Cryogenics 63 (2014) 125–128

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Analysis and measurement of thermal conductivity of polypropylene laminated paper impregnated with subcooled liquid nitrogen

Mitsuho Furuse *, Shuichiro Fuchino

National Institute of Advanced Industrial Science and Technology, Umezono 1-1-1, Tsukuba, Ibaraki 3058568, Japan

ARTICLE INFO

Article history:
Available online 11 March 2014

Keywords:
Polypropylene laminated paper
Subcooled liquid nitrogen
Superconducting power transmission cable
Thermal conductivity

ABSTRACT

We measured the thermal conductivity of polypropylene laminated paper (PPLP) impregnated with subcooled liquid nitrogen. PPLP is widely used for the electrical insulation of high-Tc superconducting (HTS) power transmission cables. Although the thermal conductivity of PPLP is an important factor in the design of HTS cables, there has been very limited work on its measurement in subcooled liquid nitrogen. We prepared PPLP samples and symmetrically stacked them on both sides of a heater. The stacked samples were immersed in liquid nitrogen in an open cryostat. A cryocooler mounted on the cryostat was used to maintain the subcooled temperature of the liquid nitrogen. The thermal conductivity of the stacked PPLPs was measured by the steady state method at a bath temperature of 65–75 K and was found to be 0.23–0.26 W/m K, which is about five times that measured in a vacuum as presented in available literature. We also discuss possible mechanisms for boosting the thermal conductivity of PPLP by liquid nitrogen impregnation.

1. Introduction

Polypropylene laminated paper (PPLP; trademarked by Sumitomo Electric Industries, Ltd.) is used for the electrical insulation of power transmission cables. It is a multilayered sheet comprising a thin extruded polypropylene film sandwiched between kraft papers. It has high dielectric strength and low dielectric loss even at cryogenic temperatures [1]. It is therefore suitable for cold dielectric power cables. Sumitomo developed high-temperature superconducting (HTS) power cables that use PPLP as a cold dielectric, and demonstrated their high performance in power transmission [2–4]. Furukawa Electric Co., Ltd. also developed and demonstrated a long-length HTS power transmission cable with a cold dielectric made of laminated paper with polypropylene [5,6]. PPLP is now commonly used as the dielectric of HTS power cables.

The thermal conductivity of PPLP is an important factor in the structural design of HTS cables. The magnitude of the thermal conductivity significantly affects the results of numerical calculations such as the analysis of the cross-sectional and longitudinal transient temperature distributions in cables [7,8], and the specification of the thickness of PPLP layers of HTS cables in which counter flow cooling is adopted [9].

There have been reports on the thermal conductivity of PPLP in a vacuum [10,11], which was found to be about 0.05 W/m K at 77 K. The experiments were appropriately conducted and the results are reliable. However, in a real HTS power cable, flowing subcooled liquid nitrogen is used as the coolant and the PPLP layers are impregnated with it. Hence, the thermal conductivity of PPLP measured under wet conditions should be used for cable design and numerical analyses. Sato et al. measured the thermal conductivity of PPLP in pressurized liquid nitrogen using a dummy cable core comprising a copper former, wrapped PPLP layers, and cylindrical heaters [12]. They determined the conductivity to be 0.1–0.3 W/m K. Akita et al. estimated the thermal conductivity of a PPLP layer of a short-length cryogenic cable (a power transmission cable with a copper conductor cooled by pressurized and subcooled liquid nitrogen flow) by measuring the temperature difference between the inner and outer sides of the PPLP layer and the Joule heat of the conductor [13]. They estimated the conductivity to be "greater than 0.2 W/m K." The values obtained under wet conditions were two to six times those obtained under dry conditions. This suggests that the impregnation of PPLP with liquid nitrogen boosts the thermal conductivity.

To the extent of the knowledge of the authors, there is little quantitative data on the thermal conductivity of PPLP under wet conditions, which has necessitated the acquisition of such data. Sato and Akita measured the thermal conductivity of PPLP using a cylindrical sample that imitated cable cores and a real cryogenic

* Corresponding author. Tel.: +81 29 861 3420.
E-mail address: m.furuse@aist.go.jp (M. Furuse).

http://dx.doi.org/10.1016/j.cryogenics.2014.02.021
0011-2275/

cable. However, it is sometimes difficult to use this method to estimate the heat flow through the PPLP layer because the heat generated by the heater is conducted longitudinally through the sample. A symmetrical sample is desirable for accurate measurement because it ensures that the entire heat generated by the heater flows through the PPLP layers.

We prepared a sample in which PPLPs were symmetrically stacked on both sides of a heater and surrounded it by polyurethane. The sample was immersed in liquid nitrogen in an open cryostat and a cryocooler mounted on the cryostat was used to maintain the subcooled temperature of the liquid nitrogen. We determined the thermal conductivity of the PPLPs impregnated with the subcooled liquid nitrogen by measuring the heater power and the temperature difference between the two sides.

2. Measurement

Fig. 1 is a schematic of the experimental setup. The cryostat was opened to the air through the port and the liquid nitrogen in the inner vacuum flask was maintained at the subcooled temperature by the cryocooler. The coolant of a real HTS power cables is pressurized at about 0.3–0.5 MPa [4,5], and it should be noted that the variation of the thermal conductivity of the liquid nitrogen with the pressure is negligibly small. The sample was suspended from the cold head of the cryocooler, which was switched off during the measurements to determine the thermal conductivity.

Fig. 2 is a cross-sectional view of the sample. The PPLP pieces used for the experiment were each 0.12 mm thick. Epoxy was used to sandwich a meandering manganin wire between two 32 mm × 32 mm pieces of PPLP. One hundred pieces of PPLPs of the same size were stacked on both sides of the heater and Type T (copper–constantan) thermocouples were inserted as shown in Fig. 2. The outermost copper blocks were used for thermal anchoring and weighting of the PPLPs. A polyurethane block (78 mm × 78 mm × 52 mm) was hollowed and the sample was inserted into it. The clearance between the sample and the sides of the polyurethane block was sealed by sticking polyimide tapes and holes were only left for the current and voltage leads. The subcooled liquid nitrogen got into the sample through the holes for the leads and the PPLPs got wet. The thermal conductivity of polyurethane is sufficiently small (0.0158 W/m K at 70 K for a specimen with a specific gravity of 0.05 [14]) and the polyurethane wall was sufficiently thick to allow for the assumption that the entire heat generated by the heater flowed through the PPLP layers and was divided in two directions in equal quantities. We placed the reference junction of the thermocouples in the subcooled liquid nitrogen bath outside the sample. The absolute temperature of the subcooled liquid nitrogen bath was measured by a calibrated thermometer (LakeShore Cernox™).

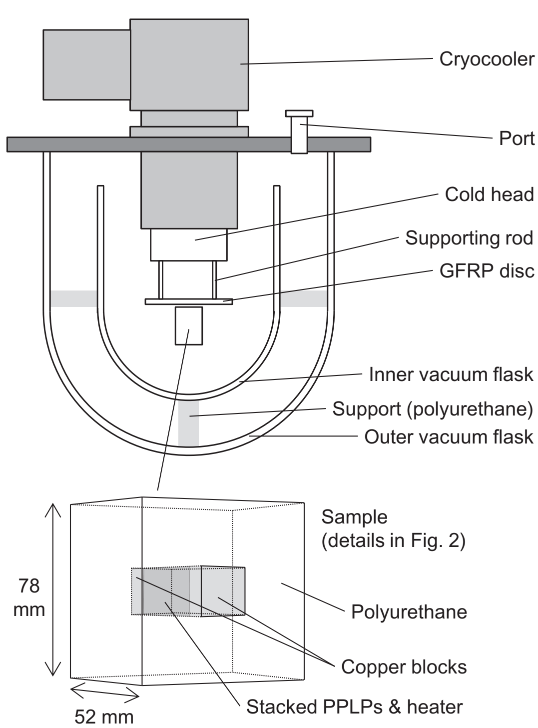

Fig. 1. Schematic of experimental setup.

We used the cryocooler to cool the liquid nitrogen in the inner vacuum flask to about 65 K and then switched it off. The thermocouples were used to measure the temperature difference between the warm and cold sides of the stacked PPLPs. Generally, when using steady state methods of thermal conductivity measurement, the temperature difference between the warm and cold ends is maintained at less than 10% of the absolute temperature to ensure accurate measurement [10]. The maximum temperature difference between thermocouples Th3, 4 and Th1 was 2.7 K, which is less than 4% of the bath temperature (the heater input power was 124 mW). The thermal conductivity of the stacked PPLPs k_{PPLP} is given by the following equation:

$$k_{PPLP} = \frac{(Q/2) \cdot l}{A \cdot \Delta T}, \quad (1)$$

where Q is the heater input power, l is the thickness of the stacked PPLPs, A is the cross-sectional area of the PPLPs ($A = 1024\ mm^2$), and ΔT is the measured temperature difference.

3. Experimental results

Fig. 3 shows the measured thermal conductivity of the PPLPs impregnated with subcooled liquid nitrogen for a bath temperature range of 65–75 K. Th2–3 and Th4–5 respectively represent the measured thermal conductivities between thermocouples Th2 and Th3 (80 stacked layers) and Th4 and Th5 (50 stacked layers). The measured temperature difference between Th5 and Th6 (30 stacked layers) was too small (<1 K) to determine the thermal conductivity Th5–6. We therefore omitted Th5–6 and calculated the average of Th2–3 and Th4–5 (dashed line in Fig. 3). The measured thermal conductivity was approximately linear within the temperature range.

4. Discussion

The measured average thermal conductivity range was 0.23–0.26 W/m K, which is in good agreement with the reports of Sato et al. [12] and Akita et al. [13]. The thermal conductivity measured under wet conditions was five times that measured under dry conditions. Akita et al. pointed out that the convection of the liquid nitrogen used to impregnate kraft papers may increase the thermal conductivity [13].

We assumed a model in which the kraft papers and polypropylene sheets were alternatively stacked (see Fig. 4). Only the kraft papers were impregnated with liquid nitrogen and we neglected the thermal resistance between the surfaces of the kraft papers. The total thermal resistance of n PPLP layers R_n is given by

$$R_n = \frac{l}{\lambda A} = n(R_{pp} + R_{kf}), \quad (2)$$

where l and λ are respectively the thickness and equivalent thermal conductivity of the stacked PPLPs, and R_{pp} and R_{kf} are respectively