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Magnetic separation of kaolin clay using free helium superconducting magnet

***Abstract**. Superconducting separators are a new generation of magnetic separators; as a source of magnetic field a dc superconducting electromagnets are used. It creates, between other things, a chance to reject weak-magnetic particles as well as extra small ones (the basic problem for beneficiation of useful minerals). The subject of this paper is the used of superconducting magnet refrigerated with cryocooler (Free Helium Magnet) to enrichment of kaolin clay.*

Streszczenie.** Separatory nadprzewodnikowe są nową generacją separatorów magnetycznych; do wzbudzania pola magnetycznego wykorzystywane są elektromagnesy nadprzewodnikowe. Stwarza to - między innymi - możliwość wydzielania cząstek o słabych właściwościach magnetycznych i o ekstremalnie małym uziarnieniu (jest to podstawowy problem przeróbki kopalin). Przedmiotem rozważań niniejszego artykułu jest wykorzystanie nadprzewodnikowego elektromagnesu chłodzonego metodą kontaktową (Free Helium Magnet) do separacji kaolinu.* ***(Separacja magnetyczna kaolinu z wykorzystaniem magnesu nadprzewodnikowego typu free helium)

Keywords: magnetic separation, superconducting magnet free helium type, enrichment of kaolin clay
Słowa kluczowe: separacja magnetyczna, nadprzewodnikowy magnes typu "free helium", wzbogacanie kaolinu

Introduction

Magnetic separation is the most commonly used method for removing minerals that affect the brightness of the clay products.

High - Gradient Magnetic Separators (HGMS) offer the potential for higher product purity and reduced operating and maintenance costs relative to alternative chemical, physical, or gravity separation processes.

The early high-intensity magnetic separators (HIMS) used in the mineral industry were resistive electromagnets using either cooled copper coils or new ceramic permanent magnets (rare earth). About twenty years ago, superconducting magnets made their first entry into these applications, and, since that time, their number and popularity has steadily increased [1].

To have an industrial potential, a superconducting separator must meet the following requirements [2], [3]:

- all cryogenic constraints on its operation (helium supplies, maintenance calling for specially trained technical staff, etc.) must be eliminated; and
- the operating costs must be low.

In other words, it is essential that a superconducting separator be a self-contained system, that it require minimum maintenance and that it be reliable.

The technique of magnetic separation with superconducting magnets enables the extraction from a solid/water suspension of superfine (even colloidal) particles that are only weakly magnetic. It finds its application in the mineral industry for the purification of industrial minerals, in particular kaolin and tale. It is also of interest for other fields such as chemistry, biology and, especially, the environment. The application of this technique has enabled the extension of magnetic separation to ores that cannot be economically upgraded by any other means as well as to completely different fields of activity. It has, in particular, led to pushing back the frontiers of standard separation methods.

Construction of the Superconducting Magnet of Free Helium Type

All superconductors require cryogenic technology for any application. Description of this engineering field, in which most applications are not motivated by superconductors, is outside the scope of the paper, but the reader should be aware that future successes in this field in reducing the cost, size weight, unreliability, etc. of cryogenic equipment will have a direct and strong bearing on how quickly various applications mentioned here can be commercialized.

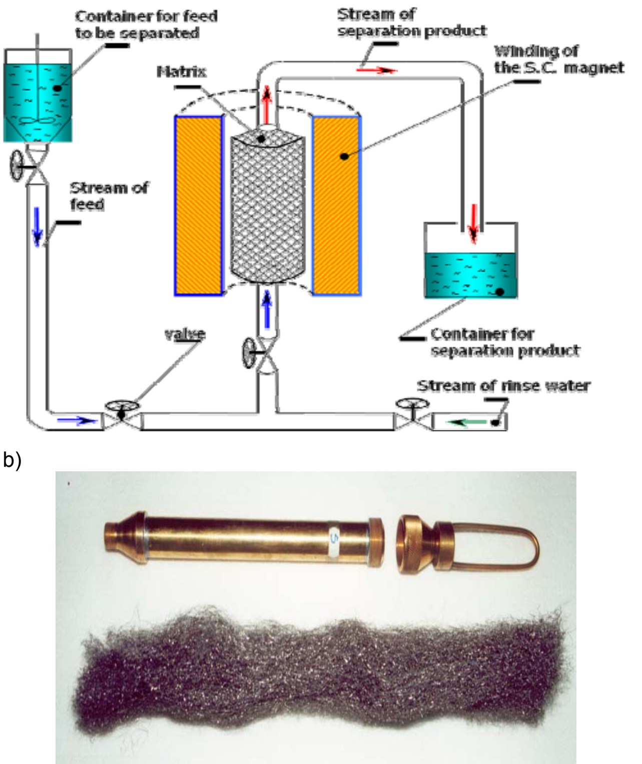
Application of cryocoolers, to refrigeration of the magnet, has highly simplified its construction and the whole co-operating scheme. Fig. 1 shows the overview of superconducting magnet with cryocooler.

Fig. 1. Overview of the Free Helium Magnet type, model HF10-100VHT-B

While comparing constructions of the two magnets: magnet refrigerated with liquid helium and with cryocooler, it can be seen, that in the case of magnet refrigerated with cryocooler, the construction is highly simplified so the conditions for using a superconducting magnet are mostly met. The construction of the magnet refrigerated with cryocooler eliminates the need for cooling the magnet winding in helium bath. Therefore the vacuum system is the only element of the complex infrastructure, which makes the application of superconducting magnet equipped with cryocoolers very attractive for economic reasons [4].

The author carried out the research on kaolin separation as it is shown in Fig. 2 and 3. The investigations were conducted in a magnetic separator, in which the superconducting magnet of Free Helium Type was the source of the field. The magnet main body: model HF 10-100VHT-B, produced by Sumitomo Heavy Industries, LTD (SHI) [5]. The described magnet can induce a magnetic field up to 10 T, that can provide a superior separation force and result high capacity slurry beneficiation.

a)



b)

Fig. 2. Superconducting matrix separator for HGMS: a) scheme of the separator, b) matrix of the separator and their filling

a) b

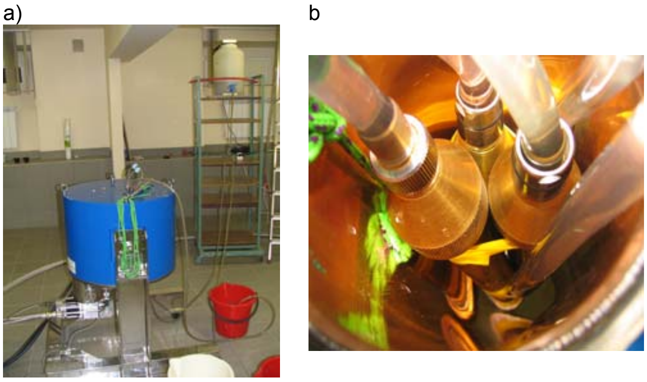


Fig. 3. Overview of the experimental system with the Free Helium Magnet type, used to enrichment of kaolin clay (a), matrix of the separator inside of the magnet channel (b)

Model of the Particles Extraction in the Matrix Separator

A comfortable tool to consider the kinetics of extraction of particles from a slurry (for example kaolin clay) by magnetic force in the matrix separator is the so-called macroscopic model [6]. In this model slurry flowing through the matrix separator is giving by equations:

(1) $$\frac{\partial P(x,t)}{\partial t} = \beta C(x,t)\left[1 - \frac{P(x,t)}{A}\right]$$

where: $P(x,t)$ - concentration of particles captured in the separator, $C(x,t)$ - concentration of particles in the slurry that flows through the separator, A - maximum value of the concentration of particles that were captured by the matrix, β - activity factor of the deposition process, which takes into account all aspects of the particle extraction by the magnetic field:

(2) $$\beta = \frac{2R_k \lambda_0 v_0}{S_k \varepsilon_0};$$

(3) $$2R_k \lambda_0 = D\left(\frac{4d^2 \chi_c H_0 H_p S_c}{9\pi\eta v_0}\right)^{1/3}$$

t - time of the extraction, x - position of the particles in the matrix, v_0 -velocity of slurry flow across the matrix.

Full description of the mathematical model and its interpretation of the symbols are given elsewhere [6].

In order to calculate factors β and $2R_k\lambda_0$ (equation (2) and (3)), motion of a single particle in nonhomogeneous magnetic field in the vicinity of a collector is analyzed (see Fig. 4).

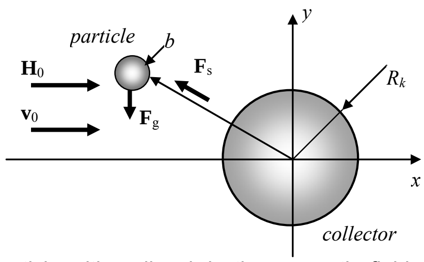


Fig. 4: Particle with radius *b* in the magnetic field around the collector with radius R_k

Svoboda [7] showed the complexity of the process of particles deposition on a collector and proposed another formulation of the problem. Accepting the above, we are going to limit or considerations only to such particle size for which the magnetic interaction is decisive. Under these conditions the following condition is assumed to be valid:

(4) $$m_c \frac{d\vec{v}_c}{dt} = \Sigma \vec{F}$$

where $\Sigma\vec{F}$ is the sum of forces affecting a particles in the matrix.

Complete equation of the particle motion including most important forces occurring in the matrix is as follows [6]:

(5) $$\rho_c V_c \frac{d\vec{v}_c}{dt} = (\rho_c - \rho_0)V_c \vec{g} + 6\pi\eta b(\vec{v}_0 - \vec{v}_c) + \\ + \chi_c V_c \operatorname{grad}\left(\frac{1}{2}\vec{H}\cdot\vec{B}_0\right)$$

General form of magnetic force influencing a particle follows from equation (5).

Equation (6) describes magnetic field distribution around the collector [6] (see Fig. 4):

(6) $$\vec{H} = A_0 H_0\left[\left(1 + \frac{K_c}{r_a^2}\right)\cos\theta \vec{1}_r - \left(1 - \frac{K_c}{r_a^2}\right)\sin\theta \vec{1}_\theta\right] \quad \text{for} \quad 1 < r_a < \frac{b}{R_k}$$

$$\vec{H} = \vec{H}_0 \quad \text{for} \quad \frac{b}{R_k} < r_a < \infty$$

where:

$$A_0 = 1/(1-\varepsilon K_c), \quad K_c = (\nu - 1)/(\nu + 1),$$
$$\nu = \mu_{wk}/\mu_{wo} \quad \text{and} \quad r_a = r/R_k.$$

ε_0 – the packing factor of the matrix, μ_{wk}, μ_{wo} – relative magnetic susceptibility of the collector and medium, respectively.

Particles affected by the magnetic force move towards the collectors and settle on their surface. Particles outside of this capture zone that is determined by the border trajectory, will not be captured by the collector. Deposition take place up to moment when balance of the holding magnetic force and shear force is achieved.

Figure 5 shows simulation of the particles trajectory for one collector and for five collectors.

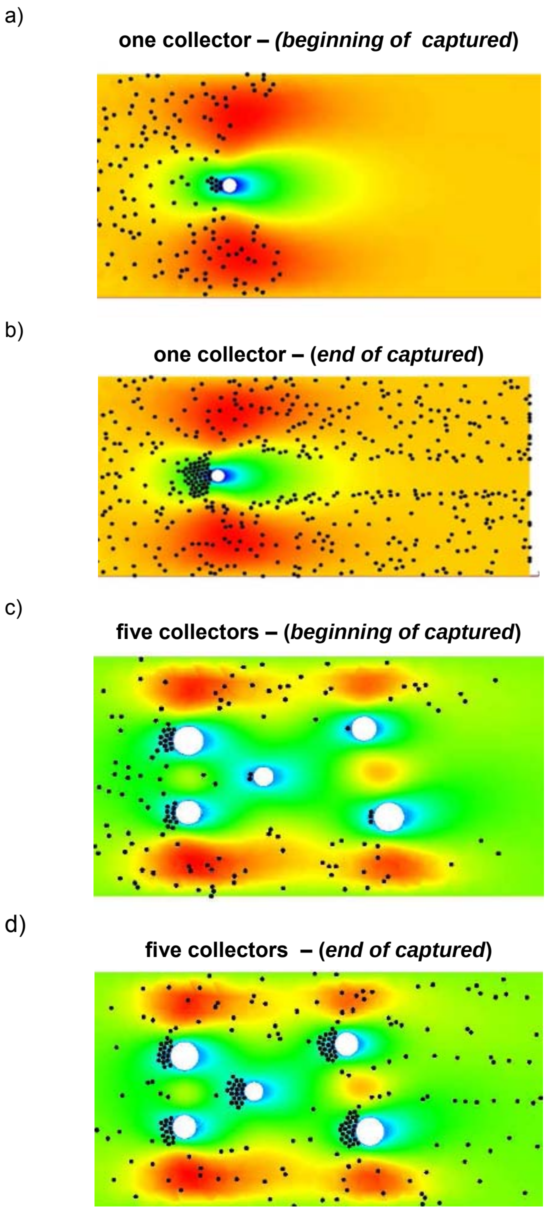


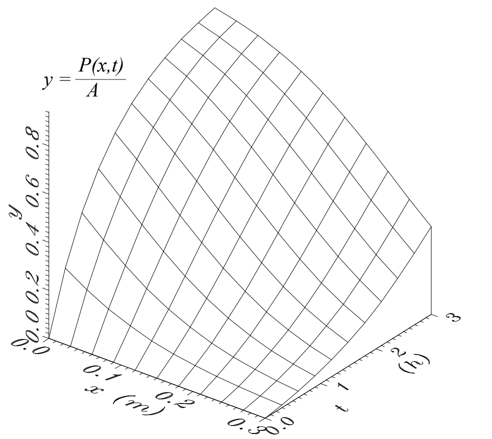
Fig. 5. Results of the particles trajectory for different conditions

The analysis of the grains movement allows to find the width of the collector "pick up" zone in the matrix, which is $2R_k\lambda_0$ (from eq. (3).

Solution of the equation (1) is as follows

$$(7)\quad P(x,t) = \begin{cases} A\dfrac{e^{-\frac{C_0\beta}{v_0}(x-v_0t)} - 1}{e^{-\frac{C_0\beta}{v_0}(x-v_0t)} + e^{-\frac{A\beta}{v_0}x} - 1} & \text{for } x\text{-}v_0t \le 0 \\ 0 & \text{for } x\text{-}v_0t > 0 \end{cases}$$

Knowledge of all model parameters (also the technological ones) allows to determine - based on equation (7) - distribution of the mass of the particles deposited in the matrix from the suspension that is being separated. Example of such calculation is shown Figure 6 [6].



a)

Fig. 6. Example of distribution of the mass of deposited particles in the matrix of the separator.

Analysis of this model show the parameters which make the extraction of the magnetic particles from the slurry possible. The values are as: velocity of slurry flow across the matrix v_0, packing factor of porous medium with ferromagnetic elements ε_0, diameter of the gradient-creating element R_k. However, the most essential parameter, influencing not only the quality of the process but also the time of the effective working time of the separator is a magnetic induction.

As the separation force is proportional to a field and a field gradient, then 10 Tesla systems offer unrivalled performance. Thus, it can be concluded, that **10 Tesla = high throughput = the highest available separation force.**

Separation of Kaolin Clay

Kaolin is a naturally occurring white clay consisting of microscopic platelets of aluminum silicate. It has scores of diverse uses, but the most important is coating and filling paper. The introduction of magnetic separators to the kaolin industry in 1969 to remove paramagnetic discoloring contaminants dramatically improved quality and doubled useful reserves worldwide.

The first large (84") separators went into production in 1973 in Georgia and a total of 29 resistive electromagnets (84'' and 120") has been installed to date. Four low temperature superconducting (LTS) magnetic separators were installed between 1986 and 1991 and another unit in 1994. In the past few years, eight of the resistive magnets have been retrofitted with LTS coils. Overseas, there are eight large resistive magnetic separators and five LTS magnets in operation on kaolin in Australia, Brazil, China, England, and Germany [8].

During the realization of the project "*Extraction of highly dispersed products from raw materials and mineral waste in extremely strong magnetic fields (up to 10 T) with the use* *of superconducting magnet – FREE HELIUM MAGNET”* (project No N N524 393834/P), the author and his research team conducted, among others , the research on kaolin clay enrichment. [9] Objectives of this work were:

1. determine if higher magnetic fields allow increased throughput while maintaining product quality,
2. determine if higher fields produce improved product quality.

Clay slurries were pumped through the top of a vertically installed canister. Tubing was connected to the canister with quick disconnect fittings for ease of installation and for reconfiguring flow during flushing.

The experimental sequence consisted of the following:

1) energize magnet: 1 – 10 min,
2) feed kaolin slurry and collect nonmagnetic product about 10 -30 min
3) displace kaolin slurry with water at same flow rate as used,
4) deenergize magnet about 4 – 8 min,
5) back flush with high velocity water to collect magnetic fraction.

Total cycle time for the LTS magnet was about 50 minutes.

The slurry which resulted from the various magnet tests was flocculated, filtered, and dried overnight in a constant temperature oven at 100°C. Clays were then crushed with a mortar and pestle and pulverized with a laboratory hammer mill.

The experiments of magnetic separation conducted under the influence of strong magnetic fields of selected materials, hard or very hard to be enriched, such as kaolins with < 0.015 mm grain- size distribution, from Turów and Czerwona Woda resulted in a significant output of iron and titanium in magnetic fractions reaching 50% at the 8T induction for both of the examined kaolins. The analyzed separation effectiveness for titanium in kaolins of Czerwona Woda can reach even 75%. The results were obtained for the input materials undergoing the alkaline-depressive treatment which contributed to the increase in the degree of those metals carriers’ release. The result has proved high efficiency of applied separation conditions in strong magnetic fields if the components being removed are in the release state.

Fig. 7. shows a technological scheme of one of the experiments, in which kaolin was made to flow through the separator matrix seven times at the magnetic field induction equal to 5 T. The other separation conditions remained the same. On the basis of the obtained results (shown in Fig. 8) it can be seen that multiseparation at strong magnetic field leads to a significant extraction of non-useful components from kaolin (Fe_2O_3 i TiO_2).

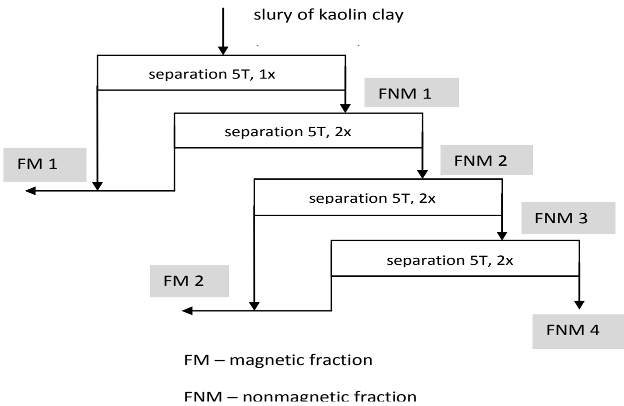


Fig. 7. Technological scheme of one of the experiments

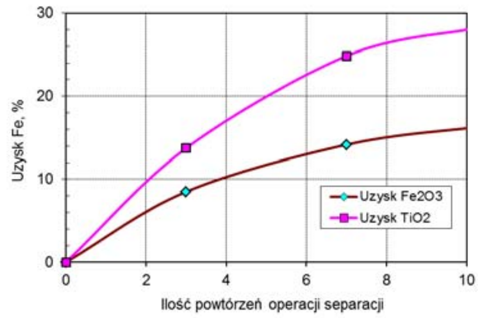


Fig. 5. Fig.8. Fe_2O_3 and TiO_2 increase in a magnetic fraction in dependence of the number of separation cycles

Consclusions

The output of the research can be considered a great step forward as for a better understanding of the mechanisms of the separation process in the case of highly scattered heavy metals’ carriers in the shape of low magnetic and extremely small grains.

The studied phenomena have indicated new approaches to the creation of technological basis of heavy metals’ purifications of materials with special applications. Furthermore, the research has determined the possibilities of application of superconducting separation as regards the obtaining of useful components scattered in mineral raw materials, whose properties have not been described yet. The examination of the output products can undermine the present knowledge concerning a character of valuable admixtures or contaminating impurities in the studied materials (for example: kaolin clay).

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