Computational study of cutting transport by drilling fluids in directional wells

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Abstract. The paper presents the computation results of the cutting transport in directional wells. Two samples of oil-based muds were prepared. The rheological parameters, incorporated in the computation model, were measured. The geometry of the real well was used for the computation. Three well slopes equal to 15, 45, 75 degrees were studied. The sludge velocity profiles in the annular channels were obtained. The average volumetric value of the particle slip velocity was obtained (the difference between the drilling fluid velocity and the sludge velocity).

1. Introduction
One of the most effective methods for exploration and development of productive formations is directional drilling. Wells, whose direction is strictly controlled during drilling, are called controlled directional wells. The borehole deviation from the vertical can be caused by real conditions or created artificially. Natural curvature results from several reasons (geological, technical, and technological). Artificial curvature is understood as any forced deviation. Directional drilling is effectively used when drilling oil and natural gas wells. Their choice depends on the technical capabilities of the drilling rig, geological features, as well as the type of embedded formations. Their main advantage is the rapid passage of complex hard rock by changing the drilling direction [1-2].

For successful well construction, it is crucial to have a clear understanding of the state of cuttings accumulated in the wellbore, as well as to know how to ensure effective flushing, especially in the case of directional wells [3-4]. Well flushing, including flushing modes, as well as drilling fluid composition and properties significantly affect the technical and economic indicators of drilling and qualitative characteristics of the well construction (stable condition of the well, prevention of complications, preservation of reservoir properties of the productive zone, ensuring the effectiveness of subsequent support, etc.)

The quality of borehole flushing from cuttings is greatly influenced by the solution viscosity, the strength of the gel, the flushing mode, the flow velocity of the solution through the annulus space, and its density. As a rule, increasing the density of the solution and its flow velocity in the annulus increases the quality of well flushing in all types of wells, however, this leads to an increase in the pressure drop, which consequently leads to certain problems.

Currently, any construction is an expensive measure, associated with various emergencies occurring when using drilling modes that do not ensure the specified flushing modes. To select the
optimal formulation of drilling fluid and drilling modes, it is necessary to have an inexpensive and effective tool that, unlike conducting expensive and lengthy field experiments, will allow predicting the occurrence of emergencies in a timely and efficient manner.

Numerical simulation can be used as an alternative tool when searching for drilling mud with specified rheological properties, as well as for well flushing modes.

Works [5-6] described an experimental setup for studying the cutting transport in annular channels with different diameter ratios, having a certain eccentricity, as well as different flow modes in laminar and turbulent regimes, and the case with the inner tube rotation. Experimental data obtained at this facility were used for testing the computational mathematical model of drilling fluid flow in annular channels [7-10]. Computational and experimental studies of turbulent Newtonian and non-Newtonian flows in the annular channel were carried out. The computational and experimental results were compared with each other and with known empirical correlations. The comparison has shown satisfactory concordance of the results.

Also in [10], we performed a computational study of the particle transport of drilled rock by drilling fluid in a horizontally directed well. The dependence of the cutting transport on the drilling fluid flow rate and its rheological parameters was studied.

In the present work, the efficiency of cutting transport in directional pipes by hydrocarbon-based drilling fluids (called usually oil-based fluid) is studied.

2. Problem statement

For the effective construction of wells, it is necessary to prepare drilling fluids that are distinguished by a flat temperature-rheological profile, designed for drilling wells with a large deviation angle from the vertical, as well as horizontal wells. If the wall of the wellbore shale and clay-containing rocks are prone to buckling, as well as when drilling in the narrow range of the hydraulic fracturing gradient, and in "cold" wells, the use of oil-base fluids is most effective, as they do not have a negative impact on reservoir properties of the productive formation.

Two oil-base drilling fluids were prepared. Diesel fuel was used as the main oil-base fluid. The volumetric ratio of water to oil-base fluid was 35/65. This ratio was chosen for the reason that when increasing the proportion of the water phase, the cost of the solution decreases, but at the same time, the solution containing more than 35% of the water phase in its composition is less stable. The rheological and other physical parameters of the prepared drilling fluids are shown in the Table. The table also presents the correlation reliability coefficient ($R^2$) of the Bingham and Power-law models. The measured viscosity of oil-based fluid is better described by a Power-law model. Therefore, rheological parameters of the Power-law are used in the calculations.

| Name | Plastic viscosity point (mPa) | Yield (Pa) | $R^2_{\text{Bingham}}$ | $n$ | $K$ (Pa s$n$) | $R^2_{\text{Power-law}}$ | $G_1$ | $G_{10}$ | Density (kg m$^{-3}$) |
|------|-----------------------------|------------|------------------------|-----|---------------|--------------------------|-------|--------|---------------------|
| N1   | 28.70                       | 12.10      | 0.971                  | 0.331 | 1.797         | 0.995                    | 5     | 7      | 1053                |
| N2   | 24.61                       | 15.04      | 0.949                  | 0.344 | 3.207         | 0.982                    | 7     | 10     | 1032                |

$a$ $n$ is the nonlinearity factor.

$b$ $K$ is the solution consistency.

$c$ $G_1$ is the static shear stress in 10 seconds.

$d$ $G_{10}$ is the static shear stress in 10 minutes.

$e$ $R^2$ is the correlation reliability coefficient of Bingham model.

$f$ $R^2$ is the correlation reliability coefficient of Power-law model.

The geometry and drilling parameters of a real well described in [10] were used as the design geometry. The length of the estimated area of the annular channel was set to 10 m. This length was...
sufficient for the sludge flow rate and concentration to reach stable values along the entire length of
the channel. To study the efficiency of cutting transport in the curse of directional wells drilling, three
cases of deviation of the well from the vertical were considered (15°, 45°, 75°); they were typical for
drift angle buildup sections of the well, and for sinking in the productive reservoir.

Computational fluid dynamics method was used to compute drilling mud motion [11-13]. Mass
conservation equation and continuity equation kept the initial form of Eulerian representation [8, 9,
14-16]. Gidaspow model was used to describe inter-phase resistance force for Eulerian approach with
granulated medium [9, 17]. In general, vortex flow of drilling mud was considered. Two-parameter $k-
\omega$ SST model was used [18].

The drilling fluid concentration profile at the well inlet was steady and uniform. The velocity of the
drilled rock particles and the velocity of the drilling fluid at the inlet to the well coincided. Spherical
particles with a size of 0.005 m and a density of 2719 kg m$^{-3}$ were considered as the drilled rock. The
cuttings concentration at the inlet to the channel was set to be 5% by volume. The flow rate at the inlet
was set to 10 kg s$^{-1}$. The computation lasted 100 seconds of real time. A comparison of the efficiency
of cutting transport was made in several cross-sections distributed along the channel length.

3. Results and discussion
Figure 1 shows the distribution of the volume ratio of the solid phase at different points in time from
the beginning of the computation for drilling fluid N1 and the angle of inclination of the well equal to
75°. A similar solid-phase distribution pattern was observed for the second solution.

Figure 2 below shows the velocity profiles for drilling fluid N2 at a point in time of 20 seconds
from the beginning of the computation.
Figure 2. Solid phase velocity profile in the annular channel after 20 seconds of computation.

As a result of the numerical study, the efficiency of well flushing was determined depending on the well inclination angle. The well inclination angle significantly was shown to affect the efficiency of the wellbore flushing. As can be seen from figure 1, the cuttings particles are distributed in the cross-section of the annular channel unevenly: a larger part of the particles are located at the bottom, at the wall of the outer tube. At small angles of deviation from the vertical, the velocity profile is redistributed, the velocity peak is shifted to the inner tube, while particles accumulate near the outer wall, and the velocity tends to zero. Thus, for example, when increasing the well inclination angle by 30 degrees, the flow area of the channel is seen to narrow due to the accumulation of solid phase particles. Besides, with an increase in the slope of the well, a significant decrease in the solid phase velocity is noted in the monitoring points.

Figure 3. The ASV dependence on time at different inclination angles (left) and for two drilling fluids (right).
To assess the effectiveness of cutting transport, the average volumetric slip velocity of the particle (ASV) is used. In other words, ASV means the difference between the drilling fluid velocity and the sludge velocity. A high ASV value means that the sludge is transported poorly. As can be seen in figure 3, the efficiency of cutting transport improves with increasing drilling fluid flow rate. Besides, the particles may accumulate in horizontal sections of wells. Therefore the dynamic pattern of the average volumetric fraction of particles in the volume of the well is also analyzed in the course of computation.

Figure 3a shows that with increasing the angle of inclination from the vertical, the ASV value also increases, which indicates that the cutting transport efficiency decreases. This is because the sludge in the annular channel accumulates and compacts. Figure 3b shows that drilling fluid N2 is characterized by a lower value of the slip rate, and thus its use is more preferential when drilling directional wells.

Conclusion
In the present paper, computations have been made using a numerical method to reveal the possibility of using drilling oil-base fluids for drilling directional wells in the course of sinking in a productive reservoir. Data on the distribution of cuttings in the annular channel have been obtained. The obtained data on the efficiency of cutting transport and the cuttings velocity profile allow concluding about the effectiveness of employing the obtained drilling fluids for drilling directional wells in productive formations. Drilling fluid N2 has manifested better efficiency of cutting transport compared to drilling fluid N1. This is due to the use of different surfactants as an emulsifier. In the future, it is planned to improve the computation method taking into account heat transfer, as well as the formulations of drilling fluids to enhance the efficiency of well flushing.

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