Problematics of the issues concerning development of energy-saving and environmentally efficient technologies of well construction

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Abstract. Specialists of Dnipro University of Technology are among the leading researchers involved in studying the specifics of implementation and functioning of rational and energy-efficient schemes of organization of circulation processes while well drilling and operating. In particular, we have carried out thorough and comprehensive studies of physicochemical phenomena used while creating, preparing, and using the washing fluids. The purpose of the paper is to study and generalize the approaches to designing the parameters of hydraulic well washing programme under complicated geological and technical conditions, analysis of the factors of its correction basing on substantiation of analytical and research regularities of well circulation processes, and optimization of a component and quantitative composition of drill cleaning agents, which are aimed at the most efficient intensification of the bottomhole breaking processes. The development and implementation of a progressive complex hydraulic washing programme for wells under construction are analyzed involving modern methods of analytical analysis and experimental studies. The drilling circulation processes in a well were modelled in terms of experimental wells involving a drill rig UKB-4P and corresponding auxiliary tools and equipment.

1. Introduction

Such a hard-formulated and multifunctional problem as development and implementation of rational schemes of hydraulic cleaning programme of wells under construction is possible to be solved only basing on integration of the data concerning physicochemical properties of rock mass and the parameters of technological well sinking cycle – rotation frequency of a rock-breaking tool in terms of acting axial load (with the available or nonavailable dynamic component) and the amount of drill mud (special disperse system), circulating within the bottomhole interval, that does not contain any environmentally sensitive reagents [1]. The muds in general and drilling
washing fluids in particular are meant as such homogeneous systems that consist of two or more substances being in a molecular-disperse state and having no division surface between the components. According to the fundamentals of physical chemistry [2], solutions are characterized by concentration – amount of the substance, dissolved in the specified volume of mud, which is defined in weight contents, weight parts, and moles of the dissolved substance. The solution process is not a simple distribution of molecules or ions of one substance among the molecules or ions of the other; in most cases, it is connected with different interactions of physical and chemical nature.

Rock breaking of the bottomhole using special tools is one of the main operations in the production cycle of constructing different-purpose wells [3]. Surface-active substances (SAS), being the components of working media (drilling washing fluids), influence both deformation and breaking of solid bodies mostly at the boundaries of sharp (dead) ends of the developing fractures. Within that body areas, adsorption influence of a working medium results in the changes in surface energy per one unit of surface and stipulates certain changes in strength properties of a solid body (P.A. Rehbinder effect) [4]. The greatest adsorption effect is observed when new surfaces, formed in the process of breaking, had time to be covered with adsorption layers.

Along with the effect of rock strength reduction, the substances added to the composition of a working medium (washing fluids) can and must perform another equally important function – improvement of lubricating action. In the process of friction, two main lubricating functions can be singled out: ability to form strong films on the surfaces of friction materials and interaction of friction pairs with the surface layers with the resulting changes in their structure and properties. These lubricating functions influence considerably the friction coefficient, wear, and boundary value of pressure and sliding rate, in terms of which inadmissible processes of vibration growth and rock-breaking tool destruction take place. Normal development of a drilling process requires elimination of slurry particles from the bottomhole, their further removing from the bottomhole zone and transporting either to the surface or to the special slurry collectors mounted at the bottom part of a drilling assembly. Insufficient well cleaning results in slurry accumulation, complicated drilling processes, and possible well accidents. Due to that, only bottomhole cleaning from the drilled-out rock and its taking to the day surface account for 70 percent of all energy consumed for well construction. The efficiency of well cleaning depends on such factors as size and shape of slurry particles, velocity of an upward flow and its motion conditions, and technological parameters of drilling washing fluids [5].

Thus, the represented brief description of current situation in terms of well construction technology and equipment demonstrates that the search for possible ways for improving efficiency and reducing capital capacity of drilling operations, i.e. their essential cycle – hydraulic cleaning programme, is rather a topical problem, which solution will help the oil-and-gas industry follow the road of sustainable innovative development.

2. Analysis of recent studies and publications and singling out of previously unsolved parts of a general problem

A process of well sinking is accompanied by continuous slurry generation (the rock broken by a rock-breaking tool). Drilling efficiency, especially in terms of complicated mining and geological conditions, depends greatly on proper cleaning of both the well bottomhole and the drill mud itself from slurry. Numerous scientific and practical papers deal with this problem; the papers consider the factors of determining the required velocity of an upward stream that provides removal of the drilled-out particles [6]; the latter gains special importance while performing operations for well shaft preparation for lowering a casing pipe and its further cementing.

It should be noted that the problems of well cleaning from slurry depends considerably on a set of factors with the following most important ones: physical properties of washing
and special process fluids; modes of their flow along the shaft; geometry of some generalized circulation channel determined by the design ratio of the well shaft elements and the drill column itself.

Arranging the measures for intensification of the slurry transportation processes, based on different physicochemical effects, may be rather an efficient method to improve the conditions for implementing a hydraulic programme of well cleaning from the rock breaking products.

In case of impact and percussive-rotary drilling, rock is broken on the bottomhole as a result of mechanical action of cutters or teeth of a rock-breaking tool. In this context, a breaking process means separation of certain particles from the rock mass by cutting, grinding, squeezing, spalling or crushing. The separated rock particles remain on the bottomhole or on the cutter blade, preventing the breaking of the next layer and resulting in the accelerated wear of a rock-breaking tool. A stream of cleaning agent is aimed at timely removal and transportation of the broken particles from the well bottomhole. In case of incomplete or untimely removal of the separated rock particles, they are subjected to secondary crushing; as a result, they complicate further effective rock breaking with the following considerable reduction in mechanical drilling rate and accelerated wear of a rock-breaking tool [7].

Great attention is paid to the analysis and formalization of the cleaning processes of well bottomhole and shaft while drilling. However, the indicated problem is far from its complex and logical solution, which is confirmed by the available numerous research and analytical works dealing with this problem and by the existing significant contradictions in the conclusions by competent authors. That is why our consideration of possible ways for further improvement of bottomhole washing while well drilling is of great practical and theoretical interest [8].

First of all, it should be noted that solution of this problem involves complicated tasks of deeper understanding of the role of different factors in the efficiency of implementing technological means for the well bottomhole and shaft cleaning [9].

Up to now, the regularities of movement as well as conditions of washing and removing functions of, generally, a cleaning agent within the bottomhole zone while drilling with different types of rock-breaking tools, have not been studied yet. Consequently, it is natural that a problem of possible design of modern advanced washing units of a rock-breaking tool has not been also solved yet [10].

One should also consider the regularities of slurry formation and its granulometric composition while drilling out the rocks, being dissimilar in their physicomechanical properties, with the help of tools of different types in terms of varying drilling conditions, taking into account the fact that nowadays we have accumulated rather considerable but unsystematized amount of data on the development of rock-breaking processes.

The influence of properties of a drilling washing fluid on a granulometric composition of breaking products should be analyzed in more detail, paying attention to the features of well manifestation of washing and removing capacities of a fluid flow.

The causes of such negative phenomena as slurry adhesion with the resulting packing have not been studied completely so far.

Deeper analysis of the effect of different factors of well washing processes on the technical and economic indices of a rock-breaking tool is of significant practical and theoretical interest [11].

It is necessary to consider thoroughly the issues concerning regulation of rheological properties of a drilling cleaning agent to increase its removing capacity; in its turn, that will allow decreasing the required rational supply of drilling washing pumps.

The improvement of a washing process is also connected with the possibility of solving a problem of washing fluid pressure decrease on the well bottomhole with the simultaneous support of technologically required pressure in the annular space of the well shaft [12].

According to some researchers, during the operation of a modern rock-breaking tool, the well bottomhole always has the excess volume of slurry, which removal will help increase the
mechanical drilling velocity by at least 30-50 percent even in terms of preserved constant axial load and rotational frequency.

Critical analysis of the available data makes it possible to outline general tendencies in the main scientific and practical papers in terms of modernization of the conditions for implementing effective hydraulic programmes of well cleaning from the rock breaking products: development of the grounds for design and functioning of the necessary circulation equipment; complex physico-mathematical modelling and numerical studies of the processes of transportation of rheologically complicated substances (washing and process fluids); determining the features of changes in fluid flow modes relative to integral characteristic of the surface shape of well shaft walls; development of methodological and practical recommendations concerning the application of technical and technological solutions and innovative operations to provide reliable use of special equipment and methods of performing the corresponding operations while well drilling under the specified conditions.

Basing on the aforementioned, the following conclusions can be made. Study of the specifics of slurry particle motion within the annular space of a well under construction and development of a methodology for calculating optimal consumption of a washing fluid taking into account all key factors affecting the washing mode while well drilling, are rather topical and have significant scientific and practical value.

3. Statement of the main research material
Methodological hydraulic calculations of a circulation process are performed for determining the required characteristics of a drill pump (compressor) as well as substantiated selection of its type, being in the best compliance with the calculated values, and the necessary number of pumps [13].

The hydraulic calculations involve also the following important technological parameters: intensity of the cleaning agent supply; mode of the agent flow depending on the movement velocity; hydraulic (aerodynamic) fluid motion resistances in terms of specific areas, total hydraulic (aerodynamic) resistances.

A technological process of washing should be designed and implemented for reaching the best technical and economic drilling indices and the overall well construction performances. In this context, main attention should be paid to being stick to key technological functions and limitations.

At any drilling type, dimension of slurry particles is characterized by a wide range: from several microns up to centimetres. To evaluate the possibility of slurry transportation by the cleaning agent flow, average size of particles, which make up the main share of generated slurry along with the smaller fractions, is usually taken. However, certain particles on the bottomhole may be more than the average size by 3-5 times. The latter circumstance transforms into such a necessary additional factor of a hydraulic programme process: while rising above the bottomhole, large particles of the broken rock are subjected to the action of a rotating drilling assembly; they are crushed and then transported by the cleaning agent flow to the surface [14].

The average slurry size depends, first of all, on the design of a rock-breaking tool. The particle size is greater while drilling in fissured and grained rocks, in case of impacting action of a tool, while drilling with considerable axial load and minor rotational frequency. Table 1 represents analytical and practical data concerning granulometric composition of the breaking products obtained as a result of studies carried out at the Department of Oil-and-Gas Engineering and Drilling of Dnipro University of Technology (DUT) and production enterprises of the corresponding area.

A slurry shape influences significantly a value of the raising force generated by the flow. Depending on the structure of rocks being drilled out and a breaking method, there can be great variety of particle shapes. The most often particle shapes are grained ones including
round and irregular samples.

In terms of flow velocity equal to critical \( V_{cr} \), the average-sized slurry particles are only retained in a suspended state without their removing to the surface. Slurry transportation requires that the flow velocity \( V_n \) will be more than the critical one; moreover, the particles will move with velocity, being equal to the difference of the indicated flow velocities:

\[
C = V_n - V_{cr}.
\]  

(1)

**Table 1.** Typical sizes of slurry particles while drilling with different rock-breaking tools (according to the DUT data).

| Type of a rock-breaking tool                  | Averaged sizes of slurry particles, Range of distribution of typical sizes (average) (typical) (maximum) |
|----------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Roller bits of an oil range                 | 5.0 0.4-12.0 20 and more                                                                               |
| Roller bits of a geological-prospecting range | 3.0 0.2-4.0 10.0 and more                                                                               |
| Diamond crowns                               | 0.2 0.01-0.25 up to 3.0                                                                               |
| Hard-alloy crowns                            | 0.4 0.1-0.5 up to 5.0                                                                                  |

A value of particle velocity transportation is selected according to the drilling conditions. It should be sufficient for preventing slurry accumulation in a well. It should be the greater, the higher the drilling velocity and well depth are.

It is commonly supposed that quantitative criteria of well cleaning is a volumetric concentration of slurry particles in flow \( X = V_{BSH} / V_{KP} \) (\( V_{BSH} \) – volume of slurry within the annular space of a well, \( V_{KP} \) - volume of annular space of a well) that should not exceed 0.05 of a relative unit, i.e. increasing density of the upward flow due to the added slurry is considered to be admissible up to the values of 20-30 kg/m\(^3\).

Drilling practice uses another criterion as well. In this context, it is possible to determine the required velocity of slurry transportation for specific conditions according to the following formula

\[
C = \frac{F_v V_m (\rho - \rho_p)}{F_{kn} (\rho_{pv} - \rho_p)},
\]  

(2)

where \( F_v \) is bottomhole area of the well under construction; \( V_m \) is mechanical velocity of drilling; \( F_{kn} \) is area of the annular space of a well; \( \rho \) is density of the broken rock particles; \( \rho_p \) is density of the drilling washing fluid; \( \rho_{pv} \) is density of the upward flow of the fluid with added slurry.

In terms of the most typical conditions of well drilling, a value of minimum velocity of slurry particle transportation is usually within the range of 0.02-0.2 m/s. Under such conditions, the transportation velocity will be as follows:

\[
C = \frac{F_v V_m}{F_{kp} X}.
\]  

(3)

Practical necessary rate of particle transportation while using gaseous agents is 0.1-0.4 m/s.

Nowadays, the practice of constructing different-purpose wells applies the following criteria for determining minimum consumption of washing fluid: magnitude of the upward flow velocity;
specific consumption per 1 cm of the rock-breaking tool diameter, concrete values of consumption
for each type and size of a rock-breaking tool as well as properties of the rocks being drilled.

To organize effective and unambiguous study of the well washing conditions, specialists
of the Oil-and-Gas Engineering and Drilling Department of DUT have developed a special
research stand of aerohydrodynamic flows with principally new design, functioning mechanism,
and control and measuring support that makes it possible to do the following: to analyze in
the simplified form the local quantitative parameters of multiphase slurry-enriched flow under
conditions being maximally close to the real ones with the addition of impurities simulating
the rock mass breaking products; to enhance the capacities of experimental methods of slurry
accumulation diagnostics; to model physicochemical interactions of the flow with the well shaft
walls and generally within the cleaning agent volume. All that helps create the conditions for
reliable development as well as testing and correction of technological characteristics of special
drilling washing fluids that will be the guarantee for eliminating complications and accidents
due to improper cleaning.

The stand for studying aerohydrodynamic flows consists of a closed case, with the connected
main pipelines with a manometer and a loss meter, and the research devices mounted in it. The
stand case is cylindrical; it is made from transparent plastic. The input unit “manometer – loss
meter – anemometer”, to control the enriched flows within the well shaft, is mounted within
the lower cylindrical part the case. A parametric unit, for which positioning can be performed,
is mounted within the middle part of the case. On one side, this parametric unit consists of
videorecorder; on the other side, it has thermoanemometer and turbine loss meter. Besides, the
upper cylindrical part of the case is equipped with the material dosing unit.

In terms of the proposed scheme, one can measure 2D or 3D fields of velocities of a working
flow in the effective volume.

Performance of the aerohydrodynamic stand for engineering studies of the well cleaning
process was tested by numerous experiments.

The stand can be used for modelling the conditions of bottomhole and well shaft cleaning,
under conditions being maximally close to the real ones, which helps obtain quite reliable local
quantitative hydroaerodynamic characteristics of multiphase flows of circulating agents formed
by the operation of drilling tool effectors. It also allows studying slurry accumulation processes
with wide variations of technological parameters of a cleaning cycle in case of problematic areas.

The recommended upward flow velocities are taken more than enough for the well cleaning
conditions. The estimated calculations and immediate laboratory and stand-based studies show
that in case of diamond drilling the upward flow velocity being 0.12-0.15 m/s can be enough;
in case of hard-alloy drilling, that is 0.15-0.2 m/s; and while drilling with roller bits of oil and
geological-prospecting range, the value is 0.3-0.4 m/s.

Analysis of the recommendations taking into account the typical sizes of annular space for
wells demonstrates that the minimum consumption of washing fluid should be selected at well
diameter being up to 100 mm – in terms of specific consumption per 1 cm of the rock-breaking
tool diameter; and if well diameter is more than 100 mm – in terms of the required upward flow
velocity (Table 2).

Table 2 represents minimum and maximum values of specific consumptions. Rational
consumption of a washing fluid is selected taking into consideration the properties of drilled
rocks within the indicated range. The consumptions gain their maximum values while drilling
in stable abrasive rocks giving great amount of slurry as well as at additional slurry falling from
the well walls.

Field studies of a well cleaning process were carried out in terms of special drill rig (figure 1)
located within the training drill field of the Oil-and Gas Engineering and Drilling Department
of DUT. The stand includes: drill plunger pump $NB3 − 120/40$ (1), loss meter $EMR − 2$ (2),
well model (3), drill collar (4), drill pipes (5), suction and injection pipelines (6) and (7), drill
Table 2. Estimated values of the indices of a hydraulic well washing programme (according to the DUT data).

| Type of a rock-breaking tool         | Specific consumption of a washing fluid, (l/min)cm | Upward flow velocity, m/s |
|-------------------------------------|---------------------------------------------------|---------------------------|
| Roller bits (under normal drilling conditions) | 7-15                                              | 0.3                       |
| Diamond crowns and bits             | 3-8                                               | 0.12                      |
| Hard-alloy crowns                   | 5-10                                              | 0.15                      |

Figure 1. Scheme of the well under consideration.

The first stage involves the following: the calculated amount of tracer material (slurry) is put into the well model; in its shape, the tracer material is similar to the natural slurry with different fractions being peculiar for each drilling type. Washing fluid is supplied by a pump into the well model. While studying, the velocity of tracer particles and the time required for complete cleaning of the well bottomhole are determined. Photographing is used to identify distribution of the well shaft particles. The influence of the value of washing fluid consumption and its properties on proper cleaning of the well bottomhole is estimated according to the time of tracer’s carrying out to the surface. The second stage involves determination of factual required
time for the complete tracer's carrying out to the surface at the specified frequency of tool drill string rotation as well as technological properties of a washing fluid and its consumption.

In case of rotary drilling, the following rates of upward flows in the annular space are recommended: 0.6-0.8 m/s while drilling with a normal-density mud; 0.4-0.6 m/s while drilling with a weighted mud; up to 1.2 m/s while drilling in clay rocks; and 0.3-1.0 m/s while drilling upper intervals of wells. When drilling wells with the use of bottomhole motors, the cleaning agent consumption is determined by characteristics of the applied device. Generally, if drilling involves turbodrill, the amount of washing fluid supplied on the bottomhole is not enough for its effective cleaning from the broken rock. That is connected with the fact that up to 10 percent of the drill mud and up to 20 percent of technical water leak, not reaching the bottomhole, due to nontight connecting parts of turbodrills. In case of electric drilling, the consumption may be 0.035-0.05 l/(s·cm²); and while drilling with hydraulic screw bottomhole motors, it is not more than 0.07 l/(s·cm²).

If there is air drilling, selection of rational air consumption is calculated taking into account the same factors as the ones while well washing. Contrary to the washing, the upper limit of rational air consumption is seen less clearly and usually determined by the compressor productivity. Minimum required consumption of compressed air is taken from the conditions of slurry transportation along the well shaft. In practice, increase in mechanical drilling velocity is determined along with the growing air consumption and when the required velocity of an upward flow is reached owing to the improved well cleaning. Having reached certain air consumption value, further growth of drilling velocity terminates. Optimal value of air consumption is determined by the condition of well cleaning; it depends on the rock-breaking tool type, composition of drilled rocks, and available water inflows. It is determined by the research methods. In terms of minor values of annular section area, selection of air consumption only according to the upward flow velocity results in the obtaining of erroneously low results. Table 3 shows guide values of specific air consumption per 1 cm of the rock-breaking tool diameter.

| Typical drilling type       | Specific air consumption, \(m^3/min\) per 1 cm of the rock-breaking tool diameter | Possible upward flow velocities in different annular sections, m/s |
|-----------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------|
| Bit drilling                | 0.7-1.0                                                                          | 14-100                                                          |
| Diamond drilling            | 0.4-0.5                                                                          | 10-50                                                           |
| Hard-alloy drilling         | 0.5-0.7                                                                          | 10-75                                                           |

Contrary to washing, rational consumption of compressed air depends on the well depth. If the depth is considerable, then the compressed air consumption should go up to compensate the reducing velocity of flow in the bottomhole zone due to the growing pressure in this zone. It is recommended to increase consumption for the first 600 m of depth with further increasing by 10 percent within the following 600 m. Certain increase in the compressed air consumption is recommended in case of water inflows in a well.

In most considered cases, the compressed air consumption coincides with the compressor productivity, which is within the range of 6-9 \(m^3/min\). This productivity is enough for blowing wells with the diameters up to 100 mm. In terms of large well diameters, it is suggested either to use two compressors in parallel or to use special highly productive compressors.
Great number of papers is devoted to the study of such practically important problem as motion of broken rock particles within the rotating upward flow. The majority of those papers are experimental. Almost all those studies are similar in the fact that while analyzing the particle motion in a flow, a problem of particle distribution within the annular space is not examined though this problem is of great practical significance – the knowledge of regularities of slurry particle motion in a flow makes it possible to identify and prevent possible shaft contamination with the resulting seizure of drill pipes and formation of packing on them.

The following types of flow modes can be identified in the flow rotating together with the drill string: 1) laminar; 2) laminar with vortexes; 3) purely turbulent; 4) turbulent with vortexes. All these flow modes can be represented while well washing [15].

According to the previously indicated conditions, the particle moving in the dense fluid flow is affected by transversal forces stipulated by the difference between velocities on the particle boundaries during flow rotation \( F'_n \), on the one hand, and the difference between the velocities of axial flow \( F_n \), on the other hand. In first approximation one may consider that the mentioned two forces are added geometrically, and the motion is determined by the resulting force. Besides, the particles rotating together with the fluid appeared to be under the effect of centrifugal force [16]. In terms of steady motion, angular velocity of particle rotation \( u_r \) is approximately equal to the angular velocity of fluid rotation with angular velocity \( \omega \).

In this context, if in case when annular space is formed by drill pipes with radius \( R_1 \) and well walls with radius \( R_2 \) and average distance between the well axis and conditional centre of the transported slurry particle is equal to some variable value \( R \), the law of linear velocity distribution in the annular space in terms of normal section is described by expression

\[
\frac{\omega}{1} \times \left( \frac{R_2^2}{R_1^2} - \frac{r^2}{R} \right). \tag{4}
\]

Force \( F'_n \) aims for particle replacing into the area with large \( u_r \), i.e. taking the particle closer to a rotating drill pipe. This force demonstrates the largest value near the wall of a rotating pipe; the smallest value is seen near the well wall.

The process of drill string rotation in a visco-plastic fluid also involves migration of particles to the well walls; moreover, the more intensive the migration is, the more deviations of the properties of visco-plastic fluid are, compared to the properties of the viscous one [17]. The lower velocity of the particle falling is and the larger well diameter is, the slower transverse motion of the particle is. In all cases, the velocity of particle migration to the well walls increases along with the growing rotation velocity.

When a washing fluid moves within the well shaft, a slurry particle located on its surface experiences the washing action of the fluid flow moving in parallel to the bottomhole. In this context, the following variants of particle separation from the bottomhole are possible (figure 2).

Motion of the washing fluid immediately on the well bottomhole is characterized by one or another degree of flow turbulence, which value is determined by the value of Reynolds criterion

\[
Re = \frac{U d_e \rho_p}{\mu}, \tag{5}
\]

where \( U \) is flow velocity on the bottomhole, m/s; \( d_e \) is equivalent flow diameter, m; \( \rho_p \) is density of a washing fluid, kg/m\(^3\); \( \mu \) is dynamic viscosity of a fluid, Pa·s.

While drilling, a boundary layer is formed on the bottomhole, in which either laminar (characterized by parabolic distribution of velocities) or turbulent (characterized by flattened distribution of velocities) mode can be at low velocities of washing fluid motion; though, irrespective of the motion mode within the boundary layer, a laminar sublayer is formed, influencing considerably the motion conditions of the broken rock particles [18]. Thickness
of the laminar sublayer depends on the washing fluid density and velocity of the fluid motion. Thickness of a laminar sublayer as well as motion velocity in it is proposed to be determined by the following formulas

\[ h_L = a \frac{v}{U_{ser}} \]  

(6)

and

\[ U_u = b y \frac{U_{ser}^2}{v} \]  

(7)

where \( h_L \) is thickness of a laminar sublayer, \( m \); \( v \) is kinematic viscosity of the fluid, \( m^2/s \); \( U_{ser} \) is average velocity of the fluid within the bottomhole zone, \( m/s \); \( U_u \) is velocity of the fluid motion within the laminar sublayer at distance \( y \) from the bottomhole, \( m/s \); \( a \) and \( b \) are coefficients that depend on the coefficient of hydraulic resistance, the washing fluid density, and other factors.

Therefore, the following conclusion can be drawn. Some rock particles formed under the influence of a rock-breaking tool are affected by the boundary layer action while others enter the zones of laminar sublayer action (figure 3). As a result, a part of slurry is not removed by the washing fluid flow; that results in further crushing of this slurry and increased wear of a rock-breaking tool.

![Figure 2. Review of possible separation patterns of the broken rock particles from the bottomhole.](image)

![Figure 3. Guided profile of velocities within the bottomhole zone of the well under construction.](image)

It is not hard to see that according to (6) and (7) the two-time growing velocity of fluid motion within the bottomhole zone results in two-time decrease in the laminar layer thickness and four-time increase in the fluid motion velocity within itself.
A turbulent state of a washing fluid within the bottomhole zone is the main factor of the well cleaning efficiency. Intensity of the flow turbulence on the bottomhole is determined mostly by the viscous properties of a washing fluid. Along with the growing density of a washing fluid, a level of turbulence decreases; thus, the conditions of well cleaning deteriorates.

In terms of roller bit drilling, a washing fluid pumped through the bottomhole zone has relative function: it catches the slurry suspended within this zone and removes it into the annular space. It can be assumed that this fluid moves around a bit in the form of vortex flow. The removing capacity of the vortex flow is higher, the greater the value of its velocity vortex is. At this vortex intensity, the value of its velocity is in reverse proportion to the area of cross section of a vortex flow $f_v$. As for the bottomhole zone, the cross-section area of the vortex flow is the cross-section area of the annular space between the bit and well wall. This area is not similar throughout the bit height.

The measuring results help state that the roller bits have maximum $f_v$ at the level being from the bottomhole at the distance that is approximately equal to the projection of the bit roller diameter on the vertical axis; it is somehow more than $f_v$ near the bit base, i.e. near the bottomhole (figure 4).

![Figure 4. Averaged values of the cross-section area of the annular space between the bit and well wall throughout the bit height.](image)

Minimum values of the cross section area of a vortex flow are observed on the shirttails, and it is lower than the maximum values by almost 2 times. Thus, at the level corresponding to the upper position of the peripheral roller cutter teeth, the velocity vortex has its minimum value. Therefore, there are conditions for slurry accumulation here.

Well drilling in sedimentary rocks is accompanied by the formation of different complications. The most often problem is seizures – unexpected accidents in a well characterized by partial or complete stopping of a drilling tool, metal tubing or geophysical (hydrogeological) devices and facilities. Seizures are the most complicated and labour-consuming accidents in drilling. There are three main types of seizures: 1) of drill strings; 2) of tubing; 3) of rock-breaking tools and rotatable drill pipes.

Table 4 shows concrete recommendations as for selection of effective washing systems for constructing wells in soft sedimentary rocks.

While studying the effect of washing fluids on the argillaceous rock swelling by the specialists of the Oil-and-Gas Engineering and Drilling Department of DUT, a swelling degree $K$ was used...
Table 4. Guide values of the indices of aerodynamic programme of well cleaning (according to the DUT data).

| Complication | Typical rock | Recommended cleaning agents |
|--------------|--------------|-----------------------------|
| Falls, washouts | Sand | Clay and chalk fluids with increased amount of solid phase, weighted fluids |
| Falls, swellings, plastic flow, washouts | Clay loam, clay, sand-clay soil | Inhibited clay fluids, chalk sapropel fluids |
| Falls, rock sloughing, minor swelling, plastic flow, washouts | Clay slate | Inhibited clay and chalk fluids with lowered filter loss. In some cases, clay fluids |
| Falls, rock sloughing, minor washouts, rock inrushes | Sandy shale | Clay and chalk fluids. Fluids based on drilled-out rocks, silicate-humic, polymer, combined |

to characterize this process (this value includes such notions as volume of swelling fluid $V_p$ and volume of dry clay particles $V_o$) being equal to the ratio of totals of volumes $V_p + V_o$; it shows by how many times the volume of dry particles increases.

$$K = \frac{\rho a}{m} + tg(\beta - 1),$$

where $\rho$ is density of dry clay; $m$ is mass of the specified sample; $\beta$ is coefficient indicating the share of the porous space volume that fits in the swollen sample; $a$ is coefficient depending on the clay properties and value $\beta$.

Since clay swelling was studied in washing fluids containing different substances, distilled water was taken as the reference fluid. The swelling process was analyzed in terms of the most active sedimentary rock – montmorillonite with the interpretation of the obtained results for other argillaceous rocks.

In terms of clay rocks available in the well section, their capacity for swelling determines complexity of the well shaft construction [19]. Clays containing montmorillonite are called bentonite clays. While swelling, they can increase in volume by 14 times. The current drilling practice proves that use of clay fluids allows in most cases preventing possible complications in the well shaft due to manifestation of different physicochemical properties of sedimentary rocks and, in our case, clays. Along with that, efficiency of clay fluid application can be maximum only in terms of drill mud conditioning that means physical and chemical processing of a disperse medium.

Even without any chemical processing, bentonite clays help prepare muds being better as for stability and other parameters. Kaolin clays dissolve badly in water. Stability of kaolin solutions is rather insignificant. Illite minerals give a solution being intermediate in its quality.

While preparing clay muds, one should control their main technological parameters (Table 5). Preparation of clay mud involves additional clay dispersion [20]. A degree of clay particle dispersion depends of the grinding intensity, physicochemical and mineralogical clay composition. Montmorillonites have the highest dispersion while kaolin clays have the lowest one. In case of bentonite, a fraction of more than 1 mcm in per cent in weight is about 15 percent; for kaolinite, it is 60 percent; less than 50 mcm for bentonites - about 40 percent, and kaolinite does not produce such a fraction.
Table 5. Types and parameters of some types of clay-based washing fluids (according to the DUT data).

| Type of washing fluid, mud | Main technological parameters |
|----------------------------|-------------------------------|
|                            | Density $\rho$, kg/m$^3$ | Funnel viscosity $T$, s | Filtration loss $B$, $cm^3/30$ min | Shearing stress (dynamic), Pa | Shearing stress (static), Pa |
| Normal clayey              | 1070-1130                  | 20-24                    | 20-30                                  | 17-20                              | 7.4-13                         |
| Normal clayey with increased amount of clay | 1150-1200                  | 25-30                    | 25-35                                  | 18-20                              | 8-14                           |
| Improved clayey            | 1060-1100                  | 19-23                    | 12-15                                  | 19-21                              | 8.2-15                         |
| Slightly polymer-bentonite clayey | 1040-1060                | 16-33                    | 3-12                                   | 2-4                                | 1-3                            |
| Weighted with barium sulfate clayey | 1600-1900                | 25-60                    | 5-6                                    | 17-25                              | 17-24                          |
| Fluid on the basis of drilled-out clay rocks, unprocessed | 1020-1050                | 16-20                    | 25-30                                  | 8-12                               | 2.5-6                          |

4. Conclusions
Basing on thorough study of literature sources and in-depth analysis of the industrial and laboratory data, the most significant factors for increasing the drilling operation quality have been identified; that also has helped determine the main directions of complex improvement of well technologies, i.e. in designing rational hydraulic programme of well washing. The features of circulation processes while well drilling as well as their physicochemical aspects have been considered comprehensively and successively. The following problems have been studied: influence of the parameters of a cleaning agent on the bottomhole processes of rock breaking; interconnection between the physicochemical characteristics of breaking products and circulation processes on the bottomhole and in the well shaft; features of the schemes of cleaning agent circulation connected with the variety of geological and technical factors.

It is necessary to continue experimental and theoretical studies of the features of implementing the principles of improved hydraulic programme of well washing that rely on the basic technologies of effect on the bottomhole and walls of the well under construction, while applying rational compositions of washing fluids. Further studies should involve identification and substantiation of the optimal technical and technological solutions with maximum consideration of specific mining and geological conditions of the deposits being developed.

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