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THE DISTRIBUTION OF MAGNETIC FIELDS AND AN ANALYSIS OF THE SEPARATION IN PROCESS IN A SPIRAL SEPARATER

ROZKŁAD POLA MAGNETYCZNEGO I ANALIZA ROZDZIAŁU W SEPARATORZE SPIRALNYM

In the magnetic separation of strongly magnetic, fine-grained minerals the forces of magnetic and surface interaction between particles play a significant role. These forces lead to the phenomenon of *magnetic flocculation*. Non-magnetic particles are held in the floc volume and these, transfered to the magnetic products, lower the quality of concentrate. In order to reduce the effects of this phenomenon, special separators with an alternating magnetic field have been constructed or, the movement of the particulate mixture through the a constant magnetic field, a system of pole shoes of alternate polarity is employed. In the latter type of separators the particles of the aggregates are subjected to several magnetization cycles, in the course of which the non-magnetic components are precipitated.

A spiral separater is a separation system using a series of magnetic fields with constant polarity. The paper discusses the principles of operation of this type of separater and determines the distribution of the magnetic fields and magnetic force in the separator's working space by means of conformal mapping. Following this the value of separation magnetic susceptibility was calculated from the balance of external forces acting on the particle.

Applying the stochastic model of magnetic separation, the author has evolved an expression for a constant rate of separation and content of magnetic component in the concentrate, the yield of the concentrate as a function of the angle of inclination of the separater, the amount of washing water supplied, the number of helix rotations and the intensity of the external magnetic field. The dependence of the Fe content in the concentrate on the amount of washing water was verified experimentally. It was observed that surface interactions between particles should be taken into consideration when a full correlation between the model and experimental values is required.

Key words: magnetic, separation, spiral separater, model of separation, constant rate of separation, distribution of magnetic field

Przy separacji magnetycznej drobnoziarnistych minerałów silnie magnetycznych istotną rolę odgrywają siły oddziaływań magnetycznych i powierzchniowych między ziarnami. Siły te prowadzą

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do zjawiska flokulacji magnetycznej. W objętości flokuły mechanicznie zatrzymywane są ziarna niemagnetyczne, które wynoszone do produktu magnetycznego pogarszają jakość koncentratu. Aby usunąć skutki tego zjawiska konstruuje się separatory ze zmiennym polem magnetycznym lub na drodze ruchu mieszaniny ziarn stosuje się stałe pole magnetyczne z układem nabiegunników o naprzemiennej biegunowości. W takich separatorach agregaty ziarnowe ulegają kilkakrotnym przemagnesowaniom, w trakcie których tracą ziarna niemagnetyczne. Jednym z separatorów o stałym polu magnetycznym jest separator zwojowy (spiralny). W pracy omówiono zasadę działania separatora oraz metodą odwzorowań konforemnych wyznaczono rozkład pola magnetycznego i siły magnetycznej w przestrzeni roboczej separatora, a następnie z bilansu sił zewnętrznych działających na ziarno mieszaniny wyliczono wartość podatności magnetycznej podziałowej.

Posługując się stochastycznym modelem separacji magnetycznej przedstawiono wyrażenia na właściwą prędkość separacji oraz zawartość składnika magnetycznego w koncentracie i wychód koncentratu w funkcji kąta nachylenia koryta separatora, ilości wody spłukującej, liczby obrotów ślimaka oraz natężenia zewnętrznego pola magnetycznego. Eksperymentalnie zweryfikowano zależność zawartości żelaza w koncentracie od ilości wody spłukującej. Zauważono, że chcąc uzyskać pełną zgodność modelu z doświadczeniem należy uwzględniać oddziaływania powierzchniowe między ziarnami.

Słowa kluczowe: separacja magnetyczna, separator spiralny, model separacji, stała prędkości separacji, rozkład pola magnetycznego

1. Introduction

Magnetic susceptibility in the magnetic separation process is a determinant of separation the value of which, together with the value of magnetic field gradient determines the existence of a sufficiently large magnetic force acting on the mineral particle. The differentiation of this force due to the magnetic properties of raw materials affects the separation accuracy of natural components of mineral mixtures. The magnetic force acting on a single magnetic particle exerted by a magnetic field is a separating force in many separater constructions. During the separation of coarse-grained mixtures this forces, besides mechanical foeces, play a dominating role in the separation process.

During the separation of fine-grained mixtures containing minerals of high magnetic susceptibility, internal, particle-interactions forces occur in the system in addition to the external forces determined by the field potentials. These are the forces of magnetic and surface interactions. The forces of magnetic interaction lead to the phenomenon of magnetic flocculation. In the floc volume non-magnetic particles are held mechanically. The entire heterogeneous floc mass is transfered to the magnetic product by the external magnetic force. This results in a lowering of the concentration of magnetically susceptible components of the ore. In order to reduce the effect of magnetic flocculation on the separation process it is necessary to carry out numerous separative washings, or to apply separation using a moving alternating field. There are many separater constructions that employ this method. The movable field is generated either by movement of a system of permanent magnets as is the case in Laurill's separater (Brożek 1996) or by the application of a three-phase current in separator coils which generates a mooving magnetic field, changing in time and space (Brożek 1999a, b). When the velocity of field movement is appropriate, the stream of magnetic particles moves in the direction opposite to the direction of field movement (Siwiec et al. 1988). The mooving field causes a continuous restructuring of the floc. By means of the change of polarity and intensity of the magnetic field, a periodic remagnetisation of the floc occurs, during which stage it is possible for the particles of waste rock to be released from the floc structure. The field movement velocity, as well as the frequency of field changes are relatively high and reach values of 2.5 m/s and 50 Hz, respectively (Topolnicka 1978).

The separater presented in the paper is an example of application of a permanent magnetic field with zones of opposite polarity in which the magnetic field, as opposed to constituting an open magnetic system, is closed by a keeper which consists of a ferromagnetic helix.

2. Operating principles of the spiral separater

Fig. 1 shows a diagram of a spiral magnetic separater. Its trough (1) is built of non-magnetic material whereas the helix itself (2) has ferromagnetic properties. The magnetic field is generated by a system of electro-magnets (7). The ferromagnetic helix is therefore, in effect, a keeper, whereby the magnetic field is enclosed. Using this

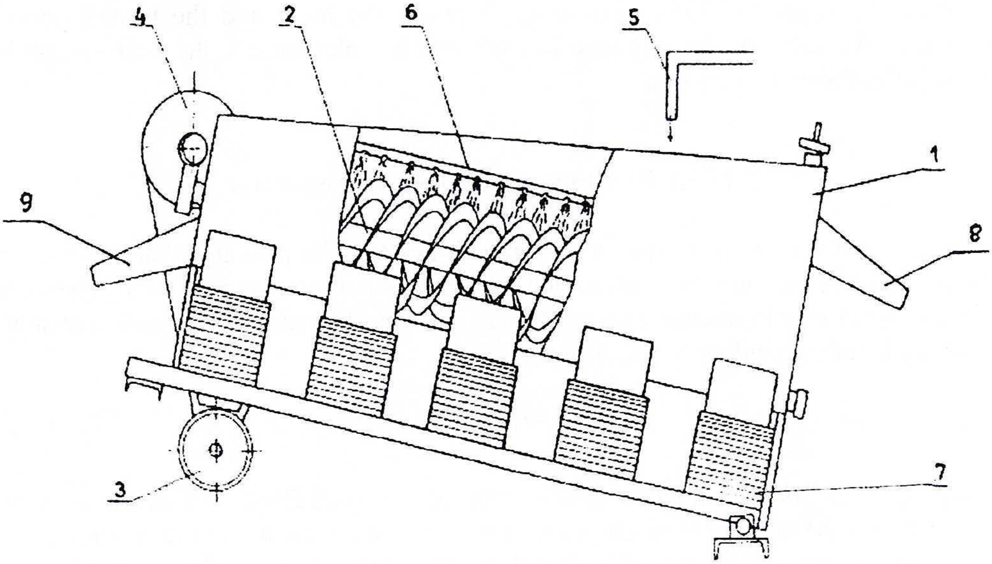

Fig. 1. Diagram of spiral separator
1 — separator trough, 2 — helix, 3 — motor, 4 — gear, 5 — feeder, 6 — water spray, 7 — coils, 8 — non-magnetic product removal, 9 — magnetic product removal

Rys. 1. Schemat separatora spiralnego
1 — koryto separatora, 2 — spirala, 3 — silnik, 4 — przekładnia, 5 — podajnik nadawy, 6 — natrysk wody, 7 — uzwojenie, 8 — odprowadzenie produktu niemagnetycznego, 9 — odprowadzenie produktu magnetycznego

structure it is possible to reduce the field intensity that is needed for particle separation in traditional drum separators. The motor-driven helix is driven by a motor (3) through a gear (4) which enables the rotational velocity of the helix to be regulated. The feed in the form of a suspension, is transported by a feeder (5) below the helix centre. Magnetic particles are attracted to the helix, lifted up and transported through the chute (9). The water spray (6) washes them down and the simultaneously moving helix transports them along the separater trough. Consequently, the magnetic particles are transported along the separater trough as a result of a combination of a mechanical and magnetic force, the latter constituting a fluidized layer between the helix and the base of the trough. The non-magnetic particles are carried in a water suspension over the overflow (8). During the transport of the magnetic fraction up the trough and at the changes of field polarity of the floccular magnetic alignments occur, resulting in the washing-out of the non--magnetic components of the floc and thereby a product of high magnetic component--concentration in a single separation.

The following factors affect the separation results: helix lead, pole pitch, clearance between the helix and the trough, the magnetic field intensity, the rotational velocity of the helix, the angle of inclination of the device as a whole, the amount of washing water and separater yield. The first three factors must be design considerations for the construction of the separater, while the others are adjustable operationally.

Since the magnetic flield distribution between the helix and the trough bottom influences the value of the magnetic force, it will be calculated in the next section by means of conformal mapping.

3. Field distribution in the spiral separater

Fig. 2 is a diagram of the separater's magnetic system. The polarity of electromagnets reverses at each section p (p — pole pitch) along the separator trough (y axis). The value of the magnetic field intensity on the trough surface, disregarding the helix, changes along its length according to the formula:

$$H_o = H_m \cos\frac{\pi}{p}y \tag{1}$$

where H_m is the maximum value of field intensity obtained from the measurement and dependant on the number of electromagnet coils, current intensity in the electromagnet coils and the magnetic properties of the electromagnet's core. The reversal of the magnetic field polarity occurs at section $y = p$ and, consequently, a change of floc magnetization direction take place. The frequency of this reversal depends on the pole pitch p, the number of helix rotations n and the helix lead s and is expressed by the formula:

$$v = \frac{ns}{p} \tag{2}$$

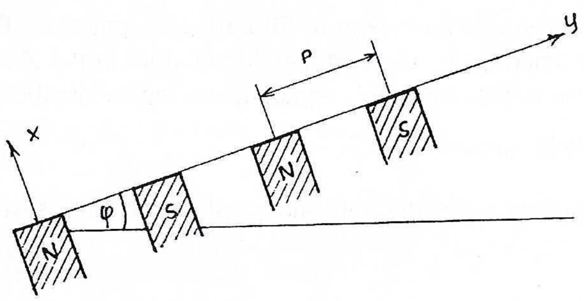

Fig. 2. Diagram of the separator's magnetic system

Rys. 2. Schemat układu magnetycznego separatora

The lowest value of magnetic field intensity and also the lowest value of magnetic force which binds the floc occurs at the points between pole shoes. There also, demagnetization occurs, causing a temporary disintegration of the floc. The most efficient washing of the non-magnetic component occurs around these points in the temporary moments of floc disin-tegrations.

The following approximation was used to determine the field distribution on the radial line connecting the helix with the trough bottom. The field distribution between two hyperbolic pole shoes was calculated. Approaching $\pi/2$ with the inclination angle of the asymptote of the concave pole shoe, it is possible to obtain the field distribution between the plane and polar shoe in the form of a thin hyperbola. Due to the fact that the clearance between the helix and the trough bottom is slight (c. 10 mm in a semi--industrial separator), it can be assumed fairly accurately that the field distribution obtained corresponds to the field distribution in the gap between the helix and the trough bottom.

The magnetic field distribution in the space between hyperbolic pole shoes was determined by the conformal mapping method (Fuks, Szabat 1964).

Let the function of a complex variable be given in the **Z** area, and be assumed to be effective over the whole area:

$$w = f(z) = u(x,y) + iv(x,y)$$

This function is mapping the **Z** area into the **W** area. The functions of the real variable $u(x,y)$ and $v(x,y)$ fulfill Cauchy-Riemann's conditions (Leja 1979):

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y} \qquad -\frac{\partial u}{\partial y} = \frac{\partial v}{\partial x}$$

Differentiating the first equation with respect to x and the second equation to y and adding by sides we obtain:

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0$$

Hence the functions *u(x,y)* and *v(x,y)* fulfill Laplace's equation. Therefore they can be identified as the functions of the vector field potential in the ***Z*** area. The function $w = f(z) = u + iv$ also fulfills Laplace's equation and represents the complex potential in the ***Z*** area. The field intensity $H = \left|\frac{dw}{dz}\right|$.

Fig. 3 shows the diagram of the pole shoes with hyperbolic surfaces according to equations:

$$\frac{x^2}{f^2\cos^2\alpha_2} - \frac{y^2}{f^2\sin^2\alpha_2} = 1 \tag{3a}$$

$$\frac{x^2}{f^2\cos^2\alpha_1} - \frac{y^2}{f^2\sin^2\alpha_1} = 1 \tag{3b}$$

where:

f — hyperbola focal distance,

α_1 and α_2 — asymptote inclination angles to the x axis.

The distance between the surfaces of hyperbolae, measured along the x axis, is the height of the working zone. As it can be seen from Fig. 3, it is equal to:

$$a = OB - OA = f(\cos\alpha_2 - \cos\alpha_1) \tag{4}$$

The next function:

$$w = C_1 \text{arc}\cos\frac{z}{f} + C_2 \tag{5}$$

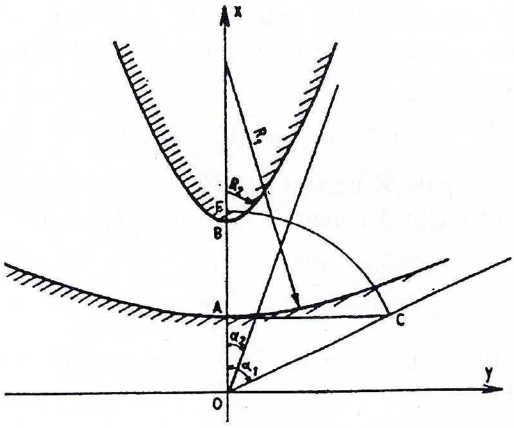

Fig. 3. Diagram of the separator's hyperbolic pole shoes

Rys. 3. Schemat nabiegunników hiperbolicznych separatora where C_1 and C_2 are constant values, transforms the area between the pole shoes into the $U_1 < Rew < U_2$ belt and represents the complex potential of the magnetic field in the $\boldsymbol{Z}$ area.

The distribution of the magnetic field intensity along the x axis may be expressed as follows:

$$H = \left|\frac{dw}{dz}\right|_{z=x} = \frac{C_1}{\sqrt{f^2 - x^2}} \tag{6}$$

Constant C_1 in formula (6) is determined from the boundary conditions on the surface of a concave pole shoe:

$$H(x = OA = f\cos\alpha_1) = H_0 = \frac{C_1}{f\sin\alpha_1} \tag{7}$$

Therefore: $C_1 = H_o f \sin\alpha_1$.
Finally:

$$H = \frac{H_o f \sin\alpha_1}{\sqrt{f^2 - x^2}} \tag{8}$$

If the distance x is read off from the surface of the concave pole shoe, then a transformation should be made: $x \to OA + x = f\cos\alpha_1 + x$. After this transformation, the expression for the magnetic field distribution is as follows:

$$H = \frac{H_o f \sin\alpha_1}{\sqrt{f^2 - (x + \cos\alpha_1)^2}} \tag{9}$$

When the α_1 angle increases to 90°, the lower hyperbolic pole shoes will become a plane while the upper ones will be a wedge with a rounded tip. Then we obtain from formula (9):

$$H = \frac{H_o f}{\sqrt{f^2 - x^2}} \tag{10}$$

Expressing the focal distance by the height of the working zone a and α_2 angle = α from formula (4), ultimately the expression for distribution of the field between the plane and the hyperbolic pole shoe, along the hyperbola axis:

$$H = \frac{H_o a}{\sqrt{a^2 - x^2\cos^2\alpha}} \tag{11}$$

The value of the field intensity H_o on the surface of a flat pole shoe changes along the y axis, according to formula (1). Therefore:

$$H = \frac{aH_m \cos\frac{\pi}{p} y}{\sqrt{a^2 - x^2 \cos^2 \alpha}} \tag{12}$$

If identical hyperbolic polar shoes are uniformly distributed along the y axis, a multi--polar system is obtained (Fig. 4a). It was assumed that the magnetic fields of neighbouring shoes did not interact.

The situation presented above is a static situation for the system: plane vs set of hyperbolic pole shoes, equidistant from one another.

The movement of hyperbolic pole shoes along the y axis with velocity v is physically equal to the movement of the separator magnetic system in the opposite direction. This will be obtained if in formula (12) the following transformation will be made:

$$y \to y - vt \tag{13}$$

If the flat system of pole shoes is replaced by a system which, instead of the yz plane, will contains a cylindrical surface and a coaxially curved system of hyperbolic pole shoes (Fig. 4b), a magnetic system will result which is very similar to the system of Fig. 4a in a small space (marked with lines in Fig. 4b). It can be assumed with good approximation that the system of hyperbolic pole shoes of Fig. 4b approximates to a situation in which the lower edge of the helix fulfills the role of a hyperbolic pole shoe. In such a case the movement of this edge along the trough bottom is equivalent to the movement of the magnetic field along the y axis. The velocity of this movement is $v = n\,s$ where n is the number of helix rotations in the time unit and s is the helix lead.

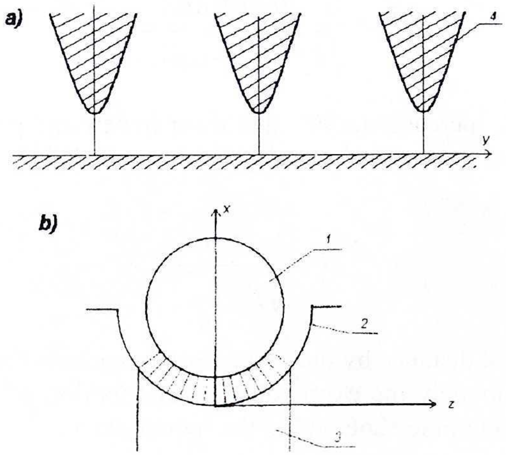

Fig. 4. Multi-polar system
1 — helix, 2 — separator trough, 3 — pole shoe of the electromagnetic system, 4 — helix pole shoes

Rys. 4. Układ wielobiegunowy
1 — ślimak, 2 — koryto separatora, 3 — nabiegunnik układu elektromagnetycznego, 4 — nabiegunniki ślimaka

Performing the transformation (13) in formula (12) and taking into account the helix movement velocity, we obtain the magnetic field distribution in the gap between the edge of the rotating helix and the trough bottom:

$$H = \frac{aH_m \cos\frac{\pi}{p}(y - nst)}{\sqrt{a^2 - x^2 \cos^2 \alpha}} \tag{14}$$

The constituents of the magnetic force acting on the particle volume unit are equal:

$$\vec{f}_x = \frac{1}{2}\mu_o \kappa \frac{\partial H^2}{\partial x}\vec{e}_x \tag{15a}$$

$$\vec{f}_y = \frac{1}{2}\mu_o \kappa \frac{\partial H^2}{\partial y}\vec{e}_y \tag{15b}$$

After calculations we obtain:

$$\vec{f}_x = \frac{\mu_o \kappa a^2 H_m^2 x \cos^2 \alpha \cos^2 \frac{\pi}{p}(y - nst)}{(a^2 - x^2 \cos^2 \alpha)^2}\vec{e}_x \tag{16a}$$

$$\vec{f}_y = \frac{\mu_o \kappa a^2 H_m^2 \frac{\pi}{p} \sin 2\frac{\pi}{p}(y - nst)}{2(a^2 - x^2 \cos^2 \alpha)}\vec{e}_y \tag{16b}$$

Both constituents of the magnetic force are directed towards the convex pole shoe, i.e. towards the lower helical edge.

4. Balance of forces acting on a particle in the spiral separater

The separation process in the spiral separator takes place in the presence of a water flow. Water passed to the helix produces hydrodynamic force. This force, in addition to gravitational and centrifugal forces, constitutes a separating force which washes out non-magnetic particles. It also washes magnetic particles from the curvi-planar surfaces of the helix. The equilibrium of the magnetic force and mechanical forces effects the transport of the magnetic particles up the separator trough. The gravitational component, acting on the unit particle volume along the x axis is:

$$G_x = -\rho g \sin \varphi \tag{17}$$

where:

ρ — particle density,

g — acceleration of gravity,
φ — inclination angle of the device to the horizontal.

The hydrodynamic force acting on the unit particle volume is expressed by Newton--Rittinger's formula:

$$F_o = -\frac{\rho_c}{2d} u^2 \tag{18}$$

where:

ρ_c — water density,
d — particle diameter,
u — water movement velocity on the curvi-planar surfaces of the helix.

The value of centrifugal force on the unit particle volume is:

$$F_R = \rho \varpi^2 R = 4\pi \rho n^2 R \tag{19}$$

where:

R — the helical radius.

In order to initiate the process of elevating magnetic particles up the trough, the following condition must exist along the y axis:

$$f_x = \rho g \sin\varphi - \frac{\rho_c}{2d} u^2 - 4\pi^2 \rho n^2 R \geq 0 \tag{20}$$

After substituting for f_x from formula (16a) we obtain:

$$\frac{\mu_o \kappa a^2 H_m^2 x \cos^2\alpha \cos^2 \frac{\pi}{p}(y - nst)}{(a^2 - x^2\cos^2\alpha)^2} - \rho g \sin\varphi - \frac{\rho_c}{2d} u^2 - 4\pi^2 \rho n^2 R \geq 0 \tag{21}$$

From the above formula we obtain the situation which must exist to achieve the process of separation of particles of susceptibility higher than κ_p:

$$\kappa_p \geq \frac{\left(\rho g \sin\varphi - \frac{\rho_c}{2d} u^2 - 4\pi^2 \rho n^2 R\right)(a^2 - x^2\cos^2\alpha)^2}{\mu_o a^2 H_m^2 x \cos^2\alpha \cos^2 \frac{\pi}{p}(y - nst)} \tag{22}$$

The amount of washing water supplied in unit time is equal to $Q = uS$, therefore $u = Q/S$ where S denotes the area of transverse section of the water stream on the curvi-planar surface, while u is the mean stream velocity. Since the average value of the $\cos^2 x$ function is 1/2, the average value of separating magnetic susceptibility:

$$\kappa_p \geq \frac{2\left(\rho g \sin\varphi + \frac{\rho_c}{2d}\frac{Q^2}{S^2} + 4\pi^2 \rho n^2 R\right)(a^2 - x^2\cos^2\alpha)^2}{\mu_o a^2 H_m^2 x \cos^2\alpha} \tag{23}$$

The above formula means that the average value of the magnetic susceptibility of the magnetic product decreases with the growth of field intensity and, consequently, the concentration of the magnetic components in the separated product is reduced. On the other hand, a higher concentration results (higher value of κ_p) if the trough is raised to a steeper angle, the water supply is increased and increase the speed of rotation.

5. Optimum working conditions for the separator

The objective of every enrichment process, from technological and economic points of view, is to obtain the highest concentrations of the target substance as efficiently as possible. Nevertheless, the required content of Fe in the concentrate is often lower than the maximally possible value to be obtained at a given ore crushing rate. Therefore the separation procedure should, ideally, be matched to the level of ore content of Fe stated and required by the purchaser.

When analysing the separation process the author has assumed a model in which the non-magnetic component is washed off from the main (magnetic) stream, the latter being transported by magnetic force along the separator trough. In this model the magnetic component of $\kappa > \kappa_p$ susceptibility passes totally to the magnetic product. As a result of the phenomenon of magnetic flocculation, the magnetic product also contains non-magnetic components. Therefore the concentrate mass is a sum of the masses of magnetic and non-magnetic components. If the $F(\kappa)$ is a distribution function of the sample's magnetic susceptibility, then the masses of the magnetic (m_m) and non--magnetic (m_n) component in the magnetic product are:

$$m_m = [1 - F(\kappa_p)]M_o$$

$$m_m = \sigma_n F(\kappa_p)M_o$$

where:

M_0 — total mass of a sample whereas,

σ_n — rest of the nonmagnetic component in the magnetic product.

Consequently, the yield of the magnetic product (concentrate) will be:

$$m_m = [1 - F(\kappa_p)]M_o \tag{24}$$

Taking into consideration the fact that $F(\kappa_p) = \alpha_n$ and $\sigma_n = 1 - \varepsilon_n$, where α_n is an average content of the non-magnetic component in the sample, whereas ε_n is the recovery of the non-magnetic component in the non-magnetic product, formula (24) will become:

$$\gamma_m = 1 - \alpha_n \varepsilon_n \tag{25}$$

Treating the process of separation as a stochastic process in which the non-magnetic component is washed out of the magnetised stream on separation path *y* Brożek (1999a), derived a formula for the recovery of the non-magnetic component in the non-magnetic product after path *y*:

$$\varepsilon_n = 1 - e^{-\mu y} \tag{26}$$

where μ represents the constant separation rate of non-magnetic particles. Therefore the concentrate yield is expressed by a formula:

$$\gamma_m = 1 - \alpha_n (1 - e^{-\mu y}) = \alpha_m - \alpha_n e^{-\mu y} \tag{27}$$

When separating the feed into two products, i.e. concentrate and waste, when the non-magnetic component in waste $\theta_n = 1$, then the magnetic component in the concentrate is equal to (Brożek 1999b):

$$\beta_m = \frac{1}{1 + \frac{\alpha_n}{\alpha_m} e^{-\mu y}} \tag{28}$$

The constant separation rate, occuring in the above formulas, is the ratio of the sum of mechanical forces $\sum_i F_c^i$ to the total potential V_c of particle interactions (1999b):

$$\mu = \frac{\sum_i F_c^i}{V_c} \tag{29}$$

The sum of the mechanical forces acting on the non-magnetic particle in the spiral separator consists of the *x* component of gravitational force, the hydrodynamic force and the centrifugal force. Therefore:

$$\sum_i F_c^i = \left(\rho g \sin \varphi - \frac{\rho_c}{2d} u^2 + 4\pi^2 \rho n^2 R \right) \frac{\pi d^3}{6} \tag{30}$$

In this case ρ and *d* relate to non-magnetic particles.

The sum of the mechanical forces is the force which causes the non-magnetic particles to be precipitated from the main (magnetic) stream.

The potential of magnetic particle interaction is the sum of three components; the potential of interactions between the non-magnetic particles with the external field V_H, the potential of interactions of the magnetic and non-magnetic particles V_{m-n} and the potential of interactions between magnetic particles V_m. The potential of interactions of the non-magnetic particle with the external field is equal to (Brożek 1996):

$$V_H = \frac{1}{12} \pi \mu_o \kappa_n d^3 H^2 \tag{31}$$

where κ_n denotes magnetic susceptibility of non-magnetic particles, i.e. the particles for which $\kappa = \kappa_n < \kappa_p$.

The potential of interaction of the non-magnetic particle with the magnetic one is expressed by the formula (Brożek 1996):

$$V_{m-n} = \frac{1}{16}\pi^2 \mu_o \kappa_n \kappa_m d^3 H^2 \tag{32}$$

where κ_m denotes the magnetic susceptibility of particles of properties $\kappa = \kappa_m < \kappa_p$.

If, between two magnetic particles of diameter d a non-magnetic particle of the same size is found, this particle will be retained mechanically as a consequence of interactions between magnetic particles. The potential of these interactions is equal to (Brożek 1996):

$$V_m = \frac{1}{144}\pi^2 \mu_o \kappa_m^2 d^3 H^2 \tag{33}$$

The forces of interaction of non-magnetic particles with the external field and magnetic particles hinder the process of leaving non-magnetic particles being shed from the main stream. Their presence in the main stream affects the efficiency of the process of magnetic separation. Neglecting the forces of surface interactions, the separation rate constant of non-magnetic particles, according to formula (29) and taking into account the magnetic field distribution (14), is:

$$\mu = \frac{24\left(\rho g \sin\varphi + \frac{\rho_c}{2dS^2} Q^2 + 4\pi^2 \rho R n^2\right)(a^2 - x^2 \cos^2 \alpha)^2}{\mu_o (12\kappa_n + 9\pi\kappa_n \kappa_m + \pi\kappa_m^2) a^2 H_m^2 \cos^2 \frac{\pi}{p}(y - nst)} \tag{34a}$$

or the average value

$$\mu = \frac{48\left(\rho g \sin\varphi + \frac{\rho_c}{2dS^2} Q^2 + 4\pi^2 \rho R n^2\right)(a^2 - x^2 \cos^2 \alpha)}{\mu_o (12\kappa_n + 9\pi\kappa_n \kappa_m + \pi\kappa_m^2) a^2 H_m^2} \tag{34b}$$

The variables by which the value of separation rate constant of non-magnetic particles can be changed are as follows: amount of washing water Q, speed of rotation n, magnetic field intensity H_m and the inclination angle of the separator trough β. Most often, however, the working conditions of separator are controlled by the changes of variables Q and H_m. When the values of other variables are determined, the dependence of the separation rate constant on the amount of washing water is as follows:

$$\mu = A + BQ^2 \tag{35}$$

where:

$$A = \frac{48(\rho g \sin\varphi + 4\pi^2 \rho R n^2)(a^2 - x^2 \cos^2 \alpha)}{\mu_o (12\kappa_n + 9\pi\kappa_n \kappa_m + \pi\kappa_m^2) a^2 H_m^2} \tag{36}$$

$$B = \frac{24 \frac{\rho_c}{dS^2} (a^2 - x^2 \cos^2 \alpha)}{\mu_o (12\kappa_n + 9\pi\kappa_n \kappa_m) a^2 H_m^2} \tag{37}$$

In such a case the dependence of the Fe content in the magnetic product and concentrate yield on the amount of washing water supplied are expressed by the formulae:

$$\beta(Q) = \left(1 + \frac{\alpha_n}{\alpha_m} C e^{-LBQ^2}\right)^{-1} \beta_t \tag{38}$$

$$\gamma(Q) = \alpha_m + \alpha_n C e^{-LBQ^2} \tag{39}$$

where:

$C = e^{-LA}$, L — length of the separation path (separator helix),

β_t — equilibrium content of Fe in the concentrate particles of magnetic susceptibility determined by formula (23).

Fig. 5 presents the pictorial dependences $\beta(Q)$ and $\gamma(Q)$. When the dependence $\beta(Q)$ is known the separation conditions (amount of washing water) can be chosen for the required Fe content in the concentrate.

For the dependence of the separation rate constant on the magnetic field intensity H_m the following formula is obtained:

$$\mu = \frac{D}{H_m^2} \tag{40}$$

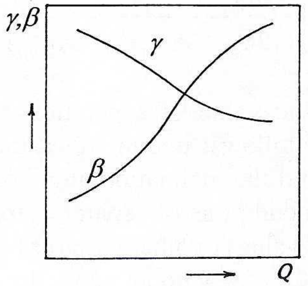

Fig. 5. Graphic representation of dependences of Fe content and concentrate yield on the amount of washing water

Rys. 5. Poglądowe zależności zawartości żelaza i wychodu koncentratu od ilości wody spłukującej

where:

$$D = \frac{24\left(\rho g \sin\varphi + \frac{\rho_c}{2dS^2}Q^2 + 4\pi^2\rho R n^2\right)(a^2 - x^2\cos^2\alpha)}{\mu_o(12\kappa_n + 9\pi\kappa_n\kappa_m + \pi\kappa_m^2)a^2}$$

In relation to expression (40) we obtain the dependence of the Fe content in the concentrate and the yield of the magnetic product on field intensity:

$$\beta(H_m) = \left(1 + \frac{\alpha_n}{\alpha_m} e^{-\frac{DL}{H_m^2}}\right)^{-1} \beta_t \tag{41}$$

$$\gamma(H_m) = \alpha_m + \alpha_n e^{-\frac{DL}{H_m^2}} \tag{42}$$

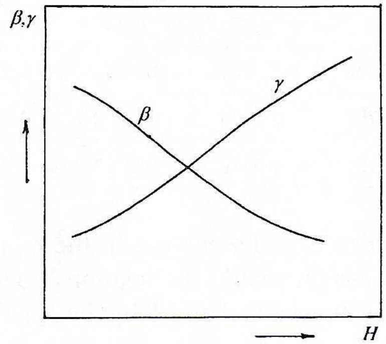

Fig. 6. Graphic representation of dependences of Fe content and concentrate yield on magnetic field intensity

Rys. 6. Poglądowe zależności zawartości żelaza i wychodu koncentratu od natężenia pola magnetycznego

Fig. 6 presents pictorial dependences $\beta(H_m)$ and $\gamma(H_m)$, the detailed course of which is affected by the values of the remaining variables.

6. The verification of dependence (38) and discussion of results

A verification of the dependence of the Fe content in the concentrate on the amount of washing water was carried out using a laboratory spiral separator of helix length $L = 0.8$ m and radius $R = 0.1$ m. The ratio of the helix length to its diameter is 4. The tests were performed using titanium-magnetite ore. Ore samples of particle size below 0.3 mm, 0.2 mm and 0.1 mm were prepared. A series of investigation for each size fraction was made in which the amount of washing water was an independent (input) variable whereas the Fe content in the concentrate was a dependent (output) variable. The experiments were performed with 30% content of solid parts in the feed mixture.

Table 1 shows the results of separations performed for 4 different quantitative supplies of washing water and constant values of α_n, α_m and β_t for the tested size fractions. The values of these constants, specific to the ore, were determined by means of Davis' tube. The number helix rotations $n = 0.57\ s^{-1}$, helix inclination angle $\varphi = 16°$, field intensity $H_m = 70$ kA/m.

TABLE 1

Results of magnetic separation

TABLICA 1

Wyniki seperacji magnetycznej

	Fe content β				α_m	α_n	β_t
Q [l/sek]	0.23	0.3	0.37	0.44			
–0.3 mm	0.4683	0.5048	0.5261	0.5395	0.2998	0.7002	0.555
–0.2 mm	0.4983	0.5702	0.5934	0.6208	0.3557	0.6443	0.635
–0.1 mm	0.5686	0.5780	0.6436	0.6723	0.4250	0.5750	0.685

Fig. 7 shows the dependence of Fe content in the concentrate on the amount of washing water. The continuous line marks the relationship to the model, obtained from formula (38) after estimating constants A and B by the least square method. The model dependences and values of A and B constants are as follows:

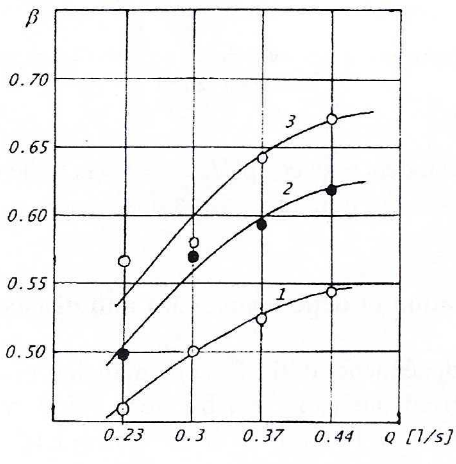

Fig. 7. Dependence of Fe content in concentrate on the amount of washing water

Rys. 7. Zależność zawartości żelaza w koncentracie od ilości wody spłukującej

a) for particles smaller than 0.3 mm

$$\beta = \frac{0.555}{1 + 0.36 e^{-13.7 Q^2}} \tag{43}$$

$A = 2.37$ [m^{-1}] $B = 17.09$ [m^{-1}l^{-2}s^2]

b) for particles smaller than 0.2 mm

$$\beta = \frac{0.635}{1 + 0.66 e^{-17.6 Q^2}} \tag{44}$$

$A = 1.26$ [m^{-1}] $B = 22.02$ [m^{-1}l^{-2}s^2]

c) for particles smaller than 0.1 mm

$$\beta = \frac{0.685}{1 + 0.72 e^{-18.6 Q^2}} \tag{45}$$

$A = 0.59$ [m^{-1}] $B = 23.25$ [m^{-1}l^{-2}s^2]

The measure of constant B is [meter^{-1}litre^{-2}second^2] because the value Q is given in litres/second.

As it can be seen from the above data the value of constant A grows as the sizes of separated particles increases while the constant B decreases. On the other hand, the dependence of constant A on a particle size does not result from Eq. (36).

Surface interactions were neglected while considering the partcle interactions. These interactions include London-Van der Waals' interactions and the interactions of electrical double layers. If these interactions are to be taken into account it is necessary to add surface interactions to the expression on the total potential V_c. After such an operation the expressions on constants A and B are as follows:

$$A = \frac{48(\rho g \sin\varphi + 4\pi^2 \rho R n^2)(a^2 - x^2 \cos^2\alpha) d^2}{\mu_o (12\kappa_n + 9\pi\kappa_n\kappa_m + \pi\kappa_m^2) a^2 H_m^2 d^2 + P} \tag{46}$$

$$B = \frac{\frac{\rho_c}{2S^2}(a^2 - x^2\cos^2\alpha) d}{\mu_o (12\kappa_n + 9\pi\kappa_n\kappa_m + \pi\kappa_m^2) a^2 H_m^2 d^2 + P} \tag{47}$$

where (Hogg et al. 1996; Overbeek 1984):

$$p = \left\{ \frac{\varepsilon(\psi_1^2 + \psi_2^2)}{16} \left[\frac{2\psi_1\psi_2}{\psi_1^2 + \psi_2^2} \ln\frac{1 + e^{-\chi h}}{1 - e^{-\chi h}} + \ln(1 - e^{-2\chi h}) \right] - \frac{A_H}{24h} \right\} \tag{48}$$

where:

ε	— dielectrical permeability of liquid,
ψ_1 and ψ_2	— particle surface potentials,
χ-Debye	— Huckel's parameter,
A_H	— Hamaker's constant,
h	— distance between interacting surfaces.

After these supplements, the dependencies A and B on the size of separated particles are consistent with the experiment. The constant A, as from formula (46), grows with the increase of particle size. Thus, an exact analysis of the wet magnetic separation process of fine particles the surface interactions cannot be neglected because reveals a significant effect on the efficiency of separation.

The theoretical model of separation in a spiral separator reveals a good consistency with the results in practical experiments. By applying it, it is possible predict the levels of enrichment of titanium-magnetite ore in this separator, after a prior assumption of separation conditions. It is also possible to choose separation conditions for the required concentrate quality.

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