ReBCO split coil magnet for high gradient magnetic separation

D N Diev, V M Lepehin, M N Makarenko, A V Polyakov, V I Shcherbakov, D I Shutova1 and M I Surin.

National Research Centre “Kurchatov Institute”, 123182, Kurchatov square 1, Moscow, Russian Federation.

1Author to whom any correspondence should be addressed shutovadi@mail.ru

Abstract. High gradient magnetic separation is a promising method for ores enrichment and industrial wastes recycling. The potential of separators based on resistive and permanent magnets is limited by the value of magnetic field and operational costs. LTS magnetic systems require liquid helium and complicated cryogenics. HTS magnets operated in solid nitrogen at 50 K can be a possible solution. In this study, we discuss the conceptual design of an HTS rotary separator prototype with the horizontally oriented rotor axis. The scheme allows to organize a continuous ore processing. The split magnet system consists of two 2G HTS coils on a soft-magnetic yoke with 50 mm room temperature gap. The paper gives the overall design of the magnetic system and the related cryogenic, together with the magnetic fields and forces calculations. The preliminary test results of the ReBCO coil in liquid and sub-cooled nitrogen are also presented.

1. Introduction
High Gradient Magnetic Separation (HGMS) is a promising method for the improvement of the quality of mining industry products and the waste reduction. In this process magnetic filters consisting of thin ferromagnetic wires in external magnetic field increase the magnetic gradient in the operational area. It allows much stronger extraction forces to be achieved in comparison with open gradient magnetic separators. This technique is the most effective for the separation of paramagnetic minerals in the $10^{-3}$ - $10^{-1}$ magnetic susceptibility range.

In particular, the rotary HGMS method is based on the following steps (see figure 1). Initially, the raw ore containing low concentration of magnetic particles is ground. Next, an aqueous slurry is prepared. The slurry flows through the ferromagnetic filters in the external magnetic field where magnetic particles are trapped onto the surface of the magnetized filters. The particular type of the filter depends on the size of the particles, their magnetic susceptibility, volumetric content etc. They can be made of thin steel fibers, ferromagnetic balls or corrugated plates. Non-magnetic (or weakly magnetic) particles pass through the ferromagnetic filters and then flush into a residues basin. Next, the water flushing removes the remaining non-magnetic particles adhered to the filters. Finally, the filter leaves the magnetic field area and the magnetic particles are washed out into a magnetic fraction basin.

The majority of industrial magnetic separators use either resistive electromagnets or permanent magnets. The resistive devices are oversized and costly to operate because of the high energy consumption. The typical value of their magnetic field is 1-1.5 T. Permanent magnets operate without
energy losses but generate relatively low magnetic fields \(< 1 \text{ T}\) \([1]\) insufficient for paramagnetic minerals separation. Superconducting (sc) magnetic systems can address these shortcomings providing higher magnetic fields at lower energy consumption. The majority of existing sc HGMS devices used low temperature superconductors (LTS) operating at liquid helium (LHe) temperature. The value of the magnetic field for sc separators varied from 2 T to 5 T. From the early 1980s there were a few large scale NbTi HGMS devices operated in industrial conditions with rather high productivities up to 20 tons of a raw material per hour \([2]\). The main mining industry applications for sc separators were magnetic concentrates enrichment \([3]\) and kaolin refining in the ceramic and paper industry \([4]\).

One of the reasons why industrial LTS separators have not become widespread was the complexity of helium cryostats’ servicing in industrial operational conditions. With the advent of high temperature superconductors (HTS) suitable for the commercial application a renewed interest in HGMS application has emerged \([5, 6]\). Low cost nitrogen cryogenics provides new opportunities. HTS coils operating in solid nitrogen have high critical currents combined with enhanced thermal stability. Thus, HTS separators can be considered as an alternative to resistive and LTS machines. The particular goal of this work is development of 2G HTS HGMS prototype magnetic system for the refining of Mn, Ti and W ores. Its conceptual design, main operational parameters, ReBCO tapes properties and preliminary HTS coil test results are presented in the following sections.

2. The overall design of the ReBCO HGM rotary separator prototype

2.1 Geometry

Our R&D is focused on the rotary operational scheme as the most promising for industrial scaling. The design of the horizontal axis rotary separator is given in figure 1. The system consists of a LN2 cryostat, additionally conduction cooled with a cryocooler to obtain ~ 50 K operation temperature, a ReBCO split magnetic system on an warm iron yoke, a horizontal axis rotor, a slurry feeding line, a flushing line, and magnetic/non-magnetic fraction basins. The 670 mm dia rotor containing steel filters rotates between two poles of the split ReBCO magnet within a 50 mm room temperature gap. The magnetic flux is looped by the tripod yoke made of a soft magnetic material. The magnetic poles of the yoke are composed of vanadium permendure cores. Two layer wound REBCO coils enclosed into a nitrogen split cryostat are placed as close as possible to the edges of the magnetic poles. The coils are arranged symmetrically with respect to the rotor central plane. The magnetic field inside the gap is almost uniformly distributed and stray magnetic fields are low as a result. The rotor speed will be experimentally adjusted in 0.7-1 rpm range, corresponding to 18-25 mm/sec liner filter velocity. The rotor drive power consumption is about 0.5 kW.

There are two main advantages of the horizontal axis scheme. Firstly, a continuous separation process can be organized. Also, this scheme can be rather effective against clogging of the filters. One of the well known issues is that the magnetic particles are locally built up near the filter inlet. It eventually leads to the filters blockage and, thus, separation efficiency decreasing. In our scheme the magnetic fraction flushing takes place in the upper rotor position (180 degrees opposite the slurry feeding point). The separated particles will be accumulated on the upper side of the filters; therefore it is easier to wash them out by the water contra flow.

2.2 Thermal parameters

The cryostat has a common vacuum volume with two independent LN2 vessels. Their outer surface is additionally conduction cooled by a Sumitomo CH-110 cryocooler (130 W @ 50 K) through flexible copper thermal bridges placed in vacuum (not shown). The coolant is supplied from two N2 feeders placed at the both sides of the cryostat. There are two resistive current leads at the top flanges of each of the N2 feeders. The electrical connection with the HTS coils is provided by flexible copper bus bars. The N2 vessels are wrapped with a multi-layer insulation to reduce thermal radiation heat losses. The calculations show that the total heat load to LN2 (less than 100 W at the maximal current) can be covered by the cryocooler cooling power.
Figure 1. The horizontal axis rotary HGM separator prototype with the vertically rotating wheel (dimensions are in mm).

Table 1. Design specifications of the ReBCO split coil magnet.

| HTS split magnet                  | Two round ReBCO coils on a tripod yoke with the vanadium permendure magnetic poles |
|-----------------------------------|-------------------------------------------------------------------------------------|
| Magnetic field in the centre of the empty 50 mm room temperature gap at 80-140 A | 1.2 T (at 80 A) - 1.5 T (at 140 A)                                                  |
| Operation temperature            | 50 - 65 K                                                                          |
| Coolant                           | Sub-cooled or solid nitrogen                                                       |

| HTS layer wound coils            | 2                                                                                   |
|----------------------------------|-------------------------------------------------------------------------------------|
| Number of coils                  | 2                                                                                   |
| Coil type                        | Layer - wound                                                                       |
| Inner diameter                   | 148 mm                                                                              |
| Outer diameter                   | 218 mm                                                                              |
| Coil cross section               | 35 mm x 45 mm                                                                       |
| Number of turns in 1 coil        | 784                                                                                  |
| Winding density                  | 50 1/cm²                                                                            |
| HTS tape length in 1 coil        | 450 m                                                                               |
| Coil inductance                  | 0.12 H                                                                               |
| Solenoid coefficients            | $k_0 = 5.26$ mT/A (centre), $k_{\text{max}} = 9.79$ mT/A (winding)                   |

| HTS conductor                    | AMSC Amperium® Type 8501 in kapton wrapped insulation (40 μm thick)                |
|----------------------------------|-------------------------------------------------------------------------------------|
| Tape width (non-insulated)       | 4.8 mm                                                                              |
| Tape thickness (non-insulated)   | 0.2 mm                                                                              |
| $I_c$ (77 K, s.f.)               | $>110$ A                                                                            |

2.3. Magnetic parameters & forces

The calculations of the magnetic field inductance and magnetic forces in the ReBCO split magnet system (HTS cols + soft magnetic yoke) were performed with ElectroMagneticWorks (EMS) by Solid Works [7]. The main criteria for the choice of the optimal magnetic configuration were the maximum magnetic flux density within the operational gap at a minimal ReBCO tape consumption and symmetrical mechanical loads in the system “coil-rotor-coil”. The calculations showed that the magnetic poles of the yoke attract each other with the force of 16 kN, while the HTS coils repel from
one another as 3.3 kN. To compensate these magnetic forces a special mechanical supporting frame was envisaged. The mechanical load is transmitted from the HTS coils to the yoke through a system of supporting tubes. The iron yoke is rigid enough to guarantee the total displacement of the magnetic poles within 0.1 mm.

The results of the magnetic field simulations at 80 A - 140 A current are given below. Figure 2a is the distribution of the magnetic flux density along the main magnetic axis ($B_z$) for different transport currents in the HTS coils. At 140 A the magnetic flux density in the centre of the operational gap reaches 1.5 T, up to 1.9 T near the magnetic poles’ surface, and up to 3.2 T within the vanadium permendure cores. Figure 2b represents the results of the magnetic field simulation for a model deposition filter made of multiple thin-walled AISI416 tubes 10 mm dia x 0.3 mm and placed in the operational gap at 140 A current. The peaks with $B_0 \sim 3$ T inside the filter tubes can be clearly observed.

3. HTS coil test results

The coil critical current is mainly limited by the radial magnetic field component (perpendicular to broad surface of the HTS tape). The dependence of the critical current vs. $B_r$ for the AMSC Amperium® HTS conductor was measured at 77.3 K, 70.1 K and 65.3 K. The results are presented in figure 3a (stars) together with the data extrapolated from [8] (lines).

![Figure 2. The magnetic field distribution along the magnetic poles’ axis for the empty operational gap (a) and with a model filter in the form of a thin-walled AISI416 tubes array (b).](image)

![Figure 3. The single HTS coil load line (a) and the photo of the winding process (b).](image)
The ReBCO coil was wound according to the specification discussed above. The photos of the winding process are given in figure 3b. During a preliminary test the critical current of the single coil (with no iron yoke) was measured at different temperatures in liquid and sub-cooled nitrogen in order to check the winding process quality. The experimental results are given in figure 3a as black triangles. The measured magnet’s critical parameters agreed well with the pre-calculated ones, allowing us to predict the results for even lower temperatures, which will be achieved with the cryocooler in future experiments. The maximum operational point (140 A/1.5 T in the center of the empty operational gap) can be achieved in solid nitrogen.

4. Conclusion and further work

HTS HGMS devices can be useful for enrichment of weakly magnetic ores (e.g. oxidized quartzite, manganese, rare earth and chromite ores), obtaining of semi-finished products with better properties (kaolin, porcelain pastes, silica and zirconium sands), industrial wastes treatment and soil decontamination from radio-nuclides and heavy ions. They can become of great importance for global environmental protection. Furthermore, HGMS magnets fabricated using 2G HTS tapes enable the operating costs to be reduced considerably since expensive liquid helium is not required.

The goal of the project is an implementation of the new magnetic separation engineering utilizing HTS superconducting magnets. Our calculations show that the rotary HGMS device with ReBCO split coil magnetic system is a promising scheme. During the preliminary tests the ReBCO coil reached the designed magnetic performance. Today, the cryostat and the rotor with optimal filters are under development. Preliminary R&D shows (to be published elsewhere), that the maximum value of the extraction force with $\gamma = |B \text{grad} B| = 16500 \text{ T}^2/\text{m}$ can be obtained, exceeding the traditional separators characteristics of typical value $\gamma = 10000 \text{ T}^2/\text{m}$. The acceptance tests of the 2G HGMS prototype are to be performed in the end of 2019.

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References

[1] Svoboda J 2004 Magnetic Techniques for the Treatment of Materials Kliwer academic publishers
[2] Kopp J 1991 Superconducting magnetic separators Magn. and electrical separation 3 17-32
[3] He S, Yang C, Li S and Zhang C 2017 Enrichment of valuable elements from vanadium slag using superconducting HGMS technology Prog. Supercond. Cryog. 19 1 17-21
[4] Zian Z et all 2017 Recent development of high gradient superconducting magnetic separator for kaolin in China Prog. Supercond. Cryog. 19 1 5-8
[5] Song J B, Kim K L, Yang D, Kim Y G, Lee J, Ahn M C, and Lee H 2013 High-Tc superconducting high gradient magnetic separator using solid nitrogen cooling system for purification of CMP wastewater IEEE Trans. on Appl. Supercond. 23 3 3700505
[6] Kumakura H, Ohara T, Kitaguchi H, Togano K, Wada H, Mukai H, Ohmatsu K, Takei H 2001 Conduction cooled Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ (Bi-2223) magnet for magnetic separation Physica C 350 76-82
[7] ElectroMagneticWorks (EMS) by Solid Works software, on-line: https://www.emworks.com/
[8] Strickland N M, Hoffmann C, and Wimbush S C 2014 A 1 kA-class cryogen-free critical current characterization system for superconducting coated conductors Rev. Sci. Instrum. 85 113907