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HTS high gradient magnetic separator prototype

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Abstract

A high gradient magnetic (HGM) separator prototype with the 2[nd] generation high temperature superconducting (2G HTS) magnetic system operated in sub-cooled nitrogen is presently under development at NRC "Kurchatov Institute" (Moscow, Russia). The main goal of the project is an attempt to shift away from the complicated liquid helium cryostats towards simple cryocooler-based nitrogen cryogenics as much more convenient for HGM separators industrial applications. Using of commercial HTS tapes allows to get a sufficient level of magnetic fields and extraction forces with low energy consumption. The expected operational parameters of the device are 1.2-1.5 T in the empty operational gap and up to 3 T on the ferromagnetic filters. In this paper we briefly describe the design of the HTS rotary separator prototype with the horizontally oriented rotor axis and propose different types of ferromagnetic filters intended for weakly magnetic ores enrichment.

Keywords: high gradient magnetic separation, REBCO coated conductor, HTS magnets

1. INTRODUCTION

High gradient magnetic (HGM) separators can be used for weakly magnetic ores enrichment in mining [1] as well as for paramagnetic impurities extraction from semi-finished products, e.g. kaolin [2, 3], or industrial wastes recycling [4]. Traditional roller type separators based on permanent magnets have rather low performances. Resistive electro-magnets working in a continuous mode are oversized and costly to operate due to high energy consumption. The final cost-price of separated products increases as a result, containing the spread of the HGM eco-sound technology in industry.

The advent of commercial high temperature superconducting (HTS) tapes offers new opportunities for HGM separation technology. HTS magnetic systems can provide high levels of magnetic flux densities in rather big volumes with low energy consumption and decreased size and weight. Besides, they can be operated in cryocooled nitrogen and do not require expensive liquid helium and complicated cryostats. A few R&D projects concerning HTS separators development are known today [5, 6, 7].

There are three types of HGM separators: rotary & reciprocating machines allowing a continuous separation process and separators-filters operating in a cycling mode [9]. Our study is focused on the rotary scheme as the most promising approach for a future industrial scaling.

In section 2 we briefly discuss the design and the main operational characteristics of the REBCO HTS HGM separator prototype. A sufficient level of extraction magnetic forces in HGM separators is achieved by means of ferromagnetic filters, producing a high gradient of the magnetic flux density. In section 3 we present new types of ferromagnetic filters for HTS HGM separation with low ferromagnetic filling factors varying from 6 to 36 % and show that higher values of extraction forces can be obtained in comparison with traditional 50 % filters for rotary separators.

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2. REBCO HGM SEPARATOR DESIGN

The design and the main operational parameters of the horizontal axis rotary separator are given in Fig. 1 and in Table I. The magnetic system consists of two round REBCO coils enclosed into two LN2 cryostats assembled on a room temperature tripod iron yoke. The LN2 vessels with HTS coils are additionally conduction cooled by a cryocooler (to obtain temperatures below 77 K). The magnetic poles of the yoke are composed of vanadium permendure cores and ARMCO enclosures. The 670 mm dia rotor with filters' slots rotates between the two poles of the split REBCO magnet within a 50 mm room temperature gap. The REBCO coils are arranged symmetrically with respect to the rotor central plane. While separated material aqueous slurry flows through the area of the maximal magnetic field, the magnetic particles are trapped onto the surface of the magnetized filters. Next, water flushing removes the remaining non-magnetic fraction adhered to the filter. Finally, the filter leaves the magnetic field area and the magnetic particles are washed out into a magnetic fraction basin on the opposite side of the rotor.

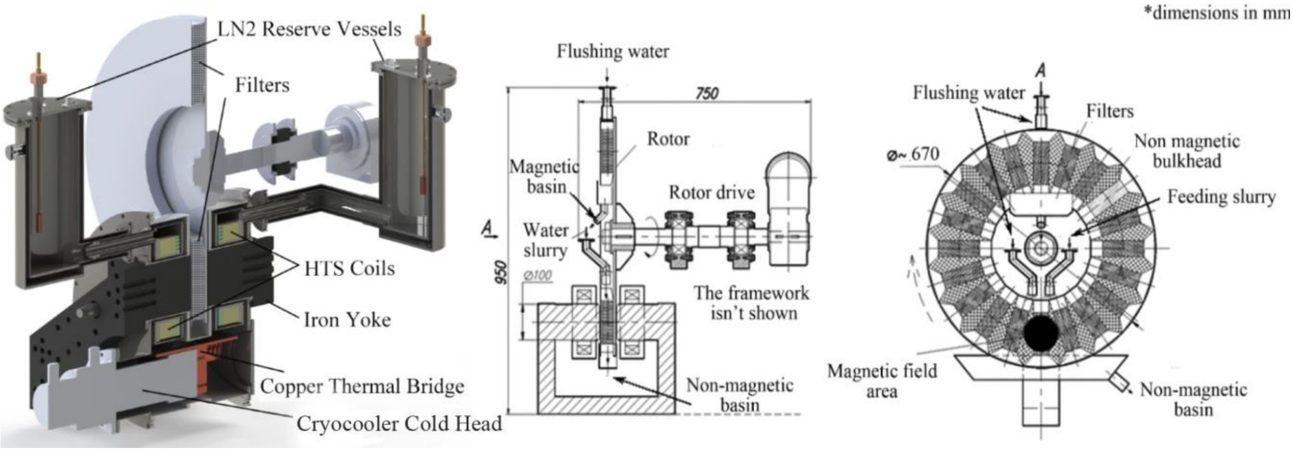

Fig. 1. The design of the HTS HGM separator with a vertically rotating wheel.

There are two main advantages of the horizontal axis scheme. On the one hand, a continuous separation process can be organized. On the other hand, this scheme is rather effective against clogging of the filters, since counter flushing takes place when the filter is in the up-side-down position in the upper point of the rotor.

In our prototype the rotor speed will be experimentally adjusted in 0.7-1 rpm range, corresponding to 18-25 mm/s liner filter velocity. The rotor drive power consumption was calculated as 0.5 kW. The mass of the mechanical part of the rotor (without the magnetic system) is about 110 kg, dimensions are 700 mm x 750 mm x 950 mm.

Usage of the vanadium permendure magnetic poles increases the operational parameters of the device. The expected level of the magnetic flux density was calculated in the range of 1.2-1.5 T in the empty operational gap depending on the coils transport current – see Table I. High mechanical loads between the magnetic system elements (up to 16 kN) will be compensated by a reinforced cryostat frame.

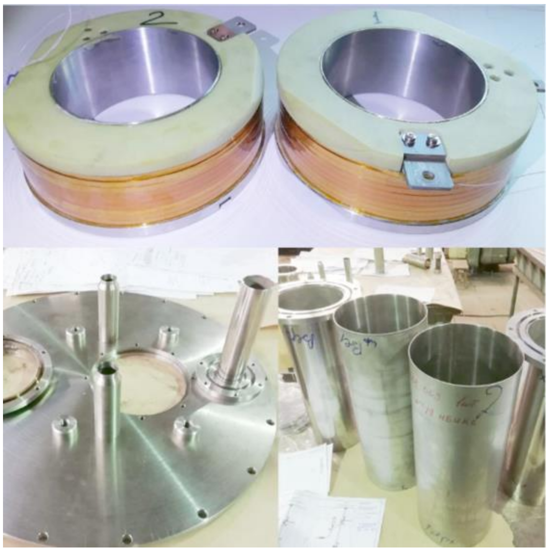

Fig. 2. The photos of the finished ReBCO coils and the parts of the cryostat under development.

TABLE I
DESIGN SPECIFICATIONS OF THE REBCO MAGNETIC SYSTEM.

HTS magnetic system	Two round REBCO coils on a tripod yoke with the vanadium permendure magnetic poles	
Magnetic field in the center 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 K - 65 K	
Coolant	Sub-cooled or solid nitrogen	
HTS coils		
Number of coils	2	
Coil type	Layer - wound	
Inner diameter	148 mm	
Outer diameter	218 mm	
Coil cross section	35 mm x 45 mm	
Turns per 1 coil	800	
HTS tape length in 1 coil	450 m	
Coil inductance	0.12 H	
Single coil I_c test	Coil 2	Coil 1
I_c(77 K), A	36	39
I_c(70 K), A	59	61
I_c(65 K), A	72	76
HTS tape	AMSC Amperium® Type 8501 (4.8 mm x 0.2 mm) in kapton wrapped insulation (40 μm thick)	
I_c (77 K, s.f.)	>110 A	
Cryocooler	Sumitomo CH-110 175 W @ 77 K 130 W @ 50 K	
Calculated total heat load to LN2 at 77 K	91.4 W (at 140 A) 68.3 W (at 0 A)	

Today, the cryostat and the rotor with the optimal filters are under development - see Figs. 2 - 6. The two REBCO coils have been wound and successfully passed preliminary tests at 77 K, 70 K, and 65 K. More details concerning the choice of the mechanical, thermal and electromagnetic characteristics of the device can be found in [8].

3. FILTERS

Slurry particles in a magnetic field are under the influence of several forces of different origin (magnetic force, gravity, buoyancy, etc.). The magnetic flux density, particle sizes, slurry concentration & velocity together with the performance of the filter all have a significant effect on the magnetic separation efficiency. In order to trap fine magnetic particles or weakly magnetic substances a high magnetic force F_m is required. It can be expressed as follows (1) [9]:

$$F_m = \alpha \cdot (\chi_p - \chi_s) \cdot V \cdot B \cdot gradB \qquad (1)$$

Here: B – magnetic flux density, $\chi_{p,s}$– volumetric magnetic susceptibility for the magnetic particles and for the solvent, V – particle volume, α – the particle's form factor.

Depending on the particles' size, their magnetic susceptibility & volumetric content in the slurry, etc., different types of filters are used. Traditionally they can be made of thin steel wires, steel wool, ferromagnetic balls or corrugated plates.

In order to define the optimal configuration of the HGM separator prototype, four types of model filters with ferromagnetic filling factors varying from 50 % down to 6 % were designed and fabricated. The ferromagnetic elements of all the filters were made of stainless steel AISI430 and enclosed into non-magnetic AISI 304 steel frames. All the filters have the same dimensions (35 mm x 40 mm x 120 mm) and may be installed inside the rotor slots interchangeably. Their layouts, photos, and the magnetic flux density distribution calculated by finite element modeling (FEM) with Ansys Maxwell software [10] are given in Figs. 3, 4, 5 and 6.

TABLE II

THE PROPERTIES OF THE MODEL HGM FILTERS.

Filter number	1	2	3	4
Ferromagnetic filling factor, %	50	36	17	5
Background field B_0, T		1.35		
Maximal magnetic field 0.01 mm away from the filter's surface B, T	2.1	2.0	3.1	2.2
$\gamma = B \cdot gradB$, T^2/m	10 000	5 600	50 000	16 500

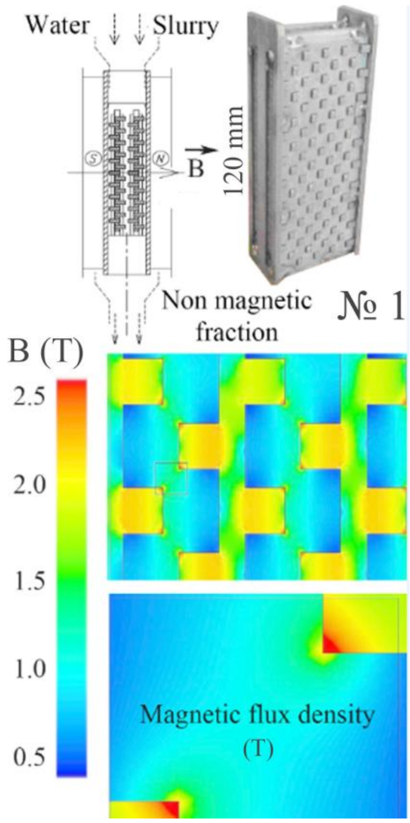

Fig. 3. Filter № 1 "plates with ledges"
(the photo, the layout, and the magnetic flux density distribution in the 1.35 T background magnetic field).

All the calculations were performed for the 1.35 T background magnetic field. The maximal magnetic flux density values listed in Table II were defined at 10 μm distance from the filter's surface.

3.1. Filter № 1 "plates with ledges".

The filter № 1 (Fig. 3) is composed of a rectangular steel elements array and has the highest 50 % ferromagnetic filling factor. In future experiments this type of the filter will be considered as a reference sample, since its geometry is very close to that for traditional rotary HGM separators. 3D heterogeneity of the magnetic field in combination with an effective slurry mixing inside the filter's channels lead to a high separation efficiency even in rather low background fields. The gap between the ferromagnetic elements is 2 mm wide, but it also can be adjusted experimentally for obtaining better results with different slurry concentrations, rotation speeds, etc. The maximal designed values for the magnetic flux density and the magnetic extraction parameter $\gamma = |B \cdot gradB|$ are 2.1 T and 10 000 T^2/m correspondingly.

3.2. Filter № 2 "rods".

The filter № 2 (Fig. 4) is composed of magnetic steel rods with different diameters (from 6 mm down to 3 mm) and has the 36 % ferromagnetic filling factor. The maximal calculated values for the magnetic flux density and the magnetic extraction parameter γ are 2.0 T and 5 600 T^2/m correspondingly. It is worth noting, that in this filter the

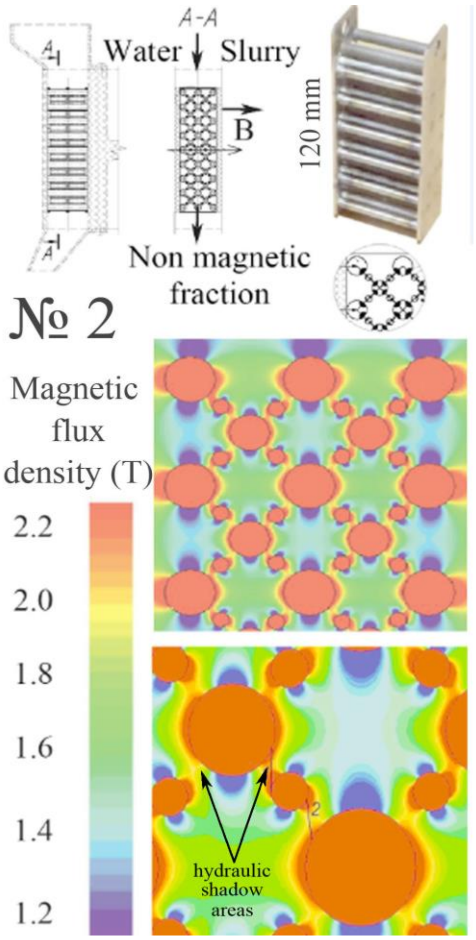

Fig. 4. Filter № 2 “rods”
(the photo, the layout, and the magnetic flux density distribution in the 1.35 T background magnetic field).

“hydraulic shadow areas” where the slurry flow rate is low while the magnetic force is high enough to trap weakly magnetic particles effectively.

3.3. Model filter № 3 “angular plates”.

The filter № 3 (Fig. 5) is composed of 2 mm x 8 mm rectangular plates inclined at 45˚ to the slurry flow direction and has the 17 % ferromagnetic filling factor. The maximal calculated values for the magnetic flux density and the magnetic extraction parameter γ are 3.1 T and up to 50 000 T^2/m. Although this filter demonstrates the highest values of the extraction forces concentrated on the sharp edges of the filter, its disadvantage is a rather low volume of such high field regions.

3.4. Model filter № 4 “plastic rods with a discrete ferromagnetic coating”.

The filter № 4 (Fig. 6) has the lowest ferromagnetic filling factor equal to 6%. It is made in the form of an array of 10 mm dia polypropylene rods. The lateral surfaces of the rods are covered with ferromagnetic particles with ~ 500 µm grain size. The maximal design value of the magnetic flux density and the magnetic extraction parameter γ for this filter were calculated as 2.2 T and 16 500 T^2/m.

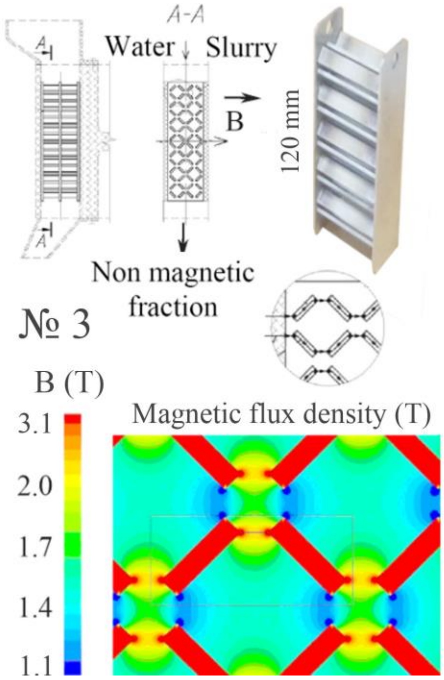

Fig. 5. Filter № 3 “angular plates”
(the photo, the layout, and the magnetic flux density distribution in the 1.35 T background magnetic field).

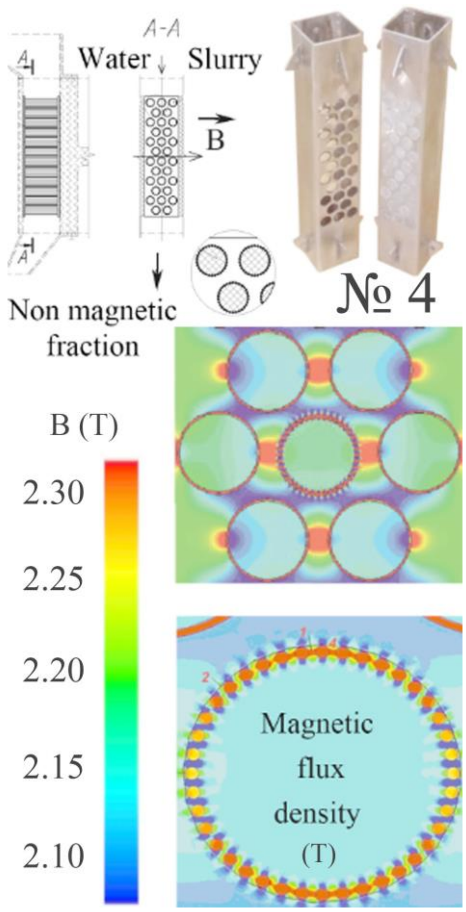

Fig. 6. Filter № 4 “plastic rods with a discrete ferromagnetic coating” (the photo, the layout, and the magnetic flux density distribution in the 1.35 T background magnetic field).

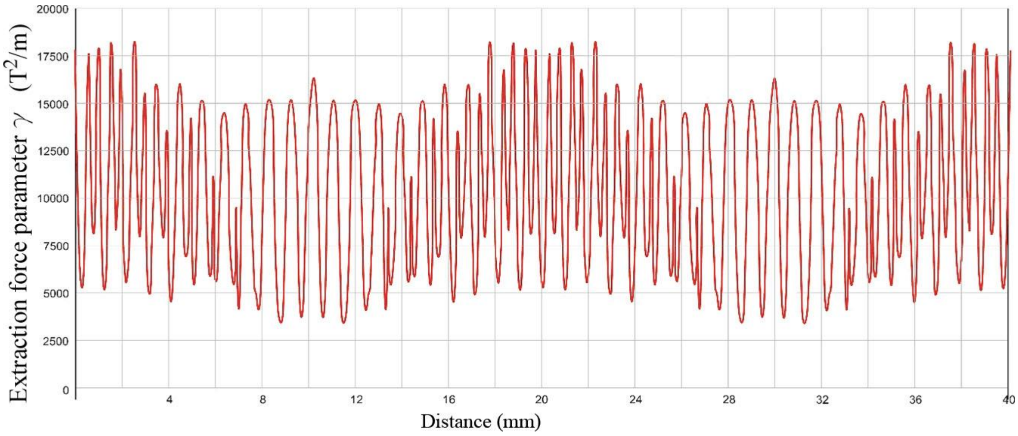

Fig. 7. The changing of the magnetic extraction force parameter $\gamma = B \cdot \text{grad}\, B$ on the surface of a plastic rod covered with ferromagnetic particles (filter № 4) in the 1.5 T background magnetic field.

Fig. 7 shows the γ parameter distribution along the perimeter of one of the plastic rods in the 1.5 T background magnetic field. It can be seen that its maximal value is at least 1.5 times higher than that for conventional HGM filters which typically does not exceed 10 000 T^2/m [9]. Our further calculations show, that the background magnetic field increasing doesn't lead to a noticeable extraction force enhancement for the filters № 1, 2 & 3. However, for the filter № 4 the increasing of the background magnetic field from 1.35 T up to 2.0 T leads to 1.36 times γ parameter rise. The reason is the magnetic coupling between the ferromagnetic particles located close one to another (< 1 mm) onto the surfaces of the plastic rods. It makes the filter № 4 the most promising candidate for superconducting HGM separators. Besides, the lowest ferromagnetic filling factor for this filter decreases possible risks associated with eddy currents problems in the system "rotor – HTS coils".

DISCUSSION AND FURTHER WORK

Superconducting HGM separators can become indispensable for paramagnetic ores enrichment (e.g., for oxidized quartzite, manganese, rare earth and chromite ores), obtaining of semi-finished products with better properties (kaolin, porcelain pastes, silica and zirconium sands) and industrial wastes recycling due to their low energy consumption and high efficiency. Our calculations and preliminary tests show that the HTS HGM rotary separator operated in sub-cooled or solid nitrogen is a promising scheme for a future industrial scaling.

Today, the pair of the REBCO windings is manufactured and successfully tested. Several types of magnetic filters with different ferromagnetic filling factors are also designed and fabricated. The results of the magnetic field calculations for different types of the filters show that it is possible to achieve high values of the magnetic force in relatively low background magnetic fields. Decreased ferromagnetic filling factors make the proposed filters optimal for using with superconducting magnetic systems. Final assembling and tests of HTS magnetic system is to be performed in early 2019. Acceptance tests of the full separator prototype with the rotor are planned for late 2019.

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