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Optimization of conduction-cooled Peltier current leads

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Abstract

A theoretical investigation for optimization of conduction-cooled Peltier current leads is undertaken. A Peltier current lead (PCL) is composed of a thermoelectric element (TE), a metallic lead and a high T_c superconductor (HTS) lead in the order of decreasing temperature. Mathematical expressions for the minimum heat flow per unit current crossing the TE–metal interface and that flowing from the metal lead to the joint of the metal and the HTS leads are obtained. It is shown that the temperature at the TE–metal interface possesses a unique optimal value that minimizes the heat flow to the joint. It is also shown that this optimal value depends on the material properties of the TE and the metallic lead but not the joint temperature nor electric current. Optimal geometric factors, viz. the ratio of the length to cross-sectional area, of both the TE and the metallic lead are obtained for various joint temperatures. A design procedure for optimizing PCLs is also proposed.

Keywords: Peltier effect; Thermoelectric element; Current lead; Heat leak

1. Introduction

Current leads, which supply power from power sources operating at room temperature to superconducting magnets operating at cryogenic temperature, represent the major source of heat leak into the magnets. The heat conduction through current leads and the heat generation due to the Joule heating in the leads are the two primary modes of such leak. A significant proportion of the running costs of the magnet systems results from the loss of liquid cryogen due to the heat leak for the liquid cooling systems or from the refrigeration power consumed to remove the heat leak for the refrigerator-cooled systems [1,2].

The heat leak through conventional current leads can be substantial since they are made of normal metals such as brass or copper with high thermal conductivity and high electrical resistivity. A binary or hybrid current lead, which replaces the lower temperature part of a conventional metallic lead with a high T_c superconductor (HTS) current lead, can help reduce the heat leak since HTSs are perfect electrical conductors with much lower thermal conductivities than the normal metals [1,3]. Another configuration of current lead, called the Peltier current lead (PCL) since it utilizes the Peltier effect to reduce the heat leak, was proposed by Yamaguchi et al. [4]. The PCL has a thermoelectric element (TE) inserted into a conventional metallic lead or a hybrid current lead at the room temperature end [2,5].

A number of studies [2,5–7] have shown that the heat leak through current leads and the electrical power required to cool the leads could be reduced significantly by using the PCLs. Xuan et al. [6] numerically obtained the optimized geometric factors, viz. the ratio of the length to cross-sectional area, of both the metal lead and the TE of a conduction-cooled PCL. Sato et al. [5] suggested the required relation between the temperature and the heat flow rate at the TE–metal interface for minimizing the heat leak through PCLs cooled by boil-off

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Nomenclature

A	cross-sectional area
FOM	figure of merit of refrigerator
I	electric current
k	thermal conductivity
L	length of current lead
P	electrical power
Q	heat flow or heat transfer rate
q	heat flow per unit electric current
T	temperature
V	electro-chemical potential of charge carriers
x	coordinate defined in Fig. 1
Z	figure of merit of Peltier element

Greek letters

α	Seebeck coefficient
ρ	electrical resistivity
τ	dummy variable

Subscripts

C	cold end
H	warm end
I	interface between TE and metal lead
J	joint of metal and HTS leads
m	metal
min	minimum
opt	optimal
P	Peltier (or thermoelectric) element
total	total

helium gas. The above works [5,6] may not, however, provide enough understanding of the mechanism of heat leak reduction as well as information on the optimal design conditions of PCLs since the thermal behaviors of PCLs were analyzed by numerical calculations and the temperature at the metal-HTS boundary was always kept at 77 K.

In this paper, the optimal conditions of both the TEs and the metal parts of conduction-cooled PCLs are investigated analytically. The optimization method of Chang and Sciver [3], originally employed to optimize hybrid current leads, is applied to PCLs. A design procedure for minimizing the heat leak through PCLs is also proposed.

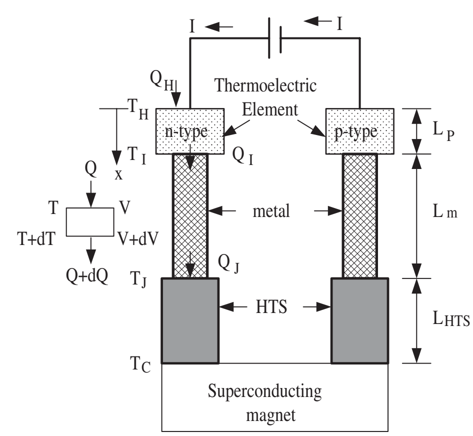

Fig. 1. Schematic diagram of a superconducting magnet system with PCLs.

2. Analysis model

Fig. 1 shows the schematic diagram of a superconducting magnet system containing PCLs. Each PCL is composed of a TE, a metallic lead and a HTS lead in the order of decreasing temperature. For a refrigerator-cooled system the joint of the metal and the HTS leads is cooled by the first-stage of a two-stage refrigerator while the cold end of the HTS lead is cooled by the second-stage of the refrigerator. Since HTSs are poor thermal conductors with zero electrical resistivity, the heat leak through them is assumed to be negligible [6,7]. Thus, the purpose of this work is to find the optimal conditions of the TE and the metallic lead of the PCL that minimizes the heat leak into the cold end of the metal lead. Subscripts H, I, J and C denote the warm end, the TE–metal interface, the metal-HTS joint and the cold end of the HTS lead, respectively. The temperature at the warm end, T_H, is assumed to be held constant at room temperature throughout the paper, but T_J and T_C are variables dependent on the heat flow through the current lead and the first- and second-stage refrigeration capabilities of the two-stage refrigerator. The temperature at the TE–metal interface, T_I, is a variable to be determined to minimize the heat leak into the joint, Q_J. The heat flow from the warm end to the cold end is defined to be positive.

Heat flow along the lead, Q, and electric current, I, can be written as follows [6]:

$$Q = -kA\frac{dT}{dx} \pm \alpha IT \tag{1}$$

$$I = -\frac{A}{\rho}\left(\frac{dV}{dx} \pm \alpha\frac{dT}{dx}\right) \tag{2}$$