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MAGNETIC FIELD EFFECT IN THE PROCESS OF RINSING A MAGNETIC SEPARATOR MATRIX

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Abstract This paper surveys fundamental aspects of the problem of rinsing matrices in high gradient magnetic separators. This is done, for the first time, in terms of the magnetic circuit design. Equations have been constructed to describe the effects of spurious remanent magnetic fields on the rinsing process.

1. INTRODUCTION

Streams of water are used to rinse the matrix in magnetic separators. Water velocity, particularly in larger matrices, is usually limited and a suitable mixture of water and compressed air is not always available. This raises problems of specifying conditions for sufficient and reliable rinsing of a matrix. Also, the demands on (i) the mechanism controlling matrix motion as well as on (ii) screening cover, or on (iii) the whole concept of the magnetic circuit of a separator, should be taken into consideration.

The paper concentrates on specifying the magnetic conditions. A single-wire model has been employed for an exact calculation and parameter values have been used which are appropriate to the high-gradient magnetic separation of (say) Kaolin. A discrete model has been used for the description of separated particles.

2. MAGNETIC FIELD AND MATRIX RINSE

Matrix rinse means the removal of all separated, (mostly magnetic) particles from the surface of ferromagnetic matrix material which is formed by a random assembly of wires of approximately 0.05 mm in diameter, occupying about 5% of the canister volume. Rinsing is carried out by the hydraulic force of water pumped into the matrix at a velocity exceeding that of the normal separation process.

During the rinsing process, some separated particles are held on to the matrix wires, despite the influence of inertial, gravitational or inter-particle forces, by magnetic forces induced by spurious magnetic fields. These magnetic forces are of a similar character to the magnetic forces in normal magnetic separation.

The spurious magnetic field in rinsing consists of a reduced (or leakage) magnetic field of the separator magnetic circuit and the residual magnetic field of the wire, and possibly also by ferromagnetic structural parts of the separator. A residual magnetic field due to the ferromagnetic portion of the separated particles also exists in theory but can be neglected in practice.

From the point of view of the presence of the spurious magnetic field, a rinse can take place under the following conditions:

a) The field current of the magnetic circuit coil is full or partly reduced; the matrix is fixed.

b) The field current is zero but residual magnetic fields are present; the matrix is fixed.

c) The field current is full, magnetic leakage and residual fields are present; the matrix is of a withdrawal type, (i.e. it can be drawn outside the magnetic circuit work space).

d) The spurious magnetic field is suppressed, the field current is full; the matrix is of a withdrawal type and in the rinsing area, it is surrounded by auxiliary screening covers containing a de-magnetizing field produced either by coils or permanent magnets.

When evaluating the rinse quality in the above-mentioned examples, it can be said that, in case (a), (paramagnetic) particles of small susceptibility will be rinsed effectively while particles of much higher susceptibility (the ferromagnetic portion) will gradually - after several separation cycles - fill the "active" zone on the wires until a complete loss of separation capability of the matrix is reached. This solution may be applicable when using high rinsing water velocities together with compressed air.

In case (b), mainly attractive forces of a non-magnetic character will act, though it would be wise to consider the presence of magnetic forces caused by residual magnetic fields that may bring about a gradual filling of the zone.

In case (c), the rinse is of the same character as in case (a), as the magnetic leakage, according to the design, can have magnetic induction field values comparable with those present under normal operating conditions.

Rinsing, according to (d) occurs with minimum disturbance by magnetic forces, but is more complicated in design.

The requirements on the choice of magnetic system for the separator, can be specified only by quantitative design. This design should include the spurious magnetic field effect in the rinsing process. Precise determination of the value of the admissible magnetic induction of the spurious field, for a given rinsing velocity, will provide an important parameter for designing the separator magnetic circuit.

The separation system, including the feed slurry. the rinsing fluid and the random assembly of fibers in the matrix can be described in terms of various vector quantities:

(i) the wire axes can be represented by $\vec{0}_d$ a unit vector whose direction is given by wire axis and whose sense can be chosen arbitrarily;

(ii) a feed velocity, $\vec{v}_s$;

(iii) a rinsing fluid velocity, $\vec{v}$;

(iv) the magnetic induction field, $\vec{B}$, of the separator;

(v) the magnetic induction of the spurious magnetic field, $\vec{B}_o$, in the rinsing zone;

(vi) the gravitational vector, $\vec{g}$;

and

(vii) the particle separation zone, represented by $\vec{0}_z$ a vector whose direction is determined by a straight line drawn perpendicular to the wire axis and lying in the symmetry plane of the zone; the sense of this vector points normal to the wire surface and its size is proportional to the distance from the top of the separation zone to the wire surface.

Depending on the directions of the feed stream velocity $\vec{V}_s$ and on the direction of $\vec{B}$, zones of various directions $\vec{0}_z$ are formed on the wires. However, from the point of view of the rinsing process, their projections, $\vec{0}_z$, on to the direction of the spurious $\vec{B}_o$ field will be decisive. The direction of the spurious $\vec{B}_o$ field is considered to be congruent with the direction of the separator field, $\vec{B}$, which will be decisive for carrying out the rinse. Different directions or senses, $\vec{B}_o$, and, $\vec{B}$, may have a limited, favorable effect upon the rinsing process and can occur in certain parts of the matrix.

A random wire arrangement enables arbitrary angles between a plane determined by axis $\vec{0}_d$ and zone $\vec{0}_z$ but the velocity component of the rinsing fluid velocity in the perpendicular direction to the wire within this plane is decisive for the rinse. Even in the case of parallelism of $\vec{v}$ and the plane determined by $\vec{0}_d$ and $\vec{0}_z$, a certain transient component of the rinsing fluid velocity,

$\vec{v}$, perpendicular to this plane may be considered (caused by, a bubble of, for example, compressed air, forced into the matrix during the rinse, passing the wire).

A particular matrix design usually contains spaces with various senses of gravitation of vector $\vec{g}$ and rinsing $\vec{v}$. To carry out the rinse, the parallelism and the opposite sense of $\vec{g}$ and $\vec{v}$ must be ensured (see Fig. 1.) The condition of rinse feasibility is defined by the non-zero triple scalar product:

$$[\vec{O}_z \times \vec{v}] . \vec{O}_d \neq 0 \quad ,$$

if the zone vector $\vec{O}_z$ is of the direction $\vec{B}_o$, the separation vector $\vec{B}$ is of the same direction and sense as $\vec{B}_o$ and the gravitational vector $\vec{g}$ is of the same direction but opposite sense to $\vec{v}$.

The basic rinsing system is defined by the mutually perpendicular vectors $\vec{O}_z$, $\vec{v}$ and $\vec{O}_d$ when their triple scalar product reaches its maximum value and the most effective rinse can be expected; i.e. the component $\vec{v}$ which, together with $\vec{O}_z$ and $\vec{O}_d$ forms the basic system, is decisive for quantitative evaluation.

When designing the matrix from the point of view of the rinse the most effective rinse is to be expected in the so-called radial arrangement where the rinsing water is forced in the radial direction of the cylindrical matrix, while the separation $\vec{B}$ is in the direction of the axis of the matrix cylinder.

3. DISCRETE DESCRIPTION OF THE ZONE

In the following, the term zone indicates the space around the wire where entrapped particles occur. By a 'discrete' description of the force relations, we mean that the particles or particle clusters within the zone are considered separately and without interaction. This assumption is justified in the case where only magnetic forces are present.

3.1 Force relations

Forces produced by a magnetic field gradient around a separation wire have been derived previously for the case when the wire has been magnetized up to saturation and magnetic field monotonically drops while the field current decreases or the matrix moves out. In this case the relations for magnetic forces in cylindrical coordinates can be used[1]. The force component in the radial direction is:

$$F_r = -2\mu_o.V.\chi.A \quad \frac{1}{r^3}\left(\frac{A}{r^2} + H_o \cos 2\Phi\right) \qquad (1)$$

and in the azimuthal direction is

$$F\phi = -2\mu_o.V.\chi.A \left(\frac{A}{r^3} H_o \sin 2\phi\right) \qquad (2)$$

$$A = \frac{I_s.a^2}{2\mu_o} \qquad (3)$$

where I_s (T) is the saturated magnetic polarization of the wire, a, the wire radius, and where the other symbols have their usual meaning.

According to Stafl,[2] the relation between the outside field intensity H_o and the intensity H_2 inside a cylindrical wire, of relative permeability μ, is

$$H = \frac{2}{1+\mu} H_o \qquad (4)$$

If $\mu >> 1$, eqn. (4) can be expressed as

$$H = \frac{2}{\mu} \quad H_o = \frac{2}{\mu} H_o \qquad (5)$$

Thus for the magnetic induction inside the wire, $(B < 1.4T)$

$$B \simeq 2B_o \qquad (6)$$

Magnetic polarization can be thus expressed (where we linearize the hysteresis curve in the observed interval) as:

$$J \cong B_r + \frac{2(I_1 - B_r)}{B_1} B_o = B_r + K_j B_o \qquad (7)$$

$I_1(T)$ is the magnetic polarization corresponding to B_1; $B_o(T)$ is the magnetic induction of the field in which the wire has been inserted, and K_j is a constant determined by I_1, B_1, B_r from the characteristic wire magnetization curve.

Equation (7) is applied to express the magnetic polarization in eqn. (3) as

$$A = \frac{(B_r + K_j B_o)\, a^2}{2\mu_o} \tag{8}$$

We are conscious of a certain inaccuracy here, as the magnetic polarization was supposed to be constant, but, on the other hand we relate the dependence of that quantity, as given by Sestak and Rieger[3], to the drop of the external magnetic field.

The particles are of heterogeneous, irregular shape and due to their mutual cohesion they form a certain volume. The suitability of various substitute bodies for particle clusters, has been considered and cylinders of different radii b_I to b_{IV}, with differing distances of their axes, to the point in question r_o r_{IV}, have been chosen (see Fig. 1).

It is possible to express the force relations for cylindrical particle volumes V at different distances r and of different cylinder radii b, thus:

$$V = \Pi\, b^2 L \tag{9}$$

where b(m) is the radius of the particle cluster of cylindrical shapes and L(m) is the cylinder length.

The resistance force, F_r, of the environment is determined by the velocity vector of rinsing medium $\vec{v}$ which is perpendicular to vector $\vec{B}_o$ and to the wire axis (see Fig. 1).

$$F_v = \rho\, v^2\, L\, b\, C \tag{10}$$

where $F_V(N)$ is the force of environment resistance acting on the cylinder, ρ (kgm^{-3}) is the environment density, $v(ms^{-1})$ is the velocity of environment motion, L(m) is the cylinder length,

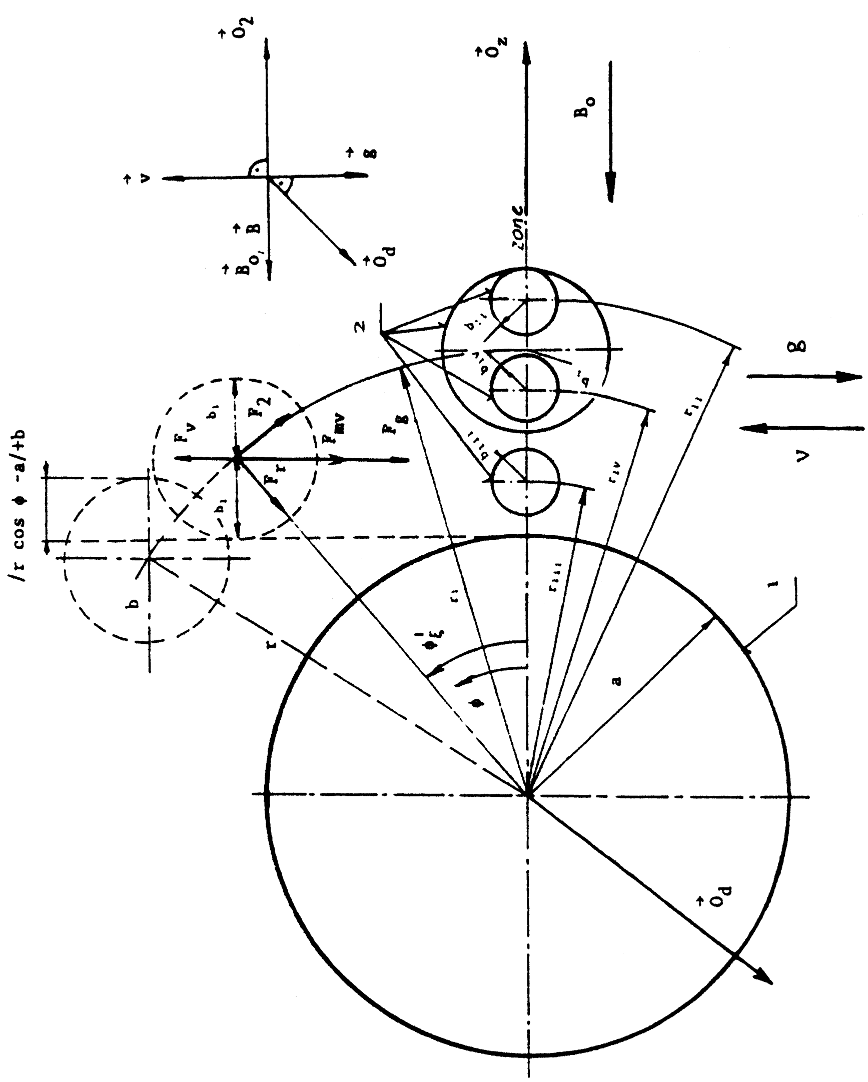

FIGURE 1   general vector directions

b(m) is the cylinder radius, and C is a coefficient of environment resistance. For the range of assumed velocities ($v = 0.08$ to $0.3\ ms^{-1}$) and for wire dimensions (including the zone of approx. $0.075 \rightarrow 0.15$)
$C = 3.7 \rightarrow 2.5$.

The gravitational force acting on the cylinder of entrapped particles is mm), then, according to Sestak and Rieger[3].

$$F_g = V(\rho_i - \rho)g, \tag{11}$$

where $\rho_i (kgm^{-3})$ is the particle density in the zone and where

$g = 9.81\ ms^{-2}$.

3.2 Critical velocity condition

Overcoming magnetic forces, which also hold the particles within the zone, may cause that particle to be released and swept away by rinsing water.

As has been already indicated, we are concerned with a simplified situation where the particle cluster of cylindrical shape is acted upon only by magnetic and gravitational forces as well as by the resistance forces of the environment. Their time variations considered are slow so that inertial forces do not act in this quasistationary state.

Until the particles are released from the zone, the zone will maintain a steady volume and it will be subject to deformation by the environment resistance forces. A particle within the zone is assumed to travel along a circular path with regard to the cylindrical wire and the direction of force action.

If the particle buildup cylinder is screened behind the wire, the reduction of the area is expressed by a coefficient ζ whose values range from 1 to 0.

If the particle cluster in a certain area of the zone is to be released, then it is necessary that

$$\xi F_v - F_g > F_{mv} \tag{12}$$

where F_{mv} is the component of magnetic forces in the velocity direction.

$$F_{mv} = -F_r \sin\phi - F_\phi \cos\phi \tag{13}$$

The force F_{mv} and coefficient ξ are functions of ϕ. Thus it follows that:

$$\frac{\partial(\xi Fv - Fg)}{\partial\phi} > \frac{\partial Fmv}{\partial\phi} \tag{14}$$

The critical velocity, at which magnetic and gravitational forces are overcome, is determined from equality in expression (12) above and by fulfilling the condition (14).

It follows that the coefficient ξ is

$$\xi = \left(\frac{r\cos\phi - a+b}{2b}\right) \tag{15}$$

in the range $\phi_\xi^{1}<\phi<\phi_\xi^{11}$ For $\phi \leq \phi_\xi^{1}$, $\xi = 1$ and for $\phi \geq \phi_\xi^{11}$ $\xi = 0$. In the interval where $1 > \xi > 0$, $\frac{\partial\xi}{\partial\phi} = 0$.

After substituting relations (1) and (2) into (13) we get:

$$F_{mv} = \Pi b^2 LX \frac{a^2}{r^3}\left[\frac{B_r + K_jB_o}{\mu_o}\right]\left[\left(\frac{B_r + K_jB_o}{2}\right)\frac{a^2}{r^2}\sin\phi + B_o\sin 3\phi\right] \tag{16}$$

From eqns. (1), (2) and (16), the partial derivatives in (14) become:

$$\frac{\partial(\xi Fv - Fg)}{\partial\phi} = -Fv\frac{r}{2b}\sin\phi\,, \quad \text{and}$$

$$\frac{\partial Fmv}{\partial\phi} = \Pi . b^2 . L . X\frac{a^2}{r^3}\frac{B_r + K_jB_o}{\mu_o}\left[\left(\frac{B_r + K_jB_o}{2}\right)\left[\frac{a^2}{r^2}\cos\phi + 3B_o\cos 3\phi\right]\right] \tag{18}$$

If the local extreme-maximum of function (16), to which ϕ_k corresponds, is determined by means of eqn. (18), and if the speed value is calculated from the equality of relation (12) for ϕ_k, the velocity v_{k_1} will be the critical velocity as long as $\phi_k < \phi_\xi$. The derivative value in the observed interval is constantly negative. This situation is shown in Fig. 2, point 1.

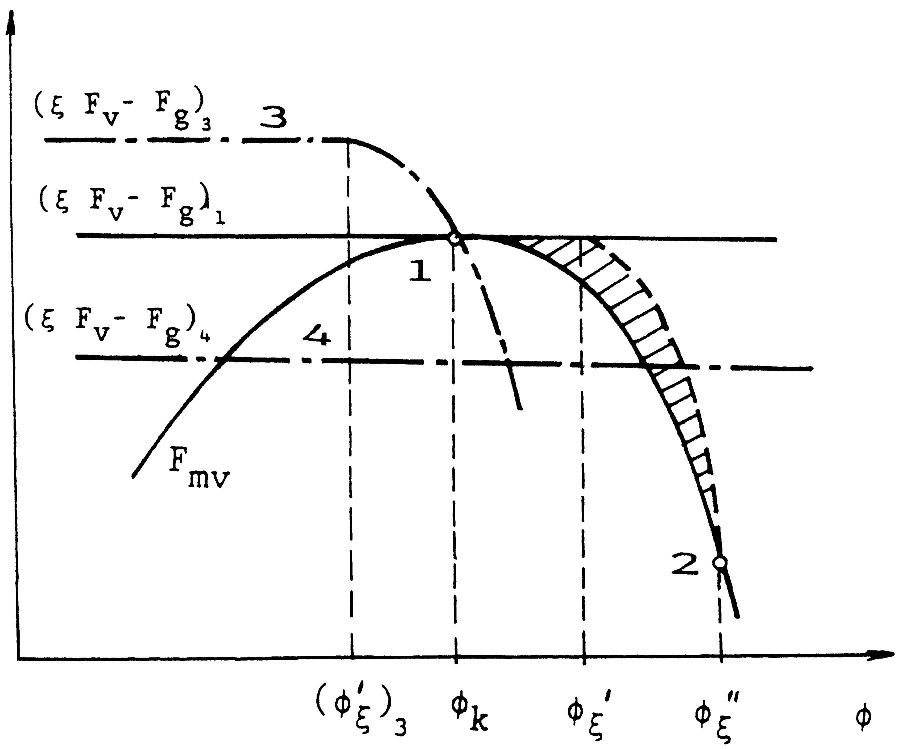

FIGURE 2 critical retention conditions

If the force plots intersect in point 2, it can be assumed that the excess of forces between the points 1 and 2 (hatched area) will shift the particle to larger radius, F_{mv} will decrease and the particles will no longer be kept in the zone. Plots 3 and 4 are dot-and-dash marked where the conditions of release are not fulfilled. (Fig. 2)

Critical velocity is calculated from the equality according to (12) after substitution from (10) and (11)

$$v_k = \frac{\Pi\, b\, \chi\, a^2\, (B_r + K_j\, B_o)}{\mu_o\, \rho\, r^3\, C\, \xi} \left(\frac{B_r + K_j\, B_o}{2}\right) \left[\frac{a^2}{r^2} \sin\phi + Bo \sin 3\phi\right] + \Pi\, b\, \frac{(\rho_i - \rho)\, g}{\rho\, C\, \xi} \qquad (19)$$

for $\phi = \phi_k$ when $\phi_k < \phi_\xi^1$. For the value ϕ_ξ^1 after re-arranging equation (15) gives:

$$\cos \phi_\xi^1 = \frac{a + b}{r} \qquad (20)$$

4. MAGNETIC PARAMETERS AND CRITICAL RINSE VELOCITY

Among the magnetic parameters we include here:

(i) the magnetic induction field (B_o) in which the matrix is situated.

(ii) the susceptibility of the separated portion in the zone (χ) and the particle size (b).

(iii) the relative permeability (μ), remanence (B_r) and wire diameter (2a). The critical rinsing velocity, v_k, is the critical velocity of rinsing water in the direction perpendicular to the wire axis and direction B_o at which the particles, held near to the wire by magnetic forces, start to be released. Values quoted in table 1 were substituted into equation (19). First of all, values, ϕ_k, have been determined by means of equation (18), they were then compared with ϕ_ξ^1 according to equation (20) and finally substituted into equation (19) for $\xi = 1$. The results are shown in Fig. 3,4 and 5, in which plots start in the points where ξ reaches the value 1. Though the exact description of the rinse (for $\xi<1$) comes to an end in the direction of decreasing

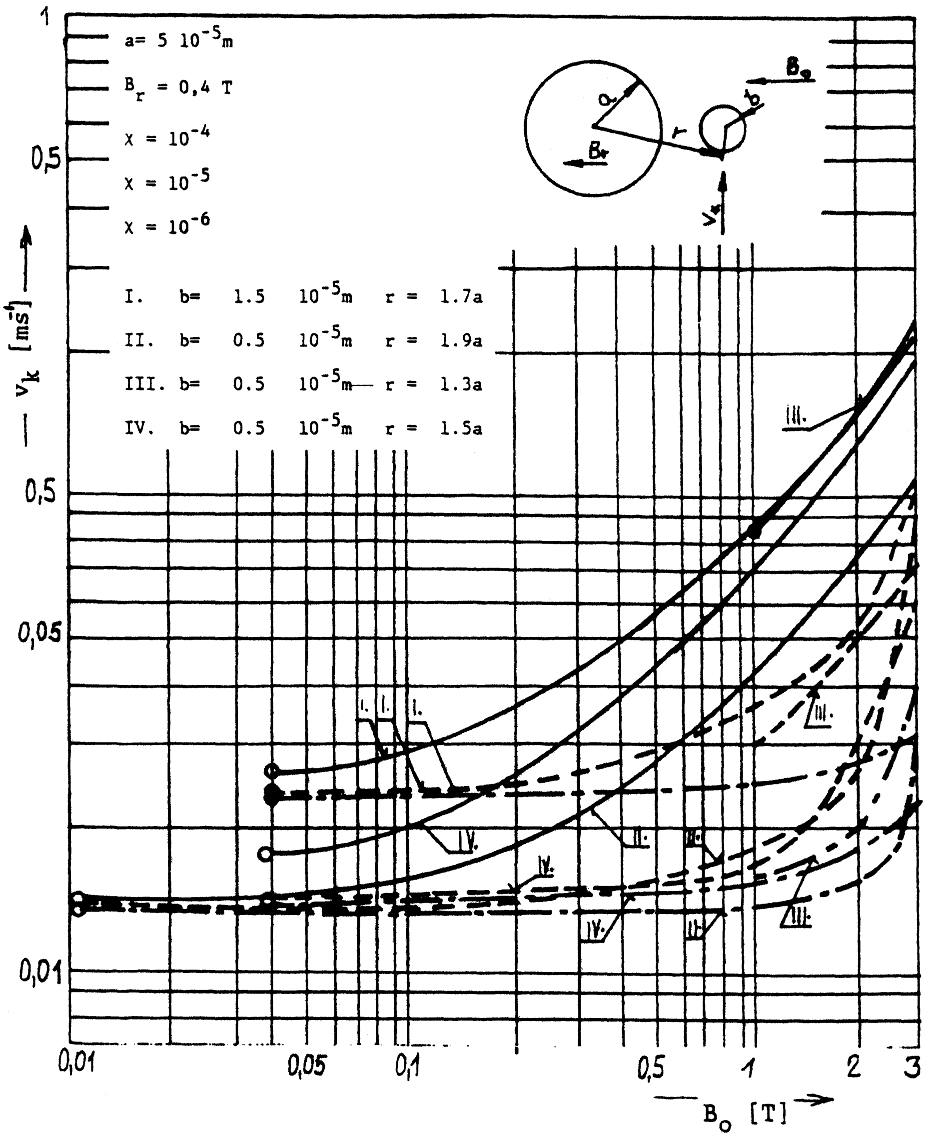

FIGURE 3 particle rinsing conditions (a=50 μm)

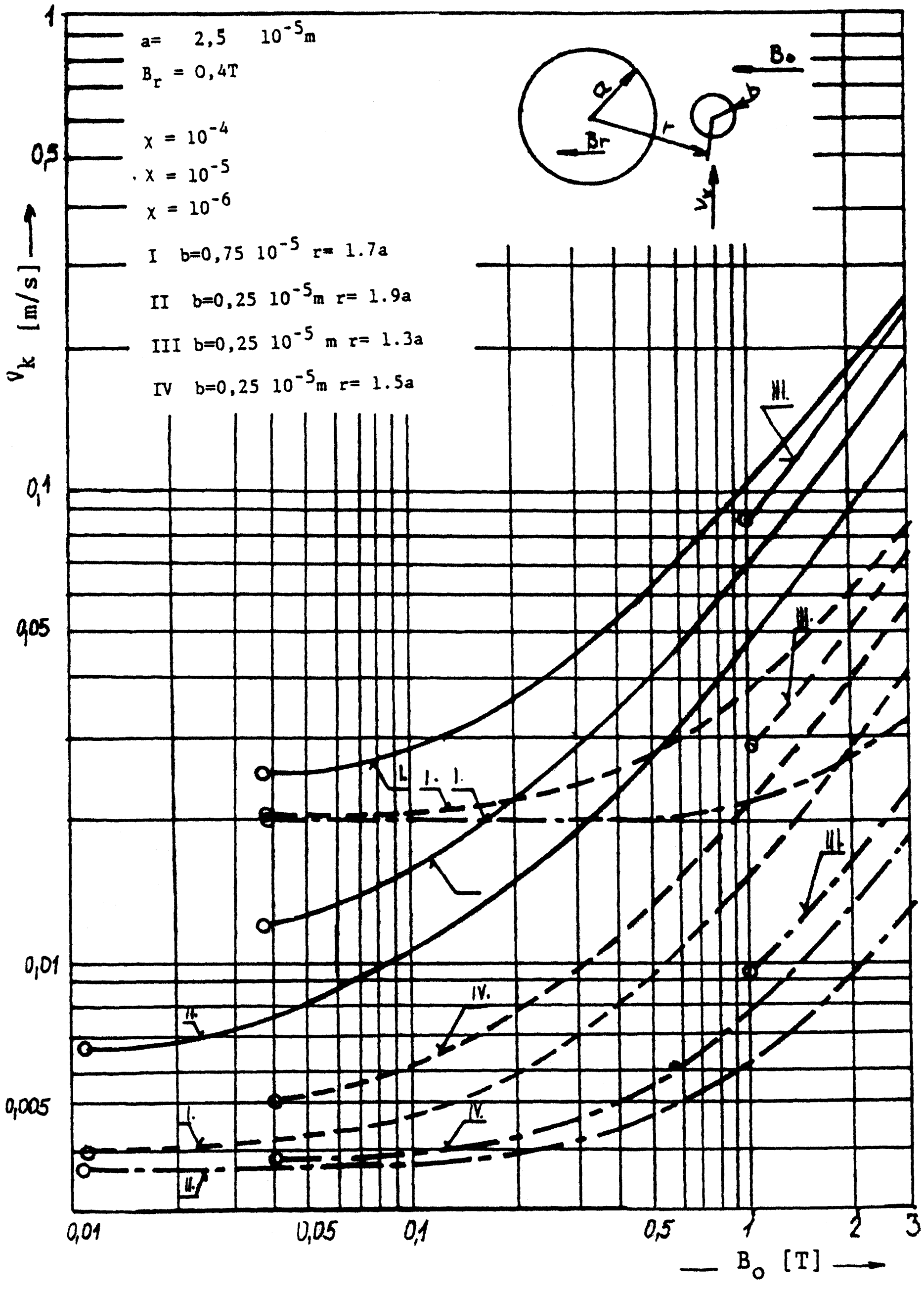

FIGURE 4 particle rinsing conditions (a=25 μm)

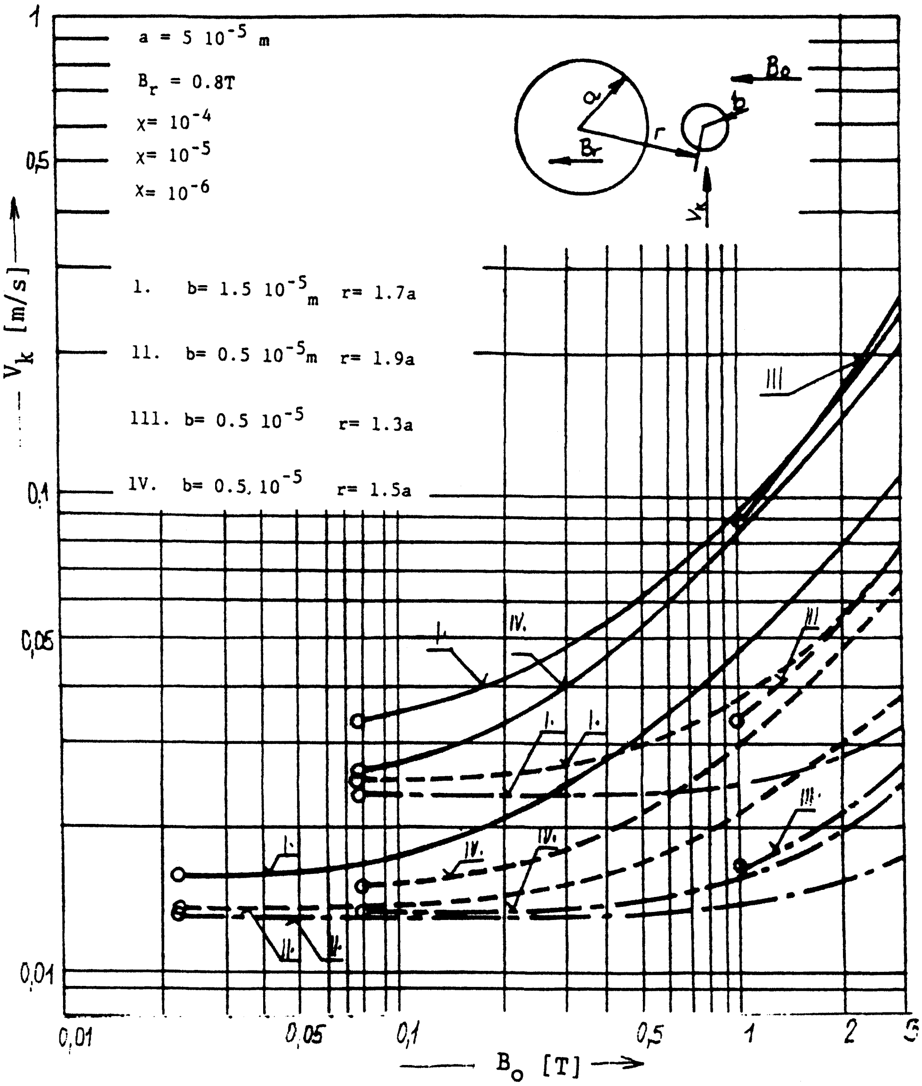

FIGURE 5 particle rinsing at higher B_r (0.8T)

$B_r = 0,4$ T, $K_j = 1.046$, $\xi = 1$, $\rho = 10^3$ kgm^{-3}, $(\rho_i = \rho) = 4,2.10^3$ kgm^{-3}

variant	a /m/	b /m/	c /m/	c /-/	/-/	B_0 /T/	V_k /ms^{-1}/	Fig	
I.	5 10^{-5}	1,5 10^{-5}		3,7	10^{-4}	0,1	0,028		I
					10^{-5}	0,1	0,024	3	I
					10^{-6}	0,1	0,023		I
	2,5 10^{-5}	0,75 10^{-5}	1,7a	2,5	10^{-4}	0,1	0,029		I
					10^{-5}	0,1	0,021	4	I
					10^{-6}	0,1	0,020		I
II.	5 10^{-5}	0,5 10^{-5}		3,7	10^{-4}	0,1	0,015		II
					10^{-5}	0,1	0,013	3	II
					10^{-6}	0,1	0,013		II
	2,5 10^{-5}	0,25 10^{-5}	1,9a	2,5	10^{-4}	0,1	0,011		II
					10^{-5}	0,1	0,005	4	II
					10^{-6}	0,1	0,004		II
III.	5 10^{-5}	0,5 10^{-5}		3,7	10^{-4}	1	0,085		III
					10^{-5}	1	0,030	3	III
					10^{-6}	1	0,016		III
	2,5 10^{-5}	0,25 10^{-5}	1,3a	2,5	10^{-4}	1	0,090		III
					10^{-5}	1	0,029	4	III
					10^{-6}	1	0,010		III
IV.	5 10^{-5}	0,5 10^{-5}		3,7	10^{-4}	0,1	0,020		IV
					10^{-5}	0,1	0,014	3	IV
					10^{-6}	0,1	0,013		IV
	2,5 10^{-5}	0,25 10^{-5}	1,5a	2,5	10^{-4}	0,1	0,016		IV
					10^{-5}	0,1	0,006	4	IV
					10^{-6}	0,1	0,004		IV

TABLE I

B_o, it may be assumed that, even in the range of small values of B_o, the rinse will take place if the velocity is higher than the velocity of the extreme left-hand point of the diagram. Critical velocities are observed for wire diameters 50→100 μ m, with particle susceptibility in the range from 10^{-6} to 10^{-4} and particle size in the range 2.5 to 15 μ m, which is in accordance with Gauss' distribution of the size occurrence of Kaolin particles. This also corresponds to the Czechoslovak Standard Specification 015030.

Plots in Fig. 3 and 4 marked II, III and IV, show the situation for rinsing medium particles.

Plots in Fig. 5 are similar but for the value B_r = 0.8 T (whereas B_r = 0.4 T in plots shown in Fig. 3).

The influence of the susceptibility of entrapped particles is apparent from the difference in plots drawn in a solid line ($\chi = 10^{-4}$), dash line ($H = 10^{-5}$) and dot-and-dash line ($\chi = 10^{-6}$)

The influence of wire diameter 2a is evident from comparing the plots in Fig. 3 and 4.

5. CONCLUSION

The paper gives a survey of the optimum arrangement of a rinsed matrix from the point of view of the magnetic circuit design. Under certain simplified conditions, force relations in the entrapped particle zone and the effects of spurious magnetic fields have been described.

Quantitative description of rinsing processes has been solved for individual particles of larger dimensions - variant I, smaller dimensions - variants II, III, IV.

The values of critical rinsing velocities, v_k, of water in the matrix were obtained by means of determining the conditions for overcoming magnetic forces which are only a part of the total force holding the entrapped particles on the wire within the zone. It is necessary to choose the minimum rinsing water velocity in the matrix with regard to critical velocity v_k for a certain value of magnetic induction B_o of the spurious magnetic field in which the matrix during rinse is situated.

For example, for a magnetic induction field B_o=0.05 T, for a magnetic volume susceptibility $\chi = 10^{-4}$, and by comparing the variants I→ IV, the minimum rinsing water velocity/perpendicular to B_o and wire axis/should be higher than $v_k = 0.05\ ms^{-1}$.

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