Cryocooled Cooling System for Superconducting Magnet

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ABSTRACT

A cryogenic cooling system using a two-stage cryocooler for a superconducting magnet has been designed, fabricated and tested. The superconducting magnet is composed of NbTi solenoid coils with an effective warm bore of 52 mm and a maximum central field of 3 T. The NbTi solenoid coils are wound around a copper form that is thermally connected to the second stage cold head of a cryocooler through a conductive link. The temperature distribution along the conductive link was measured during the cooldown process as well as at steady state. The contact resistance between the coldhead and conductive link was estimated from the cooling power of the cryocooler, the contact area, and the temperature gradient. The effect of the supplied current on the temperature distribution is also discussed.

INTRODUCTION

Cryocoolers have been applied to many academic and industrial applications, such as space exploration, cryo-surgery and liquefaction.[1-4] Recently, many superconducting magnet systems have been required to use cryocoolers alone as the heat sink, instead of liquid helium or nitrogen, to achieve increased simplicity, compactness, and efficiency. The Korea Basic Science Institute (KBSI) has initiated the development of a conduction-cooled superconducting magnet system using a two-stage cryocooler for a material control application. The superconducting magnet for material control has to be designed to have a strong magnetic field gradient in a control volume.

In the conduction-cooled superconducting magnet system examined here, a 4 K Gifford-McMahon (GM) or Pulse-tube cryocooler is employed to cool the magnet down to a certain operating temperature. The cold head of the cryocooler has a positional restriction, in that it needs to be located in a low magnetic field area to avoid degradation of its cooling capacity. Therefore, a conductive link between the magnet and the cryocooler is crucial in developing the superconducting magnet system. This paper presents the design, fabrication, and test of a conduction-cooled superconducting magnet system with emphasis on the cryogenic cooling point of view. In addition, the conductive link between the magnet and cryocooler is discussed with respect to the contact resistance and the cooling power of the cryocooler.

DESIGN OF CONDUCTION-COOLED MAGNET SYSTEM

The conduction-cooled superconducting magnet system considered here is schematically shown in Fig. 1. The NbTi solenoid coils are wound around the magnet form which is thermally connected

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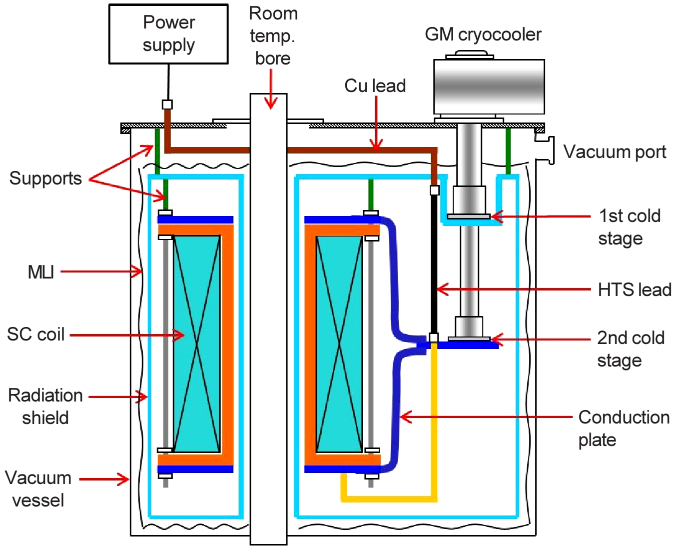

Figure 1. Schematic of conduction-cooled superconducting magnet system.

to the second-stage cold head of the cryocooler through a conductive link. The room temperature bore with a 52 mm diameter is located in the middle of the NbTi solenoid coils, which are suspended by four gravitational supports. The binary current lead, a series combination of a normal conductor in the high-temperature section and an HTS conductor in the low-temperature section, is employed for this application. The entire cold part is covered by a thermal shield and wrapped with multilayer insulation (MLI) to minimize the thermal radiation load.

In the magnet system, the cryogenic cooling requirements are continuously generated primarily by three different physical mechanisms: thermal conduction through the mechanical supports, thermal radiation, and heat transferred from the current leads. The estimated cryogenic loads at the first and second stages are 52.8 and 1.1 W, respectively; these match the cooling capacity of our two-stage GM cryocooler (Sumitomo, model RDK415D) with 20-30% margin.

The operation of the cryocooler is limited by the magnetic field. The performance of our two-stage GM cryocooler is slightly degraded when the magnetic field is over 1 Tesla around the second-stage regenerator, and the magnetic field should be lower than 500 Gauss for the stepper motor in the warm end.[5] In order to verify the performance of the cryocooler, an analysis of the magnetic field in the system was carried out and the results are plotted in Fig. 2. Several possible positions of the two-stage GM cryocooler for this application were considered. One of the simplest designs is to mount the cryocooler directly on top of the vacuum vessel so as to provide cooling to the first-stage thermal shield and the 4 K superconducting magnet, as shown in Fig. 2. The magnetic field at the second-stage regenerator and at the stepper motor are low enough with this configuration to achieve the normal performance of the cryocooler in this system.

MAGNET SYSTEM FABRICATION AND TESTING

The NbTi superconducting coils were fabricated by the wet winding method using Stycast® epoxy. The NbTi multifilamentary composite superconducting wire (I_c = 870 A at 3 T and 4.2 K) of 0.9 mm diameter was wound on the copper form which has a 1 mm width slot along the axis to reduce eddy losses during magnet energizing. A stainless steel wire of 1 mm diameter was employed to support the electromagnetic force in the coils. The copper form was thermally connected to the second-stage cold head of the cryocooler by flexible, tinned copper braids that protect the cold head from thermal contraction during the cooldown process. Cryogenic thermal grease (or indium) was applied between the copper form and the cold head of the cryocooler as a thermal contact

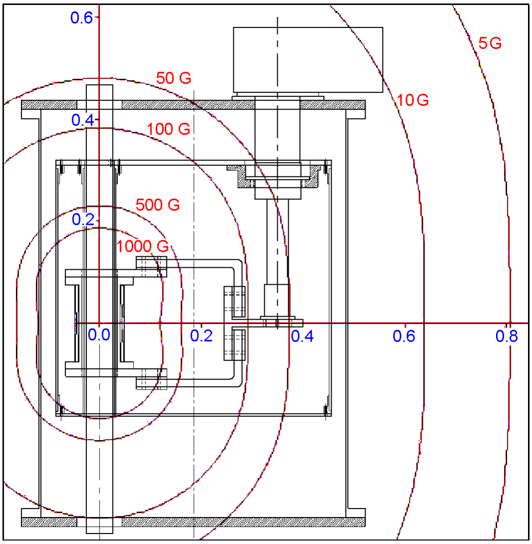

Figure 2. Magnetic field around superconducting coils in the conduction-cooled magnet system.

medium, ensuring minimum thermal resistance. A copper thermal shield was suspended from the top plate of the cryostat with gravitational supports made of threaded G10 rod, and attached to the first-stage cold head.

The temperatures in the magnet system were measured with platinum resistance thermometers (Lakeshore PT 111) for first stage, and Cernox^{TM} for second stage, at a number of locations as indicated in Fig. 3. During the initial phase of the testing, the cryostat was pumped down to the range of 5×10^{-3} torr, and then was cooled down to liquid helium temperature using the conductive link connected to the cryocooler. Once the superconducting coils were cooled down, a current was supplied by the magnet power supply, and the magnetic field at the center of the coils was measured using a Gaussmeter (Lakeshore model 460). During the cooldown process, temperatures were recorded every 2 min with a data acquisition system operated through LabView^{TM} software. Variables in this testing were the interfacial material and the magnitude of supplied current.

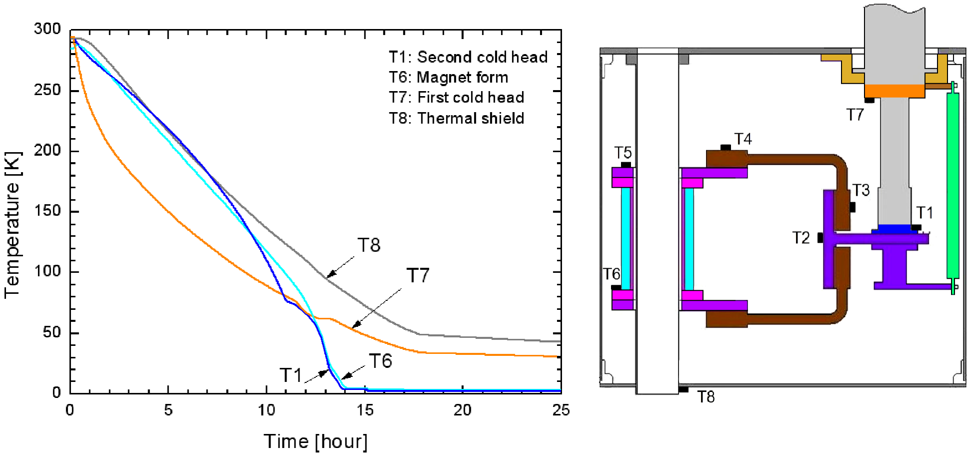

Figure 3. *Left:* Temperatures of first and second stages after turning on the cryocooler; *Right:* position of temperature sensors in the magnet system.

Table 1. Temperature distribution along the conductive link in the magnet system.

Test No.	T1	T2	T3	T4	T5	T6	Remark
1	3.21	-	5.80	5.82	5.82	6.10	
2	2.82	3.03	3.39	3.38	3.61	3.57	Cryogenic grease
3	2.89	3.24	3.57	3.55	3.75	3.71	↑
4	3.14	3.20	-	3.77	-	4.03	Indium sheet
5	2.94	3.01	-	3.35	-	3.61	↑

Cooldown

Figure 3 shows the temperature history of the first stage, second stage, and superconducting coils after turning on the cryocooler. During the initial cooldown process, the temperatures decreased almost at a constant rate; it took approximately 15 hours for the first-stage cold head to reach 50 K, and 14 hours for the second-stage cold head to reach 4.2 K. After 18 hours running of the cryocooler, the temperature of the superconducting coils was stabilized, and the temperatures at the first and second-stage cold heads were 31.2 and 3.21 K, respectively. At steady state, the temperature gradient along the conductive link in the system was observed, and the temperature of the magnet form was 6.1 K, resulting from the thermal contact resistances in the conductive link assembly. For practical contact between metals, the interface is irregular enough that only intermittent contact occurs. Therefore, even though enough force was applied to the contact, the effective contact area was much smaller than the apparent contact area. The effective contact area can be increased by the use of an interfacial film or bonding agent, resulting in increasing the thermal conductance.[6] The cooldown process was repeated using different interfacial materials between the conductive link and the cold head of cryocooler.

In Table 1, the temperature distributions along the conductive link are summarized at steady state. In test 1, no additional material was applied between the conductive link and the cold head; in other words, it was pure metal-to-metal contact. The cryogenic grease, Cryocon®, and an indium sheet were applied as bonding agents in tests 2 through 5. The existence of a bonding agent at the interface increased the thermal conductance by increasing the effective contact area so that the temperature of the magnet form was below 4 K.

The effective contact conductance, $h_{c,eff}$, can be estimated from the net heat transfer rate in steady state.

$$Q_{ref} = A \cdot h_{c,eff} (T_1 - T_2) \tag{1}$$

where A and T denote contact surface area and temperature, respectively. In our system, the effective contact conductance between the cold head and the cooling plate in the case of tests 1, 2 and 5 was 48.1, 296.1 and 887.3 W/m^2 K, respectively.

Magnet Energization

Figure 4 shows the temperatures at the second stage and the supplied current in the system with respect to elapsed time. The current was increased by 10~30 A/min up to 80 A, and the central magnetic field increased up to 1.4 Tesla. The temperatures at the second stage increased with supplied current, and the temperature at the superconducting coils was 4.89 K when the current of 80 A was supplied. In Fig. 5, the temperatures at the joints of the HTS current leads are plotted in the cooling capacity curve of the two-stage GM cryocooler. The temperature at the second-stage joint increased with the supplied current in the range of 0~80 A; this was mainly because of joule heating at the joint in our system.

CONCLUSIONS

A conduction-cooled superconducting magnet system using a two-stage GM cryocooler was successfully designed, fabricated and tested. The superconducting coils were cooled down to approximately 4 K and energized up to 80 A. A temperature gradient between the superconducting

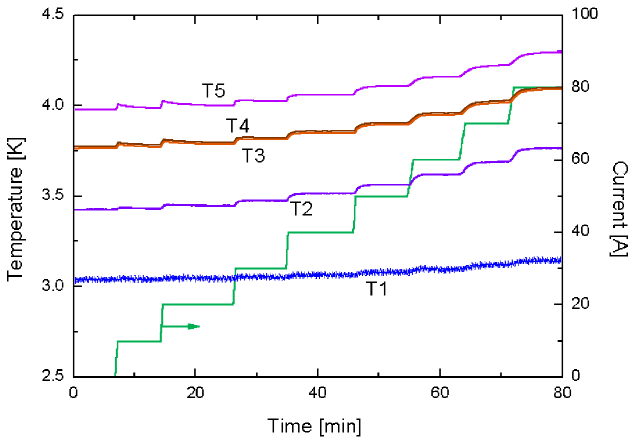

Figure 4. Second-stage temperatures versus supplied current with respect to time. (Position of temperature sensors is shown in Fig. 3)

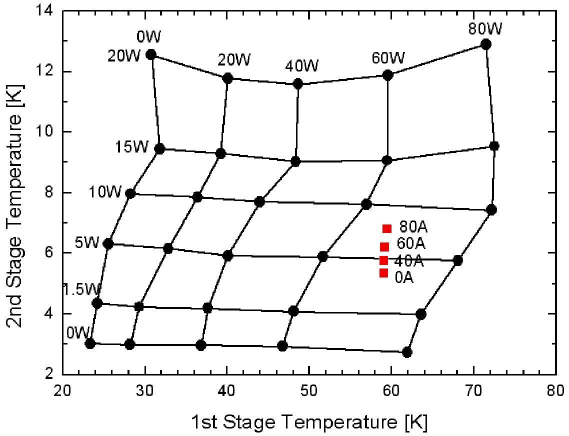

Figure 5. Temperatures achieved at the joints of the HTS current leads plotted in the cooling capacity curve of the two-stage GM cryocooler

coils and the cold head of the cryocooler was observed, and was reduced by increasing the interfacial thermal conductance using a bonding agent. An indium sheet between the cold head and cooling plate had a higher effective contact conductance than that of cryogenic grease in our application. The joint of the HTS current lead will be modified in the near future in order to maximize the cooling effect and minimize joule heating.

ACKNOWLEDGMENT

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