ISBN: 978-3-95450-250-9 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2023-WEPPP034

ALBA EXPERIMENTAL SET UP FOR THE EVALUATION OF THERMAL CONTACT CONDUCTANCE UNDER CRYOGENIC AND VACUUM CONDITIONS

O. Traver†, J.J. Casas, C. Colldelram, J. L. Frieiro, B. Molas, M. Quispe, M. Sanchez
ALBA-CELLS Synchrotron, Cerdanyola del Vallès,

Abstract

The Thermal Contact Conductance (TCC) between two surfaces plays a very important role in the design of components in particle accelerators. The TCC depends on many variables such as surface finish, type of material, pressure, temperature, etc. As a general rule, the TCC comes from experimental results reported in the specialized literature. However, it is not always possible to find this information, especially if components are designed to operate in cryogenic and vacuum conditions, for this reason, assumptions are made that render results with high uncertainty. In this context, ALBA has designed an experimental set up to carry out axial heat flow steady state experiments for the evaluation of TCC under vacuum and cryogenic conditions. The minimum pressure achievable in the set up will be 1e-5 mbar while the temperature may vary between 80 and 300 K. The results will provide inputs to further optimize ALBA designs, including ALBA II, our ongoing fourth-generation synchrotron upgrade project. This paper describes the experimental setup, the thermal and mechanical design considerations and experimental validation tests.

INTRODUCTION

Real engineering surfaces exhibit a complex three-dimensional landscape, characterized by peaks and valleys of diverse sizes and shapes. A "flat surface" contains microscopic irregularities which compose its roughness and macroscopic irregularities such as waviness and deviation from flatness [1, 2, 3]. Consequently, when two surfaces are pressed together, they touch each other at only limited discrete points separated by large gaps. Thus, the *real* contact area is found to be much smaller than the *geometrical* contact area (1-2% for metallic contact) [2]. The remaining space between the contact points can be filled with an interstitial medium, such as air or a vacuum.

Thermal contact conductance (*hj*), also known by the acronym TCC, can happen through conductance along three primary pathways: the real contact spots (h_c), conduction through the interstitial fluid (h_g) and thermal radiation (h_r).

$$h_j = h_c + h_g + h_r \ . \qquad (1)$$

Conceptually, *hj* is defined as the ratio of the heat power (Q) per unit area (A) flowing across the interface and the temperature drop (ΔT) at the interface.

$$h_j = \frac{Q/A}{\Delta T} \ . \qquad (2)$$

† otraver@cells.es

If the heat transfer takes place in vacuum conditions, the conduction through the interstitial fluid can be neglected. Radiative heat transfer can also be disregarded in the current context, as it becomes significant only above 400 ºC [3].

$$h_j \approx h_c = \frac{\frac{Q}{A}}{\Delta T} \ . \qquad (3)$$

According to [4], *hj* increases proportionally to the applied load at the interface since the real contact area is proportional to the load. When the load increases the average contact spot size remains relatively stable. However, the quantity of contact spots changes.

The *hj* dependence on temperature varies over different temperature ranges. From 30 K to 200 K, *hj* approaches a linear dependence with T, above this range it tends to a temperature-independent conductance value.

To determine *hj*, experimental research is fundamental, as it can provide realistic results compare to theoretical studies. Obtaining information on *hj* under cryogenic and vacuum conditions is often challenging. In this context, at ALBA an experimental setup has been built to evaluate *hj* values in these special conditions. This work describes relevant aspects of its design, its operating principle and the first validation tests.

EXPERIMENTAL SET-UP

Description

The experimental setup (Figs. 1 and 2). consists of a heating block (1), a cold finger (2), an insulating block (3) an insulating ring (4), a load cell (5), a mechanical loading system (6), a vacuum system (7) and two specimens (8).

The heating block is a cylindrical copper block of Ø25 mm with its cylindrical surface covered by two 45 W kapton heaters foils, which are powered by a current source. The cold finger is a cylindrical copper block of Ø25 mm x 150 mm with a hole of Ø8 mm x 110 mm where liquid nitrogen circulates. In order to avoid losses and ensure one dimensional heat flow, an insulating block made of PEEK has been provided at the top of the heating block and an insulating ring has been provided at the bottom of the cold finger. Between the heating block and the cold finger, the two specimens, with a cylindrical shape (Ø25 mm x 48 mm high) and which can be fabricated from any material of interest for the experiment are brought in contact. One of the specimens is heated, the other one is cooled, allowing the generation of a downward axial heating flow. The experimental set-up aims at measuring the TCC

Content from this work may be used under the terms of the CC-BY-4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-250-9 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2023-WEPPP034

between the two specimens when different contact pressures and temperatures at the interface are applied.

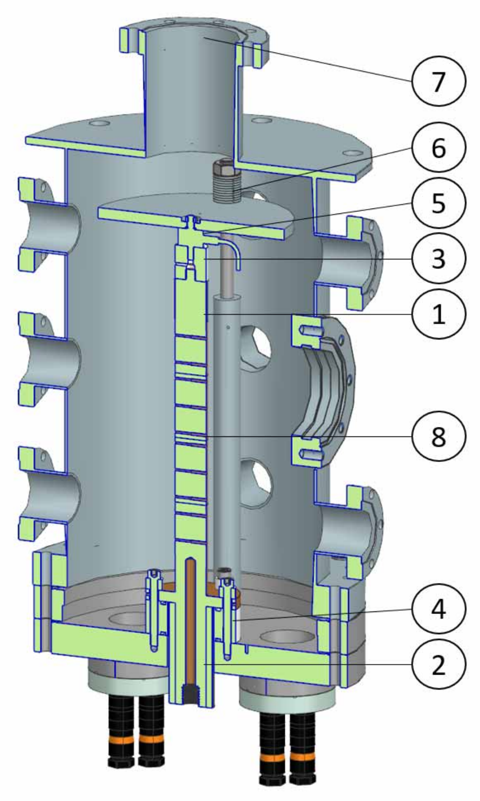

Figure 1: Cross section of the experimental set-up for the evaluation of TCC.

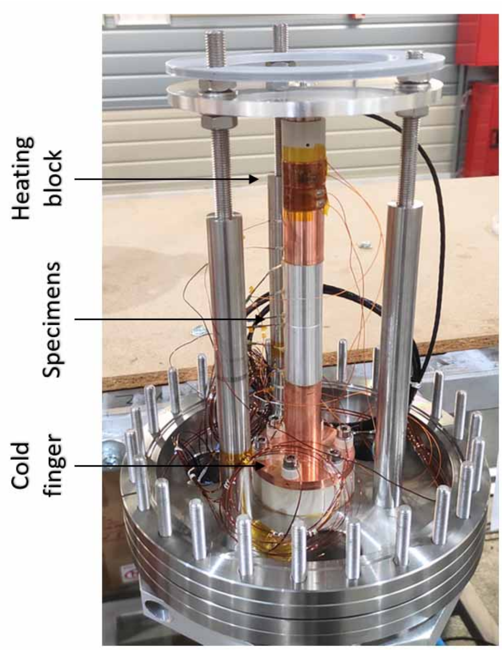

Figure 2: Image of the experimental setup manufactured in ALBA. Note that the specimens are made of aluminium instead of copper for our upcoming tests.

The interfaces between the heating block and the upper specimen, as well as between the lower specimen and the cold finger, have been filled with highly conductive paste Apiezon N, to reduce the contact resistance and to maximize the heat flow.

Platinum Resistance Temperature Detectors (RTDs) of Ø1,8 x 5 mm. have been precisely inserted up to the centre line of the column, utilizing small holes of Ø2 mm in diameter for precise placement. Apiezon N paste has been applied to fill the holes, ensuring optimal thermal contact between the temperature sensor and the column.

To conduct the experiment across a variety of contact pressures, a mechanical loading system composed of 3 screws with bellevile washers has been mounted at the top of the column in conjunction with a miniature diaphragm loadcell.

The experimental set-up can operate under vacuum by enclosing the set-up within a vacuum chamber, and using a special cryogenic Astraseal O-rings for ensuring the sealing between the cold finger and the chamber. A vacuum level of 1·10-5 mbar has been achieved by using a turbomolecular vacuum pump.

Working Procedure

The preparation of the experiment starts by cleaning all the surface of the specimen with isopropanol alcohol and then all the surface, except the test interface, are filled with highly conductive Apiezon N paste. The temperature sensors are inserted in the specimen with their holes pre-filled with paste. Before closing the vacuum chamber, the loading system is adjusted to the pressure of interest. When the pressure inside the vacuum chamber reaches 1·10-4 mbar, liquid nitrogen is allowed to circulate inside the cold finger. The heaters are operated at a fixed power reaching up to 90 W. The higher the thermal contact conductance of the specimen, higher heating power should be applied to create a measurable temperature in the interface.

The flow of the liquid nitrogen is regulated to attain a precise temperature in the cold finger. The system is left running until the temperature gradient along the heat flow column remains stable, meaning that an axial heat flow steady state has been achieved, Then the temperatures at each location of the column are written down.

EVALUATION TEST

The experimental setup has been validated through the experimental study of a pair of specimens made of copper, at a vacuum level of $1 \cdot 10^{-5}$ mbar, as described below.

Specimens

A pair of specimens has been fabricated in copper. Three holes have been drilled into each specimen at 20 mm intervals, but 4 mm away from the specimen ends (Fig. 3).

Content from this work may be used under the terms of the CC-BY-4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-250-9 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2023-WEPPP034

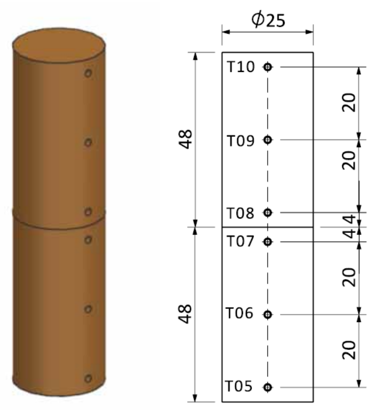

Figure 3: Isometric and front view of the specimens with the location of the temperature sensors.

Data Acquisition

The temperature distribution along the length of the specimens is observed to follow a linear dependence, while at the interface a temperature drop appears, denoted as (ΔT), which is calculated through linear extrapolation based on the temperatures in close proximity to the interface of the two specimens (Fig. 4). The heat flow across the interface (Q) is equal to the heating power supplied by the heaters at the top of the column.

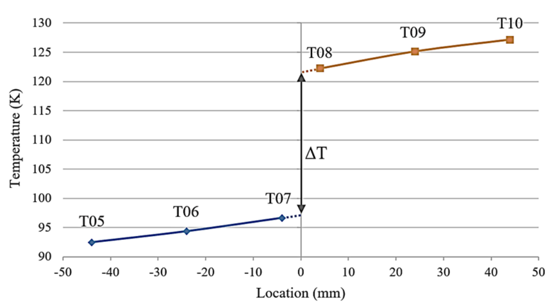

Figure 4: Plot of the temperature at different axial location in both specimens, pressure 0.4 bar.

By knowing the temperature drop at the interface (ΔT), along with the heat flow across it (Q) and the interface area (A), the thermal contact conductance (h_j) can be calculated using the Eq. (3).

Results: Effect of Pressure

Test with specimen pairs under a pressure of 0.2 and 0.4 bar and stable cryogenic temperature of 157 K have been carried out. It is observed that TCC increases when the pressure increases (see Table 1).

Table 1: TTC Values of Cu Specimens at Different Contact Pressure and Fixed Temperature

Pressure [bar]	Cu-Cu TCC [W/m²·K]
0.2	1582
0.4	2618

Results: Effect of Temperature

Experiments were conducted with interface temperatures between 110 to 170 K at a stable interface pressure of 0.4 bar. It is observed that TCC increases with increasing temperature (see Table 2).

Table 2: TTC Values of Cu Specimens at Different Temperature and Fixed Contact Pressure

Temperature [K]	Cu-Cu TCC [W/m²·K]
110	2422
147	2576
170	2674

Set-up Evaluation

With the setup we successfully generated a temperature gradient in the column and observed a temperature drop at the specimen interface enabling us to calculate their TCC.

Steady-state heat flow was reached after 45 minutes of machine running. It was at this stage that the temperature variation in the sensors remained below 0.5 K every 10 minutes while a vacuum level of $1 \cdot 10^{-5}$ mbar was reached after 15 minutes of operation and remained stable throughout the entire experiment.

Further Development

The cold finger and heating block are expected to function as a heat flowmeter by measuring its temperature gradient along its axial. This capability will be established after calibration. The liquid nitrogen flow is controlled using a manual valve, leading to challenges in achieving and maintaining precise temperatures in the cold finger. To address this, a PDI-controlled liquid nitrogen flow system is planned to be installed. To identify and measure heat losses, we plan to install temperature sensors on the inner surface of the vacuum chamber to monitor temperature variations. Currently, data recording is done manually every 10 minutes during operation. We aim to automate this process; recording more data will enable us to assess uncertainties effectively.

CONCLUSION

An experimental set up for the evaluation of thermal contact conductance under cryogenic and vacuum conditions have been fabricated at ALBA. Test with pairs of copper specimens under different interface pressure and temperature had been carried out. The TCC at the interface of the specimens has been estimated by measuring the temperature across the specimen and the heat flux.

The experimental setup is prepared to evaluate the contact of new material interfaces of interest for our current designs, and especially for the new components of the ALBA II upgrade project.

Content from this work may be used under the terms of the CC-BY-4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-250-9 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2023-WEPPP034

REFERENCES

[1] Y.A. Cengel and R.H. Turner, "Steady heat conduction", *Fundamentals of Thermal-Fluid Sciences*, Ed. 5, McGraw-Hill Education, 2016.

[2] C.V. Madhusudana, "Solid Spot Thermal Conductance of a Joint" and "Gas Gap Conductance", *Thermal contact conductance*, Ed. 2, Springer-Verlag, New York Inc, USA, 1996, pp. 23-61.

[3] J.H. Lienhard, "Heat conduction concepts, thermal resistance, and the overall heat transfer coefficient", *A heat transfer textbook,* Ed.3, Cambridge, MA, USA. J.H. Lienhard 2000, pp. 64-66.

[4] E.Gmelin *et al.,* "Thermal boundary resistance of mechanical conctacts between solids at sub-ambient temperatures", *J. Phys. D*, vol. 32, no. 6, R19-R43, 1999. doi:10.1088/0022-3727/32/6/004

Content from this work may be used under the terms of the CC-BY-4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI