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Experimental Research on Basic design and protection of High-T_c Heater Triggered Switch in Liquid Helium

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Abstract-- **This paper presents experimental and characteristic analysis of high-Tc heater-triggered switch using coated conductor (CC) in liquid and gas helium. The high temperature superconducting insert coil which can be installed in a low temperature superconducting (LTS) magnet has been proposed and researched to generate higher magnetic field for NMR. Since CC could be an attractive option for HTS insert, it is important to research the characteristics of heater-triggered switch employing CC. We performed the heater test and constructed simulation model using finite element method (FEM.) We performed a protection test and observed normal zone propagation (NZP) signals to evaluate the switch with protection of magnet.**

1. INTRODUCTION

The YBCO coated conductor (CC) has been a promising conductor for a high field superconducting coil technology. This conductor has lower critical current (I_c) dependency from external magnetic field and its substrate and stabilizer can be designed to satisfy the purpose of individual applications [1].

But the CC also has some disadvantages to be applied for high field coil. First, its rectangular shape is not adequate for a layered winding structure that is a general winding method for the high field coil. Thus a double pancake winding should be selected for the CC, but the double pancake winding causes many joints resistance to every pancake modules. Besides, there is no superconducting joint technology for high-T_c superconducting (HTS) conductor to realize a persistent current operation of HTS coil. As compared with BSCCO tape, it is still hard to purchase the CC with kilometer scale. These disadvantages report us that the high field magnet only using the CC would not be possible for the time being.

Recently, an HTS insert coil technology for the increase of field levels > 20 T has been researched by several groups. A combination of low temperature superconducting (LTS) background coils and HTS insert coils is an alternative way to produce a high field magnet with overcoming the disadvantages of the HTS conductor. Because the HTS coil will be installed inside of the LTS coils, the HTS insert coil would be operated in liquid helium (LHe) so an I_c of the HTS coil will be increased multiple times of the I_c in liquid nitrogen (LN_2.) In addition, a margin between an operating temperature (T_{op}) and a critical temperature (T_c) will also be increased and a cryogenic environment would be different from the case of the LN_2.

This paper deals with operating characteristics of a heater-triggered switch for a fluxpump in LHe. The heater-triggered switch is a superconducting device to control its superconducting/normal state transition (S/N transition) with its heater. The heater injects heat energy to the HTS conductor enough to induce thermal quench. When the switch operates in LHe, its operating characteristics could be different from the one in LN_2 because of the different cooling condition. The I_c of the HTS conductor will be increased so an operating current (I_{op}) of the switch can also be increased. But raising the I_{op} can cause unexpected damage to the HTS conductor when the switch is turned on. The differences of cooling characteristics between LHe and LN_2 also affects to an operation of the switch. We fabricated a switch with diode temperature sensor and measured the temperature of the switch in LHe while inducing heater current. We also induced the heater current while transport current (I_t) is flowing through the HTS conductor and observed its temperature and normal zone propagation (NZP) to discuss about feasibility of protection with the switch as an additional discharging circuit.

2. SETUP AND THEORETICAL MODEL

2.1. Sample Preparation

Our research group have had a plan to fabricate HTS coil with CC and purchased Superpower SCS4050. This wire was built on a non-magnetic substrate to generate high magnetic field without saturation of magnetization and had copper stabilizer whose electrical and thermal conductivity is high. We fabricated two samples with the wire to prepare the unexpected damage during tests. The only difference between the samples was thickness of impregnated epoxy resin to observe the effect of impregnation on cooling condition.

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TABLE I
SPECIFICATION OF TWO SAMPLES.

Specification	Sample 1	Sample 2
Manufacturer / Product	SuperPower, Inc. / SCS4050	
Width / Thickness	4 / 0.095 mm	
Length of wire	420 mm	
Ic (77K, 0T)	120 A	
Ic (4.2K, 0T) / Ic (77K, 0T)	11 ~ 12	
Tc	~ 90 K	
Heater resistance	Ni-Cr heater (52.2Ω)	
Temperature sensor	Diode Sensor (DT-470)	
Bobbin material	Glass Fiber Reinforced Plastic	
Bobbin diameter (outer/inner)	150 mm / 90 mm	
Thickness of Stycast 2850 FT	5 mm	10 mm

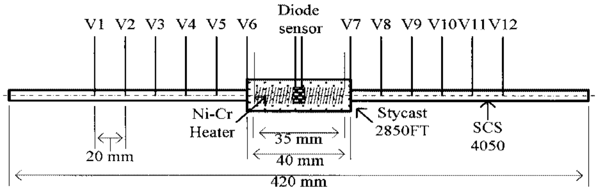

Fig. 1. Development schematic of the sample.

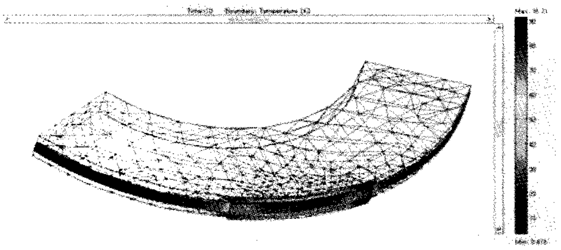

Fig. 2. Simulation result of sample 1 with heater current of 0.45 A.

Table I presents the specification of the two samples and Fig. 1 is a development figure of the sample. We first wound a Ni-Cr heater and installed a diode sensor at the center of the CC wire. This wire wound on cylindrical bobbin whose outer diameter was 150 mm. Finally, we impregnated the sample with an epoxy resin with different thickness, 5 mm for sample 1 and 10 mm for sample 2. The Fig. 1 also presents the points of voltage taps to observe NZP phenomenon and the taps were marked with ascending order from left to right and these marks were applied in figures of this paper.

2.2. Analytical Model Using Finite Element Method

We constructed simulation model using FEM and compared the theoretical model with experimental results. To analyze the heat transfer process in the sample, transient heat conduction equation (1) is given by

$$\rho C\frac{\partial T}{\partial t}-\nabla(k\nabla T)=Q \qquad (1)$$

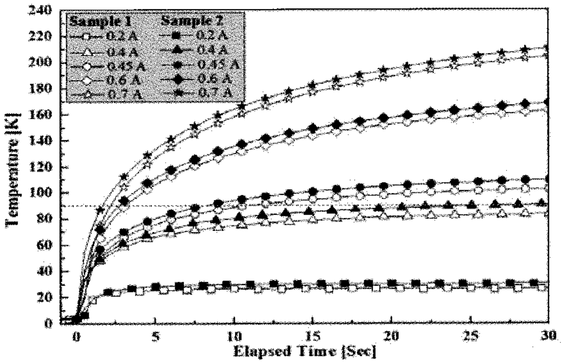

Fig. 3. Experimental results of heater test in liquid helium.

where T is the temperature, t is the time, ρ is the density, C is the specific heat, and k is the thermal conductivity. The first term on the left-hand side represents the time rate of change of the internally stored energy density, and the second term on the left-hand side represents the heat discharge by thermal conduction. The thermal input due to heater, Q, is imposed on the YBCO CC during a fixed duration. The simulation results of sample 1 by using a FEM are depicted in Fig. 2. The figure is also presenting meshed model and thermal distribution of the sample with heater current of 0.45 A. The bright region of the model means higher temperature. This 3-D model is quarter part of the whole sample including heater trigger. In case of this figure, maximum temperature reached 91.21 K after 10 s from the heater current was induced.

3. HEATER TEST IN LIQUID HELIUM

3.1. Heater Test in Liquid Helium

We performed a heater test in the LHe with inducing different current to the heater, from 0.2 A to 0.7 A. As recorded in the Table I, the T_c of the samples was 90 K, and this value was set as a criterion for S/N transition even this value is not adequate for practical heater-triggered switch applications. Fig. 3 presents an experimental result of the heater test in the LHe of the two samples. Curves with open symbols are temperature curves of the sample 1 and the others with filled symbols are curves of the sample 2. A dashed line in this figure indicates the T_c, 90 K. After 30 s elapsed, temperature of sample 1 reached about 26 K, 83 K, 103 K, 163.5 K, and 205 K with the heater current of 0.2 A, 0.4 A, 0.45 A, 0.6 A, and 0.7 A, respectively. The temperature of sample 2 reached about 30 K, 90.5 K, 110 K, 168.5 K, and 210 K with same order of heater current. The thickness of the epoxy caused a temperature difference between two samples but the difference was quite small and shapes of the curves were similar. In case of these samples, it could be assumed that there is no difference of cooling conditions between the two samples.

In the heater test with the heater current under 0.4 A, the

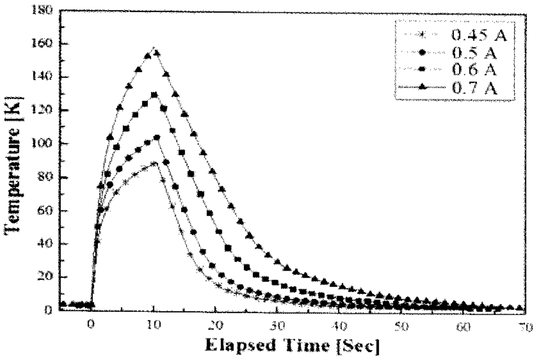

Fig. 4. Experimental result of sample 1 in liquid helium.

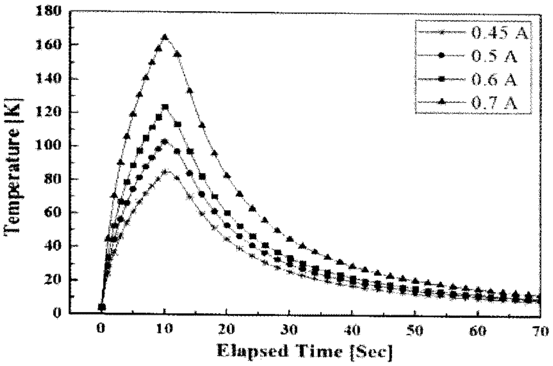

Fig. 5. Simulation result of sample 1 in liquid helium.

temperature of sample did not come over the T_c. 0.45 A was the minimum value of heater current which can produce the S/N transition. For the case of 0.45 A, 0.6 A, and 0.7 A, a time for the temperature of the sample 1 to reach 90 K was about 10.5 s, 3 s, and 2.2s, respectively. These values are directly related to the time delay from inducing heater current to S/N transition of the heater-triggered switch and also related to the pumping rate of fluxpump [2]. Between the results of 0.45 A and 0.7 A, the time difference was quite large so that a difference of pumping rates also would be large. The higher pumping rate is profitable to the fluxpump for the superconducting coils whose operating current or inductance is very large.

3.2. Simulation Result of Sample 1

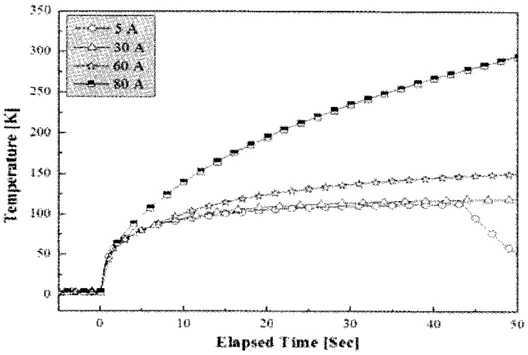

Fig. 6. Experimental result of protection test of sample 2 in LHe.

Fig. 4 presents the experimental result of sample 1 in the LHe with the heater current from 0.45 A to 0.7 A. After 10 s elapsed, the temperature reaches about 89 K, 104 K, 131 K, and 159 K with the heater current of 0.45 A, 0.5 A, 0.6 A, and 0.7 A, respectively. Because the temperature of each curve at 10 s was different, the Fig. 4 shows recovery characteristics in LHe with different initial temperatures. After the heater current turned off, because the cooling condition would be same except the initial temperature, shapes of the curve were similar. The temperature at 10 s mainly affected to the recovery time. Complete recovery for the sample to 4.2 K took over 20 s. For a practical operation of the fluxpump, this recovery time could be too long to satisfy the required pumping period. Thus an additional practical recovery time would be necessary for the practical fluxpumps and HTS coils.

Fig. 5 presents simulation results to compare with the experimental results in the Fig. 4. After 10 s elapsed, the temperature reaches about 85 K, 104K, 127 K, and 166 K with the heater current of 0.45 A, 0.5 A, 0.6 A, and 0.7 A, respectively. The simulation results agreed well with the experimental results but the recovery curves showed some difference. It is because of that a temperature dependence of cooling coefficients for the helium was not considered to the simulation model.

4. PROTECTION TEST IN LIQUID HELIUM

4.1. Protection Test of sample 2 in Liquid Helium

The NZP velocity of a superconductor is related to the protection of the superconducting magnet. Faster NZP can prevent the accumulation of heat energy that is able to do damage to the magnet in local area. For an evaluation of protection and durability of the switch, we observed a temperature and NZP voltage signals of the sample while DC current flow through the sample. The heater current for this test was set to 0.45 A which was the minimum value that can induce S/N transition, or NZP. Fig. 6 presents the result of the test with sample 2 when I_t was 5 A, 30 A, 60 A, and 80 A and a pattern of the curves showed saturation or steady increase.

Because our objective was finding the saturation of temperature curve in this test, the procedure of the test did not simulate the practical operation procedure of switch for fluxpump. The real fluxpump generally has another closed loop to bypass the I_{op} while the switch is turned on. This test procedure simulated the worst situation that hardly occurs to the fluxpump and the switch. But it is not only assuming the worst case but also aiming for evaluating the possibilities of the switch to be operated as additional active protection circuit for the HTS coil. Because the active protection to discharge the magnet current generally continues for from 10 to 30 s without damage, it is recommended for the magnets to have more normal zone during the discharge procedure to divide thermal energy load. This test was continued for 50 s which is longer than the duration of general active protection.

In addition, there were no NZP signals in these four tests whose I_t were 5 A, 30 A, 60 A, and 80 A. This is because of that the non-impregnated parts of the CC were not heated sufficiently to reach T_c. This assumption was confirmed by the FEM simulation result. Fig. 7 presents the temperature curve of the protection test along the wire when the I_t was 5 A. Two dashed lines indicate the boundary of impregnated region. The dashed lines met with the temperature curves whose temperature values were below 40 K. The I_c of the sample at this temperature was bigger than I_t, so the NZP voltage signal could not be produced in this condition.

During the protection test of the sample 2 with the I_t of 100 A, the sample 2 was damaged permanently. Fig. 8 presents the experimental result of the test with 100 A current. Compared with another results, temperature curve in Fig. 8 was not saturated and reached above 480 K. In addition, the NZP signals were also found after about 15 s from the V6-V7 signal was produced. Referring to the Table I, although the I_c of samples would be over 1000 A, perfect protection of the CC from thermal damage or burn out could be guaranteed under 100 A transport current from the test. Thus stable and precise sequence control of the heater-triggered switches is necessary to raise the I_{op} of superconducting coil to prevent from an unexpected thermal damage during the heater current is induced.

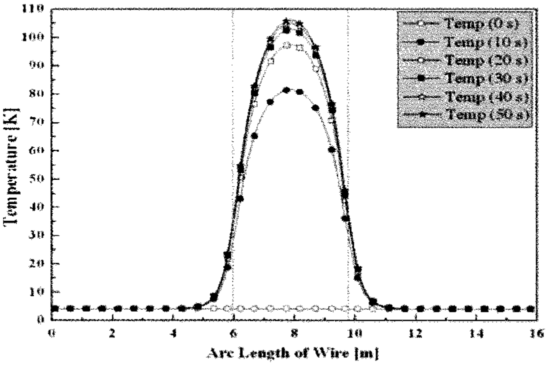

Fig. 7. Simulation result of temperature distribution in sample 2.

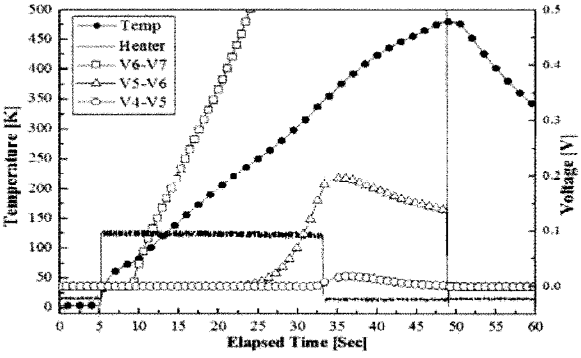

Fig. 8. Experimental result of protection test of sample 2 with 100 A.

4.2. Protection test of sample 1 in gas helium

We also performed the protection of sample 1 in gas helium whose temperature was 20 K. In the gas helium condition, we performed the test with the I_t of 5 A to 60 A. Among these tests, the test with the It of 60 A was the only result that the NZP signals were observed. Fig. 9 presents an experimental result of the test in gas helium when the I_t was 60 A. The curve with open with open-triangle symbol indicates the V5-V6 signal which starts to show non-zero value at 46 s. Compared with the result of test in LHe, worse cooling condition caused the NZP with lower I_t. The generated heat energy could be accumulated easily in this cooling condition so that the NZP signals were also generated faster than the case in LHe.

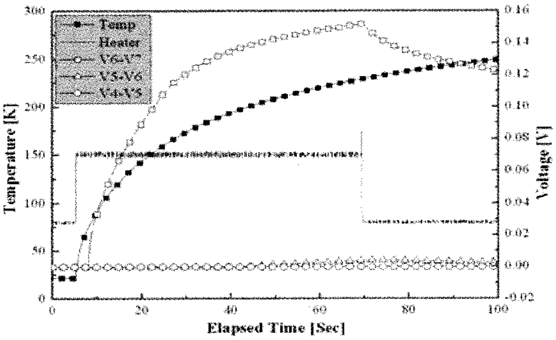

Fig. 9. Experimental result of protection test of sample 1 with 60 A in 20 K gas helium.

5. CONCLUSION

In this paper, the experiment for study characteristics of the heater-triggered switch for fluxpump in LHe was performed. The minimum value of heater current which cause S/N transition was by the experiment. Some considerations for the protection were also discussed.

From the experiments, we conclude that some additional temperature criterion for a recovery of the practical heater -triggered switch is necessary. During the test, sample 2 was damaged and it pointed out that the operating current should be raised with the consideration of protection even I_c of CC in LHe is increased multiples of the I_c in liquid nitrogen.

Even the simulation model was constructed, boundary conditions and temperature-dependent characteristics of the model were not considered. For the further research, more detailed model would be constructed and designing the switch could be more facilitate.

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