Modeling and calculation of magnetic systems of borehole grappling tools

Liubomyr Romanyshyn

PhD, Professor of Oil and Gas Equipment Department,
Ivano-Frankivsk National Technical University of Oil and Gas,
Ivano-Frankivsk, Ukraine
E-mail: romanyshynl@gmail.com

Taras Romanyshyn

PhD, Associate Professor of Oil and Gas Equipment Department,
Ivano-Frankivsk National Technical University of Oil and Gas,
Ivano-Frankivsk, Ukraine
E-mail: tarasromanushun@gmail.com

Tetiana Vengryniuk

PhD, Assistant Lecturer of Oil and Gas Equipment Department,
Ivano-Frankivsk National Technical University of Oil and Gas,
Ivano-Frankivsk, Ukraine
E-mail: tanay9@i.ua

Abstract
The methods of calculation of magnetic fields are analyzed and advantages of finite elements method use for design and calculation of magnetic systems of borehole grappling tools are proved. By results of three-dimensional modeling, the rational sizes of elements of magnetic system with the minimum stray fluxes are determined. Process of redistribution of magnetic fluxes in case of interaction of magnetic system with ferromagnetic object is investigated.
Key words: MAGNETIC GRAPPLING TOOL, MAGNETIC SYSTEM, METHOD OF FINITE ELEMENTS, PERMANENT MAGNET, CERRYING CAPACITY, MAGNETIC INDUCTION

The accidents happening in the course of construction and operation of oil and gas wells are characterized by big variety; as a result, there are metal fragments of various shape and mass at the bottom [1, 2]. For clean out of wells from the metal objects with ferromagnetic properties magnetic grappling tools are used. Their operating principle absolutely differs from other grappling tools and consists in interaction of magnetic field with ferromagnetic objects; thereby, they are caught by magnetic system.

Important task in the course of design of systems of grapping tools is calculation of magnetic fields. Inaccuracies in calculations can lead to establishment of the irrational sizes of elements of magnetic systems, and, as a result, to inefficient use of energy of permanent magnets.

Methods of magnetic fields calculation can be divided into three main groups: analytical, graphic and numerical. In analytical methods of calculation, approximate mathematical expressions which can be obtained only for simple magnetic systems are used. Graphic and graphic-analytical methods give opportunity to calculate parameters of magnetic field in more complex constructions; they are characterized by demonstrativeness and high accuracy in comparison with analytical methods [3-5]. However, they are cumbersome and inconvenient, their implementation requires a lot of time for creation of pictures of the system fields; it reduces possibility of research of magnetic fields. Currently, numerical methods including finite elements method, finite difference method and integral equation method [6-7].

For calculation of magnetic systems of grappling tools, all the presented methods [4-8] were used earlier. Low accuracy of calculations and mathematical problems are inherent in the first two methods as the designed systems are nonlinear, and their parameters depend on sizes and properties.

The obtained equations are rather complicated; therefore, it is reasonable to perform calculation only in case of complete computer program. In the paper [6], the two-dimensional finite-element model of magnetic grappling tool is developed in variational formulation. On its basis, calculation and design of magnetic systems are performed with use of specially developed program of calculation on PC (personal computer). The supposition that model geometry, media properties and parameters characterizing field sources are not changed in the direction of one of axes is the main disadvantage of two-dimensional calculation. This is significant restriction when calculating systems of grappling tool, for which only three-dimensional modeling is acceptable.

Regardless of wide-spread use of power magnetic systems including systems on the basis of permanent magnets, calculation method continuous to be complicated even for simple constructions. At present, requirements to quality of magnetic fields calculation have considerably raised; and with increasing frequency, it is necessary to solve parametrical and optimizing problems. One variant of improvement of method of magnetic systems calculation is use of the finite elements method (FEM) for modeling of magnetic field.

In course of calculation of FEM, the area of magnetic field is divided into separate parts with small sizes which are finite elements. The main idea of FME is that any continuous value (induction or intensity of a magnetic field) to be approximated by discrete model which is formed by the set of piece continuous functions determined by finite number of elements [9]. Advantage of FME is possibility of calculation of objects fields with complex geometry; these are systems of grappling tools with nonlinear properties of materials. Moreover, it is not difficult to reduce the dimensions of finite elements in the areas with big gradients of the field; it will increase result accuracy.

On the basis of analysis of the existing calculation methods of magnetic fields, it is possible to claim that FME is the most reasonable method for design and research of magnetic systems of grappling tools. This method is implemented by many software tools; however, specialized products including ANSYS Maxwell are the most suitable for calculation and magnetic fields formation. The unique algorithms, which are put in this program complex, give the opportunity to solve linear and nonlinear three-dimensional magnetostatics problems quickly and with high accuracy [10].

Design of magnetic systems presupposes the selection of materials of permanent magnets and magnetic conductors, configuration and optimum sizes of elements of systems. It is necessary to consider the operating conditions of tools in well bottom, namely, occurrence of washing liquid and slime layer between objects and system, temperature and others. High characteristics of magnetic grappling tools can be obtained by the selection of modern materials of high quality or improvement of design; this will provide a significant amount of magnetic systems variants.

Thus, the research objective is determination of rational geometrical ratios of permanent magnets and magnetic conductors, which on the one hand, will provide high power characteristics of tools, and on the other hand, maximum use of energy of permanent magnets and their minimum cost.

Magnetic systems of grappling tools consist of permanent magnets and magnetic conductors transforming and directing magnetic flux to working area of the tool. The permanent magnet forms the flow proportional to residual induction of material and area of magnet poles. The magnetic flux in magnetic conductor is proportional to the area of its section and induction of material saturation. It is necessary for the permanent magnet to form a magnetic flux which must be higher than the capacity of magnetic conductors, so that magnetic conductors to be in saturated state. In this case, we obtain the maximum carrying capacity (effort of magnetism) of the grappling tool which can be found by the formula

$$F = \frac{B^2 S_n}{2\mu_0}, \quad (1)$$

where B - magnetic induction in working gap, T;

S_n – area of working surface of magnetic system poles, m

$\mu_0 = 4\pi \cdot 10^{-7}$ – magnetic conductivity of vacuum (magnetic constant), H/m.

According to a formula (1), effort of magnetism is proportional to a square of magnetic induction and area of magnetic conductors. Therefore, magnetic conductors must occupy the great part of working surface of magnetic system.

It should be noted that expression (1) can be used for calculation only under condition of uniform magnetic field in a gap between magnetic system and attracted object that mostly does not occur. Therefore, effort of magnetism will be found by means of the program ANSYS Maxwell complex.

In grappling tools systems, the magnetic field is formed by permanent magnets. According to specified properties of materials, magnetic field distribution depends on spatial distribution of magnetic conductivity. The solution of magnetostatic problem is determined by the well-known equations of Maxwell:

$$rot\ \vec{H} = \vec{J}, \quad (2)$$

$$div\ \vec{B} = 0, \quad (3)$$

where $\vec{H}(x,y,z)$ – magnetic field strength;

$\vec{J}(x,y,z)$ – current density;

$\vec{B}(x,y,z)$ – magnetic induction.

Besides, the following dependence is used:

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) = \mu_0 \cdot \mu_r \cdot \vec{H} + \mu_0 \cdot \vec{M}_p \quad (4)$$

where $\vec{M}_p(x,y,z)$ – permanent magnetization;

μ_r – relative magnetic conductivity.

Nonlinear properties of permanent magnets as well as soft magnetic materials are considered in calculations of Maxwell. In case if permanent magnets work below “knee” of demagnetization curve, Maxwell gives the opportunity to obtain the solution based on operating point calculated earlier. Magnetic conductors in magnetic systems work near saturation; therefore, properties of materials need to be set by magnetization curves. The nonlinear tensor of magnetic conductivity is obtained with their help, it is used in iterative process of Newton-Raphson solution:

$$\vec{B} = \vec{B}_0 + [\tilde{\mu}] \cdot (\vec{H} - \vec{H}_0), \quad (5)$$

$$[\tilde{\mu}] = \frac{\partial}{\partial \vec{H}} \vec{B} = [\Delta\tilde{\mu}] + [\mu], \quad (6)$$

where $\vec{B}_0$ and $\vec{H}_0$ – previous solutions of magnetic field;

$[\Delta\tilde{\mu}]$ – total complete tensor.

For $[\mu]$ the following definition is presented:

$$[\mu] = \begin{bmatrix} \mu_x & & \\ & \mu_y & \\ & & \mu_z \end{bmatrix}, \quad (7)$$

where μ_x, μ_y, μ_z consider anisotropic properties of material.

In course of solution of three-dimensional magnetostatic problems, the magnetic field $\vec{H}$ with the following components is considered:

$$\vec{H} = \vec{H}_p + \nabla\varphi + \vec{H}_c, \quad (8)$$

where φ – magnetic scalar potential;

$\vec{H}_s$ – local solution obtained by value assignment to grid edges established by Ampere's law for all contour lines of tetrahedrons faces in grid;

$\vec{H}_c$ – field formed by permanent magnets.

Magnetic force (interaction of magnetic field with ferromagnetic object) is calculated in ANSYS Maxwell by the principle of virtual work. According to Figure 1, force applied to plate 6 is equal to derivative energy of magnetic field by the coordinate, which tends to be changed by force:

$$F_p = \frac{dW}{ds}, \qquad (9)$$

where W – magnetic coenergy of system;

s – working gap;

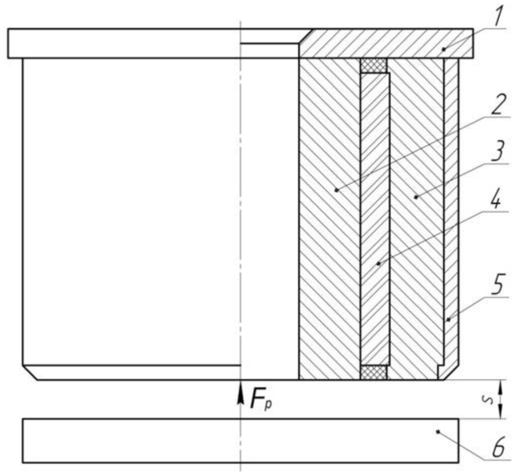


Figure 1. The scheme of determination of force applying to the object

Magnetic coenergy for nonlinear materials is determined as follows:

$$W_c = \int_V \left(\int_0^H B \cdot dH \right) dV . \qquad (10)$$

Theoretical researches of ratios of magnets sizes were conducted for system with external diameter of 150 mm (Figure 1), consisting of diamagnetic cover 1, central magnetic conductor 2 in the form of quadrangular prism and four segment magnetic conductors 3 of opposite polarity, between which permanent magnets 4 are arranged. The plug 5 is made of ferromagnetic material, therefore it performs function of magnetic conductor. In the paper [11], expediency of use of rare-earth permanent magnets in systems of grapping tools is proved; therefore, neodymium magnets of brand N38 are selected for research.

In the medium of Solid Works program, three-dimensional models of magnetic systems with various lengths of magnets, namely 6 mm, 8 mm, 10 mm and 12 mm (Figure 2) are developed. Calculation of each option of systems was carried out by finite elements method in a package of ANSYS Maxwell program, where the task of finding force applying to ferromagnetic plate for gap, which was set parametrically, was solved. By results of calculation, traction characteristics were developed, this is dependence of carrying capacity on the size of working gap, by which efficiency of each system was evaluated.

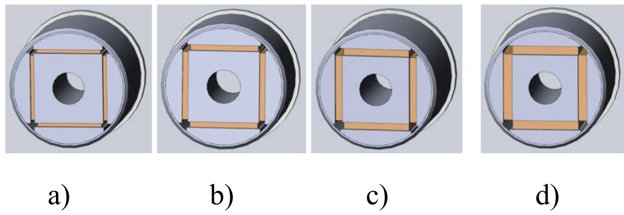


Figure 2. Models of magnetic systems with diameter of 150 mm with a length of magnets of 6 mm (a), 8 mm (b), 10 mm (c) and 12 mm (d)

The analysis of traction curves (Figure 3) has shown that the maximum values of carrying capacity with various length of magnets are almost identical to systems. With increase in working gap, capacity is decreasing more slowly for system with magnets of 12 mm length. It is explained by higher of level of magnetic field camber which depends on distance between poles; certainly, the distance will be higher for this system. Systems with magnets of 6 mm and 8 mm long have much more sharp traction characteristic. It is known that magnets of small length are less thermostable, that is irreversible magnetic losses take place at lower temperature, than in the magnets of bigger length made of the same material. Therefore, it is unreasonable to use magnets of 6 mm and 8 mm long in the systems.

In order to achieve uniform distribution of magnetic induction in the section of magnetic conductors, it is necessary that the total area of magnetic conductors of one pole coincide with the second one [4]. In case of system with the central quadrangular magnetic conductor, its area must be equal to area of four segment magnetic conductors and plug. This condition is satisfied for composition of system by permanent magnets of 10 mm long. So, for magnetic system with diameter of 150 mm, the optimum length of magnets of 10 mm is established.

In calculations of selection of rational length of magnet, height of magnetic system was accepted equal to 100 mm. For determination of the rational sizes of system, at which energy of permanent magnets will be used as much as possible, the researches of carrying capacity of systems from 40 mm to 120 mm in height were conducted.

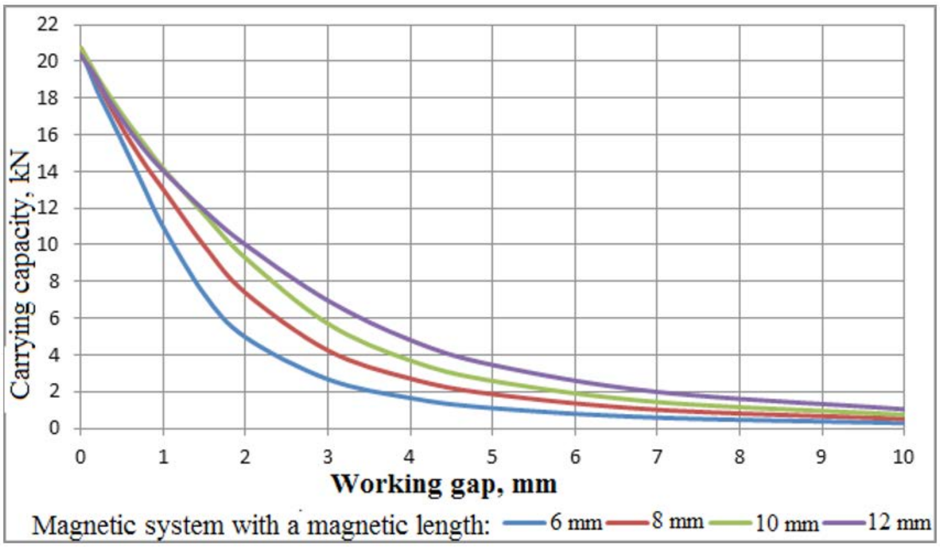


Figure 3. Traction characteristics of systems with a diameter 150 mm with magnets of different length

Results (Figure 4) show that carrying capacity increases considerably with increase in height of system from 40 mm up to 80 mm. With increase in height of system from 80 mm to 120 mm, the strength gains is only 1-2%. Thus, high power characteristics of system with a diameter of 150 mm can be obtained in the range of heights from 70 mm to 80 mm. Further increase in height of system leads to unreasonable consumption of materials.

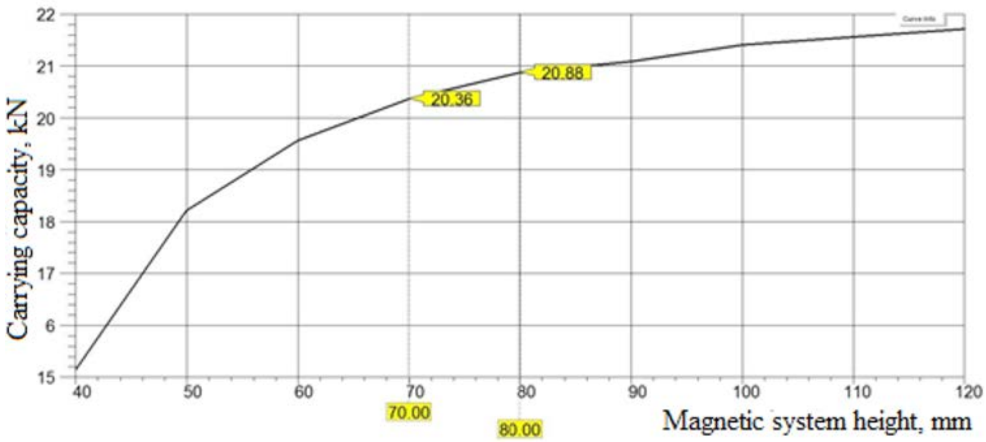
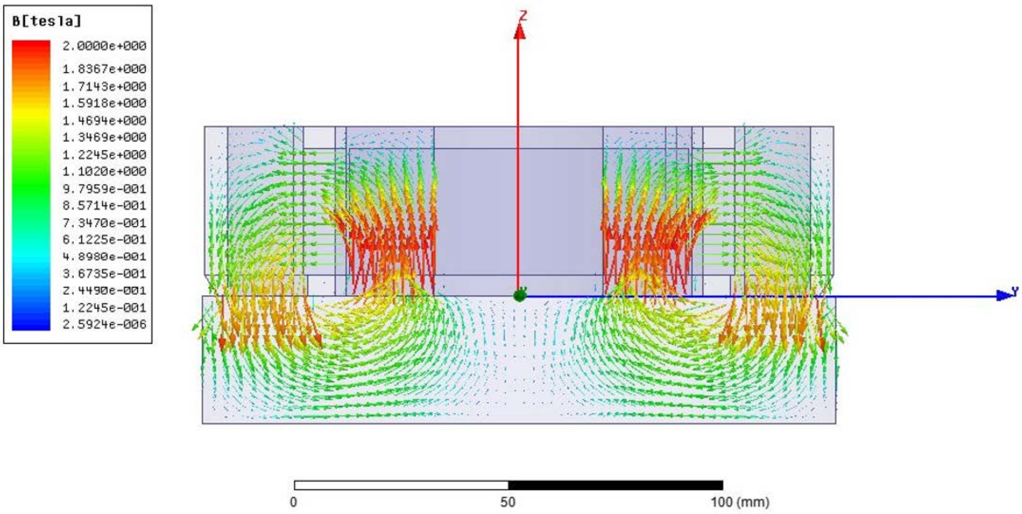
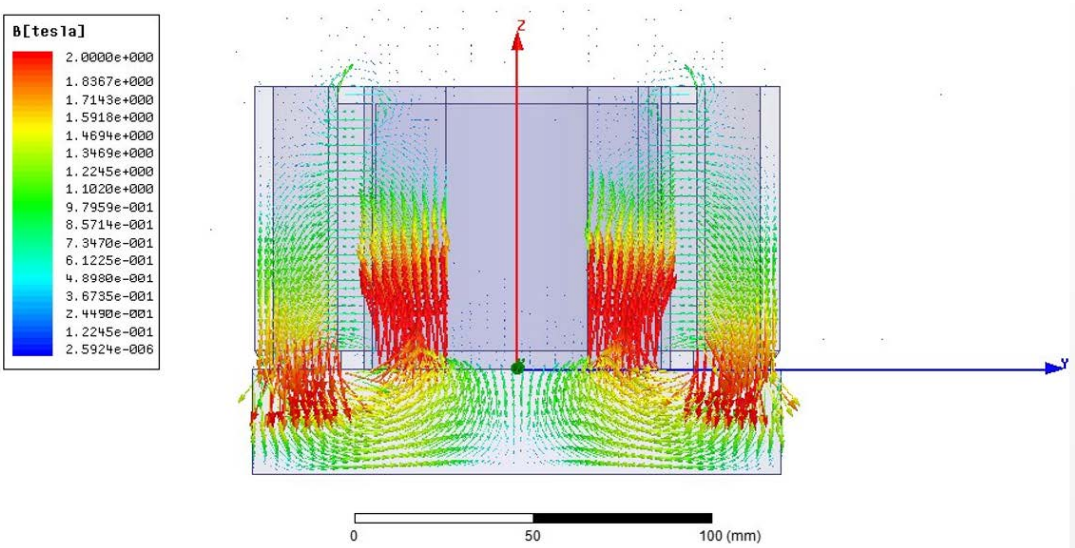


Figure 4. Dependence of carrying capacity on height of magnetic system with diameter of 150 mm

The important characteristic of magnetic systems is the dispersion coefficient, that is the ratio of complete magnetic flux, which is formed by permanent magnets, to useful one, which is carried to working gap. The less stray fluxes are, the more effective the system is, as the most part of flux performs useful work of magnetizing metal objects. According to Figure 4, the systems, which are less than 70 mm in height do not allow obtaining high carrying capacity. It confirms the vector graphic of distribution of magnetic induction (Figure 5, a), where it is seen that the system, which is 40 mm in height, forms insufficient magnetic flux. With increase in height of system up to 80 mm, the area of permanent magnets poles grows and the magnetic flux grows consequently (Figure 5, b). Saturation of material of magnetic conductors takes place that allows obtaining high values of carrying capacity. During further increase in the sizes of system, the magnetic resistance of the area, where magnetic flux passes, increases that leads to growth of fluxes of magnetic field dispersion in non-working and lateral surfaces of system (Figure 5, c). Therefore, systems of 70-80 mm in height give the opportunity to use properties of materials of magnetic system as much as possible and to reduce dispersion fluxes.



a)



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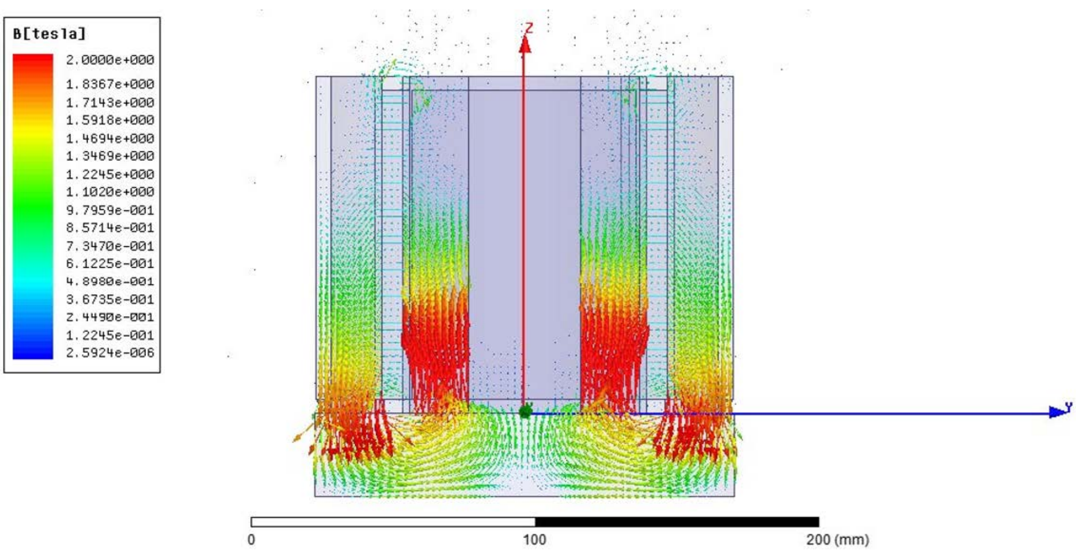

c)

Figure 5. Vector graphics of magnetic induction distribution of systems of 40 mm (a), 80 mm (b), 120 mm (c) in height

For the purpose of establishment of areas with the maximum density of magnetic field and also dispersion of magnetic fluxes, calculations of 70 mm system model were carried out. The obtained results show (Figure 6) that maxima of magnetic induction in non-operating state are observed on edges and tops of magnetic conductors that is explained by the highest density of power lines. Therefore, the small objects, which can be caught, will be on these areas, leaving washout hole in open state. Distribution of magnetic induction is identical in the working and non-working surfaces of magnetic system. When modeling of process of magnetic system interaction with ferromagnetic plate (Figure 7), redistribution of magnetic field in magnetic conductors takes place, consequently the induction in working surface of system reaches value of 2.1 T, i.e. magnetic conductors in the lower part are in the state close to saturation.

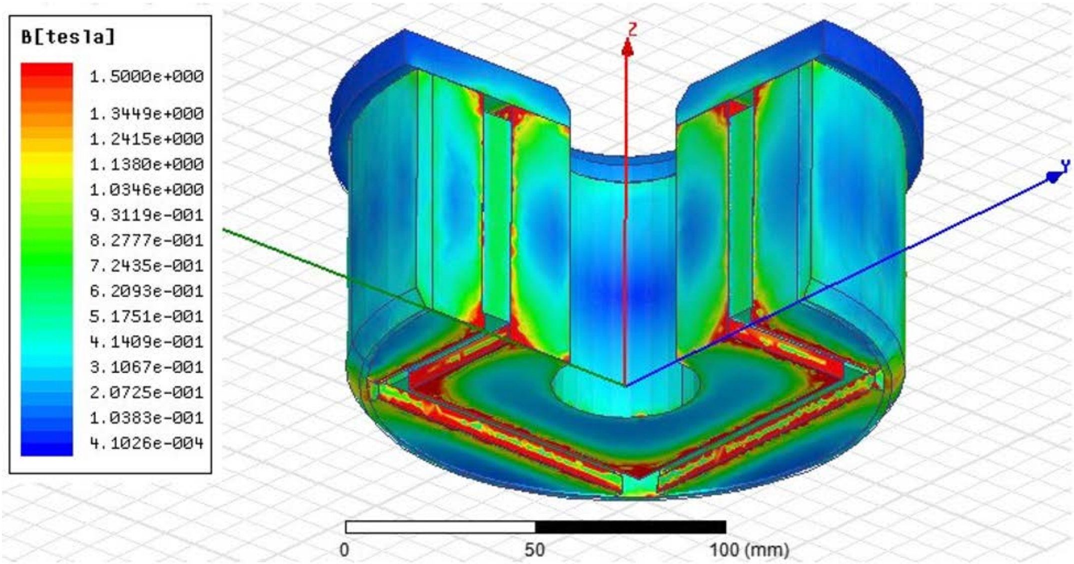

Figure 6. Distribution of magnetic induction in system without ferromagnetic plate

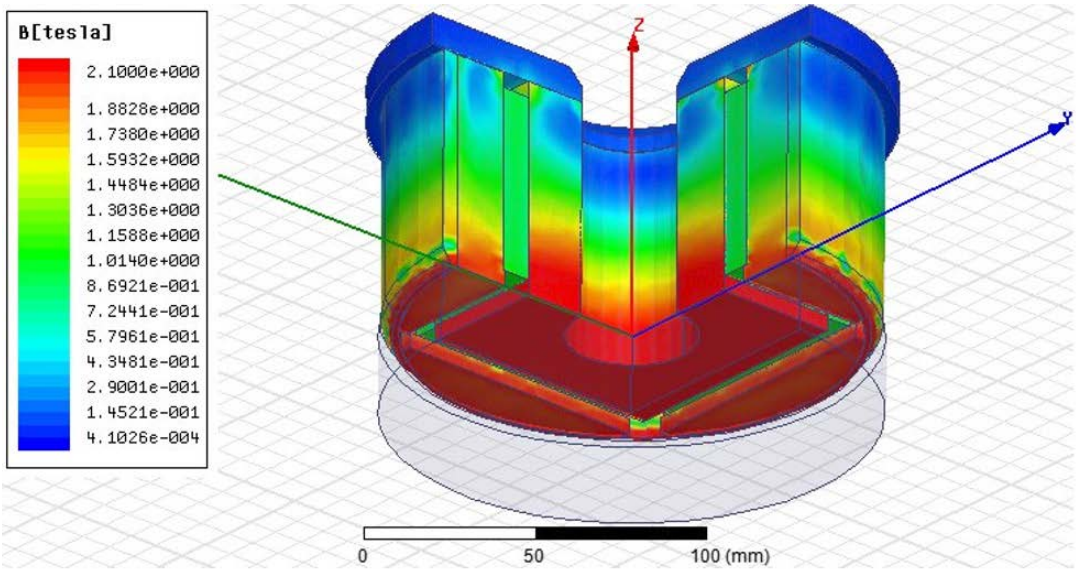

Figure 7. Distribution of magnetic induction in system with ferromagnetic plate

Thus, the obtained results of distribution of magnetic induction clearly demonstrate transformation of magnetic flux throughout the height of system at interaction with ferromagnetic plate.

On the basis of theoretical researches of magnetic systems with rare-earth neodymium magnets, design of grappling tool with a diameter of 195 mm was created. Experimental researches of power characteristics of the tool [12] have confirmed the results of theoretical calculations (divergence is 3-4%) and correctness of the suggested method of calculation of magnetic systems. The obtained value of carrying capacity (19.6 kN) exceeds analogs with cast permanent magnet by 4-6 times and with ferrite and rare-earth ones by 1.5-2 times [2, 4, 6, 8, 13].

Conclusions

On the basis of modeling, rational geometrical dimensions of elements of system with diameter of 150 mm are determined that has allowed obtaining the maximum carrying capacity of grappling tool. Theoretical researches of process of interaction of magnetic systems with ferromagnetic object have shown that systems, which are 70-80 mm in height, possess the smallest fluxes of dispersion. The suggested technique can be used for design and calculation of power magnetic systems of any designs and diameters.

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