



Thermal conductivity and Kapitza resistance of cyanate ester epoxy mix and tri-functional epoxy electrical insulations at superfluid helium temperature

S. Pietrowicz^{a,1}, A. Four^a, S. Jones^b, S. Canfer^b, B. Baudouy^{a,*}

^a CEA, Irfu, SACM, F-91191 Gif-sur-Yvette Cedex, France

^b Technology Department, STFC Rutherford Appleton Laboratory, Harwell Oxford, Didcot, Oxon OX11 0QX, UK

ARTICLE INFO

Article history:

Received 7 October 2011

Received in revised form 30 November 2011

Accepted 8 December 2011

Available online 21 December 2011

Keywords:

Thermal conductivity

Kapitza resistance

Superfluid helium

Cyanate ester

Epoxy resin

Electrical insulation

ABSTRACT

In the framework of the European Union FP7 project EuCARD, two composite insulation systems made of cyanate ester epoxy mix and tri-functional epoxy (TGPAP-DETD) with S-glass fiber have been thermally tested as possible candidates to be the electrical insulation of 13 T Nb₃Sn high field magnets under development for this program. Since it is expected to be operated in pressurized superfluid helium at 1.9 K and 1 atm, the thermal conductivity and the Kapitza resistance are the most important input parameters for the thermal design of this type of magnet and have been determined in this study. For determining these thermal properties, three sheets of each material with different thicknesses varying from 245 to 598 μm have been tested in steady-state condition in the temperature range of 1.6–2.0 K. The thermal conductivity for the tri-functional epoxy (TGPAP-DETD) epoxy resin insulation is found to be $k = [(34.2 \pm 5.5) \cdot T - (16.4 \pm 8.2)] \times 10^{-3} \text{ Wm}^{-1} \text{ K}^{-1}$ and for the cyanate ester epoxy $k = [(26.8 \pm 4.8) \cdot T - (9.6 \pm 5.2)] \times 10^{-3} \text{ Wm}^{-1} \text{ K}^{-1}$. For the Kapitza resistance, R_k , the best curve fitting the experimental data is described by $R_k = (3057 \pm 593) \times 10^{-6} \cdot T (-1.79 \pm 0.34) \text{ m}^2 \text{ KW}^{-1}$ for the TGPAP-DETD insulation and $R_k = (4114 \pm 971) \times 10^{-6} \cdot T (-1.73 \pm 0.41) \text{ m}^2 \text{ KW}^{-1}$ for the cyanate ester epoxy insulation. Our results are compared with other epoxy based composite electrical insulation found in the literature.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Within the framework of the FP7 European project EuCARD, an Nb₃Sn magnet is under development to serve as a test bed for future high field magnets and to upgrade the vertical CERN cable test facility [1]. The magnet is designed to achieve a magnetic field of 13 T at 1.9 K. As opposed to NbTi magnets, Nb₃Sn magnets require the use of fiber-based composite electrical insulation that can resist the heat treatment that creates the intermetallic Nb₃Sn component. The fiber is impregnated with an epoxy resin polymer after the heat treatment step. This type of insulation is called “dry” insulation, i.e. impermeable to liquid helium. One of the major inconveniences for this type of magnet is that the coolant does not have an intimate contact with superconducting cables therefore reducing the cooling capacity of such magnets. Heat generated in superconducting cables during the AC losses due to field ramp rate, quench process, beam losses and synchrotron radiation has to be removed from the superconducting cables to the cold source via the surrounding electrical insulation which is in fact the main thermal barrier. This process is governed by two mechanisms:

the thermal conductivity through the insulation itself and the Kapitza resistance at the helium-solid boundary. These thermal properties can be obtained only by experiments. The present paper concerns the experimental results of the thermal characteristic of the cyanate ester epoxy mix and tri-functional epoxy (TGPAP-DETD) developed during the EuCARD project [1]. The principle of our experiment is based on the measurement of the overall thermal resistance of the tested sheets separating two isothermal superfluid helium baths, where one bath is heated and the other is temperature controlled [2,3]. We measured temperature differences across the sheets as a function of heat flux. For extracting the Kapitza resistance and the thermal conductivity as a function of temperature, three thicknesses of each material are tested in the temperature range of 1.6–2.0 K.

2. Samples preparation

The composite insulation materials used during measurements were produced using a vacuum impregnation process which is similar to vacuum impregnation of a magnet structure. A stack of glass fiber was placed in a tray and aluminum plates placed in between the layers to create individual laminates. This was then evacuated to better than 0.1 mbar pressure in a vacuum tank at a temperature of 40 °C. Liquid polymer was prepared by mixing

* Corresponding author.

E-mail address: bertrand.baudouy@cea.fr (B. Baudouy).

¹ This author is on leave from Wroclaw University of Technology, Wyb. Wyspian-skiego 27, 50-370 Wroclaw, Poland.

and degassing to a similar pressure in a separate vacuum chamber, before being introduced to the glass fiber stack. After submerging the glass fiber with polymer, the pressure was returned to atmospheric pressure to impregnate the glass fibers and the stack was moved to a heated press where it was cured under 0.1 MPa pressure. The cured laminates were then removed from the tray using the aluminum plates to easily separate them. For the cyanate ester–epoxy blend (by weight 60% epoxy and 40% cyanate ester), a cure cycle of 6 h at 100 °C, 4 h at 120 °C and 17 h at 150 °C was used. For the tri-functional epoxy TGPAP-DETD, a cure cycle of 14 h at 70 °C and 15 h at 90 °C was used. The samples have a diameter of 100 mm and are simply cut from the sheets produced by the process described above.

3. Experimental apparatus

To measure the temperature difference across the samples, the “drum” technique is used [2,3]. The experimental apparatus, showed in Fig. 1, is composed of five stainless steel flanges. The sample sheets are located on both sides of a central cylindrical support. To prevent the flow of superfluid helium from the inner bath to the external helium reservoir, the sample sheets are glued to the flanges with epoxy resin which creates an approximately effective diameter of heat transfer of 80 mm (cf. Fig 2). Flanges are screwed to the central support instrumented by a Cernox temperature sensor and a heater having an electrical resistance of 8 Ω. The apparatus is placed in a pressurized superfluid helium bath of a “Claudet” type cryostat [4].

The superfluid helium fills the internal volume, which is considered isothermal in superfluid helium, via the 0.4 m long capillary tube, wrapped and glued around the stainless steel central cylindrical support. The capillary tube also carries the instrumentation wires for the temperature sensors and heater. In that way it reduces the heat transfer cross section to 0.153 mm² and therefore the heat losses through the capillary. Before each cool down, the experimental set-up is purged three times where air is replaced by helium gas by pumping for several hours. In that way, the air inside the inner volume is replaced by helium gas through the capillary.

4. Theoretical background

When a heat flux Q_s is applied perpendicularly to the samples in the inner bath, a temperature difference $\Delta T = T_i - T_b$ is created across the tested sheets and between the internal T_i and the external bath T_b . The value of the temperature difference during steady state heat load depends on the thermal resistance of the insulation R_s due to the conduction and the Kapitza resistance $R_{Kapitza}$

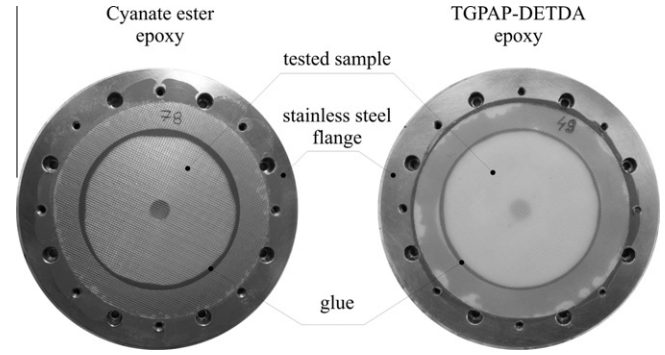


Fig. 2. Pictures of two sample sheets glued on their support flange.

between the solid and superfluid helium [2,3]. According to the Khalatnikov's theory [5], the heat flux between a solid and a liquid can be calculated based on the acoustic mismatch theory and the Kapitza resistance has a T^{-3} temperature dependence. It has been experimentally proven that the value of the Kapitza resistance is not only a function of the temperature but also depends on the solid material properties, the solid surface conditions, pressure, etc. [6]. Therefore, in practice the exponent of the temperature dependency varies around 3 from 2.5 to 4.5 [7]. Also as mentioned in [7], the exponent is temperature dependent and increases with temperature especially near T_λ which is a consequence of direct photon or roton emission, and a much shorter phonon wavelength as well.

According to the mismatch theory [5], a heat flux between the surface of the solid at T_s and the He II at a temperature of T_{HeII} can be expressed by

$$\frac{Q_s}{A_s} = h_K(T_s^n - T_{HeII}^n), \quad (1)$$

where Q_s is the heat flux going through the solid, A_s is the effective area of the heat transfer and h_K is the Kapitza conductance.

In our experimental set-up, the heat generated in the inner bath goes through the inner sample surface, the sample and the outer sample surface facing the cryostat bath. This can be formulated as

$$\frac{Q_s}{A_s} = h_K(T_i^n - T_1^n) = \frac{k}{l}(T_1 - T_2) = h_K(T_2^n - T_b^n) \quad (2)$$

where T_i , T_1 , T_2 and T_b are, respectively, the temperatures of the inner helium volume, the surface of the sample from the inner volume side, the surface of the sample from the cryostat bath side and the cryostat bath. k and l are the thermal conductivity of the tested material and its thickness.

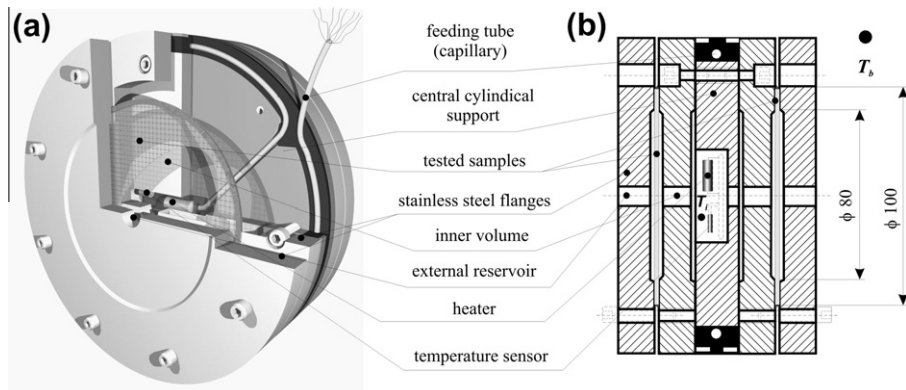


Fig. 1. Schematic of the experimental set-up.

Download English Version:

<https://daneshyari.com/en/article/1507829>

Download Persian Version:

<https://daneshyari.com/article/1507829>

[Daneshyari.com](https://daneshyari.com)