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CHARACTERISATION OF NET TYPE THERMAL INSULATORS AT 1.8 K LOW BOUNDARY TEMPERATURE

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Abstract

The Large Hadron Collider's superconducting magnets are cooled by superfluid helium at 1.8 K and housed in cryostats that minimise the heat inleak to this temperature level by extracting heat at 70 and 5 K. In the first generation of prototype cryostats, the radiative heat to the 1.8 K temperature level accounted for 70% of the total heat inleak. An alternative to enhance the cryostat thermal performance incorporates a thermalised radiation screen at 5 K. In order to avoid contact between the 5 K radiation screen and the cold mass, insulators are placed between both surfaces. Sets of commercial fibre glass nets are insulator candidates to minimise the heat inleak caused by any accidental contact between the two temperature levels. A model to estimate their performance is presented. A set-up to thermally characterise them has been designed and is also described in the paper. Finally, results as a function of the number of the spacer nets, the boundary temperatures and the compressive force in the spacer are presented.

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Characterisation of Net Type Thermal Insulators at 1.8 K Low Boundary Temperature

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The Large Hadron Collider's superconducting magnets are cooled by superfluid helium at 1.8 K and housed in cryostats that minimise the heat inleak to this temperature level by extracting heat at 70 and 5 K. In the first generation of prototype cryostats, the radiative heat to the 1.8 K temperature level accounted for 70% of the total heat inleak. An alternative to enhance the cryostat thermal performance incorporates a thermalised radiation screen at 5 K. In order to avoid contact between the 5 K radiation screen and the cold mass, insulators are placed between both surfaces. Sets of commercial fibre glass nets are insulator candidates to minimise the heat inleak caused by any accidental contact between the two temperature levels. A model to estimate their performance is presented. A set-up to thermally characterise them has been designed and is also described in the paper. Finally, results as a function of the number of the spacer nets, the boundary temperatures and the compressive force in the spacer are presented.

INTRODUCTION

The Large Hadron Collider (LHC) is a high-energy proton-proton collider under design at CERN to be installed in the 26.7 km long circular tunnel. Its superconducting magnets operate at superfluid helium temperature and are housed in a cryostat that extracts heat at temperatures of 70 K and 5 K. The radiative heat to the 1.8 K temperature level accounts for 70% of the total heat inleak (see Table 1) [1].

Table 1. Heat inleaks in 15 m dipole cryostats in nominal conditions

	Temperature levels		
	50 K - 75 K	4.5 K - 20 K	1.8 K
Heat inleaks	[W]	[W]	[W]
Support posts	14.4	1.12	0.13
Thermal shield	43.8		
Radiative insulation		0.04	1.68
Instrument feedthroughs	0.43		0.26
Conduction beam-screen supports			0.23
TOTAL	58.6	1.17	2.31

The second generation of cryostats includes two thermalised screens at both temperature levels combined with multilaler insulation [2] (Fig. 1). This set-up has proved to be better than that having only MLI between the 70 K thermal shield and the cold mass at a floating temperature [3]. Due to geometrical errors, either in manufacturing or in mounting, or to the effect of magnet quench on the screen [4] the 5 K radiation screen may touch the outer part of the 1.8 K cold mass. Insulator spacers are placed between both surfaces to avoid thermal short circuits. The net type spacer is an insulator candidate for this purpose.

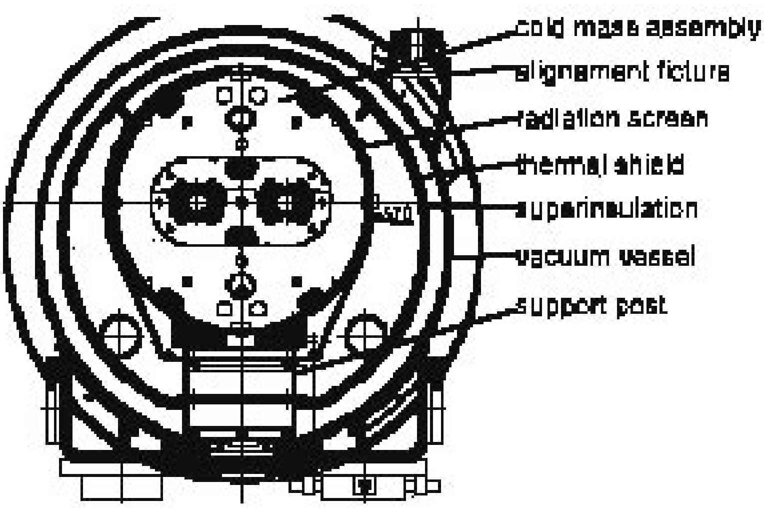

Figure 1. Second generation of prototype cryostats for the LHC 15 m dipole magnets.

The net type spacer consists of a set of nets piled up and made out of low thermal conductivity material. It allows for the transmission of forces between surfaces at different temperatures while keeping the heat flow low between them. Its performance relies on the low thermal conductivity of the material and, above all, on the high thermal contact resistance between the contact points of two different nets. The compressive load and the heat flow are spread evenly across the entire surface therefore avoiding stress concentration and temperature gradients in either of the two surfaces. Mounting is simple as it requires no machining, soldering or gluing.

In this paper, a model to estimate the performance of these insulators is presented. Due to the importance of the spacer's thermal behaviour in the decision for the insulation of the LHC cryostat, an experimental set-up has been designed and built. Experimental results for three spacer configurations are presented.

HEAT TRANSFER ACROSS A NET TYPE SPACER

Two surfaces separated by a spacer exchange heat by solid conduction, radiation and residual gas conduction. In a high vacuum environment and at low boundary temperatures, residual gas conduction and radiative heat transfer can be neglected. The conductive heat flow across the spacer depends on the nature and temperature of the two surfaces, on the compressive force and on the spacer itself.

Conductive Heat Flow

To theoretically estimate the thermal performance of a net type spacer, we assume that the heat flows from the warm surface to the first net of the spacer through the points where the threads cross. Then, it travels by solid conduction along the threads of the spacer to a contact point with the second net and so on, until it reaches the cold surface (Fig. 2). During the travel along the thread, the heat passes from the warmest fibres to the coldest ones, therefore crossing another contact resistance.

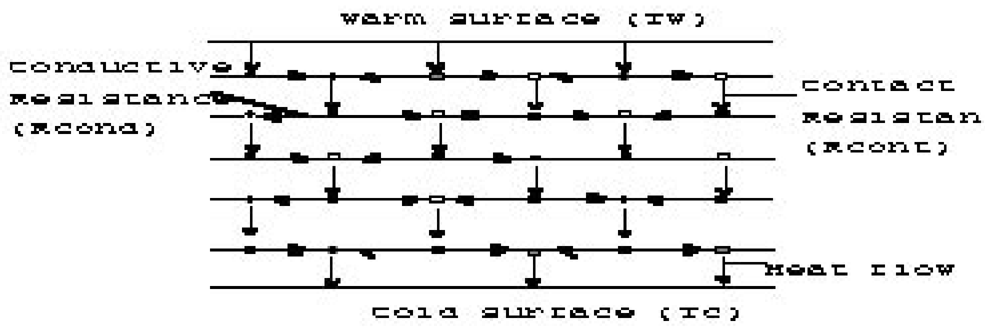

Figure 2. Solid heat transfer between two surfaces through an net type spacer.

Using Fourier s equation, the heat flow is calculated through the estimated contact and conductive resistances.

$$Q = \frac{Tw - Tc}{Rcont + Rcond} \tag{1}$$

<u>Conductive Resistance Estimation</u>

For the estimation of the conductive resistance per net, R_{cdnet}, only the path has to travel is considered, neglecting the contact resistance between nets. For a spacer made up from two kinds of nets placed alternatively, the number of parallel heat paths is equal to the number of contact points between the two different nets, Npc. The average distance between two close points of contact between two nets, Dcp, is calculated by Eq.2.

$$Dcp = \frac{L_{thread}}{Ncp} \tag{2}$$

where L_{thread} is the total length of all threads forming the net.

The distance travelled by the heat in a net for one of the heat paths, D_{heat}, depends on the relative position of the immediate upper and lower nets and it is 0 for the case where the contact points overlap and Dcp/2 for the best case. For a random placement of the nets D_{heat} is:

$$D_{heat} = \frac{DCp}{4} \tag{3}$$

the conductive resistance for each net can be estimated by Eq. 4.

$$R_{cdnet} = \frac{1}{k} \cdot \frac{D_{heat}}{S_{thread}} \cdot \frac{1}{Ncp} \tag{4}$$

where k is the net material thermal conductivity, and S_{thread} is the thread cross sectional area. The total conductive resistance is the sum of each net's individual resistance.

<u>Contact Resistance Estimation</u>

The thermal contact resistance of the spacer is estimated following a procedure similar to that used by Bapat [5] to predict the thermal contact resistance between shield and spacer of MLI systems. The contact resistance across the spacer is the sum of the contact resistances between the different layers in contact, between a surface and a net or between two nets in contact, it can be calculated as a number of punctual contact resistances in parallel, and for each contact unit the contact resistance is estimated as follows:

Due To Contact Between Threads

For each contact, the thermal contact resistance, R_{ct}, is given by Eq. 5.

$$R_{ct} = \frac{1}{2a_c k_m} \tag{5}$$

where

$$k_m = \frac{2k_1k_2}{k_1 + k_2} \tag{6}$$

k_1 and k_2 are the thermal conductivity of the two materials in contact. The radius of the contact patch between two threads, a_c, is estimated using Hertz's formula for the radius of contact patch between two spheres but substituting the spheres radii for the threads thicknesses ,t1 and t2. Eq. 7.

$$a_c = \left(\frac{3\pi(C_1 + C_2)t_1t_2P}{4(t_1 + t_2)}\right)^{\frac{1}{3}} \tag{7}$$

where $C_i = \frac{1-\nu_1^2}{E_i}$ for both materials in contact, E_i and ν_i being their Young's modulus and Poisson's ratio and P the load applied to the contact.

For the contact surface-net, a_c is estimated by Eq. 8.

$$a_c = \left(\frac{3\pi(C_1 + C_2)t_1P}{4}\right)^{\frac{1}{3}} \tag{8}$$

Due To Contact Between Fibres in the Threads

According to Bapat and assuming the threads being square, the resistance due to contact between the fibres of the thread per contact unit can be expressed as:

$$R_{ctf} = \frac{2n_f^{1/2} - 1}{2k_f n_f^{1/2} a_f} \tag{9}$$

where n_f is the number of fibres forming the thread.

The radius of the contact patch between the fibres, a_f, is estimated through the Hertz's formula for the radius of the contact patch between two crossed cylinders (Eq. 10).

$$a_f = \left(\frac{3C_fP_t}{8n_f}\right)^{\frac{1}{3}} \tag{10}$$

being t the thread thickness

EXPERIMENTAL CHARACTERISATION

An experimental study to fully determine the thermal behaviour of the net type spacers and to establish the limits for the described theory has been undertaken. For this purpose, the experimental set-up, schematically depicted in Figure 3, has been designed and built. The heat flow through the spacer is measured as a function of the compressive load and the temperature of the two plates in contact with the spacer (support plate and Plate 1). The support plate is maintained at about 2 k and the temperature of Plate 1 can be controlled between 10 K and 40 K. The pressure can be varied in steps 40 to 331 Pa. Spacers with a maximum diameter of 0.6 m can be thermally characterised in the wide part of the cryostat vacuum vessel. The assembly is mounted into a frame suspended on the top of the cryostat. It consists of two aluminium plates (upper and lower frame plate) joined by three thin stainless steel rods.

Temperature regulation

The top part of the cryostat houses three reservoirs containing saturated liquid nitrogen and helium at atmospheric pressure and saturated superfluid helium at 1.5 K. They act like cold sources for the bottom part of the vacuum vessel. The 77 K and the 4.5 K temperature levels are used for thermal shielding and thermal anchoring of the plates and wires. The 1.5 K cold source fixes the temperature of the support plate. A resistive wire (H2) is glued on the Plate1 perimeter. The centre of the same plate is thermally connected to the 5 K screen via a thermal anchor designed to account for 95% of the total temperature drop between screen and perimeter of Plate 1 when applying a constant heating power with H2. Only 5% of the total temperature drop appears in Plate 1. In this way, the Plate 1 temperature can be controlled between 10 K and 40 K by the heating power from H2 with a maximum temperature drop along its radius of about 1.5 K. The thermal anchor is also important to accelerate the cool-down of the plates from room to working temperature. Plate 2 and Plate 3 are thermally conntected to Plate 1 in order to be at the same temperature, shortening the time needed to reach the temperature equilibrium when changing the compressive force.

Compressive load regulation

The compressive load on the spacers is controlled by weights in the shape of aluminium plates of the same diameter as the spacers. The 1.5 mm thick Plate 1 gives a pressure of 40 Pa and is always lying on the spacers. Plate 2 can be placed on Plate 1 and afterwards, Plate 3 on Plate 2; the corresponding pressures applied to the spacers being 119 Pa and 331 Pa respectively. Plates 2 and 3 are suspended with three bolts on a movable plate (suspension plate) that can be actuated from outside the cryostat. When either Plate 2 or 3 is resting on the plate below, their bolts are lifted from the suspension plate. These contacts between bolts and suspension plate are used as switches in an electrical circuit wich makes possible to check, from outside the cryostat, whether a plate is resting on the plate below or hanging from the suspension plate (Fig. 4).

To ensure a good distribution of the weight on the total area of thermally treated.

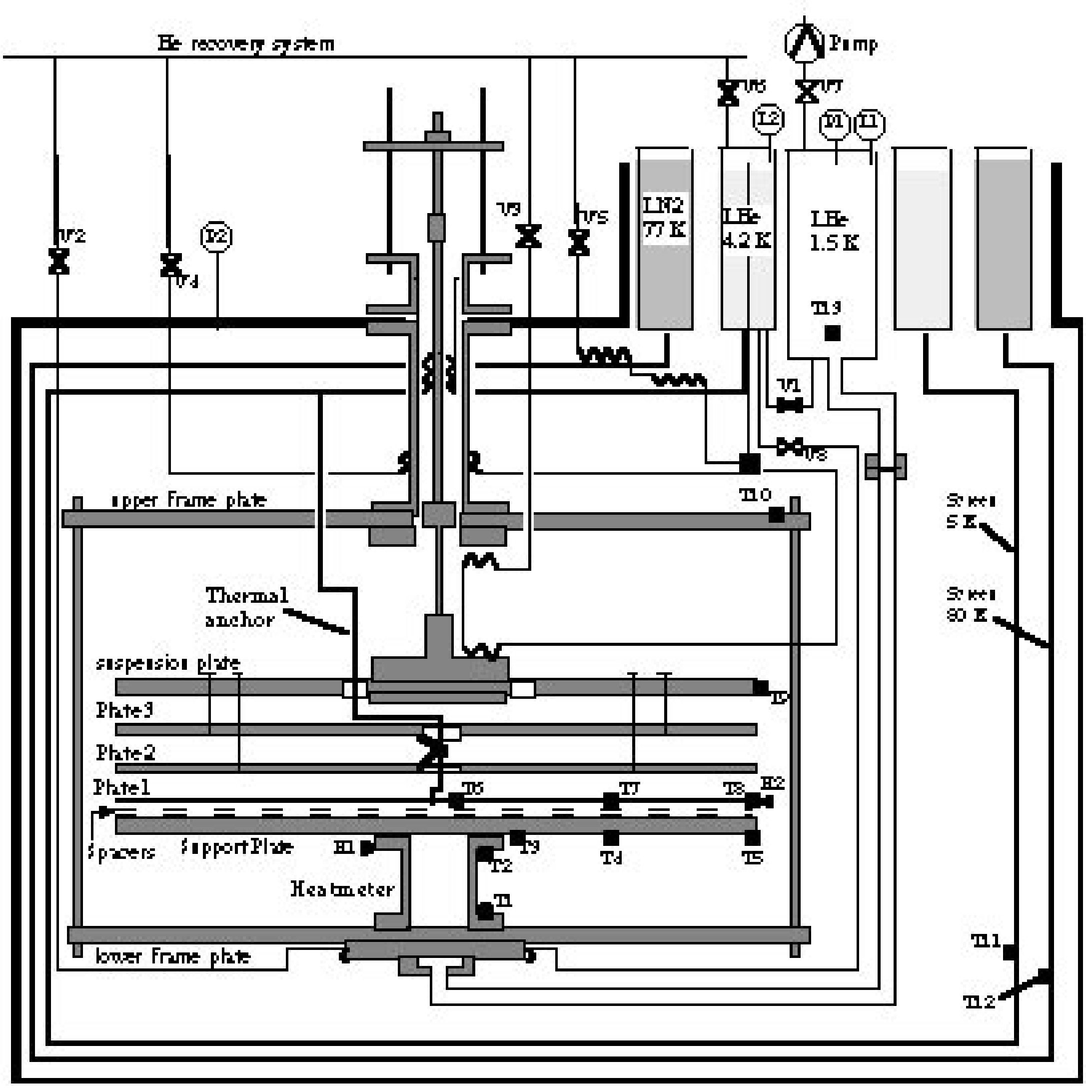

Figure 3: Experimental set-up for spacer characterisation at 3 different compressive loads and at low boundary temperature of about 2 K. T1 to T13 are temperature sensors, P1 and P2 are pressure sensors, L1 and L2 are level sensors, H1 and H2 are heaters and V1 to V6 are valves.

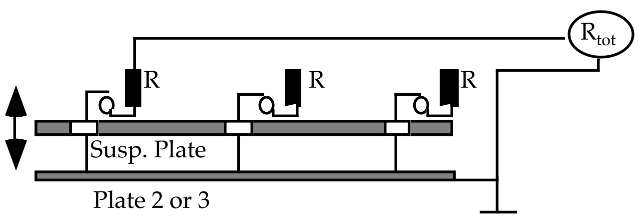

Figure 4: Electrical circuit to regulate the compressive load.

Heat flow measurement

The heat flow across the spacer is measured by means of a heatmeter [6,7]. This is a calibrated thermal impedance. The heat flow can be deduced from the measured temperatures over its length. The lower frame plate, on which the heatmeter is mounted, is cooled to about 1.5 K by a tube of 15 mm in diameter connected to the superfluid helium bath of the cryostat. The heatmeter is connected in series with the thermal circuit formed by Plate 1 and support plate, thus, all heat going through the spacers is also going through the heatmeter. The calibration function of the heatmeter is given by Eq. 11:

$$\dot{Q} = C.\left(T_2^2 - T_1^2\right) \tag{11}$$

where C is a constant that takes into account the thermal conductivity of the material and the dimensions of the heatmeter. Figure 5 shows the calibration curve of the heatmeter used in this experiment. Temperatures T_1 and T_2 are recorded as a function of the heating power Q supplied by H1. C is then calculated for each measuring point by Eq. 12.

$$C_{calib} = \frac{\dot{Q}}{T_2^2 - T_1^2} \tag{12}$$

The measured values of T_1 and T_2 and the calculated C_{calib} are shown in

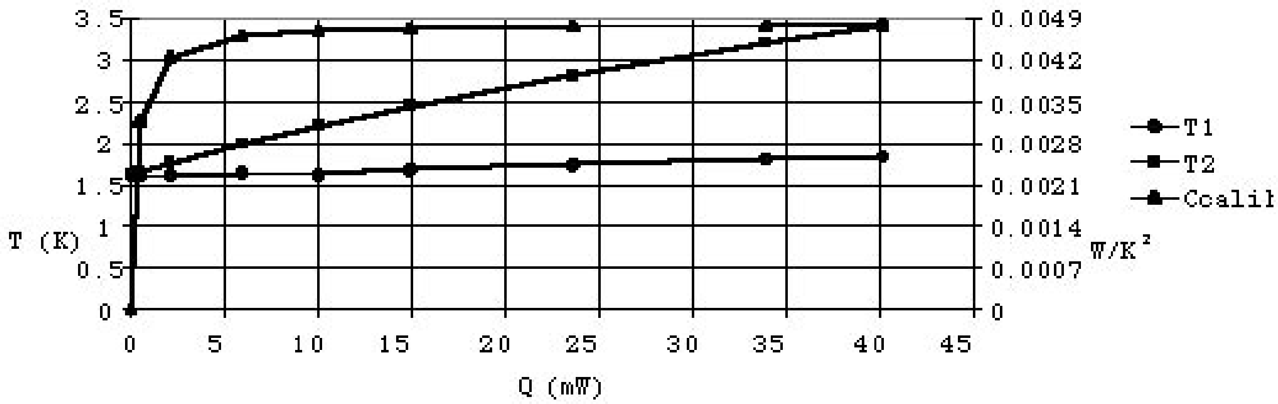

Figure 5: T_1, T_2 and calculated constant C_{calib} (the excitation current of T-sensors is 10 µA).

From Fig. 5, it is deduced that C is a constant for values of the heat load bigger than 10 mW. Table 2 compares the calculated heat values for C = 4.8 mW/K^2 to the real heating power supplied.

Table 2: Comparison of measured heat flow (Q_{calc}) and heating power (Q_{calib}).

Q_{calib}	Q_{calc}	Error
[mW]	[mW]	[mW]
0.00	0.24	0.24
0.50	0.75	0.25
2.10	2.37	0.26
10.01	10.75	0.74
14.90	15.04	0.14
23.59	23.67	0.08
33.89	33.92	0.04
40.14	40.06	-0.08

The absolute precision of this heatmeter is better than 1 mW [6]. The temperature sensors used in the heatmeter are TVO sensors from JINR (Joint Institute for Nuclear, Dubna, Russia). These are carbon-ceramic resistors [8] with a nominal precision of about ± 5 mK per thermometer at temperatures around 2 K.

Spacer Characterisation. Experimental Results

Measurements have been made for three distinct spacer configurations (S1, S2 and S3), made up from two kinds of glass fibre nets (N1 and N2) placed alternatively. N1 and N2 average thread diameters are 1 mm and 0.5 mm, their weave pitches being 10 mm and 6 mm respectively. The total number of nets is 2 for S1, 6 for S2 and 18 for S3.

Results as read from the heatmeter and as a function of compressive load for S2 are presented in Fig. 6. It is observed that the extrapolation curves do not go to 0 mW/m^2 as they should for warm temperature of 2 K but, on the contrary, to a fixed value of 15 mW/m^2 . This is due to a systematic error caused by radiative heat coming from the 75 K temperature level. Due to geometrical imperfections in the 5 K thermal shield, heat from the upper temperature level shield reaches the support plate and the nets. This error is independent from the Plate 1 temperature and from the compressive load but not from the number of nets.

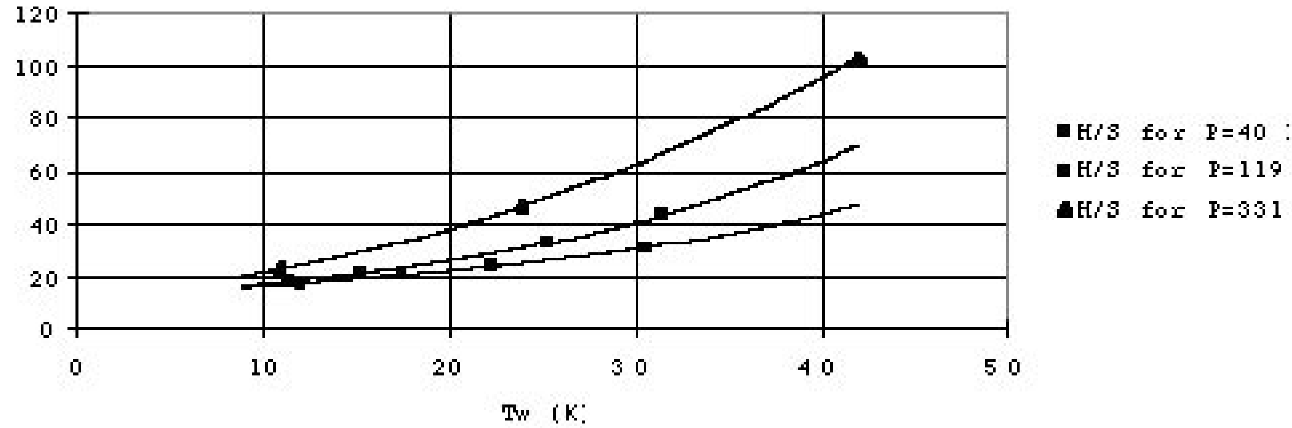

Figure 6. Thermal performance of spacer S2. Heat per unit of surface, H/S. as a function of the warm temperature, Tw, for three different compressive loads. Values as measured.

Corrected results for the three spacers are shown in Fig 7 to 9

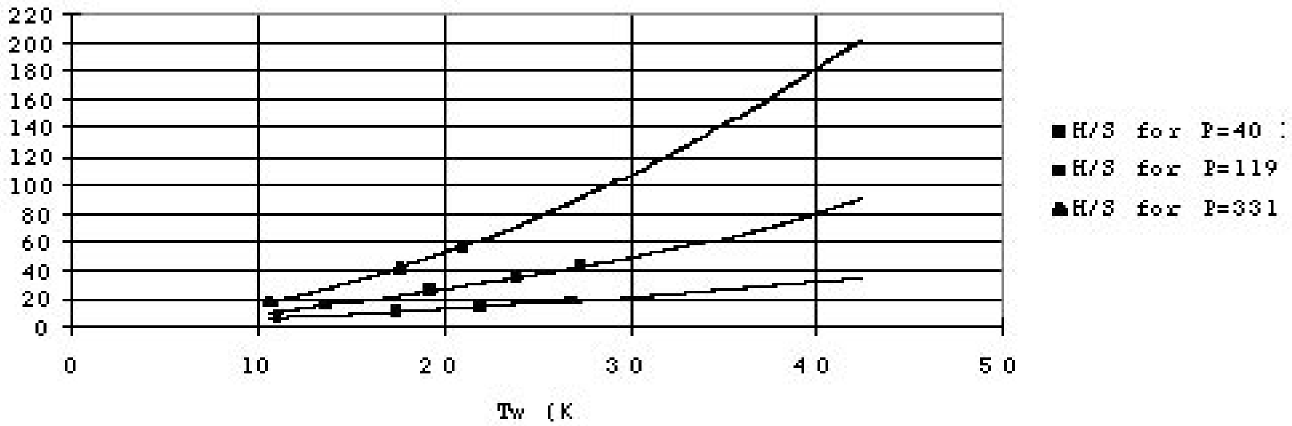

Figure 7. Thermal performance of spacer S1. Heat per unit of surface, H/S, as a function of the warm temperature, Tw, for three different compressive loads.

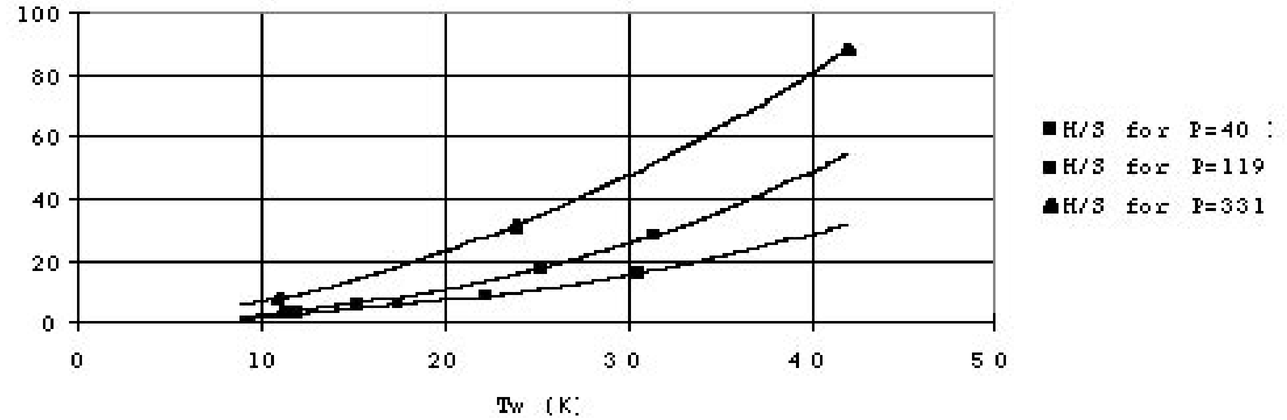

Figure 8. Thermal performance of spacer S2. Heat per unit of surface, H/S, as a function of the warm temperature, Tw, for three different compressive loads.

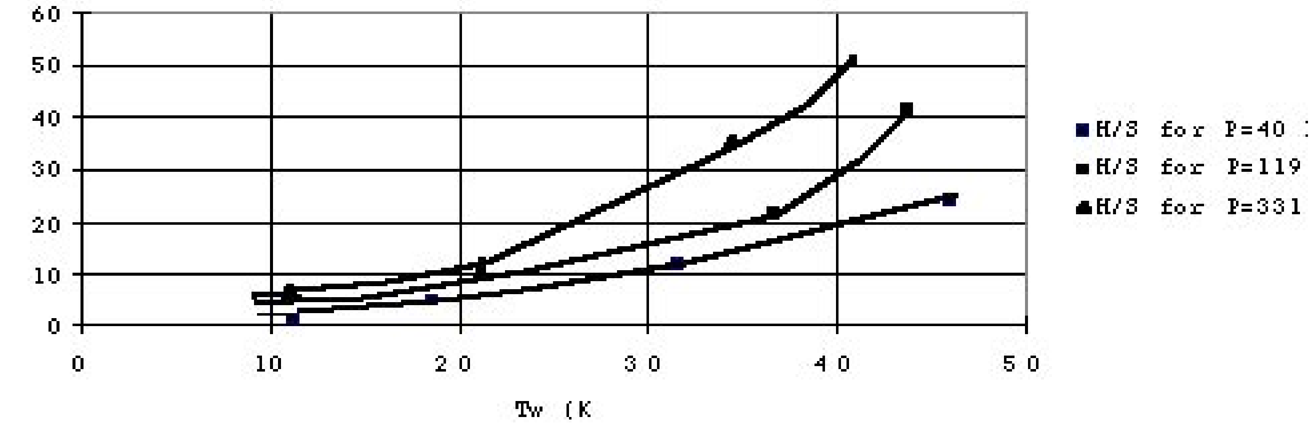

Figure 9. Thermal performance of spacer S3. Heat per unit of surface, H/S, as a function of the warm temperature, Tw, for three different compressive loads.

A fitting function in SI units for the heat flow per unit of surface, H/S, as a function of compressive pressure, P, warm temperature, Tw, and total number of nets, n, is given in Eq. 13.

$$\frac{H}{S} = \frac{1}{1000} . \frac{0.03}{n} . P^{0.468 + \frac{0.585}{n^{0.333}}} \qquad (13)$$

The relative reduction of heat load when adding one net to a spacer is calculated from Eq. 13 and presented in Fig. 10.

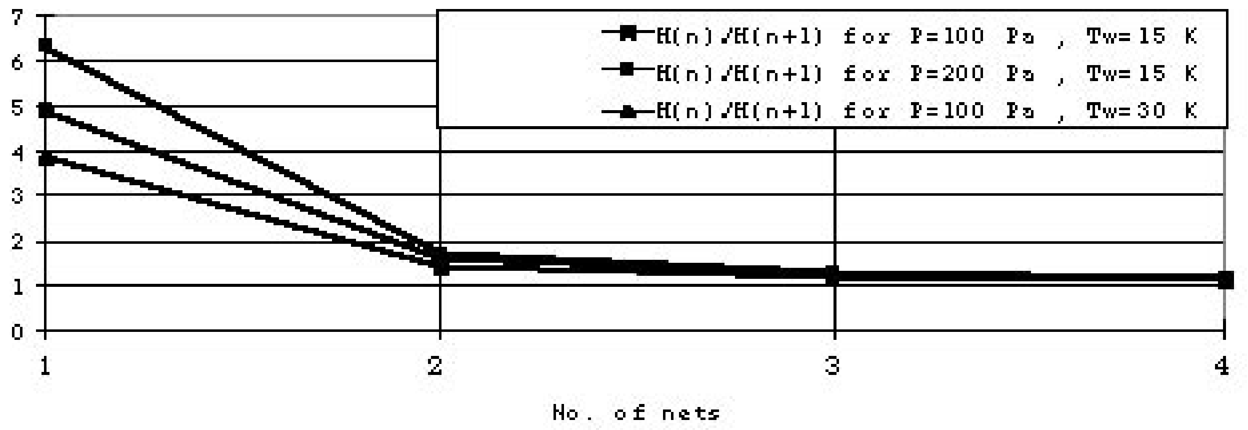

Figure 10. Heat load relative reduction by adding a net to a spacer, H(n)/H(n+1). Results aer given for three different combinations of pressure, P, and warm temperature, Tw.

DISCUSSION

Radiative heat leak to the support plate is different for each spacer as the gap between support plate and Plate 1 changes. A dedicated test has been performed to verify this assumption: a black surface has been placed on the support plate and Plate 1 has been joined to Plate 2 so that it does not rest on the support plate. The heat to the support plate has been measured as a function of the gap between Plate 1 and support plate. Values of radiative heat obtained by extrapolation are 7 mW/m^2 for spacer S1, 15 mW/m^2 for S2 and 25 mW/m^2 for S3. Similar values have been obtained for gaps corresponding to the thicknesses of the spacers.

The importance of adding a net to a spacer decreases as the number of nets forming the spacer increases. For the cases shown in Fig 10, it is observed that a spacer made of two nets performs from 4 to 6 times better than a spacer made of one net.

CONCLUSIONS

Theory estimations are in the same order of magnitude as the measured results and have proved to be pessimistic giving results from 2 to 3 times bigger than measured values.

The difficulty of measuring the thermal resistance of insulators at a low boundary temperature of about 2 K has been overcome, first, by developing a heatmeter with an absolute precision better than 1 mW and, second, by using a cryostat able to house samples with a surface of up to 0.28 m^2.

Due to inevitable imperfections on the radiative heat protection of the experimental cryostat, an undesirable heat flow reached the support plate. This has been identified and quantified and the measurements corrected in accordance.

The insulating behaviour of net type spacers has proved to be excellent. The thermal resistance of a 1 m^2 spacer made of two nets, at warm temperature of 20 K and at a compressive load of 100 Pa is about the same as that of a 1 cm long, 1.3 cm^2 Teflon block.

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