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The Estimation of Suspended Iron Separators with Arch Poles with the Use of Magnetic Modulus Method

***Abstract**. The paper deals with the design of a suspended electromagnetic iron separator with arch-shaped pole pieces. The calculation of the field in the working zone of the analyzed poles as a system of four equivalent dipoles is performed. The qualitative relations for the determination of the rational values of the poles width and the angle of the inter-pole gap in the case of arch poles are obtained. Physical modeling of electromagnetic systems with arch pole pieces at different angles is carried out. Different variants are compared. Because of the research the feasibility of the use of arch-shaped pole pieces in suspended iron separators is demonstrated, particular recommendations as to the relevant modernization of devices manufactured in series are provided.*

***Streszczenie.** Artykuł dotyczy projektu separatora cząstek żelaza z biegynami łukowymi. Obliczenie pola magnetycznego w obszarze pracy analizowanych biegunów jako systemu czterech równoważnych dipoli zostało przeprowadzone. Otrzymano jakościowe relacje dla określenia szerokości biegunów i kąta szczeliny między-biegunowej w przypadku biegunów łukowych. Przeprowadzone zostało modelowanie fizyczne systemów elektromagnetycznych z elementami biegunów łukowych przy różnych kątach. Porównano różne warianty. Z powodu badań wykonalność zastosowania biegunów łukowych w separatorach cząstek żelaznych została zademonstrowana, szczególnie przedstawiono rekomendacje co do istotnej modernizacji urządzeń produkowanych seryjnie. (**Ocena separatorów cząstek żelaznych z biegunami łukowymi za pomocą metody modułów magnetycznych**).*

Keywords: suspended electromagnetic iron separator, arch-shaped pole pieces, calculation of the field of four equivalent dipoles,
Słowa kluczowe: separator cząstek żelaznych, bieguny łukowe, obliczanie pola magnetycznego czterech równoważnych dipoli, .

Introduction

The experience of the operation of suspended electromagnetic iron separators used for the protection of the production equipment against accidental drop of ferromagnetic objects during the transportation of bulk materials by belt conveyors reveals that the common drawback of such devices consists in the insufficiency of the extracting effort created by them at the edges of the working zone [1]. As a result, a part of unwanted ferromagnetics passes through these areas not being separated from the transported non-magnetic material and gets into the operating devices of the production equipment, which results in its breakage.

Based on the analysis of the distribution of the field in the working zone of suspended iron separators, to provide the required magnetic intensity and the degree of the field heterogeneity in a relatively big volume of the extraction working zone, a new design of a suspended electromagnetic iron separator was worked out [2]. It is equipped with arch wedged-shaped pole pieces forming a gap situated at an angle to the conveyor longitudinal axis. The use of the iron separator is shown in the production chain is shown in Fig. 1.

The purpose of the paper

To demonstrate the expediency of the use of arch-shaped pole pieces in suspended iron separators based on the theoretical and experimental research, to obtain expressions for the calculation of the rational geometry of such pole pieces and to provide specific recommendations as to the relevant modernization of the devices produced in series.

The calculation of the poles parameters

The magnetic field of the analyzed U-shaped electromagnetic system of the suspended iron separator with arch poles is essentially 3D and it is impossible to use calculation methods from [3−6] as in our case we cannot single out such a direction along which the magnetic field of the system could be assumed quasi-plane-parallel. It caused the necessity for the choice of the method that would make it possible to research the analyzed system of the arch-type poles in a relatively simple way and with a sufficient degree of accuracy. A magnetic modulus method was chosen for this purpose [7–8].

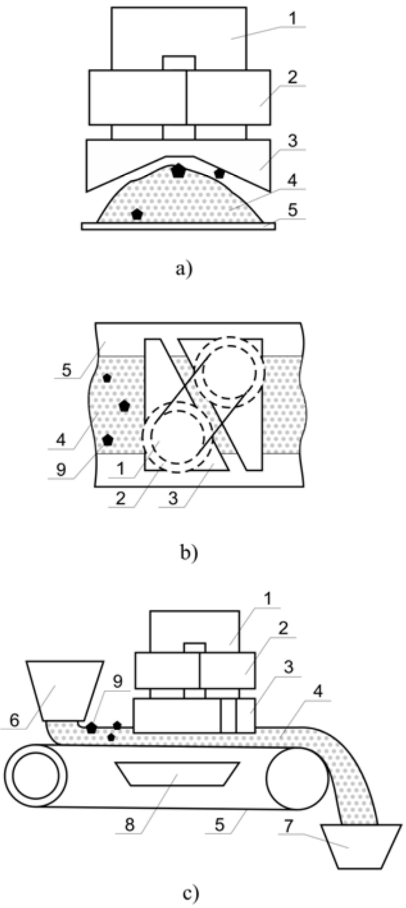

Fig. 1. Suspended electromagnetic iron separator with arch-shaped pole pieces (a – view along the conveyor belt; b – top view; c – overview), where 1 − magnetic system; 2 − magnetizing coil; 3 − pole piece; 4 − separated material; 5 − conveyor belt; 6 − initial material bunker; 7 − purified material bunker, 8 − bunker for the extracted ferromagnetic bodies; 9 − ferromagnetic bodies

Modifying this method the authors demonstrated and experimentally verified the possibility of the calculation of the field in the working zone of the iron separators with arch wedge-shaped poles as a system of four equivalent dipoles. This approach with certain assumptions can also be used for obtaining qualitative relations during the search for the rational values of the poles width and the angle of the inter-pole gap in the case of arch wedge-shaped poles.

Fig. 2 contains a calculation model of the inter-pole working space determined by the extraction working depth h_r, the poles width Z_p and their length L.

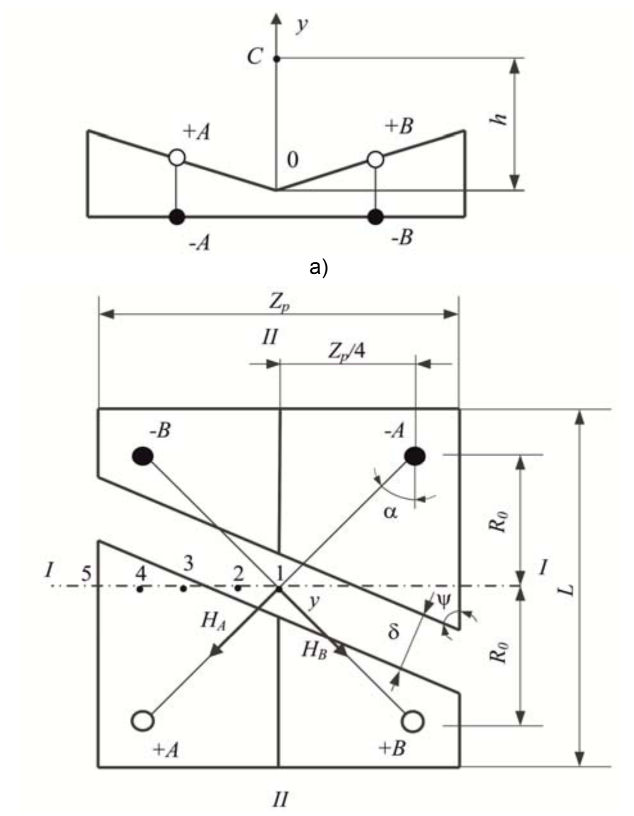

Fig. 2. Calculated model of the inter-pole work space (a – front view; b – top view)

If the equivalent dipoles are distributes as it is shown in plan in Fig. 2, (b), for an arbitrary point C on the vertical axis y (with the beginning at point 0 at the level of the poles bend) in the center of the inter-pole gap these dipoles magnetic field strength component directed along line II-II can be written down in the form

(1) $$H_{II} = (H_A + H_B)\cos\alpha ,$$

where H_A and H_B − magnetic field strength for dipoles ($+A$, $-A$) and ($+B$, $-B$) respectively, and the magnetic field strength component directed along line I-I can be written down as

(2) $$H_I = (H_A - H_B)\sin\alpha .$$

In this case magnetic field strengths H_A and H_B can be calculated by formula

(3) $$H_{A(B)} = \frac{M_{A(B)} R_0 h [h^2 + R_0 + (0.25Z_p)^2]^{-5/2}}{\cos\alpha} ,$$

where Z_p − the width of the working zone determined by the dimension type of the iron separator; $M_{A(B)}$ − the magnetic moment of respectively dipoles $\pm A$, $\pm B$; h − the distance from the level of the poles bend to the analyzed point; R_0 − the dimension characterizing the position of the dipoles across the width of the pole system.

A common assumption in the design calculation of suspended iron separators consists in the neglect of the magnetic flux from the side surfaces of the pole pieces [4]. It is assumed that the whole magnetic flux passes across the upper surfaces of the poles and value M in (3) can be determined via magnetic induction on the pole surface. Then, approximating the force line from one pole to the other by a circular arc, basing on the Ampere's circuital law, it is possible to write down for M

(4) $$M = F_c / (\pi h) ,$$

where F_c − the magnetomotive force (MMF) of the magnetization coil; πh − the length of the stated circular arc passing through the analyzed point.

As a result, taking into account (4) for H_I an H_{II}

(5) $$H_I = K_I \frac{0.25Z_p}{[h^2 + R_0 + (0.25Z_p)^2]^{5/2}} ,$$

(6) $$H_{II} = K_{II} \frac{R_0}{[h^2 + R_0 + (0.25Z_p)^2]^{5/2}} ,$$

where K_I, K_{II} − the coefficients determined by the coil MMF and the volume of magnetic moduli.

Component H_I in the total strength $\sqrt{H_I^2 + H_{II}^2}$ can be neglected as H_I is determined by the difference between H_A and H_B (2), and to optimize dimension R_0, determining the average width of the poles, expression (6) can be used. The following is obtained after simple transformations

(7) $$(R_0)_{opt} = 0.5[h^2 + (0.25Z_p)^2]^{1/2}$$

The obtained value of parameter $(R_0)_{opt}$ also determines the optimal value of angle $\alpha = \alpha_{opt}$ that can be found from the geometrical relations between the dimensions shown in Fig. 2:

(8) $$\alpha_{opt} = arctg\left[\frac{Z_p}{4(R_0)_{opt}}\right] = arctg\left[\frac{2}{\sqrt{(4h/Z_p)^2 + 1}}\right] .$$

It can be seen in Fig. 2, (b) that inter-pole gap angle ψ is always bigger than angle α, which should be taken into consideration when choosing angle ψ and determining its range during the research.

For the dimensions determined by the state standard GOST 30577-98 for suspended iron separators with the belt width of (500…2000) mm, $Z_p = 1200$ mm, and taking into account the assumed extraction depth of ($h = 300$ mm) the values are $2(R_0)_{opt} = 424$ mm and $\alpha_{opt} = 55^\circ$.

Physical modeling and experimental research

To assess the efficiency of the use of the proposed design of the pole pieces and specification of the most rational values of their geometric parameters a comparative physical modeling of an iron separator type P160 (ZHNEm-1.6x300-UZ-TU), produced in series at Luhansk Parkhomenko Engineering Works, and iron separators on its basis with arch-shaped pole pieces was performed. In the process of modernization, according to (1), of the series iron separator P160 having the distance of 510 mm between the axes of the magnet cores, which exceeds the above-recommended $2(R_0)_{opt} = 424$ mm, it is possible to make angle $\alpha \le 45^\circ \ne \alpha_{opt} = 55^\circ$ in the design.

That is why in modeling the modernized systems the maximum possible value of angle $\alpha = 45^\circ$, was adopted, which was provided by turning the iron separator yoke by this angle in relation to the direction of the movement of the separated material. In this case, the variation of two parameters is possible for arch poles. Angle Ψ (between the direction of the movement of the separated material and the axis of the air gap) varies in the range from 50° to 90° (1). Air gap δ varies in the range from 0 to δ_{max}, depending on angle ψ on the assumption of the complete overlap of the pole bracket core by the pole piece:

(9) $$\delta_{max} = D\sin(180^\circ - \alpha - \psi) - 2d \ .$$

Here D − inter-pole distance of the pole bracket; d − the diameter of the pole bracket core; α − the angle of rotation of the yoke axis to the direction of the separated material movement.

Physical modeling of the electromagnetic systems with arch pole pieces was performed at $\psi = 50^\circ$, $\psi = 60^\circ$, $\psi = 70^\circ$, hereinafter big, medium and small arch poles, respectively (angles > 70° were not researched as they can only be optimal at small angles of the natural slope of the separated material on the belt).

The force, with which the iron separator magnetic field acts on the test ferromagnetic object placed in the certain point, was measured to assess the extraction efficiency. A steel ball weighing $mg = 30$ g was used as a test object; it was located with the help of a template at the typical points of the working zone of the iron separator perpendicular to the direction of the movement of the separated material in the middle of the length of the working zone (Fig. 1). Extraction depth h was recalculated taking into account object diameter D' and template width d':

(10) $$h = h'' + d' + D' \ ,$$

where h'' – distance to the template.

The forces were measured with the assumption that the force acting on the test object is equal to the force required for its separation from the template plane.

Fig. 3 contains experimental curves of force field distribution across the width of the working zone at the depth of extraction at five points that are perpendicular to the direction of the separated material movement. Signs "○", "□", "△" designate the points at the dependences for the iron separators with arch poles and angle Ψ respectively $70^\circ, 60^\circ, 50^\circ$, sign "×" denotes the points at the dependence for the series iron separator P160.

To compare the variants the integral value of the traction force provided by the iron separator at the working extraction depth, taking into account the real distribution of the field across the width of the working zone with the help of a dimensionless coefficient, was taken as an assessment criterion:

(11) $$K_1 = \frac{\sum_{i=0}^{n} F_i}{\sum_{i=0}^{n} F_{bi}} \ ,$$

where F_i, F_b – the values of the extraction force at the i-th characteristic point at the working depth of extraction for the iron separators with arch poles and poles of the basic iron separator, respectively; n – the number of characteristic points (1, 2, 3, 4, 5; $n = 5$).

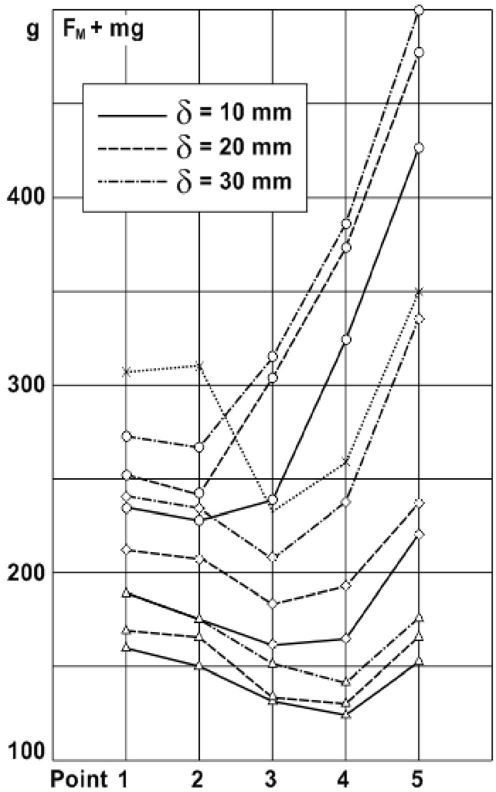

Fig. 3. Experimental curves representing the distribution of the force field across the width of the suspended iron separator working zone at the depth of extraction

To take into account the productivity factor in the comparison of variants a relative coefficient of correspondence between the working volumes of the iron separators magnetic fields and the real productivity of the conveyer was used [9]:

(12) $$K_2 = 2.08t\frac{Z_p}{B_b}\frac{L}{l_b} \ ,$$

where B_b – the width of the conveyer belt; L – the length of the extraction working zone; l_b – the basic length of the working zone, $l_b = 1$ m.

For iron separators P160 with the working zone length $L = 500$ mm – $K_2 = 1.04$ [9]. Then, other things being equal, the values of the productivity coefficients for the iron separators are determined by the relation of the working zone lengths and are given in the table.

The table demonstrates that the iron separator with arch poles and angle $\psi = 70^\circ$ and $\delta = 30$ mm (model M1:5) is characterized by the best cost/performance ratios, exceeding the serial devices as to coefficient K_1 by 1.19 times, and as to coefficient K_2 – by 1.5 times.

Table I. The values of the productivity coefficients for a serial iron separator and an iron separator with arch-shaped polar pieces at different values of the angle ψ

Type of iron separator	ψ	δ (mm)	$\frac{\sum_{i=0}^{5} F_i}{5}$	K_1	K_2	$K_1 \cdot K_2$
Iron separator with arch poles	50°	10 20 30	143 152 168	0.493 0.524 0.579	2.704	1.333 1.417 1.566
	60°	10 20 30	183 205 249	0.631 0.707 0.859	2.08	1.312 1.470 1.787
	70°	10 20 30	289 326 345	0.997 1.124 1.189	1.56	1.555 1.753 1.855
Serial P160		24	290	1	1.04	1.04

At the same time, as seen in Fig. 3, in the middle zone of the iron separator width (points 2 and 3) with the arch-shaped poles there is a decrease of the extraction effort. To assess this phenomenon impact on the quality of the separation process a statistical experiment was performed. During this experiment, the test objects were placed uniformly with the pitch of 10 mm in the working depth (the extraction zone) with the help of a template with holes. Calibrated ferromagnetic balls of the diameter of 2 and 5 mm, as the objects with the worst receptivity to extraction, were used as test objects. Complete extraction in the middle of the working zone (points 2 and 3) was observed in all the experiments in the middle of the working zone. At the same time, in the experiments with test objects of the diameter of 2 mm (in reality objects of the diameter of 10 mm) the serial iron separator P160 had "dead zones" near the side boundaries of the working zone where the balls were not extracted.

Conclusions

A relatively simple and sufficiently accurate method for the assessment of the extraction ability of iron separators with the use of the dimensionless coefficient of their efficiency has been proposed. The most rational values of the basic geometric parameters for the proposed arch-shaped pole pieces have been determined. Physical modeling and the experimental research have confirmed the high efficiency of the iron separator with arch poles. Particular recommendations as to the modernization of type P suspended electromagnetic iron separators, manufactured in series, have been provided.

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