Transactions of the Materials Research Society of Japan 30[2] 527-530 (2005)

Application of Peltier-Current-Lead for Reduction of Heat Leakage in Helium-Free-Magnet

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Peltier current lead (PCL) is a promising method to reduce the heat leakage on the cryogenic system. Thermoelectric (TE) materials such as the bismuth-telluride alloys are used in a part of the current lead on PCL to utilize the low thermal conductivity and the heat pumping by the Peltier effect of the TE materials. We applied PCL to the first stage of the helium-free superconducting magnet and compared the temperatures on the current lead with the conventional current lead (CCL) made of copper. A large temperature difference was achieved on TE part of the PCL, and the difference increased as the operation current to the magnet increased. Consequently, the temperature at a distance of 15 cm from the first stage on PCL was lower than that on CCL at the same operation current approximately by 15 K. This results proved directly that PCL reduced the heat leakage into the first stage of the superconducting magnet.

Key words: superconducting magnet, heat leakage, heat pumping, Peltier effect

1. INTRODUCTION

Thermoelectric cooling using the alloys of bismuth, tellurium, selenium, and antimony have been used for the commercial refrigeration device from the room temperature to the low temperature[1]. Thermoelectric generator also is being a commercially common technology in the same temperature range. We have proposed the Peltier current lead (PCL) as a novel usage of the thermoelectric technology for the cryogenic system[2]-[5].

Heat leakage from the room temperature region is one of the serious problems in the cryogenic system. In particular, low temperature region about 4 K in the superconducting magnet is connected to the room temperature region by the current lead that supplies the electricity to the magnet. Copper is generally used for the current lead because of its low electric resistivity. However, since copper has the high thermal conductivity and a large temperature difference appears in the current lead, the heat leakage through the current lead becomes large. Reduction of the heat leakage through the current lead is the key issue to improve the efficiency of the cryogenic system.

"Gas-cooled current lead" is a conventional method to reduce the heat leakage in the superconducting magnet[6]. On the gas-cooled current lead, a cold gas evaporates from the cryogen such as the liquid helium, and passes around the current lead with removing the heat. On the helium-free superconducting magnet, a small cryocooler is used for refrigeration instead of the liquid helium cryogen. A superconducting coil and its current leads are installed in the vacuum and no coolant is used around the magnet; therefore, the gas-cooled method cannot be used in the helium-free-magnet. On the other hand, PCL equips the thermoelectric material in the room temperature side of the current lead to reduce the heat leakage through the current lead, and can be used in the helium-free-magnet.

In this paper, we attempted to apply PCL to the helium-free superconducting octupole magnet. Temperatures on the current lead were compared with the conventional copper current lead at the operation current of 0 A to 60 A and the reduction of the temperature was measured at the low temperature side of PCL. The results of experiment were consistent well with the estimation from calculation.

2. BASIC CONCEPT OF PCL

Figure 1 shows the comparison of (a) the conventional current lead (CCL) using copper lead and (b) PCL in a cryogenic system. A helium-free cryocooler keeps low temperatures at the first stage (less than 77 K) and at the second stage (about 4 K). A high-temperature superconductor (HTS) lead is connected between the first stage and the second stage to keep the HTS temperature low (e.g., 110 K is the critical temperature of $Bi_2Sr_2Ca_2Cu_3O_x$ and 80 K is of $Bi_2Sr_2CaCu_2O_x$). Between the first stage and the second

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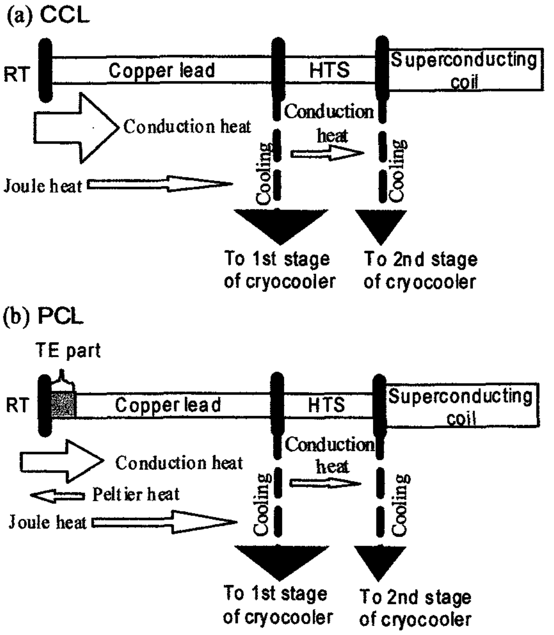

Fig. 1 Comparison of (a) conventional current lead (CCL) using copper and (b) Peltier current lead (PCL).

stage, HTS is in the superconductive state, and has causes no Joule heating. Hence, the heat leakage is the only the conductive heat from the first stage to the second stage. Consequently, we should consider the reduction of the heat *just* into the first stage to reduce the heat leakage in the whole cryogenic system.

On CCL, the first stage of the cryocooler is demanded to cool the conduction heat and the Joule heat into the first stage, and copper is employed as the lead material to suppress the Joule heat. The lead with a large cross-section and a short length causes a large conduction heat flowing from the room temperature region to the first stage of the cryocooler due to the high thermal conductivity of copper. Though the lead with a small cross-section and a long length can reduce the conduction heat, the increase of the Joule heat on the lead cannot be neglected in spite of the low electric resistivity of copper.

On PCL, a thermoelectric material such as the bismuth-telluride alloy (BiTe) is inserted into the room temperature side of the copper lead. The thermal conductivity of the BiTe is about 0.3% of that of copper; a part of the conduction heat from the room temperature side is dammed at the BiTe. Moreover, the Peltier effect of the BiTe can pump up the heat from the low temperature side to the room temperature side, when an electric current is applied. Because of the heat pumping and the reduction of the conduction heat at the room temperature side of the lead, the heat leakage into the low temperature side of the copper lead can be reduced. A copper lead is necessary to connect between the BiTe and HTS since the BiTe works as the good thermoelectric material from room temperature to 200 K[7]. Therefore, it is required to optimize the shape (cross-section and length) of BiTe and copper for the optimum design of PCL.

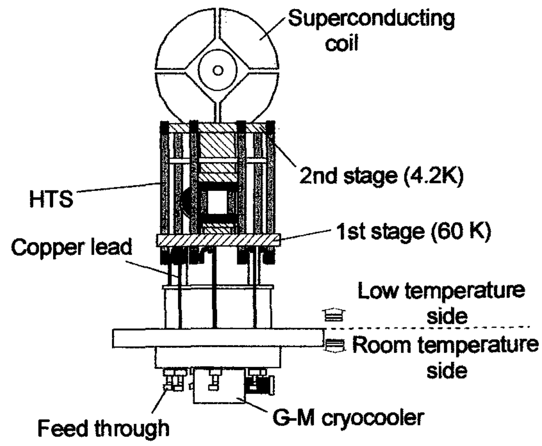

Fig. 2 A schematic diagram of the Dragon Ball magnet.

3. SETUP

3-1 Superconducting magnet

Figure 2 illustrates the structure of the octupole helium-free superconducting magnet, named Dragon Ball magnet, in National Synchrotron Radiation Research Center[8]. Table I shows the main parameters of the magnet. The magnet was designed for the soft X-ray scattering experiments of the electron storage ring. The magnet consists of eight superconducting coils to produce the magnetic field in three dimensional directions. The coils are arranged octahedrally to form four independent dipole pairs. The magnet can produce the maximum magnetic field of 3.65 T in the each direction of *x*, *y*, and *z*-axes at the operation current of 150 A. A Gifford-McMahon (G-M) cryocooler is connected to the first stage and to the second stage. The first stage, cooled down to around 60 K, is thermally connected to the high temperature side of HTS. The second stage, cooled down to 4.2 K, is thermally connected to the low temperature side of HTS and superconducting coils. The magnet is inserted in the vacuum chamber for the thermal isolation and eight current lead connect between the low temperature side and the room temperature side. Hence, reduction of the heat leakage through these eight current leads is the fundamental problem to keep the magnet superconductive state.

3-2 Current lead

Figure 3 shows the arrangement of PCL and the thermometer in the current lead. In this experiment, we

Table I Main parameters of superconducting magnet

Number of poles	8	
Operation current	150	A
Maximum field along x, y, and z-axes	3.65	T
Diameter of the octupole magnet	24.7	cm
Inductance at 150 A	3.0	H
Temperature of the first stage	60	K
Temperature of the second stage	4.2	K

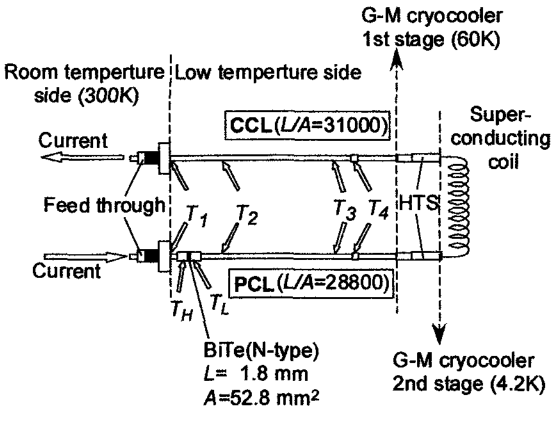

Fig. 3 Arrangement of PCL and thermometers in the Dragon Ball magnet.

applied PCL to the one pair of the superconducting coils. One lead of the pair current lead employed PCL and the other lead was left to be CCL to compare the temperature profile and the heat leakage. The *N*-type BiTe was used for the thermoelectric (TE) material as shown in Fig. 3. The dimension of BiTe was the thickness of 1.8 mm and the cross-section area of 52.8 mm^2. Two T-type thermocouples were equipped on the positions of T_1 and T_2, and two semiconductor thermometer (Lake Shore Cryotronics, Inc., Cernox CX-1070-SD) was equipped on T_3 and T_4 for both CCL and PCL. On PCL, two thermocouples were added on both sides of TE part, T_H and T_L, to measure the temperature drop on the TE part. The length from the top flange of the room temperature side to the first stage was 50.4 cm and the cross-section of the copper lead for CCL was 14.9 mm^2. For PCL, cross-section of the copper lead was also 14.9 mm^2 from the point T_4 to the first stage and 21.2 mm^2 from the top flange to T_4 except TE part to optimize the shape of the current lead for PCL.

At the steady state, the temperature profile on the current lead and the heat leakage depend on the thermal balance among the conduction heat, the Peltier heat, the Joule heat, and the heat pumped out by the cryocooler. Calculation of the thermal balance in the current lead is demanded to decide the optimum dimensions of TE part and the copper lead part in PCL. In the helium-free-magnet, the one-dimensional equation in the steady state is expressed as [3][4]

$$\frac{d}{dx}\left(\kappa A\frac{dT}{dx}\right)+\frac{\eta I^2}{A}-\left(\frac{d}{dx}\alpha TI\right)=0, \qquad (1)$$

where x is the coordinate along the current lead from the first stage of the cryocooler, A the cross-section of the current lead, T the temperature along the x-axis, I the operation current, and κ, η, α are the thermal conductivity, the electric resistivity, and the Seebeck coefficient of the current lead material, respectively. Here, it is necessary to include temperature dependence of κ, η, and α in the numerical calculation. The heat leakage Q into the first stage of the cryocooler is expressed as

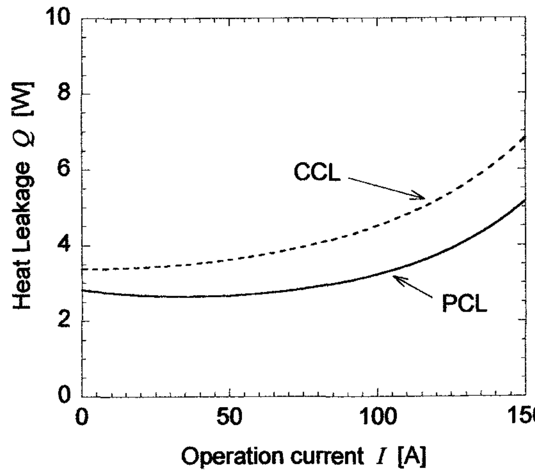

Fig. 4 Calculated heat leakage in design as a parameter of operation current. Expected reduction of heat leakage from CCL to PCL was 22 % at maximum.

$$Q=-\kappa A\frac{dT}{dx}. \qquad (2)$$

before the first stage. Equation (1) has a parameter of dx/A of the current lead. The integration of dx/A, defined as L/A, was 31000 m^{-1} for CCL and 28800 m^{-1} for PCL, as shown in Fig. 3.

Figure 4 shows the results of the numerical calculation of the heat leakage into the first stage for PCL and CCL for the dimensions in Fig. 3. Reduction of the heat leakage was expected for PCL at all current regions up to 150 A and the maximum reduction rate for PCL was estimated as 22% of the heat leakage for CCL.

4. RESULTS and DISCUSSION

Figure 5 shows the temperature profiles at I = 0 A from the first stage of the cryocooler for PCL and CCL. A steep temperature drop of 62.4 K appeared at TE part around x = 5 cm for PCL, whereas a continuous temperature decrease was measured for CCL. This large temperature drop was due to the low κ of thin BiTe (1.8

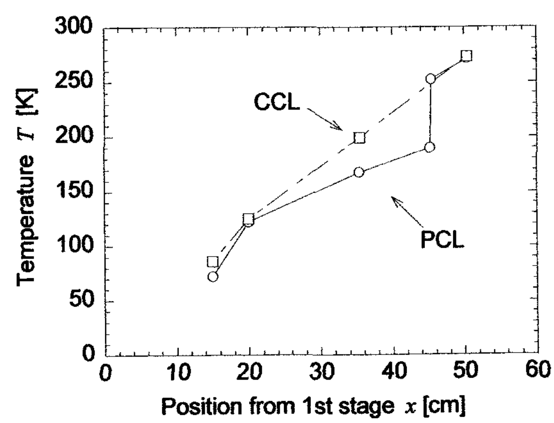

Fig. 5 Comparison of measured temperature profile on PCL and CCL at a steady state at I = 0 A.

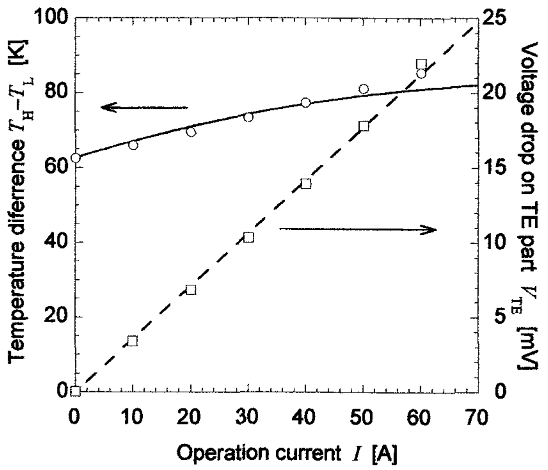

Fig. 6 Temperature difference between and voltage drop on the TE part as a parameter of the operation current in PCL. Lines were derived from the numerical calculation.

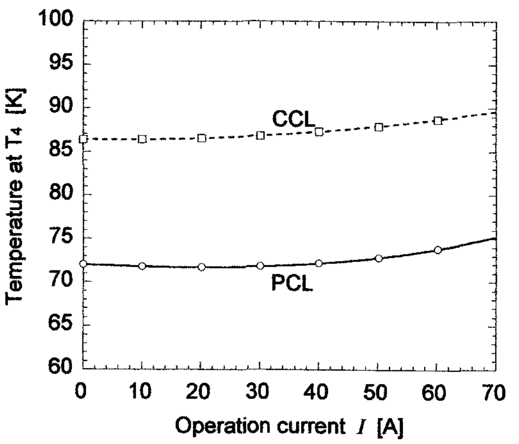

Fig. 7 Temperatures on T_4 of the current leads as a parameter of the operation current.

mm in thickness) as mentioned in Section 2.

Figure 6 shows the operation current dependence of the temperature difference T_H–T_L and the potential drop V_{TE} of the TE part. Operation current was applied up to 60 A. Lines in Fig. 6 were derived from the numerical calculation for Eq. (1) combining with the potential calculation from the Ohm's law. Because of the Peltier effect, the operation current increased T_H–T_L, and then the heat leakage after the TE part decreased. If V_{TE} is large, the additional power supply is necessary to excite the magnet. Obviously from Fig. 6, the increase of V_{TE} was sufficiently small and the additional power supply was unnecessary. Both T_H–T_L and V_{TE} were consistent well with the numerical calculation; the one-dimensional calculation was suitable to design and to analyze the performance of PCL.

Figure 7 shows the temperatures on position T_4 of the current lead as a parameter of the operation current. This position is at a distance of 15 cm from the first stage of the cryocooler. The temperature on T_4 for PCL was lower than that for CCL about by 15 K. The temperature at T_4 for PCL attained a minimum value at I = 20 A, though the temperature for CCL increased parabolically. Assuming that the temperature of the first stage was constant at 60 K, the temperatures in Fig. 7 showed the direct proof of the reduction of the heat leakage into the first stage.

5. CONCLUSION

We applied PCL to the helium-free-magnet, attempting the reduction of the heat leakage on the octupole superconducting magnet in NSRRC. The reduction of the heat leakage into the first stage of the cryocooler is important in the helium-free-magnet since only the conduction heat flows after the first stage. As a result, a steep temperature drop of more than 60 K was measured on TE part of PCL and the temperature drop on TE part was expanded due to the Peltier effect as the operation current increased. Consequently, the temperatures at a distance from the first stage reduced for PCL by 15 K compared with the temperature at the same position for CCL. This result proved the reduction of the heat leakage into the first stage.

ACKNOWLEDGEMENTS

To carry out this experiment, the authors would like to thank Mr. C. H. Chang of NSRRC. The authors are grateful to President A. Iiyoshi of Chubu University for continuous encouragement. The authors also thank Prof. Ishigohka for useful discussion. This research is partly supported by the New Energy and Industrial Technology Development Organization (NEDO) fellowship program and by a grant of the Academic Frontier Promotion Project from Japanese Ministry of Education, Culture, Sports, Science, and Technology.

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(Received December 23, 2004; Accepted February 15, 2005)