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Experimental studies of the carrying capacity of the drilling fluid

Eksperymentalne badania nośności płuczek wiertniczych

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ABSTRACT: The main factors affecting the efficiency of the carrying capacity of drilling fluid are analysed in the paper. A description of the design of an experimental setup for modeling the well flushing process is presented, which makes it possible to evaluate the efficiency of the carrying capacity of a fluid from a variety of factors under study. To conduct experimental studies of the influence of factors on the efficiency of cleaning wells from cuttings, an experimental plan was built using the Taguchi methods for six factors at three levels of their change. According to the plan, we studied the effect of such parameters on the carrying capacity of the drilling fluid at various values of its flow rate: the variability of the drill string in the well; the cuttings particle diameter; the plastic viscosity of the drilling fluid; the pulsation frequency; the rotation of the drill string and its longitudinal movement. The nature of the formation of stagnant rock zones in the annulus of directional wells has been assessed. The influence of factors according to the constructed plan of the experiment at the distance of the beginning of settlement of the cuttings was studied. Based on the results of the studies, it was found that changing the range of these factors reduces the volume of rock deposited on the lower wall of the directional wellbore. It has been established that the use of a pulsating flow of flushing fluid makes it possible to reduce the value of its consumption and improve the efficiency of cleaning the annular space of wells from cuttings.

Key words: drilling fluid; carrying capacity; cuttings; pulsating flow; experiment planning; flow rate; drilling.

STRESZCZENIE: W artykule przeanalizowano główne czynniki wpływające na efektywność nośności płuczek wiertniczych. Podano opis projektu eksperymentalnej instalacji do modelowania procesu płukania otworów, która pozwala na ocenę efektywności nośności płynu od różnych badanych czynników. W celu przeprowadzenia badań eksperymentalnych wpływu czynników na efektywność oczyszczania otworów ze zwiercin zbudowano plan eksperymentu metodami Taguchi dla sześciu czynników na trzech poziomach ich zmiany. Zgodnie ze skonstruowanym planem zbadano wpływ następujących parametrów na nośność płuczki wiertniczej przy różnych wartościach jej natężenia przepływu: mimośrodowość przewodu wiertniczego w otworze, średnica cząstek zwiercin, lepkość plastyczna płuczki wiertniczej, częstotliwość pulsacji, obrót przewodu wiertniczego i jego ruch wzdłużny. Oceniono charakter powstawania stref stagnacji cząstek skalnych w przestrzeni pierścieniowej odwiertów kierunkowych. Zgodnie ze skonstruowanym planem eksperymentu badano wpływ poszczególnych czynników na długość początkowego odcinka osadzania się zwiercin. Na podstawie wyników przeprowadzonych badań ustalono, że zmiana zakresu tych czynników zmniejsza objętość skały, która osadziła się na dolnej ścianie odwiertu kierunkowego. Stwierdzono, że zastosowanie pulsacyjnego przepływu płynu przemywającego pozwala na zmniejszenie wartości jej zużycia oraz poprawę efektywności oczyszczania przestrzeni pierścieniowej otworów ze zwiercin.

Słowa kluczowe: płuczka wiertnicza; nośność; zwierciny; przepływ pulsacyjny; planowanie eksperymentu; przepływ; wiercenie.

Introduction

In recent years, the volume of drilling of directional wells has increased, which leads to an increase in the efficiency of development of oil and gas fields and an increase in the coefficient of fluid recovery. However, the practice of constructing such wells has presented several problems to specialists, among which the most important is the provision of an effective flushing process, the level of which depends on many factors, among which the quality of cleaning the wellbore from cuttings should be distinguished (Ali et al., 2005; Al-Tammer et al., 2020).

An analysis of industrial data confirms that far more attention should be paid to cleaning the wellbore of directional wells compared with to vertical wells, since the process of flushing these wells is significantly different and more complicated than vertical wells (Nwagu et al., 2014; Elgaddafi et al., 2021). One of the reasons for poor-quality cleaning of wells

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from drill cuttings is bottom hole sludging, which can lead to various complications, namely:

1. Decrease in the speed of movement of the drilling fluid at the bottom and deterioration of the cuttings carryover. At the same time, the bottom hole is sludged even at low axial loads on the bit, which leads to a decrease in drilling speed.
2. Sludging of the bottom of the well leads to wear of the rock cutting tool and a decrease in footage per run.
3. The accumulated cuttings at the bottom are subjected to repeated destruction, which requires additional power costs and the rate of penetration (ROP) decreases.

Furthermore, poor cleaning of directional wells can lead to problems during cementing due to the accumulation of cuttings on the bottom wall of the well, which was not transported to the outer surface and the formation of a blocking wall for the flow of cement slurry (Shatskyi et al., 2021; Vytvytskyi et al., 2022). The accumulated cuttings on the bottom wall of the well makes it difficult to bring the axial load on the bit, which leads to a deterioration in the quality of well trajectory control (Wallen and Striedel, 1995).

To eliminate complications arising from poor-quality well cleaning and energy costs increase, significant funds are spent, and it is often necessary to change approaches to individual drilling processes (Vytyaz et al., 2015; Ziaja et al., 2017). This situation occurs despite the observance of the general recommendations of the flushing process and the requirements of the technical and technological documentation developed for the specific conditions of a particular well.

Despite the observance of the regime and technological parameters when drilling wells and the recommendations of the flushing process, in most boreholes, especially those drilled in Ukraine and abroad, there are complications caused by poor-quality cleaning of the borehole from cuttings. Therefore, it can be argued that the currently known measures do not ensure the effectiveness of the flushing process and high-quality cleaning of the well from cuttings, and the problem remains relevant.

One of the effective ways to solve this problem and, accordingly, improve the quality of the process of flushing a well and cleaning it from cuttings, can be the use of a pulsating flow of drilling fluid, considering the influence of other factors, which is not provided by the currently known scientific and practical methods and approaches of drilling technology.

Theoretical analysis

The efficiency of bottom hole cleaning and transportation of rock particles to the surface depends on many factors: the angle of inclination of the well axis; the ratio of the diameters of the wellbore and the drill string; type and parameters of drilling fluid; the variation of the annulus; the size and shape of cuttings particles; the penetration speed; the drilling fluid consumption; drill string rotation frequency; the nature of the flow movement in the annular space, etc.

Due to the significantly greater number of technological limitations and conditions of use, the process of flushing directional wells requires constant improvement and adjustment. This requires the development of scientific and practical support for approaches for modeling and studying the influence of mining-geological and technical-technological parameters on the implementation of the well flushing process.

One of the main functions of the drilling fluid is to effectively carry cuttings to the surface. The speed with which the upward flow carries the cuttings out of the well depends on the ratio of the velocity of the fluid and the rate of settling of the cuttings particle with in it under the action of gravity. In the case where the drilling fluid is in a stationary state, the cuttings contained with in it have a constant, downwardly directed net settling velocity.

Cuttings are transported due to the action of the buoyancy of the drilling fluid flow and the resistance forces acting on the cuttings particles in the process of its settling. This is superimposed by various effects caused by the rotation of the drill string, uneven velocity distribution profile, changes in the geometric parameters of the well trajectory and the cross-sectional area of the annulus, the shape and size of cuttings, changes in the rheological parameters of drilling fluids, and the eccentric location of the drill string (Zamora and Hanson, 1991; Femiak et al., 2022).

In the process of drilling wells, the concentric arrangement of the drill string is provided very rarely. Typically, the string is close to the borehole wall and variations will occur. An incorrect location of the drill string leads to the formation of a stagnant zone in the annular space, uneven distribution of the drilling fluid velocity, an increase in the contact area of the drill pipe surface with the borehole walls and, accordingly, the torque for its rotation (Chudyk, 2009). This can be influenced by various factors, such as the diameter of the well and the drill string, the technical characteristics of the drilling pump, the parameters of the drilling fluid, the magnitude of the variation and its position in the plane of the annular section of the wellbore (Chudyk, 2008).

It is generally accepted that one of the ways to improve the quality of well cleaning from cuttings is to increase the flow rate of the drilling fluid by increasing the productivity of the mud pump.

To date, there are no justifications for choosing the required flow rate of the drilling fluid, which ensures the efficiency of the cleaning process of directional and horizontal wells.

There are certain recommendations for choosing the flow rate of the drilling fluid (Lihots′kyy, 2002; Chudyk, 2010), consider individual factors, namely: the composition of rocks (clays, shale, sands, sandstones, etc.); experience in conducting drilling operations in a specific area with specified regime and technological parameters and technical support; type of casing string (conductor, intermediate and production). According to these data, it is difficult to choose the optimal flow rate of the drilling fluid, so there is a need to conduct both theoretical and experimental studies of this parameter.

To improve the carrying capacity of the drilling fluid, special attention is paid to the type and properties of the drilling fluid (Aston et al., 2004; Bogoslavets et al., 2022). Properly selected properties and type of drilling fluid can minimise complications when drilling wells. For a high-quality well flushing process, drilling fluids must have the following properties: have a good carrying capacity in a laminar flow regime, especially with insufficient rheological parameters of the fluid; do not negatively affect the resistance of the walls of the well; resist cuttings settling and have thixotropic properties (Alyami et al., 2020; Al-Bahrani et al., 2022).

In addition to the properties and flow regime of the drilling fluid, the quality of wellbore cleaning is also affected by the mechanical effect on the flow of the drilling fluid, which contains cuttings, namely, the divergence and rotation of the drill string (Harvey, 1990; Paliichuk et al., 2022).

The rotation of the drill string during rotary drilling is one of the ways to improve carrying cuttings to the surface in directional wells (Sanchez et al., 1997; Pilehvari et al., 1999).

The use of rotation of the drill string leads to the transfer of cuttings from the narrow lower part of the annular section, where cuttings accumulate, to the wide upper part, which leads to improved cuttings carrying in horizontal wells (Ozbayoglu et al., 2008; Dutkiewicz et al., 2022).

Rotation of the drill string can mechanically enhance the carrving of cuttings, and effective well cleanout can be achieved even at sub-critical fluid velocities in the annulus (Saasen, 1998).

Considering that various factors can influence the efficiency of well cleaning from drill cuttings, it is necessary to conduct scientific research taking into account the maximum number of influential factors.

Experimental part

Since industrial research is characterised by the scale of objects, the complexity of their implementation and the high cost of real industrial observations, it is more expedient to experimentally study the processes of well washing using laboratory modeling.

It is impossible to ensure the simulation of all similarity criteria, since the dimensions of the laboratory setup would be too large in full-scale simulation.

To study the influence of technical and technological factors on the efficiency of rock removal from the wellbore, an experimental setup was developed (Chudyk et al., 2020), a diagram of which is shown in Figure 1.

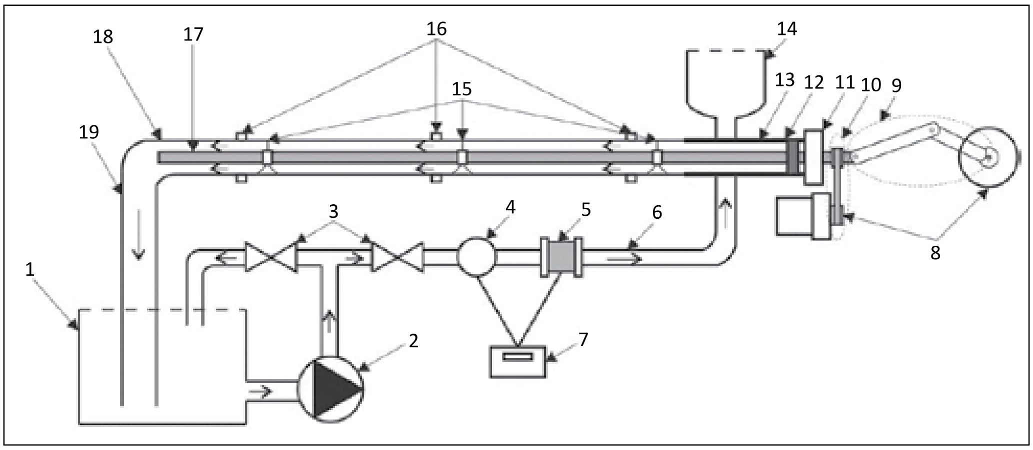

Figure 1. Scheme of an experimental unit for modeling the well flushing process: 1 – fluid reservoir; 2 – pump; 3 – valves for regulating the flow of drilling fluid; 4 – drilling fluid flow transmitter; 5 – solenoid valve; 6 – injection line; 7 – control unit; 8 – gear motor; 9 – crank mechanism; 10 – belt transmission; 11 – stuffing box; 12 – bearing; 13 – plastic pipe; 14 – rock supply tank; 15 – drill string centralisers; 16 – distance sensors; 17 – drill string; 18 – glass pipe; 19 – flow line

Rysunek 1. Schemat eksperymentalnej instalacji do modelowania procesu płukania otworów: 1 – zbiornik na ciecz; 2 – pompa; 3 – zawory do regulacji przepływu płuczki wiertniczej; 4 – czujnik przepływu płuczki wiertniczej; 5 – zawór elektromagnetyczny; 6 – linia iniekcyjna; 7 – jednostka sterująca; 8 – silnik przekładniowy; 9 – mechanizm korbowy; 10 – przekładnia pasowa; 11 – dławik uszczelniający; 12 – łożysko; 13 – rura z tworzywa sztucznego; 14 – zbiornik na surowiec; 15 – centralizatory przewodu wiertniczego; 16 – czujniki odległości; 17 – przewód wiertniczy; 18 – szklana rura; 19 – rura odprowadzająca

The length of the experimental unit is 3.5 m. A glass pipe with an inner diameter of 23.2 mm was used to model the wellbore with a diameter of 181 mm (drilling bit diameter of 165.1 mm and a linear coefficient of cavernosity of 1.1). A pipe with a diameter of 13 mm was used to model a drill string with a diameter of 101.6 mm.

The developed setup allows simulating the influence of such factors on the carrying capacity of the drilling fluid:

- drilling fluid consumption;
- drill string eccentricity;
- diameter of rock particles;
- plastic viscosity of the drilling fluid;
- pulsation frequency;
- rotation of the drill string;
- longitudinal movement of the drill string.

Conducting randomly selected experiments does not allow one to obtain a reliable regularity in order to adequately take into account the influence of all the studied factors simultaneously (Hodzic et al., 2019).

To study the influence of factors on the efficiency of rock removal from the wellbore, it is advisable to use Taguchi plans using balanced orthogonal matrices. In these matrices, control and destabilising parameters separated into different levels interact (Pradana and Sulistiyowati, 2022).

The construction of an experiment plan using the Taguchi methods is carried out using the PTC Mathcad Prime software. For its construction, six factors were used at three levels of their change in Taguchi (6, 3). The choice of levels of change in the studied factors was made on the basis of the results of previous studies (Chudyk and Dudych, 2021). The results of constructing an experiment plan using the Taguchi methods are shown in Table 1.

Results and discussion

The study of the influence of factors, according to the constructed plan of the experiment on the carrying capacity of the drilling fluid, was carried out at different values of the fluid flow rate. According to the results of test studies, the value of the fluid flow rate was established, at which the rock is not removed from the annular space under certain conditions, but settles on the bottom wall of the well. Under laboratory conditions, this value is 0.198 l/s. the linear flow velocity at this rate is 0.68 m/s. After that, the flow rate of the fluid was reduced to the moment at which a large-scale accumulation of rock is observed in the initial section of the laboratory setup (well bottom). Such cuttings settling when drilling a well

Table 1. Experimental plan for the study of the carrying capacity of the drilling fluid using the Taguchi methods

Tabela 1. Schemat eksperymentu badania nośności płuczki wiertniczej metodami Taguchi

Experiment	Parameters and range of their change					
	Eccentricity of the drill string [mm]	Plastic viscosity [mPa•s]	Diameter of rock particles [mm]	Pulsation frequency [Hz]	Rotation of the drill string	Longitudinal movement of the drill string
1	5.1	1.3	0.1	0	no	no
2	3.4	5.0	0.4	8	periodic	periodic
3	0.3	7.0	0.8	16	continued	continued
4	5.1	1.3	0.4	8	continued	continued
5	3.4	5.0	0.8	16	no	no
6	0.3	7.0	0.1	0	periodic	periodic
7	5.1	5.0	0.1	16	periodic	continued
8	3.4	7.0	0.4	0	continued	no
9	0.3	1.3	0.8	8	no	periodic
10	5.1	7.0	0.8	8	periodic	no
11	3.4	1.3	0.1	16	continued	periodic
12	0.3	5.0	0.4	0	no	continued
13	5.1	5.0	0.8	0	continued	periodic
14	3.4	7.0	0.1	8	no	continued
15	0.3	1.3	0.4	16	periodic	no
16	5.1	7.0	0.4	16	no	periodic
17	3.4	1.3	0.8	0	periodic	continued
18	0.3	5.0	0.1	8	continued	no

in an industrial environment would lead to the formation of complications or accidents.

Water with additives of DUO-VIS biopolymer with a concentration of 0.1, 0.2 and 0.3% was used as a drilling fluid. Pulsations of the pressure of the drilling fluid of different frequencies were created with the help of a solenoid valve.

During the studies, the carrying capacity of the drilling fluid was estimated by the value of the distance of the beginning of rock settling on the lower wall of the experimental setup (the distance of the beginning of settlement of the cuttings is understood as the distance from the bottom of the well to the first zone where the cuttings accumulate).

At different values of the studied factors, the volume of settled cuttings is different. The nature of its settling is also different, namely the height and length of the settlement zone and the distance of the beginning of settlement. During the studies, rock particles created both one continuous stagnant zone (Figure 2a) and several zones of different lengths and at different distances from each other (Figure 2b).

The distance of the beginning of rock settling was recorded from the place where the rock got into the experimental setup to the place where stagnant zones began to form. The results of the conducted studies are shown in Table 2.

During the research, in the case when rock settling was not observed, the value of the beginning of settling was fixed equal to the length of the main part of the setup – 3 m. Based on the analysis of the obtained results of the experiments, a dependence was constructed that reflects the influence of the flow rate of the drilling fluid and the factors under study at the beginning of settlement of the cuttings for all 18 experiments (Figure 3).

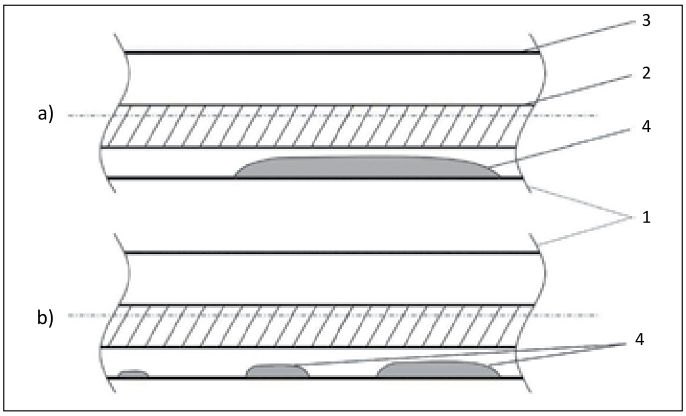

Figure 2. Types of stagnation zones of rock particles in the annular space of the well: (a) one continuous stagnant zone, (b) several zones of different lengths; 1 – cross section of the working area, 2 – model drill pipe, 3 – glass pipe, 4 – stagnant zone

Rysunek 2. Rodzaje stref stagnacji cząstek skalnych w przestrzeni pierścieniowej otworu: (a) jedna strefa stagnacji cząstek skalnych, (b) kilka stref stagnacji cząstek skalnych; 1 – przekrój obszaru roboczego, 2 – model rury płuczkowej, 3 – szklana rura, 4 – strefa stagnacji

From graphic dependence 3, it follows that the value of the flow rate of the drilling fluid has a great influence on its

Table 2. The results of the experiment of evaluating the influence of various parameters on the efficiency of removal of rock particles

Tabela 2. Wyniki eksperymentu oceny wpływu różnych parametrów na skuteczność transportu zwiercin

Experiment	Results of experiments	Drilling fluid flow rate [l/s]									
		0.198	0.189	0.167	0.156	0.139	0.127	0.109	0.094	0.083	0.075
1	beginning of rock settling [m]	2.20	1.92	1.37	1.18	1.04	0.94	0.62	0.41	0.27	0
2		3.00	2.21	2.07	1.46	1.30	1.13	0.93	0.68	0.39	0.33
3		3.00	2.23	2.16	2.05	1.47	1.34	1.19	1.03	0.71	0.43
4		3.00	2.04	1.46	1.35	1.28	1.12	0.90	0.64	0.36	0.28
5		3.00	2.19	2.04	1.42	1.35	1.18	0.97	0.71	0.42	0.31
6		3.00	2.20	2.05	1.44	1.38	1.13	1.00	0.71	0.52	0.36
7		3.00	2.10	1.44	1.33	1.25	1.18	0.90	0.66	0.38	0.28
8		3.00	2.13	1.46	1.33	1.19	1.11	0.72	0.65	0.40	0.31
9		3.00	2.17	1.97	1.45	1.30	1.19	1.04	0.71	0.47	0.34
10		3.00	2.13	1.96	1.36	1.13	1.01	0.72	0.50	0.28	0.25
11		3.00	2.22	2.15	2.05	1.48	1.32	1.14	0.96	0.68	0.41
12		3.00	2.22	1.47	1.40	1.22	1.12	1.00	0.66	0.45	0.36
13		2.17	2.06	1.46	1.32	1.11	1.03	0.69	0.47	0.30	0.26
14		3.00	2.19	2.05	1.46	1.38	1.23	1.04	0.87	0.48	0.35
15		3.00	2.12	1.99	1.40	1.33	1.15	1.05	0.90	0.55	0.34
16		3.00	2.05	1.45	1.33	1.21	1.04	0.84	0.57	0.34	0.25
17		3.00	2.13	2.07	1.45	1.33	1.25	1.06	0.65	0.43	0.28
18		3.00	2.15	2.01	1.45	1.32	1.19	1.07	0.94	0.60	0.37

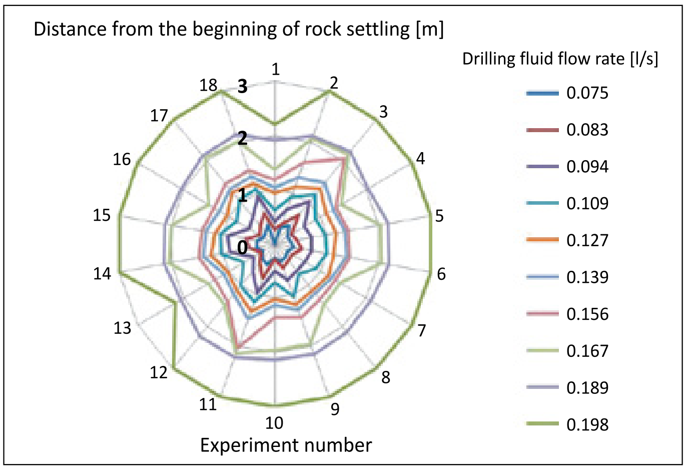

Figure 3. Dependence of the beginning of rock settlement on the flow rate of drilling fluid: 0, 1, 2, 3 – distance of the beginning of rock settlement

Rysunek 3. Zależność początku sedymentacji zwiercin od natężenia przepływu płuczki wiertniczej: 0, 1, 2, 3 – odległość od początku sedymentacji zwiercin

carrying capacity. Its increase leads to a decrease in the volume of cuttings settling in the annular space and an increase in the distance of the beginning of its settling. However, due to technical and technological limitations, such as: technical capabilities of drilling equipment; increase in the hydrodynamic component of the discharge pressure; erosive destruction of the walls of the well, it is often impossible to implement high flow rates when flushing wells.

Based on the results of the studies, it was found that a change in the ranges of the factors under study affects the carrying capacity of the drilling fluid and the distance from which it begins to settle (Figure 4).

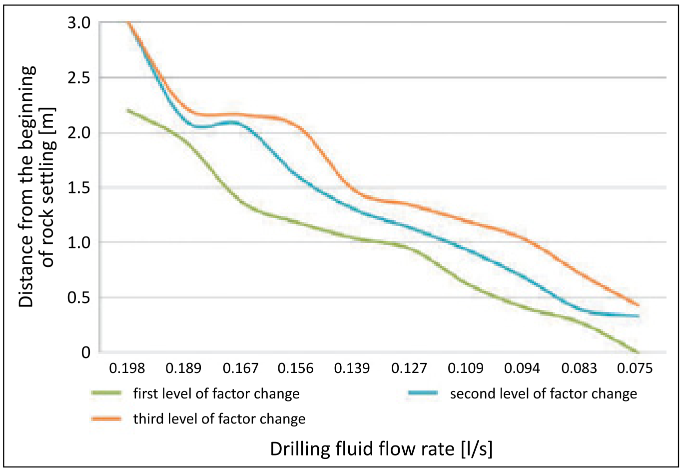

Figure 4. Dependence of the distance from the beginning of rock settling on the change in the range of factors at different flow rates of drilling fluid

Rysunek 4. Zależność odległości początku sedymentacji zwiercin od zmiany zakresu czynników przy różnych natężeniach przepływu płuczki wiertniczej

The first level of factor change is experiment 1, the second level of factor change is experiment 2, the third level of factor change is experiment 3. According to the results of the study at the first level of factor change, a smaller value of the distance from the beginning of cuttings settling is provided, in comparison with the results of studies in which the range of factor change was at the second and third levels. The range of factor changes at the second and third levels of change effectively increases the distance of rock settling at all values of fluid flow.

Consequently, the change in the levels of the studied factors increases the distance of the beginning of rock settling at all values of the fluid flow rate. A change in flow rate does not have a significant effect on the dependence of the beginning of settling of the cuttings on changes in the other studied factors.

One of the main factors affecting the efficiency of rock removal and the flushing process is the use of a pulsating fluid flow. During the experimental studies, pressure pulsations of different frequencies were created at different values of the flow rate of the drilling fluid, and graphical dependencies were constructed based on the results of the studies (Figure 5).

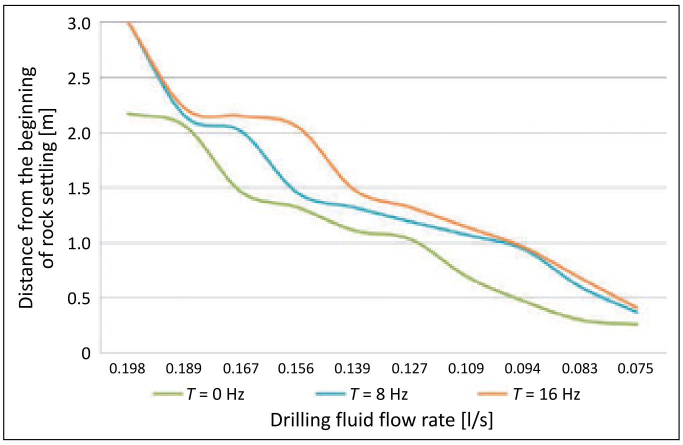

Figure 5. The dependence of the distance of the beginning of rock settling on the frequency of pulsations at different flow rates of the drilling fluid

Rysunek 5. Zależność odległości początku sedymentacji skały od częstotliwości pulsacji przy różnych natężeniach przepływu płuczki wiertniczej

It has been established that in the absence of pressure pulsation, rock settling is observed directly at a short distance from the bottom. However, the creation of pressure pulsations with a frequency of 8 and 16 Hz (according to the plan of the experiment) has a positive effect on the carrying capacity of the drilling fluid at all values of its flow rate and increases the distance of the beginning of cuttings settling.

Therefore, the use of a pulsating flow of drilling fluid improves the efficiency of removal of rock particles, increases the carrying capacity of the fluid and has a positive effect on the process of cleaning the wellbore.

Conclusions

Based on the analysis of the factors influencing the carrying capacity of the drilling fluid, an experimental plan was constructed using the Taguchi methods. Based on the constructed plan, experimental studies of the influence of factors on the distance of the beginning of rock settling in the annular space of the designed laboratory setup were carried out. The effect of changes in the studied factors on the carrying capacity of the drilling fluid at different values of its flow rate has been established. The use of a pulsating flow of the drilling fluid in the annulus improves the transport of cuttings and increases the distance from which it settles. It has been established that the creation of pulsations, with a frequency of 8–16 Hz at a fluid flow rate of 0.198 l/s, ensures complete extraction of the cuttings from the annular space of the experimental setup. Parameters with a high impact inculde flow rate; pulsation frequency; rotation of the drill string; variation of the drill string, mm and plastic viscosity. Parameters with a low impact include diameter of rock particles and longitudinal movement of the drill string.

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