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Thermal Conductivity Measurement of Insulation Material for Superconducting Application

Y. S. Choi[1*], D. L. Kim[1], D. W. Shin[1], and S. D. Hwang[2]

[1]Korea Basic Science Institute, Daejeon 305-333, Korea
[2] Korea Electric Power Research Institute, Daejeon 305-380, Korea

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Abstract— **The thermal properties of insulation material are essential to develop a high-temperature superconducting (HTS) power cable to be operated at around liquid nitrogen temperature. Unlike metallic materials, nonmetallic materials have a high thermal resistance; therefore special attention needs to be paid to estimate heat flow correctly. Thus, we have developed a precise instrument for measuring the thermal conductivity of insulating materials over a temperature range from 40 K to near room temperature using a cryocooler. Firstly, the measurement of thermal conductivity for Teflon is carried out for accuracy confirmation. For a supplied heat flux, the temperature difference between warm and cold side is measured in steady state, from which the thermal conductivity of Teflon is calculated and compared with published result of NIST. In addition, the apparent thermal conductivity of Polypropylene laminated paper (PPLP) is presented and its temperature dependency is discussed.**

1. INTRODUCTION

The superconducting cable can deliver high power for a fixed cross-sectional area comparing with conventional or copper cable; however it requires cryogenic temperature to achieve its specific property. The thermal properties of insulation materials are essential in developing a high-temperature superconducting (HTS) power cable to be operated at around liquid nitrogen temperature. Unlike metallic materials, nonmetallic materials have a high thermal resistance; therefore, the accurate estimate of heat flow is difficult in the case of nonmetallic materials. Liquid helium and nitrogen were most widely used as a heat sink in general method of thermal property measurement [1-6]. Recently, the development of 4 K cryocoolers [7], [8] opened new opportunities in thermal property measurement, mainly because continuous system operation was possible without any replenishment of cryogenic liquid. Also, a wide temperature range in measurement system is available using cryocoolers.

There are several insulating materials used in superconducting devices. Polypropylene laminated paper (PPLP) is one of the electrical insulation materials in HTS power cable due to its good insulating properties [9], [10]. In terms of thermal point of view, heat transfer is occurred through PPLP between HTS conductor and liquid nitrogen in an HTS cable cryostat. Thermal properties of PPLP, therefore, are significant too. Unfortunately, the number of measurements reported in literature is somewhat limited.

We have developed a new measurement instrument in order to obtain data for the thermal conductivity of insulating materials. The instrument is capable of measuring the temperature range between 40 K and room temperature. A Gifford-McMahon (GM) cryocooler is employed as a heat sink for experiment to meet these requirements. This thermal property facility is a precision device capable of conducting similar measurements as new materials are developed. In this paper, we describe the instrument in detail and present the thermal conductivity result of Teflon for accuracy confirmation. In addition, the apparent thermal conductivity of PPLP is presented and temperature-dependent property is also discussed.

2. EXPERIMENTAL APPARATUS

A schematic diagram of experimental apparatus is shown in Fig. 1. The main components of the apparatus basically are symmetric copper thermal link, vacuum vessel, thermal shields and GM cryocooler. The cryocooler is mounted directly at the top plate of vacuum vessel and

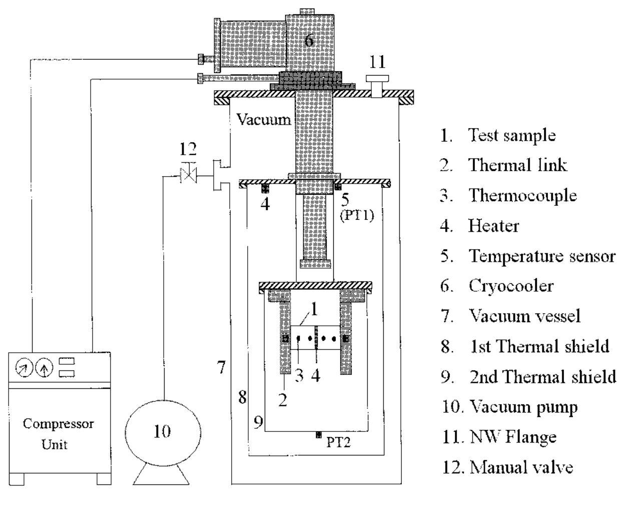

Fig. 1. Schematic overview of thermal property measurement system.

* Corresponding author: ychoi@kbsi.re.kr

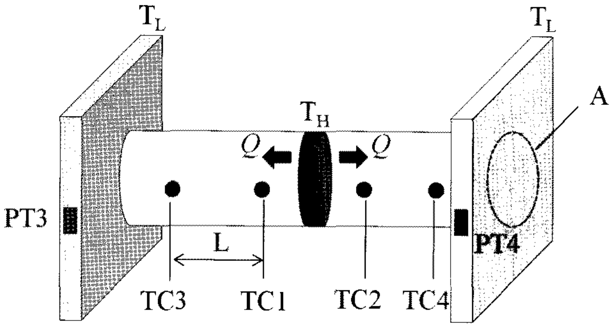

Fig. 2. Detailed drawing of test sample, heater and thermal link (TC: Thermocouple).

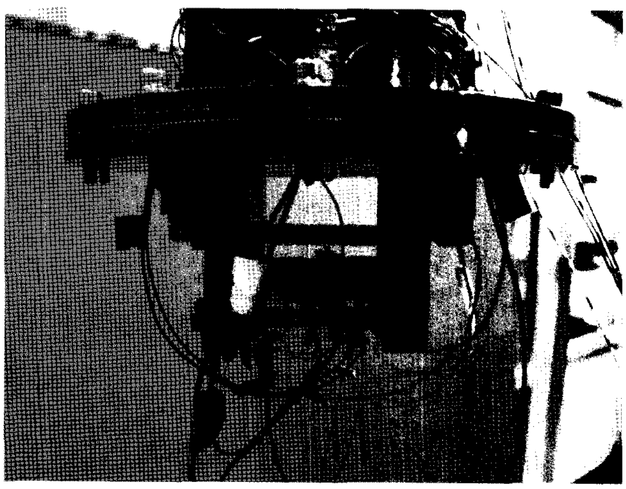

Fig. 3. Photograph of installed test sample (Teflon) without thermal shield.

thermally anchored to the thermal link, which is located at the center of vacuum vessel. Two pieces of copper thermal link are attached to the cold head of cryocooler in order to minimize temperature gradient from the heat sink. Test sample is located between two copper thermal links as shown in Fig. 1. The manganese wire heater is sandwiched between two identical copper plates and is located at the middle of test sample as a heat source, supplying a constant heat flux per unit area to the test sample; it has therefore a symmetrical structure. The heating power is regulated with a source meter (Keithley Model 2601). The temperatures of cold head, thermal shield and copper thermal link are measured with platinum resistance thermometers (Lakeshore PT103). A number of thermocouples (T-type) are used to measure the absolute temperature as well as temperature difference between warm side and cold side of test sample. Fig. 2 is a detailed figure of test sample, heater and thermal link, and Fig. 3 is the picture of fabricated test section. The locations of temperature sensor are indicated in these figures.

In most cryogenic temperature applications, heat to the sample could be occurred by conduction, convection and radiation [11]. Therefore, thermal isolation of the sample from its surroundings is required. Thermal anchor of

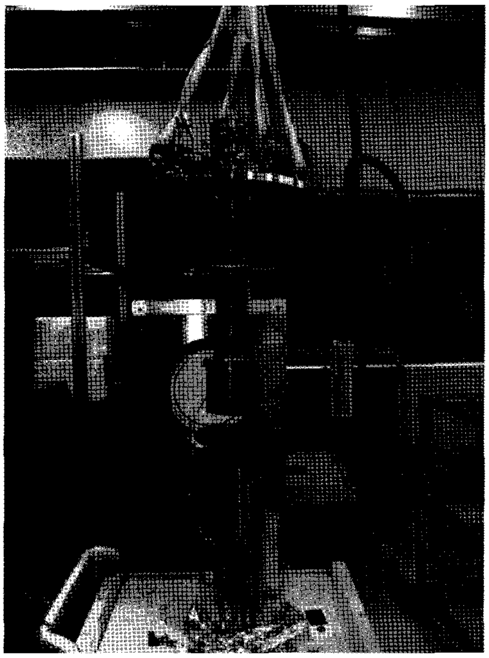

Fig. 4. Photograph of assembled thermal conductivity measurement system.

instrumental wire, evacuation of cryostat and double layers of thermal shield with multi-layer insulation (MLI) are employed in this instrument, eliminating heat invasion into the test sample. Fig. 4 is the picture of assembled thermal conductivity measurement system, showing first and second thermal shields.

At the initial phase of the experiment, the cryostat is pumped down to the range of 2×10^{-3} Torr and then it is cooled down by a cryocooler. Once the cryostat is cooled down, a uniform heat flux is supplied so that heat flows from the source through test sample. The temperature distribution along the sample is measured in steady state, from which the thermal conductivity is estimated. All temperatures in the experiment are recorded every 5 seconds with a data acquisition system operated through LabView™ software. Variables in this experiment are the magnitude of heat flux and operating temperature.

3. RESULTS AND DISCUSSION

The measurement of thermal conductivity of Teflon is performed for accuracy confirmation prior to PPLP measurement. We selected Teflon as a test sample because we could check the accuracy of our measurement by

TABLE I
Dimension of Test Sample for Accuracy Confirmation.

Parameter		Value	Unit
	Material	Teflon	-
Test sample	Length (L)	15	mm
	Diameter (D)	10	mm

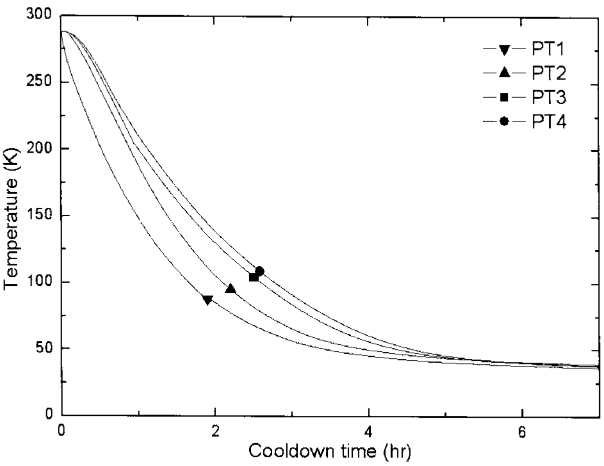

Fig. 5. Initial cool-down of thermal property measurement system using a cryocooler (Positions of PT's are indicated in Fig.1 and Fig.2).

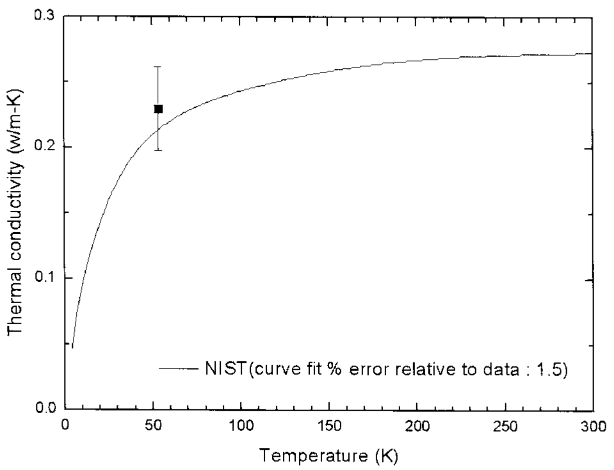

Fig. 6. Thermal conductivity of Teflon, comparing with data of NIST.

comparing with published data. The dimension of test sample is summarized in Table I.

Fig. 5 shows the temperature history of cold head (PT1), thermal shield (PT2) and thermal links (PT3, PT4) after turning on the cryocooler. During the initial cool-down process, the temperature decreased almost at a constant rate, requiring approximately 4 hours for the cold head of cryocooler to reach 50 K. Once it was stabilized, electric power was then supplied to the manganese heater so that heat was conducted through the test sample, Teflon. When the heater was on, the temperature of test sample increased gradually and the temperature difference between warm and cold side became measurable.

It is basically assumed that the amount of heat is equally divided and conducted into the left and right samples. For steady state conditions with no distributed source or sink of energy within the sample, heat transfer occurs exclusively in axial direction rather than radial direction. Thermal conductivity therefore is calculated using one-dimensional Fourier's heat conduction equation [12];

TABLE II
Specification of PPLP Sample for Thermal Conductivity Measurement.

Parameter	Value	Unit
Material	PPLP	-
Thickness (One layer)	0.08	mm
Diameter (D)	10	mm
Test length (L)	8	mm
Number of PPLP	100	layer

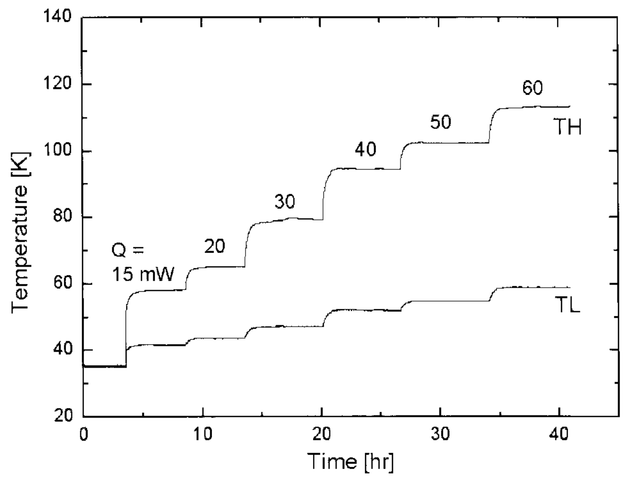

Fig. 7. Temperature history of warm and cold side of PPLP as a function of supplied heat flux with respect to elapsed time.

$$k = \frac{Q\,dx}{A(\Delta T)} \approx \frac{4Q\cdot L}{\pi D^2 (T_H - T_L)} \quad (1)$$

where Q is the amount of heat and T_H and T_L are temperatures of warm and cold side, respectively. L and A denote length and cross-sectional area of test sample, as indicated in Fig. 2.

In steady state, the measurements of the sample temperature allow the determination of the thermal conductance. The thermal conductivity of Teflon obtained from this instrument is plotted in Fig. 6 and compared with the NIST data drawn after Ref.[13]. The thermal conductivity of Teflon was 0.23 W/m-K at 55 K, which was slightly higher than that of NIST. However, two data sets were agreed well within error deviation, as shown in Fig. 6. The error bars corresponded to the deviation of temperatures at warm and cold side of test sample.

The same procedure was then repeated with PPLP. Unlike Teflon, PPLP is a kind of paper so test sample was made by stacking 10 mm diameter, 0.08 mm thick PPLP disks between heater plate and thermal link plate. To help align the stack, the stack was held by paper tape during setting the experiment. 155 layers of PPLP disk were used for measurement; so total length of test sample was 12.4 mm. While one thermocouple was inserted after the 5th

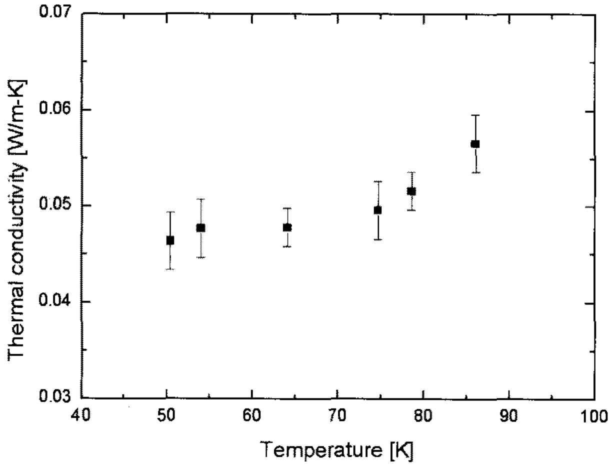

Fig. 8. Apparent thermal conductivity of PPLP.

layer of PPLP from the heater, the other was inserted after the 105th layer of PPLP from the heater for temperature measurement, therefore the length of test section was 8 mm. The specification of PPLP test sample is summarized in Table II.

The temperature of PPLP sample decreased after turning on a cryocooler. Starting from room temperature, it took approximately 8 hours for the test sample to reach at the lowest temperature, 35 K, which was then maintained for 24 hours within 0.05 K temperature variations. Heating power was then supplied from 0 to 60 mW with 10~15 mW increments. Fig. 7 shows measured temperatures of PPLP at right side of heater as a function of supplied heating power with respect to elapsed time. The temperatures of PPLP at left side of heater are agreed well with those of right side within 1% variation. We therefore could say that the amount of heat was equally divided and conducted into the left and right samples. The temperatures of warm and cold side of test sample were 58.1 K and 41.6 K, respectively, when the heating power of 15 mW was supplied. Temperature of test sample increased with supplied heating power and the temperature difference between warm and cold side was getting larger as heating power was increasing. When the heating power of 60 mW was supplied, the temperatures of warm and cold side of test sample were 113.3 K and 58.9 K, respectively.

In principle, the calculated value of k is an apparent thermal conductivity because the value might be affected by the interfacial contact between specimens. The apparent thermal conductivity of PPLP was calculated using (1) and plotted with respect to temperature in Fig. 8. The temperature in Fig. 8 represents the averaged temperature of warm and cold side of test sample. The apparent thermal conductivity of PPLP was 0.052 W/m-K at 78.6 K and slightly decreased as temperature decreased, as shown in Fig. 8. Its apparent thermal conductivity was 0.047 W/m-K at 50.4 K, thus approximately 10% of decrement was observed between 80 K and 50 K. We note here that the linear temperature dependence was not observed in the temperature range of 50~80 K and further experimental data is required to increase our experimental confidence.

4. CONCLUSION

The experiment of thermal property measurement has been developed for cryogenic cooling system application. The accuracy confirmation was carried out using Teflon and the apparent thermal conductivity of insulation material, PPLP, was measured for the temperature range between 50 K and 90 K. The apparent thermal conductivity of PPLP was approximately 0.05 W/m-K at liquid nitrogen temperature and decreased with temperature. The temperature-dependent properties of PPLP will be used for analyzing transient heat transfer in high-temperature superconducting cable cooling system.

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