

Study on the Persistent Current Switch in HTS Coils Wound with 2G Wire for Compact NMR Magnets

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Abstract. High temperature superconducting (HTS) magnets wound with REBCO wires are used in many applications, and the superconducting magnet which is operated in persistent current mode has many advantages. Therefore, we have been developing compact NMR relaxometry devices using HTS coils operated at liquid nitrogen temperature. The required strength and homogeneity of magnetic field of proposed NMR relaxometry devices are 1.5 T and 150 ppm/cm³ respectively. The proposed HTS magnet for NMR relaxometry device consists with stacked HTS double pancake coils wound with REBCO wires and operated by persistent current mode (PCM) using superconducting joint between REBCO wires. In PCM operation, the ability of persistent current switch (PCS) is very important, so, in this study, the thermal properties of YBCO wire against the various thermal inputs by heater were investigated experimentally to design the PCS for PCM HTS magnets. The thermal behaviors of the YBCO wires were measured as functions of amount of heat input using two types of epoxy resin. The current bypassing properties on the YBCO loop coil with developed PCS were studied experimentally.

1. Introduction

We have been developing the compact NMR/MRI device using HTS bulk magnets [1], [2], and the compact NMR relaxometry device using HTS wires with the persistent current mode (PCM) operation [3]. In PCM operation, the superconducting joints between stacked HTS coils are required. So, the superconducting joint techniques between HTS wires are very important issue and many researches has been studying. Recently, the K·JOINS, Inc. has developed successfully the high performance superconducting joints between REBCO tape wires by partial melting diffusion and oxygenation annealing process [4]. The development of high performance persistent current switch (PCS) is required to develop the compact NMR relaxometry operated in PCM. In this study, thin strain gauges were used as thermal heater and the thermal characteristics of two types of epoxy resin (putty and liquid) were compared to develop the compact PCS operated at liquid nitrogen temperature. Therefore, the thermal behaviors of YBCO wires by the heaters were studied experimentally to design the thermal type PCS for NMR relaxometry. In order to investigate the PCM using the developed PCS, the loop-shaped YBCO wire fabricated by wind-and-flip winding method [5]-[7] was prepared and the performances of the developed PCS operating in liquid nitrogen bath were estimated.



2. Thermal diffusion properties of 2G wires to develop the PCS

2.1. Experimental details

In order to design the PCS for NMR relaxometry, the thermal behaviors of YBCO wires by heater were investigated experimentally. Figure 1 shows the schematic draws of front views of YBCO wires impregnated by putty and liquid epoxy resins used in experiments. The 100 μm thickness YBCO wires are used, and the thickness of Cu stabilizer is 20 μm , thickness of YBCO layer is 1 μm , and the critical current at 77.4 K is 100 A. The four strain gauges with 1 k Ω were used as a heater and they were attached to the front and back sides at center region of sample wire. The transport current of heater was 50 mA and the thickness, length and width of heater are 50 μm , 11 mm and 5 mm, respectively. Four thermocouples were attached on the front side with 1 cm interval as shown in figure 1. The thermal properties of YBCO wires against the various input heat were measured using two types of epoxy resin (putty and liquid), and the samples were cooled by liquid nitrogen.

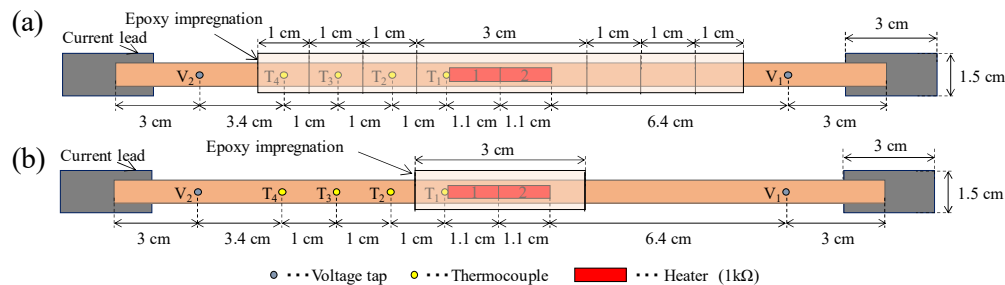


Figure 1. The schematic draws of front views of YBCO wire impregnated by (a) putty and (b) liquid epoxy resins

2.2. Measured the thermal properties of YBCO by heater

The thermal behaviors of YBCO wires with/without transport currents (0 A and 20 A) against the different input heat (10 W \times 30 s and 10 W \times 3 s) were measured using two types of epoxy resin (putty and liquid) in the liquid nitrogen bath. The impregnation lengths of putty and liquid epoxy are 9 cm and 3 cm, respectively, and the thickness of both epoxy resins is 1 cm. Figures 2 and 3 show the measured temperature properties and distributions in the longitudinal direction of YBCO wire impregnated by putty and liquid epoxy resin in the liquid nitrogen bath. They were measured at T1-T4 when the transport currents are 0 A (input heat: 10 W \times 30 s) and 20 A (input heat: 10 W \times 3 s). From figures 2 and 3, the maximum temperatures of both epoxy resins were measured at T1, and the maximum temperature on putty and liquid epoxy resins with 0A are 139.4 K and 202.1 K, and 122.3 K and 149.1 K when the 20 A transported. The temperature gradient in the longitudinal direction of YBCO wire impregnated by the liquid epoxy resin is larger than the putty epoxy resin even the length of putty epoxy is longer than that of liquid epoxy when the 0 A and 20 A were transported. The results of subtracting the temperature profile of the putty epoxy resin (Fig.2(a)) from the temperature profile of the liquid epoxy resin (Fig.2(b)) after thermal inputting by the heater are shown in figure 2 (c). On inputting the heat, the temperature at T1 of the liquid epoxy resin rises several tens of kelvin higher than that of the putty epoxy resin, and the temperature distribution from T1 to T3 also higher. When the heat input by the heater was finished, the required time of liquid epoxy resin (27 s) for the temperature at T1 to drop from 140 K to the liquid nitrogen temperature (77 K) is also longer than that of the putty epoxy resin (10 s). Therefore, it is clarified that the heat insulating ability of the liquid epoxy resin is much better than the putty epoxy resin. The cooling condition of the epoxy resin is determined by thermal conductivity, heat capacity and surface contact condition between epoxy resin and sample wire. We know the values of thermal conductivity and heat capacity of liquid epoxy resin, but these values of putty epoxy resin are still unknown. In this experiment, we were not able to measure the surface contact condition between epoxy resin and sample wire. However, it was proved that the thermal conductivity of the liquid epoxy resin is

lower than that of the putty epoxy resin, and the liquid epoxy resin is suitable for making an adiabatic conduction. When the same amount of heat has been inputted, the thermal insulation material which can make a high temperature gradient in the short area is very effective for the compact thermal type PCS. From these results, it is suitable to use a liquid epoxy resin as a thermal insulation material for the thermal type PCS.

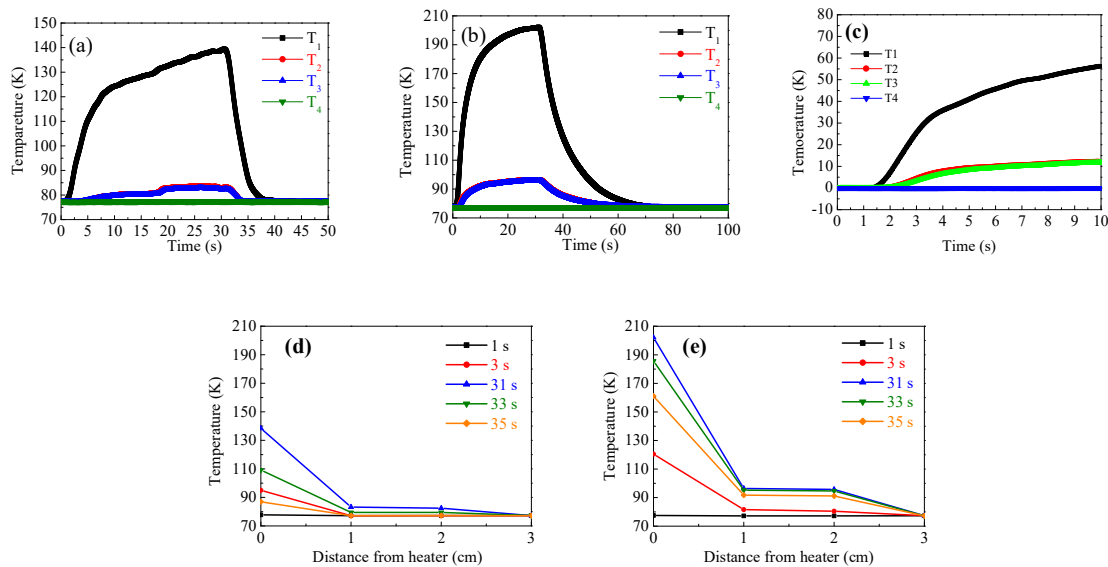


Figure 2. The measured temperature profiles and temperature distributions in the longitudinal direction of YBCO wire impregnated by (a), (d) putty and (b), (e) liquid epoxy resins at T1-T4 when the transport current is 0 A (input heat: 10 W×30s). Figure (c) shows the temperature profile obtained by subtracting figures (b) to (a).

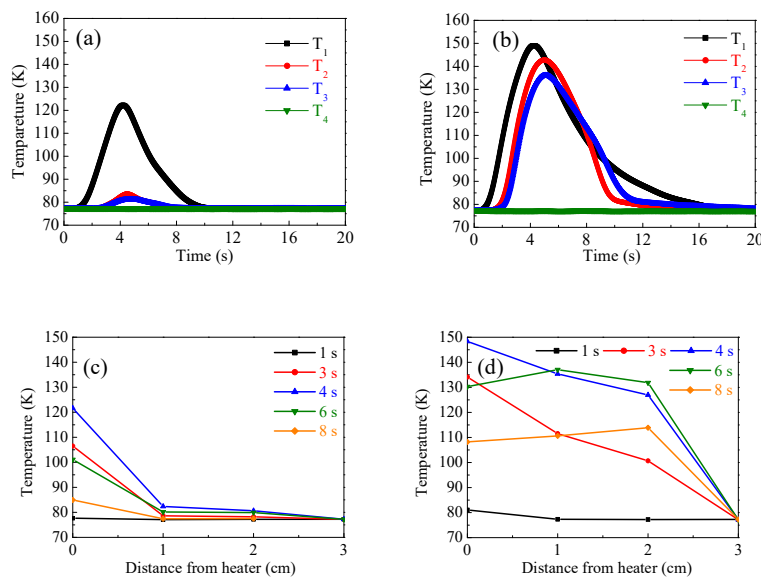


Figure 3. The measured temperature profiles and temperature distributions in the longitudinal direction of YBCO wire impregnated by (a), (c) putty and (b), (d) liquid epoxy resins at T1-T4 when the transport current is 20 A (input heat: 10 W×3 s).

3. Division of Current in the Loop-shaped YBCO Wires by Thermal PCS

In order to confirm the performance of the developed PCS, the experiments using the stacked HTS DP coils with superconducting joints are necessary. However, in this study, we performed the experiments using a simple loop-shaped YBCO wire instead of the HTS magnet.

3.1. Experimental details and the current division by different inductance

The loop-shaped HTS coil made by wind-and-flip winding method [5] - [7] was prepared and provided by W.S. Kim in Korea Polytechnic University. Figure 4 (a) shows the schematic top view of the loop-shaped YBCO wire. YBCO wire (SuperPower Inc.) with 12 mm width was cut longitudinally at its center except both of end parts, and a joint-less superconducting closed loop circuit consists of sliced YBCO wire with 6 mm width was prepared as shown in figure 4 (b). Figure 4 (c) shows the photograph of experimental setup to estimate the performances of the developed PCS. This coil is cooled down at 77 K in the liquid nitrogen bath. The four thermocouples were attached at near the heaters with 1 cm interval to measure the thermal properties during the PCS operating. Figure 5 shows the measured temperature distribution in the longitudinal direction when the thermal inputs are delayed with 2 and 3 seconds from the current transporting. In order to surely realize a PCM, it is necessary to create a normal region of over 90 K which is a critical temperature of the YBCO wire as long as 2.2 cm in PCS at least. The two hall sensors (B_1 , B_2) were attached on the surface of YBCO wire to measure the amount of both currents (I_1 , I_2). In the superconducting closed loop circuit as shown in figure 4, the current flows to the two paths proportional to their inductances because both paths have no electrical resistance. In this case, the inductances of both paths are proportional to the length of their path, and the length of shorter path with PCS is 280 mm and the other one is 580 mm. Figure 6 shows the measured magnetic flux density (B_1 , B_2) by Hall sensor and the calculated current (I_1 , I_2) by (B_1 , B_2) when the transport current is 20 A. The current flows to the PCS (I_1) is two times larger than I_2 because the current flows to the two paths in the superconducting closed loop is inversely proportional to their inductances.

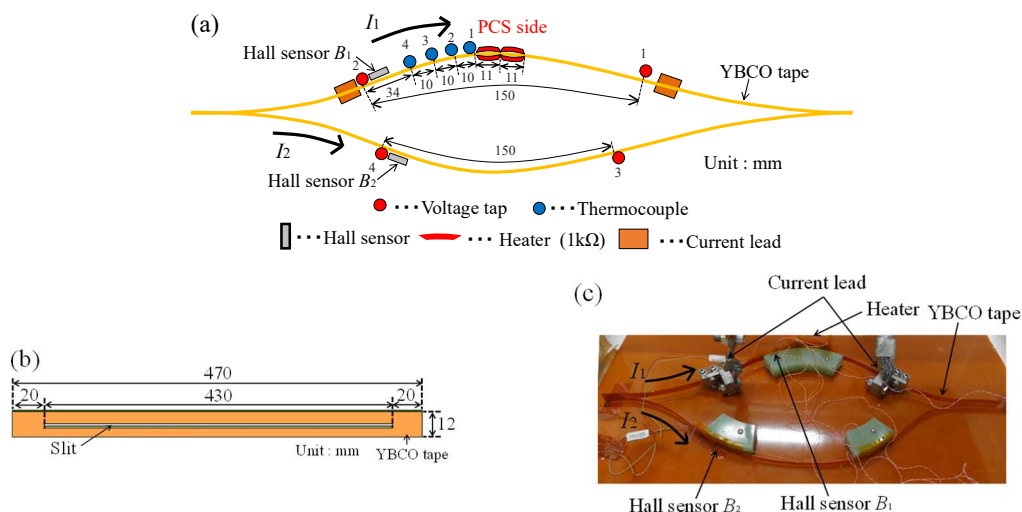


Figure 4. (a) the schematic top view of the loop-shaped YBCO wire, (b) the schematic draw of YBCO wire with 12 mm width was cut longitudinally at its center except both of end parts and (c) the photograph of experimental setup.

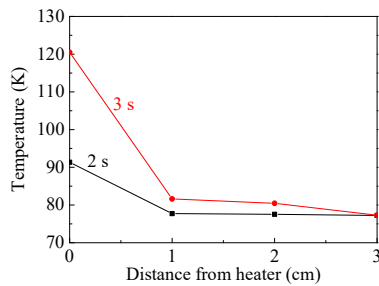


Figure 5. The measured temperature distribution in the longitudinal direction.

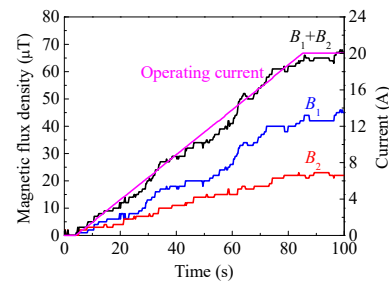


Figure 6. The measured magnetic flux density (B_1 , B_2) by Hall sensors and the calculated current (I_1 , I_2) by B_1 and B_2 when the 20 A was transported.

3.2. Measured the turn on/off properties of PCS

The stability of generated magnetic field operated in the persistent current mode is better than driven mode superconducting magnets used the achievable best power supplies, and no more energy is needed. In order to go to PCM, the supply current has been adjusting until the desired magnetic field was obtained, and then PCS was turned off. It is necessary to determine the time to stop the current transporting in closed loop circuit from the time of stopping the thermal input in PCS. Therefore, in this study, the sufficient cooling time to recovery the normal stated PCS to the superconducting state was studied experimentally, and the cooling time of PCS was investigated until the 13 s with 1 s interval.

Figures 7 (a) and (b) show the measured path currents and thermal input, and transported current was started to reduce to 0 A with 10 and 11 seconds delayed from stopping the thermal input of PCS. In Figure 7 (a), PCS was not sufficiently cooled, the current I_2 was reduced to 6 A because there were still remained the electrical resistance and operated as RL circuit. However, when the cooling time was longer than 11 seconds, PCS was fully recovered to the superconducting state, the persistent current mode was obtained as shown in figure 7 (b). So, we know that the required cooling time in order to fully return from the normal state to the superconducting state of the developed thermal PCS is required over 10 seconds.

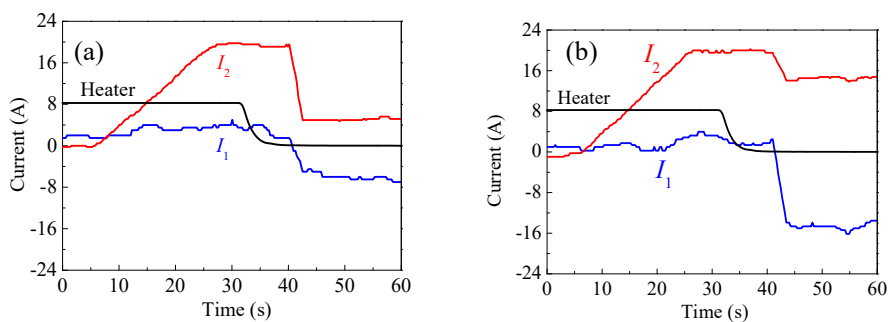


Figure 7. The measured currents I_1 and I_2 by 20 A, and the thermal inputs by heater are delayed with (a) 2 and (b) 3 seconds from the current transporting.

4. Conclusion

We have been developing the thermal type PCS operating in PCM for compact NMR devices. In order to design the thermal insulation of PCS for NMR relaxometry, the thermal properties of YBCO wires

by input heat were investigated experimentally. From the results of thermal behaviors using the two different epoxy resins, the liquid epoxy resin is better than putty epoxy resin for using thermal insulation, even though putty epoxy resin is able to be handled easily. From the simple experimental test using the liquid epoxy resin and a loop-shaped YBCO wire which has two different inductances, the PCM operating was confirmed by developed thermal type PCS.

References

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