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APPLICATION OF SUPERCONDUCTING MAGNETS TO MAGNETIC SEPARATION. SOME SELECTED ASPECTS.

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Abstract One of the possible magnetic separation processes, the high-gradient magnetic separation, is analysed. Mathematical model of separation for two alternative constructions, namely deflecting and matrix separators, is presented. The model enables the efficiency of separation to be analysed as a function of selected parameters. The performance of the matrix separator, as well as the phenomena that take place during the matrix replacement are described. Computed values of the magnetic force acting on the matrix that moves in the magnetic field are presented. A laboratory superconducting magnetic separator is described.

INTRODUCTION

Cryoelectrotechnics that connects electrotechnics with cryogenics and numerous other branches of science, makes it possible, for instance, to generate a magnetic field of high strength and of required homogeneity. Such a field can be used, among other things, for magnetic separation.

Modern separation techniques for mixtures of solid particles and slurries are based on the application of strong nonhomogeneous magnetic field (high-gradient methods). There are two kinds of separators for separation of mixtures: deflecting and capturing (matrix) separators.

The deflecting separators are continuous devices in which the magnetic field deflects the magnetic fraction from a vertical stream of a slurry. The separation takes place in the region of strong nonhomogeneity. The most common constructions of the source of the magnetic field in deflecting separators are solenoids of various configurations, e.g. dipoles, multidipoles, quadrupoles etc.

Selection of the proper configuration depends on the value of magnetic induction, as well as on physical properties of the material to be separated. The systems mentioned above are of complicated construction and of considerable cost, particularly for auxiliary equipment (nontypical forms of a cryostat, for instance).

In matrix separators the field is generated by a solenoid coil of a simpler design. The field nonhomogeneity does not result from the form of the coil but is generated by ferromagnetic elements (e.g. steel wool fibres).

This ferromagnetic material is placed in a canister introduced into the magnetic field. The magnetic fraction of the feed passes through the matrix (a canister with steel wool) and attached to the ferromagnetic elements. The non-magnetic particles are collected outside the matrix.

The efficiency of the separation process depends (besides the magnetic field strength) mainly on properties of the ferromagnetic elements (their volume and magnetic characteristics).

MATHEMATICAL MODEL OF SEPARATION

A comfortable tool to consider the extraction of particles from a slurry by magnetic force is the so-called macroscopic model. It can be assumed that the slurry flowing through the separator is homogeneous in relation to its physical properties.

Furthermore, it can be assumed that:

1. the flow of the slurry is laminar in the entire volume of the separator
2. the concentration of particles in the slurry is constant in each cross-section of the separator
3. the velocity of particles that results from the action of the magnetic field (the velocity in the direction of the magnetic field) is constant.

The extraction of particles during the separation process, taking into account the assumptions shown above, can be characterised by the following kinetic equations [1]:

$$\frac{\delta P(x,t)}{\delta t} = \alpha_1 C(x,t) \tag{1.1}$$

$$\frac{\delta P(x,t)}{\delta t} = \alpha_2 C(x,t)\left[1 - \frac{P(x,t)}{A}\right] \tag{1.2}$$

where P(x,t) is the concentration of particles captured in the separator, C(x,t) is the concentration of particles in the slurry that flows through the separator, A is the maximum value of the concentration of particles that were captured by the matrix and α_1, α_2 are the activity factors of the deposition process.

The activity factors α used in equations (1.1) and (1.2) contain all the phenomena of the particle extraction by the magnetic field (taking into account theoretical considerations as well as technological applications). These characteristics are sketched in Figure 1.

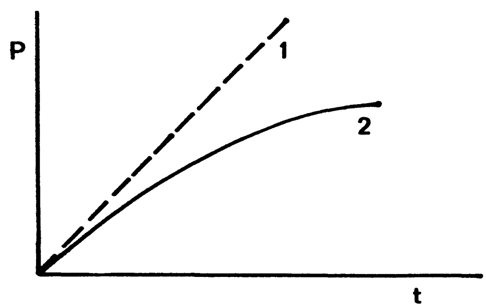

FIGURE 1 Curves illustrating two types of the separation kinetics

Equation (1.1) is linear and describes the particle deposition as a function of particle concentration in a slurry, only. As this equation states, the time derivative of the P(x,t) function is constant during the entire process. A deflecting separator works in this regime (see Fig. 1, curve 1).

Equation (1.2) describes the process in a capturing (matrix) separator where the removal of particles from the magnetic field does not take place. As a result, the matrix retains the entire mass of captured particles. A separator that operates in this regime has a limited potential for a satisfactory performance. When the maximum number of particles is deposited, regeneration is necessary before a new cycle can begin. Equation (1.2) is illustrated by curve 2 in Figure 1.

In addition to the above kinetic equations, the analysis of the slurry flow and of the particle deposition must be related to the equation of particle balance which, taking into account local changes of C(x,t) has the following form:

$$\frac{\delta P(x.t)}{\delta t} + v_0 \frac{\delta C(x,t)}{\delta x} + \frac{\delta P(x,t)}{\delta t} = 0 \tag{1.3}$$

where v_0 is the velocity of the slurry through the matrix.

Thus, the deposition of particles that were removed from the slurry can be described by the following set of equations:
For a deflecting separator:

$$\frac{\delta P(x,t)}{\delta t} = \alpha_1 C(x,t)$$
$$\frac{\delta C(x,t)}{\delta t} + v_0 \frac{\delta C(x,t)}{\delta x} + \frac{\delta P(x,t)}{\delta t} = 0 \tag{1.4}$$

For a matrix separator:

$$\frac{\delta P(x,t)}{\delta t} = \alpha_2 C(x,t)\left[1 - \frac{P(x,t)}{A}\right]$$
$$\frac{\delta C(x,t)}{\delta t} + v_0 \frac{\delta C(x,t)}{\delta x} + \frac{\delta P(x,t)}{\delta t} = 0 \tag{1.5}$$

Solution of equations (1.4) and (1.5), taking into account the following initial and boundary conditions

for $t < x/v_o$ $P(x,t) = 0$

for $x = 0$ $C(0,t) = C_o$

where C_o is the particle concentration at the inlet of the separator, has the form [1]:

For a deflecting separator:

$$P(x,t) = \alpha_1 C_0\left[t - \frac{x}{v_0}\right] \exp\left[-\frac{\alpha_1}{v_0}x\right] \tag{1.6}$$

$$C(x,t) = C_0 \exp\left[-\frac{\alpha_1}{v_0}x\right] \tag{1.7}$$

For a matrix separator:

$$P(x,t) = \begin{cases} A \dfrac{\exp\left[-\dfrac{C_0 a_2}{v_0}(x-v_0 t)\right] - 1}{\exp\left[-\dfrac{C_0 a_2}{v_0}(x-v_0 t)\right] + \exp\left[\dfrac{A a_2}{v_0} x\right] - 1} & \text{for } x-v_0 t < 0 \\ 0 & \text{for } x-v_0 t > 0 \end{cases} \tag{1.8}$$

$$C(x,t) = \begin{cases} C_0 \dfrac{\exp\left[-\dfrac{C_0 a_2}{v_0}(x - v_0 t)\right]}{\exp\left[-\dfrac{C_0 a_2}{v_0}(x - v_0 t)\right] + \exp\left[\dfrac{A a_2}{v_0} x\right] - 1} & \text{for } x - v_0 t < 0 \\ 0 & \text{for } x-v_0 t > 0 \end{cases} \tag{1.9}$$

THE FACTOR EVALUATION OF THE KINETIC AND BALANCE EQUATIONS

Considering various phenomena taking place in the magnetic field, the factor evaluation problem will be discussed separately for deflecting and matrix separators.

The deflecting separator

Equation (1.7) can assume the following form:

$$C(x,t) = C_0 \exp\left[-\frac{v_m x}{K v_0}\right] \tag{2.1}$$

where v_m is the particle velocity in the direction of the magnetic field and K is the width of a channel in which separation takes place.

On the basis of the above assumptions, the separation time can be defined as:

$$t_s = \frac{K}{v_m} \tag{2.2}$$

Comparison of equations (1.7) and (2.1) leads to the formula:

$$a_1 = 1/t_s \tag{2.3}$$

To determine the separation time, the arrangement shown in Figure 2 can be considered. The separation channel of the width K-h-i is placed at distance i from the winding. Distance i is determined by thermal insulation. A splitter that divides the slurry into magnetic and non-magnetic fractions is installed at the outlet of the channel, at the distance d_k from the winding.

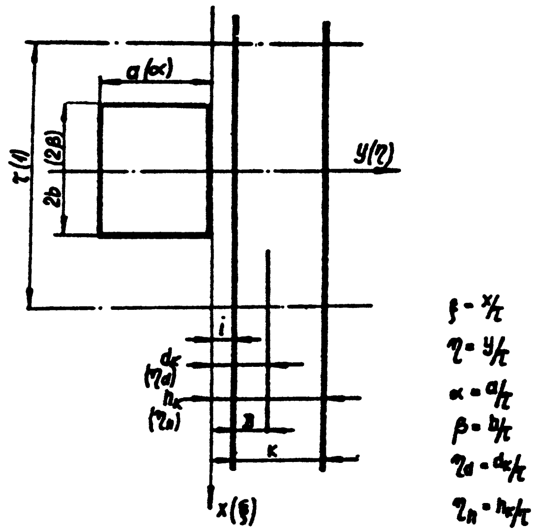

FIGURE 2 A schematic diagram of the deflecting separator

Magnetic field of intensity H affects magnetic particles of magnetic susceptibility χ_c and volume V_c by the magnetic force:

$$F_m = 1/2\mu_0\chi_c V_c \operatorname{grad}(|H|^2) \tag{2.4}$$

After transforming the coordinates and introducing relative dimensions for the coil and the separation channel, as shown in Figure 2, the following expressions for x and y components of mean elementary magnetic force are obtained [2]:

$$f_{mxsr} = \frac{F_{mx}}{\chi_c V_c} = \int_{-1/2}^{1/2} f_{mx}\, d\xi = 0 \tag{2.5}$$

$$f_{mysr} = \frac{F_{my}}{\chi_c V_c} = \int_{-1/2}^{1/2} f_{my}\, d\xi = -(2j)^2 \frac{\tau}{\pi^3}(1 - e^{-\pi})e^{-2\pi\eta}\sin^2(\pi\beta) \tag{2.6}$$

where j is the current density in the winding.

On the basis of the formula for the magnetic force, the separation of particles from a mixture, for wet and dry modes of operation, is considered.

Various phenomena in the separation region, for instance hydrodynamic resistance resulting for the viscosity of the slurry, or particle collision, lead to the following expressions that determine the time of separation:

For wet separation:

$$t_s = \frac{\pi^2 e^{2\pi\eta_d}}{2s(2j)^2(1 - e^{-\pi\alpha})^2 e^{-2\pi\eta}\sin^2(\pi\beta)} \left[e^{2\pi\eta_d(\frac{\eta_h}{\eta_d} - 1)} - 1 \right] \tag{2.7}$$

For dry separation:

$$t_s = P \frac{\pi^2 e^{2\pi\eta_d}}{2j(1 - e^{-\pi\alpha})\, e^{-2\pi\eta} \sin(\pi\beta)} \left[e^{2\pi\eta_d(\frac{\eta_h}{\eta_d} - 1)} - 1 \right] \tag{2.8}$$

where

$$s = \mu_0 \chi_c \frac{d^2}{18\eta_0} \qquad P = \left[2\rho_c N \frac{d^2}{\mu_0 \chi_c} \right]^{1/2}$$

d is the diameter of a particle, η_o is the viscosity, N is the number of particles in an elementary volume and ρ_c is the density of a particle.

The above equations lead to a conclusion that the most important parameter, besides the winding arrangement, that determines the efficiency of separation, is the current density.

Critical current density in a superconducting coil is related to the magnetic induction in the following manner:

$$j_c = \alpha_c / B \tag{2.9}$$

where α_c is the volume force of the pinning effect.

The average current density in the winding is only a fraction of the critical current density. Taking into account the filling factor λ, and assuming that $j = \lambda j_c$, we get [2]:

$$j^2 = \frac{\pi \lambda \alpha_c}{4 \mu_0 \tau \; g(\alpha, \beta)} \tag{2.10}$$

Function $g(\alpha, \beta)$, including the form of the winding is graphically given in [2].

The pinning force depends also on the magnetic induction B:

$$\frac{\alpha_c}{\alpha_{cmax}} = f(B)$$

α_{cmax} is the maximum pinning force and, for example, for Ni-Ti superconductor, it is equal to about 12 GN/m^2 [2].

When designing the winding of a superconducting magnet, the current density should be selected in such a way that α_c attains its maximum value, taking into account the maximum permissible induction value.

Equations (2.7), (2.8), (1.6) and (1.7) allow us to determine the quantity of particles captured in the separator, according to their physical properties, the arrangement of the winding and the current density. Thus, these formulae are fundamental for the deflecting separator: they make the optimization process possible, taking into account results of separation, together with the field arrangement and quantity of superconductor required.

The matrix separator

In order to calculate factors α_2 and A from equations (1.8) and (1.9), motion of a single particle in nonhomogeneous magnetic field in the vicinity of a collector is analysed. The arrangement is shown in Figure 3 and the analysis is based on a microscopic model.

Svoboda and Ross [3] showed the complexity of the process of particle deposition on a collector and proposed another formulation of the problem. Accepting the above, we are going to limit our considerations only to such particle sizes for which the magnetic interaction is decisive. Under these conditions the following condition is assumed to be valid:

$$\frac{|F_m|}{\Sigma |F|} \geq 1$$

where $\Sigma |F|$ is the sum of non-magnetic forces affecting a particles in the matrix. This limitation justifies the analysis of particle motion in which the particle moves towards the collector being influenced by the magnetic field only.

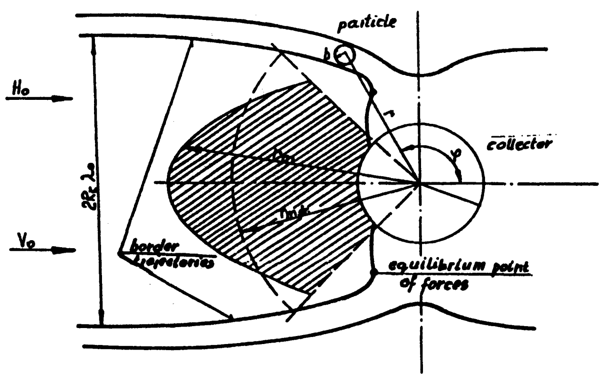

FIGURE 3 The deposition of particles onto a collector

General form of the magnetic force influencing a particle follows from equation (2.4), but the analysis for the arrangement presented in Fig. 3, in accordance with discussion [4] that leads to a conclusion that the radial component of this force plays the fundamental role in particle deposition, has the form

$$F_{mr} = -\frac{2\chi_c V_c}{r^3}\mu_0 H_0^2 R_k^2 \left[\left[\frac{R_k}{r} \right]^2 + \cos(2\varphi) \right] \tag{2.11}$$

(for magnetic induction below the point of saturation of the collector material, i.e. for $2\mu_o H_o < M_s$),

$$F_{mr} = -\frac{\chi_c V_c}{r^3} M_s R_k^2 \left[\frac{M_s}{2\mu_0} \left[\frac{R_k}{r} \right]^2 + H_0 \cos(2\varphi) \right] \tag{2.12}$$

(for magnetic induction above the point of saturation, i.e. for $2\mu_o H_o > M_s$).

Particles affected by the magnetic force move towards the collectors and settle on their surface (the shaded region in Fig. 3). Particles outside of this capture zone that is determined by the border trajectory, will not be captured by the collector.

Deposition takes place up to the moment when the balance of the holding magnetic force and shear force is achieved. The balance of forces occurs in a layer of deposited particles denoted by radius r_m in Figure 3. In view of the difficulties with determining this parameter, its average value r_{msr} is used in calculations [1].

A detailed description of the process of particle deposition and the expressions for factors μ_2 and A is given in paper [1]:

$$\alpha_2 = \frac{2R_k \lambda_0 v_0}{S_k \epsilon_0} \tag{2.13}$$

$$A = \frac{\epsilon_0}{4} \rho_c (a - 1) \tag{2.14}$$

where

$$2R_k \lambda_0 = D \left[\frac{4d^2 \chi_c H_0 H_p S_k}{9\pi\eta_0 v_0} \right]^{1/3} \tag{2.15}$$

$$a = \frac{r_{msr}}{R_k} \tag{2.16}$$

ϵ_0 is the packing factor of the matrix (ratio of the volume of the collector to the volume of the matrix), S_k is the area of the collector, D is a constant (to be experimentally determined for a specific separation process) and H_p is a perturbation factor of the homogeneous magnetic field H_0; this perturbation is caused by a collector of relative magnetic susceptibility μ_{wk}, while relative magnetic susceptibility of the medium in which the particles flow is μ_{wo}:

$$H_p = \frac{\mu_{wk} - \mu_{wo}}{\mu_{wk} + \mu_{wo}} H_0$$

On the basis of specific values α_2 and A, and using equations (1.8) and (1.9), the extraction of particles from the slurry in a matrix high-gradient magnetic separator can be analysed. The mathematical model developed in this paper is a tool for analysis of the separation processes under various circumstances and for assorted designs of the separator.

Table I shows comparison between deflecting and matrix magnetic superconducting separators.

SLURRY FLOW THROUGH THE MATRIX OF A SEPARATOR

The parameters α_2 and A were calculated for arbitrarily selected conditions of separation using equations (2.13) and (2.14). The mass distribution of particles in the matrix was calculated using equation (1.8). The results are shown in Figure 4.

The upstream layers of the matrix which are exposed to the slurry of maximum concentration get loaded after a finite period of time and lose their capturing capability. At the same time, the downstream layers of the matrix are used only infrequently.

This unfavourable effect of loaded upstream layers of the matrix hampers the flow of the slurry; moreover, some particles already deposited on the upstream layers of the matrix are swept away by the slurry flow. The utilization of the matrix at uniform rate is a problem that will not be considered in this paper.

In order to analyse a change of particle concentration at the outlet of the separator, equation (1.9) can be rewritten as:

$$\frac{C(x,t)}{C_0} = \frac{1}{1 + e\left[\frac{\alpha_2 x}{v_0} + \frac{C_0 \alpha_2}{A v_0}(x - v_0 t)\right] - e\left[\frac{C_0 \alpha_2}{A v_0}(x - v_0 t)\right]} \quad (3.1)$$

TABLE I. Comparison of deflecting and matrix magnetic separator.

Type of Separator	Deflecting	Matrix
Principle of Operation	Continuous	Cyclic
Winding Design	Complex (dipole, multidipole and quadrupole)	Simple (solenoid)
Cryostat Design	Complex (the separation channel must be near the winding)	Simple
Separator Design	Simple	Complex (matrix replacement is necessary)
Size of Material to be separated (μm)	20	1
Throughput (t/h)	up to 100	up to 20

When the concentration of particles at the outlet of the separator is analysed, equation (3.1) can be presented in a simpler form:

$$\left.\frac{C_{out}(t)}{C_0}\right|_{x=L} = \frac{C_L(t)}{C_0} = \frac{1}{1 + e^K(e^T - 1)} = N \tag{3.2}$$

where

$$K = \frac{C_0 a_2}{A}\left(\frac{x}{v_0} - t\right) \qquad T = \frac{a_2 x}{v_0}$$

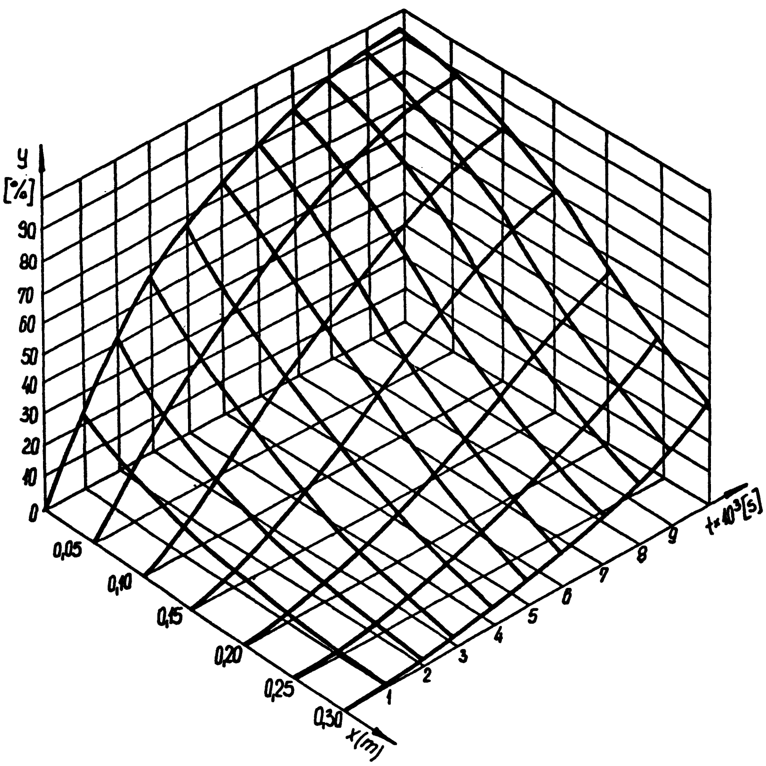

FIGURE 4 Mass distribution of particles in a matrix separator ($y = P(x,t)/A$ (%)), for: $B_o = 4T$, $v_o = 0.05$ m/s, $C_o = 10^4$ kg/m^3, $R_k = 25x10^{-6}$ m.

Calculations of the concentration at the outlet of the separator related to the inlet concentration C_o (factor N in equation (3.2), for three values of the magnetic induction are depicted in Figure 5. If the maximum concentration N_f at the outlet is allowed, the separation process must be terminated after time t_f, as is shown in Figure 5. This time is termed the effective working time of the separator. After this time, the factor N_f will exceed the permissible value. These calculations lead to a conclusion that an increase in magnetic induction increases the effective working time of the separator. In general, this time can be written as:

$$t_f = t_f(B_0, v_0, L, \epsilon_0, R_k) \tag{3.3}$$

After time t_f, the separation process must be stopped and the loading capacity of the matrix must be regenerated.

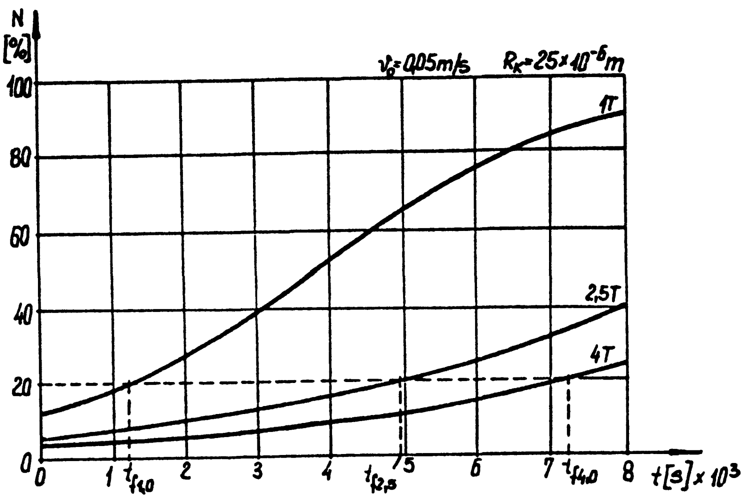

FIGURE 5 The change in concentration at the outlet of the separator, as a function of magnetic induction and time. N = C(t)/C_o at x = L.

FACTORS AFFECTING THE EFFICIENCY OF PARTICLE DEPOSITION ON THE MATRIX

The analysis given in previous sections enables us to determine a model which describes the process of deposition of particles on a matrix collector. The concentration of particles at the outlet of the separator can be calculated, under the assumption that interactions among the particles and between the particles and the fluid can be neglected.

Under practical conditions the slurry represents a well defined concentration of particles and in addition to deposition of particles on the collectors, additional interactions which complicate theoretical analysis of the process are present. The efficiency of particle deposition on the matrix depends on numerous factors such as:

a. Concentration of particles introduced into the separator which is closely related to the particle size distribution of the material to be separated. These two parameters determine viscosity of the slurry. An increase in viscosity hampers the motion of particles, reduces the throughput and worsens the efficiency of separation.

b. Particle size distribution of the material to be separated. A decrease of the size of particles causes an increase of the attractive forces among the particles [5]. The reduction of size of solid phase in a given volume leads to a decrease of the mean distance between the particles to such an degree that the molecular forces exceed the electrostatic repulsion. Particles thus coagulate into clusters composition of which becomes unfavourable taking into account the quality factors of the products of separation (e.g. aggregation of paramagnetic and diamagnetic particles). Such clusters will then be captured by the collectors if the overall magnetic susceptibility is large enough.

Diamagnetic particles thus report into the magnetic concentrate impairing its grade. If the mean magnetic susceptibility is small but mechanical forces are large, the aggregates containing paramagnetic particles will report into the non-magnetic fraction.

The author's previous investigation has shown that the relation between the particle size (particle radius b) and the size of the matrix collector (collector radius R_k) is $R_k = 2.69b$ [6, 12]. This condition creates specific requirements for mechanical properties of the matrix material as small dimensions of the collectors should be achieved. In order to extract particles of micrometer size ferromagnetic steel wool is needed.

c. Magnetic properties of the feed material. Material to be separated by a high-gradient magnetic separator is, as a rule, a mixture of particles of different magnetic susceptibilities. Magnetic force between the collectors and the particles varies in a wide range, as it depends on the magnetic field strength in the separation zone.

Particles passing through the separation zone will be affected by a magnetic force of varying magnitude, depending on the distance from a collector. Particles of low magnetic susceptibility that find themselves in the proximity of a collector will be captured as a result of a high magnetic force acting on them. At the same time, particles of high magnetic susceptibility will be captured even when their distance from a collector is large. Consequently, the magnetic fraction is a mixture of particles of varying magnetic properties. The efficiency of separation is further impaired by the presence of the aggregates of the particles.

Quantitative analysis of the effect of various factors on the efficiency of particle extraction is a complicated problem and such an analysis will not be carried out in this paper. Relevant information can be found in the literature, e.g. [5, 7, 8].

CYCLIC NATURE OF THE MATRIX MAGNETIC SEPARATOR

High-gradient magnetic separator often operates in a cyclic mode. After the matrix is loaded with captured particles (after time t_f), a cleaning stage must follow (dead time t_w). Collan et al. [9] derived an equation that relates the times t_f and t_w with parameters that characterise the separation process, such as the throughput Q, flow velocity v_0 of the slurry, and matrix cross-sectional area S:

$$Q = \frac{V_0 S}{1 + \frac{t_w}{t_f}} \tag{4.1}$$

In order to increase the throughput Q time t_f must be increased and t_w reduced. One of the ways how to achieve this is to regenerate the matrix without de-energizing the magnet. This can be accomplished by removing the loaded matrix from the separator and by replacing it with a clean matrix. This concept has been used in industrial practice under the name of "reciprocating canister" system. Detailed analysis is given, for instance, in [13]. In this case the dead time is determined solely by the time required to replace the matrix.

The replacement of the matrix is one of the most important problems that affect the behaviour of a superconducting magnet. It gives rise to several unfavourable phenomena, either mechanical (forces acting on the matrix) or electrical (the matrix movement and de-symetrisation of the field induce voltage in the coil).

A very important problem in the operation of a superconducting separator is its stability; the parameters of operation can vary in such a range that the superconducting state is maintained. A contradiction exists between the need to stabilise the operating conditions (it leads to a high degree of reliability of the operation in a superconducting state) and the efficiency of the technological process.

In the latter case, a wider and more dynamic variation of the operating parameters is usually required. A trade-off between these contradicting requirements is thus necessary. In order to select the optimum procedure it is essential to establish the range of dynamic forces related to the replacement of the matrix.

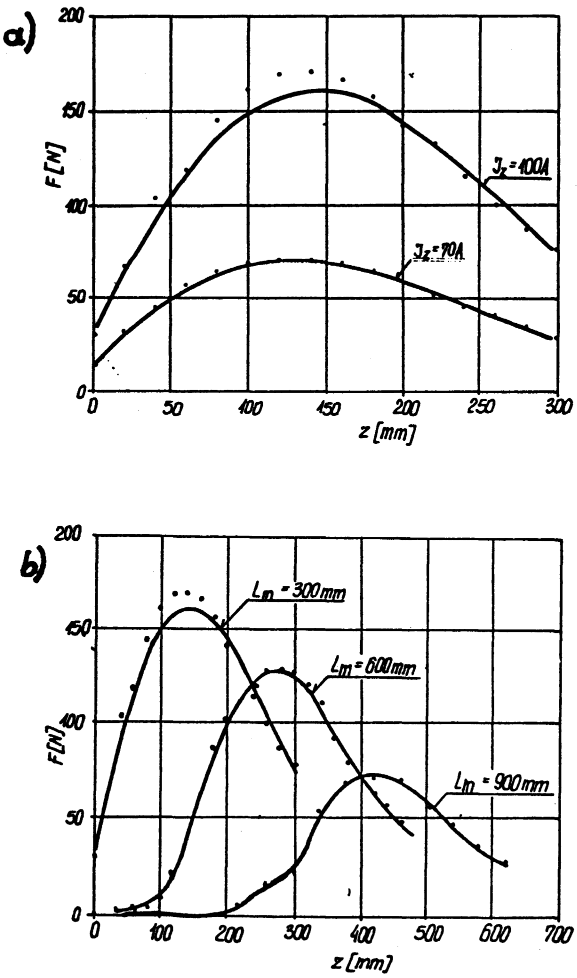

FIGURE 6 Force F acting on the matrix, as a function of position z in the channel of the separator.
a. $F = f(z)$ for $l_m = 300$ mm
b. $F = f(z)$ for $I_z = 100$ A

A suitable mathematical model and computer program were developed to investigate the process of matrix replacement [10]. The magnetic force acting on the matrix in motion was calculated under the assumption that the matrix is a ferromagnetic porous body. calculations were carried out for three different lengths l_m of the matrix: $l_m = 300$ mm, 600 mm and 900 mm and two values of the electrical current $I_z = 70$ A and 100 A. The results are summarised in Figure 6.

The analysis has led to the conclusion that the magnetic force acting on the matrix achieves its maximum value when one of its edges is at the centre of the winding.

Thus the winding must be design in such a way that it can withstand such a force. If the size of the matrix is comparable to the length of the coil, magnetic force can achieve considerable magnitude. It can be reduced either by reducing the electrical current from the supply which, however, will reduce the magnetic induction, or by increasing the length of the matrix. The latter option appears to be attractive since the use of the "long" matrix brings about a considerable reduction of the force. Moreover, the replacement of the matrix takes place outside the region of the magnetic field. First, the length of channel must be selected, preferably several times the length of the coil. Secondly, the space between the matrices in the separation channel must be filled with material of the same magnetic properties and of the same packing factor as those of the matrices.

By using the long matrix, the dead time can be reduced considerably and the separator operates in a quasi-continuous mode. Schematic diagram of such an arrangement is shown in Figure 7. The velocity of the matrix movement in the magnetic field affects the stability of operation. The critical voltage, permissible for the stable operation of the coil in the superconducting state has been determined for a system superconducting winding-feeder. The voltage induced by the moving matrix which depends on the position of the matrix with respect to the winding and on the ratio of the matrix length to the coil length must not exceed the critical value of the voltage.

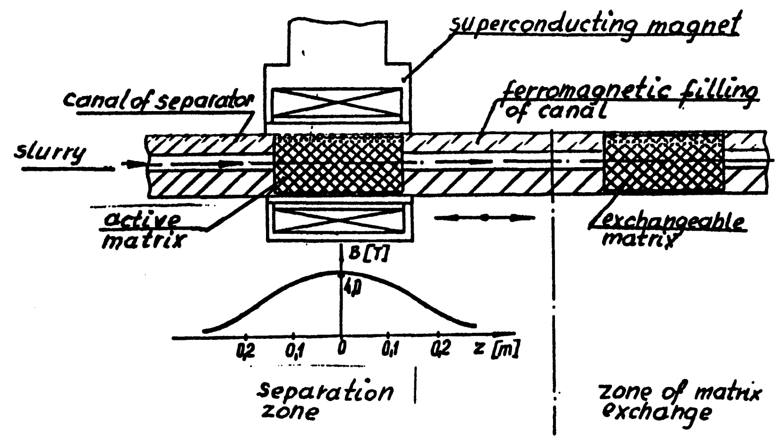

FIGURE 7 Magnetic separator with long matrix

The velocity of the matrix motion in the magnetic field, calculated under above assumptions is shown in Figure 8. It can be seen that the velocity of the matrix decreases with increasing z and reaches its minimum value when one of its edges is in the geometrical center of the winding. At this point the value of the magnetic induction and of the magnetic force are maximum. It is suggested that the matrix be replaced at minimum velocity, although there is a possibility of increasing the speed outside the geometrical centre of the winding. It would, however, require a suitable control system of the matrix movement.

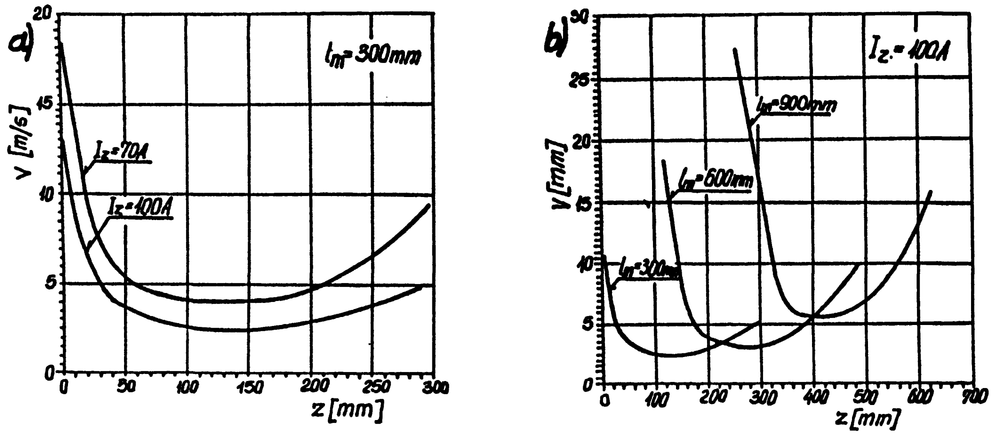

FIGURE 8 The velocity of matrix movement vs its position in the channel of the separator.
a. $v = f(z)$ for $l_m = 300$ mm
b. $v = f(z)$ for $I_z = 100$ A

DESIGN OF THE SUPERCONDUCTING MAGNETIC SEPARATOR

A superconducting magnetic separator in which the region of the magnetic field ($1.5 \times 10^{-3} m^3$) is at the ambient temperature has been designed at the Academy of Mining and Metallurgy. Magnetic induction at the centre of the magnet can be controlled in the range from 0 to 3 T. Cryostat of the magnet has a "warm" channel which makes the access to the magnetic field possible. Specifications of the magnet are given in [11].

Schematic diagram of the magnet is shown in Figure 9. Figure 10 gives an overall view of the system, including the channel that passes through the working region of the magnet.

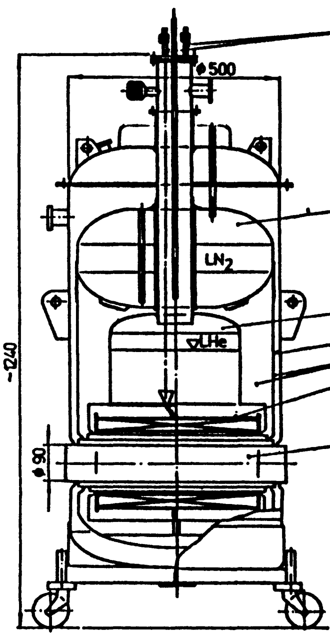

FIGURE 9 Schematic diagram of the superconducting magnet.
1-current leads, 2-liquid nitrogen vessel, 3-helium vessel,
4-nitrogen shield, 5-vacuum space, 6-superconducting winding,
7-magnet channel.

SUMMARY

Theoretical model presented in this paper makes it possible to determine basic variables that characterise extraction of particles from a slurry. It allows us to select conditions for optimum operation of a separator. Parameters α_1, α_2 and A are determined mainly by the magnetic field strength and by the magnet configuration.

It is shown that high efficiency of separation and high throughput can be obtained by using a superconducting magnet that generates a high magnetic field with required field nonhomogeneity.

In deflecting separators the form of the magnet winding is determined by the design of the separator and physical properties of particles to be separated. It is thus difficult to achieve a high degree of field nonhomogeneity in a large volume in this separator. Deflecting separators can thus be applied mainly to the extraction of strongly magnetic particles from a continuous flow of high velocity. The cryostat construction must allow the separation channel to be placed close to the winding (as close as possible) while the cryogenic liquid must have a good thermal insulation.

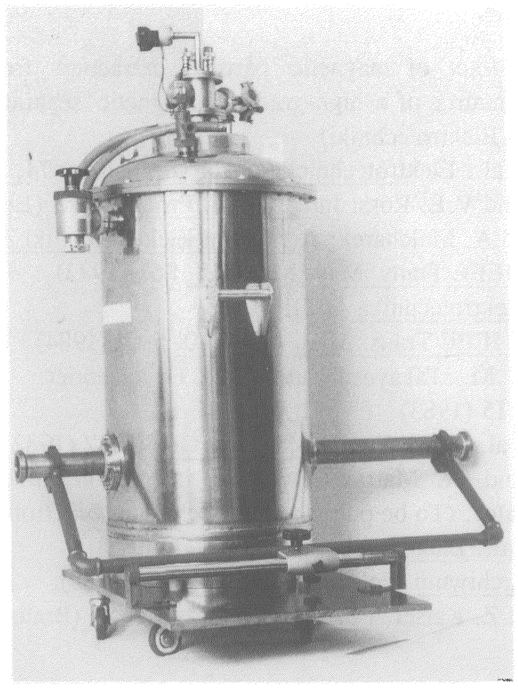

FIGURE 10 Superconducting magnet and the channel of the matrix separator

In the matrix separator a simpler solenoid can be employed. The efficiency of separation depends, apart from the magnetic field strength, on the type of the material to be separated, on the size of the collectors and on the design of the matrix. System that uses matrix removal from the field without de-energising the magnet appears to be viable approach. The magnetic force acting on the matrix can be reduced by using "long" matrix and the magnet must be designed in such a way that magnets withstands such a force. The velocity of the matrix motion decreases with its displacement; it reaches its minimum value when one of the edges of the matrix is at the geometrical ceZntre of the winding.

Such a minimum velocity appears to be optimum for the matrix movement although there is a possibility of increasing this velocity outside the centre of the winding. In order to assess the economic viability of such an approach production-scale investigation is required.

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Keywords: magnetic separation, superconducting magnets, matrix separator, deflecting separator, cyclic separator.