Simulation of cuttings removal processes in the horizontal well

V A Zhigarev¹, M I Pryazhnikov¹,², A V Matveev¹, D V Guzei¹,², A V Shebel¹

¹Siberian Federal University, 79 Svobodny pr., Krasnoyarsk, 660041, Russia
²Institute of Thermophysics SB RAS, 1 Acad. Lavrentiev pr., Novosibirsk, 630090, Russia

E-mail: zhigarev.vladimir@yandex.ru

Abstract. The paper presents the results of a numerical simulation of the process of cleaning the annulus of a horizontal well. The effect of the cuttings particle size on the efficiency of cuttings removal from the annulus of the well was studied. The geometry of a real well was used as the calculation model. Cutting particles with sizes from 2 to 5 mm were considered in the numerical study. Velocity profiles of the solid phase (cuttings particles) in annular channels were obtained in the course of conducted numerical simulation.

1. Introduction

The construction process of oil and gas wells for various purposes and their cost depends largely on the properties of the drilling fluid. The cost of the drilling fluid itself is relatively small (7-30%), however choosing the most optimal drilling fluid and maintaining its properties during drilling have a special effect on the overall cost of the well. For example, the time required to drill to the total depth depends on the bit penetration speed, the efficiency of cuttings removal, as well as the costs caused by rock collapse, drill string entrapment, loss of circulation, etc. The main problem faced by drilling crews is differential sticking and loss of circulation resulting from inefficient cleaning of the well from the drilled rock when drilling inclined and horizontal sections. To effectively clean the well, it is necessary, first of all, to use a high-quality drilling fluid that would ensure the functions that are assigned to it, such as cooling the drilling tool, maintaining the walls of the well, and cleaning out the drilled rock, as well as to drill a well in the optimal operation mode of the drilling tool and pumps providing the circulation of the drilling fluid. To choose the optimal operation mode of the drilling equipment and pumps, it is necessary to have a method which would allow calculating these processes. In turn, to study these processes, it is necessary to use data on the flows of power-law and Bingham fluids in annular channels. With the development of computer technology, works on numerical simulation of flows in annular channels with eccentricity and rotation of the inner tube appeared in parallel with their theoretical and experimental studies. First of all, it is worth noting the following works: simulation of power-law and Herschel-Bulkley fluids in an eccentric channel with a partial blockage and taking into account the rotation of the internal pipe [1]; and simulation of the viscoelastic fluid flow in a channel with eccentricity and rotating inner tube [2].

We should also highlight a series of experimental and computational works by M.P. Escuider et al. [3-4] devoted to the study of laminar and turbulent flows of Newtonian and non-Newtonian media in annular channels with eccentricity and rotation of the inner tube. At present, the turbulent flow regimes of non-Newtonian fluids to which drilling fluids mainly belong, have been studied insignificantly and only a small amount of experimental data is available for these flows. These flow
modes were studied, in particular, in the works is Nouri [5; 6] and Roy and Zamora [7; 8], in which the authors have measured only some flow characteristics. The main reason why there is not much experimental work on the flow of real pseudoplastic fluids is that for the most part these fluids are opaque, and therefore optical methods for measuring the velocity and distribution of particles in the channel and flow cross-section cannot be applied to them. Besides, one of the significant limitations to conducting experimental work with the flow of these fluids is the complexity and cost of conducting these experiments, because these experiments require selecting a pump capable of providing the necessary flow rates, as well as the need to conduct constant monitoring of the rheological parameters of the solution. Experimental facilities also require a power drive to rotate the internal pipe, as well as fairly long stabilization and measuring sections, and much more. Most researchers point out that it is necessary to have a generally accepted hydrodynamic theory of flushing directional wells with a horizontal end section to optimize the removal of cuttings and the construction of the well in general.

In this paper, a numerical study of the drilling fluid flow with different densities was performed to reveal the effect of its density on the efficiency of cuttings removal in horizontal wells.

2. Problem Formulation

2.1 Testing of the method

For the computational study of the drilling fluid flow in the annulus, we used the method of computational fluid dynamics (CFD) based on the solution of the Navier-Stokes system of equations, where the mass conservation equations and the continuity equations preserve the original model of the Euler representation [9-12]. The Gidaspow model [13] was used for numerical simulation of the movement of drilled rock (cuttings particles). It describes the interfacial resistance forces needed for the Euler approach for a granular medium [10, 13]. To simulate the turbulent flow, the two-zone two-parameter Menter SST model was employed as the main model [14]. Drilling fluids are generally non-Newtonian fluids. Therefore, it is necessary to take into account the influence of their rheology. Taking into account the non-Newtonian properties of a liquid is necessary to describe the averaged effective molecular viscosity in the region of developed turbulence. In this region, the value of the average molecular viscosity turns out to be a function of turbulent quantities and rheological parameters. For turbulent flow, the effective viscosity coefficient is the sum of the molecular viscosity coefficient and the turbulent viscosity. Turbulent viscosity is determined in accordance with our chosen turbulence model.

The calculation method was tested and proved in several papers [15-17]. As part of the present work, testing was performed using a model problem [18]. The steady flow in a straight circular channel was considered. The following geometric dimensions were selected: pipe length – 12 m, inner pipe diameter – \( d_1 = 0.0254 \) m, and outer pipe diameter – \( d_2 = 0.127 \) m. The dispersed medium was represented by an ensemble of solid balls with a density of 2619 kg m\(^{-3}\) and a diameter of \( d = 6.3 \) mm. A uniform distribution of the axial velocity of the carrier phase was set at the channel inlet, and the solid phase particles were evenly distributed over the inlet cross-section. Between the phases, there was no slip, and the flow velocity was \( V_1 = V_c \). For the carrier phase and the dispersed phase, the no-slip condition (wall functions) was set on the channel walls. Soft boundary conditions were set at the outlet boundary. The \( k-\omega \) SST model was used to simulate the flow turbulence. The drilling fluid rheology was described by a Power-law. Rheological parameters of drilling fluids consistency were as follows: \( K = 0.445 \) Pa s\(^n\), nonlinearity factor \( n = 0.61 \).
As can be seen from figure 2, the calculation model is in good agreement with the data obtained in the work of Hajipour [18], which shows the applicability of the calculation method for simulating the cuttings transport in the well.

2.2 Simulating cuttings transport in a horizontal pipe
The computational configuration described in [19] was used to calculate the cuttings transport in the annulus. The process of cuttings transport was investigated using a non-Newtonian drilling fluid, the rheology of which was described by a power law. The rheological parameters of the studied nonaligned polymer-clay solution were as follows: the nonlinearity factor $n = 0.6$, the solution consistency $K = 0.9$ Pa s$^{n}$, the density was 1050 kg m$^{-3}$. To simulate the drilled rock, spherical particles of different sizes were used whose diameter ranged from 0.002 to 0.01 m, while the density of these particles was set to 2900 kg m$^{-3}$. The drilling parameters were as follows: the flow rate of drilling fluid at the inlet to the channel was 20 kg s$^{-1}$, the rotation speed of the inner pipe was 60 rpm. The concentration of the particles at the inlet was set to 3% by weight. 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. This configuration represents the geometry of a real well. In our calculation we used structured grid consisting of 40 nodes along the radius, 120 nodes along the circumference, and 100 nodes along the channel length. The length of the computational domain was selected to meet the condition for stabilizing the flow rate and cuttings concentration along the entire length. The velocity of the drilled rock (cuttings) at the channel inlet was set equal to the flow velocity of the drilling fluid. To compare the quality of cuttings removal, data from different channel cross-sections distributed along the length were used.

3. Results
Figures 3-5 show the results of numerical simulation of cuttings transport of various diameters in a horizontal well. Figure 3 shows the distribution of cuttings particles in the channel cross-section for different particle diameters.

![Figure 3](image)

**Figure 3.** Distribution of bulk phase in the channel cross-section for 4 sizes of cuttings particles after 20 seconds of computation:

- a) 2 mm; b) 3 mm; c) 4 mm; d) 5 mm.
Figure 4. The pressure drop in the annular channel for different diameter of cuttings particles depending on the pumping time.

Figure 5. Time dependence of the average slip velocity for different diameter of cuttings particles.

4. Conclusion
A numerical study of the various size cuttings transport in the annulus of a horizontal well was carried out that allowed revealing the distribution of cuttings particles of different diameters in the well cross-section. As can be seen from figures 4-5, the increase in the particle size results in the increase of the pressure drop as well as an average slip velocity (ASV) of the cuttings particles. Accordingly, the efficiency of cuttings’ transport by drilling fluids decreases that is because it is more difficult to remove large cuttings. Also, the increase in pressure is caused by narrowing the channel cross-section due to the accumulation of large particles. In the future, it is planned to study the transport of cuttings particles of heterogeneous composition.

Acknowledgments
The research was carried out with the financial support of the Russian Science Foundation in the framework of the project (17-79-20218-P).
References

[1] Hussein Q E and Sharif M A R 1997 J. Energy Res. Tech. 120 201–207.

[2] Mori N, Eguchi T, Nakamura K and Horikawa A 1987 J. Text. Mach. Soc. Japan 33(2) 46-53.

[3] Escudier M, Oliveira P, Pinho F and Smith S 2002 Exp. Fluids 33 101-111.

[4] Escudier M and Gouldson I 1995 Int. J. Heat Fluid Flow 16 156-162.

[5] Nouri J, Umur H and Whitelaw J 1993 J. Fluid. Mech. 253 617-641.

[6] Nouri J and Whitelaw J 1997 Int. J. Heat Fluid Flow 15(2) 236-246.

[7] Roy S and Zamora M 2006 AADE Drill. Fluids Tech. Conf. (Houston).

[8] Zamora M, Roy S and Slater K 2005 AADE Nat. Techn. Conf. (Houston).

[9] Ogawa S, Umemura A and Oshima N 1980 J. Appl. Math. Phys. 31 483.

[10] Ding J and Gidaspow D A 1990 AIChE J. 36(4) 523-538.

[11] Wen C-Y and Yu Y H 1966 Chem. Eng. Prog. Symp. Series. 62 100–111.

[12] Ergun S 1952 Chem. Eng. Prog. 48(2) 89–94.

[13] Gidaspow D 1994 Multiphase Flow and Fluidization: Continuum and Kinetic Theory Descriptions (New York: Academic Press)

[14] Menter F R 1994 AIAA J. 32(8) 1598-1605.

[15] Zhigarev V A, Neverov A L, Guzei D V and Pryazhnikov M I 2017 J. Phys.: Conf. Ser. 899 (092016) 1-6.

[16] Minakov A V, Zhigarev V A, Mikhienkova E I, Neverov A L, Buryukin F A and Guzei D V 2018 J. Petroleum Sci. Eng. 171 1149-1158.

[17] Zhigarev V A, Minakov A V, Guzei D V and Mikhienkova E I 2018 J. Phys.: Conf. Ser. 1105 (012077) 1-6.

[18] Hajipour M 2020 SN Appl. Sci. 2 1-12.

[19] Zhigarev V A, Minakov A V, Neverov A L and Pryazhnikov M I 2019 J. Phys.: Conf. Series 1382 (012080) 1-6.