Experimental study of the effect of adding nanoparticles on the rheological properties of oil-based drilling fluids

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Abstract. A systematic study of the effect of nanoparticles of various concentrations and sizes on the rheological properties of various oil-based drilling fluids with nanoparticle additives has been carried out. The concentration of nanoparticles in drilling emulsions varied from 0.25 to 2 wt%, and the average size of nanoparticles ranged from 18 to 100 nm. As a result of numerous laboratory experiments, formulations and technology for the preparation of stable oil-based drilling fluids with additives of nanoparticles have been developed. The effect of nanoparticles on the viscosity and rheological properties of these drilling fluids has been studied.

1. Introduction

Currently, Russian companies have begun the development of oil and gas fields in Siberia and offshore fields in the northern seas, which were not previously exploited due to difficult mining and geological, technological, climatic and environmental conditions that require a revision of technological solutions. Traditionally used water-based drilling fluids are becoming increasingly unsuitable for drilling under these conditions. Oil-based fluids provide the required quality of drilling and penetration, which allow preserving the permeability of the bottomhole formation zone, reducing the likelihood of tool tightening, ensuring the stability of the wellbore and efficient removal of cuttings [1–3].

In the past two decades, there has been an increasing interest in the global oil and gas industry in nanotechnology. A promising application of nanotechnology in the oil and gas business is the creation of drilling fluids containing small-sized solid particles, the so-called “nanofluids”. The introduction of nanoparticles, even in small amounts, can solve a number of complex problems, such as reducing the frictional forces of drill pipes against the borehole walls, reducing the filtration of the drilling fluid, improving the conditions for the removal of cuttings to the surface, strengthening the borehole wall at passing through the weakly cemented rocks, changing the wettability of rocks, fighting with corrosion and many others [4].

The rheological properties of the drilling fluid are critical to the success of drilling operations. The effective removal of degradation products mainly depends on these properties. Unsatisfactory rheological parameters can cause many complications, such as sludging of the bottomhole zone of the wellbore, washout of the borehole walls, decrease in rate of penetration, sticking of the drill string, excessive filtration and loss of drilling fluid [1, 2, 5–7]. In the literature, there are conflicting data on the effect of the size and concentration of nanosized particles on the viscosity and rheology of drilling fluids [8–15].
For example, the authors of [8] argue that at 4% volume concentration of 36 and 47 nm Al₂O₃ particles in a hydrocarbon-based solution, the viscosity does not change, and as the volume concentration of larger nanoparticles increases, the viscosity increases. In another source [9], the authors confirm the previous experiment and show that at a particle concentration of 7 and 9% TiO₂ with a particle size of 95 and 145 nm, the viscosity increases with a rise in the particle size.

At the same time, another author in his work [10] found that the viscosity of an oil-based drilling fluid decreases with an increase in the size of SiO₂ nanoparticles. The authors in [11] came to the same conclusions for SiO₂ particles in ethanol for 3 different particle sizes: 35, 94, and 190 nm. Investigators of [12] confirmed these results for CuO and Al₂O₃ particles and explained the increase in the drag forces of liquid movement, in the case of a decrease in the particle size, by an increase in the specific area of interaction between the dispersed medium and the dispersed phase. It is noted that the chemical composition does not affect the rheological parameters of the flushing fluid, and the change in viscosity occurs only with a change in the concentration of nanoparticles and their size.

The rheological properties of oil-based drilling fluids modified by the addition of nanosized particles obviously contradict each other often. Therefore, the aim of the work is to systematically study the viscosity and rheology of oil-based drilling fluids, modified by additives of nanoparticles of various sizes, for drilling wells in difficult mining and geological conditions.

2. Research and development of formulations of oil-based drilling fluids with additives of nanoparticles

A systematic study of the physical and chemical properties of more than ten different oil-based drilling fluids with nanoparticle additives is performed. An oil-based drilling fluid is an inverse emulsion, i.e., an emulsion in which water is dispersed into tiny droplets, and the dispersion medium is a water-in-oil fluid. The solution is prepared in accordance with the time intervals and proportions of each added reagent. Initially, an aqueous brine was prepared with calcium chloride, the mass content of which was 38%. Then the oil and brine were mixed in the required volumetric ratio. After that, an emulsifier, a structurant and bridging additives were successively added.

The following components were used as the hydrocarbon base of the solutions: low-viscosity base oil “REBASE” PC-230 (NPO “REASIB” LLC, Tomsk) of grades B2 (hereinafter referred to as Oil-1), B1 (Oil-3), as well as winter diesel fuel (Oil-2) manufactured in accordance with SS 305-82. In this work, the ratio of hydrocarbon phase to water, being the most typical for drilling fluids, is equal to 70/30.

To stabilize the emulsion, we used a nonionic emulsifier “REBASE” PC-510, designed to create inverse emulsions. Organophilic clay was used as a structurant, which makes the clay powder hydrophobic and swellable in hydrocarbon media. Microcalcite and microbarite were used as a clogging additive. We used 5 different grades of CaCO₃, with the average size varying from 10 to 160 microns. For the formation of a low-permeability filter cake, variously dispersed microcalcite was mixed in the same proportion. The average size of the microbarite was 70 µm.

To modify the properties of the drilling fluid, hydrophobic (treated with polydimethylsiloxane or cetyltrimethylammonium chloride) nanosized SiO₂ particles from various manufacturers (LLC Bardakhanov, AEROSIL, Plazmoterm) were used. The concentration of nanoparticles in drilling fluids varied from 0.25 to 2 wt%. The average size varied from 18-100 nm.

After adding nanoparticles to a hydrocarbon medium to destroy conglomerates, the solution was subjected to intense sonication. Moreover, in order to exclude the fragmentation of the dispersed phase to nanoglobules, the addition of CaCl₂ brine occurred after ultrasonic dispersion of nanoparticles in a hydrocarbon medium. For ultrasonic treatment, the ultrasonic apparatus “Volna” UZTA-0.4 / 22-OM was used, and the treatment took place within 15 minutes at maximum productivity. In the preparation of emulsions, the method of coarse crushing of droplets was also used, namely, mechanical dispersion using a high-speed stirrer for 30 minutes. The preparation of drilling fluid with the sequential introduction of a hydrocarbon base, an emulsifier, a water repellant, solid components of drilling mud
and CaCl₂ brine was carried out on a HamiltonBeach three-spindle mixer and a high-speed mixer at 20,000 rpm OFITE 152-18 PrinceCastle.

To study the viscosity and rheology of emulsions, an Ofite 900 viscometer (Figure 1a) was used. It was a portable and fully automated device for determining the rheological parameters of drilling fluids, grouting mixtures and hydraulic fracturing fluids. The range of rotation speeds: 3–600 rpm corresponded to the range of shear rates from 5 to 1022 s⁻¹. Viscosity measurement error was about 2%. All measurements were carried out at atmospheric pressure and a temperature of 25°C.

Particle size distribution was measured using a DT1202 acoustic and electroacoustic analyzer (Figure 1b). Electroacoustic spectral analysis was based on the effect of the appearance of ultrasonic (US) waves when an alternating electric field was applied to a suspension of charged particles, which experience friction during the oscillation process. By analyzing the spectra of ultrasonic waves, the Colloid Vibration Current, as well as the particle size distribution, was calculated. Differential curves of particle size distribution by weight were plotted.

![Figure 1. OFITE-900 viscometer (a) and DT1202 electroacoustic analyzer (b).](image)

3. **Investigating the effect of nanoparticle additives on the viscosity of oil-based drilling fluids**

First, the viscosity of the invert emulsion drilling fluid was studied. As a result of measurements, the dependence of the viscosity of drilling fluids modified with nanoparticles on the shear rate, concentration and size of nanoparticles was determined. An essential feature of the viscosity of drilling fluids was that even without the addition of nanoparticles, these fluids are viscoplastic non-Newtonian fluids.

Microcalcite was used as a clogging additive for an emulsion drilling fluid prepared on the basis of Oil-1. The nanoparticles were silicon oxide particles with an average size of 100 nm. In comparison with the solution without the addition of nanoparticles, an increase in the concentration to 0.5 wt% did not lead to a significant increase in the effective viscosity. As the concentration of particles increased, the viscosity of the drilling fluid increased. The maximum increase in the effective viscosity was obtained with the addition of 2 wt% nanoparticles. The increase was about 30% compared to the base drilling emulsion.

Next, the effect of nanoparticle size on the viscosity of oil-based drilling fluids was considered. For this, a series of measurements was carried out for drilling fluids based on the Oil-3 with the addition of microcalcite 10, 24 and 32 microns in equal proportions. Four different average sizes of silicon oxide nanoparticles were considered: 18, 50, 70 and 100 nm.
Figure 2. Dependence of the viscosity of a drilling emulsion based on the Oil-3 with the addition of 0.5 wt% SiO$_2$ nanoparticles on the shear rate (a) and on the average size of nanoparticles (b).

Figure 2a shows the results of studying the dependence of the drilling fluid viscosity on the average size of silicon oxide nanoparticles. Analysis of the data obtained has shown that the viscosity of the studied drilling emulsions significantly depends on the size of the added nanoparticles. The effective viscosity is shown to increase with decreasing nanoparticle size. For example, for a shear rate of 170 s$^{-1}$, the viscosity of an emulsion with the addition of 18 nm nanoparticles increases by 60% compared to an emulsion with the addition of 100 nm nanoparticles. The dependence of the effective viscosity of the drilling emulsion on the nanoparticle size is demonstrated in Figure 2b. With decreasing nanoparticle size, the drilling viscosity increases.

Thus, it has been shown that the addition of nanoparticles to oil-based drilling fluids can significantly change their effective viscosity even at relatively low concentrations. This effect depends on the average size of the nanoparticles. In most of the cases considered, with a decrease in the average size of nanoparticles, the effective viscosity of the drilling fluid increases.

4. Experimental study of the rheology of oil-based drilling fluids

An experimental study of the rheology of the developed drilling fluids was carried out depending on the concentration and size of nanoparticles. The data on viscosity and shear stress obtained with a rotational viscometer were used to determine the parameters of rheological models using a least squares approximation. Generalization and analysis of the data obtained allows concluding that, on average, the behavior of the rheology of drilling fluids is described most accurately by the Herschel–Bulkley model.

In the study of the rheological parameters of the developed oil-based drilling fluids, the following regularities were revealed. With an increase in the concentration of nanoparticles, the exponent of the power-law model decreases, while the plastic viscosity, consistency index, and ultimate shear stress, on the contrary, increase. This leads to a flattening of the velocity profile during the flow of drilling fluid in the well, which is a positive factor for better removal of cuttings. The value of the yield point changes especially strongly for the Oil-2 solution with the addition of barite at a nanoparticle concentration of 2 wt%: this parameter increased 6.3 times.

Further, systematic results of the study of the dependence of rheology of oil-based drilling fluids on the size of nanoparticles were obtained (Figure 3). Four different average sizes of silicon oxide nanoparticles were considered: 18, 50, 70 and 100 nm. The rheology of solutions was also described by the Herschel-Bulkley model. It can be seen that with an increase in the particle size, the yield stress and plastic viscosity decrease, while the nonlinearity index $n$ does not actually change within the measurement error.
Figure 3. Change in yield stress (a), plastic viscosity (b) and nonlinearity index (c) depending on the size of nanoparticles for drilling fluids based on Oil-3 with the addition of 0.5 wt% SiO$_2$ nanoparticles.

Thus, it was shown that with the help of even small additives of nanoparticles it is possible to control the rheological properties of oil-based drilling fluids. In most cases, the addition of nanoparticles leads to a significant improvement in their rheological properties. The significant influence of the size of nanoparticles on the rheological properties of drilling emulsions was also shown. The smaller the nanoparticle size was, the higher the yield stress and plastic viscosity of the drilling emulsion were.

Conclusions
The effect of nanoparticles on the viscosity and rheological properties of oil-based drilling fluids has been studied. The influence of the concentration and size of nanoparticles, the type of hydrocarbon base and microcolloïd additives on their effective viscosity has been studied. In most cases, the addition of nanoparticles leads to a significant increase in viscosity.

Four different average sizes of silicon oxide nanoparticles were considered: 18, 50, 70 and 100 nm. Analysis of the data obtained has shown that the viscosity of the studied drilling emulsions significantly increases with decreasing nanoparticle size and the effective viscosity. For example, for a shear rate of 170 s$^{-1}$, the viscosity of a solution with 18 nm nanoparticles was 60% higher than with 100 nm particles. Thus, it has been shown that the addition of nanoparticles to oil-based drilling fluids can significantly change their effective viscosity even at relatively low concentrations. And this effect depends on the average size of the nanoparticles. In most cases considered, with a decrease in the average size of nanoparticles, the effective viscosity of the drilling fluid increases, which means that a smaller amount of additive can be used.

The influence of the concentration and size of nanoparticles, the type of hydrocarbon base and the type of microcolloïd additives on the rheology of drilling fluids has been studied. With an increase in the concentration of nanoparticles, the nonlinearity index decreases, while the measure of consistency and the ultimate shear stress, on the contrary, increase. In this case, the last two characteristics change much more strongly with an increase in the concentration of nanoparticles. It has been revealed that with an increase in the particle size, the yield stress and the measure of the consistency of oil-based solutions decrease, while the nonlinearity index $n$ actually weakly depends on the nanoparticle size.

Thus, it has been demonstrated that nanoparticles can be used to control the rheological properties of oil-based drilling fluids. In this case, a significant effect on the properties begins already at low concentrations and small sizes of nanoparticles.
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