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Analytical heat transfer modeling of a new radiation calorimeter

Elysée Obame Ndong[a,b], Olivier Gallot-Lavallée[b], Frédéric Aitken[b,*]

[a] Department of Industrial Engineering and Maintenance, University of Sciences and Technology of Masuku (USTM), BP 941 Franceville, Gabon
[b] Grenoble Electrical Engineering Laboratory (G2Elab), University Grenoble Alpes and CNRS, G2Elab, F38000 Grenoble, France

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ABSTRACT

This paper deals with an analytical modeling of heat transfers simulating a new radiation calorimeter operating in a temperature range from −50 °C to 150 °C. The aim of this modeling is the evaluation of the feasibility and performance of the calorimeter by assessing the measurement of power losses of some electrical devices by radiation, the influence of the geometry and materials. Finally a theoretical sensibility of the new apparatus is estimated at ±1 mW. From these results the calorimeter has been successfully implemented and patented.

1. Introduction

The calorimetric method is one of the most reliable techniques for measuring heat power loss in electrical component [1]. Therefore several calorimetric devices have been developed for that purpose. They exhibit good measurements accuracies in their operating ranges. However, the investigations led on these calorimeters [2] show that these experimental setups point out a number of limits either on their temperature range, frequency, applied voltage or the component geometry. Seen these limits, we decided to design a new radiation calorimeter enabling to take into account the advantages presented by current calorimeters and improving their limits [3]. Our calorimeter has been designed for measuring heat power loss in a controlled insulated vacuum environment in which the operating temperature ranges from −50 °C to +150 °C. The tested electrical device can have any shape but this one cannot exceed a sphere diameter of 18 cm. The maximum measurable power is of the order of 10 W for an operating temperature of 100 °C and the precision of the measurement is of the order of 2% and less for heat power losses above 100 mW.

The design of our calorimeter apparatus was achieved from a thermal modeling which is the aim of this paper. The thermal modeling of our calorimeter is based mainly on an analytical approach because it allows varying easily many parameters in order to understand their effects and the amplitude of these effects on the performance of our device. The aim of this modeling is not to have a perfect true description of the thermal response of our device but to help to evaluate the performance of our device by choosing the best materials for the different part of our calorimeter. Also an important objective of this modeling is to minimize the parasitic thermal losses such that the radiation heat transfer must be the dominating mode of heat transfer in our device. Our approach should account for the behavior both in steady-state and transient regimes.

The analytical approach requires simplifications of the heat exchange occurring in the calorimeter therefore it is not expected to have a fully quantitative description of our device. However, we will show that a good qualitative agreement has been achieved. At lower temperatures than room temperature a good quantitative agreement between our modeling and experiment is shown in the last chapter validating our approach.

An example of simulation program with Mathematica can be freely downloaded by following the link: http://mathematica.g2elab.grenoble-inp.fr/.

2. Brief presentation of the new calorimeter

Architecture for the calorimeter is shown in Fig. 1: it is composed by insulation, an isothermal system in which the electrical component to test is suspended, a heat sink and a heat vector conducting the heat power towards the heat sink. A more detailed description of the calorimeter architecture and geometry of its components have been given in Obame et al. [2,3].

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* Corresponding author.
E-mail address: frederic.aitken@g2elab.grenoble-inp.fr (F. Aitken).

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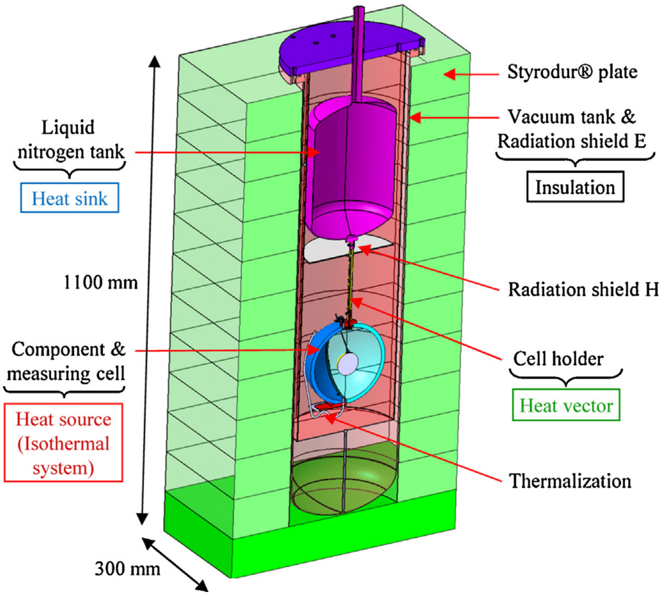

Fig. 1. Calorimetric longitudinal cross section with main functions of elements inside the system.

We draw attention to the fact that all the radiation shield surfaces were polished and some of them covered with gold in order to reduce their emissivity.

The principle used for measuring the heat power loss of an electrical device is a differential measurement method. The heat power dissipated by the electrical device is measured in two steps. For the first step, the electrical device under test is not supplied and the measuring cell is regulated at a given temperature T_0 by a set-up that provides heat power P_0 in steady state regime. In a second step, the electrical device is supplied and dissipates heat loss, mainly by radiation in our case. This loss disturbs the equilibrium temperature of the isothermal measuring cell and tends to increase it. The temperature controller reacts by lowering the heat supplied to the cell at a value P_1 in order to keep its temperature at the initial value T_0. Therefore, the heat loss dissipated by the electrical device can be calculated by $P_{loss} = P_0 - P_1$, assuming that the external disturbance of the cell can be neglected.

3. Heat transfer modeling of the new calorimeter

The calorimeter being under vacuum, heat exchange by convection will occur only for external surfaces in contact with ambient air at room temperature. Then the analytical modeling developed here is mainly based on heat conduction and radiation.

For the need of the analytical approach the calorimeter has been divided in a great number of isothermal elements. All these elements have been indexed as shown in Fig. 2.

3.1. Assumptions of the model

In order to account for possible thermal gradients, the calorimeter has been divided first in two subsystems: the lower part noted (I) and the upper part noted (S). They are separated by a heat radiation shield named H.

For the same reasons given previously the parts (I) and (S) have been subdivided in several elements for which the surfaces exchanging heat transfer by radiation are taken as gray bodies, isothermal and perfectly diffuse (*i.e.* Lambertian surfaces). These elements are indexed by their surface S_i, their total hemispherical emissivity ε_i and their temperature T_i.

In part (I) the electrical device under test (DUT) is at temperature T_1 and has an external surface S_1 which is assumed to be a sphere of 30 mm in diameter. Its total hemispherical emissivity is ε_1. The DUT support and its current leads inside the measuring cell constitute the thermal conduction resistances named respectively R_{TH1S} and R_{TH1}.

The total hemispherical emissivity of the internal surface S_2 and external surface S_3 of the measuring cell are respectively noted ε_2 and ε_3. Their respective temperatures are T_2 and T_3. The cell thickness constitutes a thermal conduction resistance named R_{TH23}.

The measuring cell support and the current leads constitute the thermal resistances of conduction named respectively R_{TH3H} and R_{TH3}. Heat exchange by radiation is considered negligible with these elements since their Biot numbers are lower than 0.3.

The emissivity of the radiation shield H surface (S_H) is named ε_H and its temperature T_H. This radiation shield decouples heat radiation between the lower part (I) and the upper part (S) of the calorimeter.

The lower part of the radiation shield E is noted EI, its surface S_{EI} has a total hemispherical emissivity ε_{EI} and a temperature T_{EI}. This part is separated from the upper part named ES by a thermal conduction resistance R_{THEE}. As for the lower part, the upper part has a temperature T_{ES} with the surface S_{ES} having a total emissivity ε_{ES}.

The lower part of the vacuum tank noted VI is separated with the upper part VS by a thermal conduction resistance recorded R_{THVV}. The surfaces, emissivities and temperatures of VI and VS are named with respective indexes VI and VS. The contacts of the elements ES – VS and EI – VI are modeled by thermal conduction resistances respectively R_{THVES} and R_{THVEI}.

It is assumed that the longitudinal thermal gradient in the Styrodur® plates is insignificant, thus we did not introduced a thermal conduction resistance between the part (I) and (S) of the Styrodur insulation

The surface S_0 of the liquid nitrogen tank is considered at a constant temperature $T_0 = -196.7\,^{\circ}C$ (77 K) and have a total hemispherical emissivity ε_0. The liquid nitrogen tank is hold in place to the vacuum tank flange noted C by a stainless steel tube constituting a thermal conduction resistance R_{TH0C}. The current leads are thermalized on the surface S_0 and are represented by a thermal conduction resistance R_{TH0}.

The internal surface of the flange is named S_C, its emissivity and temperature, are named respectively ε_C and T_C. A thermal resistance R_{THCV} represents the thermal conduction between the flange C and the vacuum tank.

The upper external surface S_S of the calorimeter formed by a low emissivity insulating film has a temperature T_S. The emissivity of that surface is ε_S. The upper part (S_S) of the calorimeter external surface is related to the vacuum tank by a thermal résistance R_{THSVS} due to the presence of Styrodur plates. The lower external surface of the calorimeter noted SI has a total hemispherical emissivity ε_I and a temperature T_I. This part is thermally related to the vacuum tank by four thermal resistances connected in parallel R_{THSVI}, R_{TH4}, R_{TH5} and R_{TH6}.

The plate that covers the top of the Styrodur plates has a surface named S_P with a total emissivity ε_P and a temperature T_P. The heat transfer between this plate and the Styrodur upper plate is assumed to be negligible. This plate is in contact with the vacuum tank through the thermal resistance R_{THPV}.

The heat transfer between the calorimeter elements in steady state regime is shown in Fig. 3 as an equivalent "electrical network". In this network arteries stand for thermal resistances of different type according to the heat transfer model taken into account between two particular elements.

The properties of the materials involved in our model are temperature-dependent. These properties are mainly the thermal