Preliminary Study of High-Temperature Superconducting Magnets Using 2G Wires

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ABSTRACT: Using a high-temperature superconducting wire in an on-board superconducting magnet for the maglev train has several advantages: improvement in the stability of the superconducting magnet, improvement in reliability through simplification of the magnet structure, and decrease in the mass of the superconducting magnet and the energy consumed by the on-board cryocooler. Therefore, we examined the feasibility of using 2G wires with a high critical current density in a high magnetic field. We performed numerical analysis to calculate the mass of the superconducting magnet and the energy consumption of the on-board cryocooler, taking into consideration the characteristics of 2G wires. Furthermore, we are now carrying out critical current measurements on 2G wires, while varying experimental conditions such as temperature, magnetic field, and magnetic field direction.

1 INTRODUCTION

Because superconducting magnets are used in the maglev high-speed mass transportation, it is desirable that they are highly reliable, lightweight, and low cost.

The development of 2G wires has progressed remarkably in recent years. This year, Selvamanickam and Xie reported critical current (I_c) in excess of 800 A/cm with a wire ≥1 m in length, and further progress is expected in the future. For application in superconducting systems, 2G wires have three main advantages over Bi wires (1G wires): First, the critical current density (J_c) at high temperature and high magnetic field is large; second, the mechanical strength of the wire itself is excellent; third, even it is bent into a curve with a radius of 10 mm, there is little degradation of I_c.

We believe that it is feasible to create a lightweight and reliable superconducting magnet for the maglev transportation using wires with such characteristics. If the wire performance improves and we can raise the operating temperature of a superconducting coil to about 50 K, some of the concepts shown in Fig. 1 will come into reality.

With increasing temperature, the thermal capacity, and hence, the stability, of the coils increases dramatically. For example, in the case of copper, the specific heat at 50 K is about 1,000 times greater than that at 4 K. 2G coils can be cooled using a single stage cryocooler, whereas a Gifford-McMahon/Joule-Thomson cryocooler is required to cool Nb-Ti coils. If the temperature of the coils is 50 K, radiation shield plates and thermal anchors are not required. As a result, the heat insulation structure can be simplified drastically, and the cross section of the superconducting magnet can be reduced. Moreover, we expect to reduce both the superconducting magnet's mass and manufacturing costs.

Since the electric gap between a superconducting coil and a ground coil also decreases when the superconducting magnet's cross section is reduced, the magnetomotive force of the superconducting coil can be reduced.

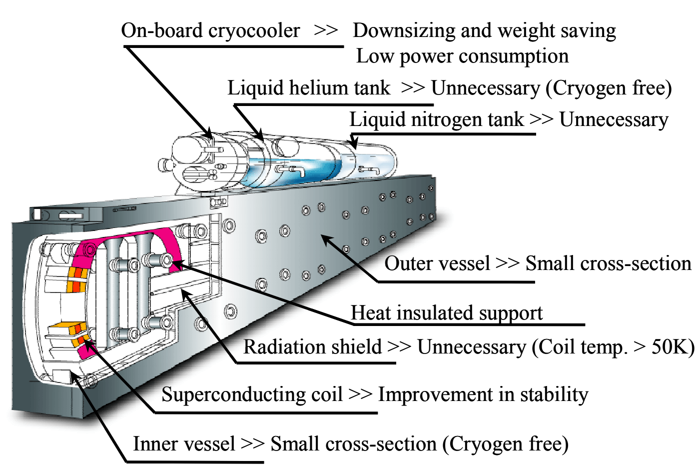

Figure 1. Merits of applying 2G wires to a superconducting magnet for the maglev train. The original figure is a schematic view of a superconducting magnet with Nb-Ti coils.

First, as a fundamental study, we estimated the mass of the main parts of a superconducting magnet using the I_c characteristics of 2G wires, as measured by Holesinger and Civale, and investigated the relationship with the coil operating temperature. The main parts are the superconducting coils and on-board cryocoolers. The mass of both depends greatly on the coil operating temperature.

2 FEASIBILITY STUDY

2.1 Mass of Superconducting Coils

I_c of 2G wire improves because of the introduction of an artificial pinning center. The improvement of I_c at 77 K in a self-magnetic field is reported in many papers. However, to estimate the mass of the superconducting coil, we have to know the magnetic field dependencies of J_c at various temperatures. There are few reports with such comprehensive data. Holesinger and Civale investigated the magnetic field dependencies of J_c at various temperatures by measuring magnetization of a small sample of 2G wire. We decided to use this data for our calculation. Although the angular dependency of the magnetic field is important for 2G wires, it was not taken into consideration in this calculation; instead, the J_c characteristics when applying a magnetic field parallel to the c axis were used. It is assumed that the coil cross section is a rectangle and the central line has a racetrack shape. The long axis length of the racetrack is 1.07 m and the short axis length is 0.5 m. The magnetomotive force is 700 kA and the wire load factor is 80%. The wire width is 4.4 mm and its thickness is 0.1 mm. The thickness of the superconducting layer is assumed to be 1 μm. Therefore, the engineering current density (J_e) of the wire decreases to 1/100 of J_c. Here, one coil is a formed by lamination of six element pancake coils, and the coil width is 26.4 mm. The coil thickness in the radial direction depends on the J_e characteristics of 2G wires.

On the other hand, the cooling temperature and the peak field to which a coil is exposed (B_{peak}) determine the operating current (density) of the coil. When current density is increased while maintaining a constant magnetomotive force, since current increases, B_{peak} also increases, as shown in Fig. 2. The design points of a coil are the crossings of this J_e–B_{peak} curve and the J_e–B curve at each temperature. In this way, the operating current density at each temperature was determined. The cross section of a coil, which determines the coil mass, is obtained from the operating current density.

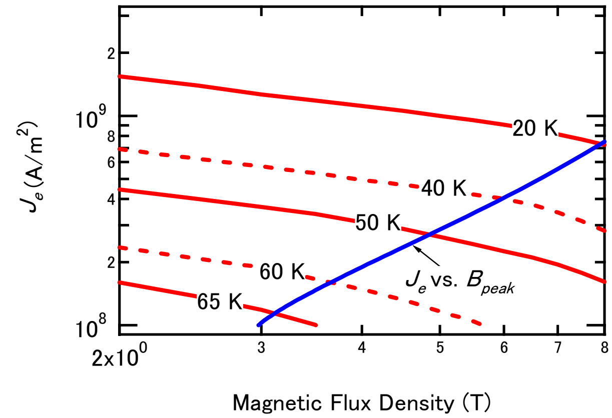

Figure 2. Estimated J_e characteristics of 2G wire and the calculated J_e–B_{peak} line of the racetrack coil. The crossings of J_e–B curves and the J_e–B_{peak} curve indicate design points of the coil at each operating temperature.

One superconducting magnet consists of four coils; thus, Fig. 3 shows the mass of four coils. When the wire load factor is taken into consideration, operating current density becomes 80% of J_c. According to Fig. 3, the mass of a coil increases rapidly with a rise in the operating temperature. Because this result changes with the characteristics of 2G wires, we need to investigate the characteristics of critical currents in commercial wires.

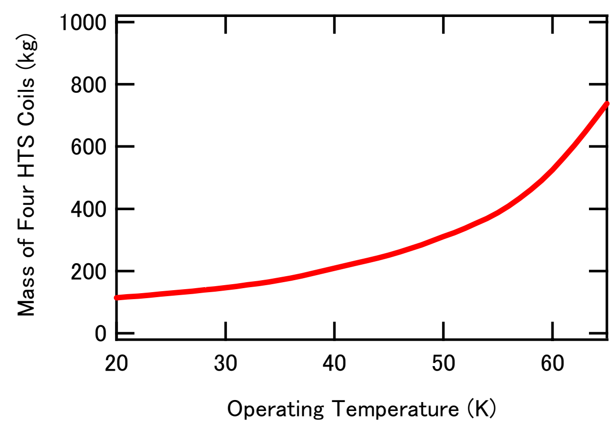

Figure 3. Estimated mass of four HTS coils as a function of the operating temperature.

2.2 Mass and Power Consumption of Cryocoolers

In general, if the cooling capacity is constant, the mass of the cryocooler increases with the cooling temperature, because mass is proportional to power consumption. Nisenoff investigated a number of commercial cryocoolers and created a very useful plot of the mass and power consumption of cryocoolers operating at various temperatures and cooling capacities, as shown in Fig. 4. From the data for temperatures between 20 and 77 K, we produced the following approximate expressions.

$$Q_{in} = 111943 \times Q_{out}^{0.8437} \times T_{op}^{-0.0247 \log Q_{out} - 1.7332} \quad (1)$$

$$M = Q_{in} / 20 \quad (2)$$

Here, Q_{in} is the input or power consumption (W) of a cryocooler, Q_{out} is the cooling capacity (W), and M is the mass (kg). Because this data is obtained from commercial cryocoolers, it is possible to develop a cryocooler with lighter mass and less power consumption than the results obtained from these expressions.

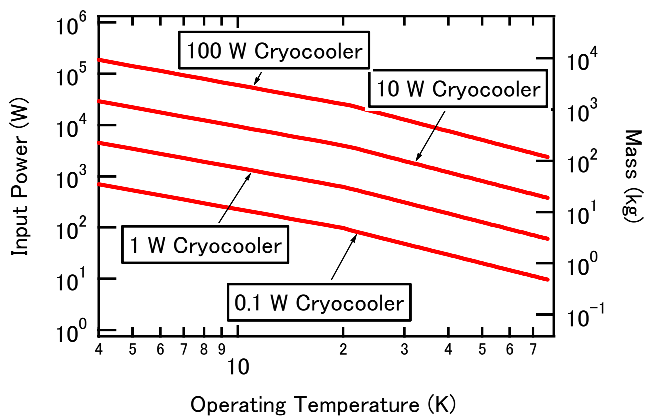

Figure 4. Plot of the mass and power consumption of cryocoolers operating at various temperatures and cooling capacities.

We considered three main factors of heat leaks to the superconducting magnet: radiation, conduction from current leads, and conduction from supports.

The mass and power consumption of the required cryocooler at various operating temperatures were calculated using these equations by assuming a certain amount of heat leakage. We examined two cases.

The first case is where a magnet has radiation shield plates and thermal anchors cooled to 77 K; the second case is where the radiation shield plates and thermal anchors are omitted for simplification of the magnet structure.

In the first case, we assume that high-temperature superconducting (HTS) current leads reported by Ogata are used. Because these current leads are made from a high-temperature bulk superconductor, they can drastically reduce heat leakage. In this case, mass and power consumption were calculated supposing two cryocoolers: a 77 K cryocooler that cooled radiation shield plates and a cryocooler that cooled the coils directly.

The second case assumes that only one cryocooler is cooling the coils. Because there is no thermal anchor, the HTS current leads cannot be used. Figure 5 shows the calculation results. Since power consumption is proportional to mass, mass is shown on the left axis and power consumption is shown on the right axis. At temperatures higher than 50 K, there is no remarkable difference due to the presence of shield plates and thermal anchors.

However, at lower temperatures, the effect of shield plates and thermal anchors is remarkable.

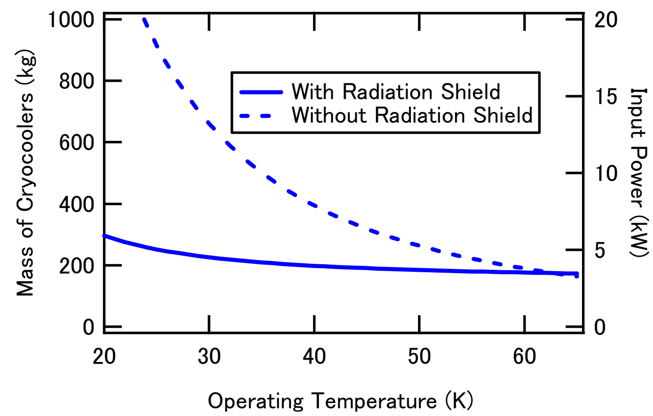

Figure 5. Estimated mass and input power of cryocoolers as a function of the operating temperature.

Figure 6 shows the total mass of coils and cryocoolers. In the case where shield plates and thermal anchors were omitted, the mass of coils and cryocoolers has a minimum at about 50 K; for the case with shield plates and thermal anchors, they reach the minimum at about 30 K. This latter minimum is lower by about 200 kg than the former.

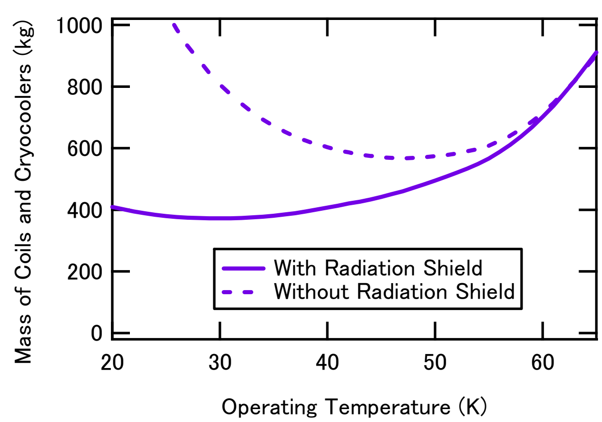

Figure 6. Estimated mass of four superconducting coils and cryocoolers as a function of the operating temperature.

3 EVALUATION OF 2G WIRES AND FUTURE WORK

Although it was not taken into consideration in the previous section, when shield plates and thermal anchors are removed, there may be weight savings and cost reduction. The characteristics of the wire used for these calculations greatly influenced the results. As the performance of the wire is improved and the mass of a coil is reduced, the optimal temperature, where the total mass of coils and cryocoolers is minimal, will increase. As a result, the optimal magnetic structure may also change.

As mentioned above, 2G wires are being developed in many countries, and improvements in performance are expected in the near future. Most wire manufacturers report an improvement in the characteristic at 77 K and in self-magnetic field. However, to examine their application to a superconducting magnet, it is essential to accurately know their characteristics at lower temperatures or in a higher magnetic field region.

We developed the HTS current leads using a superconducting material, as mentioned above. Using this same I_c measuring system, we measured the I_c characteristics while changing temperature and magnetic field direction, and the results are shown in Fig. 7.

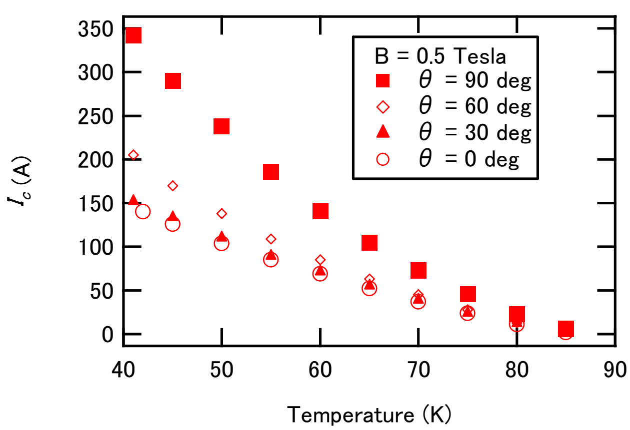

Figure 7. Measured I_c characteristics of 2G wire sample at various operating temperatures and applied magnetic field directions θ.

Here, I_c increases as the temperature is reduced. In addition, at a constant temperature, I_c is the lowest when a magnetic field is applied in parallel with the c axis of the wire.

Although this data is very important, coil design is impossible if the effect of the magnetic field intensity is not known simultaneously.

For this purpose, a cryocooler-cooled superconducting magnet, which can generate a magnetic flux density of 5.5 T, was used to fabricate test equipment shown in Fig. 8. We are now evaluating the comprehensive performance of 2G wires.

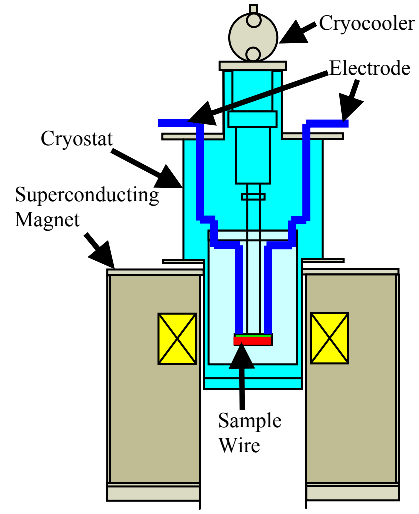

Figure 8. Schematic diagram of the system for measuring the properties of 2G wires.

Based on the fundamental data obtained here, we will manufacture small superconducting coils and evaluate their performance. In addition, we will study the optimal cryostat structure for a high-temperature superconducting magnet.

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