Numerical study of cutting transport using aerated drilling fluids

V A Zhigarev¹, S O Zazulya¹, A V Minakov¹,², A L Neverov¹

¹Siberian Federal University, 79 Svobodny Ave., Krasnoyarsk, 660041, Russia
²Institute of Thermophysics SB RAS, 1 Lavrentyev Avenue., Novosibirsk, 630090, Russia

E-mail: VZhigarev@sfu-kras.ru

Abstract. The paper deals with drilling fluid flow in a horizontal well during its drilling. As part of this work, rheological parameters of water-based drilling fluid with the addition of polymers and a foaming agent were used. Cuttings transport was studied at different degrees of foam aeration. Besides, the paper presents the study of the effects of drilling fluid flow, as well as the rotation of drill pipes on the cuttings transport.

Introduction
Currently, the consumption of hydrocarbon raw materials by the fuel and energy complex increases. On average, according to various estimates, oil demand is projected to grow until 2040, after which only a gradual, slow decline is likely due to an increase in the share of alternative energy [1]. The development of society is accompanied by a continuous increase in energy consumption, and therefore, the consumption of oil and gas in absolute terms will probably increase until the second third of the 21st century.

Most of the fields that are easily accessible and easy to develop have exhausted their potential, which is why oil and gas companies have to explore new fields in new regions, look for ways to intensify old ones, and return to discovered fields that were previously inaccessible for reasons of unprofitability or technical impossibility of development.

Thus, the development and improvement of technologies are one of the methods of achieving the provision of the world economy with hydrocarbon raw materials.

One of the technologies that allow building wells in challenging mining and geological conditions is managed pressure drilling (MPD). This technology allows drilling at abnormally low reservoir pressure (ALRP) with catastrophic levels of drilling fluid absorption due to high permeability or the presence of large filtration channels – cracks and cavities, as well as under a combination of these conditions. Various cases of using aerated solutions have shown that they really allow more efficient removal of cuttings from the bottom of wells [2], as well as contribute to the elimination of the resulting sticking.

Experimental study of liquid-gas mixtures (LGM) in borehole conditions is a challenging task, since field data are not sufficiently reliable and not always available while creating a full-fledged laboratory installation to model a well is quite a difficult task. In this case, computer simulation comes to the rescue. Contemporary computers and software allow simulating conditions that are quite close to real ones. At that, the number of model assumptions decreases over time.
Predicting the behavior of drilling fluid during its transportation to the daytime surface is both an extremely important and complicated task, which requires using comprehensive mathematical methods and advanced software and hardware.

This paper considers the cuttings transport by the aerated drilling fluid flow in a horizontal well during the drilling process.

1. Problem setting
Within the framework of the task set in this paper, the simulation object is a horizontal section of the annular cross-section. Thus, the following parameters are given: external diameter $D = 173.76$ mm; internal diameter (diameter of drill pipes) $d = 102$ mm; and section length $L = 10$ m. According to the preliminary calculations, a sufficient length of the section was found to ensure the stability of the model simulations, which was assumed to be equal to 10 m.

Simulation of cuttings transport by drilling fluid flow in the well was carried out using the model described in [3-6]. At the channel inlet, a uniform distribution of the axial velocity of the carrier phase was set, and the solid phase particles were evenly distributed over the inlet section. There was no slippage between the phases, and the flow velocity of the drilling fluid was equal to the velocity of the solid particles. The no-slip condition (near-wall functions) was set for the carrier phase and the dispersed phase on the channel walls. Soft boundary conditions were set at the test section outlet. The $k-\omega$ SST model was used to simulate flow turbulence. The rheology of the drilling fluid was described by a power law.

![Figure 1. Geometric model of the horizontal section of the well (dimensions are in mm).](image)

The rheological parameters of water-based drilling fluid with the addition of polymers and a foaming agent were used as initial data. The solution, which was used as a base for aerated fluids was composed of Gammaxan 0.5wt.%, Starch 2wt.%, and Sulfanol 0.6wt.% (during aeration). The parameters of the base solution and obtained fluids are given in Table 1.

It should be noted that with a change in the degree of aeration, not only does the density of the resulting mixtures change, which is quite natural, but also the degree of nonlinearity $n$ and the consistency index $k$ increase. The coefficient $R$ is an indicator of the reliability of the non-Newtonian power law. The flow rate of drilling fluid varied within the range from 8 to 30 l/s. The density of the cuttings was 2600 kg/m$^3$. The cuttings’ concentration in the drilling fluid was 1.71%. Also, the effect of drill stem rotation speed equal to 0, 60, 90, 120, 150, 180, and 200 rpm, was considered for some modes.
Table 1. Properties of drilling fluids.

| №  | Degree of aeration (Vmix/Vfluid) | Density, kg/m³ | n  | k, Pa*s | R²  |
|----|---------------------------------|----------------|----|--------|-----|
| 1  | -                               | 997            | 0.24 | 4.23   | 0.98 |
| 2  | 1.66 (39.8%)                    | 557            | 0.27 | 5.81   | 0.99 |
| 3  | 2 (50%)                         | 458            | 0.28 | 5.97   | 0.99 |
| 4  | 2.8 (64.3%)                     | 343            | 0.27 | 6.75   | 0.99 |
| 5  | 3.5 (71.4%)                     | 243            | 0.27 | 8.43   | 0.99 |
| 6  | 5.25 (81%)                      | 158            | 0.25 | 8.76   | 0.91 |

2. Simulation results
Initially, the effect of drilling fluid flow rate on the efficiency of cuttings transport was analyzed. The results are shown in Fig. 2.

![Figure 2](image)

At the flow rates of 8 and 12 l/s, the efficiency of the cuttings removal is low. At that, a large stable cuttings bed is formed. With a further increase in the flow rate to 18 l/s, the efficiency of cleaning the borehole from the drilled rock increases. At a flow rate of 25 l/s, improvement in cuttings removal becomes nonlinear.

Visualization of the phase distribution in the annular space (Fig. 2) also confirms the above conclusions about the effect of the flow rate on the transport of cuttings particles. After increasing the flow rate to 15 l/s and above, the thickness of the cuttings bed begins to decrease rapidly. At flow rates of 8 and 12 l/s, the cuttings bed occupies about 20% of the annular space, which is why the flow velocity also increases proportionally by ≈ 20%, while an equilibrium state is established at which the flow velocity at the place of cuttings accumulation is sufficient for its movement along the surface layer of the compacted part of the cuttings. After studying the effect of the flow rate on the cuttings transport, a study was conducted to reveal the effect of rotation of the inner pipe on the efficiency of cuttings transport by aerated solutions. The simulation results are presented in Figs 3 and 4.
Figure 3. A cross-section of the well model after the stabilization of the system with color display of the distribution of the solid phase at different rotation speeds of the boring tool in the solution with a density of 997 kg/m$^3$ and the flow rates of 8 l/s; a) 0; b) 60; c) 90; d) 120; e) 150; f) 180 rpm.

Figure 4. The drilling fluid concentration in the annular space depending on the rotation speed of the boring tool.

When studying the effect of the rotation speed of the boring tool on the transportation of cuttings, an unambiguously positive effect was revealed for the initial drilling fluid with a density of 997 kg/m$^3$. However, the effect of this factor has a limitation – with an increase in the rotation speed of more than 120 rpm, this effect strengthens extremely slightly. For the aerated fluids under consideration, the maximum efficiency for this factor falls within the range of 60-90 rpm, after which bearing capacity sharply deteriorates. In the absence of rotation of the drill stems, drill cuttings actively accumulate, and even in two minutes, their concentration reaches more than 7%, which creates high risks of emergencies even if the rotation of the drill stem is stopped for a short time. At a rotation speed of 60 rpm, the equilibrium concentration of cuttings decreases by more than 130%.

Considering the change in the size of the cuttings bed (Fig. 3), one can also note a tendency to decrease its capacity with an increase in the rotation speed of the boring tool. In the absence of rotation, the cuttings occupy about 55-60% of the annular space, covering the drill pipe, which
practically guarantees the occurrence of puffs, as well as differential sticking. At a rotation speed of 60 rpm, the power of the cuttings bed significantly decreases caused both by hydraulic erosion when a transverse component of the fluid flow velocity occurs and by mechanical destruction by the surface of the drill pipe.

The effect of the degree of aeration of drilling fluid on the cuttings transport was studied similarly. The results of the studies are shown in Fig. 5.

![Figure 5](image1.png)

**Figure 5.** A cross-section of the well model after the stabilization of the system with color display of the distribution of the solid phase at different density drilling fluid a) 997; b) 557; c) 458; d) 343; e) 243; f) 158 kg/m$^3$.

![Figure 6](image2.png)

**Figure 6.** The drilling fluid concentration in the annular space depending on the different density drilling fluid.

With an increase in the degree of aeration, the quality of cleaning the borehole from drilling cuttings improves. A pronounced effect is observed when the fluid density equals 343 kg/m$^3$. At the further change in density, the effect of the aeration on the quality of cleaning the borehole from cuttings is almost not pronounced.
The capacity of the cuttings bed also decreases, while the concentration of floating cuttings increases, i.e. the cuttings are transferred not only along the lower part of the annular space but throughout the entire volume of the well (Fig. 5), which indicates a higher retention capacity of aerated solutions. Analyzing the cuttings transfer process by solutions with different densities, it is revealed that at densities of 243 and 158 kg/m³, the cuttings move along the lower part of the well wall in waves (Fig. 6). This phenomenon was observed in the study [7], where it is stated that the wave mode of cuttings transfer is the most effective, and occurs at high values of the aeration of the drilling fluid.

![Figure 7. Wave mode of cuttings movement in the annular space of the well.](image)

**Conclusion**

The paper presents the results of the cuttings transport in a horizontal well using aerated drilling fluids. It is shown that when the drilling fluid flow rate increases, the efficiency of cuttings transport by the base solution also increases. However, in aerated fluids, the efficiency of cuttings removal is greater at low drilling fluid flow rates. The effect of drill pipes on the efficiency of cuttings transport was also studied. It is shown that for the aerated fluids under consideration, the maximum efficiency for this parameter is reached within the range of 60-90 rpm, after which the bearing capacity of the base solution sharply deteriorates. However, the effect of this factor has a limitation, namely, with an increase in the rotation speed of more than 120 rpm, the effect becomes significantly less pronounced.

The effect of the drilling fluid aeration on the efficiency of cuttings transport has been studied as well. With an increase in the degree of aeration, the quality of cleaning the borehole from cuttings increases. A pronounced effect is observed when the fluid density changes to 343 kg/m³, after which the effect of the aeration on the quality of cuttings cleaning becomes less pronounced.

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