EPJ Web of Conferences **253**, 04016 (2021) https://doi.org/10.1051/epjconf/202125304016
ANIMMA 2021

Study review of the CALORRE differential calorimeter: definition of designs for different nuclear environments

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Abstract—**This paper deals with the CALORRE differential calorimeter patented by Aix-Marseille University and the CEA in 2015. Firstly, the paper focuses on the presentation of the first prototype of CALORRE calorimeter qualified under real conditions during the MARIA irradiation campaign in 2015. Then, a review of the studies restricted to one CALORRE calorimetric cell realized thanks to experimental characterizations under laboratory conditions is detailed. Several configurations were studied to determine the influence of the cell height, its horizontal fin geometry and the nature of the material of its structure on its response for a calibration protocol: linearity, sensitivity, range, reproducibility, response time and absolute temperatures. Finally, within the framework of the new CALOR-I project, an optimization of the calorimeter assembly and its design were carried out in order to remove contact thermal resistances and provide a new configuration of CALORRE calorimeter suited for the in-core water loop of the MIT reactor (2 W.g^{-1}). The response of this new calorimeter is estimated thanks to thermal simulations.**

Index Terms—**Calorimeter, Nuclear Absorbed Dose Rate, On-line Measurements, Calibration, Irradiation campaign.**

I. Introduction

The high neutron and gamma fluxes as well as strong displacements per atom characterize conditions of material testing reactors (MTRs). These research reactors constitute major support research facilities and allow experimental and real-condition studies of the behaviour of fuels and inert materials (vessel, reflector, cladding, etc.) in an extreme radiation environment. These studies are important as they lead to progress on the understanding of the accelerated ageing of materials and/or of phenomena for advanced scenarios up to accidental conditions and consequently they bring data for safety issues, the life span of existing nuclear power plants and their advancements with new concepts.

Therefore, new instrumentation is needed to measure online key parameters both before the experiments for the device design and during the experiments for the result interpretation. The construction of the Jules Horowitz Reactor, a new MTR of 100 MWth nominal power with unequalled performances in Europe (high fast neutron flux of 5.5x10^{14} n/(cm².s) from 1 MeV leading to a high accelerated ageing up to 16 dpa/year and a high nuclear absorbed dose rate up to 20 W.g^{-1} in aluminum), initiated new collaborative research work. Since 2009 Aix-Marseille University and the CEA (within the framework of the joint laboratory LIMMEX - Laboratory for Instrumentation and Measurement in Extreme Environments) and its IN-CORE program - Instrumentation for Nuclear Radiations and Calorimetry online in REactor) have been developing a new research topic. More precisely, they have been focusing on innovation in instrumentation and advanced measurement methods for the quantification of key nuclear parameters such as neutron and photon fluxes and nuclear absorbed dose rate, also called nuclear heating rate. The online measurement of this latter quantity requires specific sensors: non-adiabatic calorimeters. With regard to the state of the art, two distinct sensors are used in MTRs: French differential calorimeters (CALMOS, CARMEN or CALORRE type) and European single-cell calorimeters (such as gamma thermometers or KAROLINA-type calorimeters) [1-5].

These two types of calorimeter allow the quantification of the nuclear absorbed dose rate thanks to temperature measurements and preliminary calibration under non-irradiation conditions from steady thermal states in the case of integrated heating elements or from transient thermal states in other cases. One main objective targeted for French differential calorimeters within the framework of the IN-CORE program and more recently of the new research program, called CALOR-I, funded by Aix-Marseille University foundation (A*Midex) and involving the Nuclear Reactor Laboratory of the MIT and the CEA is the reduction of the sensor size with the CALORRE calorimeter.

The paper will present a review of recent work carried out on this calorimeter by AMU and the CEA in 2015. The work allows the design and the characterization of several CALORRE configurations over a wide range of nuclear absorbed dose rate (up to 20 W.g^{-1}).

The first part of the paper will describe the first design of CALORRE calorimeter fabricated for a range up to 1 W.g^{-1} and its first successful qualification under real conditions during an irradiation campaign inside the Polish MARIA reactor (in November 2015). The second part will be dedicated to the characterization of the response of 6 new configurations of CALORRE calorimetric cell by means of a comprehensive approach coupling experimental, theoretical and numerical work from laboratory conditions to nuclear environments. The experimental metrological characteristics of the 6 configurations, in terms of sensitivity, linearity, range, reproducibility and response time, will be detailed.

The last part will present new results obtained within the framework of the CALORI, program (2020-2022) which will allow the mapping of an in-core water loop of the MIT reactor in terms of nuclear absorbed dose rate by means of calorimeter for the first time. The criteria for the choice of a new configuration of CALORRE calorimeter will be detailed (mass, size, temperature, sensitivity). Then, the numerical responses under real conditions of a new CALORRE differential calorimeter assembly will be presented for three values of external heat transfer coefficient.

II. First CALORRE calorimeter prototype qualified under real conditions

One main objective of the irradiation campaign realized in 2015 inside the MARIA reactor was to qualify a first prototype of CALORRE calorimeter by comparing the obtained nuclear absorbed dose rate axial profile to those measured with other already qualified calorimeters such as CARMEN calorimeter.

A. The CALORRE calorimetric cell

Figure 1 shows schematics of the first type of CALORRE calorimetric cell which was developed tested under real conditions during the irradiation campaign in the MARIA reactor. This configuration had the same head as that of CARMEN calorimetric cell in terms of geometry, height (equal to 23.1 mm) and assembly with a heating element in order to compare the responses of these two sensor-designs under laboratory and/or real conditions.

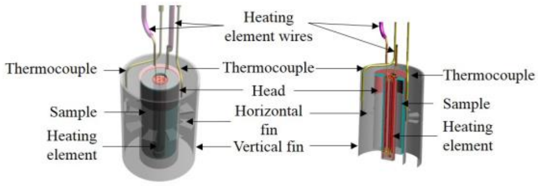

Fig. 1. A 3-D schemes of the first CALORRE calorimetric cell prototype (on the left-hand section) and of an internal view of this cell (on the right-hand section).

The heating element allows the simulation of the nuclear absorbed dose rate by Joule effect. The different parts of CALORRE calorimetric cell were already presented: a structure made of stainless steel AISI 316L which is composed of a head, a half horizontal-fin (8 metal sectors and 8 empty sectors with a same angle equal to 22.5 °) and a vertical fin , and an heating element with its holder, a sample in the case of the measurement cell and two K-type thermocouples to measure a temperature difference between two key points at hot and cold temperatures (T_{hot} and T_{cold}) respectively [1, 6]. This CALORRE calorimetric cell is called full-height and half horizontal-fin.

B. The CALORRE calorimeter

The CALORRE sensor is composed of two superimposed full-height and half horizontal-fin calorimetric cells. These identical cells host a graphite sample in the case of the measurement cell and gas for the reference cell. The reference cell is needed to remove the effect of the energy deposition on the structure of the measurement cell, the heating element, the heating element holder and the thermocouples.

Figure 2 gives a diagram of the complete CALORRE differential calorimeter. The two calorimetric cells are superimposed through the use of different thin spacers inside a jacket and filled with di-nitrogen. This external additional jacket is made of stainless steel (internal diameter equal to 17.0 mm and a thickness equal to 0.5 mm).

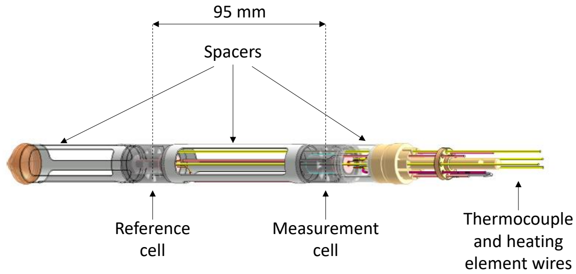

Fig. 2. 3-D scheme of the CALORRE differential calorimeter without its external additional jacket.

During the MARIA campaign, the distance between the two CALORRE cells was fixed to 71.9 mm (leading to an inter-sample space of 95 mm), as seen in the Figure 2, in order to reproduce the distance existing between the two heads of the usual CARMEN differential calorimeter.

C. Calibration of a differential calorimeter under laboratory conditions

For each calorimetric cell (reference and/or measurement), a preliminary calibration step under laboratory conditions (without nuclear rays) is crucial to obtain its calibration curve. This kind of curve represents the difference of the mean steady temperatures between the two key points (T_{hot} -T_{cold}) versus the electrical power generated by the heating element integrated inside the cell head.

In the case of the first prototype of the CALORRE differential calorimeter, the two calorimetric cells were calibrated simultaneously. Thus, the calorimeter was inserted inside a Polish bench with a fluid flow vein at fixed temperature (40 °C) and velocity (corresponding to a Reynolds number equal to 17340) [7]. Then, different successive electrical current values were injected to each heating element in order to generate a power range from 0 to 6 W with an increment of 1 W in each calorimetric cell.

The responses of the two cells of the differential calorimeter are different leading to two different calibration curves:

$$(T_{hot} - T_{cold})_{measurement} = \Delta T_S = -0.42P^2 + 21.09P \quad (1)$$

$$(T_{hot} - T_{cold})_{reference} = \Delta T_R = -0.41P^2 + 19.41P \quad (2)$$

with P the electrical power injected in W.

D. Operating protocol and MARIA irradiation campaign results

The calorimeter CALORRE was inserted into the experimental channel H-IV A thanks to a hollow cylindrical pipe (24.0 mm in internal diameter). The device was moved by applying an axial increment equal to 95.0 mm (space induced by the position between the heads of the two superimposed calorimetric cells) from -463.0 mm to 487.0 mm in order to obtain a mapping of the nuclear absorbed dose rate on ten axial positions. After each increment, 25 minutes were waited to reach a steady state inside the calorimeter. The nuclear absorbed dose rate at each axial position (z) is obtained by taking the two calibration curves into account, and by measuring the mean steady temperature difference for the measurement cell located at the z-position (step i) and the mean steady temperature difference for the reference cell moved at the same z-position (step i+1).

Figure 3 shows the axial profile of the nuclear absorbed dose rate obtained with the first CALORRE calorimeter prototype having full-height and half horizontal-fin calorimetric cell configuration. This profile and the profiles obtained with the other calorimeters were similar in term of shape once a normalization by the maximal value is performed.

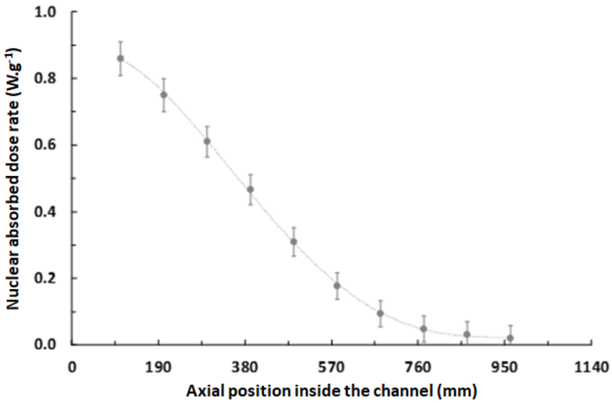

Fig. 3. Nuclear absorbed dose rate profile inside the H-IV A experimental channel of MARIA reactor.

In conclusion, the first CALORRE calorimeter prototype was well behaved under real conditions. Consequently, a parametrical study on new configurations of calorimetric cell were performed in order to show the influence of different parameters, such as the structure material nature, the height of the cell and the horizontal-fin design, on the cell response. These results are presented in the next part.

III. Parametrical study under laboratory

In this section, the responses and metrological characteristics of 7 configurations of calorimetric cell (including that used during the MARIA irradiation campaign, called configuration N°1) are presented in Table 1 by precising the height of the cell (H), the structure material nature (Material), the horizontal-fin geometry (Fin), the response time (t), the calibration curve coefficients A_1 and A_2 (of first and second orders respectively), the sensitivity at 6 W (S_{6W}), the total mass of the head structure (including shim, heating element and heating-element holder) and the sample (m), the absolute temperature located at the hot spot (T_{hot}) and the simulated nuclear absorbed dose rate (E_n) under laboratory conditions. There were obtained with the same set-up and operating protocol: only one calorimetric cell (the measurement cell) hosted by an external jacket [6] for same applied experimental conditions (T_{fluid}=33 °C and Re=1607) and with an electrical power range up to 6 W.

As expected, the absolute temperature, the non-linearity and the sensitivity decreased with the increase of the number of metal sectors within the horizontal-fin geometry and with a higher thermal conductivity of the structure material [6]. The change in cell height (11.55 mm instead of 23.1 mm) did not impact significantly the sensitivity (in °C.W^{-1}) under laboratory conditions but reduced the mass of the cell and so the mass of the sample as well as the reached absolute temperature and the response time. On the other hand, the reduction in sample mass led to a lower sensitivity (in °C.g.W^{-1}) under real conditions. This reduction in sensitivity under real conditions was confirmed by a validated predicted model based on a heat balance [8]. For example, the configuration N°1, had a sensitivity of 88.9 °C.g.W^{-1} as against 49.6 °C.g.W^{-1} for the configuration N°6 (same characteristics except for its reduced height) at 1 W.g^{-1}.

TABLE I Metrological characteristics for seven Configurations of a CALORRE calorimetric cell

Configuration	N°1	N°2	N°3	N°4	N°5	N°6	N°7
H (mm)	23.1	23.1	23.1	23.1	23.1	11.55	11.55
Material (-)	AISI 316L	Al 5754	Al 5754	AISI 316L	AISI 316L	AISI 316L	TA6V
Fin (-)	1/2	1/4	1/2	1/4	1	1/2	1/4
t (s)	291	97	88	418	208	174	287
A_1 (°C.W^{-1})	22.65	5.04	2.25	30.03	11.05	18.70	48.15
A_2 (°C.W^{-2})	-0.54	-0.02	-0.01	-0.82	-0.17	-0.30	-1.78
S_{6W} (°C.W^{-1})	16.2	4.8	2.1	20.3	9.0	15.1	26.8
m (g)	5.22	3.20	3.20	5.22	5.22	2.92	2.16
T_{hot} (°C)	169	72	62	209	122	157	272
E_n (W.g^{-1})	1.15	1.90	1.90	1.15	1.15	2.05	2.80

This parametrical study under laboratory conditions showed a high modularity of the CALORRE calorimetric cells: sensitivity from 2.1 °C.W^{-1} to 26.8 °C.W^{-1} at 6 W leading to a wide measurement range. The aluminum configurations are suited to high nuclear absorbed dose rate measurement [8]. More precisely the full-height and half-surface aluminum configuration (configuration N°3) was qualified under laboratory conditions up to 60 W thanks to a new heating element system. This very large calibration range allowed the demonstration of the good running calorimetric cell for the maximal value of the nuclear absorbed dose rate inside the future JHR (20 W.g^{-1}). The titanium configuration (configuration N°7) was the more sensitive configuration but had the most non-linear response (A_2=-1.78 °C.W^{-2}) and the highest absolute temperatures (272 °C).

After this experimental parametrical study, a validated 3-D thermal model under real conditions allowed the estimation of the responses for a whole differential calorimeter assembly and its reduction in height by decreasing the important inter-cell space (13.2 mm instead of 71.9 mm) as well as the height of the cell (11.55 mm).

IV. New design of a specific MIT-R CALORRE configuration

In this part, work conducted for the new CALOR-I research program, will be detailed. The two main aims are the design of a new compact CALORRE calorimeter prototype and the mapping of an in-core water-loop in the MIT reactor in term of nuclear absorbed dose rate.

The core of the MIT reactor has a height of 56 cm and a diameter of 38 cm. The main maximal features are a thermal power of 6 MW, a thermal neutron flux of 3.6×10^{13} $n.cm^{-2}.s^{-1}$, a fast neutron (E > 1 MeV) flux of 1.2×10^{14} $n.cm^{-2}.s^{-1}$ and an expected nuclear absorbed dose rate of 2 $W.g^{-1}$ in titanium [9]. The temperature of the fluid flow as well as its velocity can be changed inside the in-core water-loop. By considering the constraints of the experimental set-up used for the calibration under laboratory conditions [6, 8], the in-core water-loop fluid flow temperature will be fixed around 50 °C but the required speed of the fluid flow will be studied to ensure energy evacuation.

A. The new CALORRE cell design

Regarding the previous irradiation campaign results, recent work [8], the results obtained for 6 other calorimetric cells and the expected nuclear absorbed dose rate inside the MITR [9], a new CALORRE cell design was defined and studied thanks to 3-D numerical thermal simulations. The aims were to remove the thermal contact resistances by means of a simplification of the assembly and the head and to reduce the total height of the calorimeter.

As for a configuration with a reduced-height calorimetric cell (11.55 mm) and a half horizontal-fin design made of stainless steel, the experimental results under laboratory conditions and the predicted response under real conditions showed low absolute temperatures, low response time, a linear response and a good sensitivity, the configuration N°6 was chosen. But its vertical fin was increased in order to remove and replace the additional jacket which induced thermal contact resistances. Moreover, the sample and the head structure were made from a single block to avoid heater holders and other thermal contact resistance. Finally, the vertical fins of the measurement and the reference cells will be welded in order to eliminate the spacers and to obtain the whole calorimeter (cf. Fig 4). An inter-cell space of 18 mm (leading to an inter-sample space of 29.55 mm) and a total height (excluding nose and cap) of 73.7 mm were defined.

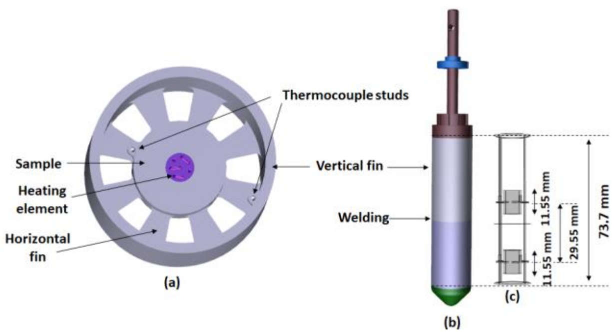

Fig. 4. Diagrams of the new CALORRE measurement calorimetric cell (a), the new assembly (b) and the geometry (c) considered for the 3-D numerical thermal simulations.

B. Study of the response under real conditions by 3-D numerical thermal simulations

The response of the new calorimeter design under real conditions (up to 2 $W.g^{-1}$) was studied by considering only the two cells and thanks to the validated 3-D thermal model [8] (cf. Fig 4). A study of the influence of the heat transfer coefficient on the response, maximal and wall temperature was carried out for a fluid flow temperature equal to 50 °C.

The Figure 5 shows the numerical responses of the calorimeter versus the nuclear absorbed dose rate for three values of the external heat transfer coefficient. There is a low influence of the heat transfer coefficient on the calorimeter response. As expected, a non-linear response is obtained $\Delta\Delta T=-2.51E_n^2+55.38E_n$ leading to a sensitivity of 45.3 $°C.g.W^{-1}$ at 2 $W.g^{-1}$ for a heat transfer coefficient of 10000 $W.m^{-2}.K^{-1}$. In contrast, the maximal temperature in the calorimeter and the maximal wall temperature decrease from 298 °C to 275 °C and from 85 °C to 56 °C respectively when the heat transfer coefficient varies from 1000 to 10000 $W.m^{-2}.K^{-1}$. The temperature field for a heat transfer coefficient of 10000 $W.°C^{-1}.m^{-2}$ at 2 $W.g^{-1}$ is provided in Figure 5.

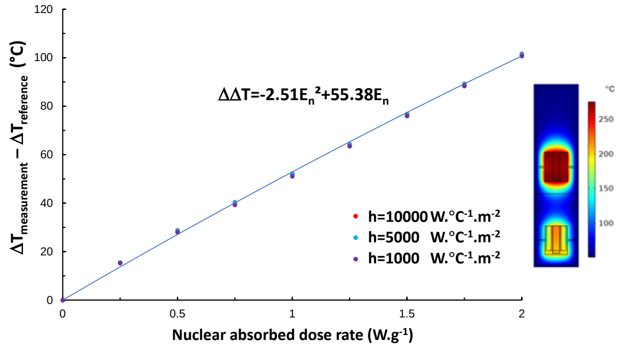

Fig. 5. 3-D numerical responses of the new design of CALORRE calorimeter for three values of the external heat transfer coefficient (on the left-hand section) and the temperature field for a nuclear absorbed dose rate equal to 2 $W.g^{-1}$ (h=10000 $W.°C^{-1}.m^{-2}$ and T_f=50 °C) (on the right-hand section).

V. Conclusions

A first prototype of the new CALORRE differential calorimeter was fabricated and qualified successfully under real conditions during an irradiation campaign in the MARIA reactor in 2015. Then, this irradiation campaign allowed the validation of predictive and 3-D models under real conditions. Then, 6 new configurations of CALORRE calorimetric cell were studied under laboratory conditions to show the influence of the structure material nature, the height of the cell and its horizontal-fin design on the cell response. One of these configurations suitable for JHR conditions up to 20 $W.g^{-1}$ was qualified under laboratory conditions up to 60 W. A new calorimeter assembly dedicated to this maximal nuclear absorbed dose rate was designed and then optimized by reducing its total height. Finally, a new design of CALORRE calorimeter for future experiments in the MIT reactor was studied under real conditions thanks to the validated 3-D thermal model. The new calorimeter defined will have a reduced height and the thermal contact resistances previously observed will be removed thanks to new cells without heating-element holders in particular, and a new calorimeter assembly without spacers and without an additional jacket. A good behaviour and the influence of the heat transfer coefficient on the response and the maximal and wall temperatures were observed and determined numerically for this new calorimeter under real nuclear conditions.

The outlooks are on the one hand the simulations of the interactions between radiations and matter with the MCNP Monte-Carlo transport code and nuclear data library in order to define the local heat sources in each part of the new calorimeter for MIT-R conditions and on the other hand the experimental characterization of this new sensor under laboratory conditions and then under MIT-R conditions.

ACKNOWLEDGMENT

"The CALOR-I project leading to this publication has received funding from the Excellence Initiative of Aix-Marseille University - A*Midex, a French “Investissements d’Avenir” programme”.

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