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Applications of Superconducting Magnetic Separation

by

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Introduction

This document examines the feasibility of various new applications for Superconducting Magnetic Separation techniques. The assessment is made from both technical and economic standpoints and examines applications that are already fully developed in addition to significant future applications.

Background

Magnetic separation is a mature, well-established technology which has found favour in the minerals processing industry since the early 20th century. The advent of superconducting magnet technology has greatly extended the range and potential of magnetic separation to include a myriad of exciting applications in many key sectors including mining, manufacturing, medicine and environmental technology.

Magnetic separation is a technique which allows materials with different magnetic properties to be separated by the use of inhomogeneous magnetic fields. The separation is achieved using a combination of a magnetic field and a field gradient which generates a force on magnetisable particles as shown in the following equation.

$$\overline{F}_m = \frac{\chi V_P}{\mu_0} \cdot \overline{B}\left(\nabla \overline{B}\right)$$

(F_m – force on particle, χ - volume magnetic susceptibility of particle, V_P – volume of particle, μ_0 – permeability of free space, B – magnetic flux density)

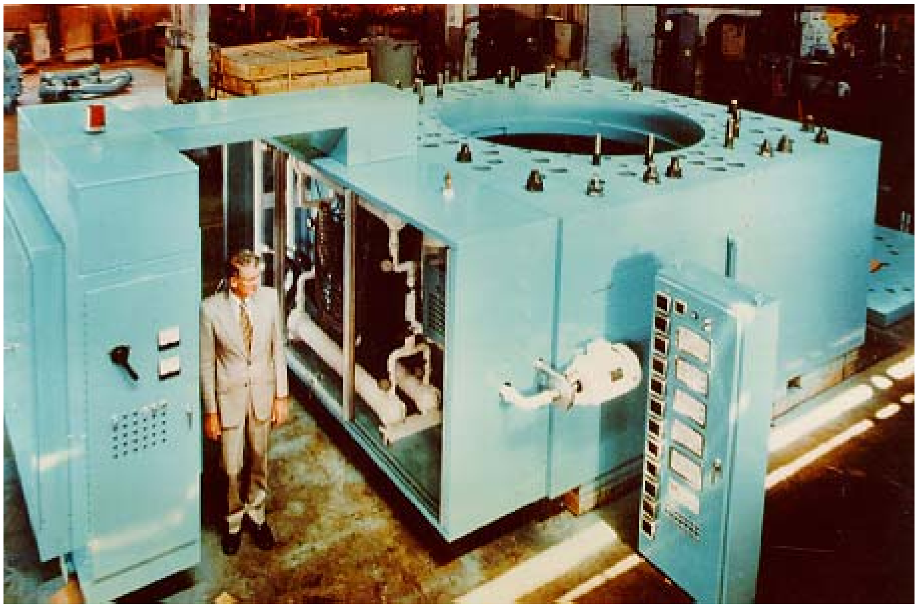
At its most basic, magnetic separation is demonstrated in scrap metal sorting in which a simple electromagnet is used to lift ferrous from non-ferrous waste. Current technologies can extend the technique to the modern-day state-of-the-art magnetic separator for the removal of very small, weakly magnetic particles from liquid or gas flows using powerful superconducting magnet technology.

Magnetic separation began to find applications in the 19th century when devices were invented for the purpose of iron ore concentration by magnetic means. Today, the minerals industry remains the largest user of magnetic separation for material sorting, ore treatment and mineral improvement. The majority of these applications use shaped permanent magnets as the source of the magnetic field and the field gradient.

The 20th century saw the technology being improved when the technique of high gradient magnetic separation (HGMS) was developed in the 1930s. This arrangement improved on the main limitation of earlier designs by using a finely divided matrix of secondary poles to improve the magnetic field gradient. This technique was further improved when the permanent magnet field sources were replaced with a copper electromagnet which allowed the use of higher magnetic fields.

These improvements led to a large-scale application for HGMS in the beneficiation of china clay, also known as kaolin. Kaolin is a white mineral whose value depends on its brightness and it was found that this could be improved by selective removal of the darker, more magnetic particles in the clay using the newly-developed HGMS technique.

The early machines for kaolin treatment contained a huge copper electromagnet producing a magnetic flux density of 2 Tesla in a 2 metre diameter separation space and were found to be economical in operation despite the huge electrical requirements to energise the electromagnet. A machine of this type from the 1960s is illustrated on the next page.



An early resistive electromagnet-based HGMS system for kaolin improvement

The major cost associated with this type of machine was the electrical power required to energise the magnet, in most cases being of the order of 0.5MW. A major potential for cost reduction was therefore enabled by the advent of superconducting magnet technology in which large magnetic fields can be generated with minimal power consumption. Superconductors are materials that have essentially zero electrical resistance and therefore make it possible to create an electromagnet with minimal electrical power requirements. Superconductivity is a quantum state of matter and therefore can only exist at low temperatures. Current technology generally requires cooling of the superconducting magnet to 4.2 degrees Kelvin (-269°C) using liquid helium and allows the generation of magnetic fields in excess of 20 Tesla.

In the mid-1980s the first superconducting magnetic separators were designed and built for china clay improvement. The early machines used a superconducting magnet capable of generating a flux density of 2 Tesla and were found to have overall costs around one third of a comparable copper electromagnet system including depreciating of initial capital costs. Running costs were a fraction of those of a resistive separator. The first system built is illustrated in the photograph on the next page. The superconducting magnet was supported at liquid helium temperature by the helium liquefier at the left of the photograph.

The first superconducting magnetic system for kaolin improvement in 1986

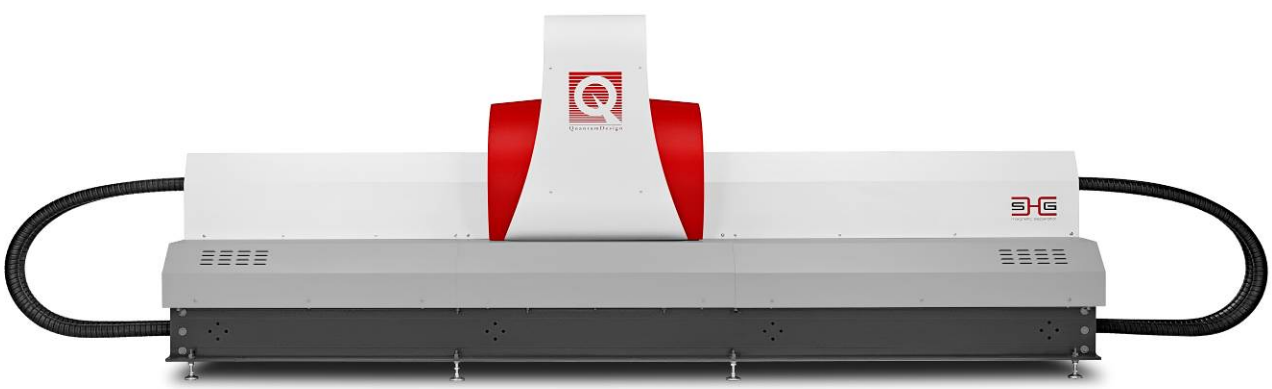
This type of machine constituted a huge step forward for the technology. Further improvements were made as superconductor and cryogenic technology improved to enable the modern state-of-the-art system for china clay treatment, as illustrated in the next photograph. This type of system operates constantly with minimal "dead time", is extremely compact and once commissioned and energised, the superconducting magnet requires no attention except periodic liquid helium filling and servicing of ancillary systems.

The first modern-type superconducting magnetic separator for kaolin improvement in 1989

This type of system has been used since 1989 in the china clay industry with ever-larger processing capacities as the magnet technology has progressed. This application of HGMS has proved to be a reliable, commercially viable technology with more than 50 systems operating in the field with no operational failures. Indeed the first commercial system, manufactured in 1989, is still operating to this day in Cornwall, England. Many of the operational systems are situated in remote regions of the world such as rural India or the Amazon rainforest in Brazil.

A large-capacity superconducting magnetic separator on final test in 1997

The state-of-the-art in superconducting magnetic separation technology is represented by the SHGMS system by Quantum Design, Inc. This system completely eliminates the need for liquid cryogens and requires only electrical power to function.



The Quantum Design SHGMS system

As opposed to immersion in a large liquid helium bath, the superconducting magnet is supported at cryogenic temperature by means of a single cryocooler. In addition to the significant cost savings of the expensive liquid helium, the cryogen-free technology has the additional benefit of allowing the system to be made much smaller for a given capacity.

A vast range of further applications in many diverse sectors has been made possible by recent developments in the technology which are discussed and presented in the next section.

New Applications of Superconducting Magnet Separation

The advent of superconducting magnet technology has greatly extended the potential range of application of magnetic separation technology. Early, permanent magnet-based systems are still widely used to this day in the minerals industry and are very effective at their intended purpose. However, the limited magnetic field and field gradient that they can produce restrict the range of their application to the extraction and concentration of relatively strongly magnetic materials.

The recent state of superconducting magnet technology allows reliable magnet systems for superconducting magnetic separation to be constructed to produce very high magnetic fields in excess of 5 Tesla. Modern secondary pole designs allow the generation of enormous magnetic field gradients which combined with the high magnetic field enable the extraction of very small, weakly magnetic materials from liquid or gas flows.

Economically, magnetic separation offers many key advantages. The modern design of superconducting separator operates continuously, 24 hours per day, 7 days per week. Essential maintenance, such as refilling with cryogens or servicing of cryocooling systems requires less than a 12 hour shutdown per year. Most separation systems could operate with minimal supervision due to high levels of reliability and automation as has been demonstrated in the china clay industry since the late 1980s.

It is possible, as is demonstrated in the case of china clay, to design the magnetic extraction process to offer targeted removal of a single solid component or range of solid components from the source material. This is obviously not possible using conventional mechanical filtration and opens up a vast range of applications where this is necessary. In many chemical techniques for extraction the source material requires subsequent treatment to remove agents introduced to enable the extraction process such as catalysts. Superconducting magnetic separation is a single-stage, targeted process which obviates the need for these complications.

The machinery required for magnetic separation is well understood, reliable and scalable being based on the technology used in MRI systems used in medical imaging. Thousands of superconducting MRI systems are built every year since their development in the early 1980s and the cryogenic and magnet technologies are extremely mature.

The volume demands of a large-scale application may be satisfied by a single machine or a number of machines working in parallel, allowing production capacity to be increased relatively easily with the cost advantages this brings. The superconducting and cryogenic technologies required to construct the magnet and its cryogenic support system have evolved to the point that there are a vast number of options for the system designer to construct cost-effective and reliable systems for each and every application.

The key to the realisation of a new application is the design of the fundamental process which involves the understanding of the magnetic and hydrodynamic forces on each type of particle within the source material. The process is designed to remove the intended range of particles leaving behind the remainder of the source material. As such superconducting magnetic separation can be a standalone process or be an integrated part of a larger scheme.

However, it is the low processing costs offered by superconducting magnetic separation that make it a potentially key technology with advantages in many sectors. A superconducting magnetic separator will be compact, require no more than a few kilowatts of electricity to run its ancillary systems, will operate almost constantly all the year round and will require very little maintenance. As a result, cost projections of the order of a few tens of cents per tonne of processed material or less have been proposed for many large-scale applications.

Applications in the minerals industry – As mentioned previously, the minerals industry is the largest user of permanent magnet-based separator systems. Present day superconducting separator technology opens up new avenues for applications in the minerals industry.

There is continual pressure in the minerals industry to increase efficiency, the reasons being economic and the ever-declining grade of ore with lower concentrations of value. At a certain point, the mining operation will cease to be commercially attractive due to the lower value of the extracted ore and a new source of the mineral is sought.

It follows that the use of more advanced separator technology make it possible to profitably process these reduced grades of ore and continue the useful operational life of the mine. In addition, such a separator could be used to extract a greater proportion of the useful material from a still profitable mine further enhancing the economics of the operation.

A logical extension of this application is in the extraction of useful materials from mineral waste dumps. In most mining operations, the material is mined and then subject to processing which removes the valuable material. The remaining material, so-called "mineral slimes" or "tailings", is usually disposed of in a waste dump in the vicinity of the mine. These dumps abound in the mining areas of the world and offer attractive opportunities.

As this waste is already above ground these waste dumps are a probable source of very cheap minerals that were unable to be removed by the initial processing methods. Such minerals are of colloidal size and hence are suitable for removal by magnetic separation. This is particularly applicable to the gold, platinum and uranium mining industries.

In addition, the reprocessing of this waste material can yield an inexpensive source of additional minerals that were not targeted during the initial processing. It is also evident that the reprocessing of these mineral wastes in a profitable and beneficial operation is an attractive way of solving potentially undesirable environmental situations.

Manufacturing industries – Superconducting magnetic separation has much to offer in the manufacturing industries. There is much scope for application of the technology to reducing or eliminating the environmental impact of manufacturing operations. Superconducting magnetic separation offers a complete pollution control and remediation solution for many industries which will be discussed in more detail in a following section.

Dedicated applications have been suggested and explored in numerous manufacturing industries. One such application is the cleaning of cutting and grinding fluids in heavy machining operations. A typical heavy machining facility such as an automotive engine manufacturing plant uses millions of litres of machining fluids within a closed-cycle process system. The fluid is sprayed over the tool heads, lubricating the process, cooling the tool and product and washing away the grinding material.

This fluid is usually cleaned of grinding materials then re-used by means of large nylon media filtration systems. This type of filtration system is rapidly falling out of favour due to its high cost and the environmental implications of the disposal of the used nylon media. Superconducting magnetic separation offers a convenient, low-cost replacement for this application in which the grinding material is removed from the fluid in a form which allows for easy recycling of the recovered metal.

This system, which completely eliminates the undesirable nylon filtration media, offers the possibility of reducing the costs of the operation to less than 1 US cent per tonne of fluid treated in addition to improvements in filtration efficiency.

The technique is particularly suitable for steel and aluminium machining. Samples of fluid from an automotive engine facility before and after treatment are shown in the following photographs.

Demonstration of the removal of grinding swarf from machining fluid from a large-scale industrial facility using superconducting magnetic separation

Many other industries can benefit from similar systems. The plating industry is one possibility where very fine particles of precious metals such as gold, silver and platinum are lost in rinse water and introduced into the environment.

Another possibility is the extraction of wood pulp from paper mill effluents preventing contamination of river systems. Applications have also been suggested in the pharmaceutical and food industries as part of large-scale process operations which are discussed in a later section.

Environmental applications – One of the main sectors in which superconducting magnetic separation presents exciting opportunities is the increasingly important area of environmental technology. There is a growing challenge to improve the environmental compatibility of industrial operations worldwide. Superconducting magnetic separation offers low-cost ways of achieving this by “bolt-on” equipment at the effluent exits of factories or mines which can remove pollutants before they can reach the outside environment.

As such, it offers certain industries the opportunity to reliably reduce their levels of undesirable effluents without changing their processes or harming their profitability. In addition, the technology is capable of cleaning up existing pollution in rivers, lakes, sediments and soils and so offers a complete solution for many types of industrial operations.

This is particularly suitable for the removal of iron and iron oxides from rinse water streams in iron and steel production. Water is widely used in steel making and rolling operations as a cooling and rinsing agent and in many cases this water is released directly into rivers and lakes. This water contains very fine particles of iron which oxidise in the water. This has the long-term effect of removing oxygen from the water and blocking sunlight to photosynthesising waterborne plants with detrimental effects on the local ecosystem. Eventually the water body becomes visibly polluted with a black, fine suspension and the local ecosystem damage is largely irreversible by natural means without first removing the source of the contamination.

To solve this problem, a separation system can be placed in the exit stream of the steelworks to intercept the iron and iron oxide particles before they can reach the outside environment. However, it is also possible that a polluted lake or river could be cleaned of existing iron oxide pollution using similar systems and as a result, magnetic separation offers a complete solution to this common environmental problem.

The large-scale remediation of rivers, lakes, harbours, soils and sediments has been discussed with superconducting magnetic separation being a key part of the process. A large-scale biological process has been pioneered using naturally occurring bacteria to remove a range of environmental pollutants such as heavy metals and organic contaminants.

The pollutants are adsorbed onto a magnetic material produced by the bacteria and this material is removed using a magnetic separation process. This process has been demonstrated in the remediation of contaminated soil on land near the Chernobyl nuclear accident and offers a vast amount of potential for the cleansing of polluted rivers, soils and harbours all over the world.

Another potentially important application of magnetic separation techniques is the removal of respirable asbestos from dust samples. Many regions of the world are active in removing asbestos insulation from ageing buildings and there is concern over the health risks associated with the carcinogenic dust this produces. Asbestos dust has weakly magnetic properties and its successful separation by magnetic means can be demonstrated.

Many applications have been proposed in large-scale water and sewage treatment. Incorporating superconducting magnetic separation into a modified version of the conventional activated sludge process presents a robust, compact solution for high-capacity wastewater treatment with a number of important advantages.

Operating a facility in this way eliminates excess sludge production thus reducing waste handling and disposal requirements. The proposed facility is additionally much smaller than a conventional design of the same capacity. Due to the mode of operation the system is essentially self-regulating and as such allows for extensive automation with reduced capital costs. These processes therefore offer low-cost, environmentally compatible methods for water use and re-use and constitute another key environmental area in which superconducting magnetic separation has revolutionary potential.

The nuclear industry – Many applications for magnetic separation have come to light in the nuclear industry, a very high technology industry which demands the highest levels of efficiency and reliability from its filtration equipment. Among other uses, radioactive contamination in the pressurised water reactor cooling system can be safely removed while contaminants can be collected and concentrated from reprocessed fission fuel rods. It has also been suggested that air exiting gloveboxes and plant ventilation systems can be filtered of plutonium dioxide dust by magnetic means owing to the strongly paramagnetic nature of PuO_2. Such filtration systems could augment or possibly replace the costly and bulky HEPA filter systems used currently in many areas of the world.

Apart from the obvious cost advantages, the magnetic system is media-free and the recovered radioactive material can be reprocessed or disposed of on is own. In the case of a HEPA filter system, the entire filter media must be disposed of due once it has become loaded with radioactive material, adding significant cost and environmental complications to the process.

The food, pharmaceutical and biochemical industries – There are a number of potential applications for superconducting magnetic separation in the food processing and pharmaceutical industries. The emerging biochemical engineering sector is another potential beneficiary of separation technology.

Many suggested applications involve the removal of metallic contamination or the treatment of suspended solids and soluble organic molecules in process streams. The removal of certain low molecular weight materials without reducing the nutritional value of foods offers numerous advantages in food quality and the removal of cholesterol from butter and milk is a proposal of enormous implications. In addition, superconducting magnetic separation offers great potential in effluent control from these key industries.

Biochemical engineering and processing is an emerging area of technology which is finding applications in a number of industries. Efforts are being made to convert food-processing wastes into higher value products using yeasts. Other possibilities involve the use of enzymes extracted from microorganisms or plants.

The potential for superconducting magnetic separation lies in the recovery of very fine particles from the water-based media which is often associated with this type of biological process. If the materials to be recovered are magnetic or can be made magnetic by pre- or post-treatment superconducting separators are appropriate for their removal due to the large volumes of water which are employed.

Such applications are all on very large scales and are in industries which require the highest levels of quality and reliability. Superconducting magnetic separation is well positioned to deliver these applications and more either as standalone technology or as key components of larger processes.

Applications in medical science – A potentially very significant range of applications has been suggested in the ever-evolving field of medical science. The removal of red blood cells from whole blood has been achieved by magnetic means, owing to the iron content of these cells.

Similar systems have been developed for use in the diagnosis of malaria as the malaria parasite alters the oxidation state of the iron in the red blood cells and allows confirmation of the parasite's presence due to the effect on the magnetic properties of the infected cells. In many developing nations of the world malaria is still a significant health risk and a simple, inexpensive and instantaneous method of diagnosis has the potential to save many lives.

Another very important application that has been suggested is in the cleansing of bone marrow and the separation of blood components. This has enormous potential in the treatment of leukaemia and other associated blood disorders. This offers considerable advantages over conventional transplant techniques as the patient's own blood and bone marrow can be cleaned outside of the body then reintroduced to the patient with no risk of rejection.

This would be achieved by magnetic "tagging" of the malignant cells which would allow their removal by magnetic means. If the technology could be perfected, a patient could be treated without the need to find a suitable donor and lead to many lives being saved.

Concluding remarks

The technology of superconducting magnetic separation offers efficient, low-cost solutions for these and many other applications in key areas. The range of potential beneficiaries of the technology is vast, enabling rapid solution of many of the world's most serious environmental problems whilst keeping industry operating efficiently and economically.

Indeed it may be asked why, with its many proven advantages, has superconducting magnetic separation not reached new markets beyond the treatment of china clay? The answer lies in that its greatest strength is also perceived as its main weakness – that on very large scales the technique is extremely effective and economically attractive.

However, to develop such large-scale applications necessarily requires research and development with the commercial payoff arriving when the application is realised. In many cases, the research is not allowed to reach its conclusion despite demonstrated successes due to an overstated perception of risk in what is still seen as a new technology.

As a result, a huge number of applications have not been fully developed despite their suitability, the potential economics and in many cases research which has proven feasibility. There therefore exists an unprecedented opportunity for research into these stimulating applications with potentially enormous significance for the world.

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