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PRACTICAL ASPECTS OF HIGH GRADIENT MAGNETIC SEPARATION USING SUPERCONDUCTING MAGNETS

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Since the 1970s, magnetic separation has been increasingly used for purification of liquid, such as heavy-metal ion removal from laboratory waste-water, purification of kaolin clay in the paper-coating industry, waste water recycling in the steel industry, and recycling of glass grinding sludge in cathode-ray tube polishing factories. In the 1980s, large superconducting magnets were adopted for the field coils of high-gradient magnetic separation system used for kaolin clay purification.

In this paper some practical aspects of the construction of a matrix high-gradient separator equipped with the DC superconducting electromagnet as well as the problems of working conditions of the separator are presented.

Key words: magnetic separation, DC superconducting electromagnet, high – gradient magnetic separation, matrix separator

INTRODUCTION

The phenomena of magnetism and magnetic behaviour of materials have allowed the process of magnetic separation to be successfully employed in industrial processing. A wide variety of magnetic separation systems exist that have been used for industrial beneficiation processes for many years. Whether by a lifting, trapping or deflection technique, a magnetic field is generated that will selectively act upon one material in preference to another by virtue of their different magnetic response. Several forms of magnetic behaviour exist but perhaps the most important, with regard to high field superconducting magnets, is the group defined as paramagnetic. Many ele-

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ments and inorganic compounds exhibit a low level positive response to the applied magnetic field, but to act upon particles by a magnetic field a high magnetic force is required. One of the most successful industrial applications of magnetic separation is the High Gradient Magnetic Separation (HGMS) removal of colour influencing contaminants from kaolin. For several decades large magnet systems have been employed to increase the brightness and remove contamination from this slurried material in order to improve its whiteness and so increase its commercial value. Initially, large power hungry resistive based magnet systems were used, but as the science and technology associated with superconductivity improved, these resistive systems have been replaced with superconducting magnet based systems. The introduction of superconductivity to this industry was significantly accelerated as a result of resistive coil burnouts. Rather than return a power hungry coil to operation, a superconducting coil replacement has been used instead. Many such "retrofits" have been carried out to reducing the power consumption from 300 to 400 kW, down to something in the in the order of 80 kW with the first system. Due to physical geometry of these systems and the requirement for a massive iron casing to focus the magnetic field, they were required to operate in switch on / switch off mode in order for the magnetic materials trapped on the gradient enhancing stainless steel matrix to be removed.

In this paper some practical aspects of the construction of a matrix high-gradient separator equipped with the DC superconducting electromagnet as well as the problems of working conditions of the separator are presented.

PRINCIPLE OF USE

When fine particles are dispersed in air, water, sea water, oil, organic solvents, etc., their separation or filtration by using a magnetic force is called magnetic separation. To increase the separation efficiency of these systems we must increase the magnetic force acting on particles by increasing the particle volume, relative magnetization between the particles (dispersoid) and the dispersion medium, the magnitude of the magnetic gradients (Ohara, 2001).

To understand the principles of magnetic separation for this, let us consider the magnetic forces (Ohara, 2001). By calculating the gradient of magneto-static energy difference between magnetized particles of volume, V_p and the dispersion medium of the same volume, ΔU_p, the magnetic force acting on a particle, $\vec{F}_m$, is:

$$\vec{F}_m = -\nabla\left(\Delta U_p\right) = -\nabla\left\{\frac{V_p\left(\mu_0\vec{M}_p \cdot \vec{H}\right)}{2} - \frac{V_p\left(\mu_0\vec{M}_f \cdot \vec{H}\right)}{2}\right\} \tag{1}$$

where:

$\vec{M}_p$ - particle magnetization, [A · m^{-1}]

$\vec{M}_f$ - magnetization of dispersion medium, [A · m^{-1}]

$\vec{H}$ - magnetic field. [A · m^{-1}]

By assuming a spherical particle with volume magnetic susceptibility, χ_p , and uniform magnetization $\vec{M}_p$, we obtain:

$$F_{m\xi} = V_p \cdot \mu_0 \cdot M^* \cdot \nabla_\xi H, \qquad \xi = x,y,z, \tag{2}$$

where:

$$M^* = H_0 \frac{9(\chi_p - \chi_f)}{(3 + \chi_p)(3 + \chi_f)} \tag{3}$$

χ_f - volume magnetic susceptibility of the dispersion medium, [-]
M^* - relative magnetization between the dispersoid and the dispersion medium, [A ·m^{-1}]
H_0 - applied magnetic field. [A ·m^{-1}]

Equation (2) indicates that the magnetic force on particles depends on three key parameters: V_p , M^*, and $\nabla_\xi H$. For $F_{m\xi} \neq 0$, V_p , M^*, and $\nabla_\xi H$ are all non-zero. Therefore, Eqs. (2) and (3) indicate that to generate a magnetic force ($F_{m\xi} \neq 0$), a dispersoid with susceptibility different from that of the dispersion medium (i.e., $\chi_p \neq \chi_f$) must be placed in nonhomogeneous magnetic field (i.e., $\nabla_\xi H \neq 0$).

When the dispersed particle is weakly magnetized, $M^* = (\chi_p - \chi_f)H_0$, and $F_{m\xi}$ is proportional to the susceptibility difference between the dispersoid and the dispersion medium; to H_0 ; and to $\nabla_\xi H$. When the dispersoid is a ferromagnetic particle, M_p becomes saturated at a relatively low magnetic field strength. The enhancement of $F_{m\xi}$ through the use of strong magnetic field is therefore limited. M_p also becomes saturated at relatively small susceptibilities of $\chi_p \sim 10$ because M_p is proportional to $\chi_p/(1 + N\chi_p)$, where N is a demagnetizing factor.

Effective ways of enhancing the magnetic force include: (a) increasing M_p by “magnetic seeding” of the dispersoid, (b) increasing $\nabla_\xi H$, (c) using high intensity magnetic fields, and (d) selecting a dispersion medium with a large value of $(\chi_p - \chi_f)$.

Various devices have been used to generate strong magnetic forces, which are described in detail elsewhere (Ohara, 2001). Methods for increasing the magnetic field gradient include superconducting coils in a drum-type separator, multi-pole superconducting coil in separators or HGMS systems. In High Gradient Magnetic Separators, a field gradient $|(\nabla H)|$, as high as $1.6 \cdot 10^{10}$ A/m^2 ($|\nabla(\mu_0 H)|$ = 20,000 T/m) is reached, and the magnetic force is enhanced by a factor of 1000 – 10,000 (Ohara, 2001).

Before the development of HGMS, magnetic separation was only performed on large diameter ferromagnetic particles, while using HGMS, weakly magnetized particles down to tens of microns can be magnetically separated in practical systems. High-gradient magnetic fields are generated near a ferromagnetic wire with several hundred microns in diameter placed under an applied uniform magnetic field. If the magnetic field is strong enough, in principle, all the particles with either positive or negative magnetic susceptibility dispersed in the medium are captured onto the wire. Weakly magnetized particles and typical dispersion media have magnetic susceptibilities much smaller than 1. Substituting this condition into Eq. (3) yields $M^* = (\chi_p - \chi_f)H_0$ and $F_m \propto (\chi_p - \chi_f)H_0(\nabla H)$ (Eq. (2)). Thus, use of high intensity, high gradient magnetic fields is necessary to increase the magnetic force on magnetic particles. In conventional magnetic separators this force is less than 0.01 % of the magnetic force acting on ferromagnetic particles, and is usually disregarded. However, because the magnetic field gradient of HGMS systems is much higher than that used in conventional magnetic separators, separation of weakly magnetized particle is now possible. It is confirmed by Fig. l. where various types of magnetic separators, used for separation of particles with different magnetic properties and granulations, are presented (Svoboda, 1987).

TYPES OF THE HIGH GRADIENT MAGNETIC SEPARATORS

The discussion presented in above section reveals that the HGMS separators have numerous applications. Thus, that type of the separators will be the subject of the following considerations.

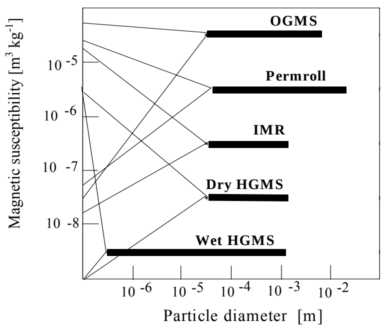

Fig. 1. Particle size ranges
of high-intensity magnetic separators
(Svoboda, 1987)

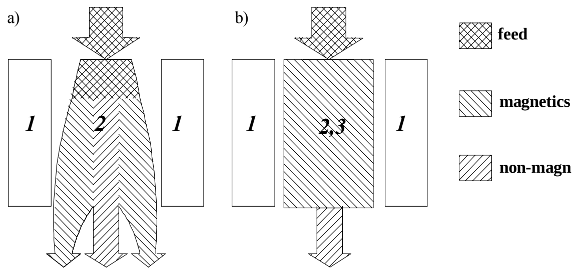

Fig. 2. High Gradient Magnetic Separators:
a) deflecting separator, b) matrix separator
1 – source of magnetic field, 2 – separation zone,
3 – matrix of the separator
(Cieśla, 1996)

There are two kinds of separators for separation of mixtures with HGMS using superconducting magnets: deflecting and capturing (matrix) separators (Fig. 2).

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 nonhomogenity. The most common constructions of the source of the magnetic field in deflecting separators are solenoids of various configurations, e.g. dipoles, multipoles, 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 a solenoid coil of a simple design generates the field. 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 fractions of the feed pass through the matrix (a canister with steel wool) and are attached to the ferromagnetic elements. The non-magnetic particles are collected outside the matrix. This type of a device is treated as a magnetic filter.

High gradient matrix separator often operates in a cyclic mode. After the matrix is loaded with captured particles (after effective time t_e), a cleaning stage must follow (dead time t_d). In order to increase the effectiveness - the time t_e must be increased and t_d reduced. Cleaning of the matrix takes place in absence of magnetic field. The field on the matrix can be removed by three methods: by ramping the current in the magnet down, by using a continuously moving matrix, e.g. carousel, and by using a reciprocating canister.

A comparison of the separators characteristics is presented in Table 1 (Cieśla, 2000)

Table 1. Comparison of deflecting and matrix magnetic separator (Cieśla, 2000)

Type of Separator	Deflecting	Matrix
Principle of Operation	Continuous	Cyclic
Winding Design	Complex (dipole, multipole 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

The comparison of both high-gradient separators presented in Table 1 leads to a conclusion that separation of μm granulation is carried out with matrix separator (magnetic filters).

KINETIC MODEL OF THE SEPARATION IN MATRIX HGMS

A comfortable tool to consider the kinetics of extraction of particles from a slurry by magnetic force in the matrix separator is the so-called macroscopic model (Cieśla, 1996). It can be assumed that the physical properties of the slurry flowing through the matrix separator (see Fig. 3) does not change.

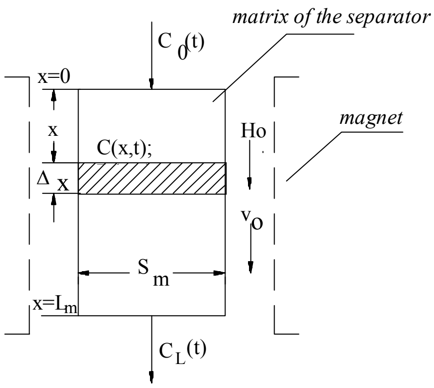

Fig. 3. Slurry of concentration $C_0(t)$ is flowing across the matrix separator (Cieśla, 1996)

The extraction of particles during the separation process can be characterised by the following equations (Cieśla, 1996):

$$\frac{\partial P(x,t)}{\partial t} = \beta C(x,t)\left[1 - \frac{P(x,t)}{A}\right] \tag{4}$$

$$\frac{\partial C(\mathrm{x},\mathrm{t})}{\partial t} + v_0 \frac{\partial C(\mathrm{x},\mathrm{t})}{\partial x} + \frac{\partial P(\mathrm{x},\mathrm{t})}{\partial t} = 0 \tag{5}$$

where:

P(x,t) - concentration of particles captured in the separator, [kg ·m^{-3}]

C(x,t) - concentration of particles in the slurry that flows through the separator, [kg ·m^{-3}]

A - maximum value of the concentration of particles that were captured by the matrix , [kg ·m^{-3}]

β - activity factor of the deposition process, which takes into account all aspects of the particle extraction by the magnetic field, [s^{-1}]

t - time of the extraction, [s]

x - position of the particles in the matrix, [m]

v_0 - velocity of slurry flow across the matrix, [m ·s^{-1}]

Solution of equation (4) and (5) by taking into account the initial and boundary conditions:

$$P(x,t)=\begin{cases} A\dfrac{e^{-\frac{C_0\beta}{v_0}(x-v_0)}-1}{e^{-\frac{C_0\beta}{v_0}(x-v_0)}+e^{-\frac{A\beta}{v_0}x}-1} & \textit{for } x - v_0t \le 0 \\ 0 & \textit{for } x - v_0t > 0 \end{cases} \tag{6}$$

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

where:

$$\beta=\frac{2R_k\lambda_0v_0}{S_k\varepsilon_0} \tag{8}$$

$$A=\frac{\varepsilon_0}{4}\rho_c\left(a^2-1\right) \tag{9}$$

$$2R_k\lambda_0=D\left(\frac{4d^2\chi_cH_0H_pS_c}{9\pi\eta v_0}\right)^{1/3} \tag{10}$$

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

Full description of the mathematical model and its interpretation of the symbols are given elsewhere (Cieśla, 1996).

To consider the influence of the parameters on the separation effectiveness, the author proposes to transform formula (7) (for x = L_m) as follows:

$$\frac{C(x,t)}{C_0}\Big|x=L_m=\frac{C_{out}(t)}{C_0}=N=\frac{1}{1+e^U\left(e^T-1\right)} \tag{11}$$

where:

$$U=\frac{C_0\beta}{A}\left(\frac{x}{v_0}-t\right), \qquad T=\frac{\beta x}{v_0}$$

Formula (11) show the parameters which make the separation 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.

Subsequent steps of a grain movement in the vicinity of the ferromagnetic element of the matrix – collecting grains of particular magnetic properties – are presented in Fig. 4. The analysis of the grains movement allows to find the width of the collector “pick up” zone in the matrix, which is $2R_k\lambda_0$ (see Eq. (10)).

One can learn from Fig. 5 that the magnetic induction determines the width of the catching zone. The rise of the zone width causes also prolongation of the effective working time of the separator. It results from the increase of ability of the matrix to accumulate greater number of particles.

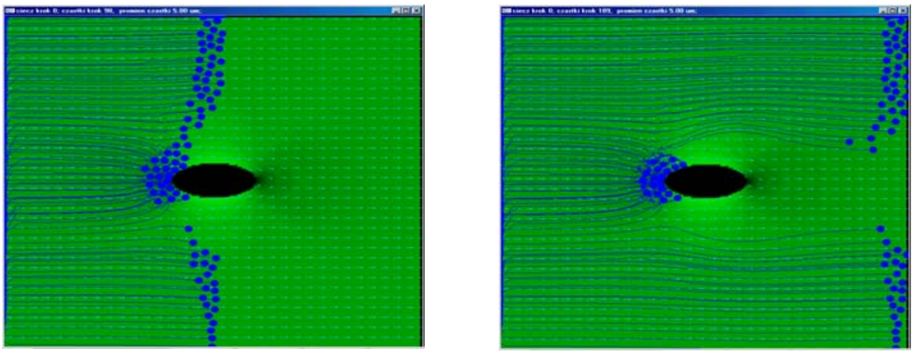

Fig.4. Steps of particles movement in the vicinity of the collector in the matrix separator (Cieśla, 2003)

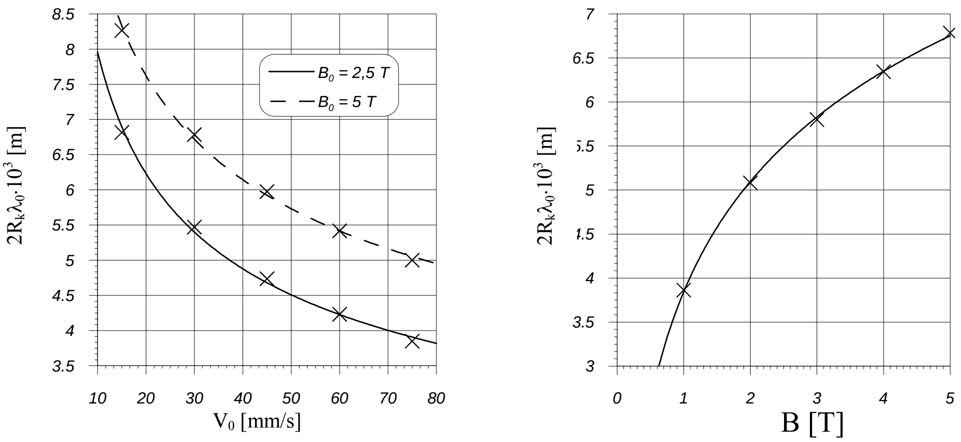

Fig.5. “Pick up” zone width ($2R_k\lambda_0$) vs. velocity of slurry flow through the matrix separator for induction B_0 = 2,5 T and B_0 = 5 T (a) and magnetic field induction in separator matrix for v_0 = 0.03 ms^{-1} (b) (Cieśla, 2000)

A confirmation of this argument is Fig. 6 presenting the dependency $N = f(t)$ (Eq.11) for three magnetic inductions and two slurry flow velocities across the matrix. The particles concentration at the separator outlet versus the inlet concentration C_0 changes considerably with the time of the separation. When a defined concentration of slurry in the filter outlet is requires, then the filtration process must be stopped after the time called the effective working time of the filter, t_e. After time t_e, the factor N exceeds the assumed value.

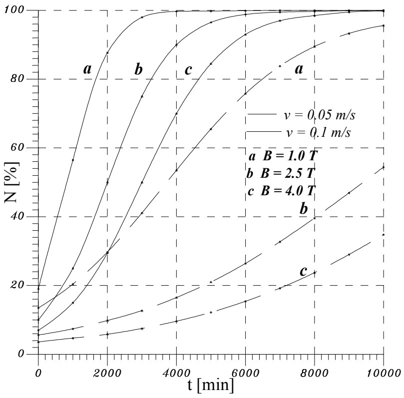

Fig. 6. Factor N vs. the separation time t (Cieśla, 2000)

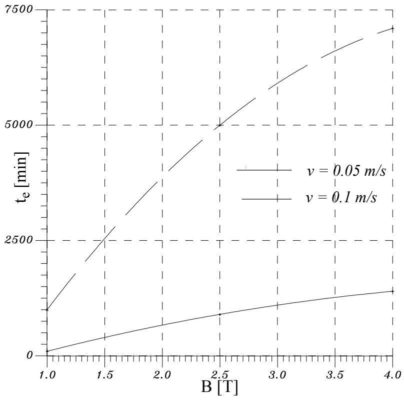

Fig. 7. Effective filtration time t_e vs. magnetic induction B (Cieśla, 2000)

For example, it has been assumed that the N value should not exceed 20% and, on the basis of data from Fig. 6, the dependency of the time t_e vs. magnetic induction has been plotted (Fig. 7). One can notice essential increasing of the effective working time of the separator following the induction growth. So, the effectiveness of the separation process also increases. The presented data univocally confirm that application of strong magnetic field in the separation process is beneficial. So, the best devices to generate the fields are the superconducting electromagnets.

CONSTRUCTIONS OF SUPERCONDUCTING MAGNETIC SEPARATORS ON A COMMERCIAL SCALE

In some references (Brevis 1996, Richards 1997, among others), one can find informations on practical applications of HGMS devices (also with superconducting magnets): e.g. for concentration of iron ores (ilmenite, hematite, goethite, limonite), concentration of paramagnetic minerals (wolframite, chromonite, ilmenite), rejection of paramagnetic minerals (siderite or ilmenite from cassiterite). There are 2 versions of magnetic separators – based on the way of matrix cleaning. In the first one, proposed by ERIEZ Magnetics, accumulation ability renewal (cleaning) of the matrix takes place when the magnetic fields is turned off. Proper position of feed check valves allows to get considerable pressure of cleaning water that rinses out magnetic particles from the steel wool fibres. After the matrix cleaning, re-set of the valves begins next cycle of the separation. The commercial scale construction of ERIEZ Magnetics is given in Fig. 8 (Watson, 1994).

Fig. 8. View of the superconducting HGMS built by Eriez Magnetics, Erie, PA, USA and installed at the plant of J.M. Huber where it has been on line since 8 May 1986 (Watson, 1994).

Another type of the superconducting magnetic separator is a " reciprocating" device constructed and patented by CARPCO SMS Ltd (Watson 1994). This construction is preferred for technical and economical reasons. The dead time is limited to the time of translocation of the matrix in the filter canal. A construction of this type device on industrial scale is presented in Fig. 9 (Bulletin, 1996).

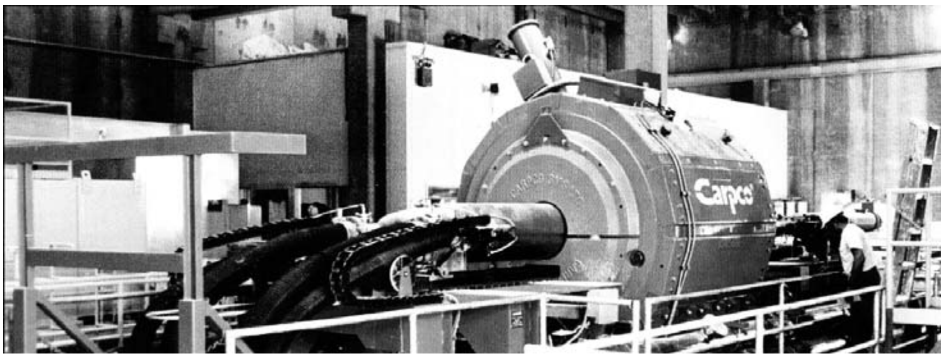

Fig. 9. View of the superconducting magnetic separator ("reciprocating canister" type), built by Carpco SMS Ltd. (Bulletin, 1996)

SYSTEMS COOPERATING WITH A SUPERCONDUCTING MAGNETIC SEPARATOR

The use and operation of superconducting electromagnets as a source magnetic field in magnetic separators and filters is much more complicated than with conventional ones owing to the existence of strong magnetic fields, high energies accumulated in windings, low temperatures and a vacuum present. Superconductor electromagnets should be equipped with installations that comply with requirements and rules of cryogenic and vacuum technologies; also, they must respect characteristic conditions necessary for an electromagnet to operate, such as: cryostat and winding cooling, feeding of the winding, normal operation conditions, and emergency states during the operation. In Fig. 10 a block diagram of a system is presented which enables the operation of a superconducting electromagnet.

The operation cycle of the superconducting separator consists of four following in succession phases: 1 - cooling of the cryostat, 2 - supplying with electrical power, 3 - stable work under rated current (separation cycle), 4 - switching off the supply and heating of the cryostat.

Some exemplary curves $T = f(t)$ and $B = f(t)$ for the operation cycle of the separator are presented in Fig. 11. The temperature change during cooling of the cryostat is presented (as magnified characteristic). The noticeable increase of temperature results from exchange of the vessel for liquid helium.

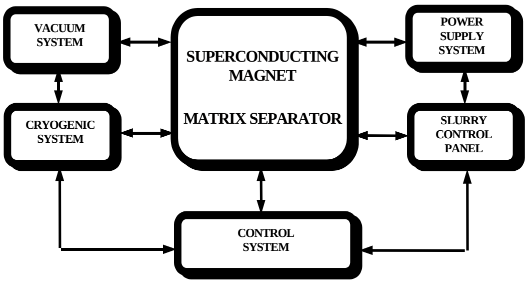

Fig. 10. Functional relations among systems co-operating with superconductor electromagnet (Cieśla, 2003)

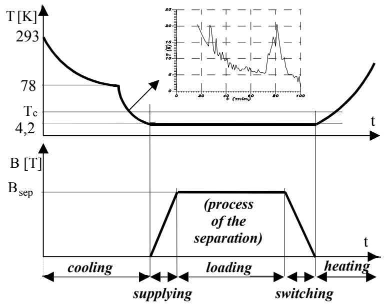

Fig. 11. Operation cycle of superconductor separator (Cieśla, 2003)

LABORATORY SUPERCONDUCTOR SEPARATOR AT AGH

A scheme of a laboratory superconductor magnetic separator at AGH - University of Science and Technology is presented in Fig. 12. Its technical data: $B_{max} = 6$ T (in the centre of the separator canal), volume of the matrix = $1{,}5 \cdot 10^{-3}$ m^3, diameter of the magnet canal = $5.4 \cdot 10^{-2}$ m.

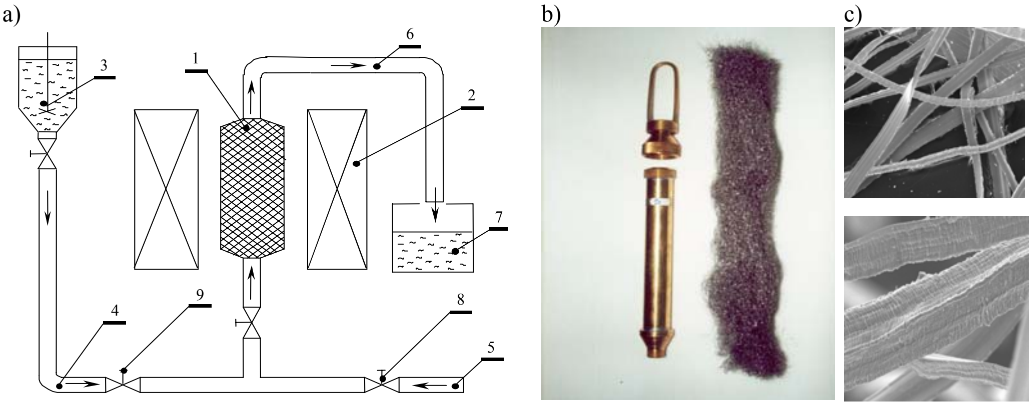

Fig. 12. Superconducting separator for HGMS: a) scheme separator, b) matrix separator, c) filling matrix with stainless steel magnetic wool (wool seen with a magnifier) 1 – matrix of separator, 2 – winding of superconducting magnet, 3 - container for feed to be separated, 4 – stream of feed, 5 – stream of rinse water, 6 – stream of separation product, 7 – container for separation product, 8, 9 – valves (Cieśla, 2003)

CONCLUSIONS

The high force separation capabilities of superconducting magnets and their application for the most difficult separation problems of paramagnetic or low susceptibility materials are now recognised. The advances made in superconducting technology over the recent years have meant that this technology, at one time limited to the research, can now truly enter the industrial processing environment with confidence.

To promote new applications for superconductor magnetic separation, the fusion of science and technology from diverse areas is required. It can be executed through the interchange and co-operation of researches working in different fields: including superconductivity, electrical engineering, and mechanical engineering for equipment improvement, chemical engineering and applied chemistry for separation system and environmental, sanitation, and resource engineering for practical utilization of these systems (Fig. 13). Organizations that promote the exchange of research information from different technical fields and collaboration are very desirable.

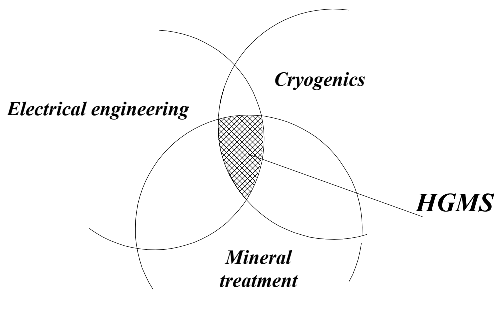

Fig. 13. HGMS process
as a complex issue of separation

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Nową metodą wzbogacania, rozwijaną od kilku lat w świecie, jest metoda magnetycznej separacji wysokogradientowej (High Gradient Magnetic Separation - HGMS) z wykorzystaniem elektromagnesów nadprzewodnikowych jako źródeł pola magnetycznego. Metoda ta stwarza nowe możliwości wydzielania składników zawartych w surowcach, a niedostępnych zarówno dla dotychczas stosowanych technik separacji magnetycznej jak i wszelkich innych fizycznych metod rozdziału. Jedną z odmian konstrukcyjnych separatora wysokogradientowego jest separator matrycowy. W pracy przedstawiono fizyczne podstawy separacji magnetycznej, z których wynika jednoznacznie celowość stosowania nadprzewodnikowych separatorów matrycowych, opisano konkretne instalacje przemysłowe, (np. zbudowane przez firmę CARPCO SMS nadprzewodnikowe urządzenie pod nazwą CRYOFILTER generujące pole o indukcji 5 T, stosowane do separacji bardzo drobnych cząstek m. in. do uszlachetniania kaolinu). Przedstawiono laboratoryjny nadprzewodnikowy separator matrycowy będący w dyspozycji Katedry Elektrotechniki Akademii Górniczo – Hutniczej. W kraju prace nad wdrożeniem separatorów nowej generacji, jakimi bez wątpienia są separatory nadprzewodnikowe, do praktyki przemysłowej przebiegają stosunkowo wolno. Decydują o tym zarówno względy materialne (duże koszty inwestycyjne) jak i psychologiczne (nowa technika, ekstremalne warunki eksploatacji). Argumentem przemawiającym za rozwojem przedstawionego typu konstrukcji separatów będą wyniki uzyskiwane na urządzeniu na skalę laboratoryjną. Muszą one być atrakcyjne zarówno pod względem technicznym jak i ekonomicznym. Dla pełnej oceny skuteczności proponowanego procesu wzbogacania magnetycznego i jego ekonomicznych aspektów konieczne jest przeprowadzenie pełnego cyklu badań technologicznych poczynając od modelowania procesu ekstrakcji ziaren w matrycy separatora wysokogradientowego, poprzez weryfikację eksperymentalną i określenie warunków technicznych możliwości aplikacji tego typu urządzenia w ciągu technologicznym. Ze względu na złożoność problematyki, badania takie muszą być prowadzone przez specjalistów kilku dziedzin nauki i techniki. Problem jest bowiem interdyscyplinarny, łączy m. in. przeróbkę kopalin, elektrotechnikę i kriogenikę.