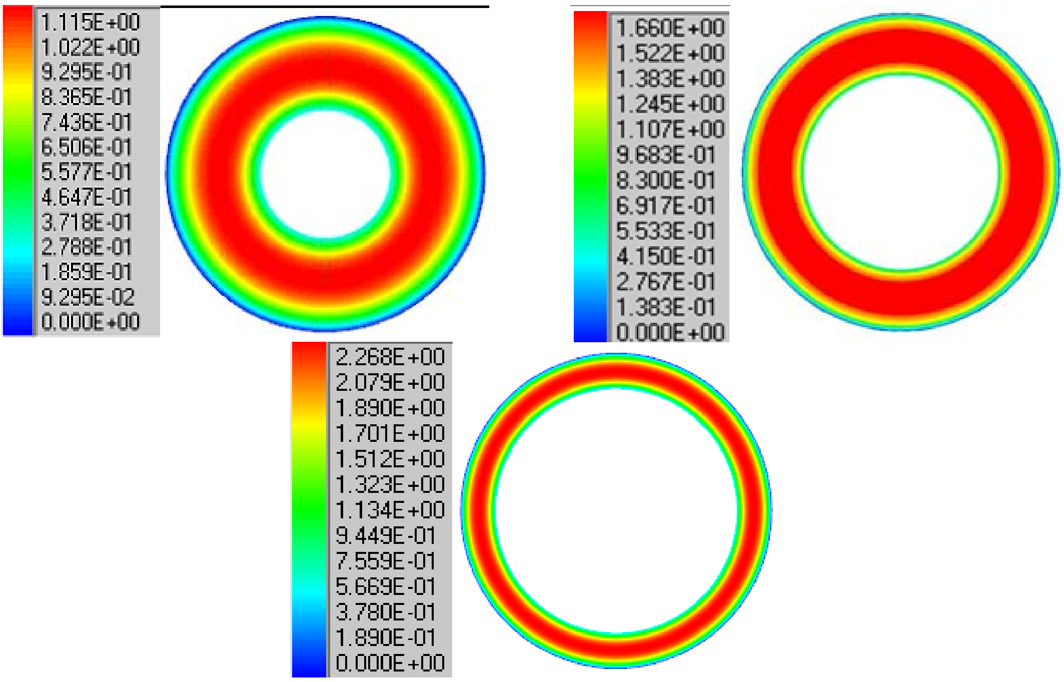


Figure 1. Isolines of the axial velocity in the cross section of the borehole for a various ratio of the inner and outer pipes diameters $D_1/D_2 = 0.40;\ 0.61;\ 0.77$ for the mud modified by 2 wt.% silicon oxide nanoparticles 5 nm in size.

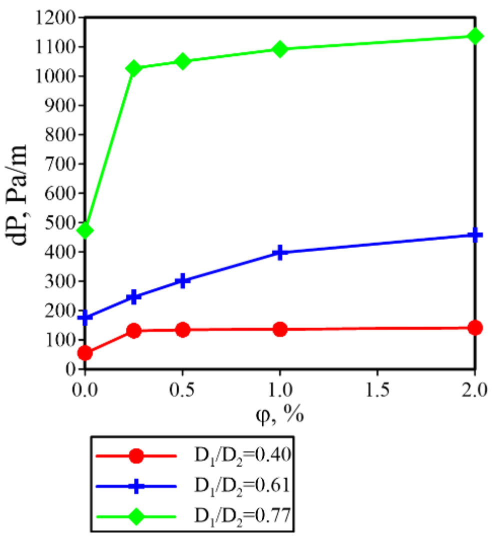


Figure 2. The pressure drop in the annular channel for the diameters ratio of the inner and outer pipes as function of concentration of silicon nanoparticles 5 nm in size.

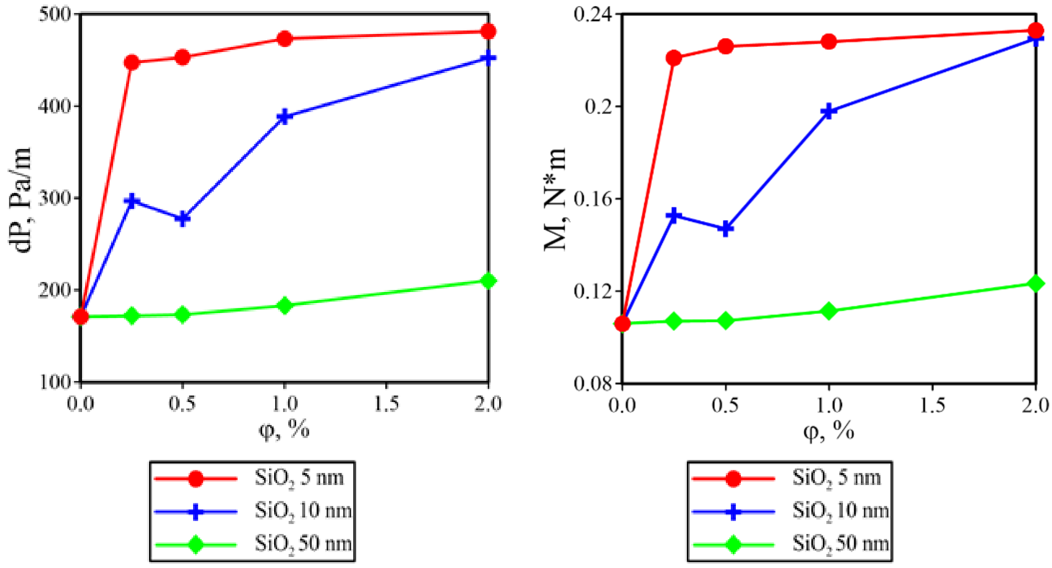
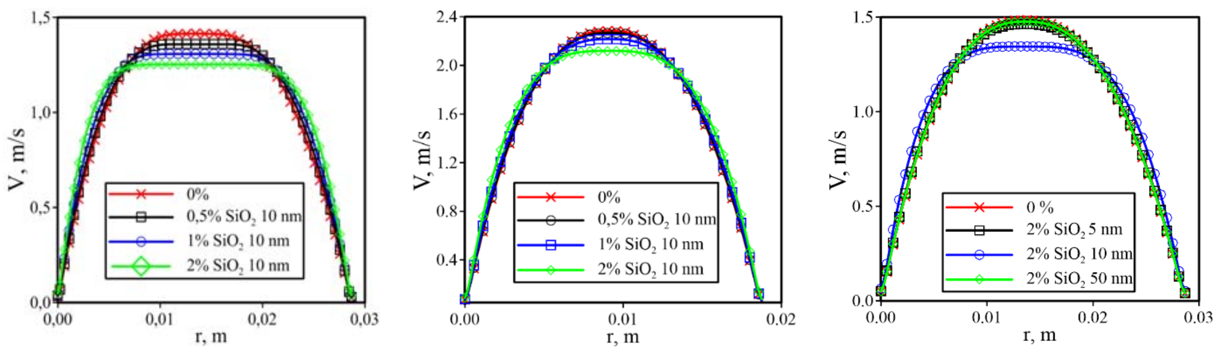


Figure 3. The pressure drop and the torque on the inner tube as function of the nanoparticles concentration and size of the /

Figure 3 shows the pressure drops in the annular channel and the torque on the inner pipe depending on the nanoparticles concentration and size . It seems the nanoparticles addition significantly affects the pressure drop in the borehole and the torque value on the inner wall. The two percent concentration of nanoparticles (5 nm) increases the pressure drop by more than two times that can be critical for the drilling. The strongest effect is observed for small nanoparticle sizes. So, silicon oxide nanoparticles (5 nm) increase the pressure drop even at very low concentrations of 0.25%. A further increase in the nanoparticles concentration practically does not affect the pressure drop. Large silicon oxide nanoparticles (50 nm) have weak effect on pressure drop even at significant concentrations.

The effect of nanoparticles addition on the axial velocity profile in the annular channel is also quite significant (see figure 4). The velocity profile is monotonically spread with an increase in the nanoparticles concentration at a given flow rate of the drilling mud, equal to 11.61 $kg{\cdot}s^{-1}$. This spreading is associated with a decrease in the index n with increasing particle concentration. The decrease of the nanoparticles size shows same effect on the velocity profile (see figure 4c). The velocity profile becomes more flat with decrease in size. This is also explained by an index n reducing with decrease of the nanoparticles size. Thus, it was shown that nanoparticles addition and reducing the nanoparticles size makes the velocity profile in the channel more uniform. This results in better cutting transport during drilling.



a b c

Figure 4. The profiles of the axial velocity component as a function of the concentration of silicon oxide nanoparticles size of 10 nm for diameter ratio a) D_1/D_2 =0.61, b) D_1/D_2 =0.77 and c) versus the silicon oxide nanoparticles size (D_1/D_2 =0.61).

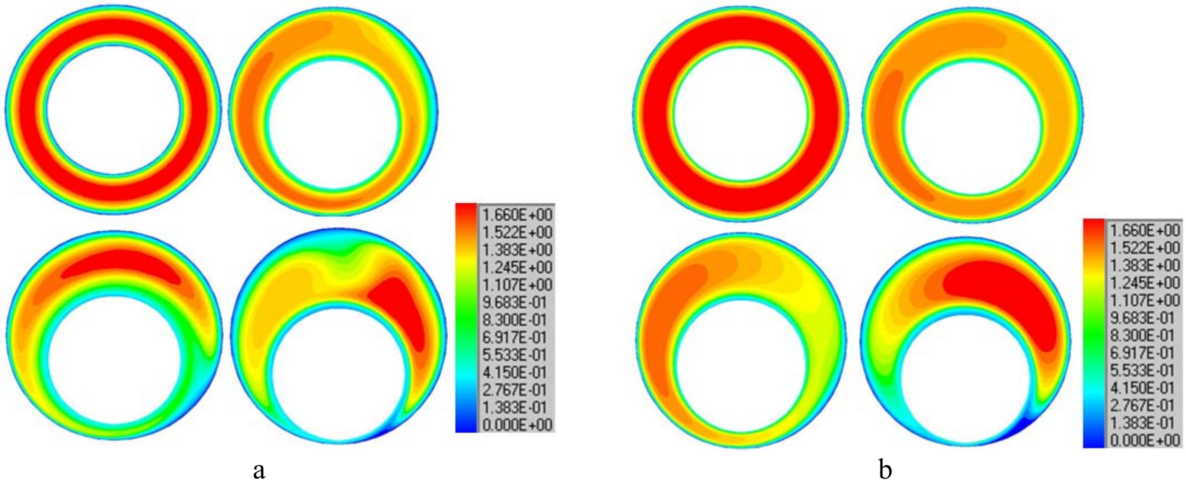


Figure 5. Isolines of the axial velocity in the cross section of the borehole for a ratio of the inner and outer pipes diameters $D_1/D_2 = 0.61$ for different eccentricities $e = 0$; $e = 0.3$; $e = 0.6$; $e = 0.9$ for the base mud (a) and the mud modified by 2 wt.% silicon oxide nanoparticles of size 5 nm (b).

The influence of eccentricity on the characteristics of the drilling muds modified by nanoparticles was investigated as well. Typical results are shown in figures 5-6. The occurrence of eccentricity leads to a pressure drop decrease for all nanoparticles concentrations. The eccentricity also significantly reduces the torque acting on the inner pipe. This decrease is stronger with increasing nanoparticle concentration. Analysis of the velocity profiles in the channel shows that for all eccentricity values and rotation speeds of the inner pipe, the nanoparticles addition makes the axial velocity profile more flat. It promotes a more effective flushing of the borehole from the slime as stated above.

3. Conclusion

The numerical simulation of the developed drilling mud flow in the borehole with the eccentric positioning and rotation of the drilling pipe during the drilling is carried out. It is established that the nanoparticles addition significantly affects the pressure drop in the borehole, as well as the forces and torque acting on the borehole walls. It was shown that nanoparticles addition to the drilling mud can significantly increase the pressure drop in the borehole. The pressure drop increase in the borehole with nanoparticle addition is negative in most cases and due to a rise in the effective viscosity of the

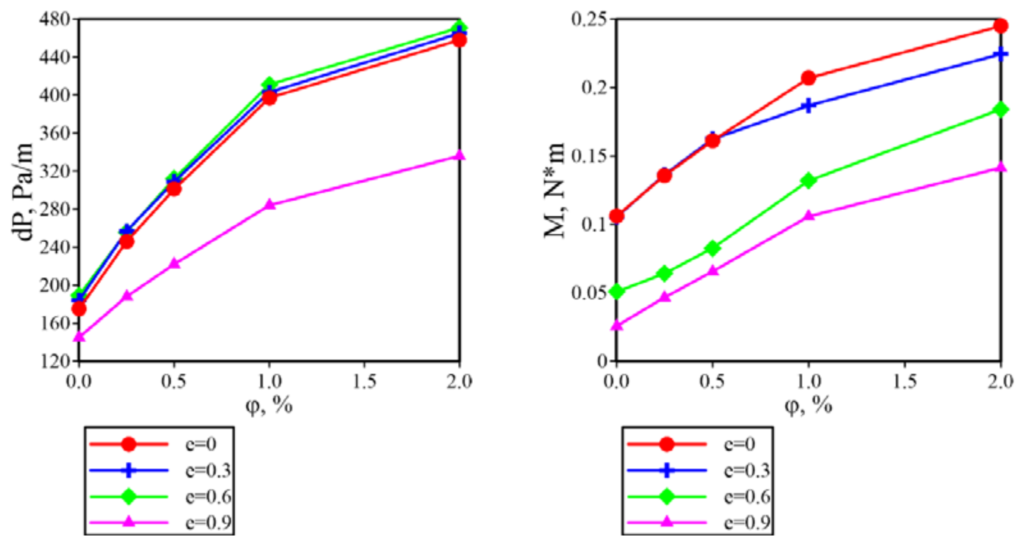


Figure 6. The pressure drop and the torque on the inner tube at the diameters ratio $D_1/D_2 = 0.61$ as a function of the concentration of silicon oxide nanoparticles - 5 nm in size.

drilling mud. On the other hand, numerical simulation showed that nanoparticles addition to the drilling mud results in a monotonic spreading of the velocity profile. This spreading is associated with an increase in the rheological characteristics of the mud with rising particle concentration. The decrease of the nanoparticles size shows same effect on the velocity profile. It was shown that nanoparticles addition and reduction of their size makes the velocity profile in the channel more uniform. This promotes a more effective flushing of the borehole from the slime during drilling. The rheological parameters of nanosuspension, the value of pressure drops, and the cutting transport efficiency depend on the size and material of the nanoparticles and are significantly modified even at small concentrations as opposed to suspensions with macro and microscopic particle sizes. This offers the prospect of using nanoparticles to control the drilling muds characteristics.

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