STEADY-STATE HEAT TRANSFER IN He II THROUGH POROUS SUPERCONDUCTING CABLE INSULATION

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ABSTRACT

The LHC program includes the study of thermal behavior of the superconducting cables wound in the dipole magnet cooled by superfluid helium (He II). Insulation of these superconducting cables forms the major thermal shield hindering the He II cooling. This is particularly a problem in magnets which are subjected to thermal loads. To investigate He II heat transfer processes an experimental model has been realized which creates a one-dimensional heat transfer in such media. Insulation is generally realized by wrapping around the superconducting cable a combination of different kind of Kapton® tapes, fiber-glass impregnated by epoxy resin or Kevlar® fiber tapes. Steady-state heat transfer in He II through these multi-layer porous slabs has been analyzed. Experimental results for a range of heat flux show the existence of different thermal regimes related to He II. It is shown that the parameters of importance are a global geometrical factor which could be considered as an equivalent "permeability" related to He II heat transfer, the transfer function $f(T)$ of He II and the thermal conductivity of the slab. We present and analyze results for different insulations as a function of the temperature.

INTRODUCTION

This work is a part of the general framework of the Large Hadron Collider study program and concerns thermal behavior of the dipoles' superconducting cables cooled by He II. It has been designed such that the whole superconducting coil of LHC will be maintained at a temperature around 1.9 K and will be immersed in a He II pressurized bath at 0.1 MPa[1]. Dipoles may be submitted to a permanent heat production up to 10^4 Wm^{-3} due to beam losses. In modeling the thermal behavior of a LHC dipole, it appeared that the cable's insulation, made of two distinct layers, is one of the critical parameters driving heat transfer. Indeed insulation of these superconducting cables forms the main thermal resistance to He II cooling[2,3]. Even if insulations are permeable to He II, current cooling of cables is insufficient. For a better understanding of heat transfer, thermal behavior of the insulation is approached through an experimental model in which characteristics can be modified. The model, rather than considering the modeling of entire heat transfer in a dipole, focuses on one-dimensional heat transport through an elementary insulation pattern. A first attempt of modeling steady-state heat transfer through this particular porous media is proposed, using the assumption of decoupled thermal paths between insulation and helium.

EXPERIMENTAL DESCRIPTION

Experimental set-up

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The main constituent of the apparatus is a stainless steel cylindrical support oriented vertically in the cryostat. Two insulation samples are attached on the sides of the cylindrical support. A schematic of the experimental apparatus is shown in Figure 1. The insulation samples have an external diameter of 80 mm and an internal diameter of 60 mm. They are fixed over 20 mm of their diameter by Stycast resin to the frame and tightened by two stainless steel clamps to avoid helium leak. A heater and a Allen-Bradley carbon resistor are located in the internal bath. In the temperature range of the experiment, this thermometer has a high sensitivity (10 O/mK at 2 K). A capillary tube of one meter length is wrapped around the support. It is insulated from the external bath by stycast resin. Instrumentation wires are located in the capillary tube. Heat through the capillary tube filled by instrumentation wires is negligible compared to the heat dissipated by the heater. The internal bath is naturally filled by He II through the insulation and through the capillary tube.

Experimental procedure

The measurement technique uses the thermal properties of the He II. Due to its high effective thermal conductivity, the internal and external temperature baths are uniform during steady-state measurement. In measuring the temperature of the two baths, temperature of the insulation walls can be reached through Kapitza boundary layer. The temperature difference of the two baths is measured as a function of heat flux. Two measurements are separated by 30 s which is higher than the establishment time of the steady state of He II and conductive heat transfer for a heat step. During tests, the external bath is regulated within 2 mK while heat is injected in the internal bath. Experimental sessions have been performed in a “double bath” cryostat which operates between 1.6 K to 2.15 K with a constant helium volume pressurized at atmospheric pressure. Before each experimental session, the thermometer is calibrated in situ between 1.6 K to 2.15 K. Calibration is governed by computer and based on calibrated Germanium thermometers. This provides a precision around 1 mK.

CHARACTERISTICS OF SAMPLES

Patterns

In most of superconducting accelerator dipoles, cable's insulation is composed of two distinct layers. The first one answers to the need of electrical insulation while the second layer protects the first one and serves as a mechanical binding for the whole coil during its manipulation. Helium cooling channels are also formed between cables by wrapping them with a gap. Generally, the first layer is composed of Kapton tapes whereas for the second adhesive Kapton or fiberglass impregnated by resin tapes are used.

For these tests, Kapton tapes were used for the first layer. For the second layer, adhesive Kapton tapes, fiberglass impregnated with epoxy resin and dry mixed Kevlar and fiberglass weaving were used. A description of the samples is listed in Table 1. For these samples, the real 3D pattern of cable’s insulation has been recreated in a 2D pattern. A representation of a typical insulation is shown in Figure 2. The preparation of the samples is exactly the same as the real insulation wrapped around a superconducting cable : same thickness, patterns and polymerization are used[2,3].

Thermal conductivity

Thermal conductivity of the samples is calculated from thermal conductivity, pattern and dimensions of the insulation foils. Conductivity of basic components as Kapton, fiber glass, epoxy resin and Kevlar fiber has been found in the literature at no lower than 2 K[4,5,6,7]. In the temperature range of investigation, values of conductivity have been linearly extrapolated. For sample #1, a series-parallel model has been considered to evaluate the conductivity. Particular attention has been given to samples #2 and #3. Models taking into account the pattern of fiber weaving and thermal contact resistance have been used for the evaluation of the conductivity of the fiberglass impregnated by epoxy resin[8]. During polymerization of sample #2, resin around fiberglass is able to flow out of the ribbon and cover the glass Kevlar. We included such a possibility in conductivity evaluation. Conductivity of the fiberglass Kevlar has been determined using a series model without taking into account the thermal contact resistance between the two components. Final results are listed in Table 1. Considering imprecision in the conductivity of components and models used, conductivity of an insulation cannot be evaluated more precisely than ± 20%.

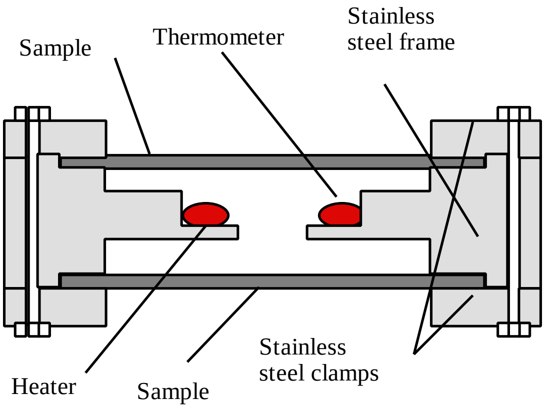


Figure 1. Schematic representation of the experiment.

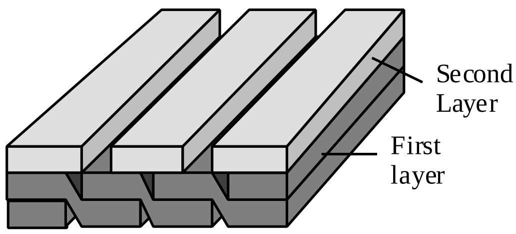


Figure 2. Schematic insulation pattern. First layers has a 50% overlap. The pattern of the second layer creates a gap.

EXPERIMENTAL RESULTS

Figure 3 shows typical data for heat flux versus temperature difference ($?T$) between the internal bath (T_i) and the external bath (T_b) for sample #1 at different external bath temperatures. Conductive heat transfer curves are also displayed in Figure 3.

At a certain bath temperature, the strong non linear variation of temperature difference with respect to heat flux suggests that turbulent He II heat transfer influences the general heat transfer. Temperature dependence of the curves follows the temperature dependence of the turbulent He II heat transfer function $f(T)$ as it is described in Eq. 1.

As $f(T)$ is maximum at 1.9 K, the curve for T_b=1.9 K presents a better heat transfer conductance than at other bath temperature. When T_i reaches $T_?$, the heat flux reaches a maximum value (Q^*) where He I appears in the internal bath around the heater. Above this maximum flux the measured temperature difference reaches a plateau increasing slightly with increasing Q. The plateau indicates that temperature reaches $T_?$ in the internal bath. Temperature of the internal bath is no longer uniform and the advantage of using the high effective thermal conductivity of He II is lost. Temperature of the inside wall is not obtainable easily. Results above Q^* are not presented in this paper.

Table 1. Samples characteristics

	Sample #1	Sample #2	Sample #3
First layer	Kapton 100 HN (25 µm x 11 mm) 50% over lapping	Kapton 100 HN (25 µm x 11 mm) 50% over lapping	Kapton 150 HN (37.5 µm x 11 mm) 50% over lapping
Second layer	Kapton XRCI (2x 38 µm x 12 mm) 2 mm spacing	Fiberglass prepreg (125 ? m x 12 mm) alternated with dry glass-Kevlar woven. (120 µm x 10 mm) (No gap)	Kapton XRCI (2x 38 ? m x 12 mm) alternated with dry glass- Kevlar woven (120 µm x 10 mm) (No gap)
Thickness after polymerization	0.132 mm	0.125 mm on prepreg 0.154 mm on glass-Kevlar	0.164 mm on Kapton 0.184 mm on glass-Kevlar
Total cross-sectional area (A_i)	2 x 2.827 10^{-3} m^2	2 x 2.827 10^{-3} m^2	2 x 5.026 10^{-3} m^2
Conductivity at 2K	0.0087 $Wm^{-1}K^{-1}$	0.0159 $Wm^{-1}K^{-1}$	0.0131 $Wm^{-1}K^{-1}$
Conductivity at 4K	0.0136 $Wm^{-1}K^{-1}$	0.0276 $Wm^{-1}K^{-1}$	0.0255 $Wm^{-1}K^{-1}$

ANALYSIS

Pure superfluid regime

Considering the problem of steady-state heat transfer with no net mass flow, He II internal convection, conductive heat transfer through insulation and Kapitza boundary are the major transport mechanisms. Above Q^*, helium channel start to be saturated and He I heat transfer, He II-He I heat transfer and thermal constriction should be considered.

Equivalent thermal permeability. As we noted previously, turbulent He II heat transport has a large influence on the total heat transfer. We can expect that it is predominant at low heat flux, corresponding to small temperature difference within the sample, because conductive heat transfer is small. We define a pure superfluid regime where we make the assumption that turbulent He II dominates the total heat transfer and where conductive heat transfer and Kapitza thermal boundary layer can be negligible. With increasing Q (causing increasing $?T$), effect of conductive heat transfer increases. The pure He II regime ends at Q_o where conductive heat transfer is no longer negligible. Heat transfer in this regime is defined by the turbulent heat transport process where the relation between heat flux and temperature gradient is expressed by the Gorter-Mellink relation[9] as:

$$\vec{q}^{\,n} = -f(T)\vec{\nabla}T\,, \tag{1}$$

where n is found to be 3 theoretically but which has been experimentally determined to be between 3 and 4, especially when the temperature approaches $T_?$. To consider Eq. (1) under that form, the linear term describing the viscous flow of non turbulent He II is neglected[9]. This assumption will be verified later. In defining a global geometric characteristic independent of temperature, Eq. (1), with n =3, can be rearranged to:

$$Q = \imath \left[\int f(T)dT\right]^{1/3}, \tag{2}$$

where $?=A/L^{1/3}$, A and L are the global equivalent cross-section and the global equivalent length of the helium channels. ? can be considered as a global “thermal permeability” of the media related to He II heat transfer with a dimension of $m^{5/3}$.

With analogy to classical concept of permeability, the higher *?* is, the lower the gradient of potential is (pressure gradient in fluid dynamics and temperature gradient in heat transfer). Notice that this parameter is only related to He II heat transfer and represents the geometrical characteristic of the heat flow conductance through the media. It is useful to introduce an equivalent permeability per unit cross-sectional of insulation, $?_u = ?/A_i$ ($m^{-1/3}$), to be able to compare different samples. Values of A_i *a*re presented in Table 1. The concept of permeability is only valid if for different bath temperatures the heat transfer curves can be fitted with the same permeability value in the low heat flux regime (He II regime). For the determination of *?*, *f(T)* data are from a curve-fit to summary data[10].

Limit of the pure He II regime. The He II regime is no longer valid as Q reaches Q_o. Q_o is obviously function of conductive and superfluid heat transfer. The ratio of conductive to turbulent He II heat transfer in the low heat flux regime has to be low. In this regime (small ? T), temperature dependence of *f(T)* and *k(T)* can be neglected, then this ratio is expressed by:

$$c = \frac{A_i}{e\iota} \frac{k(T)}{f(T)^{1/3}} \Delta T^{2/3} \tag{3}$$

where k is the conductivity and e is the thickness of the media.

We have determined ? and Q_o for *?* ˜ 0.1. Data and fits for sample #2 are shown in Figure 4 for different bath temperatures. Results of permeability are displayed in Table 2; they are the mean values taken over the different fits at different temperatures. The variation from the mean value is around 5% for the three samples. Considering the experimental variation of *f(T)* found in literature[10], assumption of a pure superfluid regime at low heat flux, where superfluid turbulence is developed, can be considered valid.

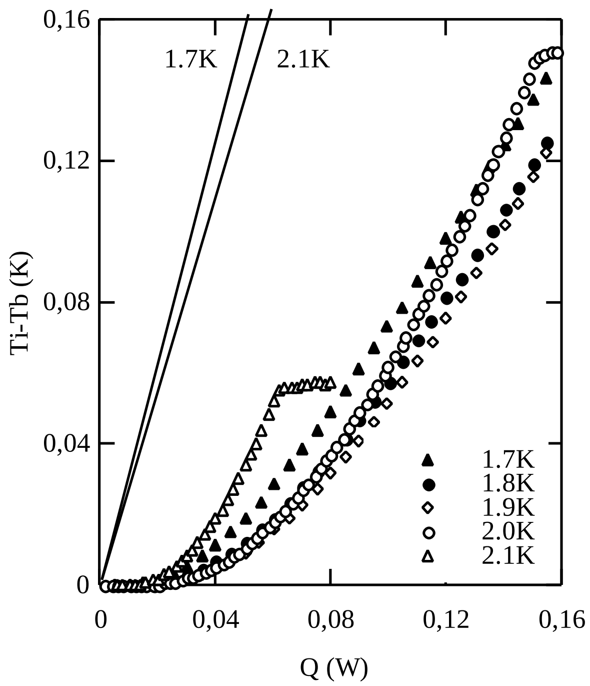


Figure 3. Measurements at different bath temperature for sample #1. Solid lines represent conductive heat transfer in the sample.

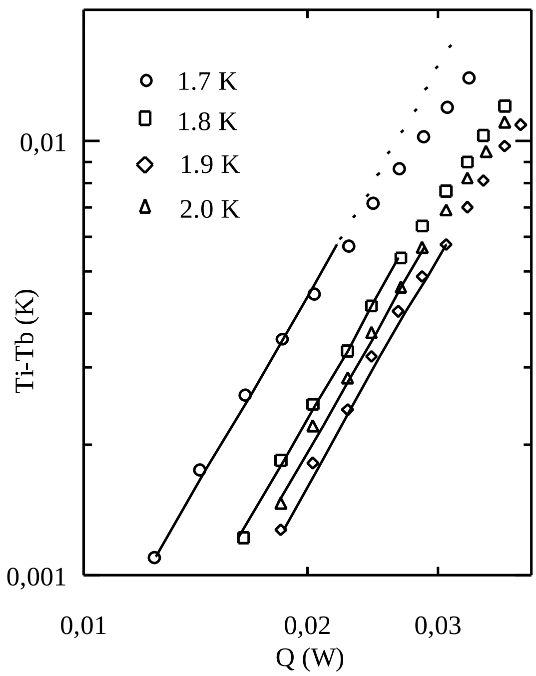


Figure 4. Comparison between measurements and fitted equations (solid lines) in the He II regime for sample #2 at different bath temperatures.

The length of He II channels can be estimated to be in order of 10 mm. A global cross-section of these channels can be calculated from *?* which is around 10^{-6} m^2. The equivalent hydraulic diameter of these channels can be estimated to be from 10 µm to 200 µm for different aspect ratios. For sample #1 at 1.9 K, the smallest heat flux generating a measurable temperature difference is 5×10^5 W/m^2. It is found in the literature[11] that the critical heat flux for development of turbulent transport at 1.9 K is 10^4 W/m^2 for a diameter of 10 µm and 2×10^3 W/m^2 for a diameter of 200 µm. From these remarks, the He II regime can be considered as fully turbulent and the linear term can be negligible as assumed in Eq. (1). Similar remarks are valid for other samples at different temperatures.

Mixed regime

We have seen that in the low heat flux regime, the Gorter-Mellink expression describes the heat transfer. But at higher heat flux, as is shown in Figure 5, measurements deviate constantly from this expression with *Q* increasing. With increasing *Q*, relative effect of conductive heat transfer increases because temperature difference increases. So, above Q_o, assumption of the pure superfluid regime is not valid anymore. We define a "mixed regime" taking in account of turbulent He II and conduction through insulation and Kapitza boundary. The mixed regime is defined for Q_o = Q = Q^* This regime is characterized by the condition of a non local thermal equilibrium between solid and helium. Indeed, at the lowest geometric level, a difference of temperature between the solid and the liquid exists locally due to Kapitza conductance. To construct the model, we assume that heat transfer in the solid and He II takes place in parallel so that there is no net heat transfer from the solid to He II. Thermal paths are decoupled. Then, in this regime, the total heat flux is given by:

$$Q = Q_{HeII} + Q_k = \iota \left[\int_{T_b}^{T_i} f(T)dT \right]^{1/3} + \frac{A_i}{e} \int_{T_1}^{T_2} k(T)dT \qquad (6)$$

where

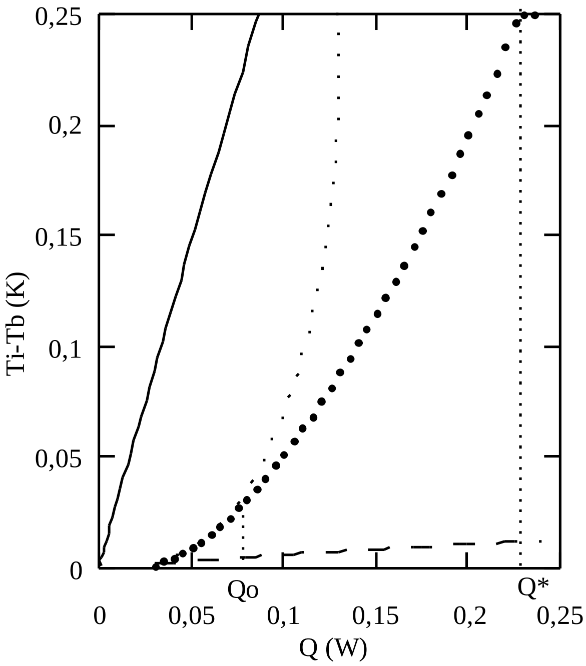
$$Q_k = \frac{A_i}{e} \int_{T_1}^{T_2} k(T)dT = 4aA_iT_b^3(T_1 - T_b) = 4aA_iT_i^3(T_i - T_2) \qquad (7)$$

Q_k is the conductive heat flux. T_1 and T_2 are the wall temperatures of the insulation, results of the Kapitza thermal boundary layer given by the right hand side of Eq. (7).

Table 2. Equivalent thermal permeability

	Sample #1	Sample #2	Sample #3
Global permeability ? ($m^{5/3}$)	9.50 10^{-6}	6.61 10^{-6}	2.80 10^{-5}
Permeability per unit area $?_u$ ($m^{-1/3}$)	1.68 10^{-3}	1.17 10^{-3}	2.79 10^{-3}

Expressions of the heat flux through the Kapitza boundary have been linearized because for all ranges of heat flux, the condition $?T$ « T is satisfied. The term $4aT^3$ is defined as the Kapitza conductance per unit cross-sectional[4]. For this model we have assumed that Ai » A. Figure 7 presents a comparison between calculation and measurements at 1.9 K for different samples. Calculations are within ±10% (Figure 6) of the measurements which is a good agreement considering accuracy on the conductivity of the samples and the function *f(T)*. For all samples error increases until it decreases after reaching a maximum in the same region.



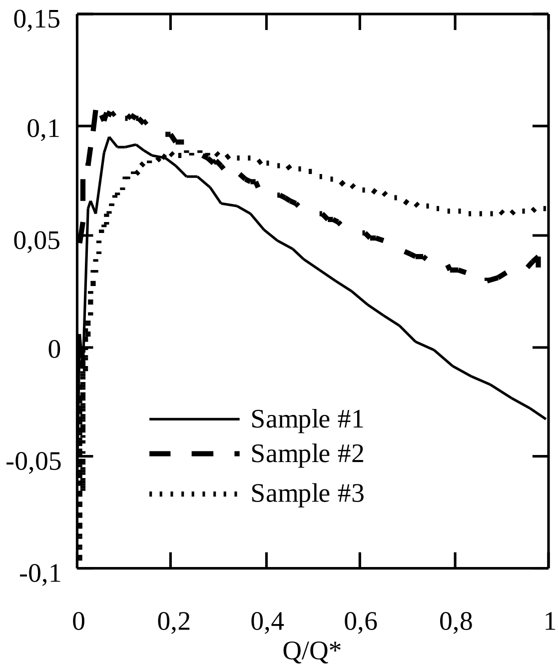


Figure 5. Heat transfer measurement for sample #1 at 1.9K. Conductive heat transfer (solid line), Turbulent He II heat transfer (small doted line) and Kapitza conductance (large doted line) are displayed.

Figure 6. Relative error ((Qcalculation-Q)/Q) in the mixed region between calculation and measurements at 1.9 K for different samples.

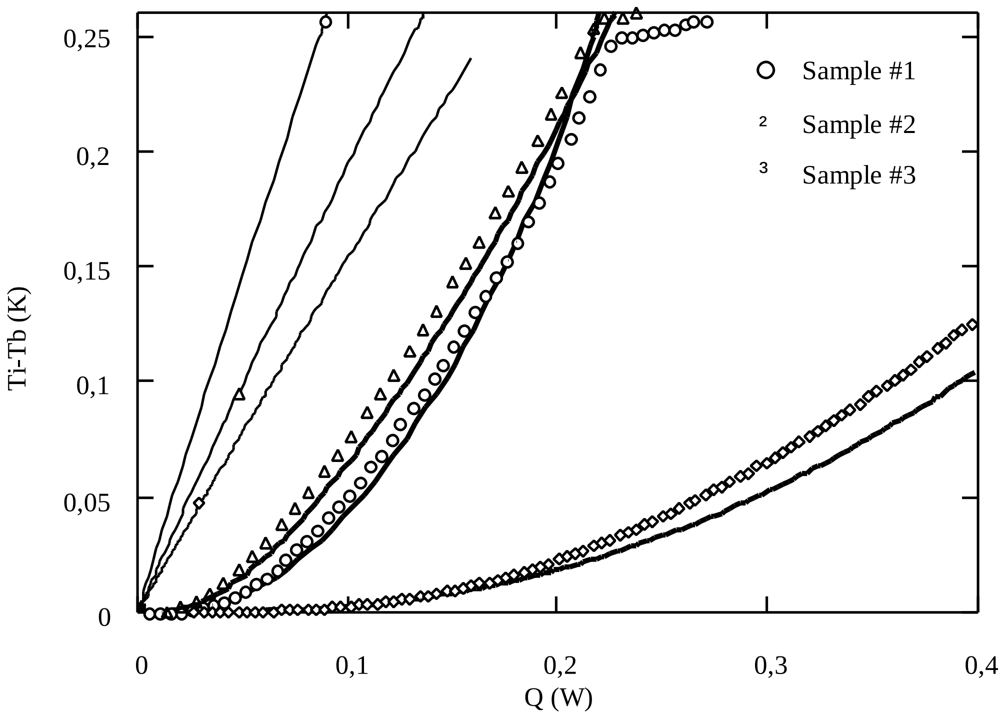


Figure 7. Comparison between measurement and calculation (thick solid line) at 1.9K for different samples. Conductive heat transfer is also displayed (thin solid line).

Sample #3 has a better cooling efficiency than the two others. It can be related to the second layer. The second layer of sample #3 is composed by a dry glass-Kevlar oven alternated with Kapton with polyimide glue whereas sample #2 has fiber impregnated with epoxy resin: the resin tends to decrease the permeability of the insulation (factor 2.4) by either reducing the number of channels or their cross-section whereas the polyimide glue does not flow. Sample #1 has better cooling than Sample #2 even if the conductivity of sample #2 is twice as high. The He II channels formed by the overlapped Kapton of the first layer end directly in the external bath. through the gap of 2 mm for the sample #1 second layer whereas for sample #2 second layer they end through the dry woven. Note that helium volume is the same in the 2 mm gap as in the dry woven.

CONCLUSION

Results show that heat transfer is influenced by He II heat transfer even for small helium volume inside insulation. At low heat flux, heat transfer is purely governed by He II and we have determined a thermal permeability of the media related to He II heat transfer and independent of temperature. Resin in the fiberglass of the second layer tends to decreases the permeability of the insulation by either reducing the number of channels or their cross-section. For higher heat flux, we proposed a first model which considers insulation and He II thermal paths in parallel. The permeability has a stronger dominance on the total heat transfer than the conductivity. Calculation agrees with measurement within ±10% but does not follow exactly qualitatively. One explanation could be that thermal paths are not decoupled. More investigations will be carried on to improve the model to take account of a non zero heat transfer coefficient between solid and He II.

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