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Experimental and numerical results for a new single-cell calorimeter dedicated to nuclear heating rate measurement

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Abstract— **This paper presents the study of a new innovative heat flow single-cell calorimeter dedicated to the measurement of the nuclear heating rate in research reactors. Before irradiating this type of sensor, it is necessary to characterize it under laboratory conditions to determine its metrological properties.**

A general description (design, geometry and materials nature) of this new calorimeter will be given, focusing on the motivations that led to its development. This part will be followed by a presentation of the experimental set-up and operating protocol used to characterize this sensor. The sensor sensitivity and response time will be quantified and discussed with a comparison of those obtained with previous calorimeters. In parallel with these experimental characterizations, parametric 3-D numerical simulations will be carried out using COMSOL Multiphysics software. These results, obtained both experimentally and numerically, will be compared to present a complete calorimeter study under laboratory conditions.

Keywords — **Calorimetry, Calibration, Nuclear heating rate, 3-D numerical simulations.**

I. INTRODUCTION

Material Testing Reactor (MTR) is a type of research reactor with multiple objectives. From the production of medical radioisotopes to the study of materials under high photon and neutron fluxes, these nuclear facilities are crucial tools for research in nuclear fission field.

The design and interpretation of experiments carried out in the core and the reflector require the accurate knowledge of specific quantities. Among these quantities, the absorbed dose rate is a key parameter. The origin of this quantity lies in the energy deposition generated by the interaction of radiation with matter expressed per unit of time and mass. In the reactor core, this mass energy deposition rate is so intense that it results in a local rise in temperature and consequently the absorbed dose rate is also known as the nuclear heating rate in $W.g^{-1}$. Thus, this quantity can be measured by using specific calorimeters. These sensors are inserted into experimental reactor channels for on-line measurements. These calorimeters are non-adiabatic sensor, by evacuating their energy with the external environment in order to ensure the sensor integrity and realize on-line measurements. The literature distinguishes two families of heat flow calorimeter dedicated to measuring nuclear heating rate:

- Differential calorimeter: with at least two calorimetric cells, including a reference cell, and incorporating heating elements in their design [1-5],
- Single-cell calorimeter: with just one calorimetric cell, in most cases without a heating element [4-9].

Since 2009, research work on the development of these calorimeters has been carried out by the LIMMEX laboratory (a joint AMU-CEA-CNRS laboratory), with the main aim of continuously improving these sensors. Various areas of improvement are targeted, such as the design, miniaturization, metrological characteristics (sensitivity, operating range, response time, selectivity etc.). The modularity of these sensors enables to meet a wide range of needs, including a prototype for measuring the 20 $W.g^{-1}$ in aluminum expected in the Jules Horowitz Reactor [3]. In 2015, a new differential calorimeter (named CALORRE) comprising two compact calorimetric cells using predominantly radial heat transfer was patented by AMU and CEA [10] and successfully qualified in the Polish MARIA research reactor [11]. Recently, this calorimeter has been improved as part of the CALOR-I project to achieve a smaller size of 89.5 mm axial height (instead of 222.5 mm previously) and an innovative design to eliminate contact thermal resistances [12]. This new prototype will shortly be qualified in the MIT reactor in-core water loop.

In parallel, a new prototype of a single-cell calorimeter called Mono-CALO is currently being studied. This research is part of the MICRO-CALOR project, and follows on a previous PhD thesis [13] leading to a first prototype of Mono-CALO and an AMU-CEA-CNRS patent [14] in 2020. The first prototype corresponds to a design of a single-cell calorimeter incorporating a thin-film deposited heating element. The aim of this innovative design is to keep the advantages of both calorimeter families by offering a single-cell calorimeter integrating a heating element.

The first section of this paper will describe the assembly of the first prototype of the Mono-CALO calorimeter with its various components, and present the experimental set-up and the protocol used to characterize it. The second section will discuss the results obtained both experimentally and numerically, and compare the metrological characteristics of this new prototype with those of other calorimeters developed in the laboratory. Finally, the last section will explain the main results and open up perspectives on future actions in order to develop a second prototype with intrinsic characteristics compatible with an irradiation campaign.

II. MONO-CALO CALORIMETER AND EXPERIMENTAL SET-UP WITH OPERATING PROTOCOL

A. *Mono-CALO calorimeter*

The first prototype of Mono-CALO calorimeter has a parallelepiped shape (H = 25 mm, w = 18 mm, t = 10.2 mm) and features the characteristic elements of previous calorimeters: at its center there is a 4-wire heating element that also incorporates a temperature sensor (T-type thermocouple). This temperature sensor is referred to a hot spot and corresponds to the temperature at the center of the calorimeter. Around this heating element, two samples of material are placed on either side. These two samples are held in the center of the calorimeter by two spacers. The entire calorimeter is encapsulated in a jacket and cap, making it watertight. All materials structure used in the calorimeter are AISI 316L, with the exception of the heating element, which is made of Kapton as insulating material and Constant and Copper for the resistive element and T-type thermocouple. The calorimeter assembly and the identification of the various components are presented in Figure 1.

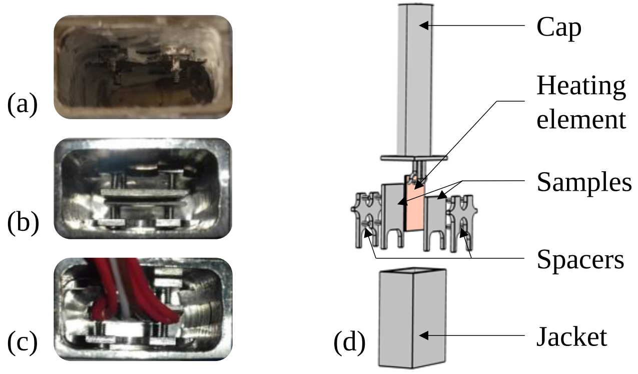

Fig. 1. Assembly of the Mono-CALO calorimeter with pictures on the left-hand section (jacket + spacers (a), + samples (b), + heating element (c)), and a diagram in the right-hand section (identification of elements (d)).

In order to limit the occurrence of contact resistance under laboratory conditions, thermal grease is applied to all calorimeter components. Another K-type thermocouple is used to measure a cold temperature, located outside the calorimeter, in contact with the cooling fluid.

B. *Experimental set-up*

A specific bench is used to characterize this sensor under laboratory conditions. The calorimeter is immersed in a thermostatic bath using water as the heat transfer fluid. The temperature and rising speed of this coolant fluid flow can be controlled by applying setpoints.

Thanks to the presence of a heating element at the center of the Mono-CALO calorimeter, the injection of a current through the resistive element creates a Joule effect. These currents are injected via a programmable power supply. The Joule effect created inside the calorimeter thus enables laboratory simulation of the energy deposition generated by the radiation-matter interactions that the calorimeter undergoes when irradiated in the reactor core. The energy deposited by the heating element will lead to a local increase in temperature.

To complete the test bench, a precision resistance is connected in series with the heating element electrical circuit to determine the value of the current injection due to limitations in the data acquisition system. All quantities are measured by a data acquisition system with a sampling time of 10 seconds. A monitoring software program plots the evolution of all these parameters in real-time. All these elements are shown in Figure 2.

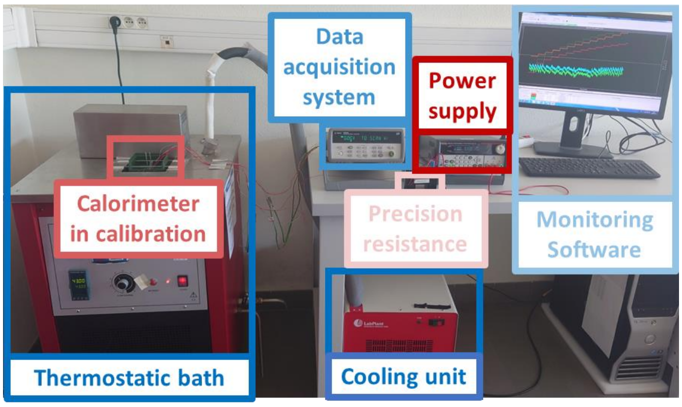

Fig. 2. Pictures of the various components of the experimental set-up.

Thanks to this bench, five quantities are measured:

- Hot temperature: at the center of the calorimeter, in the immediate vicinity of the heating element
- Cold temperature n°1: outside of the calorimeter, in direct contact with the heat transfer fluid
- Cold temperature n°2: outside of the calorimeter, in direct contact with the heat transfer fluid
- Voltage n°1: at the heating element terminals
- Voltage n°2: at the precision resistance terminals

C. *Operating protocol*

The aim of the study is to determine the calibration curve of the sensor. This curve corresponds to the difference in the mean steady temperatures between the hot spot, inside the calorimeter, and the cold spot corresponding to the temperature of the fluid, as a function of electrical power inputs in steady state. In this way, an increasing increment of the electrical current is injected into the heating element to determine the sensor response over a defined range of electrical power from 0 W to 0.8 W. As the power increment is equal to 0.05 W, 18 current injection steps are required (including the 0 W value at the start and end of the test). Each step lasts 30 minutes. This time is necessary to ensure that the system reaches a steady state. Figure 3 shows the temporal evolution of the temperatures and the generated electrical power.

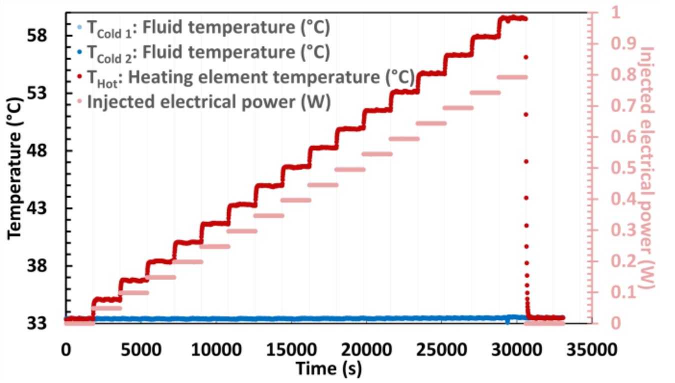

Fig. 3. Temperatures of the Mono-CALO calorimeter and fluid flow, and of the injected electrical power as a function of time for the following parietal conditions: $T_f = 33$ °C and Re = 1746.

The time curve described in Figure 3 can then be used to obtain the sensor calibration curve. That involves determining the mean steady temperatures and then calculating the difference of the mean steady temperatures between the hot and cold points of the sensor, and finally plotting this temperature difference versus the electrical power injected (cf. Fig. 4). Each mean temperature is calculated over the last 10 minutes of each step.

Thanks to this experimental protocol, various parietal conditions (coolant fluid flow temperature and velocity) could be applied to quantify and study their influence on the sensor response. The experimental study in this paper was carried out with a coolant fluid flow temperature of 33 °C and a coolant fluid flow velocity corresponding to a Reynolds number of 1746 around the calorimeter.

III. EXPERIMENTAL AND NUMERICAL RESULTS

Characterization results for the new Mono-CALO prototype were obtained experimentally using the experimental set-up described above, and by coupling these results with 3-D numerical thermal studies. The metrological characteristics obtained were then compared with those of other calorimeters.

A. Experimental results

Among the metrological characteristics that need to be determined in the laboratory before an irradiation campaign, the calibration curve coefficients are of major interest. These will be used during the irradiation to process the on-line measured data and then to determine the nuclear heating rate.

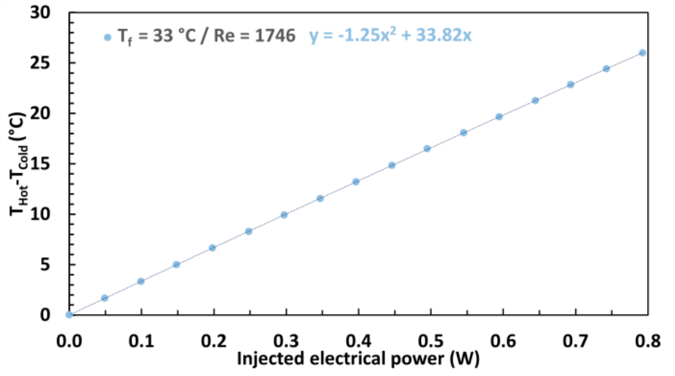

Fig. 4. Mono-CALO calibration curve obtained for the following parietal conditions: $T_f = 33$ °C and Re = 1746.

The calibration curve of the first prototype of the Mono-CALO calorimeter is given in Figure 4. It corresponds to a second-order polynomial curve. This behavior could be explained by the temperature dependence of the thermal properties of the materials. Consequently, the Mono-CALO calorimeter sensitivity is not constant (cf. Table 1). It decreases with increasing the value of injected electrical power.

In addition to this metrological characteristic, it is also important to determine the calorimeter response time. At the start of each power injection step, the calorimeter has a phase of energy accumulation before reaching a thermal equilibrium (steady state). The time required to reach this thermal equilibrium corresponds to the calorimeter response time. This response time is specific to each calorimeter and depends on its design, its mass, its materials, and the external boundary conditions. Each response time is evaluated at 3τ (95% of the final response variation). The average of the Mono-CALO calorimeter response time obtained for all steps is 121 s.

B. 3-D numerical results

A complementary 3-D numerical study was carried out using COMSOL Multiphysics software. This software, using a finite element calculation method, allows the estimation of the response of the sensor under laboratory conditions as close as possible to those achieved during the experimental study. To do that, a physics coupling the solving of the Heat and Maxwell equations was considered for this new prototype. This physics was never used for previous calorimeters. This method allows the calculation of the heat source induced by the Joule effect inside the heating element as well as the temperature field in the whole sensor. The conductive and radiative heat transfers inside the calorimeter are considered. The thermal conductivity depends on the temperature and the emissivity is taken constant and equal to 0.25. The results of this simulation in terms of calibration curve and sensitivity are compared with those obtained experimentally in Table I.

TABLE I
COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS FOR THE MONO-CALO CALORIMETER

Studies	Equation of the calibration curve	Sensitivity	Sensitivity for 0.8 W
	$\Delta T = T_{hot}$-T_{cold} in °C with P in W	°C.W^{-1}	°C.W^{-1}
Experiments	$\Delta T = -1.25*P^2+33.82*P$	-2.5*P+33.82	31.82
Simulations	$\Delta T = -0.13*P^2+35.32*P$	-0.26*P+35.32	35.11

The experimental and numerical results are consistent. However, there is a difference between the second-order coefficients. This difference can be explained by the value of the emissivity which is not well known. Nevertheless, these results provide a validation of the 3-D numerical model coupling the solving of the Heat and Maxwell equations.

C. Comparison of metrological characteristics

The main metrological characteristics (sensitivity and response time) of this new Mono-CALO calorimeter can be compared in Table II with those of previous prototypes developed in the laboratory. The comparison is realized with experimental results from two CALORRE calorimetric cells using the same structural material (AISI 316L) [15].

TABLE II
COMPARISON OF THE SENSITIVITY AND THE RESPONSE TIME FOR THREE CALORIMETERS

Calorimeter	Equation of the calibration curve	Sensitivity	Response time
	ΔT in °C with P in W	$°C.W^{-1}$	s
Mono-CALO	$\Delta T = -1.25*P^2+33.82*P$	-2.5*P+33.82	121
CALORRE (quarter-horizontal fin)	$\Delta T = -0.82*P^2+30.03*P$	-1.64*P+30.03	498
CALORRE (half-horizontal fin)	$\Delta T = -0.54*P^2+22.65*P$	-1.08*P+22.65	291

On the one hand, the sensitivity of the Mono-CALO sensor is relatively close to that of the CALORRE calorimetric cell with a quarter-horizontal fin design and a height equal to 23.1 mm and higher than that of the CALORRE calorimetric cell with a half-horizontal fin design and a calorimetric cell height of 23.1 mm. On the other hand, the response time of the new Mono-CALO prototype (121 s) is lower than that of two CALORRE calorimetric cells (4 times lower than that of the CALORRE configuration with a quarter-horizontal fin design and a height of 23.1 mm). This metrological characteristic is of prime importance during irradiation campaigns, since the protocol, the irradiation time, and consequently, the sensor ageing depend on it.

IV. CONCLUSIONS AND OUTLOOKS

Laboratory characterization of the first prototype of a new single-cell calorimeter, called Mono-CALO, incorporating a thin heating element allowed the determination of its main metrological characteristics (calibration curve, sensitivity, and response time). This new sensor has a non-linear calibration curve as previous sensitive CALORRE calorimetric cell configurations. By against, the response time of this new single-cell calorimeter is lower than that of CALORRE calorimetric cells having a similar height and made of stainless steel. Its response time is up to 4 times lower than that of the CALORRE calorimetric cell with a quarter-horizontal fin configuration. A sensitivity of 31.82 $°C.W^{-1}$ for an electrical power injection of 0.8 W and an average response time of 121 s are found. In addition, the use of 3-D numerical simulations coupling the solving of Heat and Maxwell equations led to results consistent with those obtained experimentally. The validation of this new numerical simulation model is important in order to carry out future parametrical studies to modify and optimize the sensor design and response.

Following the characterization of this first prototype in the laboratory, a 3-D parametric study under laboratory and irradiation conditions will be carried out. The aim of this new study will be to design a second prototype with a greater sensitivity, in order to carry out an irradiation campaign in a TRIGA-type research reactor. In addition to changes in the sensor design, the heating element used to calibrate needs to be modified. At present, the Kapton used as the insulating material for the resistive element is the limiting point for injecting greater electrical power, due to its low melting point. A change in the manufacturing method of the thin heating element is being studied, in order to use nuclear-hardened materials and to withstand higher temperatures. In this way, the future prototype will offer greater sensitivity and enable metrological characterization over a wider operating range.

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