Thermal study of a non adiabatic differential calorimeter used for nuclear heating measurements inside an experimental channel of the Jules Horowitz Reactor.

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Abstract. New online in-pile measurement methods are crucial during irradiations in Material Testing Reactors (MTR) for a better understanding of accelerated material ageing and nuclear fuel behaviour. In particular, instrumentation for measurements of one relevant parameter: nuclear heat deposition rate, called nuclear heating, has to be improved. The knowledge of this quantity is a great interest for various safety, scientist and end-user requirements (design of specific irradiation devices and associated cooling systems with imposed conditions). This paper focuses on thermal experimental and numerical studies carried out under non irradiation conditions on an in-pile calorimeter dedicated to nuclear heating quantification inside a new experimental device which will be dedicated to the experimental condition mapping (neutron and photon fluxes and nuclear heating) inside the JHR experimental channels. Experimental results concerning the calorimeter response during its electrical calibration (<3W) under laminar forced convection conditions show that its sensitivity does not depend on the cooling flow. Temperature and heat flux density measurements lead to the conclusion of a good directional conductive heat flow design (increased with a higher Reynolds number). A parametric numerical stationary study highlights a sensor sensitivity increasing. At last, the usual calorimeter design is compared to a single calorimeter which gives promising results (miniaturization, higher sensitivity).

1. Introduction
The nuclear heat deposition rate which is induced by several photon and neutron interactions with matter (irradiated material and fuels) represents a key quantity for the fission field at different stages. This quantity, usually called nuclear heating, is involved in the design of various cooling systems dedicated to evacuate the accumulated heat. For instance, its knowledge is necessary before construction of nuclear plants or research reactors in order to satisfy safety and radioprotection...
requirements [1]. Then it is relevant during irradiations in order to impose and to monitor targeted thermal hydraulic conditions (temperature field) into specific irradiation devices located inside or beside reactor core into dedicated experimental channels (devices containing samples and used in order to better understand phenomena during accelerated ageing of materials or fuel irradiations) [2,3]. Finally nuclear heating has to be measured after irradiations in order to take into account residual power for spent fuel storage, transportation, reprocessing [4].

However, an accurate numerical prediction of nuclear heating is still difficult and the improvement of its experimental determination is needed. Indeed, this nuclear heat deposition rate is in general numerically underestimated [5]. For instance, F. Malouch showed that the discrepancy between nuclear heating calculated by a TRIPOLI-4 3D Monte Carlo Code and nuclear heating measured by calorimetry is about -15% at the OSIRIS core mid-plane and about -20% to -25% at the edges [6]. Indeed the numerical models have to take into account several complex photon and neutron interactions with matter (fission, capture, elastic and inelastic scattering, nucleus recoil, slowing down of charged particles, ...) which depend especially on the nature, geometry, density, and composition of the matter, on the neutron and photon energy spectra, on the temperature and on the sample size [3]. Consequently, the discrepancy can be mainly explained by the use of nuclear data (flux, spectra, cross section data) which need nevertheless improved accurate measurements and determinations.

The studies presented in this paper deal with this context. Moreover they are carried out in the framework of the research program called IN-CORE “Instrumentation for Nuclear radiations and Calorimetry Online in Reactor” under progress between CEA and Aix-Marseille University since 2009 [7,8] in a joint research laboratory: LIMMEX. The aim of this research program is to measure more accurately specific and crucial physical parameters such as fast and thermal neutron fluxes, gamma flux and nuclear heating inside the Jules Horowitz Material Testing Reactor –JHR/MTR (under construction in the south of France into Cadarache). The targeted final aim is to design a new suitable mobile experimental device called CARMEN for an accurate mapping of the experimental conditions inside experimental channels of the JHR at its start-up (into the core and the reflector). Two main complementary approaches are developed respectively under irradiation conditions and under non irradiation conditions.

The works under irradiation conditions concern the design of different prototypes of the experimental device CARMEN by coupling new and/or upgraded in pile instrumentation [9], satisfying both safety requirements and scientific criteria, instrumentation and by developing a combined analysis of the different measurement results which should reduce the final uncertainties on radiation and nuclear heating measurements. The instrumentation can be divided into three categories. The first sensor category is dedicated to neutron measurements and concerns fission chambers with different fissile isotopes (\(^{235}\text{U}, {242}\text{Pu}\)) and self powered neutron detector. The second one is used for photon measurements with ionization chamber and self powered gamma detector. The last one focuses on nuclear heating measurements by means of a differential calorimeter and a gamma thermometer.

The works under non irradiation conditions focus on a specific sensor used to quantify the nuclear heat deposition rate into a material sample: a permanent differential in-pile calorimeter [10]. Thermal experimental and numerical studies were [11-12] and are carried out in order to better understand the thermal behavior of this sensor. This sensor was previously designed for a high nuclear heat deposition rate inside OSIRIS reactor (up to 13 W/g) [13]. The final aim of our experimental and numerical works is on one hand to improve its characteristics (measurement range, sensitivity, response time, temperature field) for a wider nuclear heating range occurring into the JHR channels (from few mW/g to 20 W/g) and various external thermal and hydraulic boundary conditions depending on the reactor power regime and the experimental channel location (cooling flow velocity, temperature gradient, geometrical channel characteristics) and on second hand to miniaturize this sensor which has to be coupled with other sensors into a limited space.

In this paper, experimental works under non irradiation conditions dedicated to the study of the flow boundary condition influence on the calorimeter calibration curve in the case of a laminar forced convection are presented and used to validate a numerical model. Then from numerical results, the
influence of the parameters: material thermal conductivity and sensor geometry, are shown on the
sensor response (sensitivity, maximal temperature, power range). A preliminary smaller calorimeter
geometry is discussed.

2. Experimental study of the in-pile permanent differential calorimeter

Before the development of a new testing thermohydraulic laboratory bench called BETHY (under
final construction) which will reproduce a vertical annular cylindrical channel with a hydraulic
diameter from 3 mm to 20 mm, for natural and forced convective regimes (flow velocity up to 10 m/s),
with the possibility of a vertical temperature gradient (up to ~16 °C/m) imposed on a height equal to
60 cm (JHR core height), an experimental set-up has been realized to study the thermal behavior of the
calorimeter and its response for first thermal and hydraulic conditions: laminar forced convection, low
power range (<3W) corresponding to reflector power conditions.

2.1. In-pile calorimeter

Calorimetric method is used in the nuclear fission field for various specific applications which are
different from those in chemistry field interested for instance by specific heat capacity or phase change
enthalpy measurements. In fact calorimeters in the nuclear fission field can be divided into four
categories according to its use [14-16]. One category corresponds to the radionuclide calorimeters
including radioactive source for the investigation of several parameters: activity (disintegrations per
unit time), half-life, or disintegration or residual power. The second and the third categories associated
to external sources are used as reference measurement methods to calibrate other sensors.
The last one concerns the in-pile or in-reactor calorimeter. It is devoted to the quantification of the
nuclear heat deposition rate in specific samples by means of temperature difference measurements.
Due to constrains induced by harsh nuclear experimental conditions (limited space, radiations, heating,
...), the thermal running mode of an in-pile calorimeter is mainly a permanent non isothermal mode
instead of an adiabatic one. In fact, in that permanent case, the calorimeter exchanges with its
surroundings and so no additional instrumentations (vacuum loop, shields, and heat loss compensation
system) dedicated to a high thermal insulation are required. Moreover, the permanent calorimeter can
reach a stationary thermal state, thus it can remain in the experimental channel to perform
continuously measurements. Moreover, the design of the in-pile calorimeter is often very simple.
Now, two kinds of calorimetric configurations exist: a single calorimeter which consists of one cell [1-
3] containing a sample such as stainless steel, molybdenum, aluminum or iron; or a differential
configuration: a differential calorimeter containing various identical cells (superposed [13] or
juxtaposed [6]) located in a common jacket.

The studied calorimeter consists of a permanent differential calorimeter. It is composed by
superposed twin cells divided into three main parts made of aluminum: a sample holder, a rod/pedestal
(3.6 mm in diameter and 20 mm in length), and a base (17 mm in diameter and 35 mm in length) in
contact with an external stainless steel jacket (0.5 mm in thickness). In the first cell, denoted the
sample cell, the sample holder contains a graphite kernel and in the second one, denoted the reference
cell, the graphite kernel is replaced by nitrogen. Moreover each cell is instrumented by two
thermocouples (type K, 0.25 mm in diameter) located in the upper part of the rod and on the middle
height of the base (cf. Figure 1) and each sample holder contains an electrical heater to perform the
cell calibration under non irradiation conditions by simulating nuclear heat deposition rate by means of
Joule effect.

The calorimeter is called differential because the nuclear heat deposition rate is deduced from the
two cells. In fact as the interactions between radiations and matter occur on all elements of the
calorimeter, the sample cell response \( (T_{rod} - T_{base})_{\text{sample}} \) is used to quantify the nuclear heating
transferred to the calorimeter structure and to the graphite sample, whereas the reference cell response
\( (T_{rod} - T_{base})_{\text{reference}} \) is used to quantify the nuclear heating transferred only to the calorimeter structure.
Moreover, in order to avoid the influence of the nuclear heating gradient inside experimental channels,
the long calorimeter (~210 mm) has to be moved to measure the response of each cell at the same vertical location. This operating protocol represents the major drawback of this superposed configuration.

Consequently the nuclear heat deposition rate into the graphite kernel is deduced from two temperature differences obtained respectively on the sample cell, then on the reference for the same location. Moreover, if the calibration curves are linear, this nuclear heating is equal to:

\[ P_n = K \left[ (T_{rod} - T_{base})_{sample} - (T_{rod} - T_{base})_{reference} \right] \]

with K corresponding to the calibration coefficient deduced from the sensitivity of each cell (W/°C) [13].

In our experimental and numerical studies under non irradiation conditions, the calorimeter is reduced to one cell: the sample cell because the calibration curves of the sample cell and the reference cell are similar. The slight variation can be induced by mechanical differences [13].

2.2. Experimental set-up and associated operating procedure

The experimental set-up (cf. figure 1) is composed by an instrumented jacket containing the calorimeter sample cell, a thermostated circulating bath, a power supply and a data acquisition system (temperature, tension, current intensity). The instrumented closed brass jacket (5.5 mm in thickness) is filled with nitrogen at atmospheric pressure. It contains fifteen calibrated thermocouples located vertically along its surface in order to determine the temperature profile along the internal jacket surface and to estimate the convective heat transfer coefficient. It contains three fluxmeters respectively glued on three external surfaces: upper one (10 mm in diameter, a sensitivity equal to 0.683 μV/(W/m²)), lower one (20 mm in diameter, a sensitivity equal to 1.95 μV/(W/m²)), and lateral one (50 mm in length and 5 mm in wide with a sensitivity equal to 1.77 μV/(W/m²)) at the sample holder and the rod levels (cf. Figure 1 on the right). These fluxmeters correspond to thin foil heat flux sensors measuring induced temperature tangential gradients by means of a junction array between two thin copper surfaces (low intrusive). They are used to quantify heat losses which have to be minimized to ensure a good vertical “heat flow” between the two thermocouple locations.
Figure 2. Temporal evolutions of rod and base temperatures of sample cell (on the left) and of heat flux densities (on the right) for various electrical powers for a low Reynolds number equal to 610.

The thermostated circulating deep bath is used to simulate an upward cooling water flow inside a vertical cylindrical channel under non irradiation conditions (9.9 cm in diameter and 40 cm in length). The instrumented jacket is immersed inside this cylindrical channel with an imposed laminar forced convection (Re<1900, annular geometry with an hydraulic diameter equal to 7.1 cm). The electrical heater inside the sample holder is connected to the power supply to simulate nuclear heating. For each tested flow velocity ($V < 2.5 \text{ cm s}^{-1}$), a power range from 0 to 2.5W is tested with an increment equal to 0.5W applied during 40 minutes to reach the stationary state (cf. Figure 2 on the left).

2.3. Calorimeter thermal behaviour, influence of flow boundary conditions

2.3.1. Calibration curve

For each imposed conditions, the mean rod and base temperatures (cf. locations on Figure 1) are calculated during the established stationary state in order to determine the sensor response. The calibration curve is defined by the temperature difference versus the injected electrical power. It is given for a low and a higher Reynolds numbers on Figure 3. The calibration curve is linear. It is due to the fact that for the tested power range, the thermal conductive transfer is predominant inside the calorimeter. Indeed the rod temperature is lower than 65°C (cf. Figure 2 on the left) and thus the heat losses by thermal radiative transfer are negligible into the nitrogen in front of the sample holder and of the rod. Moreover the calibration curve and the sensor sensitivity (curve slope 13.7°C/W) do not depend on the convective flow intensity in the laminar case. To conclude, for this tested power range the calorimeter can be considered as a conductive heat flow sensor with conductive heat losses through the nitrogen cavity inside the calorimeter.

Figure 3. Temperature difference versus the electrical power for two Reynolds numbers.
2.3.2. Heat losses

Figure 4. Heat losses versus the electrical power for a low Reynolds number equal to 610 (on the left) and lateral heat losses versus this number for an electrical power equal to 2.1W (on the right).

Fluxmeters allow the quantification of these heat losses in three areas. For instance, mean lateral heat losses are determined from the curve presented on figure 2 (on the left) by integration of the heat flux density on the external jacket surface limited to the height of the rod and the sample holder. For each area, the heat losses are found proportional to the imposed electrical power (cf. Figure 4) and the highest heat losses correspond to the heat evacuated through the nitrogen in front of the rod and the sample holder. Moreover Figure 4 (on the right) shows that these located lateral heat losses decrease when the Reynolds number is increased and seem to reach a stationary value. This decreasing is due to the fact that a higher convective heat transfer coefficient leads simultaneously to a higher “heat flow” from the sample holder to the base which is directly in contact to the surface jacket and to a decreasing of the conductive heat exchanges through the nitrogen cavity.

To sum up a good directional (vertical) heat flow calorimeter can be obtained with a high convective heat transfer. In particular this thermal behavior will be useful at higher temperatures under irradiation conditions in order to decrease the temperature field (safety requirements) and the radiative heat transfer through the gas cavity inside the calorimeter.

3. Numerical study of the sensor response

3.1. Validation of the numerical model

In order to perform a parametric study on the sensor characteristics, a thermal 2D axi-symetrical model is developed. The aims of these studies are to improve the sensor sensitivity and to find a new smaller calorimeter design. A similar model for natural boundary conditions was used previously [11]. To sum up these numerical works: meshed domain is reduced to the sample cell and its external closed jacket, and thus only heat equation is solved. As for a low power, the sensor corresponds to a conductive heat flow sensor, this equation is reduced to a conductive term taking into account the variation of material thermal conductivity versus temperature and contained a source term applied only into the heater area corresponding to the heat induced by Joule effect. The nitrogen cavities are considered as conductive static gas cavities and radiative transfers are neglected for the tested electrical powers. Boundary conditions are adiabatic conditions on the upper and lower horizontal surfaces of the jacket and convective conditions along its vertical external surface by using the correlation corresponding to an annular laminar forced convection. The 2009 CASTEM code is used. The computational domain is meshed by finite elements due to the complexity of the calorimeter geometry. An implicit scheme is used. Figure 5 compares the experimental and numerical temperatures (cf. locations on Figure 1). A good agreement is found. The discrepancy on the sensor sensitivity is less than 4%.
3.2. Parametric study
This numerical parametric stationary study focuses on the sensor sensitivity. The aim is to design a more sensitive calorimeter which could be used for a lower power range (<3W) in experimental channels of the reflector. For a low power range, this studied calorimeter corresponds to a conductive directional heat flow sensor. A higher “directional thermal resistance” between the two temperature measurement locations and between the sample holder and the jacket leads to a better sensitivity. Consequently the main influent parameters on its sensitivity are the size of its elements, the material property (thermal conductivity), and its geometry. For instance the study of the thermal conductivity influence for each area of the meshed domain (the heater, the sample, the cell (sample holder + rod + base), the jacket, the gas) is performed. Figure 6 shows that the sensor sensitivity can be mainly increased by changing the cell material (stainless steel instead of aluminum) or/and the nature of the gas (argon instead of nitrogen) which leads to heat loss decreasing. Concerning the influence of the size, previous works have shown that the sensitivity can be increased significantly by changing the rod dimensions [12].

Figure 5. Experimental and numerical results: temperatures (left), calibration curve (right).

Figure 6. Sensor sensitivity versus the thermal conductivity of materials located into various areas inside the calorimeter (gas on the left, solid on the right).

These results led to new calorimeter dimensions for the first CARMEN prototype: a smaller rod radius with a higher rod length. However, in order to keep the calorimeter size (no increasing), the base length had to be reduced. In conclusion, it is difficult with this geometry to reduce the size of the sensor and thus a new calorimeter design could be more suitable.
In a first approach, the response of our calorimeter is compared to a very simple single calorimeter. The calorimeter is reduced to the sample holder area. The rod and the base elements are removed. The response of this simple configuration with concentric cylindrical elements was initially estimated by a 1D stationary solution [17]. Then, the same numerical model than the one used to the differential calorimeter is applied. The single calorimeter sensitivity is higher: 173°C/W (Cf. Figure 7 on the left), but the maximal temperature inside the calorimeter is higher too (95°C for a power equal to 0.4W). Consequently this kind of calorimeter could be suitable for a low nuclear power. If a wide range of nuclear heating is targeted, the thickness of the nitrogen cavity could be reduced. This reduction leads to a decreasing of the maximal temperature and of the sensitivity (Cf. Figure 7 on the right). This preliminary simple design will be improved and new boundary conditions will be tested.

4. Conclusion and outlooks
Experimental and numerical studies on the sample cell of a permanent radiometric differential calorimeter were carried out under non irradiation conditions to determine the response of the sensor for a low power range. An instrumented jacket was realized in particular to quantify the heat losses. The experimental results showed that the calibration curve of this calorimeter does not depend on the laminar flow boundary conditions. The calorimeter design ensures a good directional heat flow (low heat losses). A thermal numerical model was developed, validated and used to perform a parametric stationary study. The sensitivity of the sample cell could be increased by taking a more resistive material for the cell and a more resistive gas. However to obtain a smaller sensitive calorimeter, a new geometry corresponding to the sample holder of the differential calorimeter gave promising results. The tested power range will be increased experimentally. Consequently, the thermal model will be modified to consider the thermal radiative transfer. Moreover, a non-stationary study will be performed to quantify the sensor response time. A low response time is relevant because it decreases the sensor ageing due to the radiations. At last, the equation source term will be applied on the whole calorimeter by taking into account the vertical gradient of the nuclear energy inside a reactor channel (the highest energy at the middle plane of the core) and the interactions between radiations and each material. These numerical works will be developed for the two calorimeter designs.

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