ARCHIVES OF METALLURGY
Volume 48 2003 Issue 3

MARIAN BROŻEK*

SEPARATION ANALYSIS IN THE BAND MAGNETIC SEPARATOR

ANALIZA ROZDZIAŁU W SEPARATORZE MAGNETYCZNYM TAŚMOWYM

In magnetic separators the phenomenon of magnetic flocculation is an inseparable feature of enrichment of strongly magnetic ores. Non-magnetic particles are bound in the floc internal structure by means of magnetic, surface and mechanical forces which leads to the deterioration of enrichment results. The intensity of flocculation depends on magnetic field intensity, content of the magnetic component in the feed and ore feed rate. The above mentioned factors affect the enrichment results.

The paper presents the separation analysis in the band magnetic separator with respect to the magnetic field distribution in the separator working space as well as internal and external mechanical forces, acting on the particle. The author determined the effect of the magnetic compound content in the feed and the amount of washing water on the recovery of this component in the concentrate as well as the effect of the magnetic component content in the feed and the magnetic force density on the residue of the non-magnetic component in the concentrate. The analysis was performed according to the physical model of magnetic separation, presented in the paper. The theoretical dependences, derived from this model, are in good agreement with the results of empirical research, found in the literature.

W separatorach magnetycznych zjawisko flokulacji magnetycznej jest nieodłączną cechą procesu wzbogacania rud silnie magnetycznych. W wewnętrznej strukturze flokuł siłami magnetycznymi, powierzchniowymi i mechanicznymi uwięzione zostają ziarna niemagnetyczne co prowadzi do pogorszenia wyników wzbogacania. Intensywność flokulacji jest zależna od natężenia pola magnetycznego, zawartości składnika magnetycznego w nadawie oraz wydajności separacji. Wymienione czynniki mają wpływ na wyniki wzbogacania.

W artykule przedstawiono analizę rozdziału w separatorze magnetycznym taśmowym z uwzględnieniem rozkładu pola magnetycznego w przestrzeni roboczej separatora oraz sił wewnętrznych i zewnętrznych typu mechanicznego, działających na ziarno. Określono wpływ zawartości składnika magnetycznego w nadawie i ilości wody spłukującej na uzysk tegoż składnika w koncentracie oraz wpływ zawartości składnika magnetycznego w nadawie i gęstości siły magnetycznej na pozostałość składnika niemagnetycznego w koncentracie.

* ZAKŁAD PRZERÓBKI KOPALIN, OCHRONY ŚRODOWISKA I UTYLIZACJI ODPADÓW, AKADEMIA GÓRNICZO-HUTNICZA, 30-059 KRAKÓW, AL. MICKIEWICZA 30

Analizę przeprowadzono na podstawie fizycznego modelu separacji magnetycznej przedstawionego w pracy. Wyprowadzone z tego modelu zależności teoretyczne są w bardzo dobrej zgodności z wynikami badań empirycznych, zaczerpniętych z literatury.

1. Introduction

The enrichment process in the band separator is continuous. In the course of the process the feed is continuously carried to the separator and the enrichment products, i.e. the magnetic and non-magnetic ones, are also continuously collected. Due to the necessity of liberating the useful minerals, the feed for the enrichment process must be crushed to dimensions up to a few tenths of millimetre. Magnetic field acts upon such a crushed material in the separator working space. Magnetic particles achieve magnetic moments whose interactions lead to the phenomenon of magnetic flocculation. Non-magnetic particles are bound in the internal structure of flocs by magnetic, surface and mechanical forces. If enrichment occurs in the constant magnetic field, then the non-magnetic particles are carried to the magnetic product with the magnetic component, decreasing the product quality. Therefore, willing to obtain the final product of high quality, separation should be applied in variable fields or in such magnetic systems that the material in its separation course would be affected by the magnetic field of alternating direction. The latter case has already appeared in band magnetic separators. When the direction of magnetic field is changed, the flocs are subject to a few remagnetizations during which the non-magnetic particles are removed from flocs volume by means of mechanical (gravity and hydrodynamic) forces. In such a way a purer magnetic product is obtained.

The effects of magnetic enrichment depend on numerous factors a part of which refers to all separator types as, for example, the content of magnetic component in the feed, ore feed rate, magnetic field intensity while the second part of factors affecting the separation process is connected with the separator type. In case of the band separator, it will be the amount of washing water and the angle of band inclination to the horizontal axis. All the above factors affect the value of particle interactions and the value of external forces acting upon the particle. Enrichment effects depend on mutual relations between internal and external forces. The next part of the paper will present the analysis of separation in the band separator with respect paid to the magnetic field distribution in the separator working space as well as the internal and external forces acting on the particle in this separator. The analysis was performed on the basis of the physical model of magnetic separation, presented in the next chapter.

2. Model of separation

As it was mentioned in Introduction, the enrichment process in the band separator is a continuous process. As a result of action of magnetic and mechanical forces the feed stream is divided into two parts, i.e. a magnetic product (concentrate) and a non-magnetic product (tailings). As a result of the process of flocculation, the non-magnetic component finds its way to the concentrate while the magnetic component, due to the heterogeneity of the liquid velocity field along the band surface, goes to tailings. This is the reason why both the recovery of the magnetic component in the concentrate and the recovery of the non-magnetic component in tailings is smaller than 1. Therefore the yield of concentrate is:

$$\gamma_k = \alpha_m \, \varepsilon_m + \alpha_n \, \sigma_n, \tag{1}$$

where: α_m – content of magnetic component in the feed, α_n – content of non-magnetic component in the feed, ε_m – recovery of magnetic component in concentrate, σ_n – residue of non-magnetic component in concentrate.

The material being enriched passes a certain rout in the magnetic field zone which is called a separation path. The separation of the non-magnetic product of susceptibility κ_n from the stream of magnetic product (main stream) will be the subject-matter of the current considerations.

Let r denotes the length of separation path. The following value:

$$P(r > s) = f(s) \tag{2}$$

will denote the probability of remaining the non-magnetic particle in the material main stream up to point s or, in other words, the probability of unseparating the non-magnetic particle to the non-magnetic product on the separation path s while the following condition is fulfilled:

$$f(0) = P(r > 0) = 1. \tag{3}$$

Unseparating the non-magnetic particle on two consecutive sections of the separation path s and u ($s, u \geq 0$) will be a pair of independent events. Consequently, a probability of unseparating the non-magnetic particle on the join section of the separation path $s + u$ will be, according to the formula of complete probability, equal [9]:

$$P(r > s + u) = P(r > u) \, P(r > s) \tag{4a}$$

$$f(s + u) = f(u) \, f(s). \tag{4b}$$

After differentiating expression (4b) in relation to u (assuming that there is density $f'(s + 0)$, $s \geq 0$) we obtain:

$$f'(s + u) = f(s) \, f'(u). \tag{5}$$

Dividing by sides equation (4b) by (5) we obtain:

$$\frac{f(s + u)}{f'(s + u)} = \frac{f(u)}{f'(u)} \tag{6}$$

and, when $u = 0$

$$\frac{f'(s)}{f(s)} = \mu_n, \tag{7}$$

where: $-\mu_n = f'(0) \leq 0$, since $f(0) = 1$ is the maximum value of function $f(s) = P(r > s)$, $s \geq 0$.

From equation (7), after taking into account condition (3), the following solution is obtained:

$$f(s) = \exp(-\mu_n s). \tag{8}$$

As it was said above, $f(s)$ denotes the probability of unseparating the non-magnetic particle of susceptibility κ_n to the non-magnetic product. The measure of this probability will constituted by a number of particles of susceptibility κ_n, occurring in the magnetic product after passing the path s (number of unseparated particles), to the total number of particles of this susceptibility, occurring in the feed:

$$f(s, \kappa_n) = \frac{N_m(s, \kappa_n)}{N(0, \kappa_n)}. \tag{9}$$

Thus, from expression (8), after taking into consideration (9), we obtain:

$$N_m(s, \kappa_n) = N(0, \kappa_n)\exp(-\mu_n s). \tag{10}$$

In the above equations $N_m(s, \kappa_n)$ denotes the number of non-magnetic particles of susceptibility κ_n contained in the magnetic product after passing the path s, whereas $N(0, \kappa_n)$ denotes the number of particles of susceptibility κ_n in the feed.
The following expression:

$$N_n(s, \kappa_n) = N(0, \kappa_n) - N_m(s, \kappa_n) = N(0, \kappa_n)\,[1 - \exp(-\mu_n s)] \tag{11}$$

represents the number of particles of susceptibility κ_n separated into the non-magnetic product after passing the path s by the main stream. The total recovery of these particles in the non-magnetic product (up to the point s of the path of main stream) will be equal:

$$\varepsilon_n = \frac{N_n(s, \kappa_n)}{N(0, \kappa_n)} = 1 - \exp(-\mu_n s). \tag{12}$$

Coefficient μ_n, by means of formulae (10)–(12), obtains the interpretation of separation rate constant of the non-magnetic component to the tailings.

Analogically to expression (12), the losses of the magnetic component in the tailings η_m are expressed by the following formula:

$$\eta_m = 1 - \exp(-\mu_m x), \tag{13}$$

where: μ_m convection rate constant of the magnetic component to the tailings.

Consequently, the recovery of the magnetic component in the concentrate will be:

$$\varepsilon_m = 1 - \eta_m = \exp(-\mu_m x). \tag{14}$$

The convection rate constant of the magnetic component μ_m is expressed by the relation of the sum of mechanical forces transfering the particles to the tailings to the total potential of interactions between magnetic particles V_c [2]:

$$\mu_m = \frac{\sum_i F_i}{V_c}. \tag{15}$$

Forces G_x, F_o and force of internal friction between particles equal $f_i\, F_i$, should be included into the sum of mechanical forces, transfering the particles to the tailings [3]. Here f_i is the coefficient of internal friction while V_c is the potential of force of interactions between magnetic particles [2]:

$$V_c = -\frac{\pi^2 \kappa^2 d^4 H_m^2 \exp\left(-\frac{2\pi}{s} y\right)}{k_1 (1 + \kappa N)^2\, r}, \tag{16}$$

where: d – particle diameter, κ – magnetic susceptibility of magnetic particles, H – magnetic field intensity on the surface of pole shoes of the magnetic system, s – pitch of poles of the magnetic system, y – distance from the pole shoe surface, k_1 – coefficient depending on the system of units, N – coefficient of demagnetization, r – average distance between magnetic particles, G_x – component of gravity force along the separator band, F_o – hydrodynamic force acting along the band.

Therefore the convection rate constant μ_m is equal [3]:

$$\mu_m = \frac{[2d\,(\rho - \rho_o) g \sin\varphi + \rho_o u^2]\, k_1 (1 + \kappa N)^2 r}{12 \kappa^2 \pi d^2 H_m^2 \exp\left(-\frac{2\pi}{s} y\right)} - \frac{f_i}{r}, \tag{17}$$

where: ρ – particle density, ρ_o – water density, g – acceleration of gravity, φ – inclination angle of separator band to the horizontal direction, u – velocity of water motion on band surface. Formula (17) is the basis to analyse the effect of the above factors on separation results.

3. Influence of the magnetic component content in the feed on the recovery of this component in the concentrate

The average distance r between magnetic particles of the same size, assuming that the sample has been mixed thoroughly, is proportional to $\left(\sqrt[3]{\alpha_m}\right)^{-1}$, while α_m represents the volume content of the magnetic component in the feed [1]. Accordingly, the dependence of the convection rate constant on the volume content of the magnetic component in the feed is as follows:

$$\mu_m = A\left(\sqrt[3]{\alpha_m}\right)^{-1} - f_i\sqrt[3]{\alpha_m} \tag{18}$$

whereas constant A is equal:

$$A = \frac{[2d\ (\rho - \rho_o)g\ \sin\ \varphi + \rho_o u^2]\, k_2(1 + \kappa N)^2}{12\pi\kappa^2 d^2 H_m^2 \exp\left(-\dfrac{2\pi}{s}y\right)}. \tag{19}$$

Taking into consideration expressions (14) and (18), the dependence of recovery of the magnetic component in the concentrate on the content of this component in the feed is expressed by the following formula:

$$\varepsilon_m = \exp\left[-\left(\frac{A}{\sqrt[3]{\alpha_m}} - f_i\sqrt[3]{\alpha_m}\right)x\right]. \tag{20}$$

The verification of dependence (20) was based on the results of separation of mixtures of magnetite and sand, taken from Ref. [6]. Mixtures of different contents of magnetite and sand were made from magnetite and sand of similar particle size distributions of the 0.063–0.2 mm range. They were separated on the laboratory band separator with the set band inclination angle to the horizontal direction equal $\varphi = 46.5°$ and the fixed amount of washing water $Q_w = 11.1$ *l/min.* the set separator productivity $Q_n = 90$ *kg/h* and the fixed average value of magnetic force density (value of expression $\frac{1}{2}\mu_o\frac{dH^2}{dy}$) on the band surface of 922 955 N/m^3.

Fig. 1 presents dependence $\varepsilon_m(\alpha_m)$ in which the points mark experimental values while the continuous line represents a model dependence drawn according to the formula:

$$\varepsilon_m(\alpha_m) = \exp\left[-\left(\frac{0.22}{\sqrt[3]{\alpha_m}} - 0.24\sqrt[3]{\alpha_m}\right)x\right]. \tag{21}$$

Numerical coefficients of formula (21) contain the length of separation path x which is equal $x = 0.9$ m for this separator.

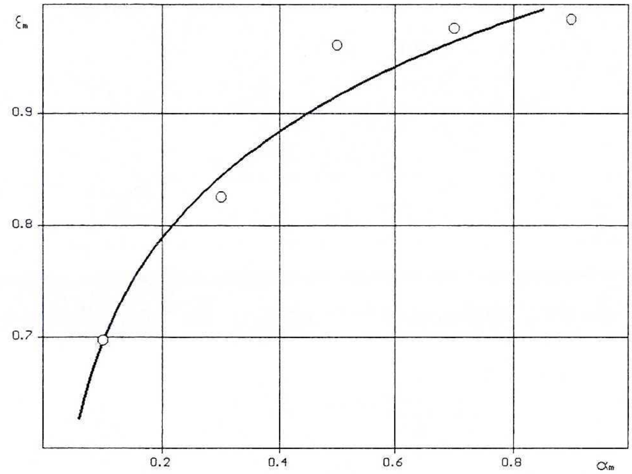

Fig. 1. Dependence of magnetic component recovery upon the content of this component in the feed

As it can be seen from Fig. 1, the compatibility of model dependence with experimental values is very good. The recovery of the magnetic component in the concentrate grows with the increase of content of this component in the feed. The average distance between magnetic particles decreases with the growth of α_m, thus the force of interactions between these particles increases which results in decreasing the losses of magnetic particles into the tailings, originated by mechanical forces.

4. Influence of the amount of washing water upon the recovery of the magnetic component in the concentrate

The amount of washing water Q_w is equal:

$$Q_w = u \; a \; h, \tag{22}$$

where a is an active band width while h is the average height of water stream on the band surface. From the above formula:

$$u = \frac{Q_w}{a \; h}. \tag{23}$$

After sibstituting dependence (23) into formula (17) we obtain:

$$\mu_m = B + CQ_w^2, \tag{24}$$

where:

$$B = \frac{k_2(1 + \kappa N)^2 (\rho - \rho_o) g \sin\varphi}{6\pi \kappa^2 d \sqrt[3]{\alpha_m} H_m^2 \exp\left(\frac{-2\pi y}{s}\right)} - f_i \sqrt[3]{\alpha_m}$$

$$C = \frac{\rho_o k_2 (1 + \kappa N)^2}{12\pi \kappa^2 d^2 h^2 \sqrt[3]{\alpha_m} H_m^2 \exp\left(-\frac{2\pi y}{s}\right)}.$$

The dependence of recovery of the magnetic component in the concentrate on the amount of washing water is expressed by the formula:

$$\varepsilon_m(Q_w) = D \exp(-CxQ_w^2) \tag{25}$$

and $D = \exp(-Bx)$.

The experimental verification has been taken from G a l a l ' s work [6] for $\alpha_m = 0.1$. The remaining conditions of the band separator operation are analogical as Chapter 3.

The model dependence, obtained on the basis of experimental results, is as follows:

$$\varepsilon_m(Q_w) = 1.06 \exp(-0.003\, Q_w^2) \tag{26}$$

while Q_w is given in [*l/min.*]. Theoretically, value D should be equal to 1. Therefore, the experimental value is close to one.

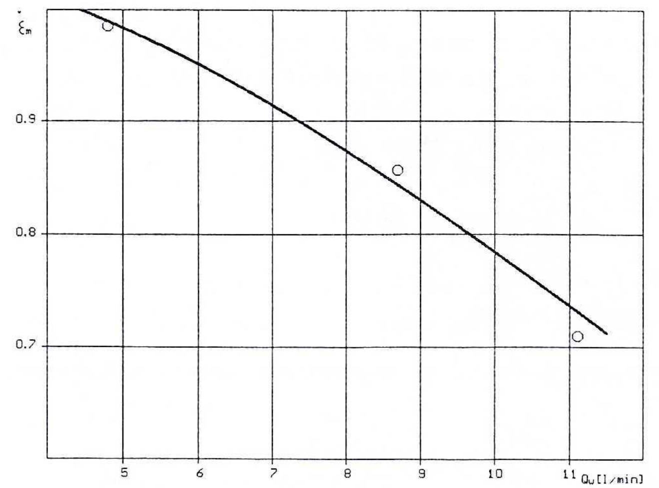

Fig. 2. Dependence of magnetic component recovery upon the amount of washing water

Fig. 2 shows a model dependence and points mark experimental values. Thus the agreement of the model with the experimental course is very good. On the other hand, however, it should be taken into account that the number of experimental points was very small (3) and this factor could have influenced the degree of compatibility of the model with experiment.

As Fig. 2 indicates, the recovery of the magnetic component decreases with the increase of the amount of washing water because the value of hydrodynamic force grows and, consequently, the losses of the magnetic component in the waste increase.

5. Influence of the content of magnetic component in the feed upon the residue of non-magnetic component in the concentrate

The residue of the non-magnetic component in the concentrate and the recovery of the magnetic component in the concentrate are expressed by the following formulas [10]:

$$\sigma_n = \frac{\gamma_m \lambda_n}{\alpha_n} \tag{27}$$

$$\varepsilon_m = \frac{\gamma_m \beta_m}{\alpha_m}, \tag{28}$$

where λ_n and β_m, respectively, represent the content of the non-magnetic and magnetic component in the concentrate.

Eliminating γ_m from the above equations, we obtain:

$$\sigma_n = K \alpha_m \varepsilon_m \tag{29}$$

and, consequently, $K = \dfrac{\lambda_n}{\beta_m \alpha_n}$.

Thus, the residue of the non-magnetic component in the concentrate is connected with the recovery of the magnetic component in the cocentrate. Due to this, the dependence of the residue of non-magnetic component in the concentrate on the content of magnetic component in the feed will be obtained from joining formulas (20) and (29):

$$\sigma_n (\alpha_m) = K \alpha_m \exp\left[-\left(\frac{A}{\sqrt[3]{\alpha_m}} - f_i \sqrt[3]{\alpha_m}\right) x\right]. \tag{30}$$

Empirical dependence $\sigma_n (\alpha_m)$ was obtained in the experiment described in Chapter 3. Fig. 3 shows the model dependence expressed by the following formula:

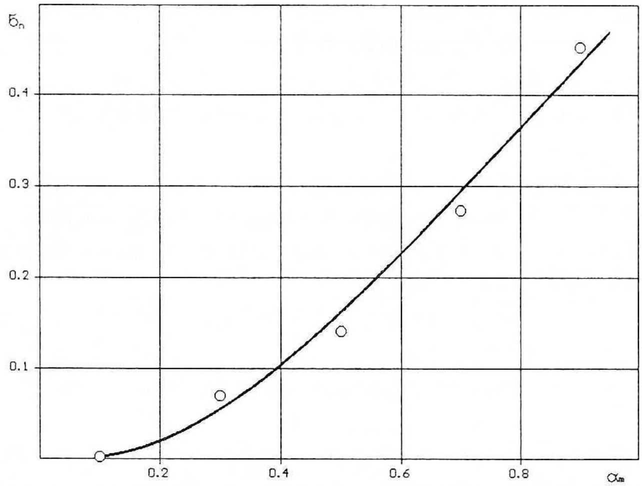

Fig.3. Dependence of non-magnetic component residue in the concentrate upon the content of magnetic component in the feed

$$\sigma_n\ (\alpha_m) = 441.4\, \alpha_m \exp\left[-\left(\frac{3.94}{\sqrt[3]{\alpha_m}} - 2.84\, \sqrt[3]{\alpha_m} \right) x \right]. \tag{31}$$

As it results from Fig. 3, the compatibility of the model dependence with the empirical course is satisfactory. The residue of non-magnetic component in the concentrate grows with the increase of the content of magnetic component in the feed. The increase of concentration of magnetic component in the feed results in decreasing the average distance between magnetic particles and, respectively, the growth of magnetic interactions between magnetic particles. Due to these interactions, the non-magnetic particles are mechanically stopped in the flocs volume. These particles cannot be easily liberated at strong interactions.

6. The influence of magnetic force density upon the residue of non-magnetic component in the concentrate

The average value of expression $\frac{1}{2}\mu_o \frac{\partial H^2}{\partial y}$ is meant to be the magnetic force density. This value is equal [3]:

$$\bar{f}_y = \mu_o H_m^2 \frac{\pi}{s} \exp\left(-\frac{2\pi}{s} y \right) \tag{32}$$

Respectively, the convection rate constant μ_m, expressed by $\bar{f}_y$, according to formula (17), is equal:

$$\mu_m = \frac{E}{\bar{f}_y} + G \tag{33}$$

whereas $E = \dfrac{[2d(\rho - \rho_o) g \sin \varphi - \rho_o u^2]\ k_3\ (1 + \kappa N)^2 r}{12\, \kappa^2 \pi d^2}$, while $G = -\dfrac{f_i}{r}$.

In this situation the dependence of the residue of non-magnetic component in the concentrate upon the magnetic force density will be expressed by the following formula:

$$\sigma_n = K_1 \exp\left(-\frac{E}{\bar{f}_y} x\right), \tag{34}$$

where: $K_1 = \exp(-Gx)$.

The verification of the above dependence was based on the results of the experiment described in Ref. [7]. The experiment was performed in the following conditions of the separator operation: amount of washing water $Q_w = 8.7$ *l/min.*, ore feed rate 120 *kg/min.*, content of magnetic component in the feed $\alpha_m = 0.7$, inclination angle of separator band to the horizontal direction $\varphi = 46.5°$.

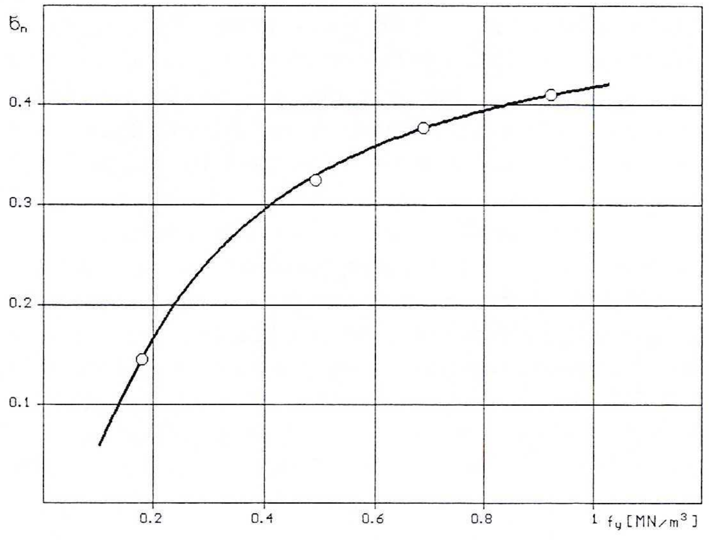

Fig. 4. Dependence of non-magnetic component residue in the concentrate upon magnetic force density

Fig. 4 presents dependence $\sigma_n(\bar{f}_y)$, obtained from the model and marked experimental values. The model dependence is as follows:

$$\sigma_n(\bar{f}_y) = 0.526 \exp\left(-\frac{0.23}{\bar{f}_y}\right). \tag{35}$$

The compatibility of the model with the experiment results is, as Fig. 4 shows, very good.

The interactions between magnetic particles increase with the growth of magnetic force density. This is caused by the increase of the value of magnetization of magnetic particles and flocs which, consequently, must lead to the growth of the residue of non-magnetic component in the concentrate.

7. Final remarks

The theoretical analysis of separation in the band separator, presented in this paper, is based on a heuristic model of magnetic separation. This model, derived with the use of another separator (plate separator) [2] and, next, generalized for any process of multiple separation by a continuous way, takes into account the external forces acting upon a particle from magnetic and gravitational fields as well as the interactions between particles. As it is indicated by the research results for the band separator with an open magnetic system, this model can be applied for the analysis of separation process in any magnetic separator. The principal problem is to enumerate all external forces, characteristic for a given separator type, particularly magnetic force, since it can be only determined when the distribution of magnetic field in the separator working space was known before. Such a heuristic approach to the separation analysis is superior to the phenomenological approach because it creates an opportunity of taking into consideration the influence of many factors on separation results at the same time, basing on the dependences, previously derived from basic physical equations. If these dependences are verified experimentally, they will confirm correctness and completeness of the considered external and internal forces.

This paper has verified the dependence of separation results (recovery of magnetic component and residue of non-magnetic component in the concentrate) upon the content of magnetic fraction in the feed, the amount of washing water and magnetic force density. The first factor characterizes the enriched material while two others control the separation process. Surface interactions were not taking into account in the analysis. As it can be observed [4, 5, 8, 11], these interactions should be taken into account when separating the finest particles below 70 μm. In the work which was used to verify the obtained dependences the tested material was in the 0.063–0.2 mm size fraction . Therefore it can be assumed that the influence of surface interactions is neglectibly small.

This work was done as part of University of Science and Technology Research Program No.11.11.100.238

REFERENCES

[1] N. Barfod, Concentration dependence of sedimentation rate of particles in dilute suspensions. Powder Technology **6**, 39–43 (1972).

[2] M. Brożek, The physical model of magnetic separation in a plate separator. Magnetic and Electrical Separation, **9**, 149–167 (1999).

[3] M. Brożek, The distribution of magnetic field and forces in a band separator. Archives of Metallurgy (in press).
[4] M. Brożek, The distribution of magnetic fields and an analysis of the separation in process in a spiral separater. Archives of Mining Sciences **47**, 139–156 (2002).
[5] L. Dobrescu, N. Muresan, A. Bogdan, Effects of the dispersing reagents in the magnetic cleaning processes of some clay raw materials by high gradient magnetic separators. Proc. XV IMPC **1**, 343–353, Cannes 1985.
[6] A. A. I. Galal, Effect of water ore feed rate and of magnetic material content in the fed ore on the recovery in the process of band wet magnetic separation. Górnictwo **11**, 65–78 (1987).
[7] A. A. I. Galal, Dependence of the recovery of non-magnetic material and the coefficient of flocculation on the magnetic force intensity and the slope of the belt at different magnetic material concentrations in feed in belt wet magnetic separation. Górnictwo **11**, 137–147 (1987).
[8] C. B. Maurya, S. G. Dixit, Effect of pH on the high-gradient magnetic separation of kaolin clays. Int. J. Mineral Processing **28**, 199–207 (1990).
[9] J. A. Rozanov, Wstęp do teorii procesów stochastycznych. PWN, Warszawa 1974.
[10] W. Stępiński, Wzbogacanie grawitacyjne, PWN, Warszawa 1964.
[11] J. Svoboda, The influence of surface forces on magnetic separation. IEEE Transaction on Magnetic **18**, 862–865 (1982).

REVIEWED BY: ANDRZEJ OLAJOSSY
Received: 20 May 2003.