Basic Research on a Magnetic Refrigeration System for Cooling to Liquid Hydrogen Temperature

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Naoki HIRANO, Yuta ONODERA, Toshiyuki MITO, Yuta MOTOKI and Akifumi KAWAGOE

Abstract— **Magnetic refrigeration technology is expected to be a highly efficient process at a temperature of around 20 K, which is the hydrogen liquefaction temperature. In magnetic refrigeration, a magnetic field change is applied to a magnetocaloric material (MCM) to obtain a magnetocaloric effect. In addition, since the greater the magnetic field change, the better the cooling characteristics, the magnetic field strength of permanent magnets is insufficient, and the use of superconducting coils that can generate strong magnetic fields with low power consumption is essential. We are researching and developing a static magnetic refrigeration system (SMRS) that does not have moving parts to obtain magnetic field changes, and generates them by altering the energizing current to the coil. The key to devising this system is an AC loss of the superconducting coil. In this study, we measured the AC loss under energization conditions of multiple palm-sized REBCO coils at liquid nitrogen temperature, and calculated the efficiency of the SMRS by improving the accuracy of the analysis method for evaluating the AC loss, based on the results. We report the results and discuss the technical feasibility of SMRS.**

Index Terms—**Magnetic Refrigeration, liquid hydrogen, AC loss, HTS Magnet, Norris's expression**

I. INTRODUCTION

Since hydrogen does not emit CO_2 even when used as a fuel for power generation, it is expected to prevent global warming and build a sustainable energy system. Technology to store large amounts of hydrogen is essential for the realization of a hydrogen powered society, and ideally it should be stored as a liquid. However, the available cooling system at a temperature of around 20K, which is necessary for long-term storage of liquid hydrogen, has a problem of low efficiency.

Since magnetic refrigeration can produce an ideal cooling cycle, high-efficiency refrigeration machines can be made even at a temperature of around 20K, and there are high expectations for it. However, in magnetic refrigeration, it is necessary to apply a magnetic field change to the magnetocaloric material (MCM). In addition, it is known that the greater the magnetic field change, the greater the cooling performance that can be obtained, and the use of superconducting coils that can generate a strong magnetic field with low power consumption is essential.We are developing a static magnetic refrigeration system (SMRS) using multiple high-temperature superconducting coils. The SMRS is a configuration that changes the magnetic field of the MCM by changing the current in the superconducting magnet. In conventional magnetic refrigeration technology, the method of changing the distance between the magnetic field source and the MCM is well known as a method of changing the magnetic field of the MCM [1]-[4]. This method increases the driving force and reduces overall efficiency.

We are also researching a method to change the magnetic field of the MCM using a magnetic shield without moving the magnetic field source or the MCM [5][6], and are investigating the use of superconductors for the magnetic shield.

A feature of the SMRS is that neither the magnetic field source nor the MCM move. As a result, it becomes a system that does not have a driving part in the magnetic field change, and it may be possible to achieve a highly reliable refrigeration system that does not require maintenance. On the other hand, it is necessary to consider the occurrence of AC loss due to changes in the current of the superconducting coil. In magnetic refrigeration, the minimum unit is an environment with a changing magnetic field and two sets of MCMs. The action of transferring cold heat from the MCM whose temperature has dropped and the action of releasing heat from the MCM whose temperature has risen are operated in series. Also, it is difficult to obtain large temperature changes with magnetic refrigeration, so combining it with other refrigeration systems that target waste heat around 20 K is a practical choice. Fig. 1 shows a conceptual example of the minimum basic unit of the SMRS and a 20K cooling system for recondensing liquid hydrogen. These units are connected in parallel to increase the refrigeration capacity. In order to expand the cooling temperature range, it is possible to connect units in series that select MCMs with different optimum operating temperatures.

We have confirmed that the SMRS achieves operation efficiency equivalent to that of existing cryocoolers through an analysis in which the AC loss is overestimated[7]. This paper presents the measurement results of palm-sized YBCO coils for AC loss, which is the key to the SMRS. Based on these measurement results, we have improved the accuracy of the AC loss analysis, calculated the power consumption of the SMRS taking into account the AC loss, and evaluated the efficiency as a ratio of the power consumption to the assumed cooling capacity of the MCM. We have investigated the technical feasibility of the SMRS using high-temperature superconducting coils.

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II. Evaluation of Approximation Methods for Calculating AC Losses in Pancake Coils

In order to estimate the operation efficiency of SMRS, the accuracy of AC loss calculations has been improved based on the measurement of AC losses in sample coils. The calculation method of AC losses in pancake coils in this paper are approximation method. This chapter describes the evaluation results of effectivity of this method.

A. AC loss measurement of HTS coils

The most important consideration in the SMRS is the AC loss of the superconducting coil. First, using commercially available YBCO wire, the AC loss was measured at liquid nitrogen temperature when a coil was fabricated. A photograph of the fabricated coil is shown in Fig. 2. The wire and coil parameters are shown in Tables I and II, respectively. The YBCO wire is made by SuperOx Japan, and its superconducting properties are standard wire with I_c of about 100 A for 4 mm wide wire at 77 K under self-magnetic field. The YBCO test coil is a double pancake one, using a stainless steel tape co-wound with a YBCO tape. Four test coils were manufactured and the AC loss was measured.

AC losses in test coils have been measured by the four-probe method. Fig. 3 shows a schematic diagram of the experimental circuit for AC loss measurement. Voltage taps on YBCO tape near the current lead terminal measure voltages, $v_s(t)$, across the sample coils, including inductive and resistive components. Resistive voltages are much smaller than inductive ones, so canceling the inductive voltages from the sample ones is done by using secondary voltages, $v_c(t)$, of the air core transformer connected to sample coils in series as shown in Fig. 3. R_{loss} is corresponding to ac losses in the sample coil. The AC loss energy of the sample coil was obtained by integrating the product of the voltages after canceling and current for one cycle. The currents are obtained from voltages of the shunt resistor, R_{shunt}.

B. AC loss calculation of HTS coils

In order to accurately calculate AC losses in the superconducting coil, it is necessary to calculate them in all the coil turns. To do so however, numerical analyses must be carried out on magnetic flux penetration into every tape of the turn, considering inter-tape electromagnetic interaction. This calculation consumes an amount of computation resources. Some computing methods to calculate AC losses in large-scale coil were proposed [8]-[10]. But high-level simulation techniques are required. Simple and easy calculation methods are desirable in the early phases of designing coils.

It is well known that a hysteresis loss property in one tape differs from that in several stacked tapes because of the interaction between tapes. It was reported that hysteresis losses in stacked YBCO tapes are in good agreement with calculation results, assuming a cross-section of the stacked tapes to the uniform superconductor, considering the applied magnetic fields of perpendicular components to the tape face [11]. The AC losses in the coils are calculated, assuming a cross-section of the winding area of the coil to the uniform superconductor and so considering a one-turn coil. Clearly, considering the winding cross-section as the one stacked conductor with all the turns, transport losses in the conductor with one turn length are calculated by Norris's expression on the elliptical cross-section.

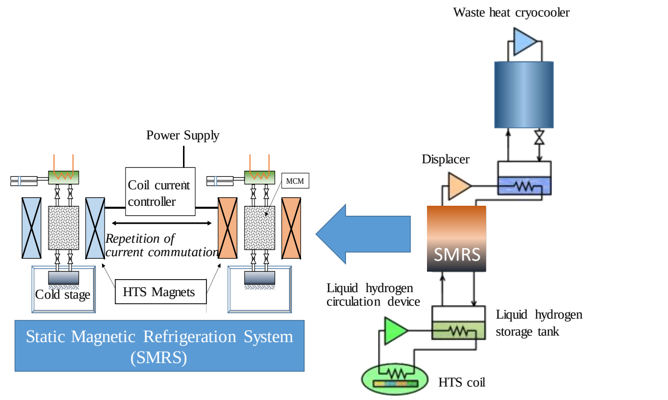

Fig. 1 An example of a liquid hydrogen recondensation system configuration using SMRS. superconducting coils.

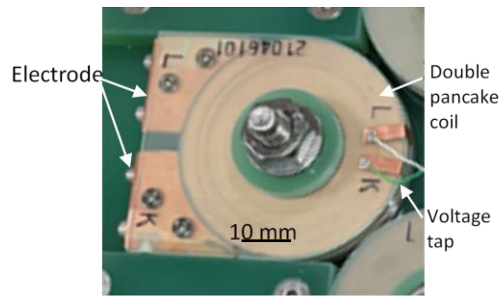

Fig. 2 Picture of YBCO test coil.

TABLE I
MAIN SPECIFICATIONS OF THE WIRE USED FOR THE YBCO TEST COIL

	Coated conductor	Co-winding
Material	YBCO	SUS316L
Width	4.25 mm	4.25 mm
Thickness	60 μm	30 μm

TABLE II
MAIN SPECIFICATIONS OF YBCO TEST COIL

Winding configuration	Double pancake coil
Number of turns	186×2
Inner diameter	30 mm
Outer diameter	63.5 mm
Coil height	9 mm

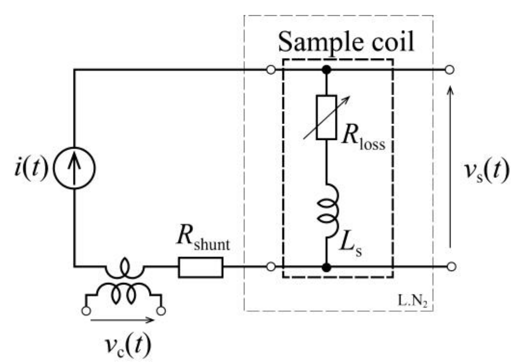

Fig. 3 Experimental circuit for AC loss measurement. R_{loss} is corresponding to ac losses in the sample coil. Inductive voltages in $v_s(t)$ is canceled by using $v_c(t)$.

C. AC loss measurement result

Prior to the evaluation of the AC loss, IV characteristics were

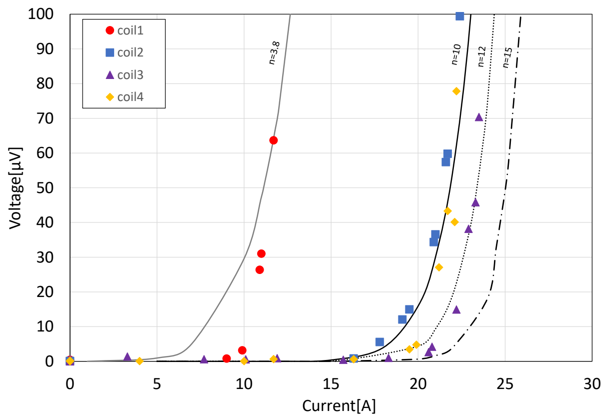

Fig. 4 I-V characteristics of the YBCO test coils and estimated I-V curve from n value model.

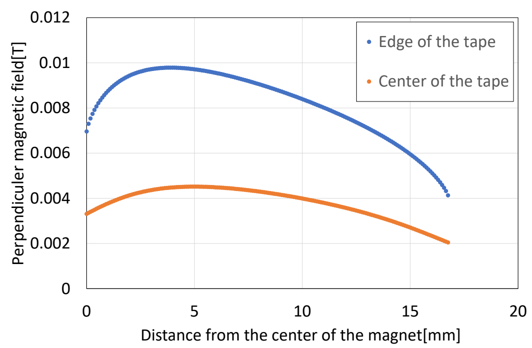

Fig. 5 Profiles of magnetic fields applied perpendicularly to the winding tape face.

confirmed in order to confirm whether the test coil had deteriorated. Fig. 4 shows the IV characteristics of the four test coils and those fitted from the n-value model. These data were measured each coil in liquid nitrogen. Several curves represent the estimated results of IV characteristics of the sample coils in which the critical current of the winding tapes is assumed 85 A at 77K under self-fields. The estimated curves are obtained based to n value model. These curves correspond to some n values. The inhomogeneity of critical currents of winding tapes was relatively large. The range is from 80-100A. But IV characteristics were estimated on the assumptions of the uniform critical current of the tape, that is 85A. Simple averages along the long length direction based on the critical current distribution data of the tapes used in coils 1- 4 were 86A, 86A, 82A, and 76A, respectively. To prevent degradations of the coil performance, transport currents have been suppressed to small value. In the measurement to obtain the IV characteristics, average electric fields whole length of the coil have been observed about 1-2 x 10^{-6} V/m, that is small to 1/100 compared with general criteria of 1 x 10^{-4} V/m. It is difficult to estimate the IV characteristics under low electric fields, but their curves for n=10-15 closely to measured data. These n values are reasonable. The critical current distributions in the windings of these coils were not uniform enough to be able to discuss the relation between the differences in the average critical currents and the IV characteristics of each coil. Therefore, in coil 2-4, damage is estimated not to exist. In coil 1, however, it was found clearly

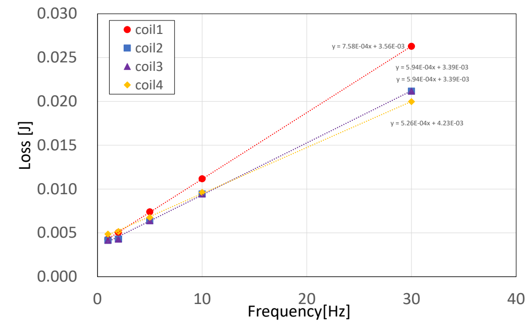

Fig. 6 Frequency dependencies of AC losses. (4 A[rms])

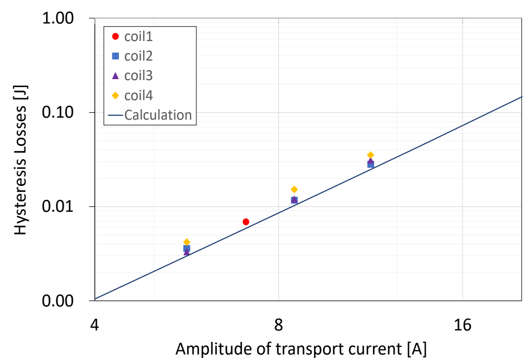

Fig. 7 Hysteresis loss for each coil and calculated loss from Norris's expression.

lower properties. So local damage may exist. The purpose of paper is to estimate AC losses of HTS coil for SMRM. So the reason of the degradations in the coil 1 is out of point. Therefore, the reason for the local damage of coil 1 have not been investigated.

As shown in Fig. 5, the magnetic field component in the direction perpendicular to the winding tape face, which affects the AC loss, was calculated. In Fig.5, blue and red lines represent magnetic fields at the edge and center of the tape, respectively. The test coils are non-insulation ones with co-winding tape from stainless steel. Therefore, inter-turn shielding currents have been induced during experiments. The shielding currents flow through the inter-turn resistances including the stainless steel tape as the co-winding tape, so Joule losses are generated between each turn. So frequency dependencies of AC losses have been observed, as shown in Fig. 6. The loss components with frequency dependences are proportional to frequency. In such cases, the Joule losses due to the shielding current is larger for coils with smaller inter-turn resistances. In case of the coil for SMRS, the HTS coils would be wound with insulated winding tapes because the sweep rate of the transport current is high. So, discussion in this paper focusses on hysteresis losses. Intercepts of the frequency dependences were obtained to get hysteresis losses.

Fig. 7 shows the hysteresis losses obtained for each of the four test coils. Both axes are shown in logarithmic scale. The hysteresis losses in coil1-3 are almost same as each other and smaller than that of the coil 4. Average critical currents of the winding tape for coil1-4 were 86-82A. That of coil-4 was low value of about 76A. The difference in hysteresis loss correlates with the average critical current. IV characteristics are seemed to be not correlated to the hysteresis losses. That is caused that

IV characteristics are determined by local low properties. In contrast, since hysteresis losses is amount of whole coil, the loss properties of the coils correlate to average critical currents. In Fig.7, the measured hysteresis losses together with Norris' analytical solution are shown. Measured hysteresis losses are close to calculated values from Norris's expression, assuming that winding cross-sections are considered one superconductor. These results indicate that individual turns are supposed to be one superconductor and are a good approximation for AC loss estimation on pancake coils, in case the width of the winding area is relatively longer than the height. This approximation is considered reasonable because the windings are electromagnetically coupled to each turn in a magnetic field perpendicular to the flat face of the winding tape. As a result, this effect remains independent of the applied magnetic field waveform.

III. Discussion

Evaluation of the SMRS efficiency from the AC loss results is obtained. Regarding the SMRS that cools at 20K, in previous research[7] we have trial-designed a system that can obtain a cooling capacity of 38W with a magnetic field change of 3T. Tables III and IV show the specifications of the superconducting wire and superconducting coil used in the design, respectively.

The MCM of the SMRS at 20 K selects $DyNi_2$. Based on the literature value of the magnetic entropy change of $DyNi_2$ [9], it obtains a magnetic entropy change of 15 J/(kg/K) with a peak at around 20K, by changing the magnetic field of 3 T [7].

When this MCM is inserted into a high-temperature superconducting magnet with an inner diameter of 100 mm, it has been confirmed that the space in which a magnetic field change of 3 T can be obtained is 70 mm in diameter and 30 mm in height [7]. The expected cooling capacity of $DyNi_2$ can be estimated from its volume and density placed in the magnet, the temperature change (5 K) [12], and the magnetic entropy change obtained by the magnetic field. In the SMRS, two magnets operate as a set, so the magneto-caloric change due to two MCMs is about 150 J. The SMRS operation cycle is assumed to be four seconds, as shown in Fig. 8 and the cooling capacity is estimated at 38W [7].

AC loss in the magnet is calculated as the summation of transport loss and magnetization loss. Fig.9 shows AC loss calculation results for an HTS magnet of the SMRS. Each loss is approximately estimated, assuming that the winding cross-section of a single pancake coil is considered one superconductor. Transport and magnetization losses are estimated from Norris's expression and the slab model, respectively. Magnetization losses are summations of losses in each turn. All turn losses are calculated based on the applied magnetic field in a direction oriented perpendicularly to the tape face of each turn.

AC loss in one magnet is estimated at 0.71 kJ at 50K during one cycle. The time of one cycle is 4 sec, so the power consumption of two magnets is 0.36 kW. The Coefficient of Performance (COP) of a 50K cryocooler is 0.05, the power consumption of a GM cryocooler to cool this heat generation is 22 kW. The COP of a refrigerator is defined as the ratio of refrig-

TABLE III
Main specifications of assumed 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 IV
Main specifications of the superconducting magnet assumed for SMRS

Number of magnets	2
Number of double pancake coils in one	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 V
Summarizes the specifications of the 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		0.353 kW
COP of cryocooler @50 K		0.05
Total power consumption		7.41 kW
Estimated COP of SMRS		0.005

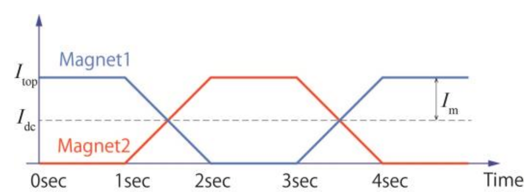

Fig. 8 Operating current pattern for SMRS

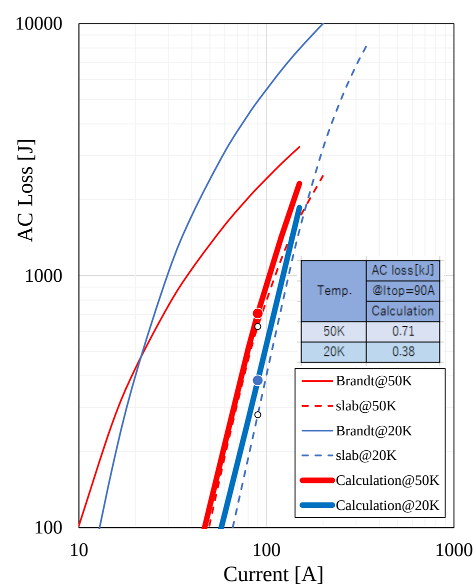

Fig. 9 AC loss calculation result for a HTS magnet of SMRS. Bold, solid and dashed lines represent Norris's expression, Brandt's expression and slab model, respectively. Red and blue represent 50K and 20K, respectively.

eration capacity to power consumption. The total power consumption of the SMRS is estimated at 7.41 kW. With a cooling capacity of 38 W and power consumption of 7.41 kW, the COP is estimated to be 0.005. Table V summarizes the specifications of the SMRS in which a high-temperature superconducting magnet is cooled at 50 K.

In order to improve the efficiency of the 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.

IV. Summary

The AC loss of the superconducting coil was measured, the accuracy of the loss analysis was improved based on the result, and the efficiency of the static magnetic refrigerator aiming at 20K cooling was calculated, and found the following results.

- ✓ The efficiency of a static magnetic refrigeration system with a cooling capacity of 38 W at 20 K is expected to be COP: 0.005.
- ✓ This value is an efficiency equivalent to a 20 K GM refrigerator.

Further reductions in AC losses could lead to more efficient cooling systems. In the future, we plan to use multiple small coils to verify whether the AC loss can be reduced by devising the arrangement of the coils and the energization method.

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