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DETERMINING THE FORCE FUNCTION DISTRIBUTION IN THE WORKING ZONE OF A DISK MAGNETIC SEPARATOR

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Проведено дослідження розподілу магнітної силової функції в робочій зоні дискового сепаратора нової конструкції, призначеного для очищення дрібнодисперсних сипких речовин, що транспортується стрічковим конвеєром, від небажаних феромагнітних домішок. Показано, що для створення в робочому об'ємі сепаратора необхідної топології магнітного поля та підвищення його енергоефективності доцільним є використання постійних магнітів. Обгрунтовано, що основною перевагою запропонованого пристрою на постійних магнітах є можливість самоочищення поверхні немагнітного обертового розвантажувального диску. Для вирішення основних задач дослідження застосований метод скінченних елементів, реалізований у програмному середовищі COMSOL Multiphysics. Досліджувалась магнітна силова функція, що діє на багатодоменні феромагнітні частинки. У зв'язку зі складністю просторової геометрії розподілу силового поля в робочій зоні дискового магнітного сепаратора розроблена тривимірна модель магнітної системи. Визначений вплив величини повітряного проміжку та, відповідно, ефективної довжини сектороподібних постійних магнітів на розподіл силової магнітної функції в робочій зоні. Показано, що при зміні повітряного проміжку змінюється як розподіл силової функції по висоті робочої зони, так і величина силової дії. Надано рекомендації щодо використання магнітних систем з різними зазорами. Встановлено, що при вилученні феромагнітних включень має значення рівномірність розподілу силової функції в напрямку розгортання спіралі магнітів. Доведено, що магнітні системи з малими зазорами доцільно використовувати в сепараторах без розвантажувального диску. В цьому випадку магнітна система може встановлюватися у безпосередній близькості до матеріалу, що сепарується, а очищення поверхні постійних магнітів здійснюватися вручну по мірі накопичення на них вилучених феромагнітних включень. В результаті проведеного дослідження визначено раціональний розмір повітряного міжполюсного проміжку, що забезпечує максимальну величину силової дії та, відповідно, більш ефективну роботу магнітного сепаратора

***Ключові слова:** постійний магніт, силова функція, магнітна система, магнітний сепаратор, розвантажувальний диск*

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1. Introduction

One of the ways to improve energy efficiency of electrical machines and devices for various functional purposes is to use permanent magnets, whose fabrication utilizes new magneto-hard materials with high energy indicators [1–6]. Specifically, such materials are used to construct magnetic systems for electrodynamic and magnetic separators, intended to clean bulk substances from undesirable metallic impurities [7, 8]. The magnetic systems of separators with permanent magnets demonstrate the following advantages over their electromagnetic analogs: they are distinguished by enhanced reliability, smaller mass-dimensional indicators, and do not require additional energy supply in the process of operation.

A variety of forms, structural assemblies and magnetization directions of permanent magnets makes it possible to construct new magnetic systems for separation devices with the required topology of magnetic field in working gaps and acquisition of new functional properties [9]. Studies in this field are of theoretical and practical interest.

2. Literature review and problem statement

Numerous publications report studies into magnetic systems of separators on permanent magnets. Features in using magnetic separators on permanent magnets were considered in paper [10]. It was shown that separators are distinguished by simplicity of the structure, low power consumption, they are convenient in operation and maintenance. It was noted that the use of separators on permanent magnets generates a series of problems related to the need to justify the structure of the magnetic system and the choice of materials for permanent magnets. Article [11] reports a method for separating small metallic colored particles from two-component metallic colored blends using a new type of a dynamic drum vortex separator with permanent magnets. It was investigated that in order to improve the efficiency of extracting metal particles the separation process occurs in two stages: first, particles with high electrical conductivity are separated at the top of the drum, and then, in the bottom part of the magnetic drum, particles with low electric conductivity. For the implementation of the two-stage separation, the procedure for arrangement of permanent magnets in a magnetic system was substantiated. The main advantages and practical limitations of the magnetic systems for separators with a high gradient magnetic field (HGMS) and systems with an open gradient magnetic field (OGMS) were described in paper [12]. It should be noted that studies [10–12] fail to address the issues related to theoretical research into the power magnetic fields of separators; the permanent magnets are arranged mainly based on empirical experience. All this allows us to assert that it is expedient to undertake a theoretical study aimed at investigating patterns in the power magnetic field distribution in the working zones of separators in order to reasonably select a magnetic system configuration.

For example, paper [13] considers the influence of a geometric shape (sphere, cone, ring, prism, etc.) of permanent magnets with different form on the distribution of their magnetic field. The study employed analytical methods. The results from experimental research into the distribution of magnetic fields of separators on permanent magnets are reported in articles [14–16].

Papers [17–20] give the results from calculating the magnetic fields of systems with permanent magnets whose task is a target delivery and localization of magnetic nanoparticles in the specified area of a biological object. Given the complex spatial geometry of a magnetic field, such a task is solved using a numerical finite-element method for a two-dimensional model employing the COMSOL Multiphysics software [21]. The structure of the magnetic field inside a drum separator with permanent magnets was considered in paper [22]. By applying a computer simulation while using a finite-element method, the authors derived a pattern of the separator's magnetic field distribution.

Thus, our analysis of publications [10–18] makes it possible to argue that at present there are no systemic solutions for determining the distribution of a force function in the working zones of devices for magnetic separation. Most publications report results from studying the influence of a shape and geometric dimensions of the magnetic systems of separators on the magnetic field distribution. The exception is paper [17] that investigated the distribution of a power magnetic function depending on some geometric dimensions of the magnetic systems and its distance from a tumor zone in order to establish the optimum size of the magnetic system.

Our analysis of publications has also revealed that the practice of designing magnetic separators had employed analytical, experimental, and numerical methods. The analytical calculation of a magnetic field in the working interpolar gaps of magnetic separators is quite a challenging task. For most configurations of magnetic systems, this task has not been resolved analytically up to now, and experimental methods are rather time-consuming. In recent years, numerical methods have become common for magnetic calculations of separators, among which the method of finite elements is the most acceptable; the affordable software have been developed for it, making it possible to implement the method using personal computers. The main advantage of numerical methods is to obtain reliable results in cases when the use of analytical methods is almost impossible. When using numerical methods, one can derive results that are most close to the actual physical processes. Therefore, in order to obtain information about the power magnetic field distribution in the working gaps of separators on permanent magnets, it is advisable to use numerical methods applying appropriate computer software.

3. The aim and objectives of the study

The aim of this work is to determine the distribution of a force function in the working zone of the magnetic system in a disk-type separator. This would make it possible to substantiate rational geometric dimensions (effective length) for permanent magnets.

To accomplish the aim, the following tasks have been set:

– to perform computer simulation of the magnetic system of a disk separator;

– to conduct a comparative analysis of results from calculating the distribution of a force function.

4. Computer simulation of the magnetic system of a disk separator

Cleaning loose substances transported by belt conveyors from unwanted ferromagnetic impurities has employed the use of suspended systems for magnetic separation. A variety of such systems is the disk magnetic separators. Using permanent magnets in certain configurations for disk separators in combination with a possibility to rotate the unloading disk forms conditions under which the devices acquire new properties. Thus, Fig. 1 shows the location of permanent magnets 2 on stationary ferromagnetic disk 1 in a spiral with an alternating poles polarity, both in the direction of deployment of the spiral and in the radial direction. This leads to the possibility to self-clean the surface of a non-magnetic rotating unloading disk (not shown in Fig. 1) from ferromagnetic impurities [13]. It should be noted that known designs of separators on permanent magnets typically imply manual cleaning of the active surface when the separation process stops.

Papers [23, 24] report results from earlier studies obtained using the method of finite elements concerning the influence of a spiral geometry of the magnetic system (Fig. 1) on magnetic field distribution in the working zone of a separator. At the same time, there were no systemic studies into the distribution of a force function depending on the geometric dimensions of the magnetic system and at a distance from the active surface of magnets (in the separation zone).

Given that the magnetic system, shown in Fig. 1, exerts a power influence on multi-domain ferromagnetic particles, the magnetic force Fm can be described according to [18] using the following expression

$$\mathbf{F}_m = V_p \chi \nabla \frac{|\mathbf{B}_0|^2}{2\mu_0}, \qquad (1)$$

where $\mathbf{B_0}$ is the magnetic induction of a non-homogeneous magnetic field at the location of a particle; V_p is the volume of a particle; μ_0 is the permeability of vacuum, which equals $\mu_0=4\pi\cdot10-7$ H/m; χ is the magnetic susceptibility of a particle's material.

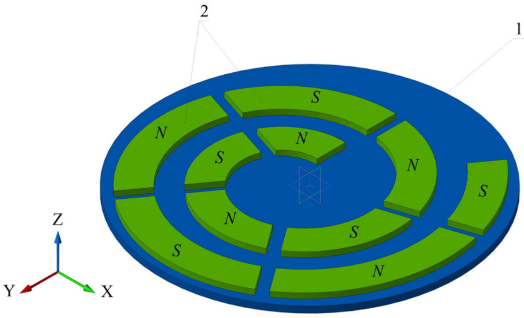


Fig. 1. Magnetic system of disk separator: 1 – ferromagnetic disk; 2 – permanent magnets

In expression (1), one selects a vector function **G**(**r**) for a point in space **r**

$$\mathbf{G}(\mathbf{r}) = \nabla|\mathbf{B}_0|^2 / 2\mu_0, \qquad (2)$$

which is equal to the magnetic force, acting on a single volume ferromagnetic particle with a single magnetic susceptibility, located at point r. The function **G**(**r**) (hereinafter referred to as **G**) is termed a force function of the heterogeneous magnetic field and is its internal characteristic.

The magnetic field in a system with permanent magnets in the absence of an electric current is described by a system of Maxwell equations, which in the magnetostatic approximation takes the form [17, 18]

$$\nabla\times\mathbf{H}=0,$$

$$\nabla\cdot\mathbf{B}=0, \qquad (3)$$

where **H** is the magnetic field intensity vector; **B** is the magnetic induction vector.

The equation for permanent magnets takes the form

$$B=\mu_0\mu_r H + B_r, \qquad (4)$$

where μ_r, B_r are the relative value of magnetic permeability and residual induction of a permanent magnet's material, respectively.

The magnetic state equation for the ferromagnetic disk (position 1, Fig. 1) and the ambient medium (air) may be recorded as

$$\mathbf{B}=\mu_0\mu_r\mathbf{H}, \qquad (5)$$

where μ_r is the relative value of magnetic permeability for a ferromagnetic disk (μ_r=1,000) and air (μ_r=1), respectively.

Based on expressions (2) to (4), a differential equation can be derived to calculate a vector magnetic potential $\mathbf{A}\ (\mathbf{B}=\nabla\times\mathbf{A})$

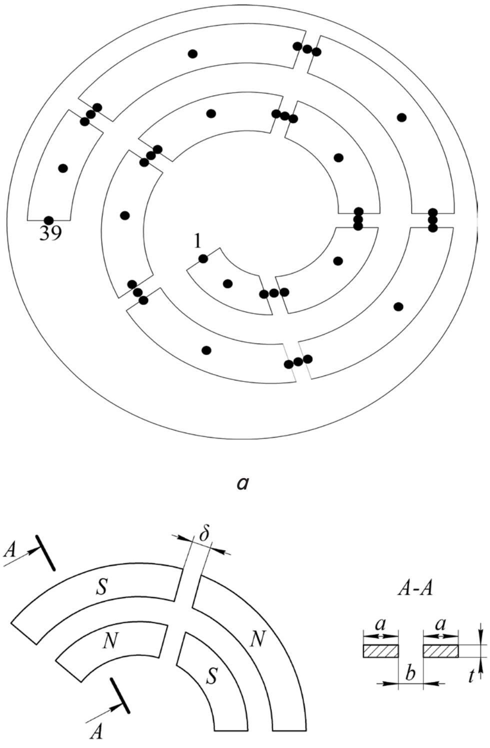
$$\nabla(\mu_0\mu_r\nabla\mathbf{A}-\mathbf{B}_r)=0. \qquad (6)$$

Given the complexity of the spatial geometry of the power field distribution in the working zone of a disk magnetic separator, differential equation (6) was solved for a three-dimensional model of the magnetic system (Fig. 1). To this end, the finite element method was applied, implemented in the COMSOL Multiphysics 3.5 software package (COMSOL group, Sweden) [21].

In the study, it was accepted that permanent magnets 2 (Fig. 1) are made from the high-quality alloy Nd–Fe–B with the following characteristics: relative magnetic permeability μ_r=1.06; residual magnetic induction $\mathbf{B}_r$=1.2 Tl. A vertical component of magnetization of permanent magnets, directed along the *Z*-axis (Fig. 1) was assigned. For the ferromagnetic disk 1 (Fig. 1), made from magneto-soft structural steel, we assumed the stability of relative magnetic permeability μr for the disk's material (μ_r=1,000). The boundary conditions applied at the outer boundaries of the estimated region (not shown in Fig. 1) implied the condition for a magnetic isolation **A**=0 [23, 24].

We have studied the impact of the magnitude for an air gap and, consequently, the effective length (that is, length along the midline) of sector-like permanent magnets on the distribution of power magnetic function **G**. The study was conducted in the working zone of the separator, both in the direction of deploying the spiral of magnets at characteristic points (points 1...39 in Fig. 2, *a*) and at different distances from the magnets' surface.

Fig. 2, *b* shows a fragment of the spiral magnetic system containing four sector-like magnets.



a

b

Fig. 2. Magnetic system indicating the structural parameters: *a* – characteristic points; *b* – fragment of the spiral magnetic system

Basic structural parameters of the magnetic system are: *d*– air gap; *a* –transverse size (width) of magnets; *b* – distance between adjacent turns of the spiral; *t* – thickness of magnets. Structural parameters for the magnetic system of the separator, adopted as basic in previous studies, were: *d*=25 mm, *a*=67.6 mm, *b*=51.7 mm, *t*=12.5 mm. The dimensions of ferromagnetic disk 1 (Fig. 1), which hosts the permanent magnets, were accepted as follows: a disk diameter – 700 mm, thickness – 15 mm. In this case, the diameter of the disk was chosen based on the dimensions of conveyor systems, which are most often used in practice.

5. Comparative analysis of results from calculating the force function distribution

The results of calculating the force function distribution **G** for the basic structure of a separator at the surface of poles of permanent magnets are shown in Fig. 3; they demonstrate that the module |**G**| is maximum at the edges of magnets. Vectors **G** show the direction and amount of force that acts on sample ferromagnetic particles with single properties.

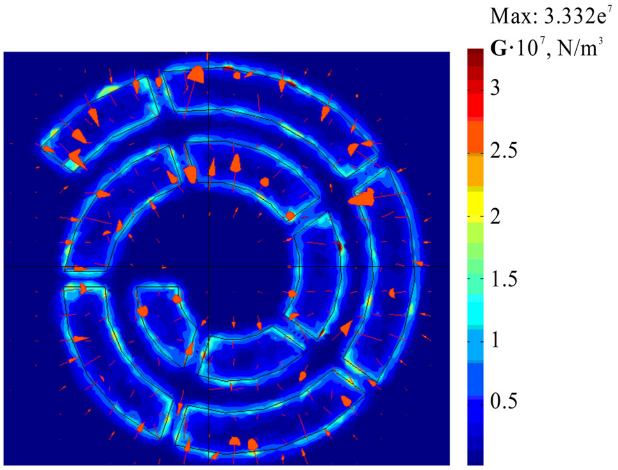


Fig. 3. Distribution of vector force function G in N/m^3 at the active surface of a magnetic system for the basic structure of a separator

It should be noted that the distribution of magnetic induction **B** in [23, 24] and vector force function **G** (Fig. 4) in the direction of deploying a spiral of magnets (along the characteristic points 1...39, Fig. 2, *a*) has a pulsating nature. The force function increases at corner zones and decreases in the middle part of the magnets' surface. The maximum magnitude of a vector **G** module at the active surface of the basic design of a separator was 3.3 ·107 N/m^3. In addition, as shown by Fig. 4, the maximum magnitude of force function **G** for points 7–19 in the first (internal) turn does not exceed 2.5·107 N/m^3. The maximum value of force function **G** at points 21–33, located in the second (external) turn of magnets' spiral, does not exceed 3.2·107 N/m^3. The exception is points 1–6 and 34–39, located on the extreme magnets. Therefore, for further research, it was decided to limit the calculation of the power distribution of a magnetic field to two air gaps:

– between magnets I and II – points 7–9 in Fig. 2, *a*, located in the first (inner) turn of the spiral;

– between magnets III and IV – points 27–29 in Fig. 2, *a*, located in the second (external) turn of the spiral.

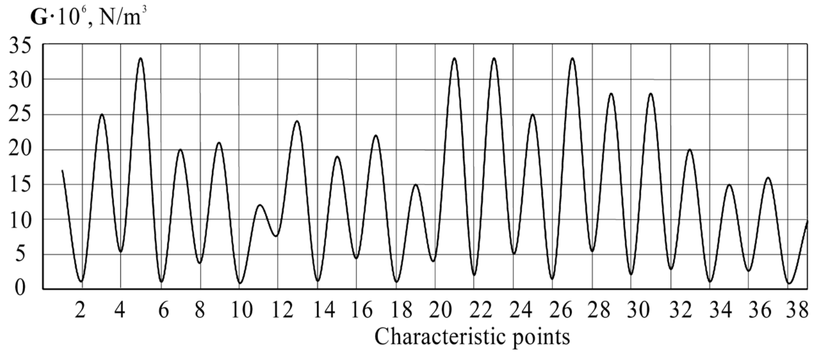


Fig. 4. Distribution of vector force function G at the active surface of the magnetic system at characteristic points (Fig. 2, *a*)

The following values for the magnitude of an air gap δ were accepted: 6.25; 12.5; 25; 37.5 mm. When changing δ, the effective length of permanent magnets changed as well. In this case, attention was paid to such factors as:

– the absolute magnitude of force function in the working zone;

– the uniform distribution of force function in the direction of deployment of the magnets spiral;

– a change in the absolute magnitude of force function in the radial direction to the periphery of the disk;

– the mass of a magnetic material.

It should be noted that such a factor as the uniformity of the force function distribution in the direction of the spiral magnet deployment is of primary importance for the extraction of ferromagnetic inclusions from a loose medium. At the same time, the factor of change in the magnetic force function in the radial direction towards the periphery of the disk plays a crucial role in the automatic unloading of seized ferromagnetic inclusions using a non-magnetic unloading disk.

The distribution of force function **G** was examined:

– along the vertical **Z** axis, located in an air gap as shown as an example for points 7–9 in Fig. 5;

– along the characteristic points 7–9 (between magnets I and II, Fig. 2, *a* and Fig. 5) and 27, 28, 29 (between magnets III and IV, Fig. 2, *a*).

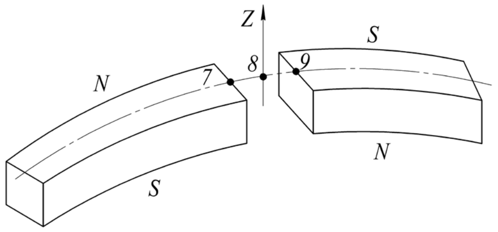


Fig. 5. Position of the vertical Z axis in an air gap in the examined zone

The results from our study are shown, respectively, in Fig. 6, 7 (we used a logarithmic scale for force function **G**).

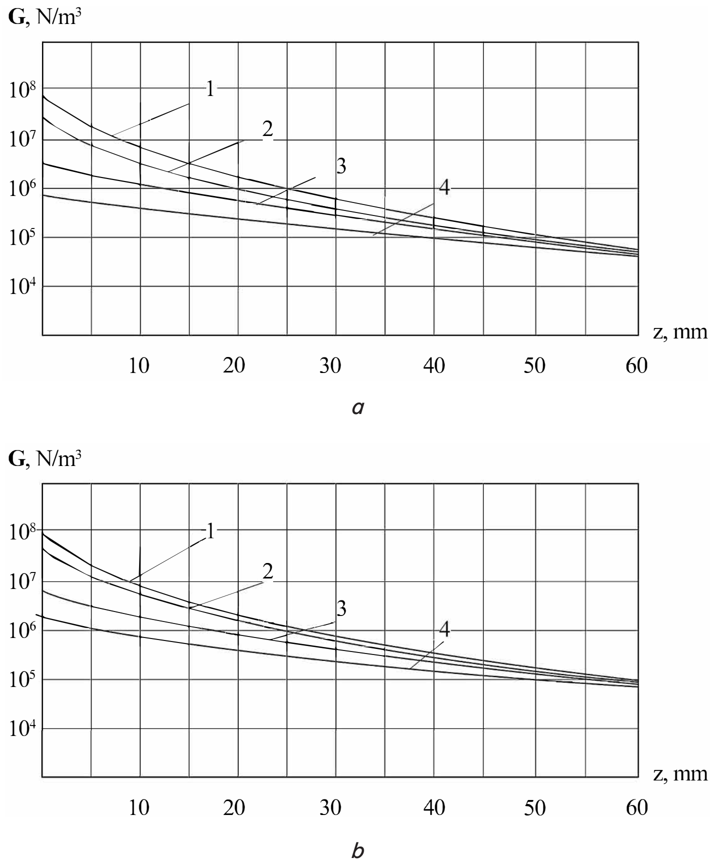


Fig. 6. Distribution of power impact G along the Z axis (at the values of air gap δ: 1 —6.25 mm; 2 — 12.5 mm; 3 — 25 mm; 4 — 37.5 mm): *a* — at point 8; *b* — at point 28

Fig. 6 shows that the magnitude of magnetic force **G** is significantly reduced in proportion to the distance from the surface of magnets. When increasing a non-magnetic air gap δ, which, in fact, includes the magnets themselves, whose permeability is little different from the magnetic constant, force function **G** is changing more slowly. Fig. 7 demonstrates that the reduction of air gap δ leads not only to an increase in the magnitude of power impact **G** on magnetic particles, but affects its distribution as well.

Thus, by analyzing dependences in Fig. 6, 7, the following conclusions can be drawn.

The force function **G** in the immediate vicinity of the active surface of the magnets ($0 \le Z \le 20$ mm) accepts the highest values at small air gaps δ. Thus, at the gap of 6.25 mm and 12.5 mm (Z=0 mm), it is, respectively, $2.7 \cdot 10^8$ N/m³ and $1.5 \cdot 10^8$ N/m³. This is due to the fact that more magnetic material is used when constructing magnetic systems with small gaps. Thus, for magnetic systems with gaps of 6.25 mm and 12.5 mm, the total weight of magnetic poles is, respectively, 16.78 kg and 15.23 kg; while for magnetic systems with gaps of 25 mm and 37.5 mm, it is 14.72 kg and 13.08 kg, respectively. It should be added that the magnetic systems with gaps of 6.25 mm and 12.5 mm ensure not only the high values of magnetic force function **G** in close proximity to the surface of the magnets, but also its more uniform distribution in the direction of deploying a spiral of magnets (Fig. 7, *a, b*). This is an important factor to ensure reliable extraction of ferromagnetic inclusions.

It should be noted that the magnetic systems with small gaps (6.25 mm or 12.5 mm) should be used for separators without an unloading disk. In this case, the magnetic system can be installed in close proximity to the separated material, and the surface of permanent magnets should be carried out manually in proportion to the accumulation of extracted ferromagnetic inclusions on them. The advantage of the magnetic system with a gap of 6.25 mm is a higher maximum value of the magnetic force function **G**, which is 1.8 times larger than the same value for the magnetic system with a gap of 12.5 mm. At the same time, the magnetic system at δ=12.5 mm differs by the larger size of a zone of the uniform distribution of force function (due to a greater magnitude δ) and requires 10 % less magnetic material.

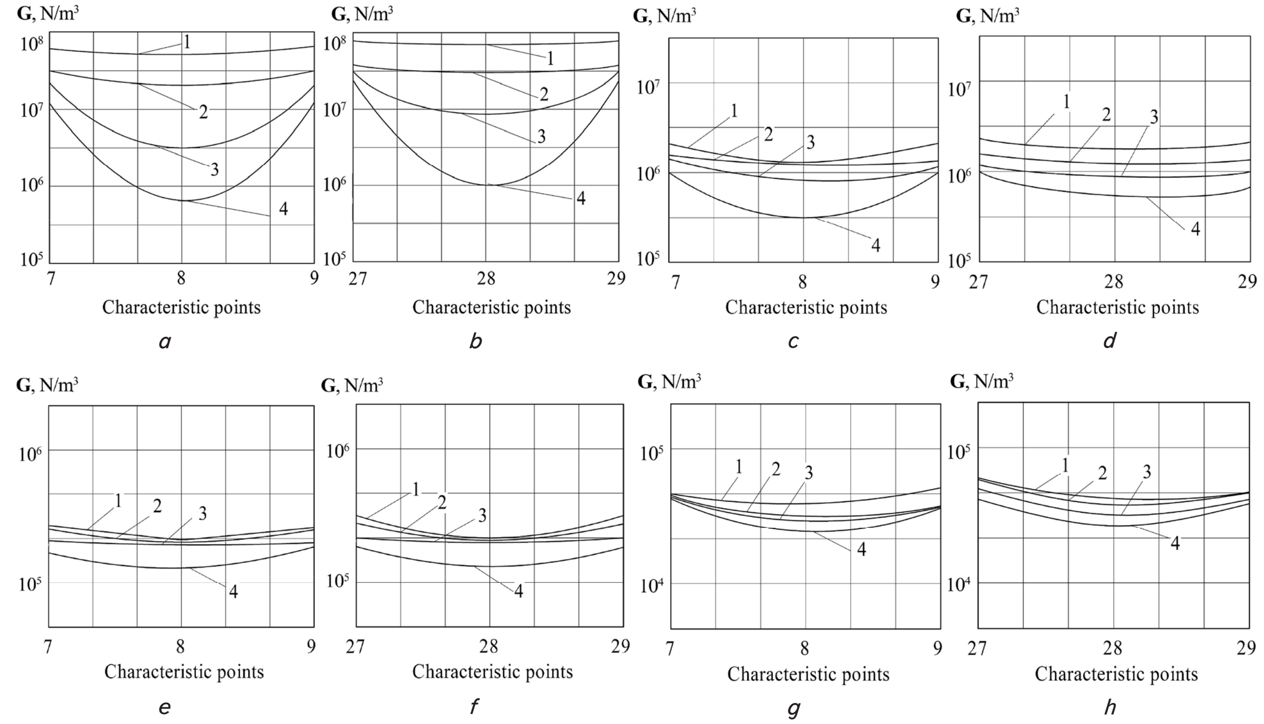
At the automatic unloading of removed inclusions (in the presence of an unloading disk), the magnetic system will be at a certain distance from the working zone, predetermined by the resulting disk thickness. For further analysis, Table 1 gives correlation values of force functions $\mathbf{G}_2$ (at δ=12.5 mm), $\mathbf{G}_3$ (at δ=25 mm), $\mathbf{G}_4$ (at δ=37.5 mm) at distances Z=0, 20, 40, 60 mm to the magnitude of force function $\mathbf{G}_1$ (at δ=6.25 mm) at the same distances for characteristic points 8 and 28.

Table 1 shows that at distance Z=40 mm magnetic systems with gaps of 6.25 mm, 12.5 mm, and 25 mm ensure an almost identical power impact: $\mathbf{G}_2/\mathbf{G}_1$=0.95, $\mathbf{G}_3/\mathbf{G}_1$=0.9 – for characteristic point 8; $\mathbf{G}_2/\mathbf{G}_1$=0.98, $\mathbf{G}_3/\mathbf{G}_1$=0.95 – for characteristic point 28. This tendency is kept to a certain extent at distance Z=60 mm, mainly for the magnetic system with δ=12.5 mm. Therefore, in the presence of an unloading disk, it can be considered reasonable to use magnetic systems with gaps of 12.5 mm or 25 mm. Fig. 7 shows that these systems also provide for an even distribution of the power influence in the gap. Given that the magnetic system with a gap of 12.5 mm is characterized by a higher power effect and is slightly inferior, in terms of mass, to the system with a gap of 6.25 mm, then this very system can be recommended for further application.

Table 1

Ratios of values for force functions

Z, mm	Characteristic points					
	8			28		
	$\mathbf{G}_2/\mathbf{G}_1$	$\mathbf{G}_3/\mathbf{G}_1$	$\mathbf{G}_4/\mathbf{G}_1$	$\mathbf{G}_2/\mathbf{G}_1$	$\mathbf{G}_3/\mathbf{G}_1$	$\mathbf{G}_4/\mathbf{G}_1$
0	0.5	0.08	0.02	0.42	0.08	0.02
20	0.93	0.57	0.21	0.97	0.49	0.23
40	0.95	0.9	0.65	0.98	0.95	0.68
60	0.75	0.63	0.5	0.89	0.78	0.67



a b c d

e f g h

Fig. 7. Distribution of vector force function G (at the following values of air gap δ: 1 –6.25 mm; 2 – 12.5 mm; 3 – 25 mm; 4 – 37.5 mm): *a* – at the surface of magnets along characteristic points 7–9; *b* – at the surface of magnets along characteristic points 27–29; *c* – at a distance of 20 mm from the surface of magnets along characteristic points 7–9; *d* – at a distance of 20 mm from the surface of magnets along characteristic points 27–29; *e* – at a distance of 40 mm from the surface of magnets along characteristic points 7–9; *f* – at a distance of 40 mm from the surface of magnets along characteristic points 27–29; *g* – at a distance of 60 mm from the surface of magnets along characteristic points 7–9; *h* – at a distance of 60 mm from the surface of magnets along characteristic points 27–29

6. Discussion of results from studying the distribution of a force function in the working zone of a magnetic disk separator

The main task of the working process of magnetic separators on permanent magnets is to keep extracted ferromagnetic inclusions in a magnetic field until removing them in the unloading zone. For most of the separators, the unloading of seized inclusions is performed manually by simply cleaning the surface of the magnets. At the same time, it is possible, for the systems on permanent magnets, by selecting a certain configuration of them, to form such a topology of the magnetic field, which would provide conditions for automated unloading. Given this, a new design of the disk magnetic separator has been proposed with a spiral magnetic system, thereby creating conditions for self-cleaning of the surface of the non-magnetic unloading disk. To investigate the power magnetic field of the proposed magnetic system, a finite-element method was implemented applying the COMSOL software package. To this end, a three-dimensional model of the magnetic system has been developed, shown in Fig. 1. The boundary conditions applied at the outer boundaries of the estimated region was the assigned condition for magnetic isolation. The use of a three-dimensional model of the magnetic system, on the one hand, brought the results of calculations to actual processes and, on the other hand, increased the time costs related to the implementation of computer simulation.

We calculated the power magnetic function $\mathbf{G}(\mathbf{r})$ from formula (2). The influence of a spiral magnetic system geometry (Fig. 1) on magnetic field distribution in the working zone of the separator was investigated in previous works by authors. At the same time, there have been no systemic studies into the distribution of force function depending on the geometric dimensions of the magnetic system and at a distance from the active surface of magnets (in the separation zone). Resolving this task has allowed us to determine the rational geometric dimensions (effective length) of permanent magnets.

Conducting a comparative analysis of calculation results was complicated by the pulsating character of magnetic force function. Therefore, for clarity and simplification of the analysis, it was decided to limit calculations only to characteristic points of the magnetic system. The disadvantages of the study also include the calculations of magnetic force function in absolute units, which makes it impossible to generalize the results. The distribution of magnetic force function in the working zone of the separator, in addition to the length of permanent magnets, is also affected by other factors, studying the impact of which was not included in the task of the current research (for example, the effect of width and height, material of permanent magnets). Defining their influence could be subject of further research.

7. Conclusions

1. Given the complexity of the spatial geometry of the power field distribution in the working zone of a magnetic separator, we have developed its three-dimensional

geometric model. To investigate the impact of the magnitude of an air gap and, accordingly, the effective length of sector-like permanent magnets on the power magnetic function distribution, a finite-element method has been applied implemented in the software package COMSOL Multiphysics 3.5a. To determine absolute values for the force function, we selected characteristic points of the magnetic system. That has made it possible to examine the distribution of a power magnetic field, both in the direction of deploying a spiral of magnets and at different distances from their surface.

We have calculated the force function distribution at selected characteristic points for different values of the magnitude of air gap δ. In the vicinity of the active surface of magnets ($0 \leq Z \leq 20$ mm), the force function accepts the highest values at gaps of 6.25 mm and 12.5 mm. Magnetic systems with gaps of 6.25 mm and 12.5 mm also provide for a more even distribution of the magnetic force function in the direction of deploying a spiral of magnets. This is an important factor for the retention of ferromagnetic inclusions at the surface of magnets. Therefore, magnetic systems with small gaps (6.25 mm or 12.5 mm) should be used in separators without an unloading disk. In this case, the magnetic system is installed in close proximity to the separated material; the surface of permanent magnets is cleaned manually.

2. When investigating a force function at a distance from the surface of magnets (in the location of a loose material with ferromagnetic inclusions), it is advisable to use magnetic systems with gaps of 6.25, 12.5, or 25 mm. At working distances, these systems ensure almost identical power impact and are characterized by the uniform distribution of the force function in a gap. For practical application, we can recommend a magnetic system with a gap of 12.5 mm, which is characterized by a higher force effect in comparison with the system with a gap of 25 mm and is slightly inferior, in terms of mass, to the system with a gap of 6.25 mm.

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