Feasibility study of high-efficiency cooling of high-temperature superconducting coils by magnetic refrigeration

Naoki HIRANO, Setsura NAGAI, Yodai Okazaki, Tetsuji OKAMURA, Yuta ONODERA and Toshiyuki MITO

Abstract*—As a high-efficiency cooling technology for high-temperature superconducting coils, we have begun research and development to examine the feasibility of a cooling assist technology that maintains a cryogenic state by combining the magnetic force generated by the superconducting coil with magnetic refrigeration technology. Magnetic refrigeration requires the magneto caloric material to change the magnetic field. In many cases, the magnetic field change is obtained by moving the magnetic source, but moving the superconducting coil is not a good idea. Although it is possible to generate a change in the magnetic field by turning on and off the power supply of the high-temperature superconducting coil, it is unlikely to be established as a system that assists cooling of the superconducting coil because the coil generates heat due to AC loss. Therefore, it was considered that the magnetic field change can be obtained if the magnetic force generated from the superconducting coil can be controlled by the magnetic shield. As a verification of the principle, it was clarified experimentally that a magnetic field change can be obtained by repeatedly inserting and removing the magnetic shield into and from the gap between the magnetic field generation source and the magneto caloric material, and the temperature change can be extracted by the magneto caloric effect. In the experiment, the temperature change obtained when a magnetic shield was inserted into the air gap was measured by a simple test device using an iron-based magneto caloric material having high magneto caloric effect performance at room temperature and a permanent magnet. The principle verification confirmation test was performed using several types of magnetic shielding materials such as Permalloy bulks and the electrical steel sheets. In addition, numerical analysis is performed on the magnetic shielding effect, and the shielding effect is improved by increasing the thickness of the shielding material and the possibility of using high temperature superconductors as magnetic shielding materials were also analyzed. In this study, we report the possibility of cooling the high-temperature superconducting coil with high efficiency by combining the magnetic field created by the superconducting coil and magnetic refrigeration.

***Index Terms*— Cryogenics, High-efficiency cooling technology, Magnetic refrigeration, Magnetic shield, Superconducting magnets.**

I. Introduction

Recently, it has become difficult to supply helium, which has affected cryogenic experiments. For this reason, we started the development of a cryogenic system that does not rely on helium. As a fundamental technology for high-temperature superconducting coil cooling, we have begun research on the feasibility of a cooling assist technology that maintains a cryogenic state by combining the magnetic force generated by the superconducting coil with magnetic refrigeration technology.

Magnetic refrigeration technology is an environment-friendly technology that does not use refrigerant which causes global warming. In addition, since operation close to an ideal refrigeration cycle is possible, there is a possibility that an efficient cooling device can be realized. Therefore, in recent years, expectations for magnetic refrigeration technology are increasing. There are already many reports about the prototyping of a heat pump around room temperature using magnetic refrigeration technology [1]-[4]. In order to obtain a temperature change by magnetic refrigeration, it is necessary to provide some magnetic field change to the magneto caloric materials. As a conventional magnetic refrigeration technique, a method of changing a distance between a magnetic field generation source and the magneto caloric materials or a method of obtaining a magnetic field change by controlling a power source such as an electromagnet is well known. Due to the large driving force and the loss associated with turning on / off the power, the overall efficiency was lowered.

As a technique to solve this problem, we experimentally verified the principle that a magnetic field change can be obtained by inserting and removing the magnetic shield from the magnetic field generation source and the magneto caloric materials gap, and the temperature change can be extracted by the magneto caloric effect. Fig. 1 shows the concept of coil cooling assist using magnetic refrigeration technology by magnetic shielding. It has been confirmed by magnetic field analysis that a magnetic field can be changed by the magnetic shield. In the principle verification experiment, it was confirmed that the magnetic calorific effect changed due to the change of the magnetic field using a magneto caloric material (MCM), a permanent magnet and magnetic shield. In addition, to enhance the magnetic shielding effect, the influence of parameters such as magnetic permeability of magnetic materials was examined,

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and the possibility of using high temperature superconductors as magnetic shielding materials was also analysed.

II. Principle Verification Experiment on Magneto Caloric Effect by Magnetic Shielding

A. Experimental Set-Up

Using a permanent magnet, a magnetic shield material and a room-temperature MCM, a principle verification experiment was performed to determine whether the magneto caloric effect could be controlled by the magnetic shield. Figure 2 shows a schematic diagram of the principle verification experimental device. By magnetically shielding the magnetic field obtained by the permanent magnet with a plate-shaped iron-based material, a magnetic field change is given to the MCM, thereby confirming the magneto caloric effect. Initially, we planned to fix the MCM and insert / remove the magnetic shield into the magnetic field space. However, it is difficult to insert and remove the magnetic shield. Thus, this time we decided to change the magnetic field by inserting the magnetic shield and confirming the relationship between the magnetic field and the magneto caloric effect. Figure 3 shows a photograph of the principle verification experimental device. The size of the permanent magnet is 50 x 30 x 60 mm. The maximum energy product of the permanent magnet is 256 kJ / m^3.

The magnetic shield was inserted into an acrylic holder and placed in the magnetic field generation space of a permanent magnet. The MCM was inserted into the center of the holder, and the temperature change of the MCM was measured with a thermocouple.

B. Numerical analysis

We analyzed whether a large magnetic shield could be achieved by devising the shield. The analysis of the magnetic field distribution by the permanent magnet and the magnetic shield was performed using commercially available electromagnetic analysis software (Finite Element Method Magnetics (FEMM)).

Fig. 4 shows the analysis result of the magnetic field distribution obtained by the permanent magnet as a contour diagram. The analysis result of the place where the magnetic material is inserted was 0.647 T. The magnetic field confirmed by the Hall element was 0.65 T, and it was confirmed that the analysis and actual measurement results were in good agreement.

C. Results

Figure 5 shows the measurement results of the magnetic shielding effect of the three types of magnetic materials and the amount of change in the adiabatic temperature as the magneto caloric effect of the MCM. Figure 5 also shows the case without magnetic shielding. The analysis results of the magnetic field distribution are also shown. The color coding by the magnetic field is the same as in Fig.4. The vertical axis of the graph is the adiabatic temperature change (ΔT) which shows the temperature difference that the temperature of the MCM changed by giving the change of the magnetic field. The horizontal axis is

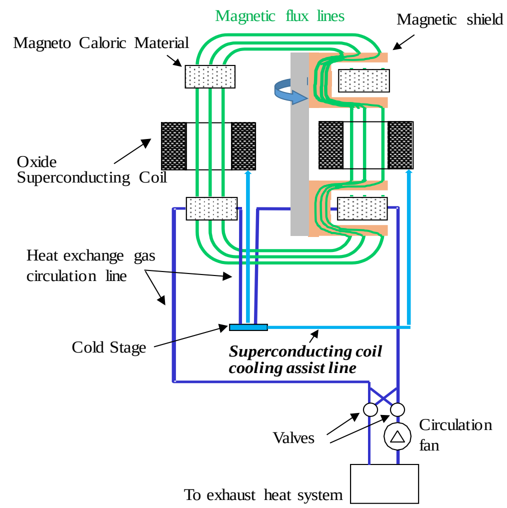

Fig. 1. Concept of coil cooling assist using magnetic refrigeration technology by magnetic shielding.

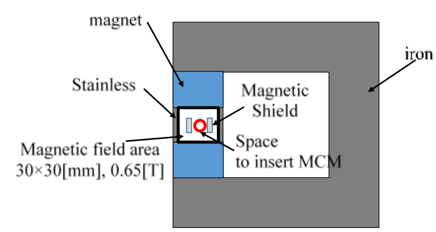

Fig. 2. Schematic diagram of simple test equipment on magneto caloric effect by magnetic shielding.

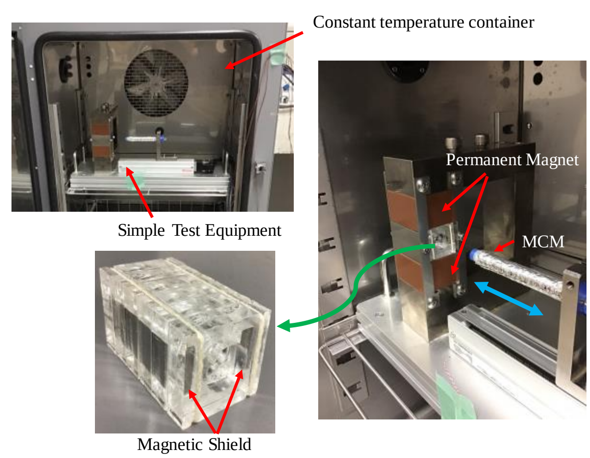

Fig. 3. Photos of simple test equipment on magneto caloric effect by magnetic shielding.

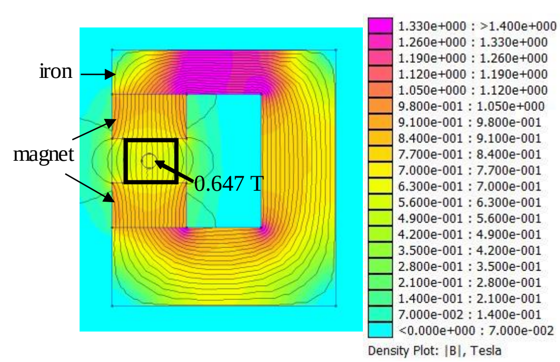

Fig. 4. Analysis result of the magnetic field distribution obtained by the permanent magnet.

the temperature of the measurement environment. It can be seen that the Curie temperature of the material measured this time is 20 °C, and that there is a peak of the adiabatic temperature change at that temperature. Table I summarizes the analysis results of the magnetic shielding effect and the magnetic field measurement results by the Hall element. It can be seen that the magnetic field analysis and the measured value are almost the same. The size of each magnetic shield is prepared as the cross section of Pure Iron is 3 mm x 12 mm and the cross section of Permalloy and the electrical steel sheet (ESS) is 5 mm x 15 mm. All are arranged with a space of 17 mm. The relative permeability of iron, Permalloy, and ESS is 5000, 100000, and 5000, respectively. The saturation magnetic flux densities of iron, Permalloy, and ESS are 2.15 T, 0.72 T, and 1.9 T, respectively.

The effect of magnetic shielding on the magneto caloric effect was confirmed, and it was verified that the greater the magnetic shielding effect, the more the ΔT was suppressed, so that the magneto caloric effect due to magnetic shielding could be controlled. However, the magnetic shielding effect is at the level of several thousand Gauss, although ESS is high, which is not sufficient.

III. Discussion

A. Improvement analysis

In order to enhance the magnetic shielding effect, the magnetic field distribution was analyzed based on pure iron by changing its magnetic permeability, saturation magnetic flux density, and volume. The results are shown in Fig.6. The color coding by the magnetic field is the same as in Fig.4. Table II summarizes the analysis results. The analysis results in Table II are the values at the center between the shields. The size of the cross section of the magnetic shielding material (Fig. 6 (c)) with different thickness is 10 mm x 15 mm, with a gap of 7 mm. From the analysis results, it was confirmed that the magnetic shielding effect was improved by increasing the volume. On the other hand, it was also confirmed that changing the magnetic permeability and the saturation magnetic flux density had almost no effect on the magnetic shielding effect. If the volume of the magnetic shield is increased, sufficient magnetic shielding is possible, but it is not realistic because a large driving force is required to drive a large magnetic shield. It is necessary to study a compact and lightweight magnetic shielding method.

B. HTS magnetic shield

The magnetic shield reduces the magneto caloric effect in response to the reduced magnetic field. It was confirmed by analysis that the magnetic shielding effect was improved by devising the shape of the magnetic shield. As a compact and lightweight magnetic shielding method, we examined the use of superconductors as magnetic shields. It has been reported that the NbTi-Cu multilayer film succeeded in shielding the magnetic field up to 0.8 T [5]. According to this report, it is concluded that it is possible to form an electric field-free space for a magnetic flux density of 1 Tesla or more by laminating NbTi-Cu multilayer films of appropriate thickness. Based on this result, it was examined whether magnetic field shielding is possible by

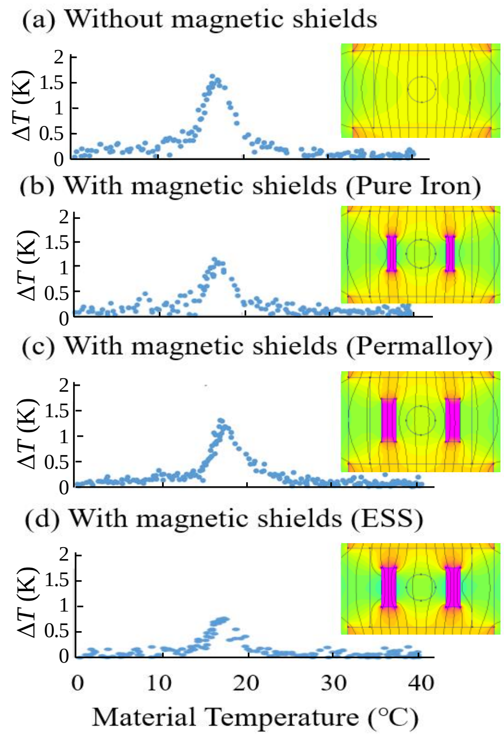

Fig. 5. Measurement results of magnetocaloric effect for MnFe-based MCM.

TABLE I
MAGNETIC FIELD AT THE CENTER OF THE SIMPLE TEST EQUIPMENT

	Without magnetic shielding	With magnetic shielding		
		Pure Iron	Permalloy	ESS
Analysis	0.647 T	0.474 T	0.503 T	0.380 T
Experiment	0.65 T	0.45 T	0.53 T	0.35 T

ESS : Electrical Steel Sheets

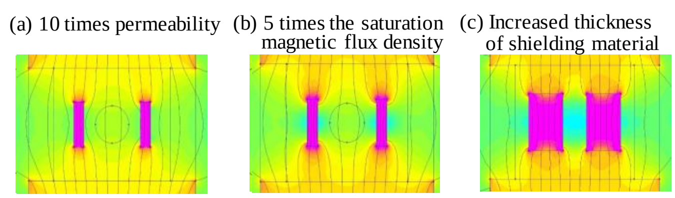

Fig. 6. Analysis results for improving magnetic shielding effect (Pure Iron)

TABLE II
ANALYSIS RESULTS FOR IMPROVING MAGNETIC SHIELDING EFFECT

No Shield	Pure Iron	(a)	(b)	(c)
0.647 T	0.474 T	0.474 T	0.404 T	0.063 T

laminating YBCO thin films in multiple layers. Figure 7 shows the shielding effect per YBCO thin film. The expected magnetic shielding ability characteristics of the YBCO film were calculated from the magnetic shielding ability of the NbTi film [6] in consideration of the difference in the critical current characteristic and the difference in the film thickness. For the critical current, the values of a general NbTi thin film and YBCO tape [7] were referred to. The J_c of the YBCO tape is assumed to be a typical tape with a characteristic of 15,000 A/mm^2 @20 K 3 T, and is calculated in consideration of the magnetic field dependence. The thickness of the superconducting layer is 5 μm. Further, it was assumed that the slope of the shielding property in a low magnetic field showing complete antimagnetism was the same for both YBCO and NbTi. The maximum shielding capacity obtained by this magnetic shielding prediction is 0.085 T. This value is in good agreement with the lower critical magnetic field characteristics of the YBCO single crystal film [8].

As can be confirmed from this characteristic, it can be seen that there is a shielding effect of about 0.004 T at 3 T even if the state shifts from the complete antimagnetism, which is a characteristic of the type 2 superconductor, to the mixed state due to the increase of the external magnetic field.

Figure 8 shows the result of calculating the possibility of magnetic shielding by multiple layers of thin films using this characteristic. The magnetic field immediately behind the laminated films was estimated when 5 μm YBCO films were inserted one by one in a magnetic field of 3 T. It was calculated that most magnetic fields could be shielded with about 410 sheets (total thickness of superconducting layers is about 2.05 mm). This result is a calculation result when superconducting films are stacked with almost no gap. Since the actual superconducting thin film has the thickness of the substrate and the intermediate layer, the overall thickness increases.

In this paper, the magnetic shielding effect by laminating high-temperature superconducting films was examined, but if the thickness of about several mm shown in this result is effective, it is possible to shield with YBCO bulk. We also consider the shielding effect of YBCO bulk.

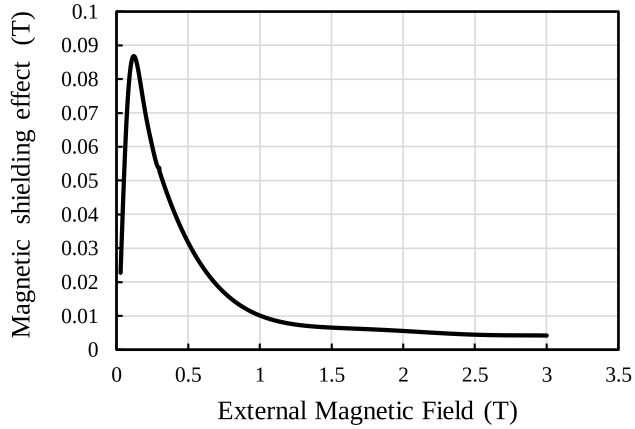

Fig. 7. Magnetic shielding effect on external magnetic field expected for YBCO film.

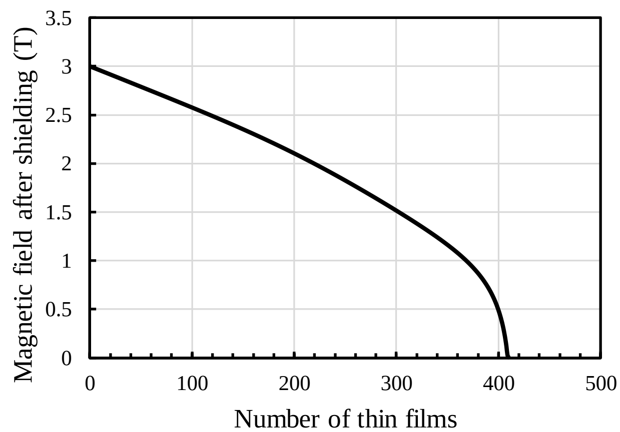

Fig. 8. Magnetic shielding effect due to multiple layers of YBCO film.

IV. Summary

The principle verification experiment that the magnetocaloric effect can be controlled by the magnetic shield was performed. A method for improving the magnetic shielding effect was examined by analysis.

The following conclusions were obtained from the results.

- ✓ There is a possibility that a magnetic refrigeration system using a magnetic shield can be constructed.
- ✓ Iron-based magnetic shielding requires a large volume of material for Tesla-class shielding, which is not realistic.
- ✓ Magnetic shielding by laminating high-temperature superconducting thin films may be able to shield the magnetism of few Tesla.

It is necessary to confirm the magnetic shielding ability of the laminated high-temperature superconducting thin film and the high-temperature superconducting bulk, and a verification test will be conducted. In the future, we would like to study the specific shape of the magnetic shield and evaluate the prototype of a magnetic refrigeration system that operates around 20 K.

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