LOW TEMPERATURE HEAT TRANSFER PROPERTIES OF CONVENTIONAL ELECTRICAL INSULATION FOR THE NEXT EUROPEAN DIPOLE

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Abstract

The heat transfer properties of the fibreglass epoxy resin impregnated electrical insulation of the Next European dipole, known as conventional insulation, has been tested at low temperature. The electrical insulation is made of E-glass fibre with a plain weave and RAL epoxy system 227 (DGEBF epoxy resin and DETD aromatic hardener). The samples have been tested in pressurized superfluid helium (He II) where heat is applied perpendicularly to the fibres between 1.55 K to 2.05 K. Overall thermal resistance is determined with temperature and compared with other electrical insulation systems.

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ABSTRACT

The heat transfer properties of the fibreglass epoxy resin impregnated electrical insulation of the Next European dipole, known as conventional insulation, has been tested at low temperature. The electrical insulation is made of E-glass fibre with a plain weave and RAL epoxy system 227 (DGEBF epoxy resin and DETD aromatic hardener). The samples have been tested in pressurized superfluid helium (He II) where heat is applied perpendicularly to the fibres between 1.55 K to 2.05 K. Overall thermal resistance is determined with temperature and compared with other electrical insulation systems.

KEYWORDS: heat transfer, electrical insulation, helium 4 superfluid phase

INTRODUCTION

The Next European Dipole (NED) is a Joint Research Activity (JRA) of the Coordinated Accelerator Research in Europe (CARE) project, funded by EU-FP6 Research Infrastructures. CARE attempts the integration of high-energy-physics-related accelerator research and development (R&D) in Europe. The initial NED proposal had three main goals: to promote efforts among European laboratories involved in high-field accelerator magnet R&D, to promote the development of high-performance Nb_3Sn wires and cables in collaboration with European industry, to get ready for a luminosity upgrade of the Large Hadron Collider (LHC) [1].

One of the key issues in the operation of a superconducting particle accelerator is the temperature margin of the dipole and quadrupole magnets the most exposed to beam losses and the ability of the cryogenic system to cope with the deposited energies. In the case of the LHC, the temperature margins of the superconducting magnet coils operated in superfluid helium is mainly determined by the heat transfer coefficient through the Kapton insulation wrapped around the NbTi-based, Rutherford-type cables. Wherever NED-like magnets are implemented, they will be subjected to beam losses, and thereby, to energy depositions, which are likely to be higher than those presently foreseen in the LHC. Furthermore, 'wind and react' Nb_3Sn coils call for the use of insulation materials and schemes that are very different from those applied in LHC magnets. Hence, the issues of heat transfer thought new electrical insulation systems must be investigated and overall thermal resistance of the material in superfluid helium conditions must be determined.

NEW CONVENTIONAL NED ELECTRICAL INSULATION

Glass-fibre epoxy sheets were produced using vacuum impregnation. This method mimics the vacuum impregnation of a magnet structure. However it should be noted that this produces an ideal material in that sheets were cured between flat mould platens, producing a consistent glass-epoxy fraction, whereas in a real magnet the insulation would be between cables which are not flat.

Plain weave glass fibre sheets were stacked between sheets of perforated polyester release film. The stack was placed in an aluminium foil tray and evacuated for 24 hours to a pressure of less than 0.1 mbar. A mixture of DGEBF epoxy resin, typified by Dow DER354, and DETDA hardener, typified by Albemarle Ethacure 100, was degassed in a separate vacuum chamber and stirred to break bubbles as it degassed. When a pressure of 0.1mbar was reached, the mixture was let up to atmospheric pressure. The epoxy mixture was flooded around the glass fibre sheets. When the level of epoxy resin covered the sheets, the vacuum chamber was let up to atmosphere. The stack was placed in a heated hydraulic press and cured at a pressure of 1MPa, at a temperature of 90ºC. When the epoxy was gelled the temperature was raised to 130ºC for 16 hours.

DESCRIPTION OF EXPERIMENT

Experimental method

The experimental method of determining the overall thermal resistance consists in measuring directly the temperature across samples as a function of heat flux [2,3]. In this method the sample sheet separates two different temperature helium volumes. The first helium volume is the superfluid pressurised bath of the cryostat, whereas the second volume is created inside of an experimental set-up. This volume is heated and its temperature T_i is higher than in the cryostat bath temperature T_b. In steady state condition the two volumes are isothermal with the high thermal conductivity of He II. With a known heat dissipation through the sample Q_s, cross sectional area of the sample sheet A and temperature difference ΔT between both volumes, a thermal resistance of the sample R_s can be determined by using following equation:

$$R_s = \frac{A(T_i - T_b)}{Q_s} = \frac{A \cdot \Delta T}{Q_s} \tag{1}$$

Experimental apparatus

The experimental set-up is composed of two support flanges and two sample holder flanges all made of stainless steel (see FIGURE 1). The tested material sample sheet has a thickness of 0.073 mm and a diameter of 80 mm of active heat transfer area and it is glued with Scotch-Weld DP190 epoxy resin to one of the holder flange (see FIGURE 2). The second holder flange pressures the glued area to ensure leak tightness of the connection. One of the support flanges comprises an open space, where a 1 Ohm resistor (heater) and Allen Bradley (AB) type temperature sensor are located. The inner volume is fed with liquid helium and a wiring to the set-up instrumentation are introduced by a 0.5 mm inner diameter and 0.4 m long capillary tube, which is wrapped around the outside surface of the support flange and insulated in a epoxy resin block. The second support flange is blind and closes the inner helium volume. All set-up flanges are screwed together and surfaces between flanges are sealed with Scotch-Weld DP190 epoxy.

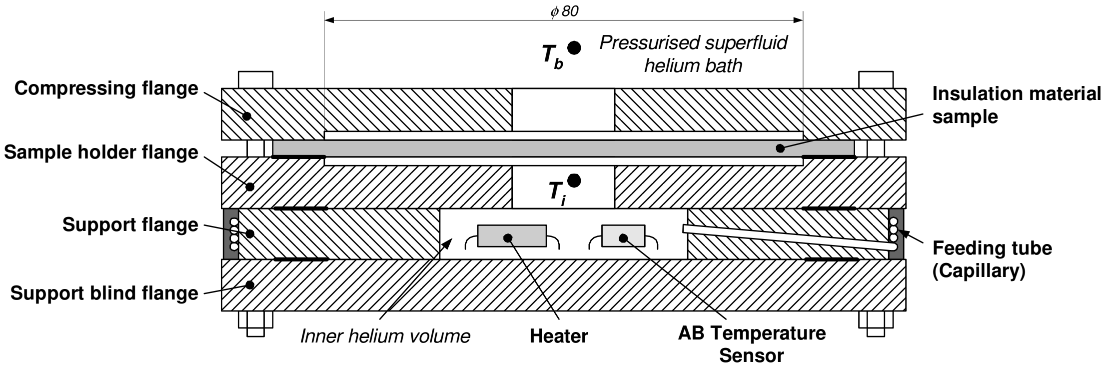

FIGURE 1. Schematic of the experimental set-up

Error discussion

The temperature of the pressurised cryostat bath, T_b, is monitored with CERNOX temperature sensor and maintained at desired level by LakeShore 332 Temperature Regulator. The calibration fit in the superfluid helium temperature range gives at most a 0.2 mK difference between measure and reference. In operation, the temperature of the cryostat bath is controlled with 1 mK.

The Allen Bradley temperature sensor in the inner helium volume was calibrated in situ and temperature – electrical resistance characteristic curve of the sensor was created before experiment. Total accuracy of the AB sensor reading, included sensor calibration, the fitting curve errors and reading reproducibility, is round ±0.3 mK.

Heat dissipated in the inner volume is controlled by KEITHLEY 2400 Source Meter with accuracy of 0.5% of the value. Total heat dissipated by the heater inside inner volume is transferred to saturated helium bath through tested sample Q_s and by heat losses Q_{los}, which includes the capillary tube and the experimental setup walls heat transfer. The stainless steel heat losses were previously determined by finite elements analysis method and do not exceed 2% of total heat flux [2, 3]. Calculation shows that for small temperature differences between inner volume and cryostat bath the capillary heat transfer is very high and reach up to 20% for ΔT<1mK. Nevertheless influence of the capillary heat loss is decreasing with increasing inner volume temperature. For ΔT higher than 10mK is up to 2.5% of total heat flux.

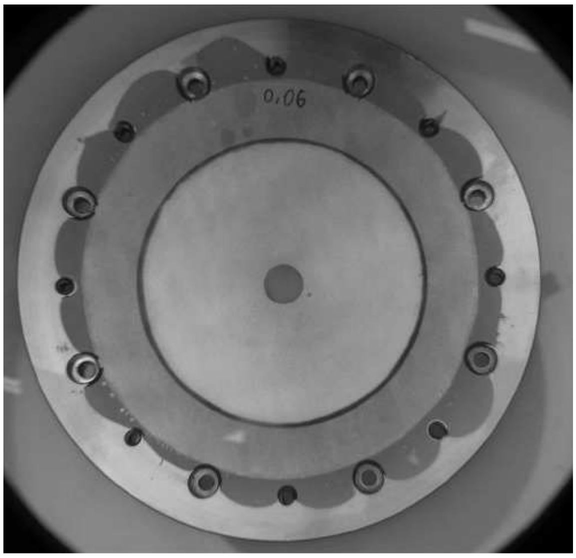

FIGURE 2. Photograph of the 0.073 mm thick sample. One can see the epoxy glue sealing the sample to the sample flange.

Active area of heat transfer through sample is delimited by the glue as it is shown in FIGURE 2. Therefore a photograph of the sample was taken and real sample active area was computer-aid determined by a pixel counting method as 0.004702 ± 0.05% m².

EXPERIMENTAL PROCEDURE, RESULTS AND COMPARISON WITH OTHER INSULATION MATERIALS

Measurements of the sample were performed in 7 different bath temperature from 1.55 K to 2.05 K. At a given temperature, applied heat was increasing by constant ramp value of 0.5 or 1 mW and the inner helium volume, T_i, and of the cryostat bath temperatures were measured at steady state condition. The time of stabilization of T_i was determined in pre-test as about 20 s, therefore time of each heat ramp was set as 30s.

FIGURE 3 shows results of the measurement as the temperature difference with heat flux at different temperature. At very low heat flux, one can see the effect of the capillary containing the instrumentation wires, where the ΔT-Q is not linear due to turbulent superfluid helium heat transfer. The effect of the capillary becomes negligible above few mW where the He II in it does not transfer heat sufficiently since the heat transfer cross sectional area is extremely small. The temperature dependence is clearly seen and the slope of the thermal characteristics decreases with 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 mentioned in the previous section and as its can be clearly seen on FIGURE 3, for ΔT <10 mK influence of the capillary heat transfer on obtained result is very strong. However, for ΔT>30 mK Kapitza resistance value can be changed and provide additional uncertainties to future analysis. Therefore for determination of the material overall thermal resistance R_s, the results from ΔT =10-30 mK range are only taken in to account.

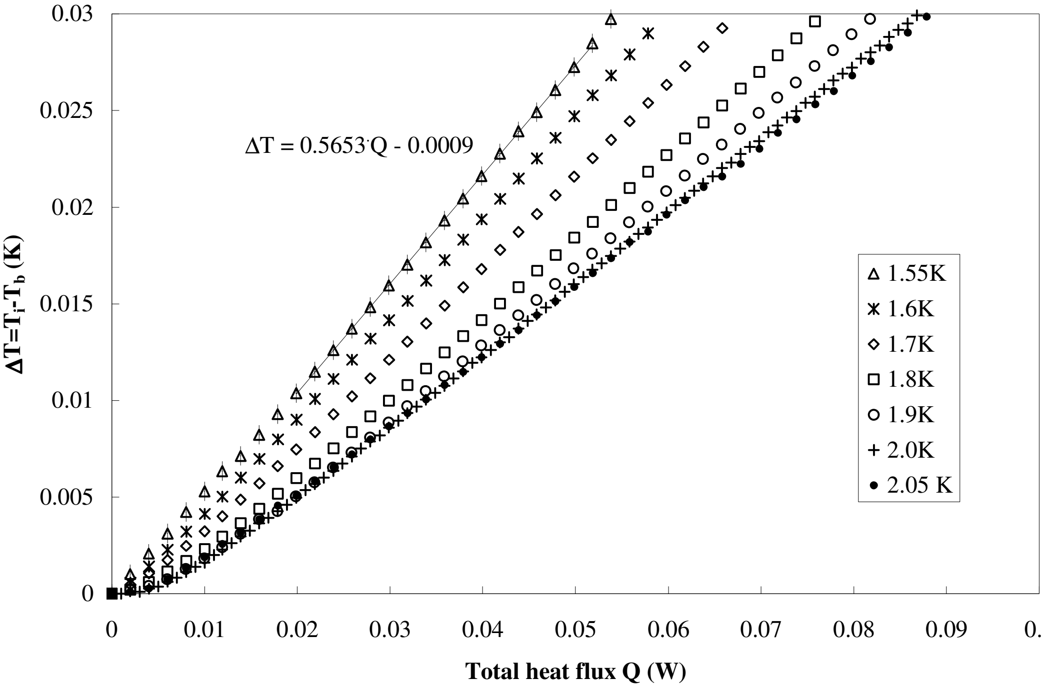

FIGURE 3. Evolution of the temperature difference across the sample with heat flux as a function of the bath temperature.

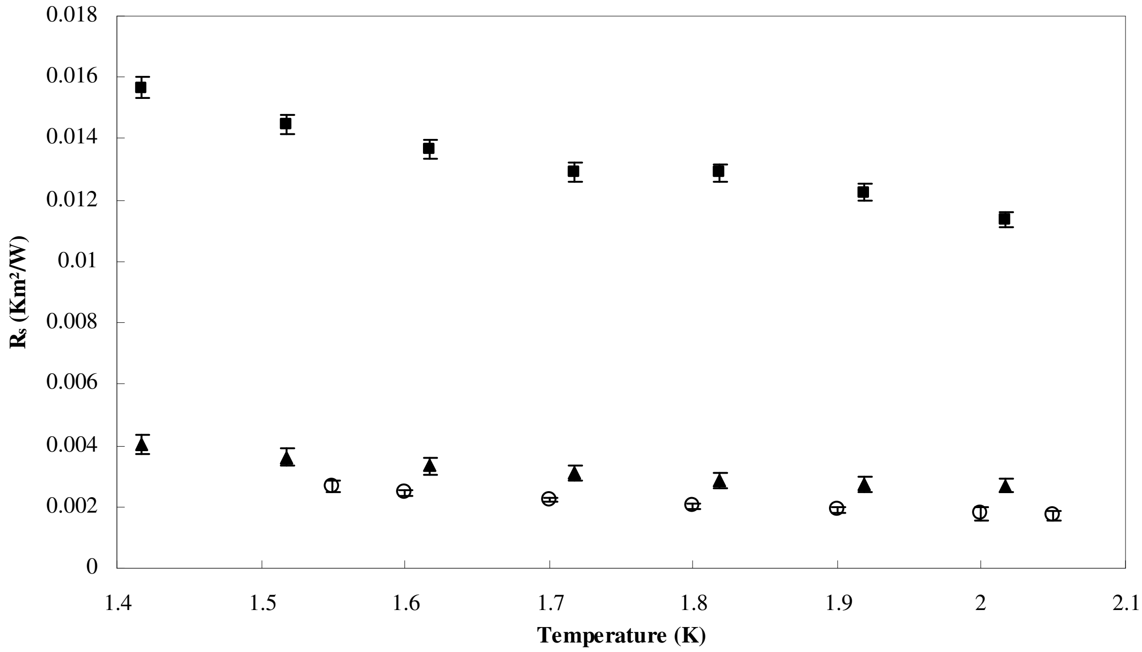

FIGURE 4. Overall thermal resistance of different electrical insulation materials. ○ - convectional insulation 0.073 mm, ■ – Kapton 0.077 mm [2], ▲ – Kapton 0.014 mm [2]

In consider ΔT range each temperature characteristics can be approximated by linear function $a+bQ$ where b parameter is stand for the overall thermal resistance of the material R_s value divided by the active heat transfer area of the sample A. To find R_s value, fitting functions were constructed with the last square method for each bath temperature. An example of the fitting function and measuring errors is presented on FIGURE 3 for T_b=1.55 K case.

FIGURE 4 presents determined values of the overall thermal resistance of the NED convectional insulation for different bath temperature. As expected the total overall thermal resistance is decreasing with temperature. It is also shown on FIGURE 4 the value obtained for two different Kapton thicknesses [2]. One can see, that the R_s of the conventional NED insulation material is more then 5 times less than Kapton material with similar thickness and even better then Kapton with 5 times lower thickness. Assuming that the Kapitza resistance is identical to the Kapton, the explanation of this difference could come from the fact that the thermal conductivity of epoxy resin and G10 is about 5 times higher than the Kapton thermal conductivity. Anyway, to go into more details on the thermal performance of this insulation system at superfluid temperature, the thermal conductivity and the Kapitza resistance should be determined in measuring more samples with different thicknesses.

CONCLUSION

The thermal characteristics of 0.073 mm thickness of the E-glass fibre with a plain weave and RAL epoxy system 227 (DGEBF epoxy resin and DETD aromatic hardener) have been determined in superfluid helium. Comparison of the overall thermal resistance of this material with two different thicknesses of Kapton (which is presently used as NbTi superconducting cables electrical insulation) shows its very good thermal heat transfer properties. Therefore its can be considered as conventional electrical insulation of the NED Nb_3Sn superconducting magnet cables.

ACKNOWLEDGEMENT

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