



Temperature Distribution on Fuel Rods: A Study on the Effect of Eccentricity in the Position of UO₂ Pellets

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ABSTRACT

This work deals with a study of heat conduction in rod type fuel elements. A method of solving the heat transfer equations applied in nuclear fuel rods using the finite element method was developed in order to evaluate the performance and safety of nuclear systems. A computational code was developed in order to evaluate the equations governing the problem, the boundary, and initial conditions. This program is coupled to GiD, which is a universal, adaptive and user-friendly pre and postprocessor for numerical simulations in science and engineering. The method was validated against an analytical solution derived by Nijsing in reference [1] with error less than 1.4% and with respect to an improved analytical solution given in reference [2] for axisymmetric rod and eccentricity rod with error less than a 3.6%. Applications have been developed using temperature dependent physical properties for the resolution of an axisymmetric rod and for the resolution of a rod with eccentricity. The present method allows the analysis of fuel rods in the given situations and other scenarios, also, it is a substantial tool for the analysis of fuel rods.

1 INTRODUCTION

The prediction of the appropriate temperature distribution and location of the maximum temperature at points of interest will be useful for the design of nuclear fuel with a higher level of security, performance and economy. The evaluation of the sensitivity of the fuel pellet eccentricity from the center of the rod will be useful to assess tolerance ranges used in the design and manufacture of nuclear fuels. The finite element method presented in this paper may be used to solve complex heat conduction problems associated with the design of rod type fuel elements. The use of temperature-dependent properties makes the problem nonlinear and impossible to be solved by analytical solutions.

2 PHYSICAL MODEL

2.1 Fuel element, fuel rod and coolant channel

The main factors affecting fuel element heat transfer are geometrical configuration, neutron flux distribution, types of fuel and cladding used and coolant flow conditions. In an individually cooled rod the heat transfer coefficient varies peripherally if the fuel rod is not concentric with respect to the channel wall. Factors inherent to the fuel rod also may have an important effect on heat transfer. Fuel and cladding are separated by gas gap. The presence of a gas gap introduces a considerable resistance against heat transfer. In case the fuel pellet is not entirely concentric with respect to the cladding the thermal resistance may vary significantly around the rod.

The non-uniform heat transfer conditions referred to above have an effect on the temperature and heat flux distribution in fuel and cladding which may be evaluated by solving the heat conduction equations. It is assumed that all the heat generation occurs in the fuel pellets. The highest temperature values found in the z direction are along the active length, as it is the place where the fuel pellets are located.

This paper solves the problem of temperature distribution in a rod and it finds the maximum temperatures of the monitored points, through a solution methodology where the equations of heat generation and heat transfer in two-dimensional sections (xy plane) of the rod are solved and engaged in the z direction by the coolant. The heat conduction between the pellets in the Z direction (axial) is neglected due to the small thermal gradient in this direction compared to the thermal gradient in the radial direction [3].

The problem of temperature distribution is considered in the rod with the maximum power level of the fuel element, as it is the rod that presents the highest levels of temperature during operation in steady state.

The analysis of an internal equivalent channel is of greater interest, because it has the highest level of power generated, so must have the highest levels of temperature, and represents the largest number of rods of an element.

One of the approaches in solving the problem is that the temperature of the coolant was modeled as constant in each Z coordinate of the coolant channel.

The heat generation profile used in this problem is illustrated in Figure 1. This profile is a good approximation for a rod composed of fuel pellets of the same level of enrichment during the initial operation and without the insertion of control rods [3].

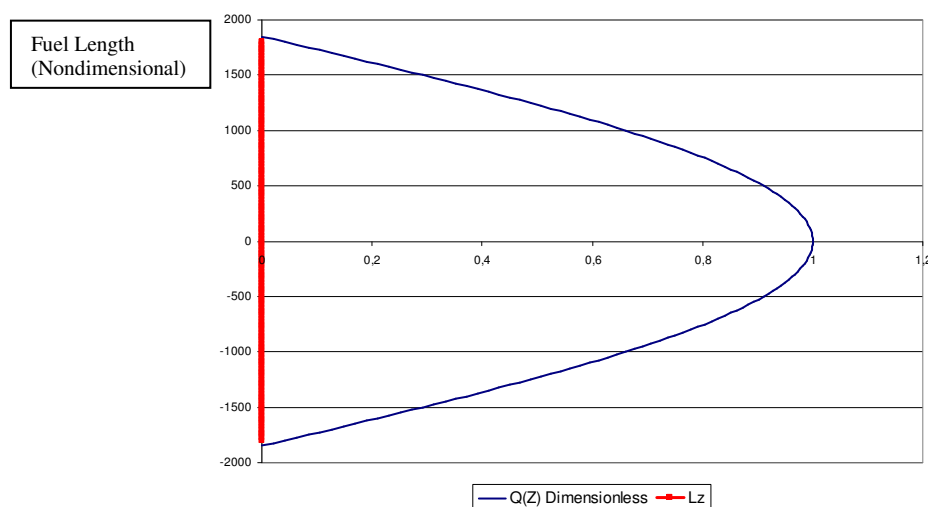


Figure 1 - Heat generation profile in the Z direction along a rod.

2.2 Integration of the energy equation of the fluid along the Z direction

It is assumed that all energy generated in the fuel pellet is transported to the coolant. The following equation shows this relationship.

$$\dot{m} \frac{\partial h}{\partial z} = Area_{pellet} \cdot q'''(z) \quad (1)$$

Assuming no change in the pellet area and no variation of mass flow, we can integrate the previous equation.

$$\dot{m} \int_{-H/2}^z \frac{\partial h}{\partial z} = Area_{pellet} \cdot \int_{-H/2}^z q'''(z) \quad (2)$$

Substituting $q'''(z)$ we can obtain:

$$\dot{m} \int_{-H/2}^z \frac{\partial h}{\partial z} = Area_{pellet} \cdot q'''_{max} \int_{-H/2}^z \cos\left(\frac{\pi \cdot z}{H}\right) dz \quad (3)$$

The result of this integral is:

$$h(z) = h(in) + \frac{Area_{pellet} \cdot q'''_{max} \cdot H}{\dot{m} \cdot \pi} \cdot \left(1 + \sin \frac{\pi \cdot z}{H}\right) \quad (4)$$

The previous expression allows finding the value of the coolant enthalpy at each section z . Consequently, as fluid pressure is known, one can determine the temperature of the coolant as well as its physical properties at this temperature.

The above analytical solution allows the determination of the fluid temperature for any specified Z coordinate along the channel. Thus, in the implementation of this method, the Z direction is discretized by dividing the total height of the channel into N equal segments so that the size of each segment is given by $\Delta z = H/N$. Consequently, the enthalpy of the fluid (and the corresponding temperature) will be calculated at $Z_i = (i - 1) \cdot \Delta z$, with i varying from 1 (input channel) to $N + 1$ (output channel).

2.3 Energy conservation in the cross section of the rod

In this model it is assumed that the axial heat conduction in the rod can be neglected when compared to the intensity of the heat flux in the cross section. In this case, the energy conservation at each cross section of the rod can be approximated by a two-dimensional problem set for each Z_i of the discretization along the channel.

Figure 2 shows a schematic representation of the cross section to be analyzed, with the identification of the domains and the boundaries. The problem is defined in the domain that includes sub domains occupied by the fuel, gap and cladding.

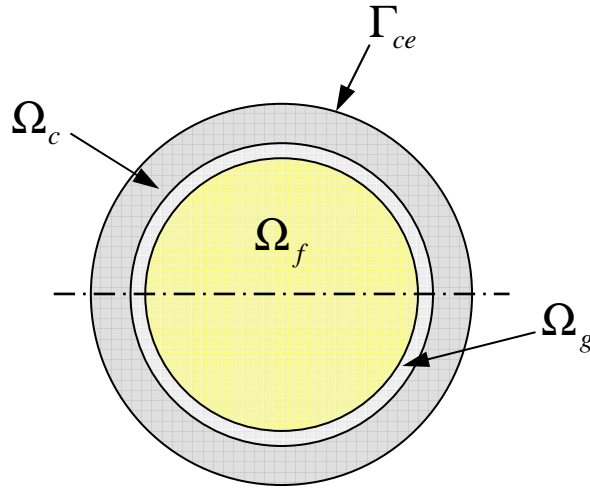


Figure 2 – The domains and boundaries of the problem

Where: Ω_f – fuel domain, Ω_g – gap domain, Ω_c – cladding domain, and Γ_{ce} – cladding and coolant boundary.

The energy conservation can be formulated by the variational form shown below. It is easy to show [4] that the variational formulation given by equation (5) implies in the satisfaction of the energy balance for each material present (fuel, gap and cladding), but also implies in the continuity of the heat flux at the interfaces between fuel and gap and between gap and cladding. The heat transfer from the outer surface of the cladding to the coolant is also satisfied by the variational formulation, which incorporates the film coefficient h and the temperature of the coolant.

Let $H^1(\Omega)$ be the space of functions defined in Ω that are integrable squares and have first order spatial derivatives that also are integrable squares [4]. The variational problem consists in determining the temperature field $T \in H^1(\Omega)$ that satisfies:

$$\int_{\Omega} \frac{\partial \phi}{\partial x_i} k \frac{\partial T}{\partial x_i} d\Omega + \int_{\Gamma_{ce}} \phi h T d\Gamma = \int_{\Omega} \phi Q d\Omega + \int_{\Gamma_{ce}} \phi h T_{\infty}(z) d\Gamma, \text{ for any } \phi \in H^1(\Omega). \quad (5)$$

The finite element method (Galerkin method) is used to discretize the variational formulation given by equation 5. It is used triangular finite elements with linear interpolation functions and the conjugate gradient method (with Jacobi pre-conditioner) is used for solution of the system of linear equations resulting from discretization [5].

3 NUMERICAL RESULTS

3.1 Validation of the methodology

The validation of the present program with the use of constant properties was intended to test the adequacy of the methodology employed by the resolution of an analytical solution. We have validated this methodology with three different cases [6].

In the first case the solution found by the proposed program was compared with the analytical solution described in the example 13-2 of reference [1]. In the second example the program was validated against the problem 13-1 of [1]. In the third example simulations were

carried out in relation to the paper of Nijssing [2]. Due to the extent of the present paper, these validations are not presented.

3.2 Case study: Fuel Rod with eccentricity

Two scenarios of interest for nuclear reactors were solved. The peripheral variation of the temperature at the outer cladding surface in the case of a symmetrical fuel rod was solved first, in order to validate the methodology. This simulation was performed with a large number of elements which enabled to obtain a solution with great accuracy [6]. This paper presents the second scenario, which is the rod with eccentricity. All pellets of the analyzed rod have about ninety-nine percent of the width of the gap on the west side of the rod. This approach is quite rigorous, because the probability that all pellets are displaced in a rod should be low.

The mesh used to model the cross sections of the rod was built with 10,730 elements and 5442 nodes. The active length of the rod was divided into 366 segments of 10 mm in height, with the aim of achieving an appropriate level of accuracy in obtaining results along the Z direction, including the accuracy of the position of the monitored sections.

Figure 3 shows a section of the rod with the mesh used in this case. Note the greater refinement of the mesh in the region where the gap is smaller.

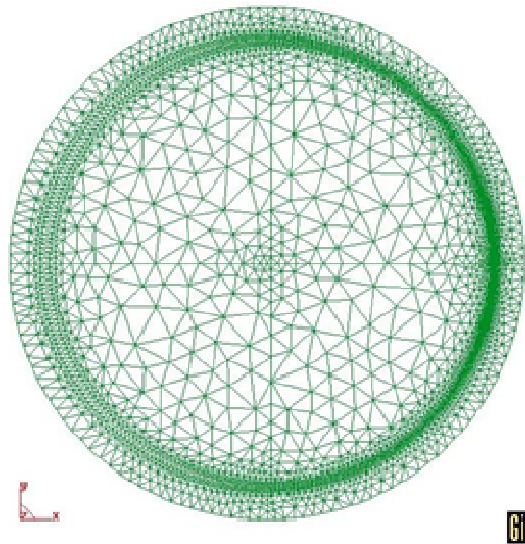


Figure 3 – Mesh used in the case of the rod with eccentricity

Table 1 lists the monitored points of the rod along the z direction, there is the displacement in x direction from the center of the pellet with respect to fuel rod axisymmetric.

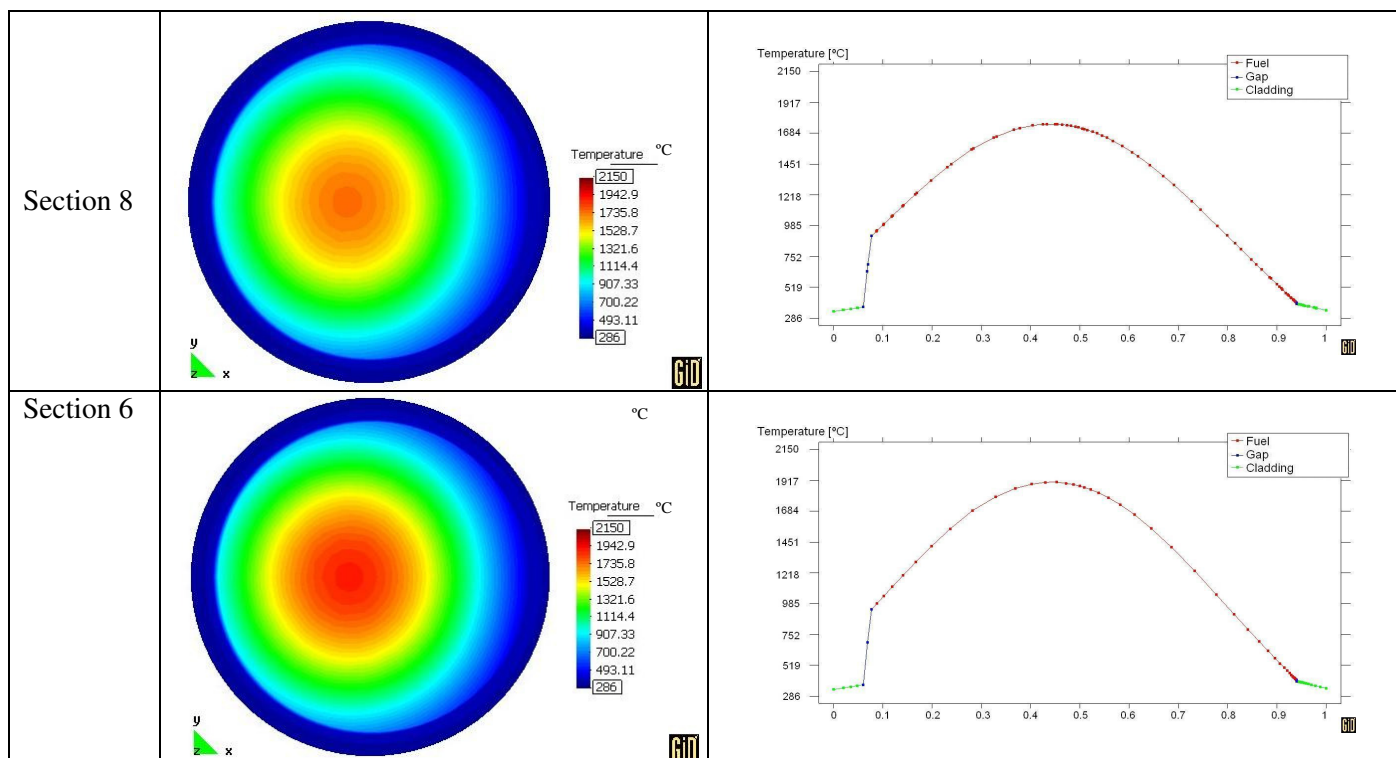
Table 2 lists the sections that are monitored. A greater number of sections is necessary due to the shift in z direction of the positions where the maximum temperatures of the internal and external surface of the cladding occur. The displacement of the positions of maximum temperatures is due to the eccentricity of the pellet and the use of real properties for water and the composition of the rod material. Figure 4 shows the temperature distribution of monitored sections and the temperature profile along the radial direction.

Table 1 – Monitored point along the Z direction

Monitored Point	Coord-X [Dimensionless]	Coord-Y [Dimensionless]	Coord-X [mm]	Coord-Y [mm]
1 – Center of the rod	0,0000	0,0000	0,00	0,00
1p – Center of the pellet	0,0083	0,0000	0,079	0,00
2 - Tcl int east	0,4400	0,0000	4,18	0,00
3 - Tcl int west	-0,4400	0,0000	-4,18	0,00
4 - Tcl ext east	0,5000	0,0000	4,75	0,00
5 - Tcl ext west	-0,5000	0,0000	-4,75	0,00
6 - Tcl int north	0,0000	0,4400	0,00	4,18
7 - Tcl int south	0,0000	-0,4400	0,00	-4,18
8 -Tcl ext north	0,0000	0,5000	0,00	4,75
9- Tcl ext south	0,0000	-0,5000	0,00	-4,75

Table 2 – Monitored Sections

Monitored Section	Coord-Z
1	-915,00
2	135,00
3	340,00
4	400,00
5	410,00
6	660,00
7	760,00
8	800,00
9	915,00
10	1829,00



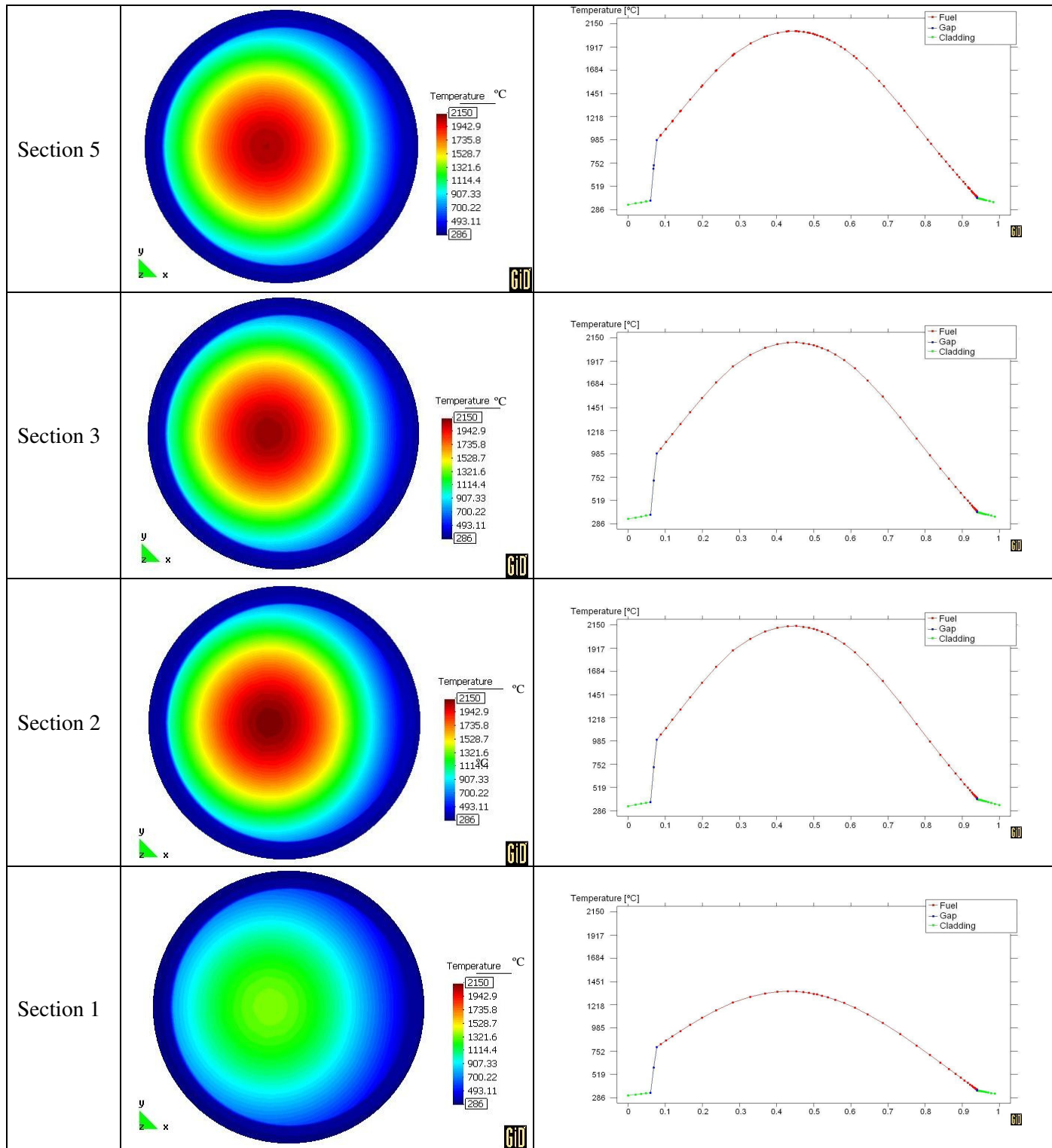


Figure 4 - Temperature distribution of monitored sections (table 2) and the temperature profile along the radial direction (Plane 0 - π)

The Figures 5 and 6 show the temperature evolution of maximum fuel, inner and outer surface of the cladding and bulk temperature. We note in Figure 5 the increased temperature level of the cladding.

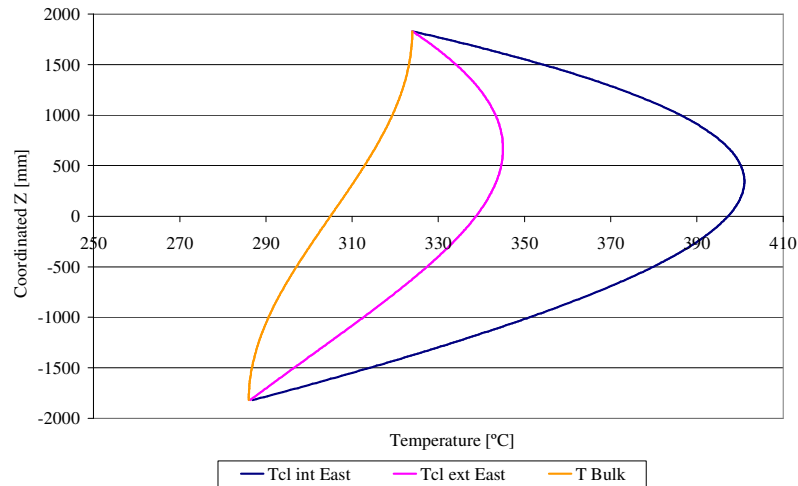


Figure 5 - Internal and external cladding temperature and coolant temperature

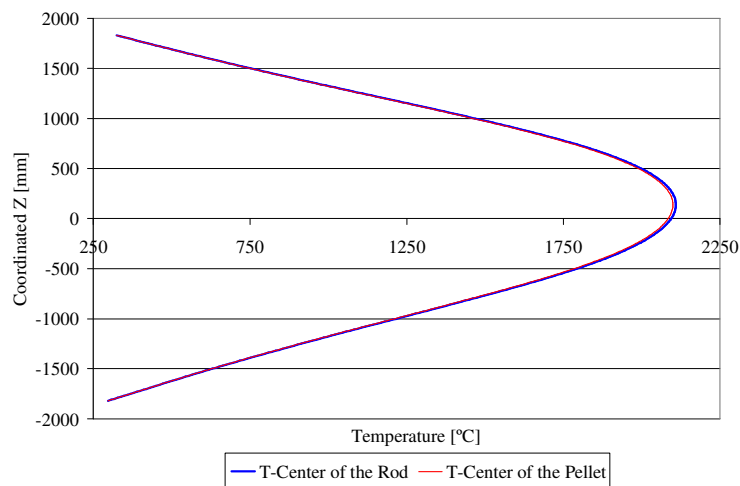


Figure 6 - Pellet and rod central temperatures

Table 3 has the values of the positions where the maximum temperatures occur in the solution of axisymmetric rod compared with the results of the solution of the rod with eccentricity. Variations in the position where maximum temperature occurs at the points 1, 6 and 7 are due to different number of segments used in the approximation of these scenarios.

The difference in the position where maximum temperature occurs at the points 8 and 9 is slightly higher (- 13,5mm) because it has the effect of eccentricity combined with the effect of the smaller number of iterations.

The monitored points 3 and 5 relating to internal and external surface of the cladding on west position are located at a greater distance from the pellet and have greater coordinates in the z direction, because they suffer little effect of heating rate. This shift does not take a penalty on performance and safety of the rod.

The points 2 and 4 referring to internal and external surface of the cladding on east are situated within a shortest distance from the pellet and have smaller coordinates in z-direction, because they suffer a greater effect of heating rate. This shift takes the penalty on performance and safety of the rod, as the points where DNB can occur are in a lower position.

The displacement of point number 2 is -45 mm and the displacement of point 4 is -76.5 mm.

Table 3 - Comparison of the locations where the maximum temperatures occur in axisymmetric rod and rod with eccentricity

Monitored Point	Maximum temperature position in the axisymmetric rod - Zmax [mm]	Maximum temperature position in the Rod with eccentricity - Zmax [mm]
1 – Center of the rod	1965,5	1970
1p – Center of the pellet	1965,5	1970
2 - Tcl int east	2220	2175
3 - Tcl int west	2220	2245
4 - Tcl ext east	2576,5	2500
5 - Tcl ext west	2576,5	2625
6 - Tcl int north	2220	2225
7 - Tcl int south	2220	2225
8 - Tcl ext north	2576,5	2590
9 - Tcl ext south	2577	2590

Table 4 lists the values of maximum temperatures of the monitored points. The monitored points 6, 7, 8 and 9 didn't show significant change between the cases of axisymmetric rod and rod with eccentricity. The small deviation is probably due to the number of segments used. Note that among them the temperature value found is equal.

The point number 2 on the rod with eccentricity has a value of temperature 18.30 ° C greater than the scenario where the rod is axisymmetric and the position where this higher temperature occurs is 45 mm below the point for axisymmetric rod.

Point number 4 on the rod with eccentricity has a value of temperature 6.08 ° C higher than the scenario where the rod is axisymmetric and the position where it occurs is 76.5 mm below, compared to the axisymmetric rod. The temperature difference between the points 4 in the two scenarios is smaller than the temperature difference of point 2 in both scenarios due to the effect of heat transfer along the thickness of the cladding.

This situation is important because the outer surface of the rod in point 4 exceeds the saturation temperature of the coolant with 0.2 ° C, indicating that for a higher power level, it needs to use a heat transfer correlation for nucleate boiling.

Table 4 - Calculated temperatures in axisymmetric rod and rod with eccentricity.

Monitored point	Maximum temperature in the axisymmetric rod [°C]	Maximum Temperature in the Rod with eccentricity [°C]
1 – Center of the rod	2214,65	2109,16
1p – Center of the pellet	2214,65	2099,49
2 - Tcl int east	382,69	400,99
3 - Tcl int west	382,69	373,14
4 - Tcl ext east	338,92	345,01
5 - Tcl ext west	338,93	335,76
6 - Tcl int north	382,69	380,05
7 - Tcl int south	382,68	380,04
8 - Tcl ext north	338,93	337,95
9 - Tcl ext south	338,93	337,94

Figure 7 shows the cladding temperature distribution along the perimeter.

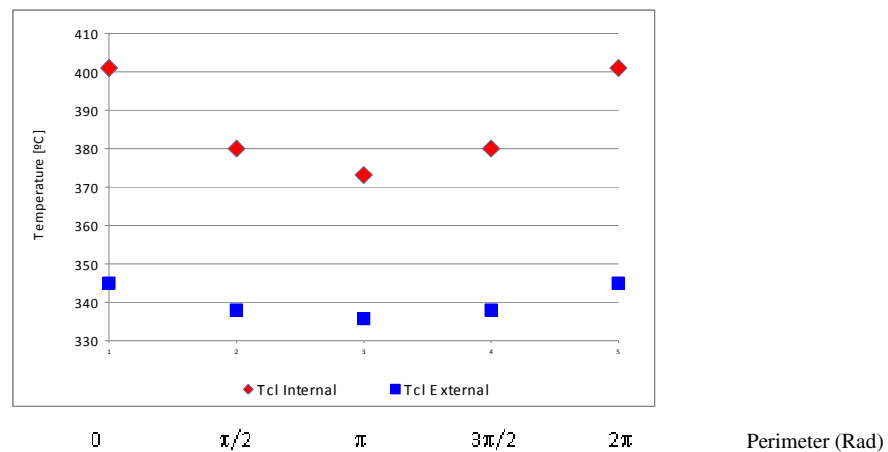


Figure 7 – Cladding temperature distribution along the perimeter

The rod with eccentricity has a temperature distribution on the outer and inner surface, because there is a temperature gradient along the perimeter. In position 0 (zero) radians, the pellet is closer to the cladding, so the cladding temperatures are higher in this angular position. The gap and cladding conductivity as a function of temperature, provides a more accurate simulation of the behavior of heat transfer in the gap and cladding

There is a heat flux from position 0 (zero) to position π . The reduction of the temperature difference between outside and inside the cladding is due to the good heat conduction ability of the cladding material.

4 CONCLUSIONS

From the numerical results presented, we can demonstrate the effect of fuel pellet eccentricity on the radial fuel and cladding temperature distribution. The results showed the position where the maximum temperatures of fuel, internal and external surface of the cladding and the coolant occur. These measurements of position and temperature are of great interest for reactor design and operation. The values of maximum temperature of the outer surface of the cladding and its position can determine the type of heat transfer, the occurrence of nucleate boiling (DNB) and more design factors. The maximum fuel temperature is crucial to understand the heat transfer process in the fuel rod, the re-structuring process of the pellet and to prevent the fuel melting in the central region [7]. The method allows the analysis of temperature distribution in the cross sections of the rod (xy plane) to obtain radial profiles of temperature, which are also of interest to the engineering of reactors.

NOMENCLATURE

$Area_{pellet}$ - Cross sectional area of the fuel pellet

k - Thermal conductivity

Q - Heat generation

q'''_{max} - Maximum power density

q''' - Power density

h - Coolant enthalpy

h_{conv} - Heat transfer coefficient by convection

H - Length of a nuclear system

T - Temperature

\dot{m} - Mass flow rate of coolant

Z_{max} - Position where maximum temperature occurs

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