HEAT TRANSFER THROUGH CYANATE ESTER EPOXY MIX AND EPOXY GPAPDETDA ELECTRICAL INSULATIONS AT SUPERFLUID HELIUM TEMPERATURE

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HEAT TRANSFER THROUGH CYANATE ESTER EPOXY MIX AND EPOXY TGPAP–DETDA ELECTRICAL INSULATIONS AT SUPERFLUID HELIUM TEMPERATURE

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ABSTRACT

In the framework of the European project EuCARD (FP7) aiming at constructing a high magnetic field accelerator magnet of 13 T with Nb_3Sn superconducting cables, new electrical insulation are thermally tested. This technology will use “conventional” electrical insulation in combination with pressurized superfluid helium (He II) or saturated helium at atmospheric pressure as coolant. Two composite insulation systems composed of cyanate ester epoxy mix or a tri-functional epoxy (TGPAP-DETDA) with fiberglass tape frame, have been chosen as potential candidates. The knowledge of their thermal properties is necessary for the thermal design and therefore samples have been tested in pressurized He II where heat is applied perpendicularly to the fibers between 1.6 K and 2.0 K. Overall thermal resistance is determined as a function of temperature and the results are compared with other electrical insulation systems used for accelerator magnets.

KEYWORDS: Total thermal resistance, electrical insulation, superfluid helium

INTRODUCTION

The main issue of EuCARD-HFM (Work Package 7) project is to develop and construct a high field magnet of 13 T with Nb_3Sn superconducting cables. The magnet will operate in He II at 1.9 K or saturated at 4.2 K helium conditions [1].

The modeling of thermal behavior of magnet has revealed that one of the critical elements in the magnet structure is the thermal properties of the 0.2 mm thick electrical insulation [2]. The electrical insulation is the main thermal barrier for the heat extraction from the superconducting cables during ramp rate (AC losses) or beam losses to the cold source. The knowledge about thermal properties, especially the overall thermal resistance, is necessary to feed the numerical code for the calculation of the operating margin temperature. The paper presents the experimental results of the overall thermal resistance for two potential electrical insulations which are two composites made of fiber glass tape and epoxy resin measured in He II. But in a near future, the thermal conductivity of both materials from 4 K to 300 K will be measured. The insulations are made with the same fiberglass tape differ in the epoxy resins which are a cyanate ester epoxy mix and a tri-functional epoxy (TGPAP-DETDA).

ELECTRICAL INSULATION SYSTEMS

The composite insulation materials were produced using a vacuum impregnation process. This process is similar to vacuum impregnation of a magnet structure. A stack of glass fiber and aluminum plates were placed in a tray and evacuated to better than 0.1 mbar pressure at a temperature of 40°C. Resin was mixed and degassed to a similar pressure, before introducing to the glass fiber stack. After filling the tray the pressure was returned to atmospheric pressure and the stack was moved to a heated press, where it was cured under 0.1 MPa pressure. For the cyanate ester-epoxy blend (by weight 60% epoxy and 40% cyanate ester), a cure cycle of 6 hours at 100°C, 4 hours at 120°C and 17 hours at 150°C was used [3]. For the tri-functional epoxy TGPAP-DETDA, a cure cycle of 14 hours at 70°C and 15 hours at 90°C was used [4].

EXPERIMENTAL SET-UP

To determine the total thermal resistance of the tested material, the “drum” technique is used [5-6]. The “drum” apparatus is composed of five stainless steel flanges (see FIGURE 1). The inner part of the apparatus is fed by helium through a capillary and heated by a heater having an electrical resistance of 8 Ω. The dissipated heat is controlled by a Keithley 2400 source meter. To measure the temperature in the inner volume a Cernox temperature sensor, with a four-wires technique and a DC battery current source, are used.

The tested sheets, having a diameter of 100 mm, 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 samples are glued to the flanges by epoxy resin. Flanges are screwed to the central support and assembled in the cryostat. The superfluid helium fills the internal volume via the 0.4 m capillary tube, wrapped and glued around stainless steel central cylindrical support. The capillary tube is also carrying the instrumentation wires for measurement of temperature and a heater. In that way it reduces the heat transfer cross section and therefore the heat losses through the capillary.

The thickness of every sample was measured at four points with the accuracy of ± 1 μm and the average value was considered as a representative thickness. For the cyanate ester epoxy mix sample, the thickness is 0.245 mm, and for the TGPAP-DETDA sample the thickness is 0.289 mm. These thicknesses’ values are very similar to the foreseen thickness of the electrical insulation in the magnet.

Before and after mounting the sample in the experimental apparatus, the sample was cleaned using methyl alcohol.

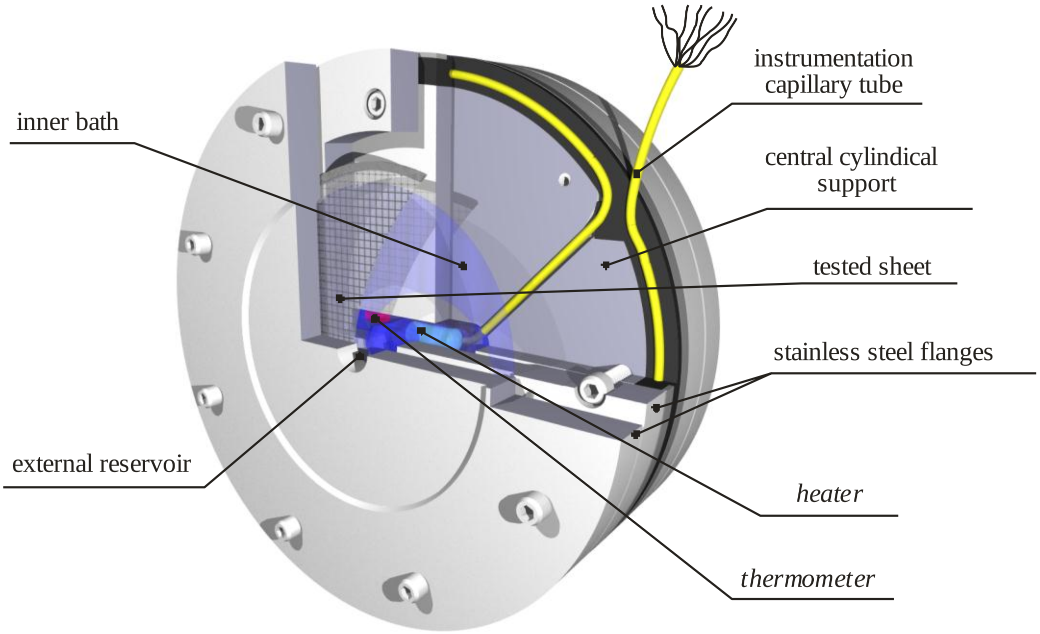

FIGURE 1. General view of the experimental apparatus.

The measurements were performed in "Claudet" type cryostat, where the pressurized superfluid helium is maintained in the temperature range from 1.6 K to 2.0 K [6]. The temperature of the helium bath is regulated by a heater controlled by a LakeShore 332 temperature regulator with accuracy of 1 mK. The bath temperature is monitored by calibrated Cernox temperature sensor. These sensors are used to calibrate the temperature sensor located in the inner bath of the "drum" apparatus with a maximum deviation of 0.1 mK.

The measurements were performed at five different bath temperatures varying from 1.6 to 2.0 K with a 0.1 K step. The total heat load was chosen individually for each thickness with the criterion that the temperature difference in the inner part of experimental apparatus reaches a value around 30 mK. This criterion is satisfied when the maximum heat load is equal to 0.045 W for all samples. In all tests, the heat load was applied in 40 steps. To obtain steady state, each measurement step was separated by a duration of about 25 s. The values of temperature in the inner and outer baths and power of heater were then collected by a NI SCXI 1320 voltage measurement system.

BACKGROUND AND FITTING PROCEDURE

The main goal of the experiment is to determine the thermal resistance of each insulation system at superfluid temperature from 1.6 K to 2.0 K. When the heat Q_s is applied perpendicularly to the fiber in the inner bath, a temperature difference ΔT is created across the tested sheet of insulation 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 $R_{insulation}$ due to conduction and the Kapitza resistance $R_{Kapitza}$ [5,6]. The sum of those two components is identified as the total thermal resistance. The total thermal resistance of the sample R_s is determined by using the following expression:

$$R_s = A\,\frac{\Delta T}{Q_s}, \qquad (1)$$

where A is effective area of heat transfer.

The total thermal resistance of the insulation can be obtained from equation (1) only when the temperature difference ΔT during one series of data points has a linear evolution with Q_s *i.e.* R_s is constant. For our experimental measurements, this condition is usually satisfied above a ΔT of 10 mK as the FIGURE 2 shows, where the R_s evolution for the TGPAP-DETDA sample as a function of ΔT is depicted at a bath temperature of 1.6 K. It is a typical result and such a curve is found for both samples and at different bath temperatures. At low Q_s, there is a nonlinear part because the heat is transferred mainly through the helium in the capillary. After ΔT=10 mK, it can be noticed that the value of the total resistance is almost constant and varying around an average value (shown in FIGURE 2 as a dot line). As it was proved in [3], the amount of the heat transferred by superfluid helium via the capillary can reach 20% of Q_s for small ΔT around 1 mK and only a few percent for ΔT comprised between 10 and 30 mK. To reduce the systematic error due to the heat loss through the capillary, the thermal resistance will be determined in that ΔT range, for each sample and bath temperature.

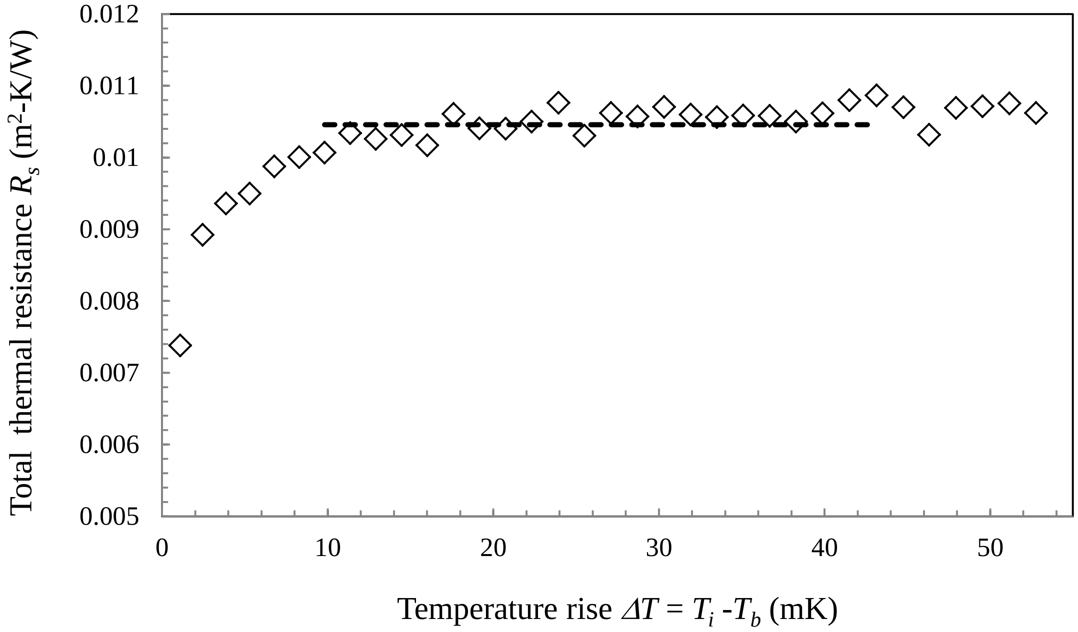

FIGURE 2. Evolution of the TGPAP-DETDA sample total thermal resistance as a function of temperature difference at 1.6 K bath temperature.

EXPERIMENTAL RESULTS

Typical results of temperature difference ΔT between the inner helium T_i and external reservoir T_b, as a function of total heat load, Q_s for the TGPAP-DETDA and cyanate ester epoxy mix insulations at different bath temperatures are presented in FIGURES 3 and 4 respectively. In these figures, the results of the fitting procedure are presented for 1.6 K by a solid line. The temperature dependence is clearly seen and the slope of the thermal characteristics decreases with the bath temperature. This effect is due to the reduction of the Kapitza resistance with temperature (T^{-3} dependence) and the increase of the thermal conductivity of the epoxy resin and the fibreglass tape with temperature as it was already measured for a fiberglass epoxy composite system [6]. The thermal resistance is the slope of the ΔT-Q_s curve is given by a first order polynomial fit.

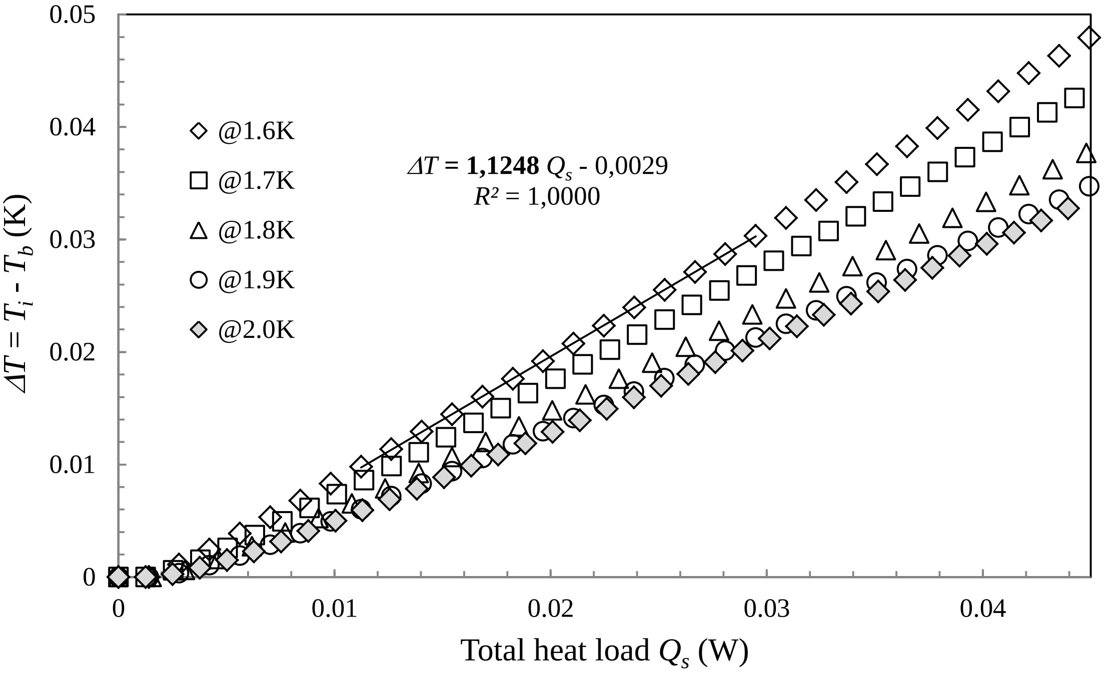

FIGURE 3. The evolution of temperature rise ΔT in the inner volume of heated superfluid helium as a function of total heat load Q_s for TGPAP – DETDA and thickness of 0.289 mm.

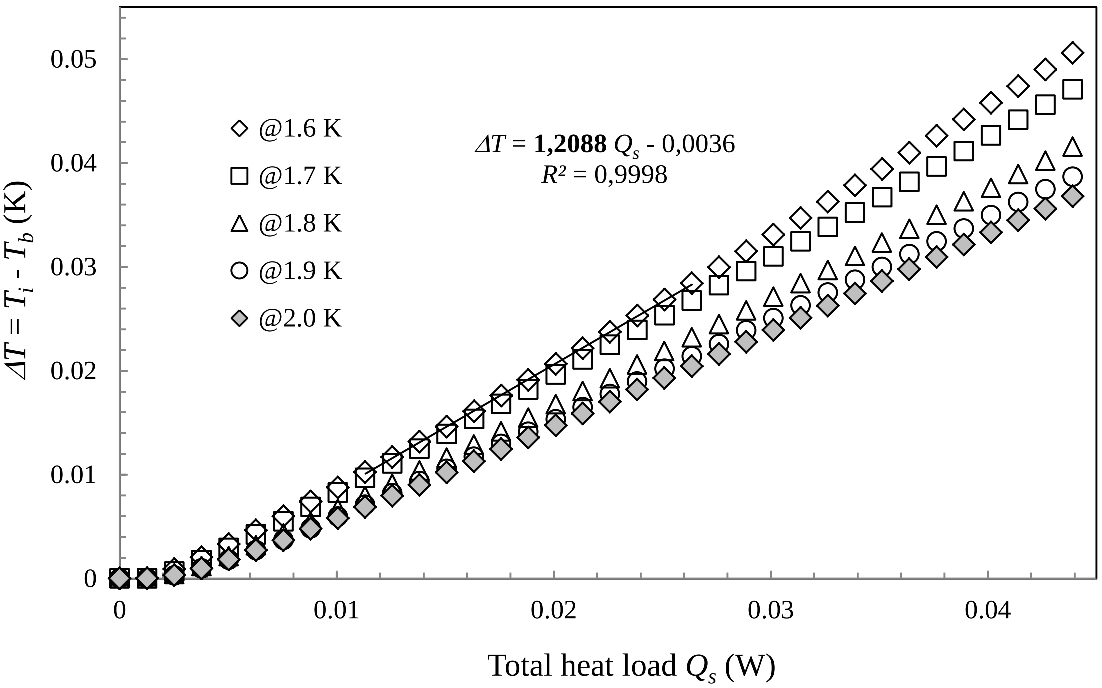

FIGURE 4. The evolution of temperature rise ΔT in the inner volume of heated superfluid helium as a function of total heat load Q_s for cyanate ester epoxy and thickness of 0.245 mm.

In FIGURE 5, the total thermal resistance of several insulation materials such as RAL epoxy system 227, developed during NED program [6], Kapton [5] and the insulations tested presently by the authors are presented. The total thermal resistances for the cyanate ester epoxy mix, TGPAP-DETDA and RAL epoxy system 227 have almost the same value and the same temperature dependence as expected and explained above. The maximum difference between the fiberglass epoxy composite is relatively small (about 15 %) in comparison with Kapton for which the thermal resistance is five times higher. For the RAL epoxy system the main influence on the overall thermal resistance is thermal resistance of the insulation $R_{insolution}$ which is around seven times higher than Kapitza resistance $R_{Kapitza}$ in the investigated range of temperatures. The tested insulations, similar to RAL epoxy system, consist of approximately 50% of fiberglass tape which plays the main role in the heat transport, explaining the similarity of the results. The small difference could be a consequence of the use of different type of resin materials.

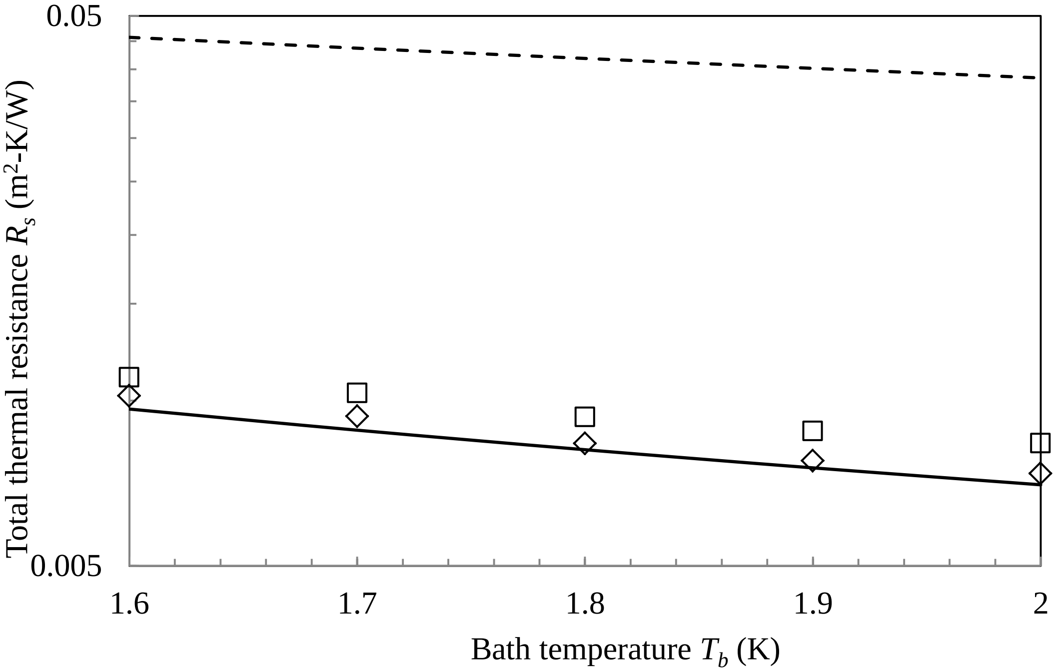

FIGURE 5. Thermal resistance R_s of different materials as a function of bath temperature T_b; measured: ☐ – cyanate ester epoxy mix, ◇ - TGPAP – DETDA; calculated for thickness of 0.245 mm: - - - - Kapton [5], ——— RAL epoxy system 227 [6].

CONCLUSION

The thermal resistance of cyanate ester epoxy mix and a tri-functional epoxy (TGPAP-DETDA) - two potential insulation materials for the Nb_3Sn high field magnet under development in the HFM Eucard project have been measured at pressurized He II conditions. The study shows that the resistances of the tested electrical insulations are very similar to each other since they are mainly composed of fiberglass tape and are five times lower than for Kapton. Additional tests are needed to complete the study and extract the thermal conductivity and the Kapitza resistance. Moreover, the thermal characterization of these electrical systems at higher temperature is required for the thermal design of the magnet and additional measurement such as thermal conductivity and heat capacity are foreseen between 4 K and 300 K.

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S. Pietrowicz is on leave from Wroclaw University of Technology, Wyb. Wyspianskiego 27, 50-370 Wroclaw, Poland.

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