Excitation Characteristics of MgB$_2$ Race-track Coi Immersed in Liquid Hydrogen

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Abstract. Our research group has been researched for developing MgB$_2$ superconducting energy apparatus in liquid hydrogen immersion cooling, such as superconducting generators.

In this study, two-pole MgB$_2$ race-track coil, which was a model for a few tens kVA superconducting generator field magnet, was designed and made. This coil consists of two pieces of a similar MgB$_2$ race-track coil which has 529 turn with straight section of 150 mm, bending diameter in the end of section of 100 mm and thickness of 34 mm. We carried out excitation tests of the coil immersed in liquid hydrogen at the temperature of 21 K to 32 K, and the load line of the coil was obtained. The critical current under self-field was obtained for various temperatures. The normal zone propagation behavior of the coil at the quench was also investigated using several potential taps installed in the coil.

1. Introduction

Liquid hydrogen (LH$_2$) is expected as new coolant for high critical temperature superconductor (HTS), such as MgB$_2$, BSCCO and YBCO because LH$_2$ has a low boiling point of 20.4 K and HTS can be cooled with a sufficient temperature margin compared to liquid nitrogen cooling. In addition, LH$_2$ has physical properties suitable for cooling such as low viscosity and large latent heat. Among HTS, MgB$_2$ is promising for superconducting application cooled by LH$_2$ because of its relatively high critical temperature (39 K) and lower processing cost and material cost [1].

From the above, we have studied MgB$_2$ superconducting energy apparatus cooled by LH$_2$ and we have aimed to develop MgB$_2$ superconducting generator especially among superconducting devices. Many MgB$_2$ superconducting energy devices have been studied, but most of them were carried out under liquid helium cooling or conduction cooling. For example, Asger B. Abrahamsen studied MgB$_2$ superconductor direct drive wind turbine generator cooled by conduction cooling [2]. Mine et al. designed 3 T magnet MRI with LH$_2$, LH$_2$ or cryo-cooler cooling and conducted excitation experiments of the test MgB$_2$ coil under conduction cooling [3]. Few of them were performed under LH$_2$ because hydrogen has a wide explosion range and is difficult to handle. Therefore, our research group set up devices that could safely conduct a large current to superconductors cooled by LH$_2$ [4,5]. In previous studies, we measured the critical characteristics of solenoid coil cooled by LH$_2$, which was relatively easy to manufacture [6]. However, in general, the field coil of the generator is a saddle type or a race
track type. Therefore, in this study, an excitation test of MgB$_2$ race-track coil immersed in LH$_2$, which was a model for a few tens kVA superconducting generator field magnet, was carried out at the various temperature conditions. The race-track coil consists of two pieces of a similar coil which has 529 turn with straight section of 150 mm, bending diameter in the end of section of 100 mm and thickness of 34 mm.

At the result of the experiment, the critical characteristics of race-track coil was measured in the condition of LH$_2$ temperature from 21 K to 32 K and load line was obtained. The normal zone propagation behavior of the coil after the quench was also investigated using several potential taps installed in the coil.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

Fig. 1 shows the schematic of the experimental apparatus. This apparatus is composed of LH$_2$ cryostat where test sample places, LHe cryostat for NbTi superconducting magnet, the feed hydrogen gas line, vent lines, and the sheathed heater. LH$_2$ cryostat has 309.5 mm inner diameter, 2122 mm height and a capacity of 61 L of LH$_2$. The pressure in the LH$_2$ cryostat can be set from 0.1 MPa to 2.0 MPa by using feed hydrogen gas line. The temperature of LH$_2$ can be set from 21 K to 32 K by using sheathed heater mounted at the bottom of LH$_2$ cryostat. LHe cryostat and NbTi magnet was not used in this experiment because external magnetic field was not applied. Electric current can be applied to the test sample up to 400 A by using DC power source (Kudo Electric, CSUE4-5 400). This DC power source can excite and degauss the test sample at the specified constant sweep speed. This power sources is equipped with a quench detector. If a voltage of 1V or more is detected from the test sample for 50 ms, it is considered that a quench has occurred and the output is stopped and demagnetized at -8 V. In addition, as a safety measure for the coil, a protective resistance 0.5Ω is installed in parallel with the coil outside LH$_2$ cryostat and the energy stored at the time of quenching is consumed by this resistance. Fig. 2 shows the power supply circuit.

The detail of this experimental set-up for investing electrical properties of superconductors cooled by liquid hydrogen was described by Shirai [4,5].

![Fig. 1 The schematic of the experimental apparatus.](image1)

![Fig. 2 The power supply circuit.](image2)

2.2. The detail of MgB$_2$ race-track coil
The schematic of MgB$_2$ race-track coil is shown in Fig. 3. This test sample has two similar coils side by side and such coil uses a 300 m long MgB$_2$ wire. MgB$_2$ wire used for the coil is MgB$_2$ multifilamentary wire which was produced by Hitachi Ltd and fabricated by using in-situ PIT process. Fig. 4 shows the cross-sectional view of MgB$_2$ wire. MgB$_2$ wire has a diameter of 1.2 mm and is composed of MgB$_2$, pure iron and Monel. The coil was made by Wind and React process and impregnated with epoxy resin for fixing. In addition, for insulation a glass braid was wound on the MgB$_2$ wire.

![Fig.3 The photo and schematic of the race-track coil.](image1)

![Fig.4 The cross-sectional view of MgB$_2$ wire.](image2)

Each coil has 23 turns per a layer and 23 layers. In order to measure the voltage inside the racetrack coil, voltage taps were attached every two layers, which are 46 turns. Due to the measurement equipment, there are 8 potential taps for each coil. In this paper, $V_{i,j}$ is the voltage between the i-th layer and the j-th layer from the inside. The detail of the position where the voltage tap is attached is shown in Fig. 5. Furthermore, in order to measure the magnetic field distribution, hall sensors were installed to the coil. The detail of the position is shown in the Fig. 6.

![Fig.5 The position of the voltage tap.](image3)

![Fig.6 The position of the hall sensor.](image4)

2.3. Experimental procedure

In this experiment, the test coil was immersed in LH$_2$. The bulk-liquid temperature was changed by 1 K from 21 K to 32 K under saturated conditions and the experiment was carried out at each Kelvin. Electric current applied to the coil was increased linearly with time at a constant sweep rate (A/s). In this experiment, the current was swept at 1.0 A/s until about 60% of the expected critical current, and then the current was increased until the quench occurred at the desired current sweep rate (0.4 A/s, 1.0 A/s, 1.6 A/s). Fig. 7 shows the relationship between the voltage at both ends of the coil and the transportation current when the excitation experiment was performed at a liquid temperature of 30 K and a sweep rate of 0.4 A/s. The tap voltage was measured by the four-terminal sensing method. The transportation current is defined as the critical current ($I_c$) when the innermost tap voltage ($V_{1,2}$) exceeded 0.184mV which 1.0 $\mu$V/cm times 184 cm (3turns long) equals.
3. Result and discussion

3.1. Maximum magnetic flux density correction

The magnetic flux density applied to the race-track coil was measured by the hall sensors. However, MgB$_2$ multifilamentary wire used for the race-track coil include pure iron and monel which are magnetic materials and it was considered that they affected the magnetic flux density applied to the MgB$_2$ filaments area in the wire. Therefore, the magnetic field distribution in the wire was calculated based on the experimental data by using FEMM, a finite element magnetic field analysis software and the maximum magnetic flux density in MgB$_2$ filaments ($B_{\text{max}}$) was corrected.

Fig. 8 shows the analysis results of the magnetic flux density distribution in the wire with the highest magnetic flux density under the condition ($T$, $I_c$) = (21 K, 264 A). The position of the wire is the center of the innermost layer of the coil arc. $B_{\text{max}}$ was calculated by averaging magnetic flux density in MgB$_2$ filaments area in the wire. In analysis results, $B_{\text{max}}$ corrected is about 5% higher than when the magnetic material in the wire is not taken into account. Similar results are reported by Matsumoto [6] and Tanaka [7]. In the following, analysis results is applied to $B_{\text{max}}$.

![Fig. 8 The analysis result of magnetic flux density distribution.](image)

3.2. Critical current property

Fig. 9 shows the critical current $I_c$ of the race-track coil measured at 21 K, 23 K, 25 K and 27 K, the load line, and the $I_c - B - T$ characteristics of short MgB$_2$ wire sample made with the same lot. The short MgB$_2$ sample was cooled by gas helium and only the low current range was measured. Therefore, the region where the current was large was extrapolated with a dotted line. X-axis shows maximum magnetic flux density applied to MgB$_2$ filaments in the wire $B_{\text{max}}$, Y-axis shows critical current $I_c$. In
Fig. 9, the data with a current sweep rate of 0.4 A/s is used. Under the conditions of this experiment, there was almost no difference in critical current depending on the current sweep rate. At the liquid temperature of 21 K, the critical current of the coil was 264 A, and 279 kAturn was achieved. The total energy stored at the condition was about 1.4 kJ. Fig. 10 shows the relationship between the current and the measurement results of each Hall sensor. Under the condition \((T, I_c) = (21 \text{ K}, 264 \text{ A})\), about 1.5 T was applied to the coil center and about 1.1 T to the coil surface. In addition, as a result of static magnetic field analysis by ANSYS, the magnetic flux density was about 0.6T on the circumference of 230 mm in diameter from the coil center. The result is shown in Fig. 11.

If the \(I_c - B - T\) characteristics of the MgB\(_2\) race-track coil matches that of the short wire of the same wire, the current value at the intersection of the critical characteristic curve of the short MgB\(_2\) sample and the coil load line can be considered as maximum current which can be applied to the ideal race-track coil under the superconducting state.

From Fig. 9, it is found that the measured \(I_c\) of the race-track coil is lower than the intersection of the critical characteristic curve of the short MgB\(_2\) sample and the coil load line at each temperature. One of the main reason for this may be that the tensile strain at the time of coil production and the bending strain caused by bending at a minimum radius of 50 mm influence the critical properties of the MgB\(_2\) wire of the race-track coil. At the time of coil production, allowable values of tensile strain and bending strain applied to the filament part that do not affect the critical characteristics was estimated, in the winding of the wire before heat treatment. Then, the coil was wound so as not to exceed the total allowable strain. However, because the ratio of the measured coil \(I_c\) to the critical current value expected from the short MgB\(_2\) sample is constant at about 90% regardless of the temperature conditions, it is considered that the strain applied to the MgB\(_2\) filaments part in the actual winding exceeded an allowable value and one or two filaments of 10 MgB\(_2\) filaments locally degraded.
3.3. The voltage behavior of the coil at the quench

Fig. 12 shows the relationship between the current and voltage at each position of the racetrack coil before and after quenching at a liquid temperature of 21 K and a sweep speed of 0.4 A/s. The black line shows the current and the other color lines show the voltage. From Fig. 12, it can be seen that $V_{1,2}$ shifts in the positive direction and then approaches 0 V as the coil current decreases. It can be seen that $V_{5,6}$, $V_{7,8}$ shift in the negative direction at first, then shift in the positive direction, and then approach 0 V. $V_{9,10}$, $V_{11,12}$, $V_{15,16}$, $V_{19,20}$ shift in the negative direction from the beginning and then return to 0 V. The voltage swings in the positive direction because of the electrical resistance generated by the normal conduction transition. The swinging in the negative direction is because of the induced electromotive force generated by the decrease in the transportation current. From Fig. 12, it is found that the normal conduction transition first occurs at the place where the experienced magnetic field is highest (the innermost layer of the racetrack coil arc), and the normal zone expands outside in the order of the second, third and fourth layers. Assuming that the normal transition zone between $V_{1,2}$ and $V_{3,4}$ is propagated only in the longitudinal direction of the wire, the normal zone propagation velocity (NZPV) is about 700 m/s and very fast. On the other hand, using the Wilson model [8], NZPV in the longitudinal direction under the adiabatic condition of the MgB$_2$ wire used is found to be about 1–2 m/s and it is considered that the normal zone propagated not only in the longitudinal direction of the wire but also in the layer direction.

Here, if the normal zone propagates also in the layer direction, the temperature of the MgB$_2$ wire in the second and subsequent layers needs to reach the critical temperature through the heat transfer of the adjacent MgB$_2$ wire that has changed to normal conduction state through the resin with low thermal conductivity. First, when considering the phenomenon of normal zone propagation between $V_{1,2}$ and $V_{3,4}$, the temperature margin to the critical temperature of the third layer wire is estimated. Therefore, the difference in the experienced magnetic field between adjacent wires was investigated by the magnetic field distribution obtained using FEMM of 3.1. The analysis results show that the maximum experienced magnetic field of the third layer is about 0.16 T smaller than that of the innermost layer. Therefore, referring to the B-T graph of the wire used, the third layer shows that the critical temperature margin is about 0.4 K greater.

Next, transient heat transfer analysis was performed using ANSYS in order to investigate the wire temperature over time when the normal zone expanded from $V_{1,2}$ to $V_{3,4}$. For the MgB$_2$ wire, the cross-section was approximated uniformly and the physical properties were averaged according to the usage rates of MgB$_2$, copper, iron, and monel. In the analysis, an increase in the temperature of the third-layer wire was obtained under the condition that the innermost layer and the second-layer wire generated Joule heat due to normal conduction transition. From the experimental results in Fig. 12, the difference in rise time between $V_{1,2}$ and $V_{3,4}$ was 0.04 s. Therefore, Fig. 13 shows the analysis model and the results of the temperature distribution at 0.04 s after the wires started to generate heat. In the analysis results, the average temperature of the third layer increased by 0.62 K after 0.04 s.

From the above analysis results, the temperature margin to the critical temperature of the wires in such layers near the innermost layer is small, and it is found that when quench occurs, the temperature of the wire adjacent to the layer increases rapidly due to heat transfer through the resin and the wire changes to normal conduction state. Thus, normal conduction zone expands in the layer direction in addition to the longitudinal direction until quench is detected and the current decreases.

In this experiment, the race-track coil quenched many times. However, the degradation of $I_c$ or the burnout of the coil was not observed. This is thought to be due to the rapid detection of quench by voltage before the hot spot occurs because of the rapid normal zone propagation.
4. Conclusion

In this study, an excitation test of MgB$_2$ race-track coil immersed in liquid hydrogen was carried out and the critical characteristics of the coil at various temperature were measured. One of the reasons for the decline in the characteristics seem to be that one or two of the filament properties of the wire were locally degraded due to strain caused by pulling or bending during coil production. Considering the production of a generator with a larger capacity, the size of the field coil and the minimum bending radius of the wire are larger than those of this race-track coil. Therefore, the coil characteristics are considered to be closer to the short characteristics. However, under the condition ($T, I_c$) = (21 K, 264 A), the magnetic flux density was only about 0.6T on the circumference of 230 mm in diameter from the coil center. Thus, it is desirable to improve the critical current density of MgB$_2$ wire.

In addition, voltage between such potential taps in the coil during quench was measured and discussed. From the results of magnetic field distribution analysis and transient heat transfer analysis using ANSYS, it was found that normal zone propagated not only in the longitudinal direction of the wire but also in the layer direction. As a result, the quench was able to be detected rapidly before the hot spot occurred, and the coil occurred quench many times, however, the characteristics were not degraded.

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