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# Study on Heat Generation of a Bulk HTS for Application to a 100 kWh SFES Superconductor Bearing

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## Abstract

This paper presents experimental and numerical investigation on heat generation of a bulk HTS for application to a 100 kWh Superconductor Flywheel Energy Storage System (SFES) bearing. An experimental device is manufactured to reproduce varying magnetic field conditions that a bulk HTS may experience during the operation of the 100 kWh SFES. The bulk HTS is directly cooled by a cryocooler while the heat is generated by the eddy currents created by varying magnetic fields induced by a coil. In order to design the cryocooling system for the 100 kWh SFES project, a preliminary experiment to investigate the actual cooling load variation under AC magnetic field has been carried out. In the experiment, two different copper holders were designed and tested. Several temperature sensors were installed on each component of the assembly and the temperatures were measured for several operating conditions of the 100 kWh SFES. The experimental investigation on the thermal response of the bulk HTS and its holder is considered to be a valuable step for the successful materialization of a large-scale SFES.

*Keywords* : 100 kWh SFES, bulk HTS, magnetic field variation

## I. Introduction

A superconductor flywheel energy storage system (SFES) is an electro-mechanical battery with high energy storage density, long life, and good environmental affinity. An SFES mainly consists of a pair of non-contacting high temperature superconductor (HTS) bearings that provide very low frictional losses, a composite flywheel with high energy storage density and mechanical strength, a motor/generator that transfers mechanical energy into electrical form and vice versa, and a vacuum chamber that minimizes windage losses. The HTS bearings, which offer dynamic stability without active control, are the key technology that distinguishes the SFES from other flywheel energy storage devices, and great effort is being put into developing this technology [1, 2].

The HTS bearings designed for the 100 kWh SFES are composed of several conduction-cooled bulk HTSs that are field-cooled to an Nd-Fe-B magnet rotor. The bulk HTSs are fixed to the stator of the HTS bearing by copper holders, which also act as cold heads. The designed operation speed of the magnet rotor of the 100 kWh SFES is around 7000 rpm. While the rotor rotates, vibrations with amplitudes up to ± 0.5mm may occur due to

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eccentricity of the rotor and external forces. This may create magnetic field variations at the bulk HTS, copper holder and cold head, and this may result in temperature rise and decrease in trapped magnetic fields [3-5]. A vacuum chamber and testing device weae built to reproduce the magnetic field variation of the 100 kWh SFES. Temperature variations of cold head, copper holder and bulk HTS have been investigated for two different HTS holder designs and their effect on the bulk HTS properties and the HTS bearing performance are discussed.

## II. Experiment

Fig. 1 shows an experimental apparatus, which consists of the magnetic field generator and the cooling system assembly for the bulk HTS. The magnetic field generator is installed on the outside of the vacuum chamber and it generates the required AC magnetic field. The bulk HTS is assembled to the cooling system in the vacuum chamber. GFRP was selected as the material of the top plate of the vacuum chamber to avoid any distortion in the magnetic field created by the magnetic field generator. Fig. 1 also shows the positions of the temperature sensors. In the experiments, three Cernox (CX-1070 and CX-1080, Lakeshore Inc.) sensors were attached to the cold head (T1), the copper holder (T2) and the top surface of the bulk HTS (T3).

### Magnetic field generator

The magnetic field generator was designed to reproduce the variation in magnetic field that the bulk HTS, copper holder and cold head may experience due to the ± 0.5 mm vibration amplitude of the SFES rotor. The coil of the magnetic field generator has 500 turns and creates a magnetic flux density of ± 20.2 mT at the copper holder surface when an AC current with a peak of 4.6 A is applied to the coil (see Fig. 2). The magnetic flux density was measured at the permanent magnet surface (H=0), the bulk HTS surface (H=19) and the copper holder surface (H=35) using a Gaussmeter, and the measured values were compared to the simulation data.

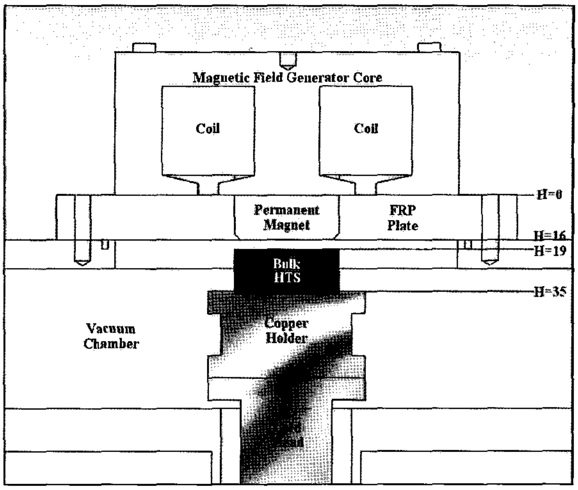


Fig. 1. Schematic diagram of an experimental apparatus and sensor installation.

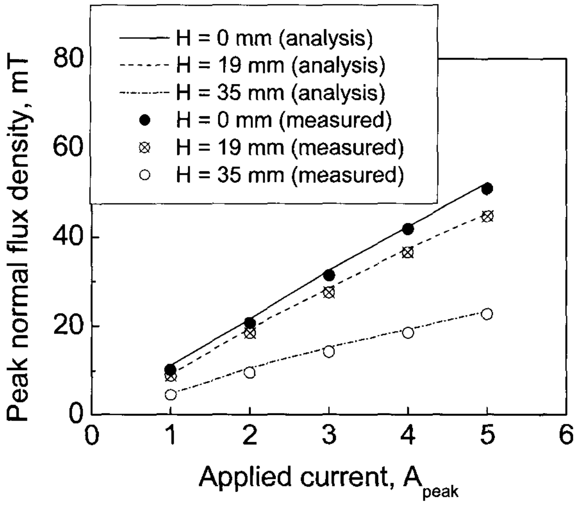
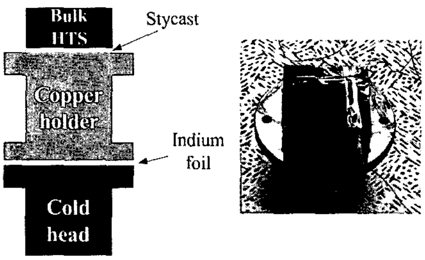


Fig. 2. Magnetic flux density by the MFG.

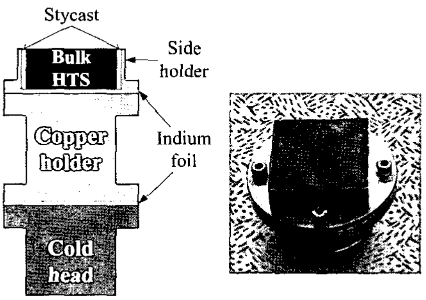
### Assembly of cooling system

In the experiment, the bulk HTS is conductively cooled by a cryocooler. The bulk HTS was fixed on the copper holder which was attached to the cold head of the cryocooler. A YBCO bulk, with a size of 40 × 40 × 16 mm is used as the bulk HTS and

CryoTelTM (LG Electronics, Inc.) as the cryocooler. Indium foil was used at the contact surface between the copper holder and the cold head to reduce thermal resistance. The experiments were performed for two different designs of the copper holder (see Fig. 3). In design #1, the bulk HTS is directly fixed on the copper holder by using a cryogenic epoxy (Stycast 2850 FT). The heat leak from outside and the generated heat is conducted through the bulk HTS. Thermal contact between the bulk HTS and the cold head exists only at the bottom of the bulk HTS. In design #2, the sides of the HTS are enclosed inside of a copper side holder. Indium foil is used at the contact surface of the bulk HTS and the copper holder and the same epoxy is fills the gap between the bulk HTS and the side holder. Heat invasion to the bulk HTS assembly and the copper holder occurs by two modes, molecular conduction and radiation. In this apparatus, the amount of molecular conduction is in the order of 1 $\mathrm{W/m^2}$ while that of radiation is in the order of 100 W/m2. Therefore, it is seen that most of the heat invasion occurs by radiation.



(a) design #1



(b) design #2

Fig. 3. Schematic diagram and photo of two different copper holders.

### Experimental procedure

Experiments are revealed in Table 1. In order to observe the effect of the bulk HTS under varying magnetic field, for cases 1 and 2, the bulk HTS was not installed on the copper holder while the bulk HTS was installed for cases 3 and 4. In case 5, the permanent magnet is installed in the middle of the GFRP plate to investigate the effect of the DC value of the magnetic field. In the experiments, the bulk HTS assembly and its holder are cooled and then the AC current is applied at 50, 100, 150 Hz to a coil to generate the magnetic field variation. Steady-state temperatures are measured before and after the generation of eddy currents. During the experiments, the room temperature was maintained constant and the input power of the CryoTelTM was 165 ~ 170 W.

## III. Results and Discussion

### No load characteristics

Table 1 shows the results of the no load test. The lower value of T1 indicates there was less heat invasion. T1 for case 1 is thought to be lower than in other cases because the surface area for case 1 is the smaller than in other cases. For cases 2 ~ 5, the surface area are similar. In the experiments, the surface finish of the copper holder and side holder was poor, allowing more heat invasion. Hence, there seems to be little difference in the heat invasion to the bulk HTS and the copper holder. T21 (= T2 – T1) for all cases are less than 1 K because the thermal contact resistance is small due to the indium foil at the contact surface. However, ΔT32 (= T3 – T2) for cases 3 and 4 are different. For case 3, the thermal contact resistance between the bulk HTS and the copper holder was large due to the absence of an indium foil layer, and all heat invasion to the bulk HTS flowed through it. This leads to the large T32. For case 4, thermal contact was good and the heat invasion to the bulk HTS passes only through its top surface, so a small T32 could be obtained.

Table 1. Experimental conditions and no load data.

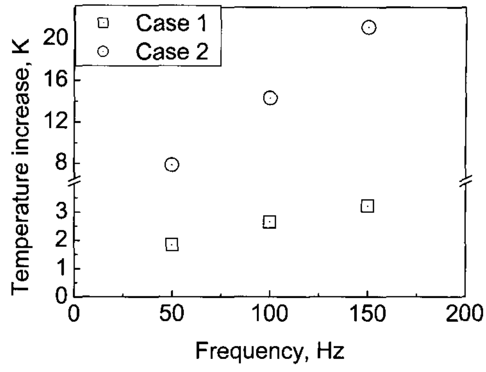
| | Experimental conditions | | | |
|---|---|---|---|---|
| | **Copper holder** | **Bulk HTS** | **Permanent magnet** | **Current to coil, $A_{peak}$** |
| **Case 1** | design #1 | X | X | 4.6 |
| **Case 2** | design #2 | X | X | 4.6 |
| **Case 3** | design #1 | O | X | 4.6 |
| **Case 4** | design #2 | O | X | 4.6 |
| **Case 5** | design #2 | O | O | 5.0 |

| | No load data | | | | |
|---|---|---|---|---|---|
| | **$T_1$, K** | **$T_2$, K** | **$T_3$, K** | **$\Delta T_{21}$, K** | **$\Delta T_{32}$, K** |
| **Case 1** | 45.5 | 45.8 | - | 0.3 | - |
| **Case 2** | 47.2 | 47.9 | - | 0.7 | - |
| **Case 3** | 47.2 | 47.9 | 59.1 | 0.7 | 11.2 |
| **Case 4** | 47.8 | 48.3 | 50.7 | 0.5 | 2.4 |
| **Case 5** | 47.9 | 48.9 | 51.7 | 1.0 | 2.8 |

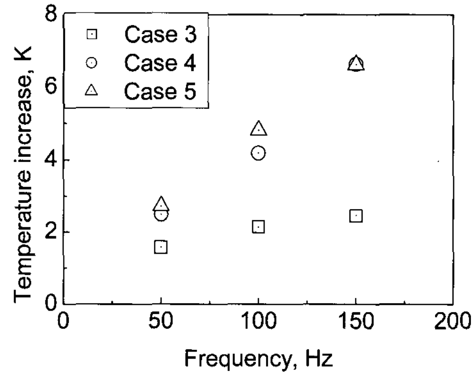
## Heat generation by eddy current

From the performance characteristics of the cryocooler was provided by the manufacturer, the temperature increase of the cold head indicates the increase of the cooling load. For the experimental conditions in this research, CryoTelTM shows a value of 0.20 ~ 0.25 W/K.

Fig. 4 shows the temperature increase of the cold head which represents the difference between the cold head temperature before and after the generation of eddy currents. The increase of the cooling load is due to the increase of the heat generation and the heat invasion. When current starts to flow through the coil of the magnetic field generator, heat is generated in the coil and return iron. Although the magnetic field generator is air-cooled, the generated heat cannot be completely removed. This increases the invasion of radiation heat during the experiments. The temperature increase for case 2 is large while that for case 1 is small. This means that the heat generation by eddy currents is governed by the side holder. For cases 3 ~ 5, the temperature increase is suppressed compared to cases 1 and 2 because the bulk HTS reduces the magnetic field variation in the copper holder and side holder by the Meissner effect. From the comparison of cases 4 and 5, it seems that the DC value of the magnetic field does not affect the heat generation by eddy currents.



(a) without bulk HTS



(b) with bulk HTS

Fig. 4. Temperature increase of cold head.

The temperature at the top surface of the bulk HTS was 62 ~ 64 K for case 3 and 53 ~ 58 K for case 4, respectively. Although design #2 might generate more heat, temperature was low because of smaller thermal resistance through indium foil. This implies that design #2 requires less cooling capacity from the cryocooler than design #1 to obtain the same top temperature of the bulk HTS. And design #2 can reduce heat flow through the bulk HTS, consequently reducing temperature non-uniformity.

### Heat generation in bulk HTS

Figure 5 shows the increase of ΔT32 for cases 3 ~ 5. In case 3, ΔT32 generally increases as the amount of heat flow through the bulk HTS due to radiation heat invasion and heat generation increases. As the operating field frequency increases, the temperature of the magnetic field generator and the radiation heat invasion increased. It was hard to quantify the amount of heat generation in the bulk HTS in this experiment. Even if there is heat generation in the bulk HTS, the amount would be less than 0.2 W. For cases 4 and 5, the increase of ΔT32 is smaller than for case 3, although more heat is generated. This is because the thermal resistance of cases 4 and 5 is smaller than that of case 3.

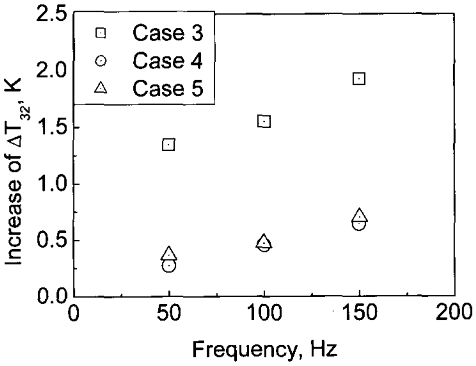


Fig. 5. Variation of T32.

## IV. Conclusions

The thermal response of the bulk HTS cooling assembly under varying magnetic fields has been experimentally investigated. From the experimental results, the design with the bulk HTS directly fixed to the copper holder (design #1) showed larger thermal resistance and smaller heat generation than the design with the sides of the HTS enclosed by the copper side holder (design #2). A lower temperature for the bulk HTS, however, was obtained in design #2 in spite of the larger heat generation. The temperature rise due to magnetic field variation had less effect on the bulk HTS compared to the temperature difference throughout the bulk HTS due to thermal resistance. Therefore, when taking only the temperature factor into consideration, design #2 is the logically advantageous choice among the two designs, since it is expected to keep the bulk HTS at a lower temperature. However, when analyzing the experimental results in a larger scale for the SFES system as a whole, further studies should be carried out to consider other factors such as rotational losses. Though the temperature of the bulk HTS is lower for design #2, the larger heat generation indicates that more eddy current has been created by the magnetic field variation. This means that more heat will be generated in design #2 by magnetic field variation caused not only by rotor vibration, but also by inhomogeneity of the rotor magnet. That is, the larger heat generation can be an indication for larger rotational loss. Therefore, further studies should be carried out, considering bulk HTS cooling as well as SFES rotational loss, to determine the optimum side holder design.

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