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Development of bit design for breaking rocks with different mechanical properties

Opracowanie konstrukcji świdra wiertniczego do zwiercania skał o różnych właściwościach mechanicznych

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ABSTRACT: This paper presents a description of a bit design with a combined cutter layout, aimed at increasing the efficiency of breaking rocks with different mechanical properties. The results from industrial testing of the manufactured bits are analyzed, revealing the need to improve their hydraulic flushing system. Computer modeling was conducted using the Flow Simulation CAD/CAM package of the Solid Works system, where various models of the design options for the bit, the borehole bottom, and a segment of the drill string were created. For each variant, numerical calculations of the fluid motion were carried out using the finite element method. Based on the simulation results, optimal angles of inclination for the jet nozzles relative to the bit axis and their distance from this axis were determined. Key factors influencing the stability of the bit cutters, which destroy the rock by cutting with axial vibrations, were identified, and analytical dependencies for their predictive stability were derived. The wear rate of the bit cutters was determined by instantaneous values of such physical parameters as: the degree of wear, rock cutting speed, temperature, axial loading force on the cutter, and the friction coefficient at the contact between the cutter and rock. Temperature is especially impactful, reaching levels exceeding 1000°C in the cutting zone; it is often regarded as the primary factor influencing bit cutter stability. To maximize the efficiency of rock-breaking in the process of drilling wells, it is necessary to set the following vibration parameters: frequency, amplitude, and vibration mode, which can be determined from the results of mathematical modeling.

Key words: bit, outflow rate, cutters, rock-breaking zone, rock, cutting speed, axial vibration, durability, drilling.

STRESZCZENIE: W artykule przedstawiono opis konstrukcji świdra wiertniczego z kombinowanym układem ostrzy, mającym na celu zwiększenie efektywności rozkruszania skał o różnych właściwościach mechanicznych. Przeanalizowano wyniki testów przemysłowych wyprodukowanych świdrów, które wykazały potrzebę ulepszenia ich systemu płukania hydraulicznego. Modelowanie komputerowe przeprowadzono przy użyciu pakietu Flow Simulation CAD/CAM systemu Solid Works, w którym utworzono różne modele wariantów projektowych świdra, dna otworu wiertniczego oraz segmentu przewodu wiertniczego. Zidentyfikowano kluczowe czynniki wpływające na trwałość ostrzy, które kruszą skałę poprzez skrawanie drganiami osiowymi oraz wyprowadzono zależności analityczne dla ich przewidywanej stabilności. Stopień zużycia ostrzy określono na podstawie chwilowych wartości takich parametrów fizycznych jak: stopień zużycia, prędkość skrawania skały, temperatura, siła obciążenia osiowego ostrza oraz współczynnik tarcia na styku ostrza ze skałą. Temperatura jest czynnikiem mającym szczególny wpływ, ponieważ osiąga poziomy przekraczające 1000°C w strefie skrawania; jest ona często uważana za główny czynnik decydujący o trwałości ostrza. W celu zmaksymalizowania wydajności rozkruszania skał w procesie wiercenia otworów, konieczne jest określenie następujących parametrów drgań: częstotliwości, amplitudy i trybu drgań, które można określić na podstawie wyników modelowania matematycznego.

Słowa kluczowe: świder wiertniczy, natężenie wypływu, ostrza, strefa rozkruszania skał, skała, prędkość skrawania, drgania osiowe, trwałość, wiercenie.

Introduction

The technical and economic indicators of deep well drilling primarily depend on the efficiency of rock-breaking achieved by the cutting structure of the bit. Over the past decades, bits that break rock by cutting have become widely used due to their numerous advantages compared to other types of bits. Notably, they allow for a combination of various types of mechanical impact on rock, such as cutting and axial vibration, which significantly enhances bit efficiency.

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PDC bits are highly effective in breaking rock through cutting with their cutters (Jones et al., 2008; Xiaofeng et al., 2022). Many scholars have focused on the rock-breaking efficiency of PDC bits. For instance, the rock cutting process of worn PDC cutters at different worn flat inclinations has been studied (Liang et al., 2009), and optimal back rake angles have been identified by considering factors such as cutting section, wear state, and cutting state (Zhu and Li, 2015). In high stress petroleum drilling conditions, understanding the ductile–brittle failure transition of rocks is crucial for improving drilling efficiency. As the depth of cut exceeds the critical depth for ductile–brittle failure transition, rock failure shifts from ductile to brittle (Wang et al., 2023). Researchers have analyzed how factors such as cutting area, contact arc length, back rake angle, rock strength against drilling and cutter wear height impact the forces on PDC cutter (Liang et al., 2009).

A review of theoretical and practical studies on PDC bits from domestic manufacturers and leading international companies allows indicates that bit performance is primarily influenced by the stability of the cutting elements. Insufficient stability of the these elements can slow well construction, alter borehole wall geometry, and lead to various complications during their casing and operation (Vytyaz et al., 2015; Shatskyi et al., 2019, 2021). This issue is particularly pronounced in well sections composed of mixed rocks with different mechanical properties, where a single type of cutting tool and drilling mode cannot be effectively applied (Karkashadze, 2004; Biletskyi et al., 2012). This problem can be solved by developing a bit design that will enhance the efficiency of drilling wells in such sections and increase the accuracy of wall calibration while ensuring effective cuttings removal.

Description of the BuH1-218-MSHV bit design and analysis of its operation

The authors have developed a blade drilling bit design (Kryzhanivskyi et al., 2013; Biletskyi et al., 2014), with the schematic design shown in Figure 1.

The bit consists of a body 1 equipped with a central port 2 and end ports 3 for supplying drilling fluid, a connecting thread 4, and working components, including cutters 5 and calibration cutters 6, mounted on cuttes 7. The cuttes 7 are made as a single unit with the body of the bit 1. The teeth 8 of the working elements 5 and 6 have a fastening section 9 and a working surface with a cutting edge 10 protruding beyond the body of the bit at a distance of at least 0.25 times the body diameter along both side and end surfaces, ensuring contact of the cutting edges with rock at a specific angle α. This angle corresponds to the inclination of the cutting elements axis 5 relative to the horizontal plane. The bit body 1 is designed as a geometric shape with protruding cuttes 16. Its end part 11 transitions smoothly along a given radius 12 into a cylindrical part 13 and then into the connecting threaded part 4. The cutting teeth 5 are positioned along the cuttes 16 and the end part 11 of the body 1 along the length in a ratio of 2/3 of the diameter for the outer cutting teeth 5 and 1/3 of the diameter for the inner cutters 14 located on the cuttes 16 and the inner conical section. The calibration cutters 6 are spirally arranged on the cuttes 16, while the cutters 5 and 14 are positioned at various angles relative to a plane passing through the body axis, parallel to the working plane of the cutting part, with angles increasing from the center to the periphery. The body 1 is also equipped with end channels 3 set at various angles to the body axis, with corresponding nozzles to provide a hydromonitor effect. A central circulation port is included for cleaning the bottom of the well.

Two prototype bits, coded BuH1-218-MS-HV (Figure 2), were developed based on this design and tested at the fields of LLC *The Novy Urengoy Drilling Company*. One bit was tested on the Yaro-Yakhinskoe field in the interval of 628–750 m, the second on the Novo-Chiselskoye field in the interval of 1447–1480 m. Table 1 presents bit performance results, and Figure 3 displays photos of the used bits.

Bit No.1 was used to drill a well interval composed of argillaceous deposits interbedded with mudstones and siltstones, with a soft to medium hardness category. The average ROP was 15.2 m/h with a maximum of 17.1 m/h. Bit wear

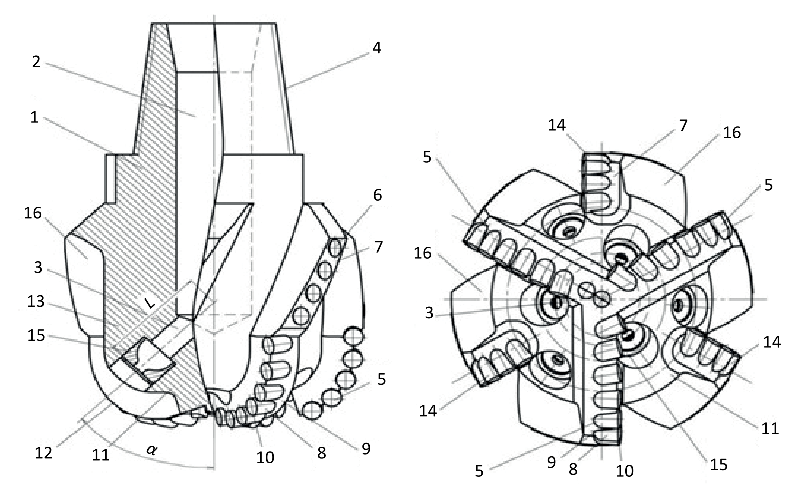

Figure 1. Schematic design of the BuH1-218-MSHV bit (see description in the text)

Rysunek 1. Schemat konstrukcji świdra BuH1-218--MSHV (patrz opis w tekście)

Table 1. BuH1-218-MS-HV bits test results
Tabela 1. Wyniki testów świdrów BuH1-218-MS-HV

Bit no.	Drilling interwal [m]		Meterage per run [m]	Net time on bottom [time]	Average drilling rate [m/h]	Drilling operating conditions				Drilling mud characteristics					
	from	to				weight on the bit, 10^3 [N]	standpipe pressure 10^6 [Pa]	mud circulation rate 10^{-3}[m^3/s]	angular rotation rate of the bit [s^{-1}]	density [kg/m^3]	funnel viscosity [c]	water loss [cm^3/30 m]	mud cake thickness [mm]	static shear stress 1/10 m [dPa]	pH indicator
1	628	750	122	8.0	15.20	40	7.5–9.0	32	9.42–12.56	1140	32	4	0.5	33/90	9.0
2	1447	1480	33	11.5	2.87	40–80	7,5–9.0	32	7.85–8.37	1120	30	4	0.5	12/32	8.5

Figure 2. Manufactured BuH1-218-MS-HV bits
Rysunek 2. Świdry BuH1-218-MS-HV po wyprodukowaniu

Figure 3. Worn bits (view of the working section)
Rysunek 3. Zużyte świdry (widok sekcji roboczej)

analysis revealed that all the cutters remained in place, the bit outer diameter did not change; however, erosional damage was observed on the end part of the body, as shown in the accompanying photographs. Bit No. 2 was used to drill a well interval composed of layers of mudstones and siltstones, with a hardness category from medium to hard, and with low abrasiveness. The average ROP was 2.87 m/h, reaching a maximum of 30.0 m/h. Moreover, during drilling, the ROP peaked several times, only to drop sharply to minimum values afterwards. Based on the results of the bit run, it was found that all the cutters remained in place, and the bit outer diameter also did not change. However, erosional destruction occurred on the end part of the body, resulting in the loss of one jet nozzle, after which the bit was raised to the surface.

The analysis reveals that bit No.1 provided penetration of 122 m, with a maximum drilling rate of 17.1 m/h in certain intervals, while bit No. 2 – 33 m, with a maximum drilling rate of up to 30 m/h in certain intervals. However, as the results of testing two bits showed, their hydraulic mud system needs to be improved. It is necessary to determine the optimal flow rate of the drilling fluid in order to ensure effective bottomhole cleaning, facilitate the removal of rock cuttings to the surface via an upward flow, and allow for a jet effect. Additionally, this flow rate should help prevent turbulent flows and minimize erosional damage to the bit body.

Improvement of the hydraulic bit flushing system BuH1-218-MS-HV

The hydromonitor effect is achieved whn the jet speed of drilling mud from the nozzles exceeds 80 m/s. With a drilling mud flow rate of $Q = 32 \cdot 10^{-3}$ m^3/s, six nozzles ($n = 6$) and a nozzle diameter of $d_H = 9 \cdot 10^{-3}$ m, the average jet velocity is 83.8 m/s, which is sufficient to achieve the jet effect (Biletskyi et al., 2016). However, since jest speed can vary across different areas, this value is average. The actual outflow pattern of the drilling fluid from the circulation ports of the bit will depend on the local hydraulic resistance characteristics encountered by each jet, potentially causing uneven distribution of total flow among the bit channels. Based on these considerations, the results of the performed analytical studies were used to simulate the movement of the drilling fluid through the jet nozzles of the bit using the Flow Simulation CAD/CAM package of the Solid Works system (Biletskyi et al., 2020a; Moisyshyn et al., 2020). The simulation was carried out under the following conditions: the number of nozzles in the bit – 6, the circulation rate of the drilling fluid – 0.03–0.04 m^3/s, the hydrodynamic pressure on bit nozzles – 8–10 MPa, 15 rad/s, drilling fluid density 1100–1150 kg/m^3, temperature up to 100°C, viscosity model of the drilling fluid – Herschel-Bulkley. In the course of simulation modeling, the following parameters were studied: the placement of nozzles at various distances from the bit axis and well bottom, pressure distribution at the well bottom as the drilling fluid exits from each nozzle, jet velocity, changes in the flow rate of the drilling fluid as it exits into the space between the bit and borehole wall, and jet vorticity at the bottomhole and borehole walls. The simulation results can be obtained in two forms: global maxima of the studied parameters and local minima. The global values of the results refer to the entire model under study, while the local values show the limiting values of the parameters only for the selected section (or area). Solid models of various design options for the bit, the bottom of the borehole, and the drill string fragment were created. These models were then used to construct a variant of the calculated bit assembly at the bottom of the well (Figure 4). For each variant, a numerical calculation of the fluid motion was carried out using the finite element method.

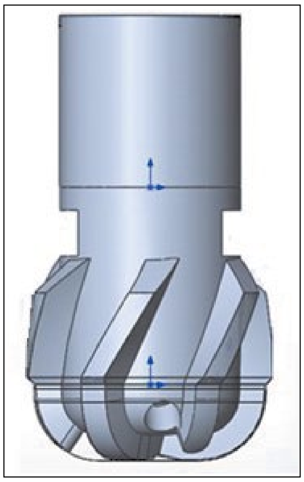

Figure 4. The bit model at the bottom of the well
Rysunek 4. Model świdra w dolnej części odwiertu

Calculations were conducted with flow parameters reflecting real drilling conditions at the Novo-Chiselskoye field: fluid volume flow 32 l/s and a pressure of 2 MPa in front of the bit. These calculations were carried out to determine the nature of the fluid outflow through the circulation ports of the bit at different angles of the ports relative to the bit's axis and at different distances of the jet nozzle from the longitudinal axis of the bit. The results of the computer simulation of fluid jet leakage rates from the circulation ports of the bit are presented in Figures 5–7.

As can be seen from Figure 5, at the initial design angle of inclination of the circulation ports relative to the axis of the bit (Figure 5a – an angle of 30°), fluid outflow from the circulation ports is characterized by intense vortex formation, which does not effectively contribute to cleaning the bottomhole from cuttings. Additionally, an increased velocity (100 m/s) of the flow is observed along one of the bit cuttes, which can lead to increased abrasive wear on the surface of that blade. When the angle of inclination of the circulation ports relative to the bit axis is reduced to 25° (Figure 5b), vortex intensity decreases, and the high-velocity flow from the blade surface shows some deviation.

At an angle of inclination of the circulation ports of the bit relative to its axis of 20° (Figure 5c), slight vortices and a decrease in the fluid velocity along the surfaces of the bit cuttes are observed. High-velocity flows are now directed between the cuttesbit cuttes, facilitating rapid removal of cuttings from the bottomhole zone. A subsequent reduction of the circulation port inclination angle to 15° (Figure 5d) results in a nearly vortex-free fluid flow. However, fluid velocities along the bit cuttes increase again, reaching 90–100 m/s cuttes.

Figure 6 shows the fluid flow characteristics along the bit at various angles of circulation ports placement relative to the longitudinal axis of the bit. As shown, an inclination angle of 20° relative to the bit axis results in less vortex formation compared to other tested angles. With this configuration, the fluid velocity along the bit reaches 30 m/s and is higher than the velocities observed at other angles. This promotes more effective removal of cuttings from the bottomhole zone, contributing to effective cleaning. Therefore, an angle of 20° can be considered optimal for such a bit design from the standpoint of ensuring effective cuttings removal from the bottomhole and ensuring abrasive wear resistance of bit surfaces.

Another numerical study was carried out to investigate the influence of jet nozzles placement depth within the circulation ports of the bit on the characteristics of fluid outflow into the bottomhole zone. The study considered jet nozzle placement options at distances of 90 mm, 85 mm and 80 mm from the bit axis. This narrow range of nozzle placement distances is due to design constraints. The results are presented in Figure 7. As can be seen from the figure, deeper placement of the jet nozzle within the body of the bit results in increased vortex formation in the fluid flows, which negatively

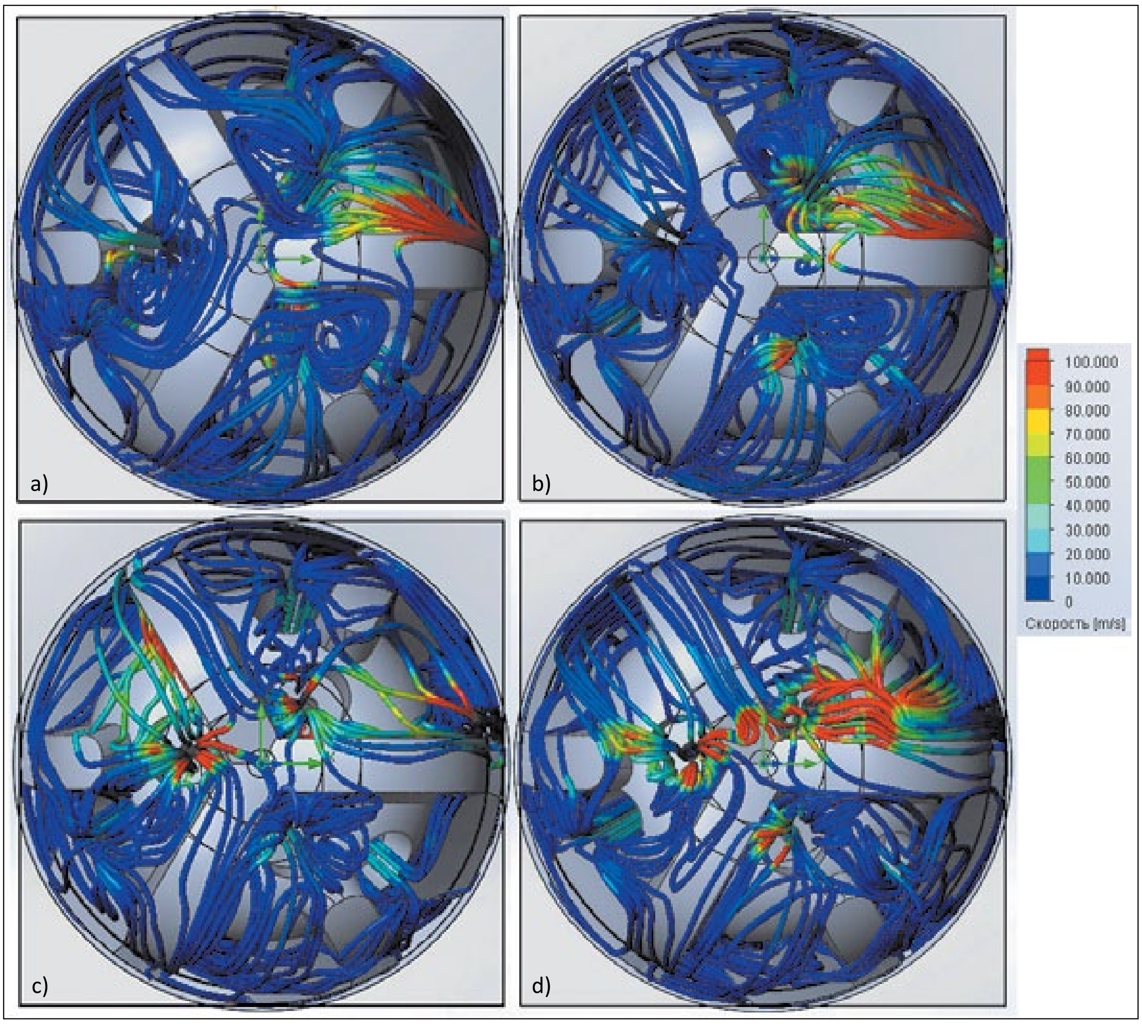

Figure 5. The nature of the flow of fluid through the circulation ports of the bit at different angles of placement of the ports relative to its axis: a) 30°; b) 25°; c) 20°; d) 15°

Rysunek 5. Charakterystyka przepływu płynu przez otwory cyrkulacyjne świdra przy różnych kątach nachylenia otworów względem jego osi: a) 30°; b) 25°; c) 20°; d) 15°

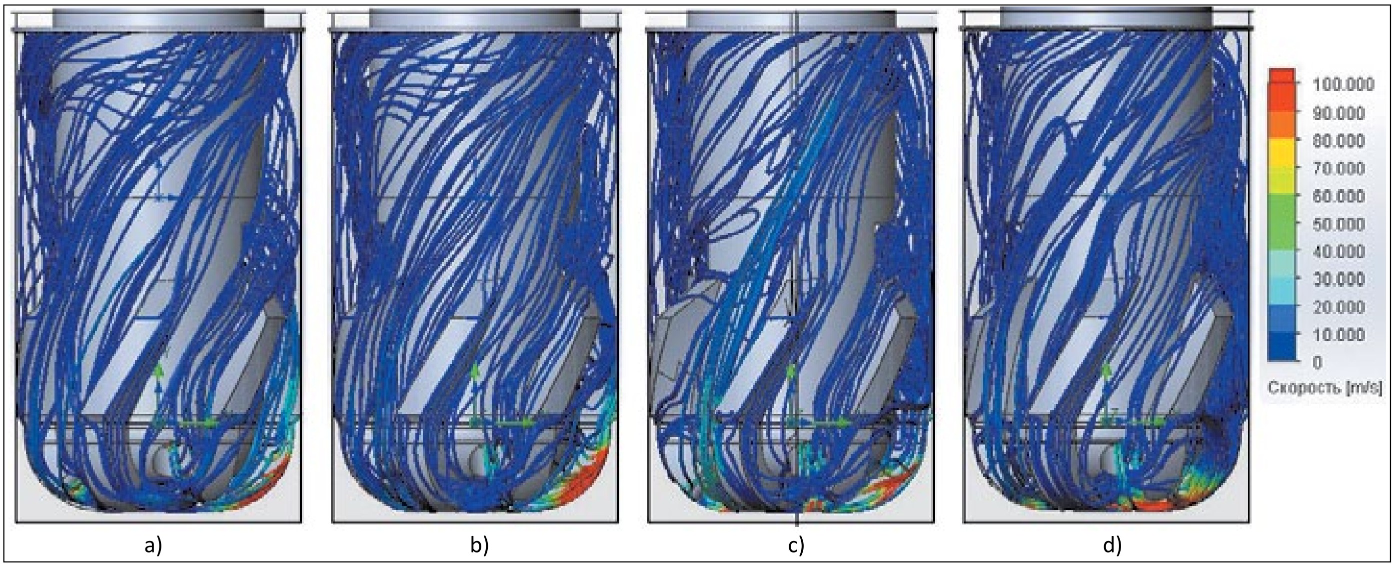

Figure 6. Fluid flow characteristics along the bit at different angles of the circulation ports relative to its axis: a) 30°; b) 25°; c) 20°; d) 15°

Rysunek 6. Charakterystyka przepływu płynu wzdłuż świdra przy różnych kątach nachylenia otworów cyrkulacyjnych względem jego osi: a) 30°; b) 25°; c) 20°; d) 15°

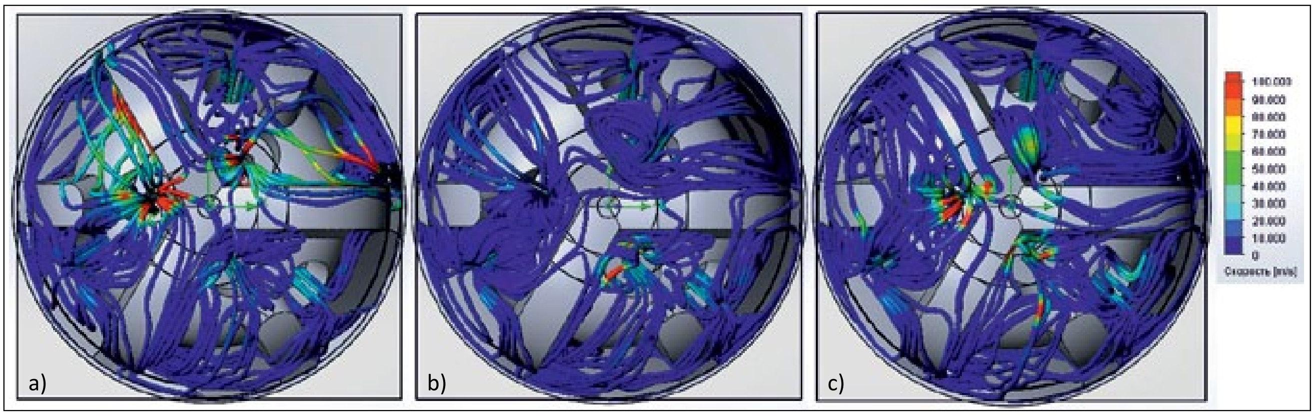

Figure 7. The characteristicsof the fluid outflow through the circulation ports of the bit at different distances of the jet nozzle from the axis of the bit: a) 90 mm; b) 85 mm; c) 80 mm

Rysunek 7. Charakterystyka wypływu cieczy przez otwory cyrkulacyjne świdra dla różnych odległości dyszy od osi wiertła: a) 90 mm; b) 85 mm; c) 80 mm

Table 2. Bit characteristics and drilling parameters

Tabela 2. Charakterystyka świdra i parametry wiercenia

Bit characteristics					
Bit diameter [mm]	**Number of nozzles [pcs]**	**Nozzle diameter [mm]**	**Nozzle shape factor [μ_ϑ]**	**Total cross-sectional area of nozzles [m^2]**	
218	6	10.3	0.9	0.000499	
Drilling fluid density 1120 kg/m^3					
Characteristics of rocks and drilling design parameters					
Type of rock	**Compression strength, σ_{cm}'' [MPa]**	**Minimum effective pressure, $p_{min(e)}$ [MPa]**	**Discharge rate of drilling fluid from nozzles, ϑ [m/s]**	**Circulation rate, Q'' [m^3/s]**	**Weight on bit [10^3 kN]**
Consolidated clays	5.5–6	1.65–2.0	48.9–53.8	0.0243–0.0268	40–60
Siltstone	22–23	6.6–6.9	97.7–99.9	0.0487–0.0498	60–70
Sandy shales	9–12	2.7–4	62.5–76.0	0.031–0.0379	60–70
Sandstone	28–31	8.4–9.3	110.2–116	0.055–0.0578	70–80

Table 3. Bit performance in industrial conditions

Tabela 3. Wydajność świdra w warunkach przemysłowych

Bit	Total meterage [m]	Total drilling time [hours]	Average drilling rate [m/h]	Maximum drilling rate in the interval [m/h]
Bits tested in 2015				
1	122	8.00	15.20	17.10
2	33	11.50	2.87	30.00
Bits tested in 2019				
3	558	30.75	18.14	28.25
4	552	103.65	5.33	22.00

impacts the removal of cuttings from the bottomhole zone. Therefore, it is preferable to postion the jet nozzle in such a design of the bit as far as possible from the bit axis and closer to the bottom. The results of the simulation were used to improve the design of the fluid-discharge ports for the developed bit design (Biletskyi et al., 2020b). Two new bits with improved jet ports were manufactured for testing, and the corresponding technological parameters were established. The table below shows the characteristics of the fluid-discharge ports of the bit, the rock properties of the well section, and the calculated drilling parameters.

Bit No. 3 was used at Berehove OGCF, well No. P-86 in the period from June 13 to June 24, 2019, achieving the total penetration of 558 m in the interval of 1603–2161 m.

Bit No. 4 was used at Urengoy OGCF, well No. 2P in the period from 17.10 to 28.10.2019, achieving the total penetration of 552 m in the interval of 438–990 m.

The table below compares the performance of two previously manufactured bits with the two bits featuring improved fluid-discharge ports design.

Consequently, the testing results of two improved bit designs indicate significantly higher tability and penetration rates. However, despite achieving high drilling rates, the individual cutters of the drill heads exhibited insufficient stability, resulting in the predicted technical and economic drilling indicators not being achieved.

Study of the stability of the bit cutters in the process of rock-breaking

The problem of increasing the stability of cutters and consequently of the bit as a whole, can be solved by conducting analytical studies aimed at deriving relationships between stability and key factors. These relationships facilitate improvements in the layout of the cutters and enhance the efficiency of breaking rocks with different mechanical properties, ultimately expanding the range of optimal drilling modes. The choice of cutters configuration for a bit should be justified based on the strength characteristics of the rock, which may change as these characteristics vary along the section of the interval drilled with a particular bit. The aim of the study is to identify the factors affecting the stability of bit cutters that break the rock by cutting with axial vibrations, and to derive analytical dependencies to assess their predictive stability.

Combined methods of applying various types of mechanical loads to bodies subject to processing or destruction are considered one of the most progressive areas of research. Cutting rocks with PDC bits with simultaneous application of axial vibrations significantly increases the efficiency of their rock-breaking process. The combination of cutting and vibrations changes the continuous interaction of the working surfaces of the bit with the rock into an intermittent one, and then the movement of these elements along the bottom of the well consists of separate phases: the rock-breaking phase when the cutting element cuts the rock, when the vibrations are directed towards the bottom, and the movement phase without rock-breaking, when the vibrations are directed away from the bottom. The presence of these phases alters the flow characteristics of thermal processes in the cutting zone, positively impacting cutters stability. Vibrations during cutting can be set externally by a special vibrator included in the drill string assembly, or they can occur spontaneously as a result of the movement of the bit along the bottom of the well. Vibrations of the first type are always given certain parameters: frequency, amplitude, and waveform, which contribute to the efficiency of the rock cutting process, while vibrations of the second type can adversely affect the stability of the cutters due to the arbitrariness of their parameters.

According to the results of the research, it was established that the relationship between the rock cutting rate (ϑ_p) for a single cutter and its stability period (T) can be expressed as follows:

$$T = \frac{C_\vartheta}{\vartheta_p^{1/m}} \tag{1}$$

where:

C_ϑ – a coefficient dependant on the rock type, the depth of immersion of the cutter into the rock, load on a single cutter, cutter geometry, properties of the material from which it is made, and the cooling and lubricating properties of the drilling fluid;

m – a relative stability index – a coefficient that characterizes the relationship between the rock-breaking rate and stability period under certain drilling conditions. Its value depends on factor similar to those affecting coefficient C_ϑ, along with the wear nature of the cutter.

According to the research results (Bondarenko, 2006), the temperature, which can exceed 1000°C in the cutting zone, significantly influences bit cutters stability, as a result of which it is often considered the key factor determining the stability of the cutters. In the absence of axial vibrations, the cutting rate is the parameter that unambiguously determines the key factors characterizing the stability of the cutter, namely: temperature in the cutting zone, dynamic tension of this zone, and the friction conditions at the contact surfaces. However, during rock-breaking with axial vibrations, this relationship is more complex, since the temperature in the cutting zone depends not only on the cutting rate but also on the length of the cut section and on the ratio of time during which the cutter cuts the rock (t_p) and the time when the cutter moves, as a result of vibration, along the bottom of the well without contact with the rock (t_0).

To derive the dependency ($T – \vartheta_p$) in the process of rock-breaking with axial vibrations, we use relative wear and wear rate. Relative wear is defined as the ratio of the largest width of the blunting edge to the rock-breaking length by the cutter. The wear rate (gt) at a given time (t) is the ratio of the wear of the cutter at time (t) to its maximum allowable wear. Therefore, ($g = 0$) at the initial moment of the bit operation at the bottomhole, and ($g = 1$) when the cutters are worn out and the bit must be replaced. Degree of wear (g_t) is a non-decreasing function, since spontaneous restoration of the edge of the cutting element is impossible during the wear process.

Then, the wear rate of the cutter can be written as the following dependence:

$$\frac{dg}{dt} = f(g, \vartheta_p, Q, G_i, \mu) \quad (2)$$

At the same time, it is assumed that the wear rate does not depend on the state of the friction contact surface at a given moment and is not determined by the preload on the cutter in the process of rock-breaking. Therefore, at each moment in time, the rate of wear is entirely determined by the instantaneous values of such physical parameters as: wear rate $g(t)$, rock cutting speed (ϑ_p), temperature Q, axial loading force on the cutter (G_i), coefficient of friction (μ). The total wear over time (t) will thus equal to the sum of elemental damage to the cutter over an infinitely small time intervals (d_t). This wear at time (t) equals:

$$G = \int_0^t f(g, \vartheta_p, Q, G_i, \mu) dt \quad (3)$$

The stability period of the cutter, i.e., the time during which the wear criterion is reached ($g = 1$), can be written as:

$$G = \int_0^t f(g, \vartheta_p, Q, G_i, \mu) dt = 1 \quad (4)$$

If the process of rock-breaking by the bit cutter occurs in the absence of vibrations, i.e. if it is assumed that the physical parameters in the rock-breaking zone are constant, then the stability determination method in this scenario is as follows. Given the linear summation, the wear rates at time (t) can be written as:

$$g(t) = \frac{t}{T} \text{ where } 0 \le t \le T \quad (5)$$

Taking into account, that $T = C_\vartheta / \vartheta_p^{1/m}$ we will get:

$$g = \frac{\vartheta_p^{1/m}}{C_\vartheta} t; \quad \frac{dg}{dt} = \frac{\vartheta_p^{1/m}}{C_\vartheta} \quad (6)$$

Then, from condition (6), we can derive the previously written expression for the stability of the cutter:

$$\int_0^T \frac{\vartheta_p^{1/m}}{C_\vartheta} dt = 1, \text{ i.e. } T = \frac{C_\vartheta}{\vartheta_p^{1/m}} \quad (7)$$

Similarly, the stability of the cutter can be determined for the so-called quasi-stationary rock-breaking processes, which are characterized by minor changes $\vartheta_p(t)$, $\delta(t)$, $S_0(t)$, (where δ, S_0 denote the depth of cut and penetration per bit per revolution, respectively). In this case, the physical conditions acting on a single cutter are comparable to the conditions of rock-breaking in the absence of axial vibrations. Such conditions are characterized by continuous rock-breaking, which can also occur with low-frequency vibrations. In such cases, the wear rate is determined by the dependence:

$$\frac{dg}{dt} = \frac{1}{T(t)} \quad (8)$$

where the rate of wear over time (t) is:

$$g(t) = \frac{1}{C_\vartheta} \int_0^t \vartheta_p^{1/m}(z) S_0^x(z) \delta^y(z) dz \quad (9)$$

where:

x – an indicator characterizing the effect of temperature in the rock-breaking zone and related parameters on the stability of cutters,

y – an indicator characterizing the influence of the breaking rate and related parameters on the stability of cutters.

In the process of continuous rock-breaking with axial low-frequency vibrations, the thickness of the rock layer separated from the bottom changes first, while other parameters can be taken constant in the first approximation. Then, an empirical relationship can be used to determine the stability of the cutter for rock-breaking in the absence of vibrations

$$T = \frac{C_\vartheta}{\vartheta_p^{1/m} \cdot S_0^x \delta^y} \quad (10)$$

The use of this dependence is acceptable for rock-breaking with low-frequency vibrations, when the parameters ϑ_p, δ, S_0 change over time. However, the rate of their change is so small that the conditions on the contact surfaces at each moment of time do not differ from the conditions (Q, G_i, μ) in the process of rock-breaking without vibrations, with constant values $\vartheta_p = \vartheta_p(t')$, $\delta_p = \delta_p(t')$, $S_0 = S_0(t')$, (where (t') represents the time during which the cutter cuts the rock without vibration).

Taking into account the assumption of a linear wear accumulation, the expression for determining the stability of the cutter during rock-breaking with low-frequency vibrations T_1 can be written as:

$$\int_0^{T_\beta} \vartheta_p^{1/m}(t) S_0^{x_0} \delta^{y_0}(t) dt = g \quad (11)$$

When $S_0(t) = S_0 + \Delta S_0 \sin \omega t$, where $\omega = 2\pi/t_0$, and $\vartheta_p = \text{const}$, $t_p = \text{const}$, the integral can be represented as:

$$\vartheta_p^{1/m} \delta_p^{y_0} \int_0^{T_\beta} \left[S_0 + \Delta S_0 \sin \omega t \right]^{x_0} dt = \\ = \vartheta_p^{1/m} \delta_p^{y_0} T_1 \frac{1}{T_1} \int_0^{T_\beta} \left[S_0 + \Delta S_0 \sin \omega t \right]^{x_0} dt = g \quad (12)$$

Or, taking into account the periodicity of the function:

$$T_\beta = \frac{g t_0}{\vartheta_p^{1/m} \delta_p^{y_0} \int_0^{t_0} \left[S_0 + \Delta S_0 \sin \omega t \right]^{x_0} dt} \quad (13)$$

$$\frac{T}{T_\beta} = \frac{1}{S_0^{x_0}\delta_0}\int_0^{t_0}\left[S_0 + \Delta S_0 \sin \omega t\right]^{x_0} dt \qquad (14)$$

where:

ΔS_0 – the amplitude of the change in the thickness of the rock fragmented by the cutter with axial vibrations,

ω – the angular speed of bit rotation.

Therefore, when $0 \le x_0 \le 1$ and $T_в \ge T$, i.e., with the same rock-breaking rate and the volume of rock fragmented per unit of time, we observe an increase in the stability of the cutter. This is because almost always $x_0 < 1$ and is $x_0 = 0.3–0.6$. In the case where $x_0 > 1$, stability decreases, i.e. $T_в < T$.

In the specific case where $x_0 = 1$, stability is maintained:

$$\frac{T}{T_\beta} = \frac{1}{S_0\delta_0}\int_0^{t_0} S_0 dt + \frac{1}{S_0\delta_0}\int_0^{t_0}\sin\frac{2\pi}{t_0} t dt = 1 \qquad (15)$$

i.e. $T = T_в$.

Qualitatively different conditions for determining the stability of cutter arise when the rock is fragmented with axial vibrations, as there is no mutually unambiguous relationship between the primary technological parameters ϑ_p, δ, S_0 and the physical conditions in the rock-breaking zone g, Q, G_i, μ. As noted above, the same temperature observed during rock-breaking without axial vibrations can be achieved at different ratios $\vartheta_p – S_0$. This is also true for rock-breaking with axial vibrations, where in order to obtain the dependence of the stability of the cutter, it is necessary to establish the patterns of variation of each of the physical parameters and the functional relationship between them, which should be confirmed experimentally. Therefore, the stability for such a case can be obtained by separating the temperature from expression (1), since it depends on the nature of the movement of the cutter and generally does not coincide with the temperature in the steady state. Then, the rock-breaking rate can be considered constant, and the wear rate dg/dt and cutters stability $T_в$ at any time are given by:

$$\frac{dg}{dt} = \frac{1}{C_{\vartheta Q}}\vartheta_p^x Q^y(t); \text{ here } C_{\vartheta Q} = C^y C_\vartheta \qquad (16)$$

$$\text{Then: } \frac{\vartheta_p^x}{C_{\vartheta Q}}\int_0^{T_\beta} Q^y(t)dt = 1; \ T_\beta = \frac{C_{\vartheta Q}T}{\vartheta_p^x \int_0^T Q^y(t)dt} \qquad (17)$$

The resulting formula is fundamental for determining the stability of bit cutters in rock-breaking with axial vibrations.

Conclusions

Based on the results of testing the developed bit and modeling, the necessary design changes were made. These modifications enhanced the hydromonitor effect by generating faster jets on the bottom-hole surface, enabling additional cavitation destruction of the bottom-hole surface and improved removal of cuttings due to reduced likelihood of formation of stagnant zones. This positively impacted the technical and economic performance of the drilling. The primary factors influencing the stability of the cutting elements during rock-breaking with axial vibrations were identified, and analytical dependencies of their predictive stability were established. The research results will inform improvements to the bit design, particularly in the layout of its cutters, for which it is planned to simulate the process of rock cutting with vibrations using the ANSYS Workbench 19.2 software package. During the simulation, the vibration parameters, the value of the axial force of the cutters depending on the scheme of their location on the bit, the bit rotation speed, and the temperature at the contact surfaces will be modified. Based on the assessment of the predictive stability of the cutters, bits will be manufactured taking into account the results of the modeling, and industrial tests will be conducted during well drilling.

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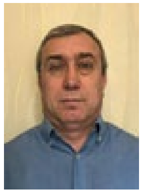

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