Performance Test of a Metal Insulated HTS Magnet with Conduction Cooling

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Abstract. In the fabrication and operation of an HTS magnet, ensuring thermal stability against uneven quench is the most important factor. A sample HTS magnet was designed and fabricated with the metal insulation (MI) method and its fundamental characteristic analysis was conducted under the liquid nitrogen cooling system. On the basis of the electromagnetic analysis results, the thermal and mechanical structural design and detailed experimental analysis of the MI HTS magnet under the conduction cooling condition were performed in this paper. The conduction cooling condition was achieved using the 1st stage GM cryo-cooler. The characteristic resistances and the charging and discharging times of the magnet were measured according to the operating temperature of 32 K of the HTS magnet. The long-term current flowing test was conducted by monitoring the coil temperatures. In addition, the thermal stability of the HTS magnet was analyzed when the over current flowed into the magnet. The test results will be applied to the large size HTS MI magnet.

1. Introduction
In the fabrication and operation of an HTS magnet, ensuring thermal stability against uneven quench is the most important factor. The no insulation (NI) winding method allows the HTS magnet to maintain the best thermal stability by distributing the quench energy evenly [1-4]. The NI HTS magnet has the characteristic resistance connected to the inductance of the magnet in parallel. The charging and discharging time are dependent on the characteristic resistance. In the case of, however, the characteristic resistance of the NI HTS magnet is too small, the charging and discharging time takes too long to generate the desired magnetic field.

In 2013, our research team had developed and tested a NI HTS magnet for a 10kW-class prototype DC induction heater. In the previous research, the characteristic resistance was measured to be 98 \(\mu\Omega\), and it required 2,300 s to charge the current of the magnet of 230 mH with the maximum magnetic flux density [5-7]. Thus, we employed the winding method of metal insulation (MI) using stainless steel to reduce the long charging and discharging time. A sample HTS magnet was designed and fabricated with the MI method and its fundamental characteristic analysis was conducted under the liquid nitrogen cooling system. The characteristic resistance was measured to be 2.9 m\(\Omega\) and the charging and time constant of the discharging mode was calculated to be 2.5 s. For the higher than critical current flowed to the sample magnet, detailed investigations through voltage and temperature characteristic analysis were conducted [8].

On the basis of the electromagnetic analysis results, the thermal and mechanical structural design of the MI HTS magnet under the conduction cooling condition were performed and the detailed experimental analysis results were presented in this paper. The minimum cooling temperature of the 1st
stage of the conduction cooling system was 14.6 K, while the total heat invasion was calculated to be approximately 25 W. The temperature of the HTS magnet was saturated to be 21.4 K after 6 hr. The inductance of the MI HTS magnet including iron core was calculated to be 52.5 mH. The characteristic resistance was calculated to be 20.6 mΩ. This characteristic resistance is higher than that of the MI HTS magnet without the stycast painted. At that time, the time constant was measured to be 2.5 s. The input current was hold on the 600 A, and the quench occurred. However, the HTS tape in the coil was not damaged, because the current bypassed into the different layers of the magnet.

Through the characteristic analysis results of the MI HTS magnet, the large scale implementation of 2G HTS technology for commercial application has been researched. For various designs of the HTS commercial applications, their optimal designs will be presented.

2. Design of a MI HTS magnet under the conduction cooling system
Prior to the real fabrication and experiment, the cooling system with cryostat for the HTS magnet was designed. In this section, the heat transfer and mechanics analysis using a FEM tool was performed and the results were presented. When the conduction cooling system design is performed, the heat invasion components including conductive and radiative parts should be considered above all [9-12]. A MI HTS magnet with a cryostat was fabricated and tested using the conduction cooling method. As shown in Figure 1, the first stage GM cryo-cooler was installed on the cryostat and the MI HTS magnet was equipped with the cryostat using GFRP supporters. In addition, the metal current leads were connected to the current terminals of the magnet. The height of the cryostat was 709 mm. The cryostat radius was fabricated to be 240 mm. The detailed specifications for the cryostat with the conduction cooling system will be presented in this section.

![Figure 1. 3D design model of the MI HTS magnet with conduction cooling system.](image)

2.1. Specifications of the MI HTS magnet and the cryostat
The experimental specifications of the MI HTS magnet and the cryostat were presented in detail, as indicated in Table 1. The HTS tape from the SuNAM in Korea was used for the MI HTS magnet. The minimum critical current of the HTS tape was measured to be 365 A under the LN2. The total length of the HTS tape was 134 m. The inductance of the magnet was measured to be 4.5 mH. The critical current of the MI HTS magnet under the 77.4 K and 32 K were measured to be 196 A and 600 A, respectively. The single stage GM cryo-cooler donated by Sumitomo Korea was used on the fabricated MI HTS magnet. The saturated temperature of the 1st stage of the conduction cooling system was measured to be 14.6 K with no current condition, and the total heat invasion was 25 W as shown in the cooling curve of the cryo-cooler in Figure 2. The critical current at the target cooling temperature of 40 K of the MI HTS magnet was estimated to be 430 A, considering only the perpendicular magnetic flux density as shown in Figure 3. The perpendicular magnetic flux density was 1.9 mT at the current of 1 A from the FEM analysis results.
Table 1. The experimental specifications for the MI HTS magnet fabricated with the cryostat using a conduction cooling.

| Parameter                                           | Value                                                                 |
|-----------------------------------------------------|----------------------------------------------------------------------|
| HTS tape maker                                      | SuNAM, Korea                                                          |
| HTS tape (Width × Thickness)                        | W12.1 (±0.1) mm × T100 (±15) μm                                      |
| SUS tape (Width × Thickness)                        | W12 mm × T100 μm                                                     |
| Minimum critical current (77 K)                     | ≥365 A (copper laminated)                                            |
| Substrate material                                  | Hastelloy                                                             |
| HTS magnet type                                     | MI, racetrack, double pancake                                       |
| Size (Radius × Length)                              | R115 mm × L300 mm                                                    |
| Number of turns in a SPC                            | 50                                                                   |
| Total length of the HTS tape                        | 134 m                                                                |
| Inductance of the magnet without iron core          | 4.5 mH                                                               |
| Critical current at 77.4 K                          | 196 A                                                                |
| Critical current at 32 K (ramping rate 1 A/s)       | 600 A                                                                |
| Target operating current of the magnet              | 350 A at 40 K                                                       |
| Position of the magnetic field sensor               | (x, y, z) = (27.5 mm,0,0)                                            |
| $B_{\text{norm}}$ at the center of the magnet       | 3.43E-4 (T/A)                                                        |
| Maximum perpendicular magnetic flux density         | 1.90E-3 (T/A)                                                        |
| from FEM analysis results                           |                                                                      |
| Cryo-cooler                                         | Sumitomo 1st GM cryo-cooler SRDK-500B                                |
| Total heat invasion                                 | 25 W under no load condition                                         |
| Minimum cooling temperature                         | 14.6 K at the 1st stage                                              |

![Figure 2](image2.png) Cooling curve according the temperature of the single stage cryo-cooler (ref. by the Sumitomo Korea).

![Figure 3](image3.png) Critical current estimation curves of the MI HTS magnet according to operational temperatures.
2.2. Thermal analysis of the MI HTS magnet with conduction cooling system

The heat transfer analysis of the HTS magnet with GFRP supporters was performed and the results were presented in Figure 4. The 8 GFRP supporters were installed to fix the HTS magnet. Two brass current leads including the copper terminals on the room temperature of 300 K were connected to the 1st stage of the conduction cooling system. The total heat loads of 8 GFRP supporters were calculated to be 1.93 W, as described in Table 2. The two metal current leads have the heat loads of 42.7 W generated by the target current of 350 A under the temperature varying from 300 K to 20 K. The radiation loss of the magnet was calculated to be 3.73 W. After the cooling was completed, the saturated temperature of the 1st stage was 19.2 K and the highest temperature of the magnet was 24.4 K. The total heat load of the 1st stage was calculated to be 48.8 W.

![Figure 4. Heat transfer analysis results of the MI HTS magnet with the operating current of 350 A.](image)

**Table 2.** Heat load calculation of the MI HTS magnet with the operating current of 350 A.

| Stages | Heat transfer methods       | Parameters                                      | Qty. | FEM results |
|--------|----------------------------|-------------------------------------------------|------|-------------|
| 1st stage | Conduction | Metal current leads with the current of 350 A | 2 ea | 42.7 (W)    |
|        | Conduction | GFRP supporters (50 mm)                     | 8 ea | 1.93 (W)    |
|        | Conduction | Copper current leads at HTS magnets         | 2 ea | 0.42 (W)    |
|        | Radiation  | Radiative heat loads (MLI): emissivity:0.03 | 1 ea | 3.73 (W)    |
|        |             | Total heat load of the 1st stage            |      | 48.8 (W)    |

2.3. Thermal analysis of the MI HTS magnet with conduction cooling system

As shown in Figure 5, the body load condition caused by Lorentz forces from the HTS magnet was applied to the FEM analysis model and the fixed constraint at the bottom surface of the cryostat was applied for the stress analysis. The maximum stress of the MI HTS magnet was 13.5 MPa at the supporters arranged in the straight section of the cryostat. The HTS magnet was assumed that it was under solid state with the painted stycast, a kind of cryogenic epoxy. The coil maximum stress was calculated below 1 MPa. These results were acceptable according to the material properties of the GFRP [13].
3. Fabrication and the experimental results of the MI HTS magnet with conduction cooling system

3.1. Numbering
The fabrication process of the MI HTS magnet with conduction cooling system was described in Figure 6. First, the MI HTS magnet was fabricated and assembled with each part. The stycast was painted on the side of the magnet to improve the thermal contact between the bobbin cover and the HTS coil. The HTS magnet was installed on the cryostat and the two metal current leads were connected on the copper terminals of the HTS magnet. The multi-layer insulation (MLI) was wound around the HTS magnet to shield the radiation heat invasion.

3.2. Conduction cooling test results
The temperature curves of the MI HTS magnet were presented in Figure 7 when the magnet cooled down. The minimum cooling temperature of the 1st stage of the conduction cooling system was 14.6 K, while the total heat invasion was calculated to be approximately 25 W. The temperature of the HTS magnet was saturated to be 21.4 K after 6 hr. In comparison with the thermal FEM analysis results in Figure 8, the difference is about 1.4 K as represented in Table 3. In the real conduction system, the radiation loss was minimized by over 25 turns of the MLI and heat load in the contact parts of the metal current leads decreased.
Figure 7. The cooling temperatures of the MI HTS magnet under the conduction cooling operation.

Figure 8. Heat transfer analysis results of the MI HTS magnet with no load condition.

Table 3. Comparison with heat loads of the MI HTS magnet between in FEM analysis and in the real experiment with no load condition.

| Stages   | Heat transfer methods | Parameters                             | Qty. | FEM results | Experimental results |
|----------|-----------------------|----------------------------------------|------|-------------|----------------------|
| 1\textsuperscript{st} stage | Conduction            | Metal current leads with no load condition | 2 ea | 25.3 (W)    | 25 (W)               |
|          | Conduction            | GFRP supporters (50 mm)                | 8 ea | 1.94 (W)    |                      |
|          | Radiation             | Radiative heat loads (MLI): emissivity:0.03 | 1 ea | 4.75 (W)    |                      |
|          | Total heat load of the 1\textsuperscript{st} stage |                                      |      | 31.99 (W)   | 25 (W)               |
|          | The saturated temperature of the 1\textsuperscript{st} stage |                                      |      | 15          | 14.6 (W)             |

3.3. Charging and discharging test results of the MI HTS magnet

The input current and the terminal voltage curves of the MI HTS magnet were presented in Figure 9. The inductance of the MI HTS magnet including iron core was calculated to be 52.5 mH. The series resistance of the MI HTS magnet was calculated to be 17.5 \( \mu \Omega \). In the case of the charging operation, the characteristic resistance was calculated to be 20.6 m\( \Omega \). This characteristic resistance is higher than that of the MI HTS magnet not to paint the stycast. At that time, the time constant was measured to be 2.5 s as shown in Figure 10. The temperature of the MI HTS magnet didn’t increase at that point, the temperatures at the 1\textsuperscript{st} stage and the metal current lead started increasing.
3.4. Over current test results
When the input current flowed into the magnet until 600 A with the ramping rate of 1 A/s, the terminal voltage and temperatures were presented in Figure 11. The AC loss in the charging sequence was generated and it made the coil temperature increase slightly. The input current was hold on the 600 A, and then the quench occurred. However, the HTS tape in the coil was not damaged, because the current bypassed into the different layers of the magnet on the basis of the R/L circuit. More details about the magnet protection scheme of MI HTS magnet were referred to [8].
3.5. Thermal stability of the conduction cooling system during long-term current flowing test

The current of 350 A was supplied to the magnet for 8 hours and the temperatures at the 1st stage and the MI HTS magnet was saturated to be 36 K and 37.5 K, respectively, as presented in Figure 12. The results demonstrate that the long-term operation of the MI HTS magnet is stable at the target excitation current.

The final temperature of the HTS magnet is a very important factor to consider thermal stability for the HTS magnet to be re-excited within a reasonable timeframe after the quench. The total absorbable heat energy of the HTS magnet bobbin and other structures is calculated according to the temperature. The minimum quench duration is determined by considering the limitations of the temperature increases of the HTS magnets. The total absorbable heat energy of the bobbin and other structures in the cooling system was calculated as 300 kJ at the limiting temperature of 50 K. The quench duration should be below 1 s, after which time the HTS magnet is excited again.

Figure 12. The temperature characteristics during the long-term current flowing test.

4. Conclusions

The thermal and mechanical structural designs of the MI HTS magnet under the conduction cooling condition were performed and the detailed experimental analysis results were presented in this paper. The saturated temperature of the 1st stage of the conduction cooling condition achieved at 14.6 K using the 1st stage GM cryo-cooler. The characteristic resistance was calculated to be 20.6 mΩ. The time constant of the charging and discharging sequences of the magnet were measured to be 2.5 s at the operating temperature of 24.5 K. The current of 350 A was supplied to the magnet for 8 hr and the temperatures at the 1st stage and the MI HTS magnet was saturated to be 36 K and 37.5 K, respectively. In addition, the thermal stability of the HTS magnet was tested, when the current of 600 A flowed into the magnet, continuously. The temperature of the magnet reached 40 K after about 200 s. It was demonstrated that the HTS magnet was thermally stable, even when the quench had occurred. The large scale implementation of 2G HTS technology for commercial application has been being researched through the characteristic analysis results of the MI HTS magnet in this study. The optimal designs for the superconducting application will be presented in the near future.

Acknowledgments

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