Development of static magnetic refrigeration system using multiple high-temperature superconducting coils

Naoki HIRANO, Yuta ONODERA, Toshiyuki MITO, Yuma UENO and Akifumi KAWAGOE

Abstract—**It is expected to build a sustainable social system that uses "hydrogen" as a fuel to generate electricity without emitting CO2. To realize this, technology for storing a large amount of hydrogen is indispensable, and storage as liquid hydrogen is ideal. However, the efficiency of the cooling device in the temperature range around 20 K required for long-term storage with liquid hydrogen is low, and the equipment is huge and expensive, so it has not been established as a widely used technology. Magnetic refrigeration is expected to be a highly efficient refrigerator in the temperature range of around 20 K because it can realize an ideal refrigeration cycle. However, in magnetic refrigeration, it is necessary to give a magnetic field change to the magneto caloric material (MCM). Further, in order to perform cooling with a large capacity and extremely low temperature by magnetic refrigeration, the magnetic field strength of a permanent magnet is insufficient, and it is indispensable to use a superconducting coil capable of generating a strong magnetic field with low power consumption. This study aims to develop a static magnetic refrigeration system using multiple high-temperature superconducting coils. By utilizing the energy storage characteristics of the superconducting coil, we are considering a magnetic refrigeration system that can repeatedly generate magnetic field changes to save energy without the need for large amounts of energy to be taken in and out of the outside. We report on the technical feasibility of a static magnetic refrigeration system using HTS coils. The power consumption including the AC loss of two superconducting coils, which is the basic configuration of the static magnetic refrigeration system, is calculated, and the efficiency is estimated as a ratio to the assumed refrigeration capacity of the MCM.**

***Index Terms*—Magnetic Refrigeration, AC loss, HTS Magnet, Brandt's expression, Slab model**

I. Introduction

It is expected to build a sustainable social system that uses "hydrogen" as a fuel to generate electricity without emitting CO_2. Technology for storing a large amount of hydrogen is indispensable, and storage as liquid hydrogen is ideal. However, the efficiency of the cooling device in the temperature range around 20 K required for long-term storage with liquid hydrogen is low, and the equipment is huge and expensive.

Magnetic refrigeration is expected to be a highly efficient refrigerator in the temperature range of around 20 K because it can realize an ideal refrigeration cycle. However, in magnetic refrigeration, it is necessary to give a magnetic field change to the MCM. Further, in order to perform cooling with a large capacity and extremely low temperature by magnetic refrigeration, the magnetic field strength of a permanent magnet is insufficient, and it is indispensable to use a superconducting coil capable of generating a strong magnetic field with low power consumption.

This study aims to develop a static magnetic refrigeration system using multiple high-temperature superconducting coils. By utilizing the energy storage characteristics of the superconducting coil, we are considering a magnetic refrigeration system that can repeatedly generate magnetic field changes to save energy without the need for large amounts of energy to be taken in and out of the outside. In this paper, we explain the concept of the static magnetic refrigeration system and calculate the AC loss of the two HTS magnets that are the basic configuration. We also discuss the COP of a magnetic refrigeration system as the ratio of the power consumption including this AC loss to the assumed cooling capacity of MCM.

II. Static Magnetic Refrigeration System (SMRS)

A. Features of SMRS

As a conventional magnetic refrigeration technique, a method of changing a distance between a magnetic field generation source and the MCM is well known [1]-[4]. Due to the large driving force, the overall efficiency was lowered.

We are also studying a method using a magnetic shield to change the magnetic field in MCM without moving the magnetic field source or MCM [5][6]. In this study, SMRS is defined as a configuration that changes the magnetic field in MCM by changing the current of the superconducting magnet.

The feature of SMRS is that neither magnetic field source nor MCM move. It is also a feature that a large magnetic field

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change can be obtained by turning on and off the current of the superconducting magnet. It is necessary to consider the occurrence of AC loss due to current changes. Furthermore, since it is difficult to obtain a large temperature change with magnetic refrigeration, it is a realistic choice to combine waste heat with other refrigeration systems targeting around 20 K. An example of the system concept for a liquid hydrogen recondensation is shown in Figure 1.

B. Basic concept for system operation

In magnetic refrigeration, the temperature rises when a magnetic field is applied to a material due to the effect of magnetic heat, and the temperature drops when the magnetic field is lowered. By repeating this, the temperature of the material is gradually lowered, but as the smallest unit in order to coexist the action of exhausting heat to the MCM whose temperature has risen and the action of transferring cold heat from MCM whose temperature has dropped. It is rational to prepare two sets of coils and MCMs. In this smallest unit, the coil and MCM are the same and arrange them side by side as shown in Fig. 2. To increase the refrigerating capacity, connect these units in parallel. To widen the cooling temperature range, connect units in series that select MCMs with different optimum operating temperatures. Moreover, by utilizing the power storage performance of the superconducting coil and moving the current back and forth, it is possible to construct a system in which the energy supply from the outside is minimized. Figure 3 shows the concept of an operation sequence using two coils. When one magnet is demagnetized from the excited state, the current flowing through the magnet is transferred to the other magnet, and the other magnet is excited at the same time. Demagnetization lowers the temperature of the MCM, and the cold heat is transferred by a heat exchange fluid such as helium gas to cool down the cold stage. On the other hand, since the temperature of the MCM rises during excitation, the heat is transferred to the waste heat part by the heat exchange fluid. A low temperature is obtained by repeating this cycle.

III. Establishment of SMRS by AC loss calculation

A. High temperature superconducting magnets for SMRS

For SMRS, it is important to estimate the AC loss caused by the change in the current of the superconducting coil in order to evaluate the operating efficiency. The superconducting magnet, which is the premise of the analysis, was designed with a magnetic field change of 3 T and an inner diameter of 100 mm required for arranging the MCM in the magnet bore. Table I shows the main parameter of the superconducting wire used, and Table II shows the main specifications of the magnet. In addition, it was calculated as Equation 1 from the use of a wire that assumes the analysis equation of the magnetic field dependence of I_c required for the calculation of AC loss. Table III shows the values of each variable in Equation 1 at 20K and 50K. Fig. 4 shows the load characteristics of the designed magnet.

$$I_c = \alpha B^{\gamma-1}\left(1-\frac{B}{B_{c2}}\right)^{\delta} \qquad (1)$$

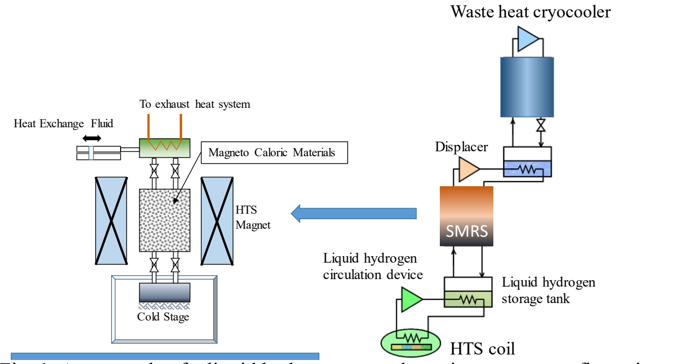
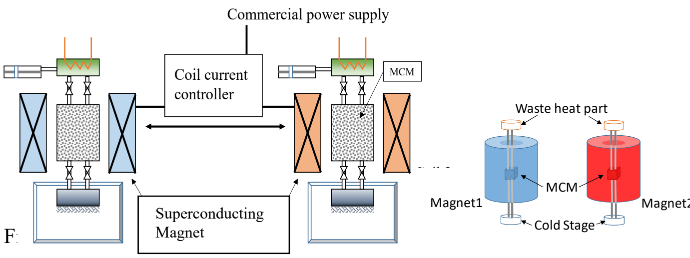


Fig. 1. An example of a liquid hydrogen recondensation system configuration.



F superconducting coils.

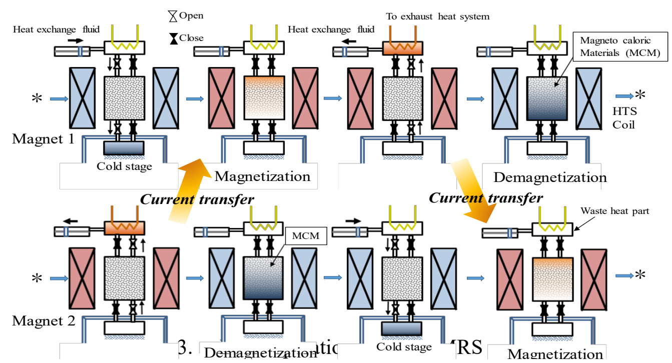


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TABLE I
PARAMETERS OF THE SUPERCONDUCTING WIRE FOR SMRS

Material	YBCO
Width	4 mm
Thickness	0.1 mm
I_c @77K, s.f.,	120A
@50 K, 5 T	169 A
@20K, 3 T	655 A

TABLE II
PARAMETERS OF THE SUPERCONDUCTING MAGNET FOR SMRS

Number of magnets	2
Number of double pancake coils in one magnet	5
Height of one magnet	100 mm
Inner diameter	100 mm
Outer diameter	200 mm
Turn number of one magnet	5000
Operating top current	90 A

TABLE III
VALUE OF EACH VARIABLE IN EQUATION 1

	20 K	50 K
α	1090	426
γ	0.708	0.706
B_{c2}	90	30
σ	4.53	2.61

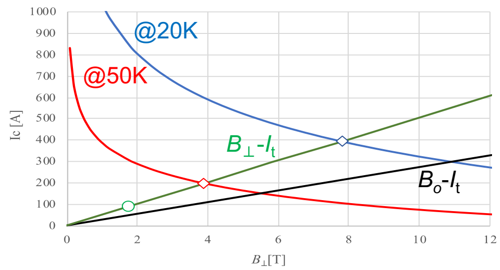


Fig. 4. Load line of the designed magnet.

B. Static magnetic field analysis

Fig. 5 (a) shows the magnetic field distribution when the magnet shown in Table II is energized with 90 A, which is about 50% of the critical current at 50K. This calculation was calculated using commercially available electromagnetic analysis software, JMAG®. As shown in Fig.5 (a), it is confirmed that a space of 3T is secured in the magnet. Further, Fig.5 (b) shows a magnetic field component perpendicular to the wire tape surface that affects the AC loss. As shown by Fig. 2, two magnets are set side by side in our SMRS. However, the magnetic fields are smaller than 1/10 of that at the outermost layer over 200 mm from the magnet's axis. Therefore, in the next section's calculations, the magnetic field is considered only one magnet, assuming enough distance between two magnets exists.

C. AC loss calculation result

AC losses in the magnet are calculated. The magnet is wound with one tape, so ac losses are considered to be only hysteresis losses in the superconducting layer of the tape. In the calculation, magnetic fields in direction of the perpendicular to the flat face of the tape are considered. In this study, the ac losses in two cases, which are calculated by Brandt's expression and slab model, are shown in Fig.6. Transport currents are composed of dc current as a half values of top current and changing current with amplitude of half values of top currents. Therefore, amplitude of the changing magnetic fields are corresponded to the amplitude of the changing current. Figure 6 shows the current change pattern of the magnet assumed by SMRS.

Ac losses in each turn are calculated with critical current of each turn under magnetic fields when transport current is I_{dc}.

Brandt's expression can calculate magnetization losses ($Q_{h,strip}$)in the superconducting strip under changing magnetic fields in direction of the perpendicular to the tape face. w is the tape width. H_e is the applied magnetic field.

$$Q_{h,strip} = \mu_0 w I_c H_e \cdot g\left(\frac{H_e}{H_c}\right) \quad \text{[J/m]} \tag{2}$$

$$H_c = I_c / w\pi \tag{3}$$

$$g(x) = \left(\frac{2}{x}\right) \ln\cosh x - \tanh x \tag{4}$$

Slab model can calculate magnetization losses ($Q_{h,slab}$) in the superconducting slab under changing magnetic fields in parallel to the slab. In this calculation, since the direction of the magnetic fields are considered the perpendicular to the tape face, thickness, t, of the slab is substituted the width of the winding tape.

$$Q_{h,slab} = \frac{4\mu_0}{3}\frac{{H_e}^3}{J_c t} \quad \text{[J/m^3]}, \quad H_e < \frac{J_c t}{2} \tag{5}$$

$$Q_{h,slab} = t\mu_0 J_c\left(H_e - \frac{J_c t}{3}\right) \text{[J/m^3]}, \quad H_e > \frac{J_c t}{2} \tag{6}$$

In case the winding thickness of magnets is relatively tiny, t hysteresis losses in the whole magnet conducting AC currents can be calculated from the magnetization losses obtained from Brandt's expression. However, in this study, the winding thickness of the magnet is relatively large, so hysteresis losses might be affected by the many tapes stacking [8]. The slab model gives the limit value for infinite stacking tapes. Figure 7 shows the results of the AC loss calculated by Brandt's equation and the slab model at 20 K and 50 K. The results of the two models are highly different in the lower current region. The slab model has less AC loss than the result of Brandt's equation. The differences decrease with an increase in currents. The results indicate that in most regions of the winding, the magnitudes of the magnetic field applied perpendicular to the flat face of the winding tape do not exceed the penetration field of its tape. Therefore, AC losses in the actual magnet with a thick winding area might be near the result of the slab model because of stacking tapes. In the following discussion, however, since the purpose of this paper is to confirm the feasibility of SMRS, we will proceed based on the calculation results using Brandt's equation, which may be an overestimation.

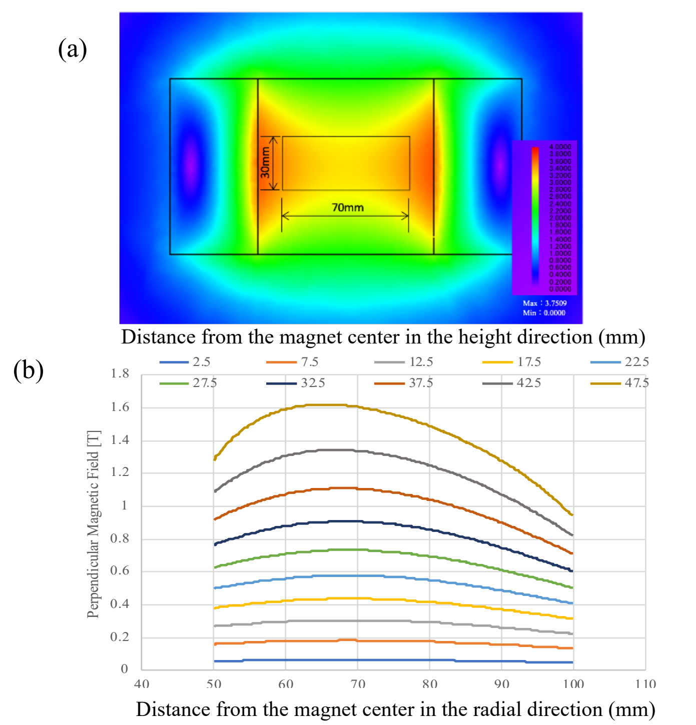


Fig. 5 Magnetic flux densities when a magnet conducting current of 90 A. (a) magnetic fields contour plot, (b) profiles of magnetic field of perpendicular to the flat face of the tape.

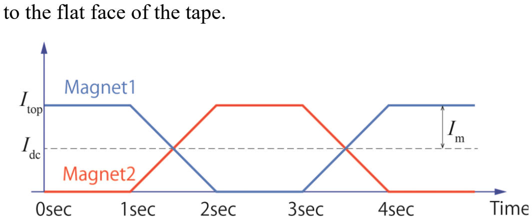


Fig. 6 Operating current pattern for SMRS

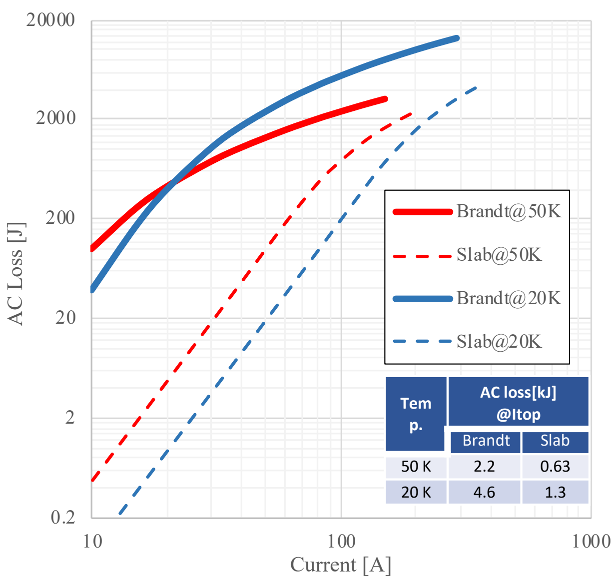
It was confirmed that the higher the temperature of the magnet, the smaller the AC loss. This tendency is that the calculation result using Brandt's equation appears from the lower current than the calculation result using the slab model.

When 90 A is changed in the pattern of Fig. 6, AC loss was calculated 2.2 kJ at 50 K by Brandt's equation.

IV. Discussion

The efficiency of SMRS is evaluated based on the result of the obtained AC loss. First, $DyNi_2$ is selected as the MCM for SMRS at 20 K. The amount of change in the magnetic entropy of $DyNi_2$ has been reported [9], and in order to calculate the capacity of the magnetic refrigerator using this material, the molecular weight of $DyNi_2$ was used to convert the values in the paper into units. The molecular weight of $DyNi_2$ is 279.9. The literature values show the results of 0 to 2 T and 0 to 5 T, and the values in 1 T increments are supplemented from these values. It is estimated that $DyNi_2$ can obtain a magnetic entropy change of 15 J/(kg/K) with a peak near 20K by changing the magnetic field of 3T.

This material is inserted into a magnet having an inner diameter of 100 mm, and the volume at which a magnetic field change of 3 T can be obtained is confirmed. From the magnetic field distribution in Fig. 5, the area where the MCM can be placed, where a magnetic field of 3 T can be applied, is 70 mm in diameter and 30 mm in height. The cooling capacity expected of $DyNi_2$ is estimated from the volume and density (8690 kg/m^3) of $DyNi_2$ placed in the magnet, the amount of temperature change (5 K) [9] and the amount of magnetic entropy change obtained by the magnetic field change of 3 T. Since it is



operated with two magnets, the amount of heat that can be absorbed by the MCM of 2 is about 150 J. Since one cycle is 4 seconds, the cooling capacity is estimated to be 38 W.

TABLE IV
Summarizes the Specifications of SMRS

Magneto caloric material $DyNi_2$	Diameter	70 mm
	Height	30 mm
	Density	8690 kg/m^3
Δ B		3T
Magnetic Entropy change @ΔB=3T		15 J/kgK
ΔTemp.		5 K
Cooling power of the SMRS		38 W
AC losses in the two magnets		1.1 kW
COP of cryocooler @50 K		0.05
Total power consumption		23 kW
Estimated COP of SMRS		0.0017

The ... wo magn... ive power consumed by the magnet operation is 1.1 kW. The power consumption of GM cryocooler to cool this heat generation is 22 kW from COP = 0.05. The power consumption for operating this SMRS is 23 kW. With a cooling capacity of 38W and power consumption of 23 kW, the COP is estimated to be 0.0017. Table IV summarizes the specifications of SMRS in which a high-temperature superconducting magnet is cooled at 50 K.

In order to improve the efficiency of SMRS, it is indispensable to increase the cooling capacity or reduce the AC loss. In order to improve the cooling capacity, it will be possible to develop an MCM with a high magneto calorific effect and efficiently apply a larger magnetic field change to the MCM.

On the other hand, it is well known that scribing the HTS tape is effective in reducing the AC loss [10]. By reducing the HTS tape width to 1.3 mm, which is 1/3, the AC loss can be reduced to about 1/3, so the COP can be achieved to be about 0.005, which is equivalent to that of GM cryocooler at 20 K.

V. Summary

We examined the feasibility of using a high-temperature superconducting coil for a static magnetic refrigerator aiming for 20K cooling, and found the following.

- ✓ When the current YBCO wire is used, the efficiency equivalent to that of the existing small refrigerator may be obtained by cooling the coil for magnetic refrigeration to 50K.
- ✓ If the AC loss can be further reduced, there is a possibility that a highly efficient cooling system can be realized.

In the future, we plan to make a prototype of a small coil and verify whether loss can be reduced by devising the coil arrangement and operating method.

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Fig. 7 AC loss calculation result for a HTS magnet of SMRS. Bold and dashed lines represent Brandt’s expression and slab model, respectively. Red and blue represent 50K and 20K, respectively.

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