§6. Thermal Analysis on Current Leads for Large Scale Superconducting Applications

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Fusion energy is expected as a new clean energy without CO_2 emission. For the nuclear fusion, plasma should be confined by large superconducting magnets, for which large current is fed by huge bus lines. For such large current transmission, superconducting distribution systems seem to be effective. And also, future large energy generation by fusion systems would require highly effective transmission systems for actual use of electric power. Thus, we should develop high performance superconducting systems with low thermal loss.

For short distribution systems, dominant heat leak comes from current leads at the terminals. We have developed a Peltier current lead (PCL) for the thermal insulation on the current lead[1)]. In the PCL, the Peltier modules are inserted in the current lead. On the current lead, main heat sources are Joule heat and conduction heat from the outside. Thermoelectric materials can pump out the heat from the low temperature part by the Seebeck effect and also insulate the conduction heat by the low thermal conductivity. We develop a simulation code to calculate the heat leak of the PCL and optimize the shape of them. We used thermal balance equations for the heat leak estimation including the Seebeck effect[1)], where the temperature distribution and the heat leak were calculated by the developed code.

In this report, we discuss the dependence of the heat leakage from the PCL on the current and material parameter[2)]. We used two different thermoelectric materials that had higher resistivity or lower resistivity with a different temperature dependence of Z. Samples 1 and 3 have higher resistivity and smaller thermal conductivity than samples 2 and 4. Using these thermoelectric parameters, we calculated the heat leak on the PCL with the optimum shape factor at I = 160 A. We call the corresponding PCLs as PCL 1, PLC 2, PCL 3 and PCL 4, respectively. Optimum L/A for the samples with low-resistivity thermoelectric elements are smaller compared with those with high resistivity. For optimized shape factor L/As optimized for 160 A, the current dependence of the heat leak is shown in Fig. 1. The cryogenic load has a minimum at I = 160 A under these conditions for PCLs 1, 2, 3 and 4. For PCL 1, the increase of the heat leak is small for under-currents below 160 A and steep for an over-current above 160 A when compared with PCL 2 of an n-type material (Fig. 1 (a)). A similar tendency can be seen for the p-type material (PCLs 3 and 4) in Fig. 1 (b).

We then estimated the heat leaks of PCLs by doubling the length of the thermoelectric elements while keeping the shape factors for the copper lead constant. These results are referred to as PCL 5, 6, 7 and 8. One of the reasons why the current leads experience over-current conditions is the deviation of the optimum L/A caused by variation of the thermoelectric properties. Therefore, we only change the L/A of thermoelectric elements to compare the actual devices in CASER-2.

Due to these parameters and the optimum current giving the minimum heat leak shift to a small level, the initial optimum current of 160 A corresponds to an over-current condition. The current dependence of the heat leak with the double-length PCL is shown in Fig. 1. In the calculation, the optimum current for the actual current leads with the minimum heat leak is actually shifted. As shown for the current dependence, PCLs 6 and 8 are in a severe condition at the over-current state. The heat leak rapidly increases as the current increases above 100 A, and it is very large at 160 A. On the other hand, the heat leak increase is small for PCLs 5 and 7. Thus, the high resistive samples such as PCLs 5 and 7 are better in over-current conditions.

For comparison, we also calculated the dependence of the cryogenic load on current for conventional current leads (CCL; without the thermoelectric element). For the case where the length of an optimized current lead is doubled, the cryogenic load at 100 A is approximately 5 W (about 50 W/kA) and increases very quickly at a current above 140 A.

In general, electric power applications have a wide range of feeding currents, and current leads are therefore sometimes used under over-current conditions. Based on the current dependence of the heat leakage and analysis of the over-current conditions, higher-resistivity elements seem to be better for the lowest increase in heat leakage at over-current conditions. For PCL, Z and resistivity seem to be important factors for optimization.

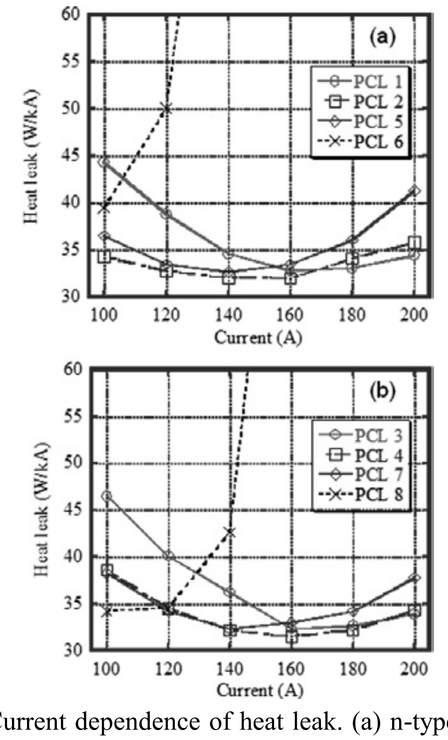

Fig. 1. Current dependence of heat leak. (a) n-type and (b) p-type materials.

1) S. Yamaguchi *et al.*: Rev. Sci. Instrum. **75**, 207 (2004).
2) T. Kawahara *et al.*, J. Electron. Mater., **41**, 1205 (2012).