Запропоновано конструкцію магнітної системи ловильного пристрою з сегментними радіально намагніченими постійними магнітами із рідкісноземельних матеріалів. Встановлено раціональні геометричні співвідношення елементів систем, що забезпечують високі силові та магнітні характеристики. Розроблено три типорозміри ловильних пристроїв невеликого діаметру для очищення свердловин від феромагнітних предметів. Проведено експериментальні дослідження силових характеристик магнітних систем ловильних пристроїв

Ключові слова: ловильний пристрій, магнітна система, постійний магніт, вантажопідіймальна сила, тягова характеристика, магнітна індукція

Предложена конструкция магнитной системы ловильного устройства с сегментными радиально намагниченными постоянными магнитами из редкоземельных материалов. Установлены рациональные геометрические соотношения элементов систем, обеспечивающих высокие силовые и магнитные характеристики. Разработаны три типоразмера ловильных устройств малого диаметра для очистки скважин от ферромагнитных предметов. Проведены экспериментальные исследования силовых характеристик магнитных систем ловильных устройств

Ключевые слова: ловильное устройство, магнитная система, постоянный магнит, грузоподъемная сила, тяговая характеристика, магнитная индукция

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DESIGN AND RESEARCH OF FISHING TOOLS WITH RATIONAL PARAMETERS OF MAGNETIC SYSTEMS

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1. Introduction

Security of the national power system is the main objective of the Energy Strategy of Ukraine. In the implementation of this strategy, the important task to be accomplished is a build-up of energy production. One of the promising sources of increasing oil and gas production is the restoration of inactive and abandoned oil and gas wells numbering almost eight thousand in Ukraine. Due to putting into operation the producing horizons which were previously considered unprofitable, it is possible to produce extra 5 to 6 billion cubic meters of gas and 1.5 to 2 million tons of oil annually [1]. In addition, stepping-up of low-flow-rate well productivity can be considered a significant reserve for growth of production volumes.

In restoration of non-operating stock wells, a method of drilling slant and horizontal branch holes has become most widespread. Efficiency of this method is due to lower material and time costs compared with drilling new wells. In this case, most section of the existing wellbore depth and the available field infrastructure are used. The experience gained in successful work of well recovery shows that there is a practical feasibility of restoration of hydrocarbons production to the initial level [2–4].

Drilling of branch holes is preceded by the process of cutting a “window” in the casing string. The metal scrap formed in this process is not completely carried out to the surface by the flow of washing liquid [5]. Insufficient cleaning of the bottom hole from the metal scrap reduces mechanical speed of drilling and causes rapid wear of the drilling bit cutting structure [6]. Besides, the accidents occurring in the process of drilling cause abandonment of metal debris in the bottom holes.

As it is known, one of the effective methods for extracting ferromagnetic metal objects is the use of magnetic fishing tools [7, 8]. Considering the design of wells and the geological and technical conditions of drilling, opening of producing horizons by branch holes is carried out mainly with the help of 120.6–139.7 mm diameter drill bits [3]. Therefore, development of efficient small-diameter fishing tools for cleaning wells from metal debris and objects is definitely a relevant task.

2. Literature review and problem statement

In spite of their numerous disadvantages, tools with permanent magnets are widely used to date to clean the bottom holes from foreign metal objects. For example, in the structures given in [9], one or more cast aluminum alloy magnets placed between two poles are used. Essential disadvantages of the tools are extremely low hoisting capacity because of a considerable dispersion of magnetic field and the tendency of the cast magnets to self-demagnetization. This results in loss of their magnetic and power characteristics during operation and storage.

The authors of work [10] developed tools with permanent ferrite magnets for cleaning bottom holes from metal. Small diameter devices feature a design of the magnetic system containing a central magnetic core in the form of a triangular prism. Permanent magnets are placed between the segment and the central magnetic cores and are connected in parallel to form magnetic circuit. Disadvantages of these tools include scatter of magnetic flux at the corners of the central magnetic core and the open-end faces of the magnets and a low durability of the magnetic system due to a rapid wear of the working surface.

Design and application of rare-earth permanent magnets in magnetic systems has enabled a 2 to 4-fold growth in power characteristics of the fishing tools [11–13]. In this case, the magnetic system designs have not undergone significant changes, so they are characterized by similar disadvantages.

The authors of article [14] have developed an end-face seal-trap which is used to inspect the "head" of the object left in the well with its simultaneous capture and taking off the bottom hole. The dimensional series includes three tools with external body diameter from 114 mm to 132 mm and a conditional hoisting capacity of 5.5 to 7.0 kN. Disadvantages of the seal-traps include reduction of fishing capacity because of presence of an operating clearance between the object and the system formed by a lead pad.

Rare-earth Nd-Fe-B permanent magnets are used for the fishing tools described in [15]. The magnetic system installed in a diamagnetic shell consists of two permanent magnets mounted between the magnetic cores. The hoisting capacity of the 118-mm diameter device is 5.9 kN. Despite their simple design, such systems have a significant disadvantage. They are characterized by high scatter of magnetic flux on the outer surfaces of the opposite magnetic cores.

Analysis of papers [9–15] indicates that all designs of magnetic systems in fishing tools have certain disadvantages. Although replacement of cast and ferrite permanent magnets by rare-earth magnets significantly increased the hoisting capacity of devices [14, 15], they contain significant apparent magnetism on non-working surfaces. For effective fishing of metal objects, it is necessary to concentrate the entire magnetic flux on the working surface of the system and direct it to the bottom hole. That is, effectiveness of devices with permanent magnets affects both the design of the magnetic system and the materials used in it.

It was also found that it is advisable to use armored systems characterized by a minimal scatter of magnetic field in fishing tools. The known designs of such systems include laminated permanent magnets arranged between a multifaceted prism made by central and peripheral magnetic cores [10–13]. Given this, development of effective armored systems is of considerable practical and scientific interest.

Strong demagnetizing factor of armored systems requires the use of high-coercivity magnets. Rare-earth neodymium permanent magnets have the best properties among magnetically hard materials [16]. Therefore, it is advisable to use these magnets in fishing tools to provide high power and magnetic characteristics. In this case, a special attention has to be paid to the choice of the magnet shape and magnetic cores and establishment of rational geometric parameters of the magnetic system elements.

3. Objective and tasks of the study

This work objective was to work out new designs of fishing tools of enhanced efficiency for cleaning wells from ferromagnetic objects during cutting "windows" in the casing and in the process of drilling branch holes.

To achieve this goal, the following tasks had to be solved:

– develop designs of magnetic systems with an efficient use of power of the permanent magnets;

– establish rational geometrical interrelations of the magnetic system elements to provide high power characteristics of the tools;

– conduct experimental study of power characteristics of the developed fishing tools.

4. Development of a design and a procedure of theoretical and experimental research of magnetic system power characteristics

4. 1. Development of designs of small-diameter fishing tools

At the initial stage of development of fishing tools, it was necessary to specify outside diameter which should be 0.85–0.95 diameter of the well. Taking into account the fact that branch holes are mainly drilled with 120.6–139.7 mm diameter bits, it was proposed to develop tools of three sizes with outside diameters of 90 mm, 103 mm, and 115 mm. They will provide for cleaning of wells from the metal scrap produced during cutting windows in casing columns of 114 mm, 127 mm, and 140/146 mm diameter, respectively.

Magnetic system is the main assembly on which operation efficiency of the fishing tool depends. Outside diameters of the systems were determined from the condition of providing required strength of fishing tools and made up, respectively, 73 mm, 81 mm, and 94 mm.

The magnetic fishing tool (Fig. 1) consists of adapter 1 for connection with a drill pipe column and a housing 2 within which a magnetic system is mounted. The teeth cut in the lower part of the housing are designed to destroy the layer of slime on the bottom hole and direct metal objects to the work surface of the magnetic system.

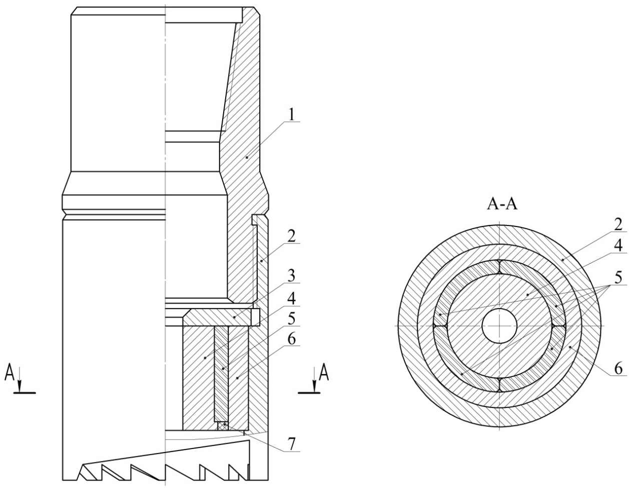

Fig. 1. Schematic diagram of a magnetic fishing tool: adapter (1); housing (2); cover (3); central magnetic core (4); permanent magnets (5); peripheral magnetic core (6); resin (7)

The magnetic system contains cylindrical central 4 and peripheral 6 magnetic cores between which segmented permanent magnets 5 are placed. To generate opposite polarity of magnetic cores 4 and 6, radially magnetized permanent magnets with anisotropic properties in the radial direction are used in the system. The work [13] substantiates feasibility of using rare-earth $Nd_2Fe_{14}B$ magnets in the systems of fishing tools. Therefore, neodymium magnets of N38 brand with a maximum energy product up to 303 kJ/m^3 and a residual flux density of 1.26 T were used for the systems.

A hole is provided in the central magnetic core 4 for supplying washing liquid to the well during fishing works. After all, metal objects in the bottom hole are mainly found in a layer of slime. Its presence hinders capture of ferromagnetic objects. During drilling of soft or medium hardness rocks, fragments can be squeezed into the well walls or the bottom hole. The flushing liquid also cools the magnetic system. This makes it possible to operate the fishing tool at temperatures exceeding the operating temperature of the permanent magnets.

The magnetic system is mounted in housing 2 by means of a diamagnetic cover 3 and a collar in the bottom of the housing. The clearance between magnetic cores 4, 6 and magnets 5 is filled with high-temperature resin 7 on an epoxy base, which provides rigidity for the magnetic system and prevents corrosion and erosion of the system elements.

4. 2. Methods for conducting theoretical research

Conventional hoisting capacity is an indicator of the purpose of magnetic fishing tools. It is determined by tear-off of the magnetic system from a steel plate completely contacting the working surface. This indicator is the main criterion for determining technical level of the fishing tools. To calculate the hoisting capacity, the ANSYS Maxwell software complex in which the method of finite elements was implemented was used.

At the first stage, research was conducted to choose a rational length of the permanent magnets. The developed systems employed radially magnetized permanent magnets for which length was determined by the difference between the outer and inner radii of the segments. In the Solid Works programming environment, three-dimensional models of magnetic systems with outside diameters of 73 mm, 81 mm, 94 mm and different magnet lengths, namely 4 mm, 6 mm, 8 mm, 10 mm, were constructed. In the ANSYS Maxwell 16.0 software, the force acting on the ferromagnetic plate for operating clearances between the plate and the system in the range from 0.01 mm to 8 mm was determined for each of the system variants. Since large gradients of magnetic field appear at small clearances, a greater number of points of calculation were set in the interval up to 1 mm. The Maxwell software takes into account nonlinear properties of materials, so the characteristics of the permanent magnets were set by demagnetization curves. Properties of the magnetic cores, which operate in the magnetic systems at a saturation limit, were indicated by magnetization curves.

To determine height of the magnetic system, which is characterized by the maximum use of energy of permanent magnets, a similar problem of finding the hoisting capacity was solved. The height of the magnetic systems was set parametrically in the range from 20 mm to 100 mm in a step of 5 mm. The operating clearance between the plate and the system surface was 0.01 mm.

Upon establishment of rational length of the magnet and height of the magnetic system, traction characteristics of the systems were constructed and their reliability was verified in experimental study.

4. 3. Procedure for conducting experimental research

The most common method of determining the hoisting capacity of the magnetic systems for a certain operating clearance or its absence is implemented with the help of a tear-off machine [17]. To determine traction characteristics, clearance was set by the use of non-magnetic gaskets that requires an additional time. Besides, this method has an insufficient accuracy.

Therefore, study of the magnetic system power parameters was carried out on a Gotech-AI7000-M universal testing machine which provides real-time recording of the separation force depending on the size of the operating clearance. For the experiment, a scale with a maximum force of 10 kN was taken. The permissible measurement error was ±0.5 %.

The research was conducted by separating the designed magnetic systems from the test plates made of steel 10 secured in the bottom grip of the machine. The plate diameter corresponded to the diameter of the magnetic system, and thickness was not less than the intrapolar distances. The magnetic system was shifted with a rod fixed in the top grip of the machine. In the end of the experiment, the obtained values of the hoisting capacity in the operating clearance were uploaded to the computer for their processing and construction of traction characteristics.

5. Results obtained in the research of the magnetic system power characteristics

According to the results of theoretical research, the hoisting capacity values of the magnetic systems with various magnet lengths were obtained for the specified operating clearances. To construct tractive characteristics, a polynomial approximating function of the fourth degree was taken with approximation validity $R^2>0.99$ for all curves.

In a 94-mm diameter magnetic system, hoisting capacity reached a maximum of 9.44 kN at magnet lengths of 4 mm (Fig. 2). With increase in the magnet length, the attractive force decreased at a zero clearance, which is explained by smaller surface area of the magnetic cores. The hoisting capacity of systems with different lengths of magnets was approximately equal at operating clearances of 0.3–0.5 mm. However, with increase in clearance, the system with 10 mm long permanent magnets had the greatest force. This is due to an increase in convexity of the magnetic field which depends on the intrapolar distance. Accordingly, the system with 4 mm long magnets had a much steeper tractive characteristic.

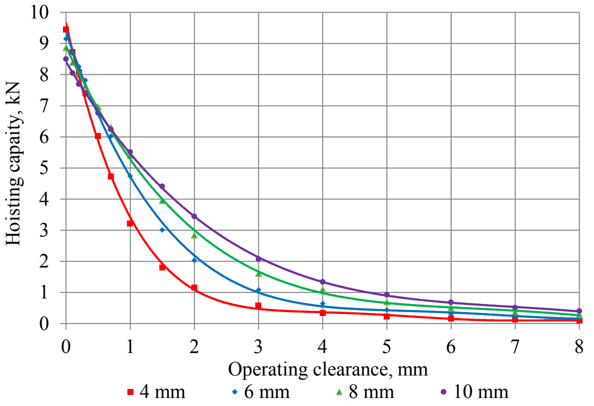

Fig. 2. Tractive characteristics of 94 mm diameter systems with magnets of different lengths

The total area of the magnetic cores of one pole must correspond to that of the other pole for a uniform distribution of magnetic flux density in the cross sections of the magnetic cores. This requirement was provided for all variants of the magnetic systems.

To determine the rational system dimensions at which maximum use of the permanent magnet power takes place, a research of the hoisting capacity for a 20 to 100 mm high system has been carried out. Analysis of results obtained in the study (Fig. 3) gives grounds to assert that the curves constructed for magnetic systems with different diameters had a similar character. For example, the hoisting capacity increases sharply with an increase in the system height up to 40 mm. The further force growth is negligible as the magnetic cores get saturated and magnetic resistance of the magnetic flux passageway increases accordingly. This is also confirmed by the fact that when the system height reaches 60 mm, a gain in force with an increase in the system size by 5 mm is less than 1 %.

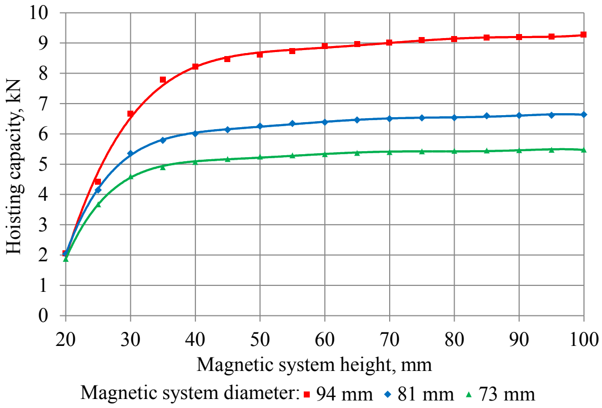

Fig. 3. Dependence of the hoisting capacity on the height of the magnetic systems

For the developed magnetic systems with defined rational geometrical dimensions, we obtained the character of distribution of magnetic flux density over the surface and in the section of the system during interaction with the ferromagnetic plate (Fig. 4). Particular attention should be paid to the process of transformation of magnetic flux density which results in a growth of its value on the working surface of the system up to 2.1 T. It should be noted that steel 10 with saturation flux density up to 2.13 T was used for making magnetic cores. That is, it appears reasonable to say that the operating surface of the magnetic cores was in a state close to saturation.

Fig. 5 shows tractive characteristics of the magnetic systems. With an increase in the operating clearance, a sharp decrease in hoisting capacity occurs. This feature is inherent for all armored-type systems which, in fact, include the developed magnetic systems. However, despite the relatively small length of the magnets, high force values are preserved for operating clearances up to 4 mm. This enables capture of metal objects from the slime layer. The maximum value of the hoisting capacity increases with an increase in the outside diameter of the device because the operating surface area of the magnetic cores increases.

Discrepancy between the results of theoretical and experimental research of magnetic system tractive characteristics measured 6 % to 8 %. This indicates correctness of the calculation method and the proper choice of the experimental procedure.

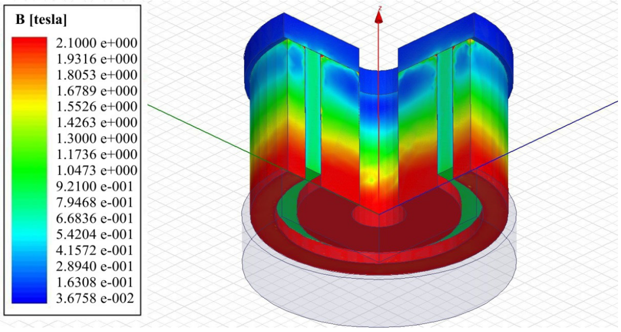

Fig. 4. Distribution of magnetic flux density in a 94-mm diameter system

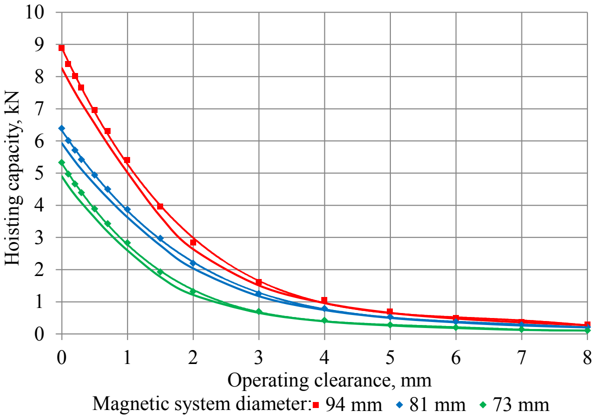

Fig. 5. Tractive characteristics of the magnetic systems

6. Discussion of the results obtained in the study of the hoisting capacity of the fishing tools magnetic systems

As it is shown by the results of experimental research (Fig. 5), the obtained designs of 90, 103, and 115 mm diameter fishing tools possess high power characteristics. For example, concerning the main indicator of their purpose, that is, hoisting capacity, they are 4 to 6 times superior to their counterparts with cast and ferrite magnets and 25 to 35 % better than those of the known tools with rare-earth permanent magnets [10–13]. Compared to the tools based on rare-earth magnets, the gain in force was achieved through the use of a magnetic system of an optimal design and rational geometric ratios.

Interesting and at the same time contradictory results obtained in the research of choice of a rational length of permanent magnets are demonstrated on the example of a 115 mm outside diameter magnetic system for a fishing tool (Fig. 2). Magnetic fishing tools should have a maximum possible hoisting capacity to catch all ferromagnetic objects found in the bottom wells. According to the Maxwell formula, the maximum force is provided by increasing the area of the poles through which the magnetic flux approaches the object being captured. That is, the use of smaller (for example, 4 mm) length magnets (Fig. 2) will ensure satisfaction of this requirement. However, in a presence of clearance between the objects and the magnetic system, it is necessary to create a magnetic field sufficient to attract the objects. Hence, along with the hoisting capacity, the attractive force which characterizes the measure of force action on the subject at a distance from the system and is estimated by the tractive characteristic is important for the fishing systems.

Extension of the zone of interaction between the magnetic field and ferromagnetic objects can be reached by increasing the intrapolar distance, that is, by the use of permanent 10 mm long magnets (Fig. 2). Because of the limited dimensions of the system, this reduces the area of the working surface of the poles and, consequently, the fall of the total hoisting capacity. Thus, an attempt to improve the hoisting capacity invariably leads to a decline of the attractive force in the operating clearance.

The systems of magnetic fishing tools are intended for attraction, holding, and lifting metal objects to the surface. In any case, it is necessary to achieve a direct contact of the ferromagnetic objects with the working surface of the system. This is provided by a thorough destruction and washout of the slime layer with boring bits. However, the debris found in the bottom well have an irregular geometric shape that brings about a small area of contact with the surface of the magnetic system. Therefore, the 8 mm long permanent magnets were chosen for a 94-mm diameter magnetic system to ensure reliable capture and holding of metal fragments in the course of their lifting to the surface.

Similar research has found that permanent 8 mm long magnets should also be used in a 81 mm diameter system and that 6 mm long magnets are appropriate for a 73 mm diameter system.

The cost of a magnetic system is more than 50 % of the tool cost, mainly due to the high price of rare-earth neodymium permanent magnets. Therefore, rational use of the permanent magnet power is of high importance. The required magnetic fields should be created by the systems with minimal cost on materials. This will provide high power characteristics of the tools on the one hand and the minimum costs on the other hand.

The high values of the hoisting capacity are achieved provided that the maximum possible magnetic flux density values are created in the magnetic cores. In order that the magnetic cores be in a saturated condition, it is necessary that the permanent magnets created a magnetic flux exceeding throughput of the magnetic cores. As is known, permanent magnets create a flux proportional to the residual flux density of the material and the area of the poles. At fixed dimensions of permanent magnets, it is only possible to change the area of poles by changing height of the magnets and the system as a whole.

As the results show (Fig. 4, 5), saturation of the magnetic cores occurs in the systems with a height of 40 mm to 60 mm. Further increase in height does not lead to a significant increase in force since the magnetic flux is spent on the apparent magnetism on the non-working area of the magnetic force. Thus, the high power characteristics of the developed systems can be obtained in the specified range and an increase in the size of the system will lead to an unreasonable consumption of materials.

Experimental research into the hoisting capacity was carried out on a tear-off machine by separating the test plate made of Steel 10 in a condition of a complete coverage of the working magnet system surface. In real conditions of fishing works, the shape, weight, and location of the objects found in the well are rather manifold. In addition, the debris materials (alloyed steels, pig irons, hard alloys) possess varied magnetic properties. In view of this, it is advisable to carry out appropriate research. This will confirm the possibility of extracting the bit roller cones and legs, elements of supports and armament of the bits including those made of hard alloys and other objects that have weak ferromagnetic properties. It is also important to determine impact of operating factors: washing liquid, temperature, hydrostatic pressure, vibration, and other impacts on the power characteristics of magnetic systems.

7. Conclusions

1. Designs of armored magnetic systems were developed and small-diameter fishing tools of three standard sizes were worked out on their basis. The systems are characterized by a uniform distribution of magnetic flux density over the working surface and the minimum apparent magnetism. This was achieved by the use of segmental radially magnetized permanent magnets of rare-earth materials mounted between the magnetic cores of a cylindrical form with opposite polarity.
2. According to the results of theoretical research, rational geometric parameters of magnetic systems, namely, the length of permanent magnets and the height of the magnetic system were determined. It was established that high power characteristics are provided at a minimum material consumption for magnetic systems with a height of 40 mm to 60 mm. The length of the permanent magnets affects both the maximum hoisting capacity and the value of the operating clearance. Rational lengths of permanent magnets for each diameter of the magnetic system were substantiated taking into account the factors influencing the process of fishing metal objects.
3. It was found in the course of experimental research that the developed fishing tools had 25–35 % higher hoisting capacity than the known counterparts with rare-earth permanent magnets. Comparison of the obtained values with the results of theoretical research confirmed correctness of the method applied. Discrepancy of the results did not exceed 10 %.

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