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Development of Peltier Current Lead for DC cable

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Abstract

The widespread expectation is that superconducting technologies will be one of the effective technologies to decrease energy loss and improve efficiency in energy grids. Especially, in recent circumstances, applications connecting with renewable energy receive attention. Yamaguchi et al successfully developed 200 m-class superconducting direct current transmission and distribution system (CASER-2) in Chubu University and carried out the demonstration of this system. On this demonstration, "Peltier Current Lead (PCL)" was employed, wherein Peltier device was used for the purpose of pumping up the heat through the down-leads, It was observed that PCL reduced heat leak into cryostat as compared to usual Cu current leads on this demonstration, but some issues to be solved remained, such as heat-cycle performance etc.. In this paper, we designed a prototype PCL for the purpose of improvement of the mechanical strength and the durability for the heat cycle, and evaluated the performance.

Keywords: Direct current transmission; Cryogenics; Peltier current lead; high temperature superconductors

1. Introduction

The environmental issues are very focused in recent years. Superconducting transmission systems are one of the effective applications to solve these issues. Mostly superconducting transmission systems are focused on AC systems. On the other hand, DC transmission system is free from AC loss. Superconducting direct current transmission and distribution system (CASER-2) has been developed in Chubu University by Yamaguchi et al [1]. DC superconducting transmission project is planed at Aluminum plant by Chinese Academy of Science during recent years [2].

In developing superconducting applications, the reduction of heat leak is one of the most important integrant. At superconducting transmission systems, heat leak into cryostat is from the surface of cryogenic double pipes and current terminal. In demonstration test of CASER-2, "Peltier Current Lead (PCL)" is employed to reduce heat leak from terminal. The effectiveness of PCL was investigated in experiment and calculation by Yamaguchi et al [3-10]. In this test, it was reported that PCL reduced heat leak compared to conventional Cu current leads (CCL). In p-type, heat leak of a PCL is 3.6 W and that of a CCL is 4.3 W. In n-type, heat leak of a PCL is 2.6 W and that of a CCL is 3.7 W.

However, some issues become apparent. One of the issues is that electrical resistance increases going through the experimental cycle (this cycle consists of cooling from room temperature (RT) to 190 K, applying current 100 A and

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warm up to RT). For the purpose of solving this issue, we carried out designing prototype PCL and evaluated the performance. In this paper, we report these evaluation results.

2. Samples

We predicted some causes of these issues, and took countermeasures for each cause as shown in Table 1.

Table 1. Causes and countermeasures for problems.

Issue	Kind of cause	Cause	Countermeasure
Increasing of electrical resistance	Cooling cycle	Thermal stress	Changing layout of Peltier elements
	Handling	Mechanical stress	Changing structure of terminal

PCL used in CASER-2 consists of high temperature terminal (HT terminal), Peltier element and low temperature terminal (LT terminal). The causes of increasing electrical resistance issue are predicted that Peltier elements become stressed by cooling cycle and handling. In attempt to control the increasing of electrical resistance, layout of Peltier element is changed to enhance the strength against thermal stress and structure of terminal is changed to ease up mechanical stress. Prepared sample is shown in Fig. 1. GFRP cylinder joins HT and LT terminal for reinforce. The structure of LT terminal is changed from simple Cu block to two Cu blocks jointed by flexible Cu conductor to absorb thermal stress caused by the difference of coefficient of thermal expansion a between Cu and GFRP. Previous PCL doesn't have GFRP cylinder and flexible Cu conductor. To observe the contribution of each changed part, the samples imitated the structure of PCL near Peltier element were prepared. The layout of prepared samples are shown in .

Sample 10 and sample 3.3 are mostly same structure. The only difference of both samples is layout of Peltier element as shown in Fig. 2. Sample GFRP has same layout of Peltier element with sample 3.3. The structure of terminal is changed in both samples. Sample 10 and sample 3.3 were used to observe the contribution of layout of Peltier element. Sample GFRP and sample 3.3 were used to observe the contribution of terminal structure.

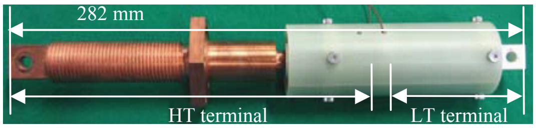

Fig. 1. Prototype PCL

Table 2. Sample compositions.

Sample name	GFRP cylinder	Peltier elements
Sample 10	×	φ10 mm × 1 piece
Sample 3.3	×	φ3.3 mm × 9 pieces
Sample GFRP	○	φ3.3 mm × 9 pieces
Previous PCL	×	10 mm × 10 mm × 1 piece
Prototype PCL	○	φ3.3 mm × 9 pieces

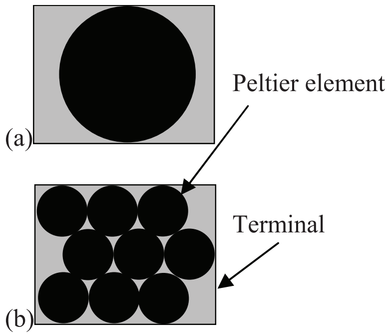

Fig. 2. (a)Layout of Peltier element in sample 10. (b)Layout of Peltier element in sample 3.3.

3. Experimental results

3.1. Cooling cycle

Cooling cycle test was performed like below. First, cool down the temperature of LT terminal T_L about 190 K (which temperature is near the condition in CASER-2) by liquid nitrogen. In order to stabilize the system, we had kept T_L constant for 5 minutes. Current I was applied to PCL from 20 to 200 A in step of 20 A. At the each step of applying current, the system held for 5 minutes. When the temperature of HT terminal T_H exceeded 420 K, current was stopped immediately to avoid the adverse affect to solder connecting part. When the test was finished, the system was warmed up to RT and measured the electrical resistance of the sample.

The result of sample 10 and sample 3.3 was shown in Fig. 3. This figure shows the normalized electrical resistance of samples. Where x, $R(x)$ and $R(0)$ mean number of current applying, electrical resistance after x times current applying and initial electrical resistance, respectively. Circular plots mean sample 3.3 and triangular plots mean sample 10. $R(x)$/ $R(0)$ of sample 3.3 didn't increase but that of sample 10 increased with x as shown in Fig. 3. Next, in

Fig. 4 circular plots show prototype PCL and triangular plots show previous PCL. $R(x)/R(0)$ of prototype PCL increased slower than Previous PCL. Fig. 5 and Fig. 6 show I dependence of T_H, T_L and temperature difference ΔT on prototype and previous PCL respectively. T_H on both samples increased with I. On the other hand, T_L first decreased, reaching a minimum near 100 A, and then increased with I. T_H and T_L increment on prototype PCL above 100 A was smaller than that on previous one.

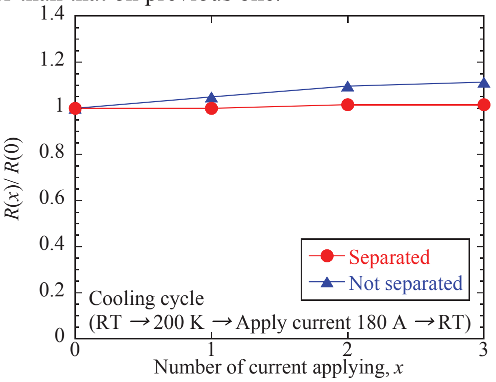

Fig. 3 x dependence of $R(x)/R(0)$ at test samples.

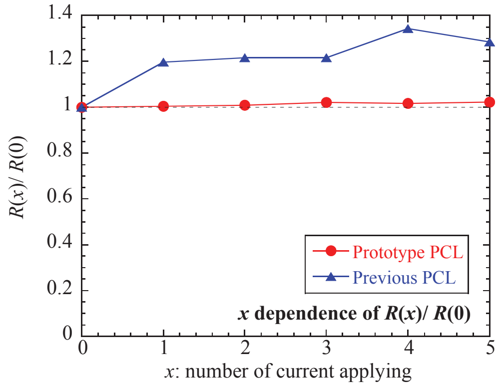

Fig. 4. x dependence of $R(x)/R(0)$ at PCLs.

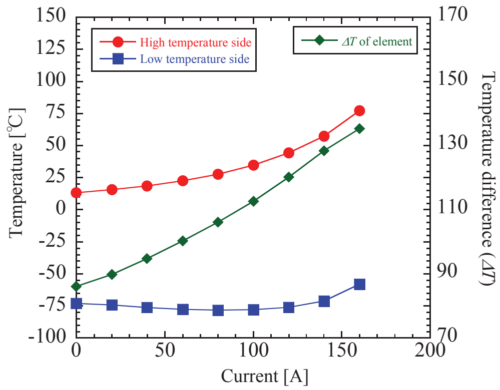

Fig. 5 I dependence of temperature on prototype PCL in Table 2.

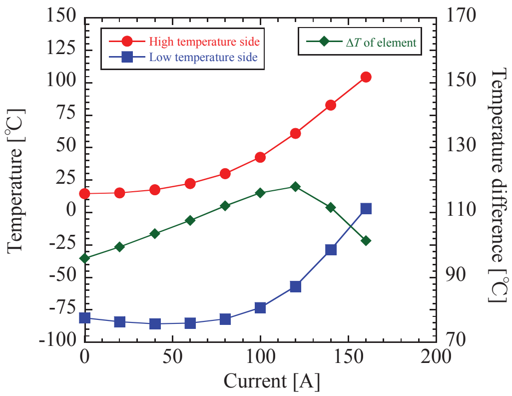

Fig. 6. I dependence of temperature on previous PCL in Table 2.

3.2. Strength test

The strength test was performed to observe the structural strength against the stress of handling. PCL was fitted in the hole of vacuum case flange. Then, the LT terminal of PCL is stuck out below the flange. This stuck out terminal is very weak against horizontal force. Therefore, we carried out strength test like below.

The voltage terminal was connected with HT and LT terminal of PCL. The HT terminal was anchored to the measurement equipment and LT one was impressed horizontal force. Impressed force (F) was increased by increasing stroke in increment of 1 mm/ min. When the voltage rapidly increased with impressing F, it could be considered that PCL was broken. The F when PCL was broken was converted the torque N_C. The results were assessed by comparing N_C. The results are shown in Table 3. From this result, N_C of GFRP sample was above fifteen times that of sample 3.3.

Table 3. N_C of both sampels

	Sample 3.3	GFRP sample
N_C [N m]	3.66	> 57.7

4. Discussion

4.1. Increasing resistance – Cooling cycle

In cooling cycle test, we found out the effect of separating Peltier element. The Peltier element of sample 3.3 has nearly same cross sectional area of sample 10. These Peltier elements are set in hexagonal closest packing with a little gap. Other condition is standardized in both sample 3.3 and sample 10. The reduction of $R(x)/R(0)$ increment in sample 3.3 is contribution of separating Peltier element (Fig. 3). When samples are cooled and heated, it is impressed to Peltier elements that compression or expansion stress from difference of a between Peltier element and terminal. Since there is little gap between separated Peltier element, portion of compressional stress is absorbed by this gap.

In Fig. 4, this difference also observed between prototype PCL and previous PCL. Previous PCL has a piece of not separated Peltier element. Since Peltier element is not separated, $R(x)/R(0)$ increases in previous PCL. On the other hand, since Peltier element is separated, $R(x)/R(0)$ doesn't increase in prototype PCL. In Fig. 5 and Fig. 6, the ΔT between both sides of prototype PCL is lower than that on previous one. This result means that the contribution of heat leak through the GFRP cylinder is smaller than other contributions and we can neglect the contribution of heat leak through GFRP cylinder. The decrement of ΔT of previous PCL above 100 A is considered that the Joule heat become much larger than the Peltier heat absorption at the LT side of Peltier element. Since LT terminal of previous PCL consists of single Cu block, the heat capacity of LT terminal is lower than HT terminal. As a result, T_L more increases than T_H and ΔT of previous PCL decreases above 100 A.

4.2. Increasing resistance – handling

GFRP sample has GFRP cylinder joining LT and HT terminals. In previous PCL which doesn't have it, LT and HT terminals are joined by only four plastic material spacers and connecting surface (Fig. 7). Therefore, this connection is very weak for the stress to LT terminal. On the other hand, LT terminal of prototype PCL is protected with GFRP cylinder. Since LT terminal is protected, the stress to connection of Peltier element in prototype PCL is smaller than previous one.

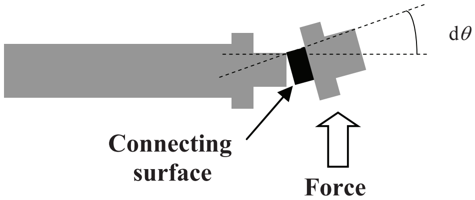

Fig. 7. Condition of the force to low temperature terminal

5. Conclusion

We carried out development of PCL based on the result of CASER-2. The changed points are shown in below.

- Peltier element used in PCL is separated some pieces to reduce the thermal stress.
- GFRP cylinder and flexible conductor is employed to reduce the handling force.

The effect of separated Peltier elements was confirmed by cooling cycle test refer to Fig. 3 ~ Fig. 6. Electrical resistance of PCL using separated Peltier elements didn't increase by applying current with cooling LT terminal. The effect of GFRP cylinder and flexible conductor was confirmed by strength test refer to Table 3. The strength of PCL against the horizontal handling force was improved about fifteen times stronger than the previous structure.

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