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Research of the force function distribution in the workplace of the magnetic disc type separator intended for the cleaning of bulk substances from the ferromagnetic impurities

Iryna Shvedchykova[1], Inna Melkonova[2]

[1]*Kyiv National University of Technologies and Design (KNUTD)*
Nemyrovycha-Danchenka Street, 2
Kyiv, Ukraine, 01011, ishved89@gmail.com

[2]*East Ukrainian National University named after Vladimir Dal*
59a Central ave., Severodonetsk, Ukraine, 93400, inna.mia.lg@gmail.com

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Abstract. The paper deals with the magnetic system of the disk separator with permanent magnets. It is shown that the developed magnetic system can be used to purify finely dispersed friable substances from unwanted ferromagnetic inclusions. The main advantage of the magnetic system is the ability to self-clean the surface of a non-magnetic rotating discharging disk. The research of the distribution of the force function acting on multi-domain ferromagnetic particles in the working zone of the disk separator was carried out. To solve the main tasks of the study, a finite element method was implemented, realized in the COMSOL Multiphysics software environment. It is shown that when changing the air gap or the effective length of the poles, the distribution of the force function over the height of the working zone, as well as the magnitude of force, varies. The rational size of the air interpolar gap, which provides the maximum value of power force, was determined.

Keywords: permanent magnet, force function, magnetic system, magnetic separator.

INTRODUCTION

In modern conditions, with the appearance of new magnetically hard materials with high energy indices, permanent magnets are widely used in electric machines and apparatus of various functional purposes [1-6]. Particularly, they have found applications for the construction of magnetic systems for electrodynamic and magnetic separators designed to purify bulk substances from unwanted metallic impurities [7, 8].

Separators magnetic systems with permanent magnets have certain advantages over their electromagnetic analogues. They differ in higher reliability, smaller mass-dimensional indicators, do not require additional energy consumption during the operation. The variety of forms, structural layouts and directions of magnetization of permanent magnets allows to create new magnetic systems of separating devices with the necessary topology of the magnetic field in working spaces and acquiring new functional properties [9].

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

When developing new magnetoseparating devices, it is important to have a sound choice of methods for studying their magnetic field strengths. In practice of design of magnetic separators analytical, experimental and numerical methods have been used. For example, in [10] analytical calculations of magnetic fields of permanent magnets of different geometric shapes (sphere, cone, ring, prism, etc.) are considered. The results of experimental studies of magnetic fields of separators on permanent magnets are presented in papers [11-13].

In recent years numerical methods have been widely used in magnetic calculations of separators, among which the finest element method is most suitable for which sufficiently accessible software products are developed that allow the method to be implemented on personal computers. The main advantage of numerical methods is to obtain reliable results in those cases where the use of analytical methods is practically impossible. As the experience of designing magnetic separators shows [8, 14-15], using numerical methods one can obtain results that are most closely related to real physical processes.

The finite element method has been used, for example, to calculate magnetic systems with permanent magnets whose purpose is to address the delivery and localization of magnetic nanoparticles in a given region of a biological object [14-17]. Due to the complex spatial geometry of the magnetic field, such a problem was solved using the finite element method for a two-dimensional model using the software product COMSOL Multiphysics [18].

Thus, as shown in the analysis of publications [10-15], the calculation of the magnetic field in the working interpolar gap of magnetic separators is a rather complex task, which for most of the configurations of magnetic systems has not been solved until now analytically, and experimental methods are labor-intensive. In developing new structures of magnetic separators for obtaining information on the distribution of force magnetic field in working gaps it is advisable to use numerical calculations with the use of appropriate computer programs.

OBJECTIVES

The purpose of this work is to study the magnetic system of a disk type separator depending on the geometric dimensions (effective length) of permanent magnets for obtaining the distribution of the force function in the working separation zone, that is, in the zone of location of the bulk material with ferromagnetic impurities, which is located at a certain distance from the surface of the magnetic system.

RESULTS AND DISCUSIONS

For the purification of bulk substances transported by belt conveyors, undesired ferromagnetic impurities have been found to be used for suspension systems for magnetic separation. A variety of such systems are disk magnetic separators. The use of certain configurations in disk separators of permanent magnets, in conjunction with the possibility of rotation of the discharging disk, creates conditions for the acquisition of new properties by devices. Thus, the location of the permanent magnets 2 on a fixed ferromagnetic disk 1 in a spiral at the same distance from each other with the polarity alternation, both in the direction of deployment of the spiral, and in the radial direction, as shown in Fig. 1, leads to the possibility of self-cleaning the surface of a non-magnetic rotating discharging disk (not shown in Fig. 1) from ferromagnetic impurities [10]. It should be noted that in known designs of separators on permanent magnets, as a rule, manual cleaning of the active surface during stopping of the working process of separation is carried out.

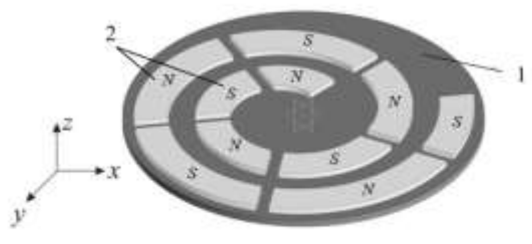


Fig. 1. Disk separator magnetic system: 1 – ferromagnetic disk; 2 – permanent magnets

The papers [19, 20] present the results of previous studies on the spiral geometry influence of the magnetic system (Fig. 1) on the distribution of the magnetic field in the working region of the separator. At the same time, systematic studies of the force function distribution, depending on the geometric dimensions of the magnetic system and on the distance from the active surface of the magnets (in the separation zone), were not carried out. Estimation of the maximum value of the force function and the nature of its attenuation when removed from the source of the magnetic field is necessary for the implementation of a comparative analysis of various magnetic systems in terms of the efficiency of their removal of ferromagnetic inclusions and the establishment of requirements for rational dimensions of magnetic systems.

Given that the magnetic system is depicted in Fig. 1, has a force influence on multi-domain ferromagnetic particles, then the magnetic force can be described in [15] with the help of the following expression

$$F_m = V_p \chi \nabla \frac{|B_0|^2}{2\mu_0} \qquad (1)$$

where B_0 is a magnetic flux density of an inhomogeneous magnetic field in the location of a particle; V_p is a volume of particle; χ is a magnetic susceptibility of a particle material; μ_0 is a magnetic permeability of vacuum equal to $\mu_0 = 4\pi \cdot 10^{-7}$ H/m.

In expression (1) we distinguish a vector function $\boldsymbol{G}(\boldsymbol{r})$ for the space point $\boldsymbol{r}$

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

which is equal to the magnetic force acting on the ferromagnetic particle of a single volume with unit magnetic susceptibility and which is located at the point *r*. Function *G(r)* (hereinafter referred to *G* as simply) is called the force function of a nonuniform magnetic field and is its internal characteristic.

The magnetic field in a system with permanent magnets in the absence of electric current is described by the system of Maxwell equations, which in the magnetostatic approximation takes the form [14, 15]

$$\begin{aligned} \nabla \times H &= 0, \\ \nabla \cdot B &= 0, \end{aligned} \qquad (3)$$

where H is a vector of magnetic field strength; B is a vector of magnetic flux density.

The equation for permanent magnets has the form

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

where μ_r, B_r – the relative value of the magnetic permeability and the residual induction of the permanent magnet material, respectively.

The equation of the magnetic state for the ferromagnetic disk (item 1, Fig. 1) and the environment (air) can be written as

$$B = \mu_0 \mu_r H \quad (5)$$

where μ_r is a relative value of magnetic permeability for a ferromagnetic disk (μ_r =1000) and the air (μ_r =1), respectively.

On the basis of expressions (2) - (4) a differential equation can be obtained for calculating the vector magnetic potential $\boldsymbol{A}$ $(\boldsymbol{B} = \nabla \times \boldsymbol{A})$

$$\nabla(\mu_0 \mu_r \nabla \boldsymbol{A} - \boldsymbol{B}_r) = 0 \quad (6)$$

In connection with the complexity of the spatial geometry of the distribution of the force field in the working area of the disk magnetic separator, the differential equation (6) was solved by conducting a computational experiment for a three-dimensional model of the magnetic system (Fig. 1) using the finite element method in the software complex COMSOL Multiphysics 3.5a [18].

In the study, it was assumed that the permanent magnets 2 (Fig. 1) are made of high-corrosion Nd-Fe-B alloy with the characteristics: relative permeability μ_r = 1,06; residual magnetic flux density B_r = 1.2 T; the vertical component of the magnetization of permanent magnets was directed, directed along the Z axis (Fig. 1). For a ferromagnetic disk 1 (Fig. 1), made from magnetically soft structural steel, an assumption was made that the relative magnetic permeability of μ_r of disc material (μ_r = 1000) is constant. As the boundary conditions on the external boundaries of the calculated area, the condition of magnetic isolation $A = 0$ was used [19, 20].

The influence of the air gap value and, accordingly, the effective length (that is, along the middle line) of the sector-like permanent magnets on the distribution of the force magnetic function G in the working zone in the direction of deployment of the spiral in the characteristic points (points 1 ... 39 in Fig. 2a) and at different distances from the surface of the magnets was investigated.

In Fig. 2, b is shown a fragment of a spiral magnetic system containing four sector-like magnets, indicating the following structural parameters: δ – air gap; a – transverse dimension (width) of the magnets; b – the distance between the neighboring spiral turns; t – magnitude of the magnets. The structural parameters of the magnetic system of the separator, adopted in previous studies for the base, were: δ = 25 mm, a = 67.6 mm, b = 51.7 mm, t = 12.5 mm. The dimensions of the ferromagnetic disk 1 (Fig. 1), on which the permanent magnets are located, were taken as follows: the diameter of the disk – 700 mm, the thickness – 15 mm.

In this case, the diameter of the disk was chosen, based on the dimensions of the conveyor systems, which are most often used in practice.

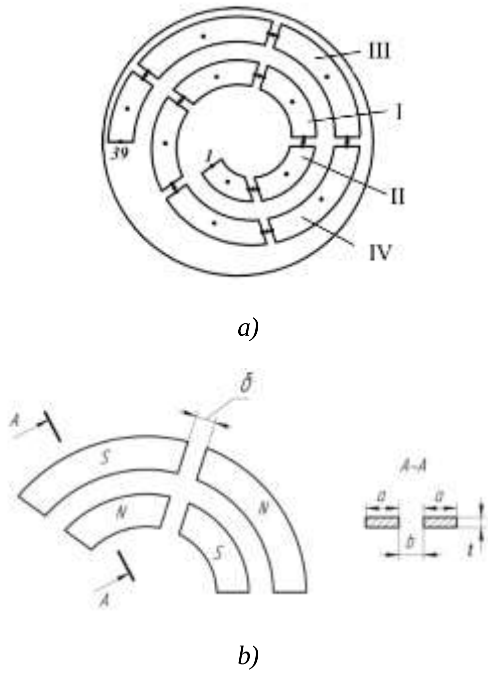


Fig. 2. Characteristic points (a) and a fragment of a spiral magnetic system (b) with the indicating the design parameters

The results of calculating the distribution of the force function G for the base design of the separator on the surface of the poles of permanent magnets are shown in Fig. 3, from which one can see that the module $|\boldsymbol{G}|$ is maximal on the edges of the magnets. The vectors G indicate the direction and magnitude of the force acting on the test ferromagnetic particles with singular properties.

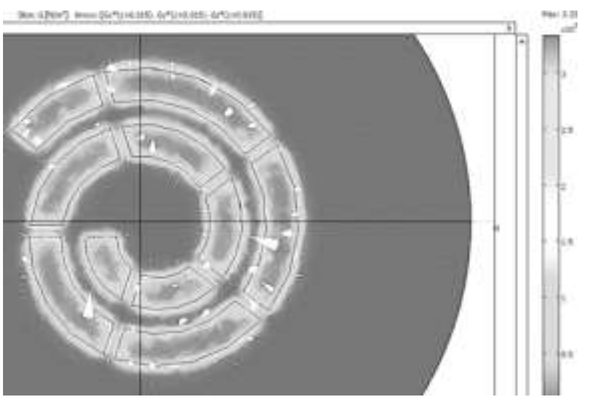


Fig. 3. Distribution of the vector force function G in H/m3 on the active surface of the magnetic system of the basic design of the separator

It should be noted that the distribution of both the magnetic flux density B [19, 20] and the vector force function G (Fig. 4) in the direction of deployment of the magnitude spiral (along characteristic points 1 ... 39, Fig. 2, a) has a pulsating character, increasing in angular zones and decreasing in the middle of the surface of the magnets. The maximum value of the vector module on the active surface of the basic design of the separator was $3.3 \cdot 10^7$ N/m^3. In addition, as can be seen from Fig. 4, the maximum value of the force function for points 7-19 of the first (inner) turn is less (not more than $2.5 \cdot 10^7$ N/m^3) compared to the value of the force function at points 21-33 (not exceeding $3.2 \cdot 10^7$ N/m^3) located on the second (outer) coil of the magnets spiral (except for points 1-6 and 34-39 located on the extreme magnets). Therefore, for further research it was decided to limit the calculation of power distribution of the magnetic field in two air intervals:

- between magnets I and II - points 7-9 in Fig.2, a, located on the first (inner) spiral coil;
- between magnets III and IV - points 27-29 in Fig. 2, a, located on the second (external) spiral coil.

In the study, the following values of the air gap δ were taken: 6.25; 12.5; 25; 37.5 mm. When changing δ, the effective lengths of permanent magnets also changed. At the same time, attention was drawn to such factors as:

- absolute value of the force function in the working area;
- the uniform distribution of the force function in the direction of deployment of the magnet spiral;
- an increase in the absolute value of the force function in the radial direction to the periphery of the disk;
- mass of magnetic material.

It should be noted that a factor such as the uniform distribution of the force function in the direction of the deployment of the magnet spiral is of paramount importance in removing ferromagnetic inclusions from the friable medium. At the same time, the increase in the magnetic force function in the radial direction to the periphery of the disk plays a decisive role in the automatic unloading of the removed ferromagnetic inclusions with the help of a non-magnetic discharging disk.

The distribution of the force function *G* was investigated:

- along the vertical axis Z, located in the air gap, as shown for the example for points 7-9 in Fig. 5;
- along characteristic points 7, 8, 9 (between magnets I and II, Fig. 2, and Fig. 5) and 27, 28, 29 (between magnets III and IV, Fig. 2, a).

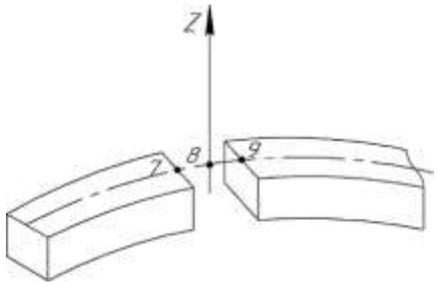


Fig. 5. Location of the vertical axis Z in the air gap in the study area

The results of these studies are presented, respectively, in Fig. 6, 7 (for a force function, the logarithmic scale is used).

From Fig. 6 it is seen that the magnitude of the magnetic force *G* significantly decreases when removed from the surface of the magnets. With an increase in the nonmagnetic air gap δ, which, in essence, includes magnets themselves, the magnetic permeability of which is slightly different from the magnetic constant, the force function *G* changes more slowly. Fig. 7 demonstrates that the reduction of the air gap δ leads not only to increase the magnitude of the *G* force influence on the magnetic particles, but also to its distribution.

Thus, from the analysis of dependencies (Fig. 6, 7), we can draw the following conclusions.

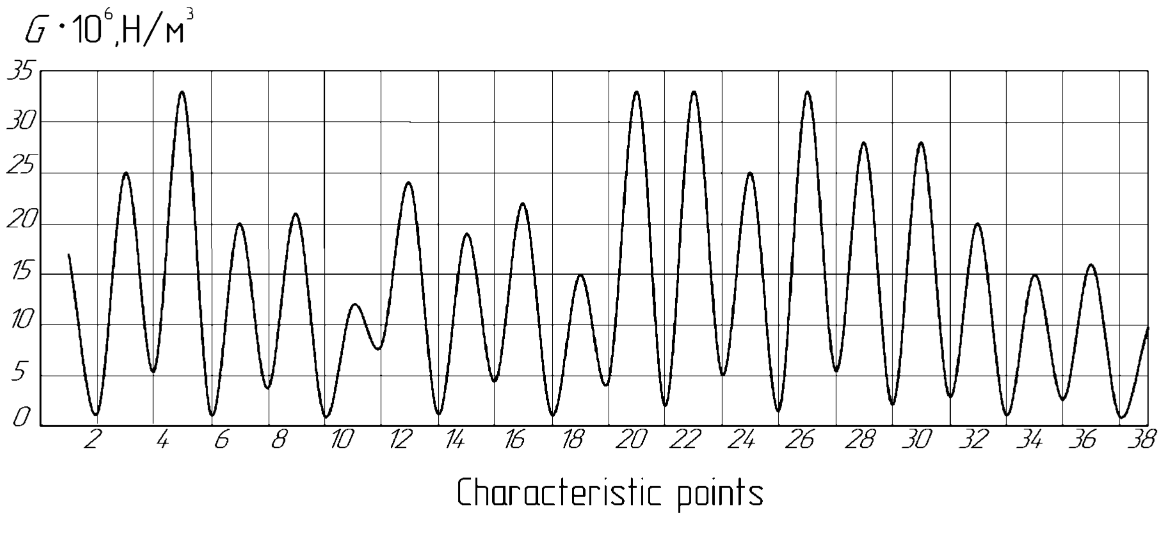


Fig. 4. Distribution of the vector force function on the active surface of the magnetic system in the characteristic points of 1 ... 39 (Fig. 2, a)

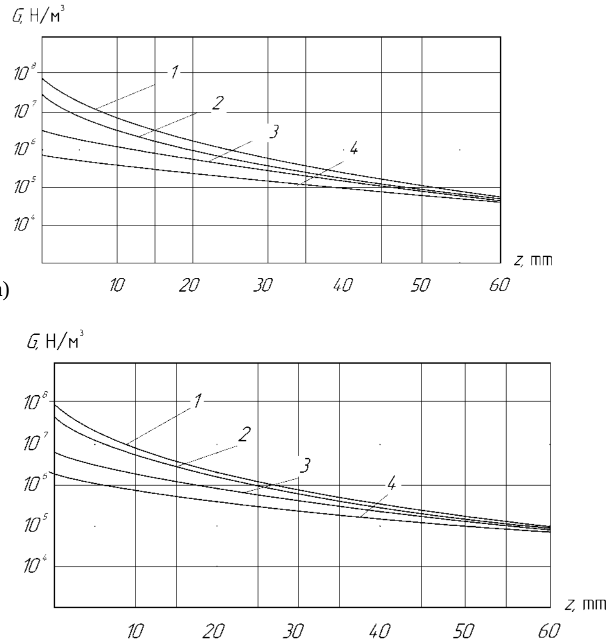
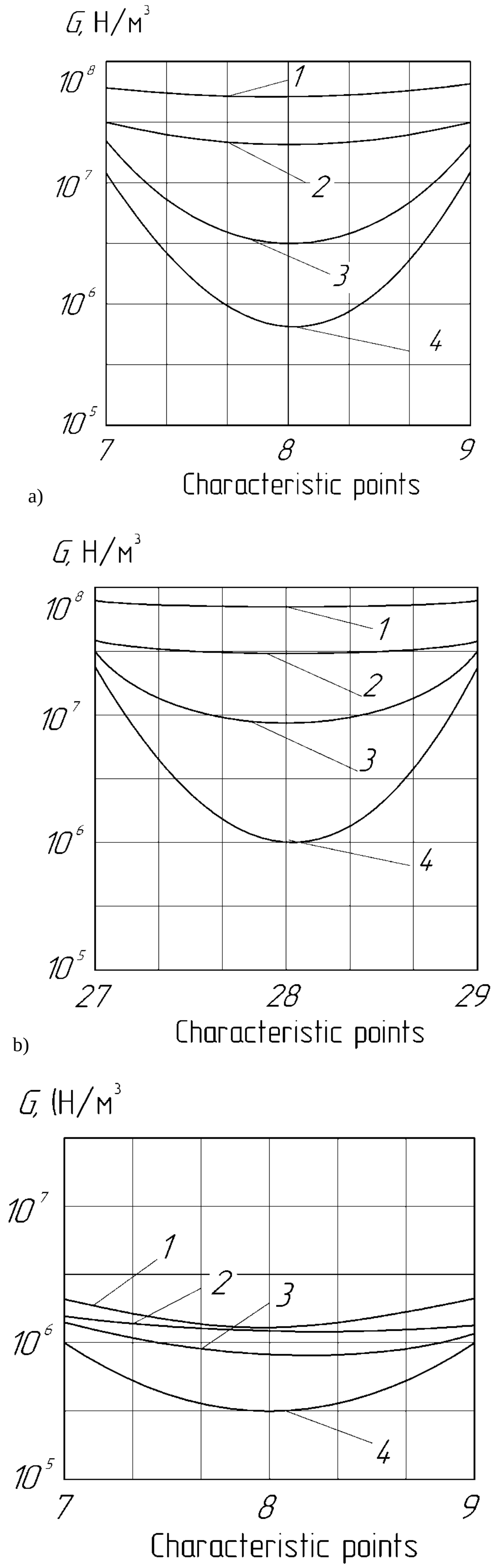
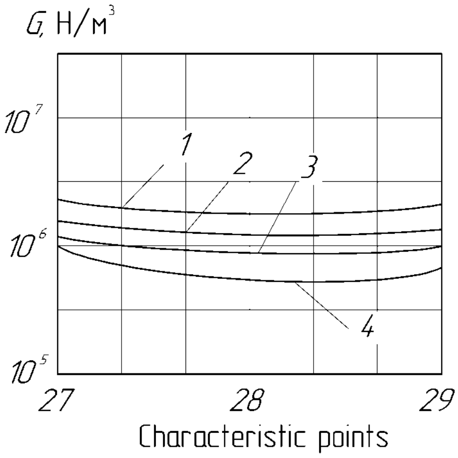


Fig. 6. Distribution of force influence along the Z axis at points 8 (a) and 28 (b) at the following values of the air gap δ: 1 - 6.25 mm; 2 - 12.5 mm; 3 - 25 mm; 4 - 37.5 mm

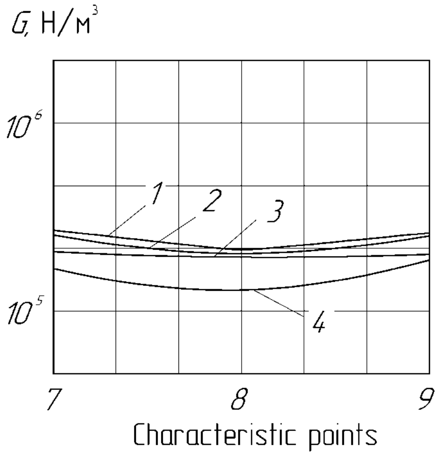
The force function *G* in the immediate proximity of the active surface of the magnets (0≤Z≤20 mm) takes the greatest value at low air gap δ. Thus, at gaps of 6.25 mm and 12.5 mm (Z = 0 mm) it is, respectively, $2.7 \cdot 10^8$ N/m^3 and $1.5 \cdot 10^8$ N/m^3. This is due to the fact that when constructing magnetic systems with small gaps, more magnetic material is used. So, if for magnetic systems with gaps of 6.25 mm and 12.5 mm the total mass of magnetic poles is 16.78 kg and 15.23 kg respectively, then for magnetic systems with gaps of 25 mm and 37.5 mm –14, 72 kg and 13.08 kg, respectively. It should be added that magnetic systems with gaps of 6.25 mm and 12.5 mm provide not only high values of the magnetic force function *G* in the immediate proximity of the surface of the magnets, but also a more even distribution of it in the direction of deployment of the magnet spiral (Fig. 7, a, b). This is an important factor in ensuring the reliable removal of ferromagnetic inclusions.

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

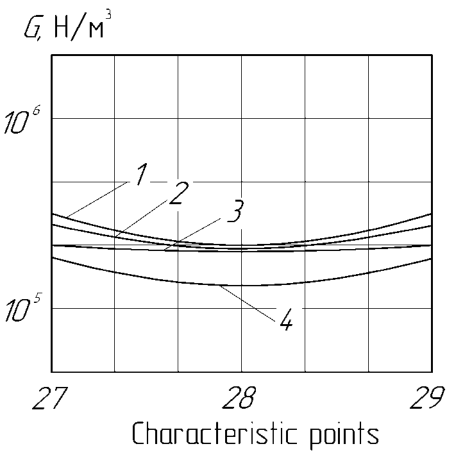




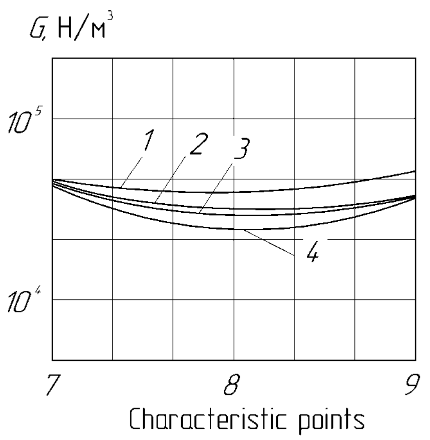
d)



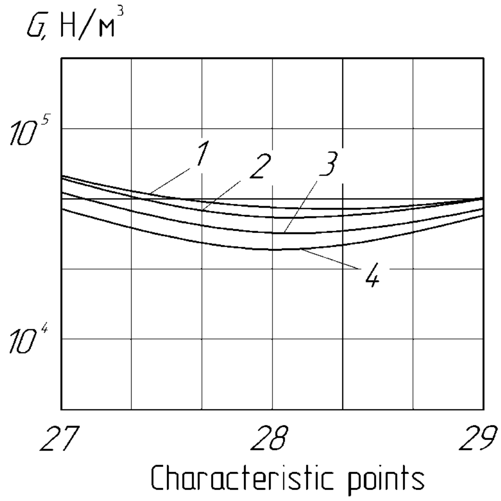
e)



f)



g)



h)

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

When automatic unloading of the removed inclusions (the presence of the discharging disk), the magnetic system will be located at a certain distance from the working area, which is due to the finite disk thickness. For further analysis in Table. 1, the ratios of the values of the force functions $\boldsymbol{G}_2$ (for δ = 12.5 mm), $\boldsymbol{G}_3$ (for δ = 25 mm), $\boldsymbol{G}_4$ (at δ = 37.5 mm) at distances Z = 0, 20, 40, 60 mm are given to the magnitude of the force function $\boldsymbol{G}_1$ (at δ = 6.25 mm) at the same distances for the characteristic points of 8 and 28

As can be seen from Table 1, magnetic systems with gaps of 6.25 mm, 12.5 mm and 25 mm provide almost the same force influence: $\boldsymbol{G}_2/\boldsymbol{G}_1 = 0.95$, $\boldsymbol{G}_3/\boldsymbol{G}_1 = 0.9$ – at a distance Z = 40 mm (in the location of the loose material with ferromagnetic impurities) for a characteristic point 8; $\boldsymbol{G}_2/\boldsymbol{G}_1 = 0.98$, $\boldsymbol{G}_3/\boldsymbol{G}_1 = 0.95$ for the characteristic point 28. This tendency remains to some extent also at a distance Z = 60 mm, mainly for a magnetic system with δ = 12.5 mm. Therefore, in the presence of a discharging disk, it may be considered expedient to use magnetic systems with gaps of 12.5 mm or 25 mm. As can be seen from Fig. 7, these systems also provide a uniform distribution of force influence in the gap. Given that the magnetic system with a gap of 12.5 mm is characterized by a higher force influence and slightly inferior to the mass system with a gap of 12.5 mm, then this system can be recommended for further application.

. CONCLUSIONS

A new configuration of the magnetic system of a disk separator, which is capable of providing extraction and unloading of ferromagnetic inclusions from bulk material transported by a belt conveyor, is proposed. It is shown that when changing the air gap or the effective length of the poles, both the distribution of force and its value in the working zone varies.

Magnetic systems with small gaps of 6,25 mm or 12,5 mm should be used in separators without a discharging disk. It is established that the advantage of a magnetic system with a gap of 12.5 mm is a larger area of uniform distribution of the force function and the use of 10% less magnetic material.

In magnetic separators with an unloading disk it is expedient to use magnetic systems with gaps of 12.5 mm or 25 mm. For further application a magnetic system with a gap of 12.5 mm is recommended due to higher force influence.

Thus, the magnetic system of a disc type separator depending on the geometric dimensions (effective length) of permanent magnets is investigated in the work, and the rational size of the air interpolar gap is determined, which is 12.5 mm.

The direction of further research is to determine the effect of the thickness of permanent magnets on the distribution and the magnitude of the force function in the working area of the magnetic separator.

TABLE 1. THE RATIO OF VALUES OF FORCE FUNCTION

Z, mm	Characteristic point					
	8			28		
	G_2/G_1	G_3/G_1	G_4/G_1	G_2/G_1	G_3/G_1	G_4/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

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