Antoni CIEŚLA

AGH – University of Science and Technology

Use of the low (LTS) and high (HTS) termperature superconductors in the magnetic separation. Economic comparison

***Abstract**. High gradient magnetic separation (HGMS) is physical method to separate, according to magnetic susceptibilities, material mixtures consisting of particle immersed in fluid. The principle of this method is that different forces are exerted on particles, depending on their magnetic nature, in relatively strong fields with a large degree of short-range non-uniformities. Superconductivity is used to make the separation process significantly effective. The advantages of superconducting magnetic separation systems are as follows: reduced power requirements, reduced weight and volume, due to elimination of the soft iron core and the compactness of windings relative to those of conventional systems. Higher field strengths, which allow for higher processing velocities for a given separation effectiveness or higher separation effectiveness for a given processing velocity. In the paper some technical and economical aspects connected with the application of superconductivity magnets in HGMS have been discussed. Advantages resulting from the use of low (LTS) and high (HTS) superconductors in the HGMS systems have been described.*

***Streszczenie.** Magnetyczna separacja wysokogradientowa (ang.: High Gradient Magnetic Separation) jest fizyczną metodą separacji wykorzystującą różnice we właściwościach magnetycznych cząstek. Zastosowanie magnesów nadprzewodnikowych do wzbudzania pola magnetycznego w takich separatorach skutkuje zmniejszeniem wagi i objętości urządzenia (separatora), eliminacji jarzma ferromagnetycznego oraz zmniejszeniem wymiarów uzwojenia. Stwarza także możliwość zwiększenia skuteczności separacji i jej wydajności. W artykule autor dokonał porównania wybranych aspektów technicznych i ekonomicznych wykorzystania nadprzewodników niskotemperaturowych (LTS) i wysokotemperaturowych (HTS) w procesie separacji magnetycznej. (**Użycie nadprzewodników nisko- i wysokotemperaturowych w separatorach magnetycznych. Porównanie ekonomiczne**)*

Keywords: magnetic separation, low temperature superconductors (LTS), high temperature superconductors (HTS)
Słowa kluczowe: separacja magnetyczna, nadprzewodniki niskotemperaturowe (LTS), nadprzewodniki wysokotemperaturowe (HTS)

Introduction

The conventional magnetic separators used in the mineral industry are equipped with traditional magnetic circuits or with permanent magnets (rare earth). However, when processing minerals with low magnetic susceptibilities or minerals of very small particle size, these separators are inefficient. In addition, a conventional magnetic circuit consumes considerable amounts of electricity to generate a relatively low magnetic field (~2 Tesla). The equipment is also heavy and bulky. Only a separator having a superconducting magnet can contribute to solve most of the problems, and only such a filter can produce high magnetic fields with low energy consumption**.** It is clear that in large-scale high gradient magnetic separators (HGMS), low-temperature superconducting (LTS) technology is displacing conventional water-cooled copper magnets. With the recent discovery of high-temperature superconductivity (HTS), it remains to be seen if these new ceramic-oxide superconductors will replace the traditional intermetallic low-temperature superconductors. In his work economic aspects of applying LT and HT superconductors for magnetic separation have been presented.

Principles of the magnetic separation

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. Principles of the particles mixture with different magnetic properties are shown in Fig. 1.

To understand the principles of magnetic separation for this, let us consider the magnetic forces. Magnetic force acting on a material in magnetic field is given by equation:

$$F_m = M_m \frac{dH_m}{dx} = \frac{M_m}{\mu}\frac{dB}{dx} \tag{1}$$

where: H_m is magnetic field, B - magnetic flux density, μ - th relative permeability of the substance receiving the force, and M_m - the magnetization. This is given by:

$$M_m = \chi_m H_m = \frac{\chi_m}{\mu} B \tag{2}$$

where χ_m is magnetic susceptibility. The magnetic susceptibility of paramagnetic material is positive and that of a diamagnetic material is negative. According to equations (1) and (2), if a magnetic field is applied to paramagnetic and diamagnetic mixture, the force acting on paramagnetic particle is opposite to that acting on diamagnetic particle (see Fig.1.).

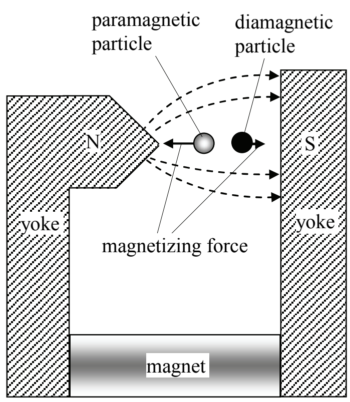


Fig. 1. Magnetizing force under magnetic field

In other words, a mixture para- and diamagnetic particles can be separated in a strong magnetic field. According to equations (1) and (2), the magnetic force acting on a magnetic material is given by:

$$F_m = \chi_m H_m = \frac{\chi_m}{\mu^2} B \frac{dB}{dx} \tag{2}$$

We can see, that a high gradient is needed $\left(B\, dB/dx\right)$ to separate mixtures.

Various devices have been used to generate strong magnetic forces, which are described in detail elsewhere [1], [4]. Methods for increasing the magnetic field gradient include superconducting coils in a drum-type separator, multi-pole superconducting coil in separators or High Gradient Magnetic Separators (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 [2].

Technical aspects

Conventional magnetic separation

In general, 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 field strength of most commercially available HGMS systems for industrial applications is about 2 T (see Fig. 2).

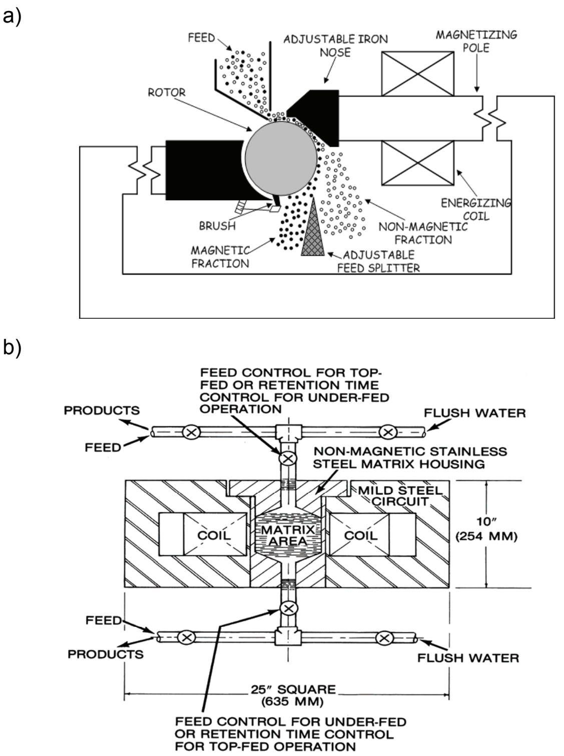


Fig. 2. Conventional separators: a) drum magnetic separator [4], b) HGMS matrix separator [4]

Higher field strengths would be expected to lead to higher separation efficiencies and/or higher flow velocity. Typically, however, the incremental increase in separation effectiveness tends to diminish as field intensity increases, whereas the incremental costs of the system increases as field strength increases. The trade-off is compounded by the fact that separation effectiveness decreases at in increasing rate as flow velocity increases.

Superconducting technology for magnetic separation

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.

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

1. all cryogenic constraints on its operation (helium supplies, maintenance calling for specially trained technical staff, etc.) must be eliminated; and
2. 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 talc. 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. Table 1 lists some applications for high gradient magnetic separators [3]. Fig. 3 presents High Gradient Magnetic Separators with superconducting (LTS) windigs [5], [6].

Table 1. Industrial applications of high gradient magnetic separators [3]

Industry or Process	Specific Application
Minerals processing	Separation of diamonds from garnets; Removal of weakly magnetic materials from alumina, bauxite, calcite, clay, feldspar, glass, sands, limestone, manganese, zircon, etc.
Food, chemical processing	Removal of ferrous contaminants
Pipelines	Removal of ferrous contaminants from liquid flows.
Environmental protection	Desulfurization of coal; Removal of particulate matter from flue gases; Treatment of boiler condensate and process water.
Recycling	Recovery of aluminium from municipal solid waste; Recovery of ferrous metals from car shredders.

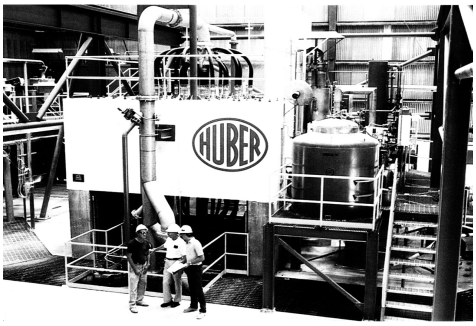
A superconducting magnet generates a higher magnetic field because it is not restricted by the saturation of iron. This can be used to advantage in several ways:

- The main advantage is to separate small-diameter and weakly magnetic particles that cannot be separated by conventional magnets.
- The flow rates can be increased through a fixed matrix configuration.
- The matrix volume can be reduced for a given flow rate.

The recent discoveries of materials that are superconducting at temperatures above the boiling point (77K) of LN_2 may allow the development of apparatus with significantly higher operating efficiencies and, hence, greatly reduced operating costs. These materials also have the advantage of remaining in the superconducting state at significantly higher magnetic fields than previously seen in Type I and II superconductors. At present, these high-temperature superconductors (HTS) appear to be extremely "brittle" and have a low current density (nominally 100 A/cm^2). However, reports of wires and ribbons being fabricated from the materials offer hope that potential fabrication problems can be solved. Also encouraging is

IBM's announced increase of current density in thin films by a factor of 100 [3].

a)



b)

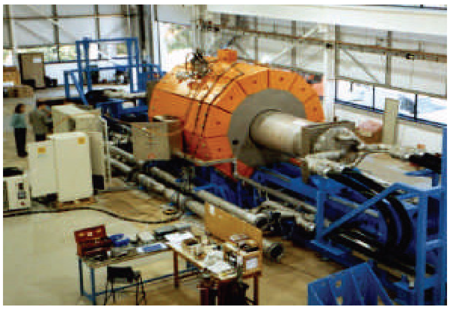
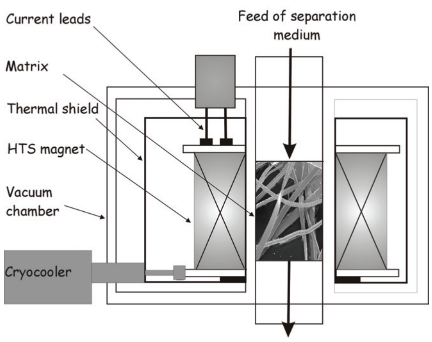
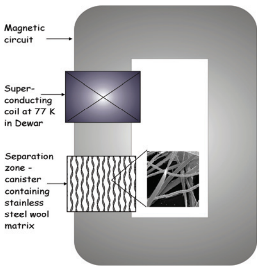


Fig. 3. Superconducting (LTS) separators: a) view of the superconducting HGMS built by Eriez Magnetics, Erie, PA, USA and installed at the plant of J.M. Huber where it has been on line since 8 May 1986 [5], b) Over view of the CARPCO cryofilter [6].

a)



b)



c)

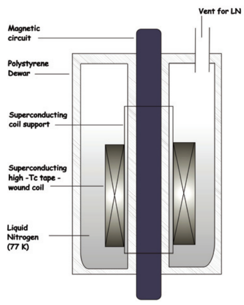


Fig. 4. Superconducting (HTS) separators
a) HTS magnet operation scheme for HGMS [6], b) magnetic separator with HTS [7], c) proposed design of the HTS magnet and Dewar [7]

The use of LN_2 as a coolant implies immediate advantages over the previously required LHe. LN_2 is considerably less expensive, because the basic raw material is free and the production process is considerably more efficient. In fact, the process is so inexpensive that the operation of HTS apparatus at LN_2 temperatures may well be considered for other technical reasons even if higher-temperature superconductors are found.

In general, the advantages of superconducting magnetic separation systems are as follows
1. Reduced power requirements.
2. Reduced weight and volume, due to elimination of the soft iron core and the compactness of windings relative to those of conventional systems.

Higher field strengths, which allow for higher processing velocities for a given separation effectiveness or higher separation effectiveness for a given processing velocity.

Economical aspects

The efficiency of HGMS systems would be increased further by the introduction of high-temperature superconductors (HTS). These systems permit much more intense fields than iron-based magnetic systems but do not entail the Joule heating losses.

A preliminary economic comparison of conventional HGMS with 4-K (LTS) and 77-K (HTS) superconducting HGMS systems indicates the following:

1. The annual operating costs (including capital) for a 4-K superconducting HGMS are about 8 % lower than those for a conventional HGMS. Operating costs for power consumption are reduced by 80 %.
2. The annual operating costs (including capital) for a 77-K superconducting HGMS are 15 % lower than those for a 4-K HGMS and 20 % lower than those for a conventional HGMS. The power operating costs for 77-K HGMS are about 7% of the 4-K HGMS costs and about 98 % of the conventional HGMS costs.

A summary comparison of the principal characteristics of a conventional 2-T separator for clay processing, the Eriez 2-T superconducting (LTS) separator, and a hypothetical 77-K (HTS) separator is presented in Table 2 [3].

Because the primary advantage of a superconducting HGMS is the reduction in power requirements relative to a conventional system, the cost effectiveness of the system depends on the price of electricity and the operating capacity factor of the system. Given economic assumptions prescribed for this analysis, the 4-K system is cost-effective relative to conventional HGMS system at a capacity factor of 50% (Table 2) and would be cost-effective at a capacity factor as low as about 20% (Fig.5 [3]). The additional reduction in power requirements and the reduction in capital cost for a 77-K system relative to a 4-K system would make the former cost-effective relative to a conventional system regardless of capacity factor.

Table 2. Summary comparison of High Gradient Magnetic Separation System [a] [3]

Item	Conventio-nal System	4-K (LTS)	77-K (HTS)
Power requirements [kW]			
Field	270	0.007	≈0.007
Cooling	30	60	≈3-4
Total	300	60	3-4
Weight [Tons]	490	230	<230
Capital costs [$$10^6$]	1.6-1.7	1.7-1.8	1.5-1.6
Annual operating costs [$$10^3$] [b]	81.0	15.8	1.1
Annual capital costs [$$10^3$] [c]	425.6-452.2	452.2-478.8	399.0-425.6
Total annual costs [$$10^3$]	506.6-533.2	468.0-494.6	400.1-426.7

[a] Magnetic field strength is 2 T for all three systems.
[b] Electricity price = 5c/kWh, capital factor = 50%, and levelization factor =1.20
[c] Fixed charge rate = 26.6%

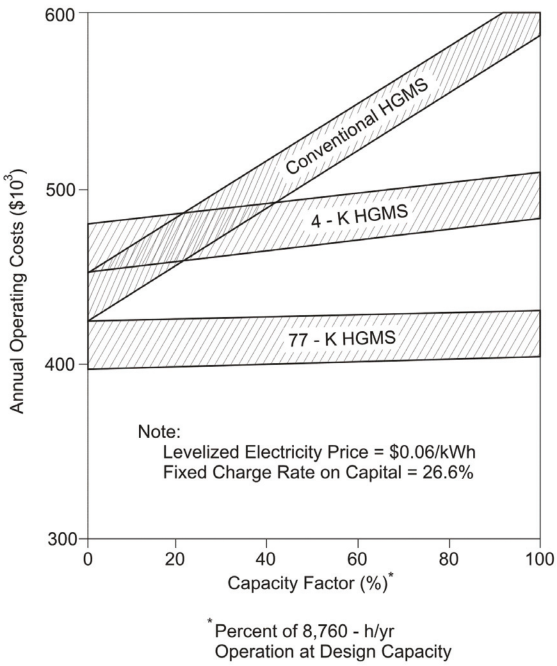


Fig.5. Annual operating costs of of alternative 2-T HGMS systems for kaolin processing at 500 gal/min [3]

Conclusions

Magnetic separations technology represents a potential application for the new HTSc. This evaluation was predominantly and economic scoping study developed from previous work on a conventional separator. This technology shows a strong potential for significant cost reductions using HTSc, when evaluated on this basis of operating cost.

Several key areas of research appear to have been uncovered by this evaluation. The obvious need for higher current densities and bulk current capability has been previously stated by many researches. A better understanding of the HTSC physics and material properties is also needed.

Magnetic separations technology (HGMS) is perhaps the easiest technology in which to apply HTS in place of LTS superconductors. Indeed, it appears to be quite cost-effective under less than optimal design conditions and requires a relatively modest superconducting magnet operating under steady DC conditions. This technology could see applications in mining separations, waste treatment, coal beneficiation (by removing sulphur before combustion to decrease SO_2 emissions), and perhaps removal of NO_x from boiler flue gases using HGMS or OGMS) technology.

Acknowledgement

The work presented in this paper was supported by the Polish State Committee for Scientific Research, Warsaw, in the frame of the project No N N524 393834 (2008 – 2010).

REFERENCES

[1] Lee P. J. *Engineering Superconductivity*, J. Wiley &Sons, 2001

[2] Ohara T. et al.: *Magnetic separation using superconducting magnets*, Physica C 357 – 360 (2001), 1272 – 1280.

[3] Wolsky A. M [et al.] *Applied Superconductivity (Part 9: Industrial Separations and Material Handling),* NDC, 1989, pp. 119 - 128

[4] Svoboda J.: *Magnetic Methods for the Treatment of Minerals.* Elsevier Science Publishers B.V. 1987

[5] Richards D. et al.(1997): *Commercial acceptance of superconducting magnetic separation*. Proceedings of the XX IMPC – Aachen, 21 - 26 September 1997, 638 - 648.

[6] Jin J. X., Liu H. K., Zeng R., Dou S. X.: *Developing a HTS magnet for high gradient magnetic separation techniques,* Physica C 341 – 348 (2000), 2611 – 2612.

[7] Cieśla A.: *Superconductor Magnetic Filter: Industrial Construction*, Proc. Third Intetnational Conference Electromagnetic Devices and Processes in Environment Protection ELMECO2000, Nałęczów, 4 – 6 June 2000, pp.174 – 182.

***Author**: prof.nz. AGH, dr hab. inż. Antoni Cieśla, Akademia Górniczo - Hutnicza, Katedra Elektrotechniki i Elektroenergetyki, al. Mickiewicza 30, 30-059 Kraków, E-mail: aciesla@agh.edu.pl.*