Current Leads for Conduction-Cooled Magnets at 20–30 K

Ho-Myung Chang and Seung Ill Lee

Abstract—**Cryogenic current leads are designed and tested for conduction-cooled superconducting magnets operating at 20–30 K. These magnets are under development in Korea for electrical machinery with MgB_2 wires or YBCO tapes. Since a single-stage cryocooler is employed, the current leads are made of metal over the entire length. Different sizes of copper conductor are fabricated for 80–100 A level and experimentally tested with a commercial Gifford-McMahon cryocooler. Temperature is measured at the coldhead and several axial locations along the conductor in order to estimate the cryogenic load. A geometric condition to minimize the cooling load is clearly demonstrated by the experiment. An analytical model is also presented to explain the optimal condition, taking into account the properties of copper and the refrigeration capacity of cryocooler.**

Index Terms—**Conduction-cooling, copper, cryogenics, current leads.**

I. Introduction

Superconducting magnets operating at 20–30 K are under development for a variety of applications, such as magnetic energy storage (SMES) [1], magnetic separation [2], electrical machinery (motors and generators) [3]–[5], and magnetic resonance imaging (MRI) [6]. In particular, 10 MW-class superconducting generators have a potential to enter the offshore wind turbine market in near future. These magnets are designed to operate at 20–30 K for taking advantage of a larger critical current density of YBCO conductors or making use of less expensive MgB_2 wires.

From a cryogenic point of view, the 20–30 K magnets are far different from LTS magnets at liquid-helium temperatures (2–4 K) or HTS magnets at liquid-nitrogen temperatures (65–90 K), mainly because no liquid cryogen is readily applicable. Even though liquid neon or gaseous helium may be used as coolant, direct conduction-cooled systems with a cryocooler have been designed or developed for compactness and easy operation [2]–[6]. At 10–30 K, pure copper is an excellent thermal conductor [7], [8] capable of effectively delivering cryogenic load to the coldhead of cryocooler. Single-stage GM (Gifford-McMahon) coolers are commercially available for the cooling of 50–100 W at 20–30 K [9], [10]. Since the refrigeration capacity of these coolers shrinks sharply as temperature drops below 20 K, it is crucial to reduce the cryogenic thermal load from various sources including current leads.

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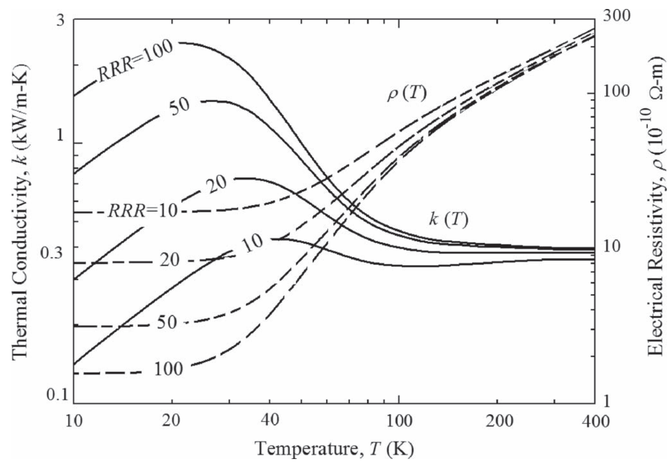

Fig. 1. Temperature-dependent thermal conductivity and electrical resistivity of oxygen-free copper with various RRR values [7].

Several standard optimization methods [11]–[16] have been developed for various current leads at liquid-helium or liquid-nitrogen temperatures. On the other hand, the current leads for 20–30 K magnets should be designed in careful consideration of three additional aspects. First, copper is used as conductor over the entire length. HTS leads are generally effective in reducing the cryogenic load, but are not applicable to these single-stage systems. Second, the thermal conductivity (k) and electrical resistivity (ρ) of copper are sensitive to residual-resistance ratio (RRR) [7], [8], [14], [15] below 50 K, as shown in Fig. 1. In practice, however, an accurate RRR value is neither provided by material suppliers nor easy to measure. Third, the boundary condition at the cold end of current leads is associated with the thermal contacts and electrical insulation to the coldhead, which makes the optimization of current leads difficult and complicated.

This study is proposed to investigate the current-lead design for conduction-cooled magnets at 20–30 K with a single-stage cryocooler. An experiment is planned to test different sizes of conductor fabricated with oxygen-free copper for 80–100 A. Based on the results, an analytical model is presented to demonstrate how to impose the boundary conditions on the existing optimization method [16], taking into account the thermal connection to coldhead and the refrigeration capacity of cryocooler. An immediate application goal is the wind turbine generators under development in Korea.

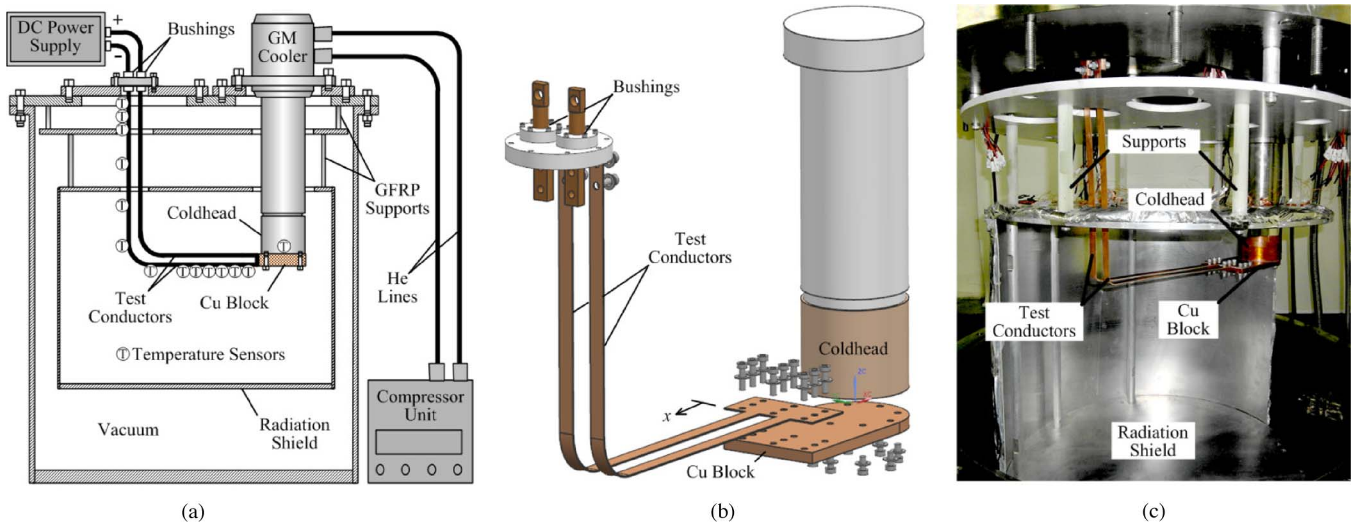

Fig. 2. Experimental set-up. (a) Schematic overview, (b) assembly of test conductors and coldhead, and (c) photograph of assembled current leads.

TABLE I
DIMENSION OF SIX TEST CONDUCTORS

Dimension (unit)	(I)	(II)	(III)	(IV)	(V)	(VI)
thickness (mm)	1.50	1.50	1.18	1.18	1.08	1.08
width (mm)	15.0	15.0	15.0	15.0	15.0	15.0
active length (mm)	720	760	640	660	620	680
length/area (mm^{-1})	32.0	33.8	36.2	37.3	38.3	41.9

II. EXPERIMENT

A. Experimental Set-up

Fig. 2(a) is a schematic overview of experimental set-up. A single-stage GM cryocooler is mounted on the top plate of vacuum cryostat. A pair of bushings is also mounted on the top plate, where a pair of test conductors is bolt-jointed. In order to focus on the thermal behavior, two conductors are simply short-circuited at the cold end without superconductors and conductively cooled by a cryocooler. The cryocooler is Cryomech Model AL300 [9], whose coldhead has been lately rebuilt by the manufacturer to increase the capacity at 20 K, as called Model "AL300R".

Test conductors are prepared in different sizes by cutting an oxygen-free copper sheet in "long U" shape and bolt-jointed as shown in Fig. 2(b). There are several reasons for selecting a sheet conductor instead of typical shapes such as rod, tube, or wires. First, it is easy to fabricate the sheet conductor with any cross-sectional area. The flat surface of sheet conductor is also convenient to attach temperature sensors. The machined surface at cold end provides an excellent contact area for heat transfer to the cryocooler. The sheet conductors are round-bent and fitted as flexible "L shape" for protecting the coldhead from cryogenic thermal stress. The active length and cross-sectional area of test conductors are listed in Table I.

At the bottom of coldhead, a machined copper block ($100 \text{ mm} \times 190 \text{ mm} \times 10 \text{ mm}$) is attached by bolt-joints as shown in Fig. 2(b) in preparation for repeated assembly of conductors. The axial distance, x, is measured from cold end.

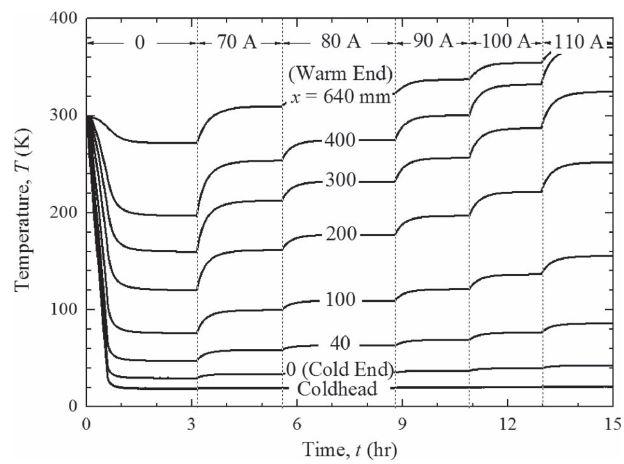

Fig. 3. Measured temperature history at selected locations during cool-down followed by stepwise increases of current level in case of test conductor (III).

A film heater is impregnated with epoxy on engraved surface of the block as a thermal load when the refrigeration capacity of cryocooler is measured. Cryogenic thermal grease is applied to contacting surfaces. In order to reduce the heat leak, every cold part is wrapped with multi-layer insulations and surrounded by a cylindrical radiation shield. Fig. 2(c) is a photograph of assembled current leads.

B. Instrumentation and Procedure

Temperature is measured at the coldhead of cryocooler and 13 axial locations of test conductor with silicon diodes sensors (Lakeshore DT-670) and recorded every second with two units of data logger (Lakeshore Temperature Monitor 208). At the beginning, the cryocooler is turned on without current supply. After the coldest steady state is reached, the current level is quickly raised to 70 A, and then increased up to 110 A by a step of 10 A with an interval of 2 or 3 hours. Fig. 3 shows a complete temperature history at selected locations for initial cool-down followed by stepwise increases of current level.

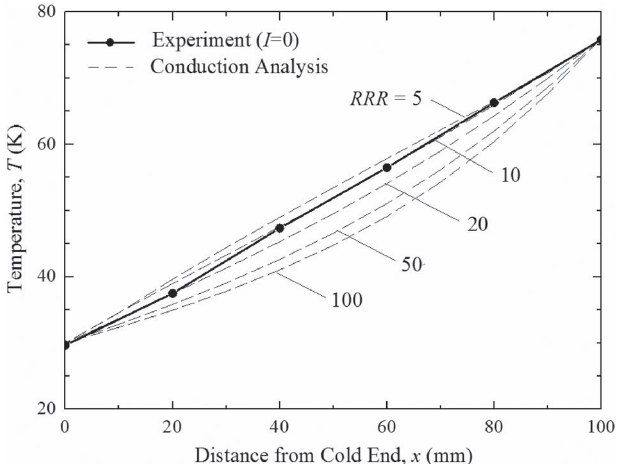

Fig. 4. Temperature profile near the cold end when $I = 0$ for estimating the RRR value of copper conductor.

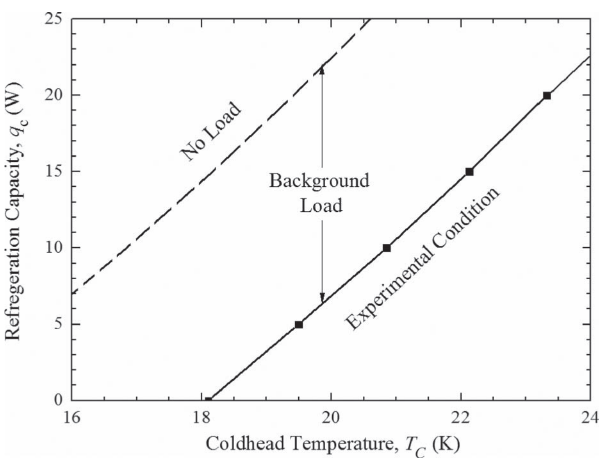

Fig. 5. Measured refrigeration capacity of GM cryocooler (Cryomech AL 300R) in experimental cryostat as a function of coldhead temperature.

C. Estimate of RRR Value

The RRR value of copper conductor used in experiment is estimated from the temperature profile near cold end, because the thermal conductivity is very sensitive to RRR at cryogenic temperatures as shown in Fig. 1. Fig. 4 compares the measured data $(I = 0)$ with analytical profiles calculated from conduction equation with selected RRR values, indicating that RRR of test conductors is approximately 10. In theory, the minimum cooling load per unit current is identical for all Wiedemann-Franz materials regardless of RRR, but the geometric condition to achieve the minimum is dependent on RRR [14], [16].

D. Refrigeration Capacity of Cryocooler

The refrigeration capacity of AL300R in the experimental set-up (without test conductors) is accurately (up to 0.1 K) measured as a function of coldhead temperature with the heater attached on copper block. In Fig. 5, the measured capacity is plotted and compared with the full capacity at no load. As indicated by an arrow, the vertical difference between two curves is 15.0 W, which is the background load of our experimental system. This capacity curve plays an important role in estimating the actual cooling load in the experiment.

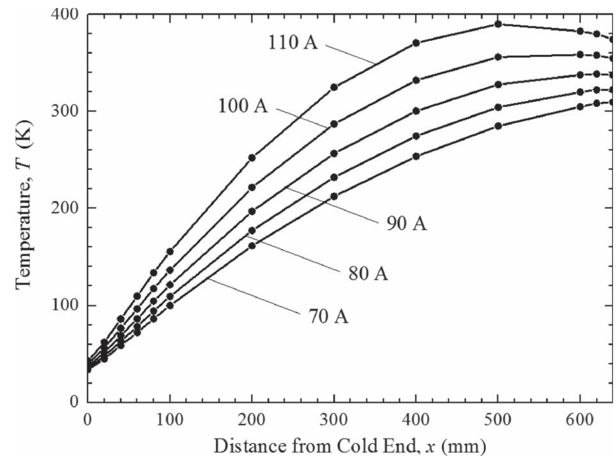

Fig. 6. Steady-state temperature profiles for various current levels in case of test conductor (III).

III. Results and Discussion

A. Temperature Profiles

The six conductors listed in Table I are tested in the same procedure as demonstrated in Fig. 3. Steady-state temperature profiles are plotted from the measured data set, as shown in Fig. 6 for test conductor (III). The distance between temperature sensors is 100 mm in the central part and 20 mm near the cold or warm ends, where more precise profile is needed.

In Fig. 6, the temperature gradient at warm end $(x = 640\ \mathrm{mm})$ is almost zero when $I = 90$ A, which is called "optimal" operation [16], as discussed later. For $I < 90$ A, the gradient is positive over the entire length, which means that conduction heat is dominant over Joule heating (as called "under-current" operation). On the contrary, for $I > 90$ A, a temperature overshoot occurs, which means that Joule heating is dominant over conduction heat (as called "over-current" operation).

B. Cooling Load

In steady state, the total cooling load of current leads (q_C) is equal to heat removed by cryocooler, which is estimated with the measured coldhead temperature (T_C) and the refrigeration capacity curve (Fig. 5). For example, T_C is 20.4 K from Fig. 3 in case of test conductor (III) at $I = 90$ A. The corresponding load is approximately 8.9 W from Fig. 5.

This cryogenic load is a sum of heat from two conductors $(2q_0)$ and heat dissipation at cold end.

$$q_C(T_C) = 2q_0 + I^2R_C = 2kA\frac{dT(0)}{dx} + I^2R_C \tag{1}$$

where A is the cross-sectional area of a conductor and R_c is the resistance of cold end. Since the temperature gradient at $x = 0$ is obtained from Fig. 6, R_c can be calculated with (1). For test conductor (III), R_c is approximately 17 $\mu\Omega$.

The experimental results are summarized in Fig. 7 as a plot of cooling load vs. dimensional (length-to-area) ratio. As the ratio increases, the cooling load decreases for $I = 70$ A, but increases for $I = 110$ A. For $I = 90$ A, however, the cooling load has a local minimum of 8.9 W when $L/A = 37.3\ \mathrm{mm}^{-1}$.

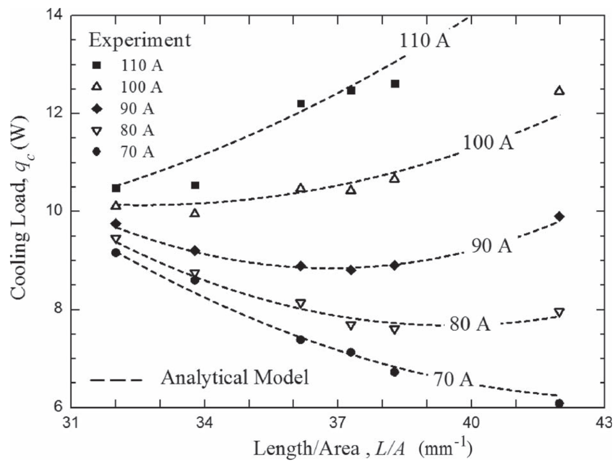

Fig. 7. Cooling load versus dimensional (length-to-area) ratio from experiment and analytical model.

C. Analytical Model

An analytical model is presented to explain the thermal load shown in Fig. 7. The optimal lead parameter [13] is given by

$$\left(\frac{IL}{A}\right)_{opt} = \int_{T_0}^{T_L} \frac{k}{\sqrt{2\int_T^{T_L} k\rho dT}} dT \tag{2}$$

where T_0 and T_L are the temperatures at $x = 0$ (cold end) and L (warm end), respectively. The thermal load at cold end (q_0) is related with the dimensional (length-to-area) ratio (L/A) as

$$\frac{L}{A} = \int_{T_0}^{T_L} \frac{k}{\sqrt{q_0^2 - 2I^2\int_T^{T_L} k\rho dT}} dT \tag{3}$$

for under-current operation, and

$$q_0^2 = 2I^2 \int_{T_0}^{T_P} k\rho dT \tag{4}$$

$$\frac{L}{A} = \int_{T_0}^{T_P} \frac{k}{\sqrt{q_0^2 - 2I^2\int_T^{T_L} k\rho dT}} dT + \int_{T_P}^{T_L} \frac{k}{\sqrt{2I^2\int_T^{T_P} k\rho dT}} dT \tag{5}$$

for over-current operation, where T_P is the peak temperature of overshoot [16]. The boundary condition at cold end is given as

$$q_C = UA_C(T_0 - T_C) \tag{6}$$

where UA_C is the overall heat conductance between cold end (T_0) and coldhead (T_C), including the copper block and bolt-joints. In the experimental condition, UA_C is 0.56 W/K from the measured temperatures and cooling load.

In Fig. 7, the dotted curves are the solution of (1) through (6) by setting the same warm-end temperature as experiment. It is recalled that $k(T)$ and $\rho(T)$ with $RRR = 10$ in Fig. 1 [7] are incorporated into (2) through (5). A fairly good agreement is obtained especially near the optimal condition at $I = 90$ A. One of the reasons for discrepancy is that the mechanical contacts may be more or less uneven, depending on surface roughness and bolt-joints. For Wiedemann-Franz materials, the theoretical minimum load [13] is 8.58 W for a pair of conductors with $T_L = 300$ K, $T_0 = 20$ K, and $I = 90$ A, which is compared with 8.9 W in the experiment. It may well be stated that the cryogenic current leads for 20–30 K magnets are reasonably designed and demonstrated at 80–100 A level.

IV. Conclusion

Metallic current leads are developed for conduction-cooled magnets at 20–30 K. An experiment is successfully executed to measure the cooling load on different sizes of conductor. At 80–100 A, the geometric condition to minimize the cooling load is clearly demonstrated by experiment and reasonably verified by an analytical model. The results are immediately applicable to superconducting generators under development in Korea and also a variety of 20–30 K magnets.

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