

Development of large bore superconducting magnet for wastewater treatment application

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Abstract

Water issue, especially water pollution, is a serious issue of 21st century. Being an significant technique for securing water resources, superconducting magnetic separation wastewater system was indispensable. A large bore conduction-cooled magnet was custom-tailored for wastewater treatment. The superconducting magnet has been designed, fabricated and tested. The superconducting magnet was composed of NbTi solenoid coils with an effective horizontal warm bore of 400 mm and a maximum central field of 2.56T. The superconducting magnet system was cooled by a two-stage 1.5W 4K GM cryocooler. The NbTi solenoid coils were wound around an aluminum former that is thermally connected to the second stage cold head of the cryocooler through a conductive copper link. The temperature distribution along the conductive link was measured during the cool-down process as well as at steady state. The magnet was cooled down to 4.8K in approximately 65 hours. The test of the magnetic field and quench analysis has been performed to verify the safe operation for the magnet system. Experimental results show that the superconducting magnet reached the designed magnetic performance.

Keywords : Conduction-cooled, Magnetic separation, Large bore, wastewater treatment

1. INTRODUCTION

Since the 1970s, magnetic separation has been increasingly used for the purification of liquid, such as heavy-metal ion removal, purification of kaolin clay, waste recycling, and recycling of glass grinding sludge [1]. As we know, there is only 2.5% of the water on Earth being fresh, and also climate change modeling forecasting that many areas will become drier, the ability to recycle water and achieve compact water recycling systems for sewage or ground water treatment is critical [2]. Compared to the conventional activated sludge water treatment system, superconducting magnetic separation water treatment system can achieve not only high separation efficiency and high processing speed but also significant cost reduction. The full-scale application of magnetic separation processes will greatly contribute to preserving the global environment.

Compared to liquid helium-cooled superconducting magnet, conduction-cooled superconducting magnet has many advantages, such as operating convenience, low operating costs, compact size, flexibility, mobility and so on [3]. The technology can provide the customer access to high magnetic fields in applications or locations, where the use of liquid helium is difficult or expensive [4, 5]. Since the first successful conduction-cooled superconducting magnet demonstrated by K. Watanabe in 1992 [6], the

superconducting magnet technology has experienced great advance and has been commercially available. The cryogen-free superconducting magnet system is almost developed toward the high magnetic field generation [7, 8]. The superconducting magnet is the core of the superconducting magnetic separation water treatment system. The wastewater flows through the warm bore. High performance of the water treatment system needs a magnetic field within large space (higher than 0.7T and larger than 0.15m²) [2]. In order to increase the capacity of the superconducting magnetic separation water treatment system, large bore superconducting magnet is needed for magnetic separation. Nowadays, large bore (larger than 400mm) superconducting magnet is mostly operated in the liquid helium with zero boil-off [9]. Due to limited solid thermal conductance relative to liquid helium, conduction-cooled superconducting magnet suffers from larger temperature difference and weaker cryogenic stability. Therefore lots of works need to be done to develop much larger bore conduction-cooled superconducting magnet for magnetic separation. In this work, a large bore conduction-cooled superconducting magnet with a warm bore of 400mm providing a center field of 2.56T is developed in our laboratory.

2. SUPERCONDUCTING MAGNET DESIGN

This conduction-cooled magnet is composed of a solenoid

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NbTi coil. The inner diameter of the coil bore is set to 460mm to meet the warm bore size requirement. The coil is fabricated with three pieces of multi-filamentary NbTi/Cu superconducting wires in hand, which were bought from Western Superconducting Technologies Co., Ltd. (WST). The wires have same characters, which are listed in Table 1. The wire diameter is 0.55 mm, Wire insulation is no less than 2.5 kV for the 0.025 mm thickness varnish coatings. The three pieces of wires are wound onto a 5mm thickness aluminum former successively, and then be connected in series and powered with a single power supply.

The solenoid magnet is designed to operate at current of 65A and produce a central magnetic field of 2.56T. Using a simple simulation program developed by ourselves, the magnetic field distribution is calculated. The magnetic field inside the solenoid coil is all larger than 2.56T, and the maximum magnetic field is 3.4T. Outside the solenoid winding, magnetic field decrease rapidly as distance away from the centre of the coil. Fig. 1 shows the magnetic field distribution.

The design parameters of the superconducting magnet are listed in table 2. Owing to the so large diameter of coil, the instabilities resulted from conductor motion and other spot disturbances should be considered specially. Therefore a safety margin of 20% is set considering the conductor critical performance. The superconducting coil is wound directly onto an aluminum former with a slit along axial direction. The slit reduces heat generation due to eddy current induce in the former during charging and thick and 378mm high respectively. two end plates flange are 14mm thick, the former and the end plates are to be welded together.

TABLE 1
SPECIFICATION OF SUPERCONDUCTING WIRE FOR COIL.

Superconductor	NbTi/Cu
Wire Diameter (mm)	0.55±0.007
Cu/Sc Ratio	1.8
Filament Diameter (μm)	20
Number of filaments	55
Twist Pitch (mm)	30±5
Insulator	PVF
Critical Current (A)	≥130A(6T)
RRR	160

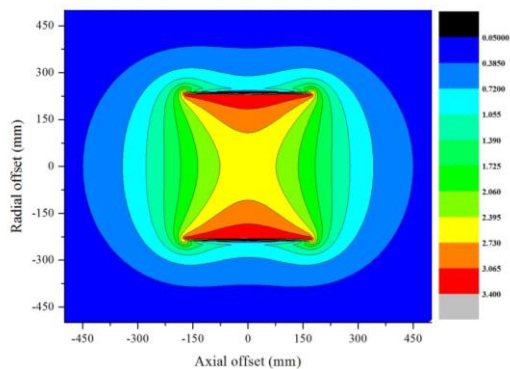


Fig. 1. Magnetic field distribution of magnet along both axial and radial direction.

TABLE 2
MAJOR PARAMETERS OF THE SOLENOID MAGNET COIL.

Inner Diameter (mm)	460
Outer Diameter (mm)	493
Height (mm)	350
Self inductance (H)	140.3
Total turns	19091
Layer number	30
Operating Current (A)	65
Central magnetic field (T)	2.56
Maximum magnetic field (T)	3.4

The superconducting magnet coil is manufactured by dry winding technology, which are frequently used for small-bore and low-field application because of their low manufacturing costs. Stabilities of dry-wound solenoid magnet have been investigated by several authors [10-12]. Before the winding process, electrically insulation is made by spraying a layer of 20 microns thick PTFE on the outside of former and the insides of the two end plates. During wire winding, a maximum tension of 80 N/mm² is applied to the wires to overcome the huge hoop stress when magnet generate strong field. To increase the insulation and resistance to the conductor motion between layers and turns, a 30microns thick fiber-glass cloth together with STYCAST 2850 is wrapped between two adjacent layers. When a layer of wire winding is done, a thin layer of STYCAST 2850 is brushed onto the wire layer, and the thin fiber-glass cloth is wrapped, then another thin layer of STYCAST 2850 is added. After that superconducting wire is directly wound onto the epoxy resin and press it to deform freely. As the epoxy being solidified, there will be a large number of serrations formed between the fiber-glass cloth and the superconducting wire, as in fig. 2 shows. The notches of the serration keep the conductors at its location to prevent possible conductor motion. In order to improve layer to layer conductance, the layer of epoxy together with the fiber-glass cloth should be as thinner as possible. As mentioned above, the coil diameter and height is large, which makes the temperature difference in the coil bigger. So in order to improve thermal conductance between superconducting wires and the outer thermal link, a layer of copper braided strips are laid outside of the last wire layer, after the last layer wire winding is finished. The thickness of the copper braid is 1.5mm and the width is 22mm. Totally 70 strips are uniformly laid along axial direction of bobbin. The two ends of all the copper braids are pressed and bolted to the two end plates of bobbin by two pair collars. After that, a total thickness of 5mm binding layer is applied to control hoop stress due to large Lorentz force. The bandage is a layer of fiberglass tapes together with DW-3 epoxy resin, a maximum banding tension of the order of 120 N/mm² is applied to the fiberglass tapes during banging. After finishing the windings and bandings, the two magnet end plates are bolted together to form a rigid structure. Fig. 2 shows the layout of the coil layers.

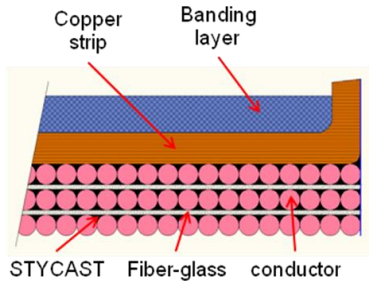


Fig. 2. Layout of the coil layers.

3. CRYOGENIC SYSTEM DESIGN

Fig. 3 shows the configuration of the cryostat, the cryostat has a penetrating horizontal room temperature bore of 400mm in diameter, and the dimension of the cryostat is about 977mm long, 574mm wide and 792mm high. The cryostat basically consists of GM cryocooler, SS vacuum chamber, the thermal radiation shield, multilayer insulation (MLI), supports, thermal conduction link and so on. The vacuum chamber is made by 316 stainless steel. The two-stage GM cryocooler is mounted off-the-centre on the top plate of the chamber. The cryocooler is carefully arranged at the position where the magnetic field is lower than 0.38 T for the second-stage cold head and lower than 900G for the motor, to avoid a decrease of cooling capacity caused by the influence of the magnetic field. The thermal radiation shield is cooled down to 40 K by the first-stage of the cryocooler using copper braids thermal link, and the magnet is thermally anchored to second-stage of the cryocooler through flexible high purity copper braid. Indium gaskets and Apiezon N grease have been used at all the contact interfaces to reduce thermal resistance. The magnet, weighing about 80kg, is mechanically fixed by four pairs of epoxy-fiberglass track type rings to the upper vacuum flange and four stainless steel rods to the lower vacuum flange. The MLI of 40 layers and 60 layers are provided around the superconducting magnet and thermal shield to reduce thermal radiation heat losses. A pair of hybrid current leads, consisting of pure copper leads in the warmer region and Bi-2223 leads in the colder region are used to charge the magnet. Copper current leads are joined with Bi-2223 current leads with lead-tin solder, and the joints are thermally anchored to the top plate of the thermal shield and electrically insulated by using of AlN disc spacers. Similarly the magnet terminals are soldered to Bi-2223 current leads, and cooled down through pieces of AlN chips with maintaining the electrical insulation with heat transfer plate.

4. TEST RESULT AND DISCUSSION

Five rhodium iron resistance thermometers are placed at both sides of magnet, both stages of the cryocooler, and lower flange of the thermal shield respectively. At the top of the vacuum vessel a pressure gauge is installed to monitor

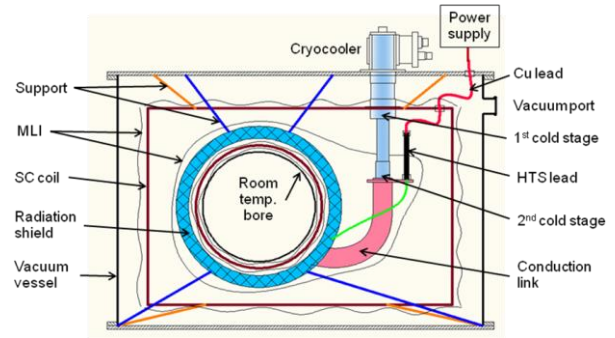


Fig. 3. Schematic of the cryostat in the conduction-cooled magnet.

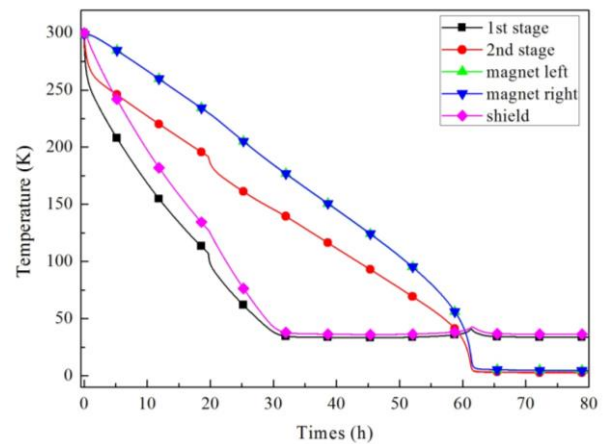


Fig. 4. Initial cool-down temperature of conduction-cooled magnet system after turning on cryocooler.

the vacuum status. When the cryostat system obtain the vacuum pressure of 10^{-2} Pa, the GM cryocooler is turning on, the temperature of the thermal radiation shield reached 37K in about 32h, and the temperature of the superconducting magnet is cooled down to about 4.8K in approximately 65h. Fig. 4 shows the temperature of system changing with the time during initial cooling down.

The magnet coil is connected to two pairs of diodes in parallel to protect the coil during quench. The magnet has been energized many times to enable the magnet to function at its full designed current and fields. The first quench occurred at 55 A (2.16 T), second at 62 A (2.44 T) and third at 69 A (2.72 T). Finally, the magnet produced a field of 2.56 T at a current of 65A without quench. The B-I data obtained and quench positions are plotted in Fig. 5. During the quench of the magnet in current of 69 A, the maximum temperature rise is lower than 70K. The test results show that the superconducting magnet is reliably protected during quench, and the maximum hot-spot temperature can be pressed. Fig. 6 shows the temperature changing with time during quench and recovery. The superconducting magnet can be recovered to superconducting state after 2.5 h. After the training, the maximum ramping rate is about 0.025 A/s due to diode voltage limitation, and the charging time is about 43 min. During charging the superconducting magnet, the maximum temperature rise is lower than 1K.

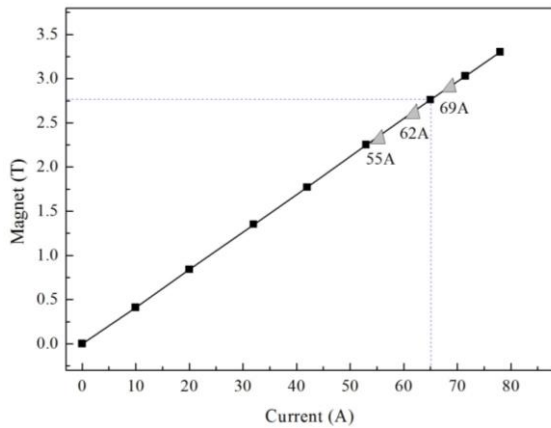


Fig. 5. B-I data obtained and quench positions during magnet training.

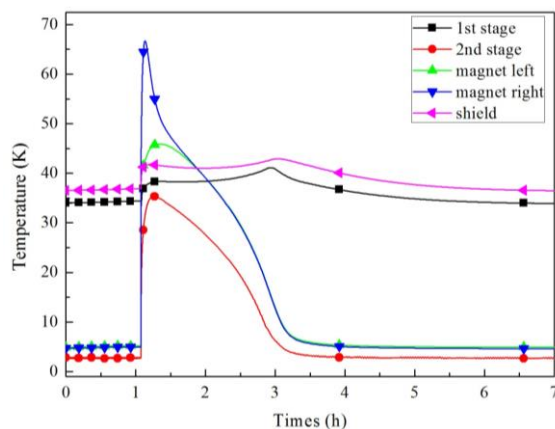


Fig. 6. Temperature changing with time when the magnet was quenched.

The conduction-cooled magnet is designed for magnetic separation wastewater system. Fig. 7 shows a flow chart of a cleaning of wastewater. The magnetic separation wastewater system consists of a reaction tank, a separation tank and a solid-liquid-magnetic-separation tank. The latter mainly includes the superconducting magnet and several magnetic filters. Contaminants in wastewater are magnetized in the reaction tank, heavy density contaminants sediment in the separation tank, and the remaining floating magnetic flocks are captured by magnetic force on the magnetic filters. The whole wastewater treatment system is under development, the capacity of the system is designed to be about 5000 tons per day.

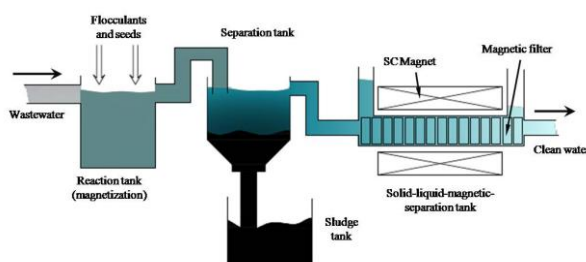


Fig. 7. A cleaning process of wastewater treatment by using superconducting magnet.

4. CONCLUSION

A large bore superconducting magnet is designed, fabricated and evaluated. The magnet system can provide a 2.56T center magnetic field with warm bore of 400mm. The superconducting magnet system is cooled by a two-stage 1.5W 4K GM cryocooler. The test of the magnetic field and quench analysis has been performed to verify the safe operation for the magnet system. The magnet is expected to be used for superconducting magnetic separation wastewater treatment.

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