https://doi.org/10.33271/nvngu/2023-5/048

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INFLUENCE OF DRILLING MUD PULSATIONS ON WELL CLEANOUT EFFICIENCY

Purpose. Determination of the influence of the non-stationary flow regime of the drilling mud on the efficiency of cleaning the wellbore in the annulus from drill cuttings.

Methodology. The study on the carrying capacity of the drilling mud in a laboratory installation is carried out by simulating the process of its pulsations at different frequencies. The choice of the studied frequencies was made on the basis of previous studies. The evaluation of the influence of factors on the efficiency of rock removal was carried out using Latin experimental plans, which allowed us to evaluate the influence of the selected factors with a minimum number of experiments without losing the quality of the result.

Findings. The influence of factors (mud flow rates, eccentric placement of the drill string, plastic viscosity of the drilling mud, pulsation frequency, rotation of the drill string) on the efficiency of cuttings removal along the annular space of the wellbore is analyzed. Three factors with the best interaction were found, which made it possible to build dependencies of their influence on the efficiency of rock removal on the surface. The effect of changing the frequency of pulsations of the drilling mud has been studied, and graphical dependences of their influence on the decrease in the volume of rock particles in the annular space have been obtained.

Originality. Based on the results of experimental studies, the effectiveness of the impact of drilling mud pulsations on cleaning the well from rock particles has been proven.

Practical value. The effectiveness of the use of drilling mud pulsations for hydrotransportation of cuttings along the horizontal section of the wellbore has been confirmed.

Keywords: *drilling mud, carrying capacity, pulsations, well, cuttings*

Introduction. Today, building up the resource potential of hydrocarbons as well as oil and gas production is critical for Ukraine's energy independence. The solution of this problem requires an increase in the technical and economic indicators of drilling wells and a reduction in the time spent on field development. For this, in the world practice, the volume of construction of directional wells is increased. In Ukraine, drilling of such wells is carried out in insufficient quantities. The practice of constructing directional wells has posed a number of unresolved problems on specialists: the formation of well casing; ensuring an efficient flushing process and others. The efficiency of oil and gas well construction largely depends on their effective cleanout.

Trouble-free operation of any well is especially relevant for directional and horizontal wells, where complications often arise associated with poor-quality formation of the wellbore (the presence of grooves, keyseats and other deviations from the nominal diameter) and the eccentric location of the casing in it. Therefore, the simplest solution to this problem lies in the formation of a high-quality wellbore during its deepening, which in the future will allow one to lower the casing string without any problems, achieve its concentric location using technological equipment, avoid the occurrence of stagnant zones in the annular space and fully fill it with cementing slurry [1, 2].

The process of well flushing can also be accompanied by various complications and accidents.

A necessary condition for ensuring trouble-free flushing of wells is high-quality cleaning of the well from cuttings. Its quality is influenced by a number of factors; therefore, it is necessary to solve diverse and multifactorial tasks.

One of the spheres of activity, where man has obtained the most significant scientific and technical solutions with the help of modeling tools, is the process of drilling wells.

Modeling of phenomena and processes occurring during well drilling is an effective tool for the scientific and technological progress of the industry in solving problematic issues. The scale of real industrial objects of research, their technological complexity and high cost are limitations that are easily overcome by modeling without significant loss of accuracy of the results obtained.

Experimental studies during well drilling provide a qualitative and quantitative assessment of the correctness of mathematical models designed for calculations in various technological processes and, in turn, are an independent and necessary stage of scientific activity.

Today, analog and laboratory modeling is the main method of experimental research on the implementation of technological processes in a well.

To date, an increase in the production of oil and gas deposits is carried out through the construction of directional and horizontal wells. The issue of their high-quality cleaning from drill cuttings requires much more attention, since the process of flushing such wells in comparison with their vertical structures is more complex and has the following features [3, 4]:

- the annular space during flushing is eccentrically displaced, the drilling fluid flow channel has the shape of a feather-edge section, in which a flow different from concentric is formed;
- the flow velocity vector is directed perpendicular to the force lines of the Earth's gravitational field, due to which the hydrodynamic head plays a secondary role in the hydrotransport of cuttings, while for vertical wells the flow velocity is the main factor in this process;

- the vertical component of the cuttings trajectory when it settles in the drilling fluid flow on the walls of a horizontal well is negligible compared to the depth of a vertical well;

- the presence of stagnant zones on the bottom wall of the wellbore contributes to the accumulation of cuttings and the formation of a cuttings bed, while there are no such zones in the vertical wellbore.

During the well flushing, hydrotransport of cuttings is created as a result of the lifting forces of the flow of the flushing fluid and the resistance forces that act on the drill cuttings.

The velocity at which the upward flow of flushing fluid transports the cuttings depends on the ratio of their settling rate and the flow velocity of flushing fluid. If the flushing fluid is in a stationary state, then the cuttings have a constant downward-directed resultant settling rate.

The study on the well flushing process using modern and advanced technologies and tools is an urgent task, the solution of which will increase the production of hydrocarbon deposits by reducing the time of well construction, increasing drilling efficiency, and reducing accidents due to the accumulation of cuttings in the annulus.

The efficiency of cleaning the bottomhole of directional and horizontal wells and transportation of rock particles to the surface depends on many factors [5, 6]: the ratio of the diameters of the wellbore and drill string; drilling fluid parameters; eccentricity of the annulus; size and shape of cuttings; chemical activity of cuttings; penetration rate; consumption of drilling fluid; drill string rotation frequency, etc.

Theoretical foundations that would solve the problems of flushing are not considered sufficiently; namely, there are no specific answers to the question of whether the uniform movement of the upward flow along the wellbore is the most effective in all conditions, whether it ensures effective removal of cuttings from the bottomhole and its transportation along the wellbore in directional and horizontal wells and the required performance of mud pumps for this.

In view of the urgent need to improve the quality of the construction of directional and horizontal wells [7, 8], its fulfillment is also seen in the issue of optimizing the process of flushing those wells using pulsating flows of drilling fluid.

Literature review. According to the analysis of well-known scientific studies in the field of improving the efficiency of flushing directional and horizontal wells, it was found that one of the main factors affecting the quality of the process is the eccentric location of the drill string in the borehole, which leads to uneven flow rates of the flushing fluid in the annulus [9]. In the process of drilling wells, the drill string is usually close to the wall of the well and the same time its eccentric placement relative to the axis of the well is observed. This leads to the formation of stagnant zones in the annular space, an increase in the contact area of the surface of the drill pipes with the walls of the well and, accordingly, the torque on its rotation.

In the well flushing process with an eccentric placement of the drill string, different flow regimes can simultaneously exist in different parts of the annular space. Both laminar and turbulent flow regimes may be observed, or the fluid may not move.

Other factors affecting the efficiency of rock removal are the type, properties and flow rate of the drilling fluid, its rheological properties [10, 11].

The composition of the drilling mud should be compatible with all rocks of the drilling interval. During the selection of components, well drilling conditions are taken into account, considering the lithological characteristics of the drilled rocks, as well as reservoir temperatures and pressures.

Drilling mud should not negatively affect the stability of the walls of the well, have a high carrying capacity, especially with insufficient rheological parameters, and also resist cuttings settling.

However, in addition to the properties and flow regime of the drilling fluid, the quality of well cleaning is also affected by the divergence and rotation of the drill string [12, 13], which provide drilling-out of the cuttings and improve transportation through the annulus [14].

In rotary drilling of directional wells, the rotation of the drill string improves the transportation of cuttings by transferring the cuttings from the narrow lower part of the annular section to the wide upper part.

During the rotation of the drill pipes, when the concentric location of the drill string relative to the axis of the well, a rotational movement of the fluid is formed and the trajectory of the drilling fluid flow becomes spiral.

In a swirling flow, the carrying capacity of the drilling mud improves due to an increase in the total flow rate. However, the time of transportation of cuttings may increase due to an increase in the path of their movement in a spiral.

In [15], to improve the cleaning of the horizontal wellbore, it is recommended to use radial vibrations of the drill string. It is noted that an increase in their amplitude entails an increase in the speed of the upward flow in the lower zone of the annular section – the stagnant zone.

Taking into account the laws of hydrodynamics and known effects, we noted that the use of pulsed flushing has an advantage over uniform flushing, especially in directional wells, where there is a high probability of potentially dangerous accumulation of cuttings on the bottom wall of the well [16]. It is noted that a rational area of application of pulsating flushing is drilling wells with areas close to horizontal. This is explained by the fact that when switching to a pulsating flow regime at a certain point in time, the flow velocity decreases to almost 0 m/s. Accordingly, the flow passes from a turbulent regime to a laminar one, while the removal of cuttings is improved due to an increase in the drag coefficient.

Despite a large amount of research, generalization and dissemination of advanced domestic and foreign experience, the issue of constructing directional and horizontal wells remains the subject of constant discussion and requires further study.

Unsolved aspects of the problem. To select a technology for effective cleaning of a particular well, an individual approach is required, taking into account the practice of drilling in a particular area, analyzing the risks of complications for the given mining and geological conditions of well construction. Finding an effective combination of influencing factors on the set of acceptable alternatives for their application to maximize the efficiency of transporting cuttings to the bottom from complicated horizontal sections is a complex engineering task.

The use of a pulsating flow of drilling fluid in certain sections of wells is becoming increasingly popular in the world practice in order to improve the efficiency of cleaning bottom hole or problem areas of the well and, as a result, increase the rate of penetration (ROP). Most of these works are devoted to the study on the effect of unsteady flow of drilling fluid on the ROP [17, 18]. In a directional well, only the upper layer of cuttings moves, while the lower one remains motionless. Therefore, in order to improve the cleaning of the wellbore, it is proposed to apply the pulsation of the drilling fluid.

The influence of pulsating flushing on the efficiency of bottomhole cleaning is not well understood and requires further research. In particular, the influence of the pulsating flow of the drilling fluid with a change in other main factors of the flushing process and their cumulative effect on the process of transporting the cuttings to the day surface requires further study. Industrial studies on this process are quite complex and costly. Therefore, the study on this issue should be carried out using the methods of laboratory modeling and planning of experiments. In this case, it is necessary to take into account the maximum possible number of factors that affect the efficiency of cleaning the bottom of the well and the flushing process as a whole in order to construct an optimization problem of the form

$$\begin{cases} k\left(factors^{v}\right) \to \max, \quad k \in K, \quad v \in \vartheta, \quad factors^{v} \in D^{v} \\ \varphi\left(factors^{v}\right) \le 0 \end{cases},$$

where $factors^{v} = (factors_1^{v}, factors_2^{v}, \ldots, factors_k^{v})^T$ is a vector of possible factors of v^{th} admissible combination; ϑ is a subset of equivalent combinations; D^v is a vector definition area $factors^v$; $\varphi(factors^v)$ is a system of restrictions on factor parameters.

The purpose of the research is to study the effect of the pulsating flow of the drilling fluid on the efficiency of cuttings transportation to the daylight surface. It is also important to assess the significance of the influence of the main factors of the well washing process and their total impact when changing the range of their allowable values.

An effective combination of influential factors for cleaning the borehole will increase the ROP, reduce the total construction time, and reduce the required flow rate of the drilling fluid in certain sections of drilling.

Methods. The impact of the pulsating flow of drilling fluid and other main parameters of the well flushing process on the quality of cuttings removal is carried out on a unit designed on the basis of the theory of similarity and dimensions (Fig. 1) [6].

Necessary conditions that should be taken into account when planning experiments are [19]:

- minimization of the number of experiments;
- simultaneous variation of all parameters;
- use of mathematical apparatus that formalizes the actions of the experimenter;
- choosing a clear strategy that allows one to make informed decisions after each series of experiments.

When using this unit, it is possible to simulate the process of flushing a well in laboratory conditions.

The unit makes it possible to evaluate the influence of the main factors of washing wells on the effectiveness of their cleaning from cuttings, in particular:

- drilling liquid consumption;
- eccentric placement of the drill string;
- plastic viscosity of the drilling fluid;
- rock fraction size;
- pulsation frequency;
- rotation of the drill string;
- longitudinal movement of the drill string.

From the point of view of conducting experimental studies on the well washing process, low-frequency pulsating flow is effective.

To assess the influence of these factors on the efficiency of well cleaning from cuttings due to a large number of influential factors, studies were carried out using Taguchi experimental designs [20]. This approach made it possible to minimize the number of experiments according to the objective criterion of robustness ("signal-to-noise ratio"). To do this, the factors were divided into groups so that one of them contained the factors responsible for the main response ("nominal"), and the other, those responsible for differences. To identify such groups, a generalized response like the coefficient of variation called "signal-to-noise ratio" is introduced, which makes it possible to obtain two independent optimization problems. This, in turn, allowed us to filter out those factors that contributed the largest noise component, and therefore worsened the adequacy of the obtained regression models and the quality of the processing of the experimental results. Of the seven factors (fluid flow rate; drill string eccentricity; plastic viscosity of the drilling fluid; rock fraction size; pulsation frequency; rotation and longitudinal movement of the drill string), two were rejected (rock fraction size; longitudinal movement of the drill string); as they introduced more "noise" to evaluate the effectiveness of cleaning the wellbore. When the number of factors is reduced to five in order to build a model and obtain regression dependencies, it is convenient and rational from the point of view of the number of experiments to use Latin plans.

When conducting experimental studies using experimental plans, a necessary condition is the study of flushing parameters in a wide range of their variables. In this class of tasks, taking into account the modern level of computer technology, the optimal properties of plans (orthogonality, rotatability, etc.) are not critically important. Consequently, the Latin experimental plans can be used to study the effect of the pulsating flow of the flushing fluid on its carrying capacity.

To build the Latin plan, 5 factors were changed at 5 levels, namely: the eccentricity of the drill string (0.3; 1.5; 2.7; 3.9; 4.1 mm); pulsation frequency during fluid movement (0; 5; 10; 15; 20 Hz); plastic viscosity of the drilling fluid (1.3; 4.0; 5.0; 6.0; 7.0 mPa · s); rotation of the drill string (0; 15; 30; 45; 60 rpm); flushing fluid consumption (0.075; 0.105; 0.135; 0.165; 0.195 l/s). The flow rate of the drilling fluid was chosen taking into account the required speed in the annulus, which, when drilling directional wells, is 0.75–1 m/s. Such an implementation of the Latin plan of the experiment will allow obtaining the dependence of the influence of individual factors with a minimum number of experiments without losing the quality of the result.

The statistical model for the Latin square is as follows

$$y_{ijk} = \mu + a_i + \tau_j + \beta_k + \varepsilon_{ijk},$$

where $i = \overline{1, p}$, $j = \overline{1, p}$, $k = \overline{1, p}$; y_{ijk} are observations in i row, k column and j processing; μ – mathematical expectation of the average total; a_i – effect of the i^{th} row; τ_j – effect of the j^{th} processin; β_k – effect of the k^{th} colum; ε_{ijk} – random error.

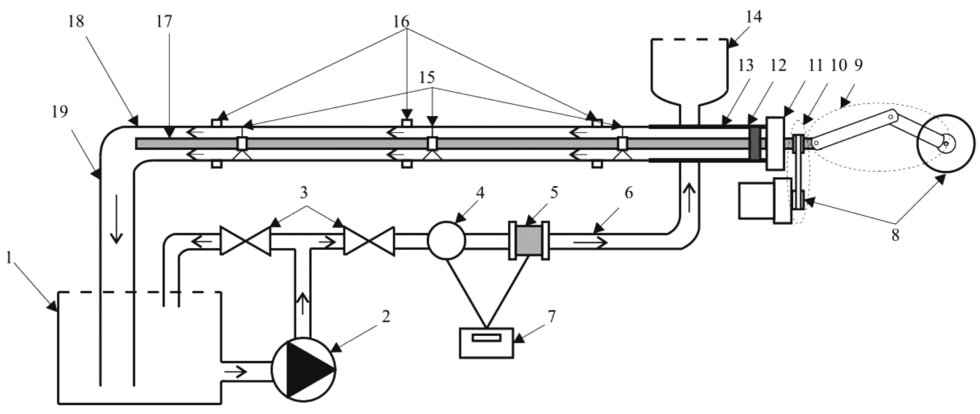

Fig. 1. Scheme of an experimental unit for modeling the well flushing process [6]:

1 – fluid reservoir; 2 – pump; 3 – valves for regulating the flow of drilling fluid; 4 – drillingfluid 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 centralizers; 16 – distance sensors;17 – drill string; 18 – glass pipe; 19 – flow line

According to the Latin plan of the experiment for 5 factors at 5 levels of their change, we get 25 experiments. This number of factors is sufficient to study their influence on the efficiency of rock removal from the wellbore. Such an implementation of the Latin plan of the experiment will allow obtaining the dependence of the influence of individual factors with a minimum number of experiments without losing the quality of the result. The plan of experiment is presented in Table 1.

Results. According to the constructed plan of the experiment, the thickness of the cuttings layer was determined using distance sensors. These values were transmitted to the control board, after which the total volume of the cuttings setting was calculated using computer software.

After the experimental studies, the value of the volume of rock deposited on the lower wall of the annular space was obtained (Table 2).

The research results were studied by the methods of correlation and regression analyses. Regression models are built in the class of third-order polynomials. The parameters of the polynomial model are determined in the class *E* of various combinations of basis functions with minimization of the residual variance. Class *E* is formed from the linear part of the polynomial with the inclusion of combinations of products, squares and cubes of the original factors and consists of 1300 models.

Table 1

Experimental plan for evaluating the influence of factors on the efficiency of rock removal using Latin squares

Experiment	Factors and the range of their change				
	eccentricity of the drill string, mm	pulsation frequency, Hz	plastic viscosity, mPa · s	drill string rotation, rpm	consumption of drilling fluid, l/s
1	5.1	10	7.0	45	0.135
2	3.9	10	1.3	0	0.075
3	1.5	5	6.0	0	0.135
4	2.7	0	6.0	15	0.075
5	2.7	5	5.0	45	0.105
6	2.7	15	1.3	60	0.135
7	1.5	10	5.0	15	0.165
8	5.1	5	1.3	15	0.195
9	2.7	20	7.0	0	0.165
10	1.5	0	7.0	60	0.195
11	0.3	10	6.0	60	0.105
12	5.1	15	6.0	30	0.165
13	1.5	15	4.0	45	0.075
14	3.9	15	7.0	15	0.105
15	5.1	0	4.0	0	0.105
16	0.3	15	5.0	0	0.195
17	3.9	0	5.0	30	0.135
18	2.7	10	4.0	30	0.195
19	1.5	20	1.3	30	0.105
20	3.9	5	4.0	60	0.165
21	3.9	20	6.0	45	0.195
22	0.3	20	4.0	15	0.135
23	0.3	0	1.3	45	0.165
24	5.1	20	5.0	60	0.075
25	0.3	5	7.0	30	0.075

Table 2

Results of the experiment to assess the influence of factors on the efficiency of rock removal

Experiment	Cuttings setting volume, cm^3	Experiment	Cuttings setting volume, cm^3
1	0.69	14	2.54
2	3.4	15	1.18
3	0.6	16	2.81
4	3.09	17	0.041
5	1.76	18	0.89
6	0.46	19	0.069
7	0.13	20	0.77
8	0.092	21	0.35
9	0.085	22	0.054
10	0.062	23	0.31
11	0.73	24	0.19
12	0.26	25	2.85
13	0.69		

After processing the data, we can note that the plastic viscosity, flow rate and pulsation frequency of the drilling fluid have the best interaction with each other and significantly affect the cleaning of the wellbore.

The selection of 3 factors with the best interaction will allow building adequate graphic dependences of their influence on the efficiency of cuttings removal.

Using the Mathcad software, the necessary calculations were made to build graphical dependencies (Figs. 2–5) of the influence of factors with the best interaction on the carrying capacity of the drilling fluid. Figs. 2 and 3 feature graphical dependences of the volume of cuttings settling on the flow rate of the drilling fluid.

Fig. 2 shows that with increasing fluid flow, the volume of settled cuttings decreases non-linearly and goes to zero at values greater than 0.195 l/s. The impact of plastic viscosity and pulsation frequency is significant at low flow rates, and as the flow rate increases, their influence is minimized. An increase in plastic viscosity can reduce the volume of cuttings settling by up to 30 %.

Fig. 3 shows that the creation of pulsations makes it possible to almost halve the volume of cuttings in the annular space at drilling fluid flow rates up to 0.165 l/s.

Fig. 4 shows that the use of a pulsating flow of drilling fluid reduces the volume of rock settlement in a linear relationship. As the flow rate increases, the influence of the pulsation frequency decreases. When creating minimal pulsations – up to 5 Hz, the decrease in rock volume is less compared to the frequency of pulsations of 5–20 Hz.

Fig. 5 shows the dependence of the influence of plastic viscosity and the frequency of pulsations at a consumption of drilling fluid of 0.075 l/s. The degree of influence of plastic viscosity is much smaller than the degree of influence of pulsations. The creation of pulsations with a frequency of 15–20 Hz allows one to reduce the volume of rock in the annular space by 43–57 % in comparison with the frequency of pulsations of 0–5 Hz. When the value of plastic viscosity is less than 5 Pa · s, there is no significant decrease in the cuttings settling volume. This indicates that the drilling fluid must have sufficient rheological properties to ensure effective cleaning of the annular space of wells.

Conclusions. According to the obtained results of experimental studies, 3 factors with the best interaction between themselves (plastic viscosity, flow rate of drilling fluid and frequency of pulsations) have been identified which improve the efficiency of well cleaning.

On the basis of graphic dependencies, the positive influence of the studied factors on the reduction of the volume of

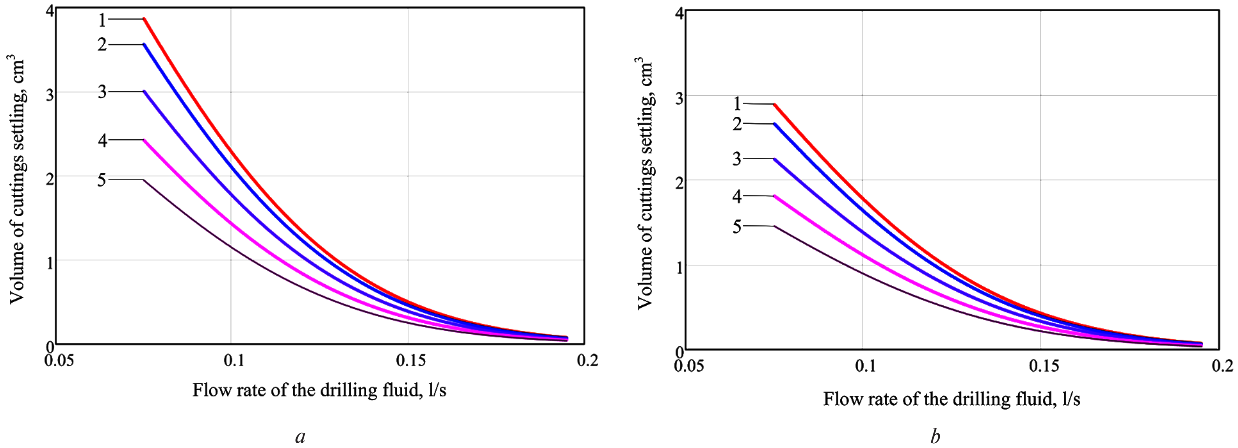

Fig. 2. Dependence of the volume of cuttings settling on the flow rate of the drilling fluid with a change in the frequency of pulsations:
a: η = *1.3 mPa · s*; *1 – T* = 0 *Hz*; *2 – T* = 5 *Hz*; *3 – T* = 10 *Hz*; *4 – T* = 15 *Hz*; *5 – T* = 20 *Hz*; *b*: η = 7.0 *mPa · s*; *1 – T* = 0 *Hz*; *2 – T* = 5 *Hz*; *3 – T* = 10 *Hz*; *4 – T* = 15 *Hz*; *5 – T* = 20 *Hz*

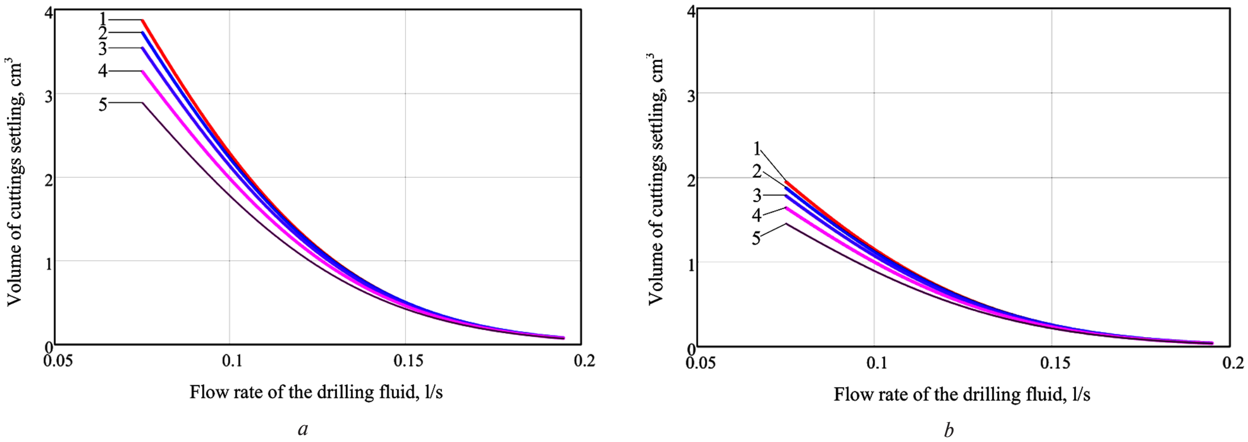

Fig. 3. Dependence of the volume of cuttings settling on the consumption of drilling fluid with a change in plastic viscosity:
a: *T* = 0 *Hz*; *1* – η = 1.3 *mPa · s*; *2* – η = 4.0 *mPa · s*; *3* – η = 5.0 *mPa · s*; *4* – η = 6.0 *mPa · s*; *5* – η = 7.0 *mPa · s*; *b*: *T* = 20 *Hz*; *1* – η = = 1.3 *mPa · s*; *2* – η = 4.0 *mPa · s*; *3* – η = 5.0 *mPa · s*; *4* – η = 6.0 *mPa · s*; *5* – η = 7.0 *mPa · s*

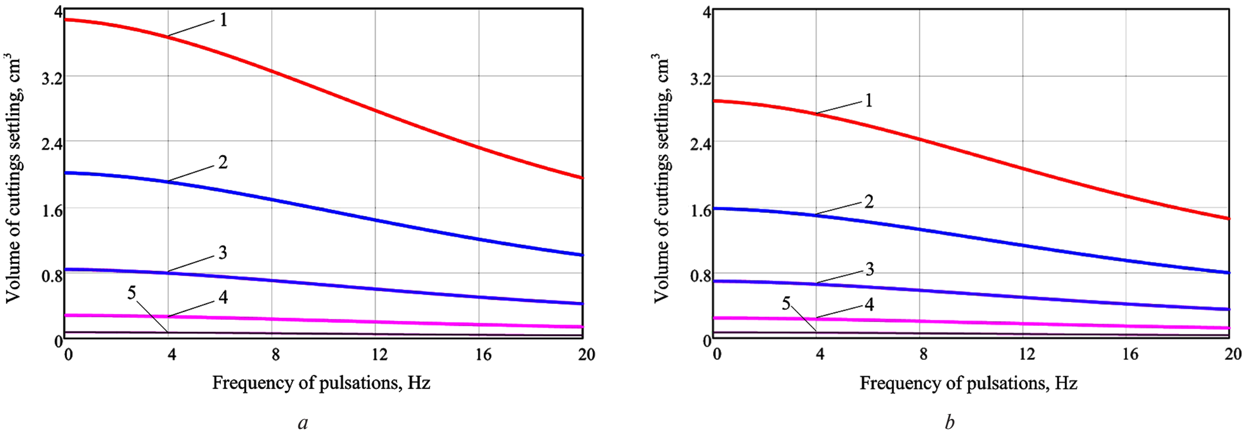

Fig. 4. Dependence of the volume of cuttings settling on the frequency of pulsations with a change in the flow rate of the drilling fluid:
a: η = 1.3 *mPa · s*; *Q* = 0.075 *l/s*; *Q* = *0.105 l/s*; *Q* = 0.135 *l/s*; *Q* = 0.165 *l/s*; *Q* = 0.195 *l/s*; *b*: η = 7.0 *mPa · s*; *Q* = 0.075 *l/s*; *Q* = 0.105 *l/s*; *Q* = = 0.135 *l/s*; *Q* = 0.165 *l/s*; *Q* = 0.195 *l/s*

cuttings in the annular space is substantiated. The degree of significance of the influence of these factors was compared.

The effectiveness of the use of a pulsating flow of drilling fluid to improve the efficiency of cleaning wells from drilled rock is substantiated. In some cases, the creation of pulsations made it possible to reduce the volume of rock sedimentation in the annular space by half.

In further studies, it is planned to carry out experimental studies regarding the influence of the pulsating flow of the drilling fluid for a specific well.

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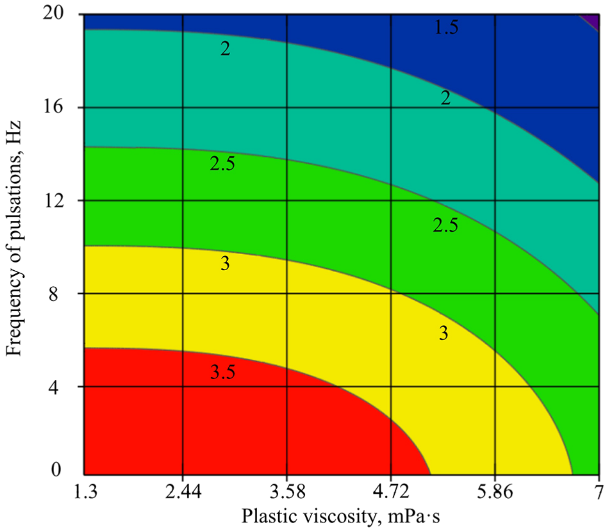

Fig. 5. Dependence of rock settlement volume on plastic viscosity and pulsation frequency

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Вплив пульсацій промивальної рідини на ефективність очищення свердловин

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Мета. Визначення впливу нестаціонарного режиму течії бурової промивальної рідини на ефективність очищення стовбура свердловини в кільцевому просторі від вибуреної гірської породи.

Методика. Дослідження виносної здатності промивальної рідини на лабораторній установці виконується шляхом моделювання процесу її пульсацій за різних частот. Вибір досліджуваних частот здійснено на основі раніше проведених досліджень. Оцінку впливу факторів на ефективність винесення гірської породи проводили з використанням латинських планів експериментів, що дозволило оцінити вплив виокремлених факторів з мінімальною кількістю дослідів без втрати якості отриманого результату.

Результати. Проаналізовано вплив факторів (витрати промивальної рідини; ексцентричного розміщення бурильної колони; пластичної в'язкості промивальної рідини; частоти пульсацій; обертання бурильної колони) на ефективність винесення шламу по кільцевому простору стовбура свердловини. Виділені три фактори із найкращою взаємодією між собою, що дозволило побудувати залежності їх впливу на ефективність винесення гірської породи зі свердловини на денну поверхню. Досліджено вплив зміни частоти пульсацій промивальної рідини та отримані графічні залежності їх впливу на зменшення об'єму частинок гірської породи в кільцевому просторі.

Наукова новизна. За результатами експериментальних досліджень доведена ефективність впливу пульсацій промивальної рідини на очищення свердловини від частинок гірської породи.

Практична значимість. Підтверджена ефективність застосування пульсацій промивальної рідини на гідротранспортування шламу по горизонтальній ділянці стовбура свердловини.

Ключові слова: *промивальна рідина, виносна здатність, пульсації, свердловина, шлам*

The manuscript was submitted 24.02.23.