Design study of conduction-cooled high temperature superconducting magnet

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We are designing and fabricating a separator using the conduction-cooled high temperature superconducting (HTS) magnet for a National high-technology program in China. The magnet is made of Bi-2223 double pancake coils, and has inner and outer coil diameters of 120 mm and 211.2 mm, respectively and coil height of 202.8 mm. The superconducting magnet includes 20 double pancake coils. The operating current is about 87.8 A. This magnet is cryocooler-cooled with no liquid helium and should generate a magnetic filed of 3 T at a temperature of 20 K. We developed and tested a model Bi-2223 double pancake coil. The design and technique of the magnet is reported in the paper.

INTRODUCTION

With advent of Bi-based high temperature superconducting (HTS) tape, the critical current density for Bi-based superconducting tape is $J_C=10^4\text{-}10^5$ A/cm^2 in the operating temperature of 20-30 K and self-field. The applications of HTS tape for the superconducting magnet have been employed in fabrication of magnetic separator system. An HTS magnetic separator has no moving parts, consumes no power beyond refrigeration requirements, has no liquefying system to maintain, takes up less space, and costs less to purchase and operate than a conventional magnetic separator[1]. The HTS magnetic separators have a variety of industrial applications, most notably in the pharmaceutical, environmental, chemical fields and treatment for waste water in steel industry[2]. A high gradient magnetic separator has been conducted using a HTS magnet in China. It is supported by high technology project of China. The conceptual design and fabrication details of a conduction-cooled HTS Reciprocating Magnetic Separator are reported. Reciprocating magnetic separators are used in waste water treatment for special steel factory. The salient features and results of the electromagnetic, thermal, and quench protection analyses are discussed. The model coil has been fabricated and tested.

DESIGN OF HTS MAGNET FOR MAGNETIC SEPARATOR

The HTS magnet has 202.8 mm in length and 120 mm in inner diameter. The central operating magnetic field is a nominal 3.2 T with a design operating current of 87.78 A. The HTS magnet has a stored energy of 10 kJ. The specific parameters of the HTS magnet are listed in Table I. The configuration for the magnet is illustrated in Fig.1. The system operates in a vacuum and is conduction cooled via two-stage GM cryocooler with a nominal operating temperature of 20 K. The HTS conductor uses Bi-2223 tape and coil will be reinforced by a stainless steel tape. The HTS magnet is made of 3960 meters of Bi-2223 superconducting tape. The main parameters for the high temperature superconducting tape are listed in the Table II. The HTS tape was tested in liquid nitrogen. The profile of the critical current with respect to the magnetic field in various angles is illustrated in Fig.2 under the external field and 77 K. The HTS current leads to be used in the magnetic separator were designed to improve shock resistance. The current leads were designed to operate with the warm end at about 40-50 K and the cold end at 20 K. The HTS magnet, current leads, and thermal shield are supported by G-10 tubes and hung from the lid of the vacuum vessel. The cryocooler is mounted on the vessel lid and connected to the thermal shield top plate and the magnet cooling plate with flexible links to provide vibration isolation. The upper stage of the cryocooler cools the thermal shield and the heat pipe thermal intercepts. The heat pipe thermal intercepts combine high thermal conductivity with good electrical insulation and ensure that the upper end of the HTS portion of the current leads is adequately cooled. The lower stage of the cryocooler cools the HTS magnet and the bottom of the HTS current leads. The bottom of the leads is connected to the cooling plate by copper braid. The magnet is bolted to the cooling plate. The bottom plate of the HTS magnet and the magnet bore tube are made of copper and provide the conductive path into the windings for cooling. The magnet consists of individual double pancake windings stacked on the copper bore tube. Current lead mounting pads are provided to bolt the current leads to the magnet.

TABLE I MAGNET DESIGN PARAMETERS

Design Parameter	Value
peak radius Br-field	1.52 T
central B-field (B_{op})	3.29 T
operating current (I_{op})	87.74 A
operating temperature(T_{op})	20 K
HTS conductor	Bi-2223 PIT
Self Inductance (H)	4.355
stored energy (kJ)	10
no. of double pancakes	20
total conductor length (km)	~3.9
coil height (m)	0.2028
coil inner diameter (m)	0.12
coil outer diameter (m)	0.2112

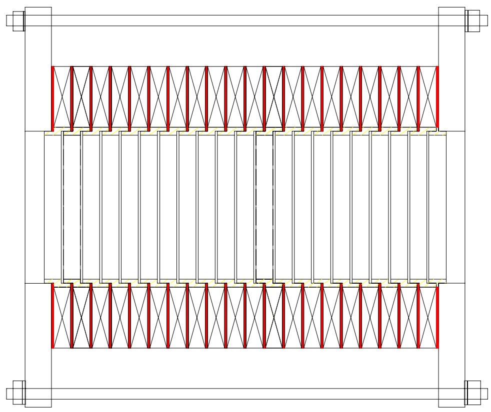

Fig.1 Configuration of HTSC magnet for separator

TABLE II Main parameters for Bi-2223 tape

Wideness	4.2±0.2mm
Thickness	0.24±0.02mm(with insulation thickness in 0.01mm)
Length	200m
Filamentary number	61
Filling factor	0.3 ~ 0.35
Density	4.5g/cm^2
Engineering current density	≥60A(77K, self field)
Max. tensile stress	100Mpa(5%Ic degradation)
Max. tensile strain	0.15%(5%Ic degradation)
Min. bending radius	30mm(5%Ic degradation)
Critical temperature	110 K
Insulator	Maylar
Breakout voltage	300V(10μm, 300 K)
Thickness of insulator	≤ 10μm

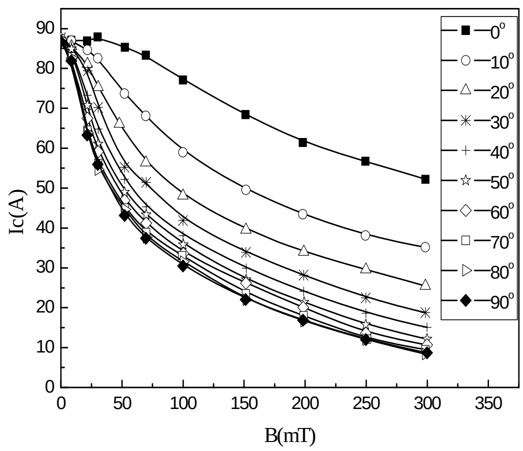

Fig.2 Critical current versus magnetic field

For the turn-to-turn coil insulation, a coating of 0.01mm in thickness was applied to the Bi-2223 tape as the tape was being wound into its double pancake coil. The double pancake coil was separated from its winding mandrel and spiral wrapped with glass insulation. The wrapped pancake coil was then placed on top of a copper sheet. The purpose of the copper sheet was to improve axial thermal conduction. The double pancake coil and its copper insert were then epoxy impregnated. After epoxy resin DW-3 impregnation, the double pancake coils were stacked and spliced together on the inner diameter to form a continuous double pancake coil. The double pancakes were then stacked in a precision fixture and subsequently spliced at the outer diameter using a copper transition piece.

The magnetic field analysis was performed on the HTS magnet. There were the primary areas of interest in the analysis: axial B-field strength and homogeneity to establish the waste water processing parameters, radial B-field strength to establish the critical current margins and performance of the HTS tape. The distribution for magnetic field in the HTS magnet is plotted in Fig.3. Where the center field in the magnet is about 3.23 T. The maximum radius magnetic field in the magnet is shown in the Fig.4, where the maximum radius field is located at the center of top in the magnet.

The analysis in HTS magnet on mechanical characteristics is shown in the Fig.5 for strain and Fig.6 for the hoop stress, the maximum hoop strain in the HTS magnet is about 2.0×10^{-6} . The maximum hoop stress is located at the inside middle-plane in the magnet. Its value is about 4.747 MPa.

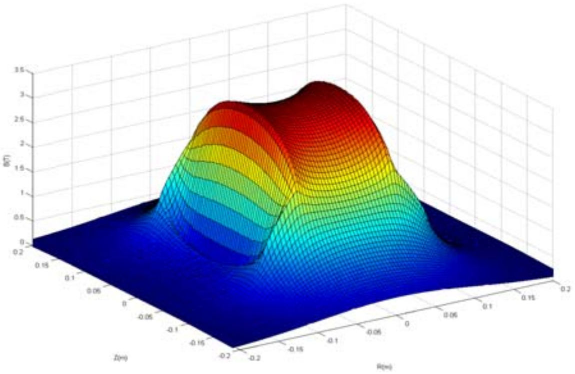

Fig.3 Magnetic field distribution in magnet (unit: T).

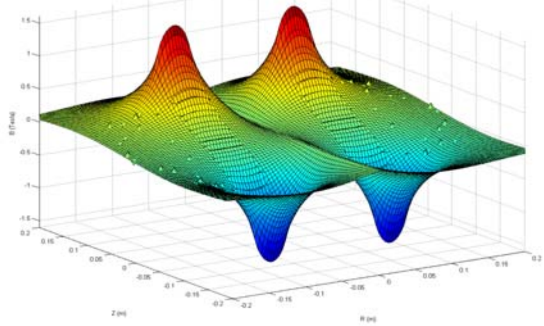

Fig.4 Radius component of magnetic field distribution(unit: T).

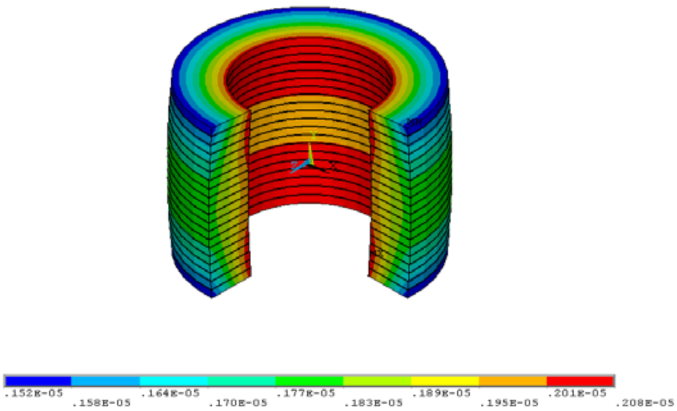

Fig 5 Hoop strain in HTS magnet.

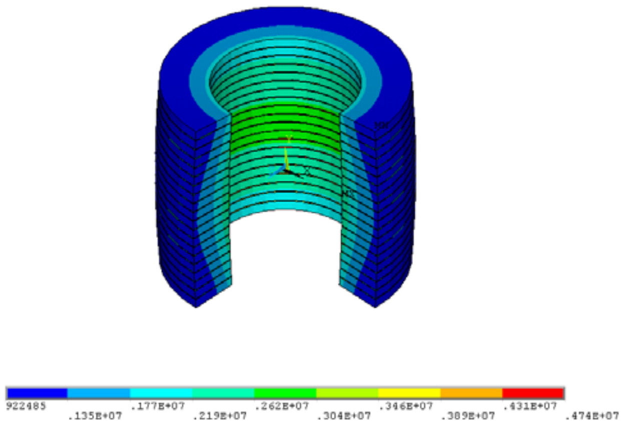

Fig 6 Hoop stress in HTS magnet (Unit: Pa).

CRYOSTAT, THERMAL LOAD AND MODEL HTS COIL

The cryostat for the high temperature superconducting magnet has the outer diameter of 650 mm and height of 805mm and weight of 160 kg. The cryostat had a penetrating room-temperature bore of 61 mm in diameter. The two-stage GM cryocooler was adjacently mounted on one side of the cryostat. In order to avoid a decrease of cooling capacity caused by the influence of the magnetic field, the magnet was cooled down using high purity copper braid for a flexible thermal link which connected magnet with second stage. Super-insulation of 15 layers was provided around the superconducting coil to minimize thermal losses. Coil terminals was cooled through pieces of ALN chips. The magnet was protected by using 4 diodes. A pair of copper current leads was anchored between the room temperature and the first stage of cryocooler. A thermal radiation shield was mounted on the flange of first-stage to reduce heat radiation to the coils and HTS current leads. A slit was installed in the wall of the thermal radiation shield to cut the eddy current, and two reinforcements with stainless ring were mounted to the two ends of the thermal radiation shield. Operational heat loads for the thermal analysis were calculated. The heat load at the first cool head of cryocooler is about 11.08 Watt and the heat load at second-stage cool head is about 2.075 Watt. The cooling capacity of the cryocooler as a function of temperature was obtained from the commercial manufacturer, and at 20 K the cooling capacity is about 20 Watt. Fig.7 shows the temperature different (ΔT) between the magnet and second-stage cool head with respect to the heat load during thermal contact length (L) and cross-sectional area (A) given. It shows that the highly pure copper as the thermal contact can reduce the temperature different. Fig.8 shows ΔT with respect to cross-sectional area of the thermal contact during heat load given.

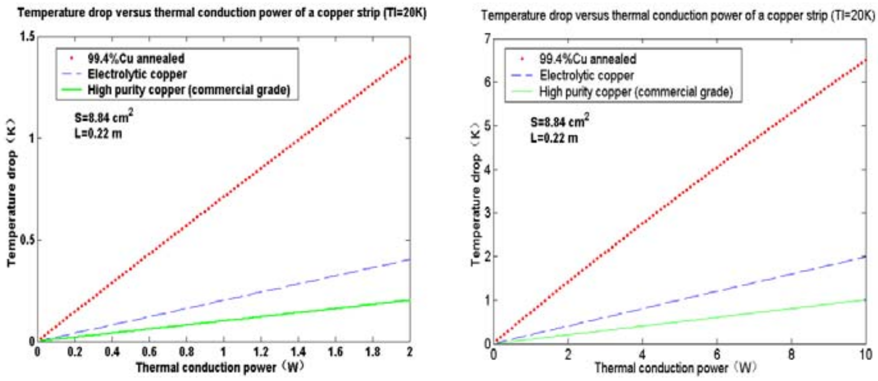

Fig.7 Profiles of temperature different with respect to heat load.

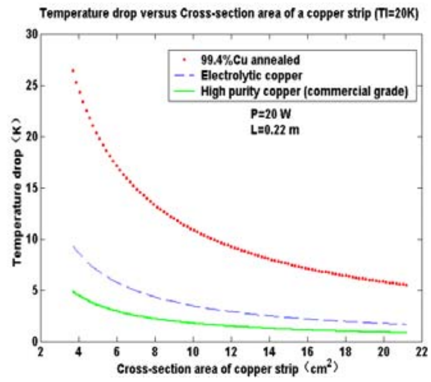

Fig.8 Profile of ΔT versus cross-sectional area.

In order to study the fabricating technology, a double pancake coil has been fabricated and tested. The photograph of the double-pancake coil is shown in Fig.9. The fabrication technology is based on the wet-winding technology, and it is impregnated by DW-3. The first double pancake coil is with an inner diameter of 80 mm, outer diameter of 199.3 mm, thickness of 8.75 mm and total turn of 222. It was tested in liquid nitrogen with voltage criteria 1 μ V/cm. The critical current is 36.5A. The calculation shows the maximum radius field 0.15T, and axis magnetic field is 0.3T. The E-J curve is shown in Fig.10.

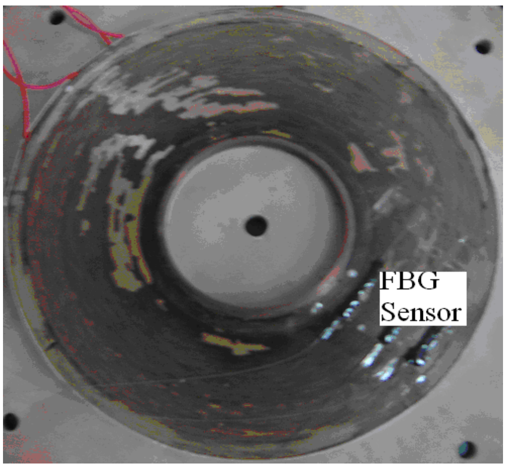

Fig.9 Photograph of fabricated HTS coil.

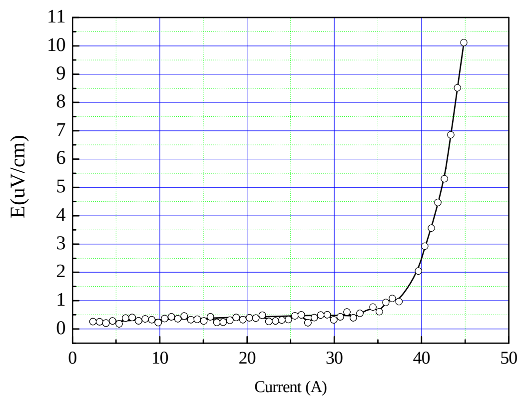

Fig.10 Test results for HTS coils

CONCLUSION

The design of HTS magnet for the magnetic separator has been completed, The fabrication of the full size HTS magnet will be finished by the end of the July, 2004.

REFERENCES

[1] H. Kumakura etc. PhysicaC 350(2001)76-82.
[2]K.Ohmatsu etc. IEEE Transactions on Applied Superconductivity 9(1999)924-928.