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Theoretical validation for changing magnetic fields of systems of permanent magnets of drum separators

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Abstract. This article is devoted to the theoretical validation of the change in magnetic fields created by the permanent magnet systems of the drum separators. In the article, using the example of a magnetic separator for enrichment of highly magnetic ores, the method of analytical calculation of the magnetic fields of systems of permanent magnets based on the Biot-Savart-Laplace law, the equivalent solenoid method, and the superposition principle of fields is considered.

1. Introduction

Magnetic separators with systems of permanent magnets are the main machines for the enrichment of ore minerals [1]. In this case, drum separators of wet separation are used to enrich highly magnetic iron ores, in the first enrichment steps (rough separation for the purpose of producing tailings and intermediate products) for coarse-grained, and in the latter - for fine-grained materials. However, these machines are characterized by the inability to control the magnetic field due to the lack of analytical methods for calculating its parameters, which reduces the efficiency of separators [2, 3]. Therefore, the mathematical modeling of magnetic fields generated by the system of permanent magnets is relevant.

2. Main part

Mathematical modeling of magnetic fields can be carried out on the basis of the Biot-Savart-Laplace law [4, 5], the equivalent solenoid method, and the superposition principle of fields. According to the Biot-Savart-Laplace law, the magnetic induction produced by a straight section of conductor *dL* with current *I A* at a point in space *A* is expressed by the formula:

$$d\vec{B} = \frac{\mu_0 \mu I d\vec{L}\vec{r}}{4\pi|\vec{r}|^3}, \quad (1)$$

where μ_0 – universal magnetic constant; μ – magnetic constant; I – current strength in the conductor, A; $\overline{dL}$ – vector, co-directional with current in the conductor and equal to the length of its rectilinear elementary section, m; $\bar{r}$ – vector connecting the origin of the vector with point A, m.

Using this law, the Cartesian coordinate system and the principle of superposition of magnetic fields, one can calculate the value and direction of the vector of magnetic induction created at some point in space by a conductor of arbitrary shape and length with current I A. In order to apply the law to the calculation of the field of a constant cylindrical magnet, let us use the assumption (equivalent solenoid method) that the current in the conductor of an imaginary solenoid described around a magnet is equal to the product of the remanent magnetization of the latter by its length, referred to the number of turns of an imaginary equivalent solenoid $I = \frac{LM}{W}$, where L – length of magnet, m; M – residual magnetization of the magnet, A / m; W – number of turns of an equivalent solenoid.

Let us define:

$$d\vec{B} = \frac{\mu_0 \mu L M d\vec{L}\vec{r}}{4\pi W |\vec{r}|^3}, \tag{2}$$

Formula (2) can be used to calculate the magnetic field created by the system of permanent magnets of the drum separator (fig. 1). For this purpose, each magnetic column of the system should be divided into thin disks, likening them to turns of an equivalent solenoid, which are then broken down into elementary vectors. Calculating and adding elementary induction vector created in a specific point in space, each element of the magnetic system can determine the induction field at a given point, then one can construct three-dimensional graphical picture of changes in the magnetic field.

It is necessary to take into account some features of the separation process and introduce additional notation:

1. As the pulp moves along the cylindrical surface of the bath, the calculation of the induction field at plane formulation should be carried on concentric with the tub and drum arcs (fig. 1) or directly placed in the working area of the machine parallel to axis Z. In the voluminous statement of the problem, it is most informative to build three-dimensional graphic images of magnetic field induction for points belonging to a section of a cylindrical surface located in the working zone of the machine.

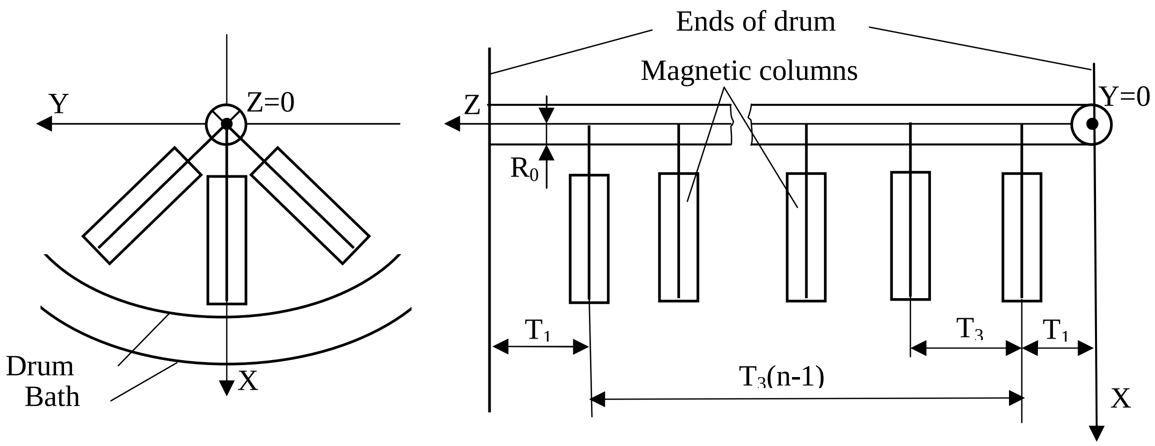

Figure 1. A scheme of the magnetic drum separator system

2. The attraction of particles to the drum occurs under the action of the magnetic force of its normal surface. In view of this, the coordinates of magnetic induction vector B_x, B_y, B_z can be transformed for the convenience of perception into coordinates B_n, $B_{\tau 1}$, $B_{\tau 2}$, natural with respect to the drum (fig. 2), reflecting normal component B_n on the graphs.

In accordance with fig. 2, the coordinate grid has x_{ij} of the investigate points, forming in the space a cylindrical surface of *i* arcs and *j* straight lines. To calculate the induction of the field at point A*ij* by formula (3), let us find its coordinates in system O*xyz* (fig. 3).

$$\begin{cases} A_{ijx} = R \cdot \cos\varphi_j, \\ A_{ijy} = R \cdot \sin\varphi_j, \\ A_{ijz} = z_i = \Delta l(i-1). \end{cases} \tag{3}$$

where R — the radius of the investigated surface relative to the center of rotation of the drum, m; φ_i — the angle between the line connecting the investigated point with the OZ axis and the OX axis.

$$\varphi_j = -\frac{\varphi}{2} + \Delta\varphi(j-1), \tag{4}$$

where φ - the central angle of the cylindrical portion of the surface under study; Δφ - the angular pitch of the mesh.

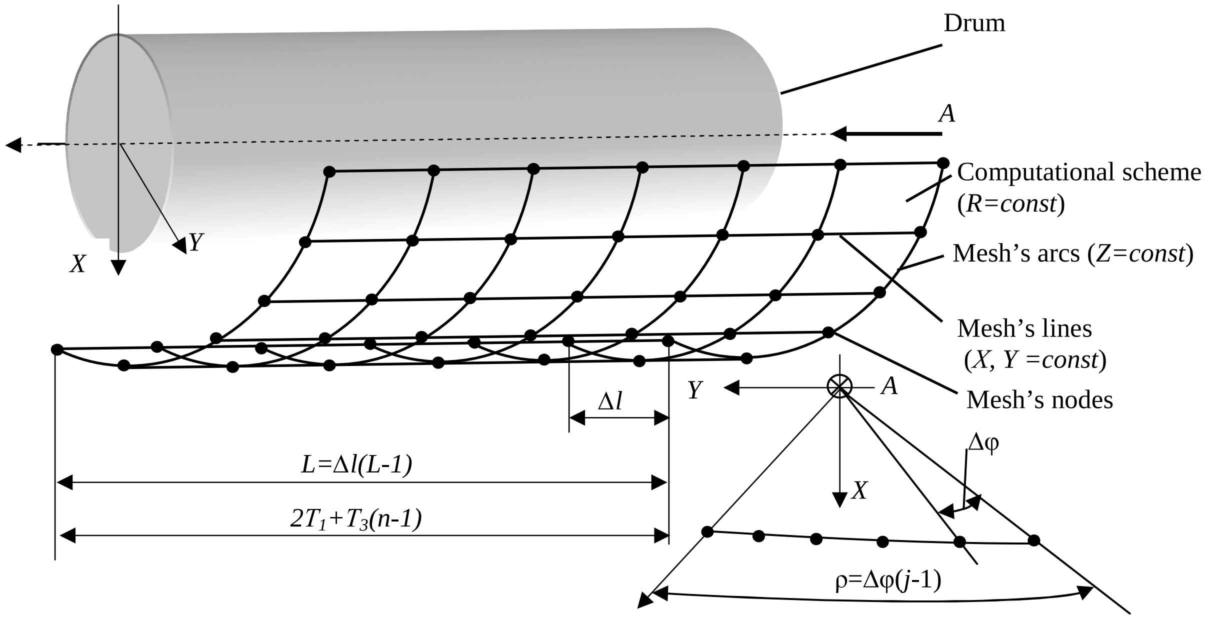

Figure 2. A computational scheme of the magnetic field of the drum separator

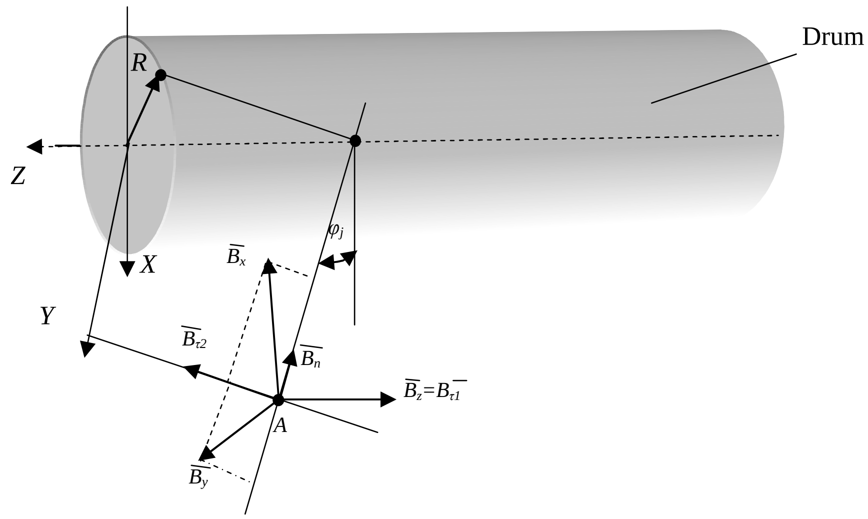

Figure 3. The magnetic induction vector of point A in Cartesian (X, Y, Z) and natural (n, τ1, τ2) space.

Magnetic mesh has *C* magnetic rows comprising n magnetic columns with the equal column for each row with a length *Lk* of the magnetic induction vector at point *Aij* can be found as the sum of the induction vectors created at this point each column of the magnetic system.

$$\vec{B}_{ij} = \frac{\mu_0 \mu M}{4\pi W} \sum_{k=1}^{k=c} L_k \sum_{t=1}^{t=n} \vec{B}_{ijkt} \ , \tag{5}$$

where $\vec{B}_{ijkt}$ - the vector of magnetic induction created by the n-th column of the k-th magnetic series at point A_{ij}, T_l.

For the calculation of vector $\vec{B}_{ijkt}$, it is necessary to break up the magnetic column generating it into elementary vectors making up the equivalent solenoid, and determine in the O_{xyz} system the coordinates of the points of their end and origin.

Composing the design scheme of vector $\vec{B}_{ijkt}$ (fig. 4).

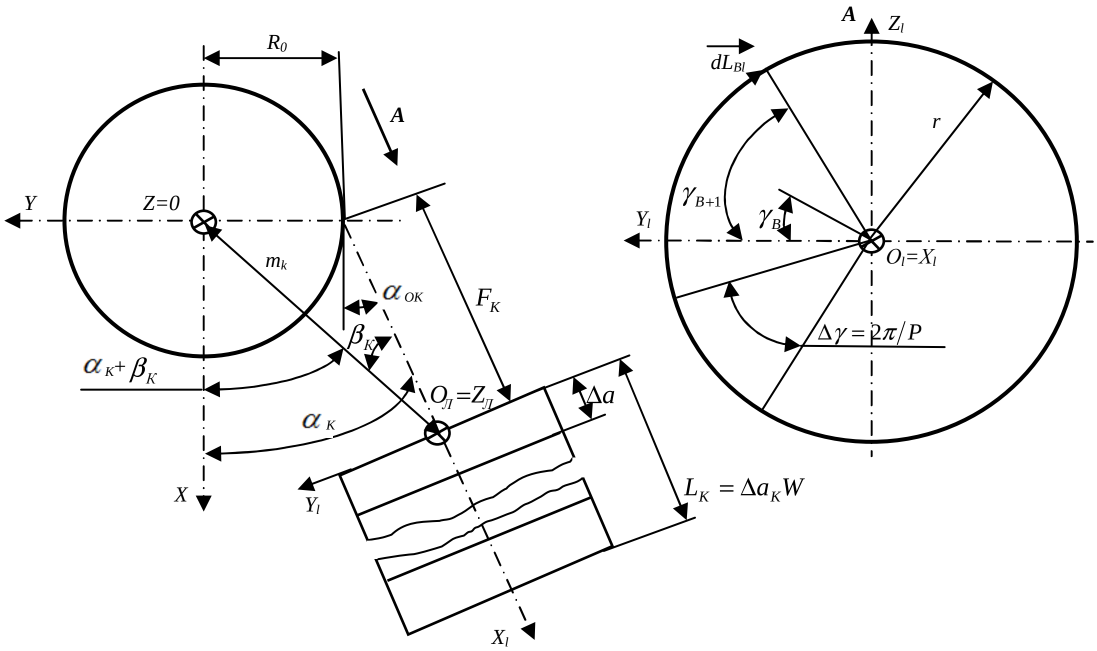

Figure 4. A calculation scheme to determine the coordinates of vector $d\vec{L}$ and the point of its origin in the O_{xyz} system

To obtain elementary vectors, the column is divided into W turns (circles), and they - into p sectors, on the largest chords of which let us construct the vectors of the equivalent solenoid. In this case, the inter-turn pitch will be $\Delta Q_k = L_k/W$, and the angular step is $\Delta\gamma = 2\pi/p$.

Then the column will appear as a collection of p-W vectors $d\vec{L}_{Be}$ ($B \in [1, p]$; $e \in [1, W]$; $e, B \in N$). Let us determine the coordinates of these vectors in a local system, whose center is located at center Ol_{kt} of the upper base of the column (fig. 4). Ozl_{kt} axis is parallel to the Oz axis, and axes $(Ol\ Xl)_{kt}$ and $(Ol\ Yl)_{kt}$ are rotated relative to the initial ones by some angle α_k, common for all columns of the k-th row.

$$\begin{cases} x_l dl_{Be} = 0, \\ y_l dl_{Be} = r(\cos\gamma_{B+1} - \cos\gamma_B), \\ z_l dl_{Be} = r(\sin\gamma_{B+1} - \sin\gamma_B). \end{cases} \quad (6)$$

where is r - the radius of the magnets in the column, m;
γ_{B+1}, γ_B – the angles between axis $(Ol\ Yl)_{kt}$ and the straight lines dropped from the points of the end and the origin of the vector, respectively, onto axis $(Ol\ Xl)_{kt}$

To determine the coordinates of vector $\vec{r}$, the coordinates of the point of its origin (that is, the origin of vector $d\vec{L}$) are needed. Let us express them in the local coordinate system.

$$\begin{cases} x_l dl_{Be1} = \Delta ae, \\ y_l dl_{Be1} = r\cos\gamma_B = r\cos(\Delta\gamma b), \\ z_l dl_{Be1} = r\sin\gamma_B = r\sin(\Delta\gamma b). \end{cases} \quad (7)$$

where e – the ordinal number of the layer (coil), counting from the top of the base of magnetic column 6 of the magnetic column. From fig. 4, one can conclude the following:

$$\begin{cases} X = X_l\cos\alpha_k + Y_l\cos(\alpha_k + \frac{\pi}{2}) = X_l\cos\alpha_k - Y_l\sin\alpha_k, \\ Y = X_l(\alpha_k + \frac{\pi}{2}) + Y_l\cos\alpha_k = -X_l\sin\alpha_k + Y_l\cos\alpha_k, \\ Z = Z_l. \end{cases} \quad (8)$$

where X_l, Y_l, Z_l – coordinates X, Y, Z of the local system; α_k – angle between axis OX and $(O_l\ X_l)_{kt}$ (fig. 4).

To determine the coordinates of point O_{lkt} in the global system, it is convenient to use distance m_k between points O and O_{lkt} and angle $\alpha_k + \beta_k$ between axis OX and segment m_k (*OOl*). However, it is not possible to measure these quantities directly. Therefore, let us express them through known angular and linear dimensions (fig. 4).

Formulas for determining the coordinates of the center of local coordinate system $O_{\text{л}kt}$ in global *Oxyz*, based on the data in fig. 4.

$$\begin{cases} X_{0l} = m_k\cos(\alpha_k + \beta_k), \\ Y_{0l} = m_k\sin(\alpha_k + \beta_k), \\ Z_{0l} = T_1 + T_3(t-1). \end{cases} \quad (9)$$

Here T_1 - the distance from the end of the drum to the first magnetic column, m; T_3 - distances between neighboring magnetic columns, m.

Let us obtain the coordinates of vector $\left(d\vec{L}_{Be}\right)_{kt}$ in coordinate system Oxyz:

$$\begin{cases} X_{dlbe} = -r(\cos\gamma_{B+1} - \cos\gamma_b)\sin\alpha_k, \\ Y_{dlbe} = r(\cos\gamma_{B+1} - \cos\gamma_b)\cos\alpha_k, \\ Z_{dlbe} = r(\sin\gamma_{B+1} - \sin\gamma_b). \end{cases} \quad (10)$$

On the basis of expressions (8), (9), (10), there is:

$$\begin{cases} X_{rbe} = A_{ijx} - \Delta ae\cos\alpha_k + r\cos\gamma_b\sin\alpha_k - m_k\cos(\alpha_k + \beta_k), \\ Y_{rbe} = A_{ijy} + \Delta ae\sin\alpha_k - r\cos\gamma_b\cos\alpha_k - m_k\sin(\alpha_k + \beta_k), \\ Z_{rbe} = A_{ijz} - r\sin\gamma b - T_1 - T_3(t-1). \end{cases} \quad (11)$$

After determining the vectors in global coordinate system $\vec{r}_{Be}$ and $d\vec{L}_{Be}$, formula (2) can be transformed as follows:

$$B_{ij} = \frac{\mu_0\mu M}{4\pi W}\sum_{k=1}^{k=C} L_k \sum_{t=1}^{n}\sum_{e=1}^{p} \frac{d\bar{l}_{be} \times r_{be}}{\left|\bar{r}_{be}\right|^2} \ . \quad (12)$$

In accordance with the above-described conditions of the separation process, it is advisable to reflect only the component of the magnetic induction vector normal to the drum surface on the graphs. As can be seen from fig. 4, it will be composed of vectors $\vec{B}_x$ and $\vec{B}_y$. The formula for its definition is:

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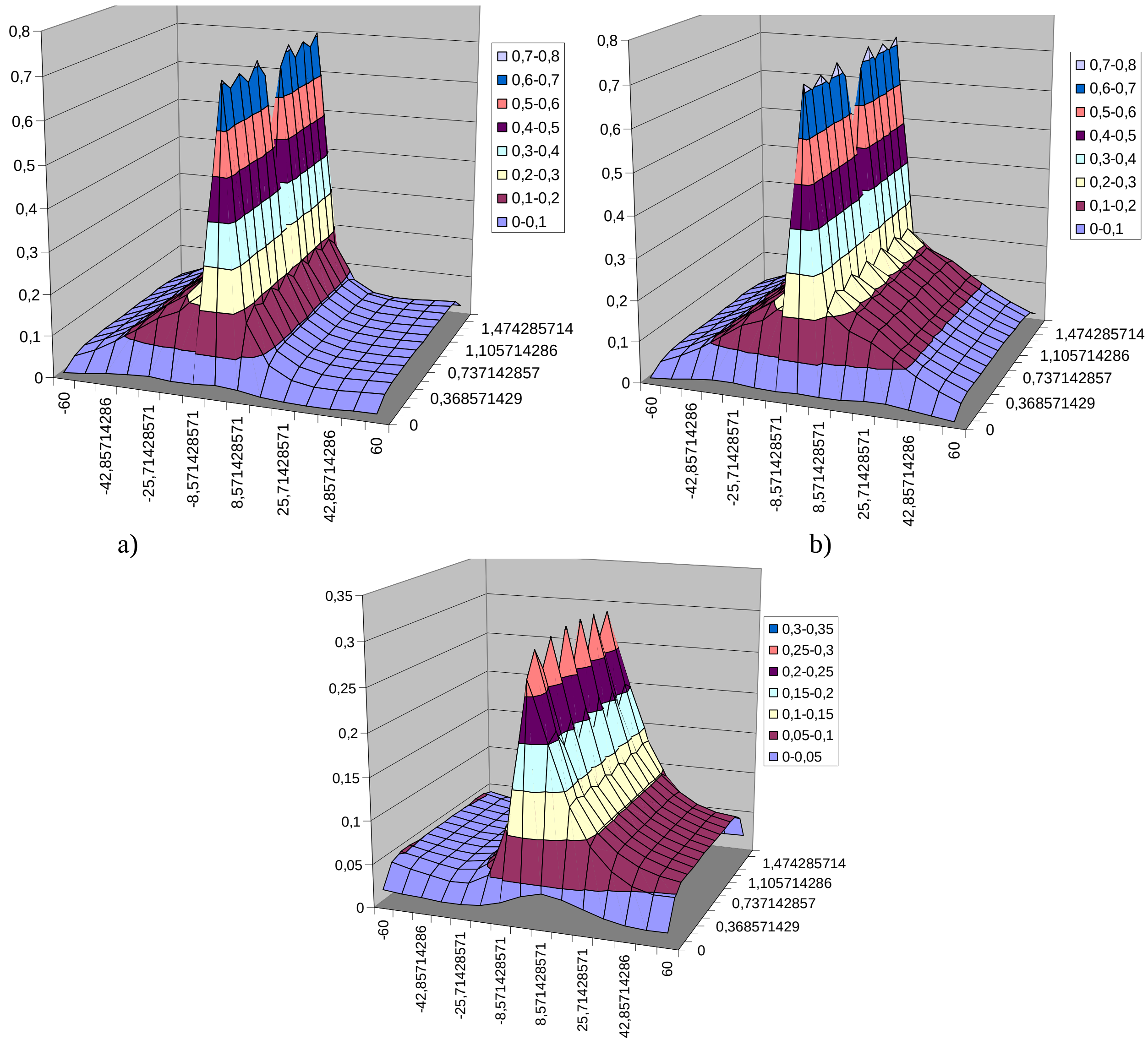
$$\vec{B}_{nij} = \vec{B}_{xij} \cos\varphi_j + \vec{B}_{yij} \cos(\frac{\pi}{2} + \varphi_j) = \vec{B}_{xij} \cos\varphi_j - \vec{B}_{yij} \sin\varphi_j . \quad (13)$$

where φ_j – angle between the straight line dropped from point A_{ij} to axis Oz and axis Ox.

On the basis of formulas (11) and (12), it is possible to calculate the induction of the magnetic field for any point A_{ij} or system of points belonging to a cylindrical surface concentric with the drum of the machine.

For using this formula, a computer program was created, which allows an analytic calculation of the fields of the permanent magnet system (fig. 5) and protected by the certificate of registration of software product N. 2016614807 (Russian Federation) [6].



c)

Figure 5. The field created in the working area of the drum magnetic separator at the angles of the solution of the rows of magnetic system (-30; 0; 60)º (a); (-30; 0; 30)º (b); (-60; -30; 60)º (c)

3. Conclusion

Based on the analysis of the configuration of magnetic fields, the following conclusions can be drawn:

The field created in the working zone of the machine at angles of the solution of the rows of magnetic system (-30, 0, 60)º (fig. 5, a) has a sufficiently wide zone for maximum extraction of particles of iron by the zone of maximum induction. In this case, the given configuration of the magnetic field differs favorably from that observed at the angles of solution (-30; 0; 30)º (fig. 5, b). The advantage is that in the asymmetrical magnetic system, after the maximum induction zone ends, the latter sharply decreases by almost an order of magnitude, which ensures the complete and simultaneous separation of the magnetic fraction from the drum. This circumstance makes it possible by turning the entire magnetic system to achieve a position in which all the particles of the magnetic fraction, after detachment from the drum, enter the flushing tray for the concentrate, and not fall to the bottom of the bath and stick to the drum. Therefore, this configuration of the magnetic system is preferred for the primary and final separation stages, where maximum recovery of the valuable component is required.

The field, observed at the angles of the solution of the rows of the magnetic system (-60, -30, 60)º (fig.5, c), is similar to the above-described form. But its induction is approximately half that of the solution angles (-30, 0, 60)º (fig. 5, a), which makes it possible to extract the most magnetic particles from the pulp and to obtain a high-quality concentrate. Therefore, this mode of tuning the magnetic system is beneficial in the purging operations.

The latter allows us to assume that the separator with an adjustable magnetic system can be operated in several modes:

1. At small angles of the solution of the rows of the magnetic system, the zone of maximum induction will be wide enough for the overwhelming majority of iron-ore particles to be captured by the drum and taken to the concentrate. Therefore, this regime will ensure the maximum extraction of iron ore from the pulp, but the quality of the concentrate will be very low, due to the penetration of weakly magnetic agglomerations of iron ore and gangue, which will require additional processing operations. In view of this, it is advisable to apply this setting of the separator in the primary separation stage in order to extract the maximum amount of the valuable component from the pulp that enters the bath, subjecting it to further grinding and clean separation.

2. At large angles of the solution of the rows of the magnetic system, the magnitude of the maximum induction will decrease insignificantly, but the width of the section at which it is observed will be extremely small so that the weakly magnetic particles and agglomerations can become magnetized to the drum. Thus, the most magnetic fraction with the maximum Fe content will be extracted. Therefore, this mode of operation is advantageous in the purification of primary separation concentrates and at the final stage of separation to obtain the richest concentrate.

The results of theoretical studies and numerical experiments confirm the possibility of controlling the intensity and uniformity of magnetic fields by changing the configuration of magnetic systems and, as a consequence, the high efficiency of using separators with adjustable systems of permanent magnets.

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