Nafta-Gaz 2024, no. 11, pp. 696–704, DOI: 10.18668/NG.2024.11.04

Enhancing the efficiency of well milling devices and cleaning wells from milled objects by implementing cavitation in the milling zone

Zwiększenie wydajności urządzeń do frezowania i oczyszczania odwiertów z resztek po frezowaniu poprzez zastosowanie kawitacji w strefie frezowania

Amir G. Mustafayev, Mahmud A. Ismayilov, Mirkamran M. Salimli, Chingiz R. Nasirov

Azerbaijan State Oil and Industry University

ABSTRACT: Technological leadership on a global scale is closely linked to advancements in novel technologies and materials. Increasing the operating temperature of composite materials is a critical objective in the development of innovative materials and products derived from them. Advances in technology have demonstrated that extensive alloying, combined with optimal heat treatment and advanced material processing methods, enhances their heat resistance. High-temperature materials based on composites with an elevated temperature threshold fulfill this requirement. In the current stage of oil and gas industry development, methods to increase oil and gas production include the introduction of effective technological processes aimed at enhancing oil recovery, maintaining production wells, and implementing preventive measures. Particularly important are efforts to accelerate emergency maintenance of production and drilling wells. In this context, the introduction of new, highly efficient repair equipment designs and the improvement of existing tools and devices used in the field play a crucial role. The primary well maintenance activities include fishing and milling. Tools and devices used in these operations are classified into gripping, cutting, and auxiliary categories. One of the most versatile tools in well repair are cutting devices, designed for continuous milling of pipes, preparing the deformed ends of emergency pipes for fishing, opening casings, and cutting out drilling columns. Restoring damaged wells by milling is one of the most complex types of repairs. The productivity of wellbore milling is characterized by the life of the tool, the rate of metal penetration, and durability.

Key words: well milling devices, cleaning wells, milled objects, cavitation, milling zone, composite materials, operational temperature, heat resistance.

STRESZCZENIE: Globalna przewaga technologiczna jest ściśle związana z postępem w zakresie innowacyjnych technologii i materiałów. Zwiększenie temperatury pracy materiałów kompozytowych jest decydującym czynnikiem w rozwoju innowacyjnych materiałów i produktów z nich wytwarzanych. W wyniku postępu technologicznego okazało się, że szerokie zastosowanie stopów, w połączeniu z optymalną obróbką cieplną i zaawansowanymi metodami przetwarzania materiałów, zwiększa ich odporność na ciepło. Materiały odporne na wysokie temperatury oparte na kompozytach o podwyższonym progu temperaturowym spełniają ten wymóg. Na obecnym etapie rozwoju przemysłu naftowego i gazowego metody zwiększania wydobycia ropy naftowej i gazu obejmują wprowadzenie skutecznych procesów technologicznych mających na celu zwiększenie odzysku ropy naftowej, utrzymanie odwiertów produkcyjnych i wdrożenie środków zapobiegawczych. Szczególnie ważne są działania mające na celu skrócenie czasu konserwacji awaryjnej odwiertów wydobywczych i poszukiwawczych. W tym kontekście kluczową rolę odgrywa wprowadzanie nowych, wysoce wydajnych modeli sprzętu naprawczego oraz ulepszanie istniejących narzędzi i urządzeń wykorzystywanych w terenie. Podstawowe czynności związane z konserwacją odwiertów obejmują prace związane z usunięciem zablokowanych lub uszkodzonych narzędzi z odwiertu i frezowanie. Narzędzia i urządzenia używane w tych operacjach są podzielone na chwytające, tnące i pomocnicze. Jednymi z najbardziej wszechstronnych narzędzi do naprawy odwiertów są urządzenia tnące, przeznaczone do ciągłego frezowania rur, przygotowywania zdeformowanych końców rur awaryjnych do operacji związanych z usunięciem zablokowanych lub uszkodzonych narzędzi z odwiertu, otwierania kolumn okładzinowych oraz wycinania kolumn wiertniczych. Wydajność frezowania odwiertów zależy od żywotności narzędzia, tempa penetracji metalu i trwałości.

Słowa kluczowe: urządzenia do frezowania odwiertów, czyszczenie odwiertów, frezowane obiekty, kawitacja, strefa frezowania, materiały kompozytowe, temperatura robocza, odporność na ciepło.

Corresponding author: Ch.R. Nasirov, e-mail: *cina-01@mail.ru*

Article contributed to the Editor: 24.02.2024. Approved for publication: 21.10.2024.

Introduction

In the present study, the main objectives are to reduce the temperature and thermal stresses in the drilling-milling zone by using cooling agents. This involves determining the dependence of the thermal-heat regime of the cutting-destructive tool on the operating parameters (angular velocity of the tool, longitudinal load on the tool, resistance force of the materials to be destroyed, consumption of the flushing cooling agent). The study also aims to mathematically describe the physical model of the milling process and construct graphical dependencies on the operating parameters.

During the research, the effect of the "liquid-air" mixture on reducing the temperature in the milling process was examined. Since the combined impact of these two factors on temperature had not been previously studied, the influence and efficiency of the cavitation they generate in the destruction of metals and rocks inside the well, as well as in well flushing, were not previously evaluated.

Based on theoretical research, operating parameters that ensure milling (milling revolutions, milling load, physical-mechanical characteristics of materials to be destroyed) were selected, and numerous research works using the "liquid-air" mixture were conducted.

Relevance of the work

The relevance of the work lies in the creation of cavitation in the milling zone to break down the objects being destroyed into small and large parts, as well as to clean wells from debris (rocks, metals, petrified cements, etc.), with significant modifications in the design of the milling device.

Aim of the study

The main objective of this study is to reduce the temperature and thermal stresses in the drilling-milling zone through the use of cooling agents. This involves determining the dependence of the thermal regime of the cutting-destructive tool on the operating parameters (angular velocity of the tool, longitudinal load on the tool, resistance force of materials to be destroyed, consumption of the flushing cooling agent). The study also aims to mathematically describe the physical model of the milling process and construct graphical dependencies based on the operating parameters.

Discussion

The mismatch between the demands of new technologies for structural materials and the capabilities of classical alloys is addressed through the development and application of composite materials (Mustafayev et al., 1997). While a wide range of materials used in engineering can be classified as composites, it is challenging to discuss them all within a single article. Therefore, this study focuses on matrix-based materials specifically designed for use in high-temperature well conditions.

Composite materials are inherently heterogeneous, and their structures are often oriented in specific ways. They are divided into two groups: fibrous and layered composited, and dispersion-strengthened composites. This division is helpful when studying metal matrix composites (MMC), although mixed materials do exist. Pseudo-alloys can be distinguished as a separate group of composite materials.

Fibrous composites consist of reinforcing components such as wire-like crystalline fibers. Layered composites consist of alternating reinforcing components in the form of sheets, plates, or foils, which are firmly bonded along the entire contact surface. Dispersion-strengthened composites, on the other hand, consist of materials in which fine particles, uniformly distributed, do not interact with or dissolve into the matrix. In fibrous and layered composites, the load-bearing elements are the reinforcing fibers, wires, and foils, while in dispersed-strengthened composites, the matrix bears the load. Since high strength, a relatively high elastic modulus, and low density are required for reinforcing elements, the presence of ultra-dispersed particles that do not dissolve in the base material is crucial. A homogeneous dislocation structure also contributes to effectively hindering dislocation movement up to the material's melting point.

In fibrous materials, the protection of fibers and prevention of reinforcement damage is ensured by the base material, which bonds them into a single monolith. Load transfer occurs through the composite base to the fibers. If some of the reinforcing elements fail, the matrix redistributes the stress. Furthermore, the mechanical properties of the matrix determine the behavior of the composite under shear, compression, and fatigue failure. In dispersed-strengthened materials designed for high-temperature applications, the composite components are selected to minimize interaction (Pustovoytenko, 1987).

At elevated temperatures, the shape of grains (length and diameter) becomes particularly important in dispersion-strengthened materials. Like fibrous composites, dispersion-strengthened materials, are reinforced with ultra-dispersed particles, which help redistribute loads and stresses between the fibers through the boundaries and adjacent areas. In such cases, strength at elevated temperatures can be increased by modifying the grain boundary area to promote greater alignment of the grains with the direction of applied stresses. This is achieved by increasing the ratio of grain length to diameter, known as the grain disequilibrium coefficient. For these composites, a directional structure with highly elongated grains is formed during deformation-thermal treatment.

A linear relationship between most strength characteristics of dispersed composites and the grain disequilibrium coefficient has been determined. This coefficient depends on both temperature and deformation rate. It is worth noting that the strengthening effect due to the grain aspect ratio is most pronounced at low deformation rates and high temperatures. However, the grain disequilibrium coefficient is not always the key structural characteristic governing high-temperature strength. When assessing the impact of structural factors on the high-temperature properties of dispersion-strengthened materials, it is important to consider not only the grain shape and size but also the density of dislocations, their distribution, the size of dispersed particles, and the distance between them. This involves creating a stable structure formed during deformation-thermal treatment under the influence of fine reinforcing particles uniformly distributed in the matrix, which do not dissolve into it.

The structural heterogeneity formed as a result of deformation and subsequent high-temperature annealing persists in dispersed-strengthened materials across the entire temperature range (up to 0.97 Tm) and is a typical structure of these materials. The good creep resistance of such materials at elevated temperatures is attributed to a sufficiently stable substructure, which provides a significant advantage in heat resistance at (0.8–0.9 Tm) compared to traditional materials. Nickel-based superalloys, designed for operating temperatures of 550°C, exhibit high strength, fatigue resistance, creep resistance, and corrosion resistance, maintaining their properties for extended periods at elevated temperatures. Approximately half of the total mass of a rocket engine is composed of nickel-based superalloys or nickel-iron alloys (Agapova and Bitekhtina, 2012).

The use of molybdenum-based composite materials as tool materials for the hot processing of steels and pressure alloys is justified by their high strength, hardness at elevated temperatures, and good thermophysical properties. One notable application of molybdenum alloys in recent times is their use as thin, high-strength wire reinforcement in composite materials. In terms of specific strength, this wire outperforms that made from other refractory metals and alloys at temperatures up to 1100°C (Aramcharoen et al., 2008).

The strength properties and anisotropy in both the longitudinal and transverse directions have been studied in deformed rods made of composite materials based on tungsten, molybdenum, and niobium. It has been established that the strength level increases with higher tungsten content in the material composition, and the anisotropy is greater in tungsten-based compositions than in molybdenum-based ones (Aurich et al., 2022).

The high effectiveness of strengthening extruded powder molybdenum with zirconium diboride (ZrB_2) has been demonstrated in the temperature range of active recrystallization (1400–1600°C). Additionally, the temperature ranges of effective strengthening of molybdenum- and tungsten-based compositions with nitride additives have been identified (Geistanger et al., 2022).

Foreign researchers also focus on developing composite materials based on refractory metals and alloys. A composite material based on molybdenum reinforced with TiC particles was produced. Using spark plasma sintering and subsequent annealing, the authors obtained a material with a density of 97–98% of the theoretical value (Jacyna et al., 2022). Additionally, using powder metallurgy technology, a composite material La–TZM was obtained and studied. La_2O_3 was added to the solid phase of the TZM molybdenum-based composition powder, and processes such as sintering, hot, warm, and cold rolling were applied, which increased the strength limit and elongation of the material (Archontoulis and Miguez, 2015). The thermal stability and mechanical properties of a composite material based on tungsten, dispersed and strengthened with HfC particles, were investigated using methods of spark plasma sintering and forging. The studies revealed that the forged tungsten-based composite exhibited superior thermal stability, thermal conductivity, and mechanical properties compared to the composition obtained by spark plasma sintering (Sigal, 2002).

One of the promising materials for operation in the temperature range of 1200–1400°C is a natural composite material based on the Nb–Si system. For additional alloying of the Nb–Si system composite, titanium and hafnium have proven effective, enhancing its oxidation resistance, impact toughness, and strength. To mitigate pitting corrosion at medium temperatures (800–900°C), these materials are alloyed with small amounts of tin and germanium. Positive results have been obtained in producing high-temperature composite material based on niobium using mechanochemical synthesis, and the technological properties of granules have been established. The microstructure and phase composition of the Nb–Si–Ti composite system were also studied, with an evaluation of the impact of iron impurities on hardness and density of samples, and the optimal duration for mechanical alloying was determined (Makarova and Trofimov, 2002).

Various technologies for obtaining composite materials have emerged from efforts to optimize their structure and mechanical properties. Eutectic composite materials have been produced using the directional crystallization method from a liquid melt. In this method, the structure of the material is naturally formed during the crystallization process of the eutectic composition melt, rather than through the artificial introduction of a second phase. A distinctive feature of this method is that the material is formed in a single operation (Milton and Arnold, 2005). Gas-phase methods for producing composite materials include gas-thermal spraying and deposition from the gas phase, which are primarily used for coating applications (Peltzman, 2002).

A technology based on powder metallurgy for manufacturing parts with dimensions close to the desired specifications and with a specially designed microstructure has been considered. Some of these technological schemes were investigated at the European level through the HYSOP project, which aimed to develop efficient coating systems based on multilayer EBC (Environmental Barrier Coatings) coatings (Goldin, 2002). Powder injection molding (PIM) technology enables the high-precision manufacture of parts from various materials suing fine-dispersed powders with sizes <5 μm, with spherical powders being preferred over flake-shaped ones (Ondiaka, 2016).

An analysis of existing studies on the mechanical processing of metallic objects shows that hard alloys in the tungsten carbide (WC) group and titanium-tantalum-tungsten (TTW) group exhibit the best cutting properties (Mustafaev et al., 1997).

A common characteristic of hard alloys is their high hardness (HRA 86-92) and heat resistance (700–1000°C), which offer advantages over high-speed steels by providing increased wear resistance and enabling machining at high cutting speeds (Pustovoytenko, 1987; Agapova and Bitekhtina, 2012).

However, hard alloys are characterized by a relatively low bending strength limit, σ = 90–165 kgf/mm^2, which is significantly lower than that of high-speed steels.

The low bending strength limit of hard alloys leads to brittle fracture of the cutting part of hard alloy tools during interrupted cutting with sharp changes in load. Hard alloys, both within and across different groups, vary in their physical-mechanical properties, which must be taken into account when selecting the appropriate hard alloy component for the cutting edge of the tool. The structure of one type of the tungsten carbide hard alloys consists of hard tungsten carbide grains cemented by cobalt. It is characterized by a reduction in hardness within the range from HRA 90 to HRA 86, along with increased wear resistance, heat resistance, ductility, and a bending strength limit ranging from 100 kgf/mm^2 to 165 kgf/mm^2.

Foreign companies have noted that factors such as carbon content, residual porosity, surface condition, and deformation speed significantly influence the bending strength limit of hard alloys when reinforcing the cutting part of the tool (Aramcharoen et al., 2008; Aurich et.al., 2022; Geistanger et al., 2022; Jacyna et al., 2022).

Practice shows that technical hard alloys made from fine-grained low-temperature carbide powder (VCM) are less strong than medium-grain hard alloys VC, which, in turn, are less strong than alloys of the VCM group made from high-temperature carbide powder (Mustafaev et al., 1997; Aramcharoen et al., 2008).

The most effective method for destroying metallic objects remaining in the borehole is mechanical milling (Archontoulis and Miguez, 2015). This process involves the continuous removal of thin layers of metal in the form of chips and their subsequent removal from the borehole surface using a flushing-cooling agent.

When designing the cutting edge of a milling tool, several factors must be considered, such as the characteristics of milling high-strength corrosion-resistant alloys in the well. These include the tool size limitation imposed by the borehole diameter, uneven metal removal from different parts of the milled surface, vibration, longitudinal, transverse, and torsional oscillations, and dynamic impacts.

The design of the cutting edge of a well milling tool must meet the following requirements: ensuring high milling performance (metal removal), stability of the tool's cutting edge against impact loads, hydro-abrasive wear, exposure to high temperatures, and resistance to aggressive components in the formation. It also involves the technological design of the tool, optimal distribution of specific contact loads across the entire contact surface of the cutting edge, and providing a rational route and quantity of flushing-cooling liquid delivered directly to the cutting zone.

The creation of a cutting tool design that meets these requirements will significantly reduce the duration of the milling process, improving the efficiency of eliminating accidents in the wellbore.

The objective set in the article is to choose and justify research on determining the effectiveness of the hard alloy component of the cutting edge of well-destructive tools.

The studies conducted involved a detailed analysis of various technologies for producing composite, focusing on optimizing their structure and mechanical properties. Special attention was given to powder metallurgy technologies for manufacturing parts of different sizes with specific microstructure. In addition, methods of restoring the working part of used well-breaking and cutting tools using modern techniques were also explored, taking into account the factors influencing the composition of the composite materials formed.

However, the discussed studies did not consider the deformed stress state that affects the further operation of well-cutting and breaking tools after the restoration of their working edge. The deformed stress state in the cutting zone significantly influences the plasticity and durability of the material. The resistance force of the tool edge increases with the rise in resistance forces, contributing to higher strength and wear resistance. However, the increase in deformation stresses in the cutting zone leads to a rise in cutting forces, resulting in premature wear and reduced operability. These identified negative factors necessitate a reconsideration of various parameters affecting the operation of well-cutting and breaking tools to enhance their efficiency and service life.

Countries in the Commonwealth of Independent States produce cemented carbide materials based on tungsten carbides such as VC2, VC3, and VC8, which exhibit high wear resistance and chip formation, as confirmed by experimental and practical research. An assessment of the wear resistance and metal chip formation of well-cutting tools with cutting edges made from composite materials containing crushed particles of tungsten carbide alloy showed that the best wear resistance is observed in composite materials composed of cutting elements with crushed grains of the VC8 cemented carbide grade (Pustovoytenko, 1987).

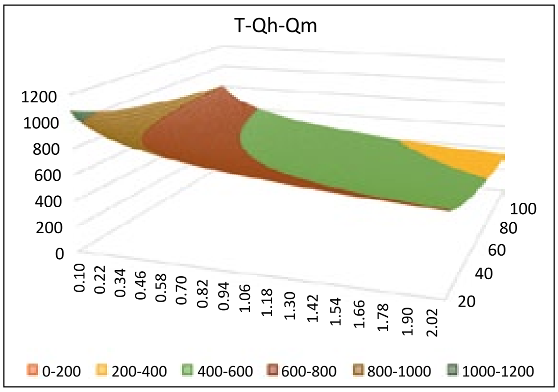


Figure 1. Three-dimensional graph illustrating the temperature dependence on the quantities of flushing liquid and air at average values of ω, σ, and P

Rysunek 1. Trójwymiarowy wykres ilustrujący zależność temperatury od ilości płuczki i powietrza przy średnich wartościach ω, σ i P

Methodology

Based on the analysis of regression equations, the results of the experiment were processed, and a mathematical model was developed that describes the temperature and thermal stresses in the cutting part of the tool depending on the milling mode parameters. Using this model, graphical dependencies of temperature and thermal stresses on the milling mode parameters were constructed (Mustafayev et al., 2023). During the research, a "liquid-air" or "liquid-gas" mixture was used as the cooling agent.

To create high-quality cavitation from the "liquid-air" mixture, a new design for a well milling tool was proposed. This design included a special chamber inside the mill, equipped with a bladed nozzle and a roller valve, as well as special rubber tubes resistant to high pressure and temperature for transporting air through the drilling fluid (Figure 5). The bladed nozzle is capable of receiving a liquid-air (liquid-gas) mixture in the mixing chamber and creating a turbulent regime. Inside the nozzle, a roller valve (Figures 4a, 4b) is located to block the flow to the liquid-air (gas) chamber, and rubber tubes resistant to high pressure (Figure 6) are used for transmission.

This article explores enhancing the efficiency of well milling devices and cleaning of wells from milled objects (chips, metallic debris, etc.) by applying cavitation in the milling zone. Based on theoretical studies, numerous experimental investigations were conducted at various milling process parameters using a coolant, i.e., flushing fluid, air, and their mixture. Based on the equation:

$$T = 5.825665 \cdot \omega + 0.046099 \cdot P + 0.2388 \cdot \sigma - 1.6439 \cdot Ql - 82.253262 \cdot Qa \quad (1)$$

a three-dimensional graph illustrating the relationship between temperature and the quantities of flushing liquid and air was constructed at average values of ω, σ, and P (Figure 1).

The values along the diagonal of the three-dimensional graph showing the temperature dependence on the values of P, σ, and ω are provided in Table 1.

Table 1. Values along the diagonal of the three-dimensional graph depicting the temperature dependence on the values of P, σ, and ω

Tabela 1. Wartości wzdłuż przekątnej trójwymiarowego wykresu przedstawiającego zależność temperatury od wartości P, σ i ω

No.	*Qm*	*Qh*	*T*	No.	*Qm*	*Qh*	*T*	No.	*Qm*	*Qh*	*T*	No.	*Qm*	*Qh*	*T*
1.	20	0.10	1080.189660	26.	45	0.60	678.9233021	51.	70	1.10	516.7617546	76.	95	1.60	411.4318209
2.	21	0.12	1044.677572	27.	46	0.62	670.4541591	52.	71	1.12	511.7755540	77.	96	1.62	407.8850481
3.	22	0.14	1013.821631	28.	47	0.64	662.2184137	53.	72	1.14	506.8693020	78.	97	1.64	404.3786452
4.	23	0.16	986.4378254	29.	48	0.66	654.2031488	54.	73	1.16	502.0404426	79.	98	1.66	400.9116973
5.	24	0.18	961.7552088	30.	49	0.68	646.3965177	55.	74	1.18	497.2865421	80.	99	1.68	397.4833205
6.	25	0.20	939.2419763	31.	50	0.70	638.7876262	56.	75	1.20	492.6052811	81.	100	1.70	394.0926605
7.	26	0.22	918.5146944	32.	51	0.72	631.3664319	57.	76	1.22	487.9944472	82.	101	1.72	390.7388911
8.	27	0.24	899.2870592	33.	52	0.74	624.1236553	58.	77	1.24	483.4519289	83.	102	1.74	387.4212133
9.	28	0.26	881.3391426	34.	53	0.76	617.0507035	59.	78	1.26	478.9757090	84.	103	1.76	384.1388538
10.	29	0.28	864.4979968	35.	54	0.78	610.1396031	60.	79	1.28	474.5638594	85.	104	1.78	380.8910641
11.	30	0.30	848.6249170	36.	55	0.80	603.3829404	61.	80	1.30	470.2145356	86.	105	1.80	377.6771193

cont. Table 1/cd. Tabela 1

No.	*Qm*	*Qh*	*T*	No.	*Qm*	*Qh*	*T*	No.	*Qm*	*Qh*	*T*	No.	*Qm*	*Qh*	*T*
12.	31	0.32	833.6067826	37.	56	0.82	596.7738100	62.	81	1.32	465.9259723	87.	106	1.82	374.4963173
13.	32	0.34	819.3500002	38.	57	0.84	590.3057681	63.	82	1.34	461.6964783	88.	107	1.84	371.3479776
14.	33	0.36	805.7761574	39.	58	0.86	583.9727921	64.	83	1.36	457.5244329	89.	108	1.86	368.2314408
15.	34	0.38	792.8188353	40.	59	0.88	577.7692437	65.	84	1.38	453.4082817	90.	109	1.88	365.1460672
16.	35	0.40	780.4212266	41.	60	0.90	571.6898366	66.	85	1.40	449.3465331	91.	110	1.90	362.0912365
17.	36	0.42	768.5343241	42.	61	0.92	565.7296074	67.	86	1.42	445.3377549	92.	111	1.92	359.0663468
18.	37	0.44	757.1155222	43.	62	0.94	559.8838892	68.	87	1.44	441.3805714	93.	112	1.94	356.0708139
19.	38	0.46	746.1275234	44.	63	0.96	554.1482885	69.	88	1.46	437.4736599	94.	113	1.96	353.1040705
20.	39	0.48	735.5374711	45.	64	0.98	548.5186637	70.	89	1.48	433.6157486	95.	114	1.98	350.1655659
21.	40	0.50	725.3162556	46.	65	1.00	542.9911059	71.	90	1.50	429.8056137	96.	115	2.00	347.2547649
22.	41	0.52	715.4379523	47.	66	1.02	537.5619218	72.	91	1.52	426.0420769	97.	116	2.02	344.3711476
23.	42	0.54	705.8793632	48.	67	1.04	532.2276179	73.	92	1.54	422.3240033	98.	117	2.04	341.5142086
24.	43	0.56	696.6196391	49.	68	1.06	526.9848859	74.	93	1.56	418.6502994	99.	118	2.06	338.6834565
25.	44	0.58	687.6399658	50.	69	1.08	521.8305899	75.	94	1.58	415.0199109	100.	119	2.08	335.8784135

The obtained dependencies also allow the determination of the performance of the pump and compressor, as well as the diameter for the hose that will pass through the inner part of the pump-compressor tube to create cavitation inside the mixing chamber of the milling tool.

A new assembly design (Figure 5) is proposed for creating cavitation in the internal part of the mill. Blades, a ball valve, and special rubber hoses with fittings capable of withstanding high air pressures inside the flushing liquid have been added to the well milling tool design.

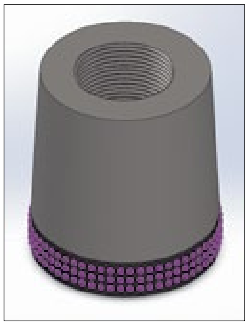


Figure 2a. 3D model of the milling tool
Rysunek 2a. Model 3D narzędzia do frezowania

The assembly of the mill differs from the existing one in the following features:

Downhole milling cutters are designed for continuous milling of metal objects that remain in the wellbore due to accidents during the drilling and milling operations. The cutting portion of the milling cutter is made of crushed particles of a composite alloy and represents the most crucial working component. Consequently, the composite alloy must possess properties that ensure the durability of the milling operations.

The composite alloy, designated for outfitting downhole milling tools, comprises crushed particles of a hard alloy and a binding material. The milling of an emergency object within a well is undertaken for the following objectives:

To clear the wellbore of cemented pump-compressor pipes, rods, drill bits, and other objects through continuous milling (see Figures 2a, 2b).

A blade attachment (Figures 3a, 3b) can be easily fitted into the mixing chamber with tension. The bladed nozzle is mounted on the internal diameter of the milling cutter with tension on the protrusion of the last turn of the drilled groove.

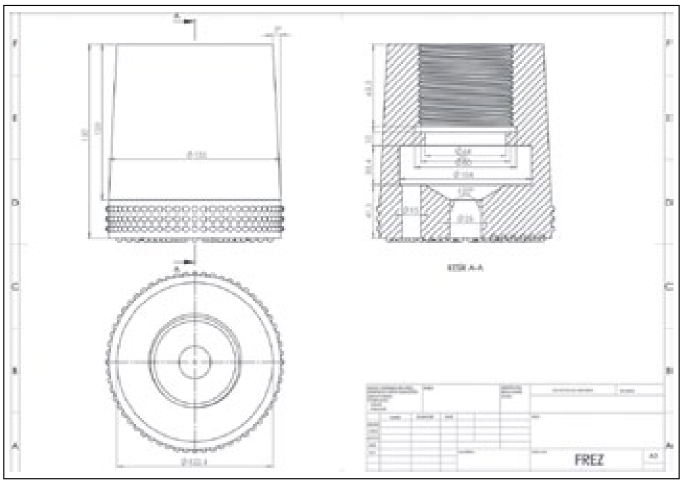


Figure 2b. Sketch of the milling tool
Rysunek 2b. Szkic narzędzia do frezowania

The bladed nozzle is used for two purposes:

1. To supply air under high pressure from the rubber tube into the gas-liquid mixing chamber;
2. To prevent the entry of liquid into the chamber when the air transportation is stopped.

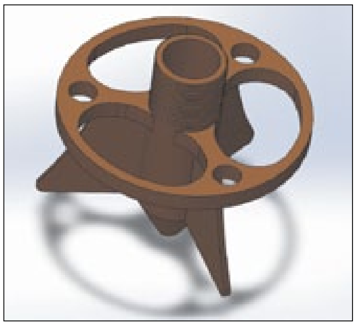


Figure 3a. 3D model of the blade attachment
Rysunek 3a. Model 3D mocowania ostrza

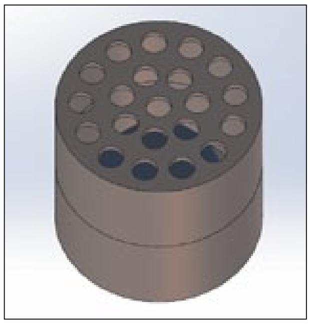


Figure 4a. 3D model of the control valve
Rysunek 4a. Model 3D zaworu sterującego

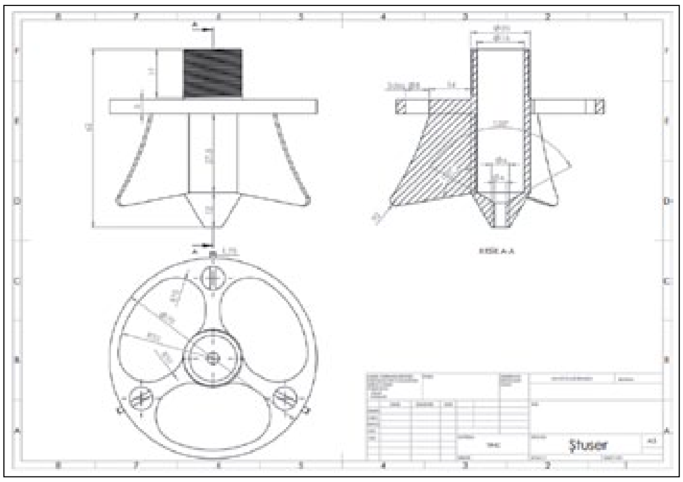


Figure 3b. Sketch of the blade attachment
Rysunek 3b. Schemat mocowania ostrza

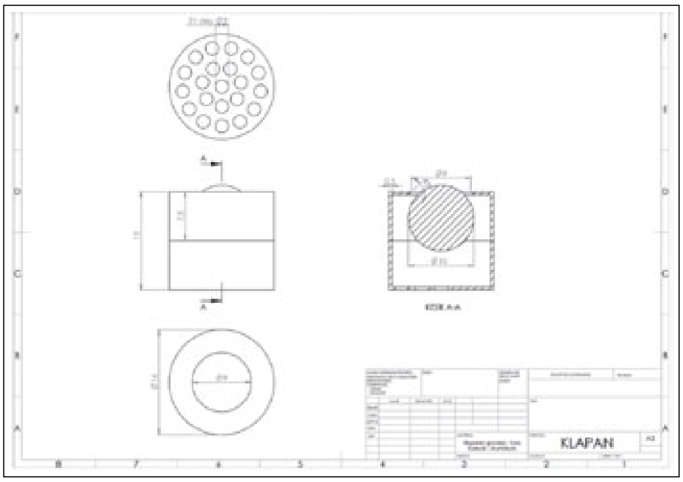


Figure 4b. Sketch of the control valve
Rysunek 4b. Szkic zaworu sterującego

A ball valve is also installed in the chamber (Figures 4a, 4b) to regulate the supply of air and flushing liquid to the displacement zone, i.e., to create cavitation in the required amount.

To regulate the exit of air and washing liquid (creating cavitation) entering the "air-liquid" mixing chamber, a roller valve is installed inside the nozzle. The roller valve serves the following purposes:

1. Ensuring continuous pumping of air into the "air-liquid" mixing chamber;
2. Blocking the washing liquid from entering the chamber when air intake is interrupted.

It should be noted that the pressure of the air entering the chamber is greater than that of the washing liquid.

The assembly design of the milling tool (Figure 5) presented in the new design differs from the existing design in that the capacity of the liquid chamber of the "air-liquid" displacement is relatively larger. Installing the bladed nozzle in the "air-liquid" mixing chamber is straightforward.

A sketch of the milling tool assembly, executed in the new design, is presented in the Figure 5. The proposed new milling tool design is not expensive, and its manufacturing technology is simple.

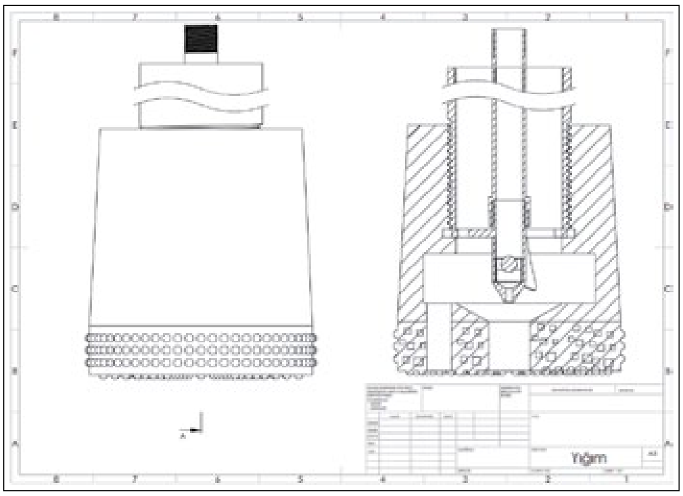


Figure 5. Assembly sketch of the milling tool and blade attachment
Rysunek 5. Szkic montażowy narzędzia do frezowania i mocowania ostrza

After attaching the part to the milling tool structure, research was conducted in accordance with the instructions outlined in (Mustafayev et al., 2023). During the research, the degree of cavitation's impact on objects subject to destruction (metal, rock, petrified cement, etc.) was determined. When cavitation bubbles strike the objects to be destroyed from a certain distance, micro-cracks form on their surface, followed by erosion, leading to disintegration. The structure between the particles is disrupted, cracks grow, and the object either breaks into large pieces or is completely destroyed.

Small particles of rocks and metals are removed by washing out from the destruction zone. Thus, the bottom of the well is cleaned of abrasive or other deposits using cavitation. By applying cavitation, it is possible to save time spent on drilling wells or milling metal objects in the borehole, while also cutting, crushing, handling lifting operations, and flushing the well using rapid technologies.

For pumping air or gas into the "gas-liquid" mixing chamber, special rubber tubes (Figure 6) resistant to high pressures and temperatures were used. These rubber tubes inject air into the chamber mixing gases and liquids, passing inside the drilling pipes. The rubber tubes (length – 10 m; 3-layer; diameter – 6 × 13 mm; working pressure – up to 20 atm; quick-release; weight – 1900 kg; volume 0.003666 m^3) are connected to each other using couplings with brass sleeves, which are resistant to high pressure. One end of the rubber tube is connected to the compressor at the wellhead, while the other end connects the hoses. The transport of liquid and air to the milling zone is controlled by a top drive from the wellhead.

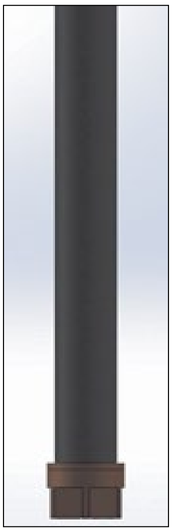


Figure 6. 3D model and sketch of a special hose for air supply

Rysunek 6. Model 3D i szkic specjalnego węża doprowadzającego powietrze

Flushing liquid and air were supplied from the wellhead. As a result of the study, metallic objects with a yield strength of 380–950 MPa were subjected to cavitation. Striking the bubbles against the metallic objects led to the formation of cracks, and in some places, to breakages and destructions.

Fine chips and dirt were removed from the milling zone and lifted from the bottom of the well through cavitation (high-speed air with displacement of the flushing liquid). Thus, the application of cavitation effectively cleans the milling zones, accelerates continuous milling, reduces the time for removing milled elements from the milling zone, ensures the stability of the mill, prevents wear, and streamlines operations when replacing worn-out mills.

The proposed design is cost-effective and easy to manufacture. Temperature in the milling zone and operating conditions can be regulated.

Conclusions

1. As a result of experimental research, nonlinear regression equations were determined.
2. The modified design of the milling tool and the effect of cavitation allow for increased efficiency in drilling, milling, and well flushing.
3. The new milling device enables regulation of the temperatures in the milling zone and the operational parameters of the milling process.

References

Agapova E.G., Bitekhtina E.A., 2012. Processing experimental data in MS Excel: methodical guidelines for laboratory work for full-time students. *Publishing House of the Pacific State University, Khabarovsk*, 32.

Aramcharoen A., Mativenga P.T., Yang S., Cooke K.E., Teer, D.G., 2008. Evaluation and selection of hard coatings for micro milling of hardened tool steel. *International Journal of Machine Tools and Manufacture*, 48(14): 1578–1584. DOI: 10.1016/j.ijmachtools.2008.05.011.

Archontoulis S.V., Miguez F.E., 2015. Nonlinear regression models and applications in agricultural research. *Agronomy Journal*, 107(2): 786–798. DOI: 10.2134/agronj2012.0506.

Aurich J.C., Kieren-Ehses S., Mayer T., Bohley M., Kirsch B., 2022. An investigation of the influence of the coating on the tool lifetime and surface quality for ultra-small micro end mills with different diameters. *CIRP Journal of Manufacturing Science and Technology*, 37: 92–102. DOI: 10.1016/j.cirpj.2022.01.004.

Geistanger A., Braese K., Laubender R., 2022. Automated data analytics workflow for stability experiments based on regression analysis. *Journal of Mass Spectrometry and Advances in the Clinical Lab*, 24: 5–14. DOI: 10.1016/j.jmsacl.2022.01.001.

Goldin A.M., 2002. Statistics. Textbook. *Publishing and Trading Corporation "Dashkov & Co.", Moscow*, 368.

Jacyna J., Kordalewska M., Wiczling P., Markuszewski M.J., 2022. Evaluation of robustness in untargeted metabolomics: Application of multivariate analysis, linear regression and hierarchical modeling. *Journal of Chromatography Open*, 2: 100035. DOI: 10.1016/j.jcoa.2022.100035.

Makarova V.B., Trofimov I.A., 2002, Statistics in Excel: A Study Guide. Finance and Statistics, Moscow, 192.

Milton J.S., Arnold J.C., 2005. Analysis of Statistical Data Using Microsoft Excel for Office XP. *BINOM, Knowledge Lab, Moscow*, 296.

Mustafaev A.G., Aliev E.A., Guseynov K.A., Kerimova L.S., 1997. Thermal regime of milling devices and increasing their efficiency in well repair. *Elm, Baku*, 124.

Mustafayev A.G., Ismayilov M.A., Salimli M.M., Nasirov Ch.R., 2023. Improving the efficiency of the milling tool by reducing the temperature in the milling zone depending on the main mode parameters. *Nafta-Gaz*, 79(12): 764–775, DOI: 10.18668/NG.2023.12.02.

Ondiaka M.N., 2016. Prediction of Behaviour Kinetics and Toxicity of Engineered Nanomaterials in Aqueous Environment Using Neural Networks. *Stellenbosch University*, 256.

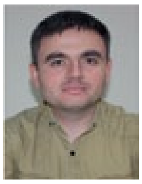
Peltzman S., 2002. Analysis of Data in Excel for Financiers. *Williams Publishing House, Moscow*, 302 .

Pustovoytenko I.P., 1987. Prevention and methods of eliminating accidents and complications in drilling: a training manual for vocational education. *Nedra, Moscow*, 237.

Sigal E., 2002. Practical Business Statistics. *Williams Publishing House, Moscow*, 1056.

Amir Gochu MUSTAFAYEV, Ph.D.
Associate Professor at the Department of Mechanics
Azerbaijan State Oil and Industry University
16/21 Azadliq Ave., AZ1010, Baku, Azerbaijan
E-mail: *mustafaev-1959@mail.ru*

Mahmud Azer ISMAYILOV, Ph.D.
Lecturer at the Department of Mechanics
Azerbaijan State Oil and Industry University
16/21 Azadliq Ave., AZ1010, Baku, Azerbaijan
E-mail: *ismahmud17630@sabah.edu.az*



Mirkamran Mirrahim SALIMLI, Ph.D.
Laboratory assistant at the Department of Mechanics
Azerbaijan State Oil and Industry University
16/21 Azadliq Ave., AZ1010, Baku, Azerbaijan
E-mail: *mirkamran_1979@hotmail.com*

Chingiz Rahim NASIROV, M.Sc.
Master at the Department of Oil and Gas Transportation and Storage
Azerbaijan State Oil and Industry University
16/21 Azadliq Ave., AZ1010, Baku, Azerbaijan
E-mail: *cina-01@mail.ru*