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ADVANCES IN THERMAL-HYDRAULIC STUDIES OF A TRANSMUTATION ADVANCED DEVICE FOR SUSTAINABLE ENERGY APPLICATIONS

Laura García Fajardo[1], Carlos García Hernández[2], Facundo Alberto Escrivá Castells[3], Leorlen Rojas Mazaira[2] and Carlos Brayner de Olivera Lira[4]

[1] Technology Department. European Organization for Nuclear Research (CERN), Geneva, Switzerland
laura.gf@cern.ch

[2] Higher Institute of Technologies and Applied Sciences, Havana, Cuba
cgh@instec.cu, lrojas@instec.cu

[3]Energetic Engineering Institute, Polytechnic University of Valencia, Valencia, Spain.
aescriva@iqn.upv.es

[4] Nuclear Energy Department. Federal University of Pernambuco.
cabol@ufpe.br

ABSTRACT

The Transmutation Advanced Device for Sustainable Energy Applications (TADSEA) is a pebble-bed Accelerator Driven System (ADS) with a graphite-gas configuration, designed for nuclear waste transmutation and for obtaining heat at very high temperatures to produce hydrogen. In previous work, the TADSEA's nuclear core was considered as a porous medium performed with a CFD code and thermal-hydraulic studies of the nuclear core were presented. In this paper, the heat transfer from the fuel to the coolant was analyzed for three core states during normal operation. The heat transfer inside the spherical fuel elements was also studied. Three critical fuel elements groups were defined regarding their position inside the core. Results were compared with a realistic CFD model of the critical fuel elements groups. During the steady state, no critical elements reached the limit temperature of this type of fuel.

1. INTRODUCTION

The Transmutation Advanced Device for Sustainable Energy Applications (TADSEA) [1, 2, 3] is a pebble-bed Accelerator Driven System (ADS) initially conceived to transmute the nuclear wastes generated during the operation of conventional Light Water Reactors (LWR) and to obtain energy at very high temperatures of the coolant at the nuclear cores outlet, that make it ideal to produce hydrogen by means of thermochemical processes or high temperature electrolysis with high efficiency. It is a pebble-bed type nuclear system cooled by gas helium flowing downward through the core and uses as fuel plutonium and minor actinides confined into TRISO particles. The pebble bed has a hexagonal close configuration. In previous studies, the number of pebbles that fit inside the nuclear core was calculated and hence, the packing fraction of the pebble bed with hexagonal configuration. Taking into account the results, neutronic studies were performed to check the capability of the TADSEA to transmute nuclear wastes. Also, from the results of the neutronic calculations, thermal-hydraulic analysis and simulations were done in order to study possibility of obtaining coolants temperature at the cores outlet around 1000^oC [4].

A very important topic from the point of view of a nuclear reactors safety that should be studied is the fuel temperature during normal operation and transients, in order to assure the integrity of the materials that compose the fuel elements and avoid the fission products release. Heat transfer inside the pebbles is carried out by conduction to its surface, and heat transfer from the pebble to the fluid is carried out by forced convection. The theoretical temperature limit of the TRISO particles, which is the fuel type of the TADSEA, is fixed at 1600^oC according to different reasons [5, 6, 7, 8].

There are two main approaches for the CFD simulation of the geometry of the close packed pebbles: the porous approach and the realistic approach. In the previous thermal-hydraulic studies [4], the nuclear core was considered as a porous medium with the packing fraction calculated from the results of the number of pebbles contained in the core. In the porous approach, an averaged concept of porosity is applied to simulate the close packed geometry.

With the dramatic progress in computational capability, a realistic approach for the pebble geometry has been recently adopted by several researchers to simulate the distribution characteristics of gas flow within close packed pebble geometries. In the realistic approach, every pebble is modelled [9, 10, 11], this model has higher simulation detail as it allows to study the non-uniform thermal-hydraulic behavior within the closely packed pebble geometry, in order to locate hot spots and calculate the maximum temperatures in the fuel elements more accurately.

The main goals of this paper are: 1) obtaining a mathematic model to describe the temperature distribution inside the pebbles in the steady state, 2) applying the mathematic model to the fuel elements that present greater risk to reach the maximum temperature to verify that their maximum temperature does not exceed 1600^oC (1873 K), 3) Comparing the results of the mathematic model with a simulation of the detailed geometry of the pebble bed, performed in ANSYS FLUENT.

2. THE GEOMETRY OF THE TADSEA

For simulation purposes, the TADSEA's core has been divided into ten concentric cylinders and ten horizontal levels (Fig. 1) integrating the calculations in each ring formed by their intersection. At the beginning of the operation, each level is filled with fresh fuel; this is the initial load (IL). Then, every 99 days the lowest level of pebbles is extracted, the other levels change their position one level downwards and the upper level is filled with fresh fuel [12]. This way the fuel of the upper layer is burned during 990 days from its insertion to its extraction. After this point, the system has reached the equilibrium state, in which there is fresh fuel only in the upper level while fuel in the lowest level has passed by all the other levels; this is called the beginning of cycle (BOC). After reaching the equilibrium state, the end of the cycle (EOC) is the moment before the extraction of the fuel in the lowest level.

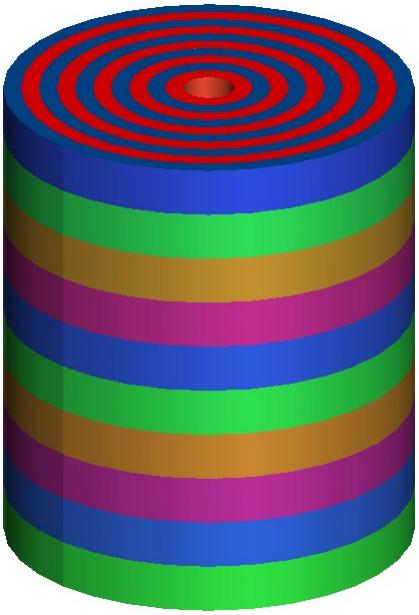


Figure 1: TADSEA's core model for simulations.

3. HEAT TRANSFER INSIDE THE FUEL ELEMENTS

Due to the big amount of TRISO particles randomly distributed inside each fuel element (each pebble in the core) it is very complicated and computationally expensive to make a heterogeneous model of it. In this work, two models have been performed: a homogeneous model where the fuel element is considered as a 3 cm radius sphere, composed by a homogeneous mixture of fuel and moderator with uniform properties, and a model in which the fuel element is considered as a 3 cm radius (R_B) sphere formed by a 2.5 cm radius (R_A) sphere composed by a homogeneous mixture of fuel and moderator with uniform properties, surrounded by a 0.5 cm layer of moderator (Fig. 2).

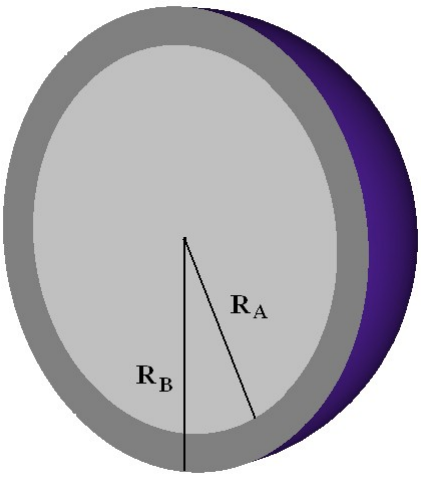


Figure 2: Non-homogeneous model for the fuel element.

For each conceptual model of the fuel element (homogeneous and non-homogeneous), a mathematical model is obtained to calculate the temperature distribution inside the fuel element during the normal operation of the TADSEA and verify that the limit temperature of the TRISO fuel used is not surpassed. The goal of developing two models is to compare the results and evaluate how the heterogeneity of the conceptual model influences the temperature distribution inside the fuel pebble.

a) Homogeneous sphere model:

To obtain the temperature distribution inside the fuel elements in this case, the Poisson's equation should be solved assuming the Neumann's boundary conditions for the centre of the sphere and the Robin's for the external surface.

Taking into account that the temperature and the heat flux are continuous at r = R_A, the solution of this boundary problem is:

$$T(r) = T_{\infty 1} + \frac{\dot{q}}{6k}\left[R^2 + \frac{2kR}{h_1} - r^2\right] \tag{1}$$

Where T is the ball's temperature and $T_{\infty 1}$ is the coolant's temperature [K], h_1 is the heat transfer coefficient [W/m^{2}K], $\dot{q}$ is the internal volumetric energy generation [W/m^3], k is the thermal conductivity of the pebbles material [W/m K] in the radial direction and R is the pebble's radius [m].

This equation permits calculating the temperature at each point of the fuel element considering that the energy generated in the sphere is conducted radially to the surface.

b) Non-homogeneous sphere model:

In this model, the fuel element is considered to be composed by two different material media: medium A, which is the sphere with radius R_A where the energy is generated, and medium B, which is the moderator layer (Fig. 2). To obtain the temperature distribution inside the sphere with radius R_B during the steady state, it is necessary to solve the Poisson's equation for medium A and the Laplace's equation for medium B.

The solution to the problem is, for medium A:

$$T(r) = T_{\infty 1} + \frac{\dot{q}R_A^3}{3k_B}\left[\frac{k_B}{R_B^2 h_1} - \frac{1}{R_B} + \frac{1}{R_A}\right] + \frac{q}{6k_A}\left[R_A^2 - r^2\right] \tag{2}$$

Which permits calculating the temperature at each point of the fuel element in the range $0 \leq r \leq R_A$, and for medium B:

$$T(r) = T_{\infty 1} + \frac{\dot{q} R_A^3}{3 k_B} \left[\frac{k_B}{R_B^2 h_1} - \frac{1}{R_B} + \frac{1}{r} \right] \tag{3}$$

Which permits calculating the temperature at each point of the fuel element in the range $R_A \leq r \leq R_B$.

Where T_A is the temperature of the internal sphere, T_B is the temperature of the graphite layer, k_A is the thermal conductivity of the material composing medium A and k_B of the medium B [W/m K] in the radial direction of the whole sphere. The other parameters have the same meaning as in Eq. 1.

4. TEMPERATURE DISTRIBUTION INSIDE THE FUEL ELEMENTS DURING THE NORMAL OPERATION OF TADSEA

In order to apply both analytical models to the calculation of the temperature distribution in the fuel elements during TADSEA's normal operation, three pebble types considered critical where chosen: 1) those that are in the region where the highest power density is generated (generically called "pebble 1"), 2) those that are in the region where the coolant is hottest (pebble 2) and those that are in the region where the produced power per unit volume and the coolant's temperature are relatively high (pebble 3). If they dont surpass the permitted temperature limit, the rest neither will. These three groups of pebbles will be analysed in the three core's states previously defined (IL, BOC and EOC).

a) Application of the homogeneous sphere model

The temperature distribution in this case is obtained through Eq. 1. The thermal conductivity (k) of the fuel elements, which were considered to be composed by a homogeneous mixture of pyrolytic graphite and the elements that compose the particle, is normally calculated using the volumetric average [13]:

$$k = \frac{\sum_i V_i k_i}{V} \tag{4}$$

Where i is the index for the material region and V is the total volume of the fuel pebble. Taking into account that each pebble has 4321 TRISO particles in this case, the characteristics corresponding to each region are shown in Table 1.

The heat transfer coefficient (h_1) was calculated according to the German Safety Guide [14], as well as the Nusselt and Reynolds numbers that appear in the equations. The physical properties of the helium also needed for the calculation of h_1, such as specific heat, dynamic viscosity and thermal conductivity, were calculated according to [15].

The power generated in the different rings of the core model (Fig. 1) was obtained from the neutronic studies. Dividing the power generated in each ring by the number of

Table 1: Characteristics of each material region in the fuel element [13].

Material	Kernel	Buffer	IPyC	SiC	OPyC	Graphite
Radius [m]	2.50E-04	3.45E-04	3.85E-04	4.20E-04	4.60E-04	3.00E-02
Total volume-V_i [m^3]	2.83E-07	4.60E-07	2.90E-07	3.08E-07	4.21E-07	1.11E-04
Thermal conductivity-k_i [W/m K]	3.46	1	4	18.3	4	25
Density [kg/m^3]	1.04E04	1.05E03	1.90E03	3.18E03	1.90E03	1.75E03
Specific heat [J/kg K]	3.12E02	7.10E02	7.10E02	1.30E03	7.10E02	1.73E03

pebbles it contains and by the pebble's volume, the energy generated per unit volume inside each pebble (q) is calculated. The helium temperature in the different rings ($T_{\infty 1}$), was obtained from the thermal-hydraulic studies of the porous core model [4].

The characterization of the critical pebbles after applying the homogeneous sphere model is shown in Table 2, and the temperature profiles from their centre to their surface, is shown in Fig. 3.

Table 2: Results applying the homogeneous sphere model.

Parameter	Pebble (1)	Pebble (2)	Pebble (3)
q [W/m^3]	3.46E07	2.23E06	1.35E07
k [W/m K]	24.7	24.7	24.7
$T_{\infty 1}$ [K]	1209	1443	1377
h_1 [W/m^2K]	5192.44	5383.14	5331.82
Centre temperature [K]	1485.75	1460.65	1484.30
Surface temperature [K]	1275.62	1447.14	1402.32

Using the homogeneous sphere model, pebbles 1 and 3 are the most critical fuel elements as they reach the highest temperatures, as shown in Table 2. Pebble 1 produces the highest power per unit volume, but the temperature of the surrounding helium is the lowest, so the heat extraction is higher and the temperature in the centre doesn't increase

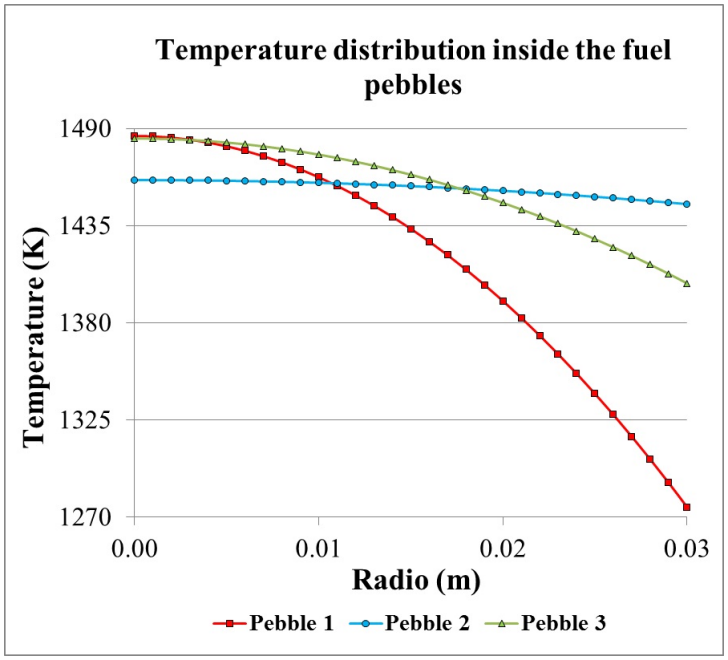


Figure 3: Temperature profile inside the critical fuel pebbles using the homogeneous sphere model.

so much. The opposite occurs in pebble 3: it produces lower power per unit volume than pebble 1, but the surrounding helium temperature is higher, so the temperature gradient is smaller than in the pebble 1 and the centre temperature is very similar to that of pebble 1.

Pebble 2 is the less critical using the homogeneous sphere model because its centre temperature is the lowest compared to the other critical pebbles. This is due to the fact that it is located in the region where the fuel is more burned. Nevertheless, the surrounding helium temperature is the highest, so the temperature gradient between the centre and the surface, and between the surface and the helium, is the smallest.

b) Application of the non-homogeneous sphere model results

The temperature distribution in this case is obtained through Eq. 2 and Eq. 3.

The thermal conductivity of the sphere with radius R_A (k_A) is obtained using Eq. 4 being now V the volume of the sphere with radius R_A. The thermal conductivity of the moderator layer is that of the graphite, shown in Table 1. The helium properties do not depend on the selected model for the heat transfer inside the fuel elements, so h_1 and $T_{\infty 1}$ are the same as those calculated for the homogeneous sphere model.

To obtain q, the same procedure as in the homogeneous sphere model is followed, this time dividing the power generated inside the pebble by the volume of the sphere with radius R_A.

The characterization of the critical pebbles after applying the non-homogeneous sphere

model is shown in Table 3, and the temperature profiles from their centre to their surface, is shown in Fig. 4.

Table 3: Results applying the non-homogeneous sphere model.

Parameter	Pebble (1)	Pebble (2)	Pebble (3)
q [W/m^3]	5.98E07	3.85E06	2.33E07
k_A [W/m K]	24.5	24.5	24.5
k_B [W/m K]	25	25	25
Centre temperature [K]	1612.94	1468.86	1533.72
Interface temperature [K]	1358.69	1452.47	1434.65
Surface temperature [K]	1275.63	1447.14	1402.32

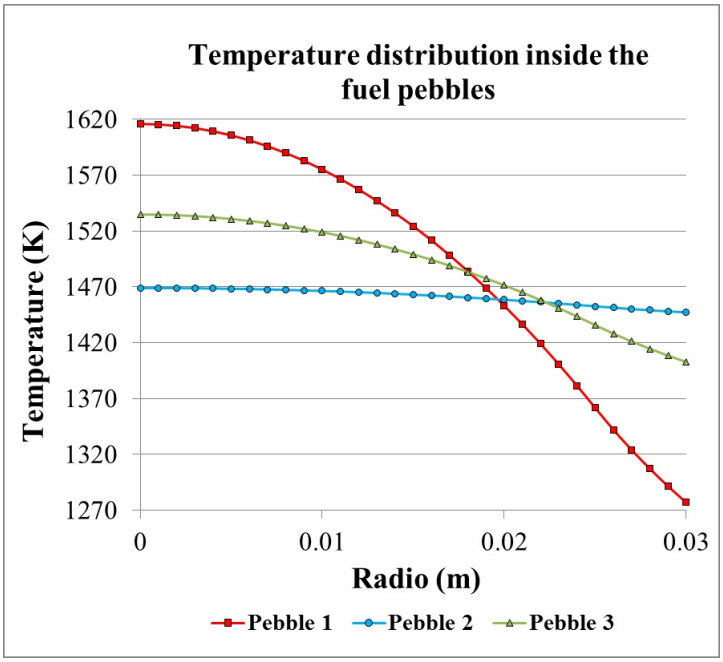


Figure 4: Temperature profile inside the critical fuel pebbles using the non-homogeneous sphere model.

Using the non-homogeneous sphere model, pebble 1 is the most critical because it reaches the highest temperature among all, followed by pebble 3 and then by pebble 2, in the same decreasing order of power generation (Table 3).

Comparing the results of the models, (Tables 2 and 3) the surface temperatures of the corresponding pebbles are practically the same since the helium extracts the same heat

from the fuel element regardless the heat transfer model considered. However, the temperatures in the centre are higher using the non-homogeneous sphere model; this happens due to a higher power density in the pebbles since the same power is generated in a smaller volume (the sphere of radius R_A), which in addition has a lower thermal conductivity.

During the steady state, none of the pebbles considered as critical fuel elements reach the limit temperature of this type of fuel (1873 K), as shown in Fig. 3 and Fig. 4. However, the maximum temperature reached by pebbles 1 and 3 when applying the non-homogeneous sphere model, is above the maximum temperature during normal operation (1523 K) according to Fig. 5.

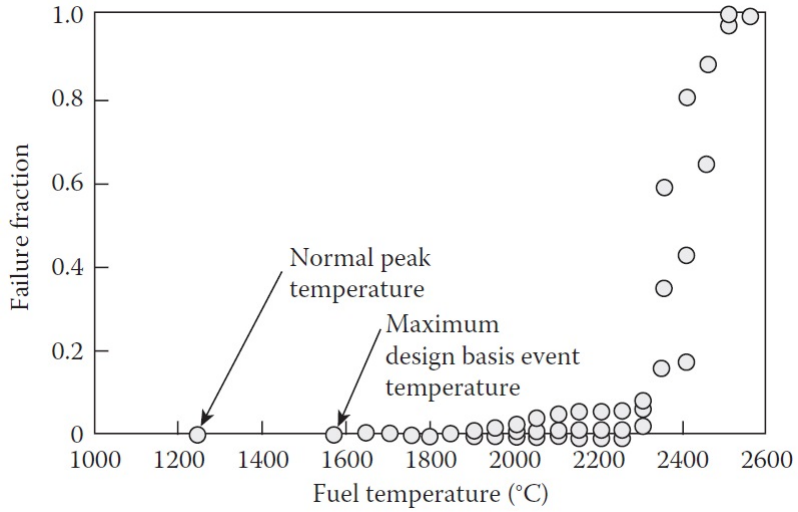


Figure 5: Failure rate of TRISO particles [16].

5. DETAILED CFD SIMULATIONS OF DIFFERENT CORE SECTIONS

In the case of the PBR (Pebble Bed Reactor), the distribution of the spherical fuel pebbles causes a highly complicated flow regime which finally results in differences in the degree of local cooling. The Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) model with the realistic approach can reasonably simulate the anisotropic thermal-hydraulic characteristics within the closely packed pebble geometry. In [9], the flow through the pebbles is simulated in a BCC (body-centered cubic) lattice as a segment of a PBR core with the large eddy simulation (LES) technique. In [10], advantages and disadvantages of realistic and porous approaches in the close packed pebbles with the BCC arrangement are investigated, comparing CFD simulation results. In [11], the effects of BCC and FCC (face-centered cubic) arrangements on the thermalhydraulic characteristics within pebbles have been investigated using a CFD methodology.

In previous studies [4], the simulation of the whole TADSEA's core was carried out using the porous medium approach. Then, in previous sections of this paper, the heat transfer inside the critical fuel elements was studied. Now, from the results used for the homogeneous model ($q, k, T_{\infty 1}$) will be established as boundary conditions to perform a detailed representation of one cores section with the following characteristics: 1) a FCC arrange-

ment is used with a spacing between pebbles such that the porosity is 0.64; 2) it contains 3 entire pebbles, 8 halves and 12 quarters, which amounts a total of 10 pebbles in five layers; 3) the helium flows from top to bottom (Fig. 6).

The simulation was performed for the critical pebbles 1 and 2: the pebbles that generate the highest power per unit volume and the pebbles in the region where the helium has the highest temperatures, respectively.

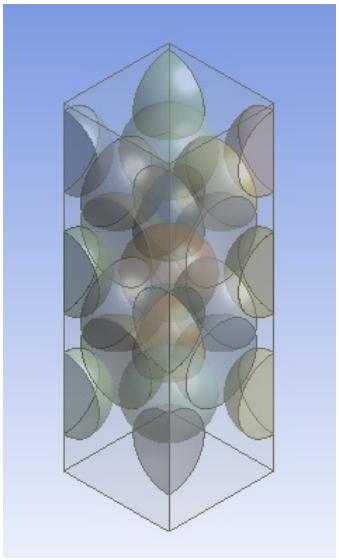
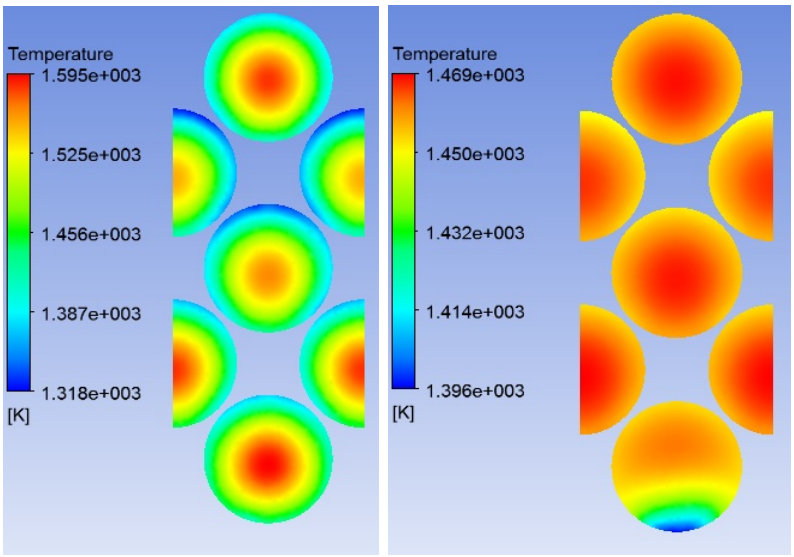


Figure 6: Detailed geometry of one section of the TADSEA's core.



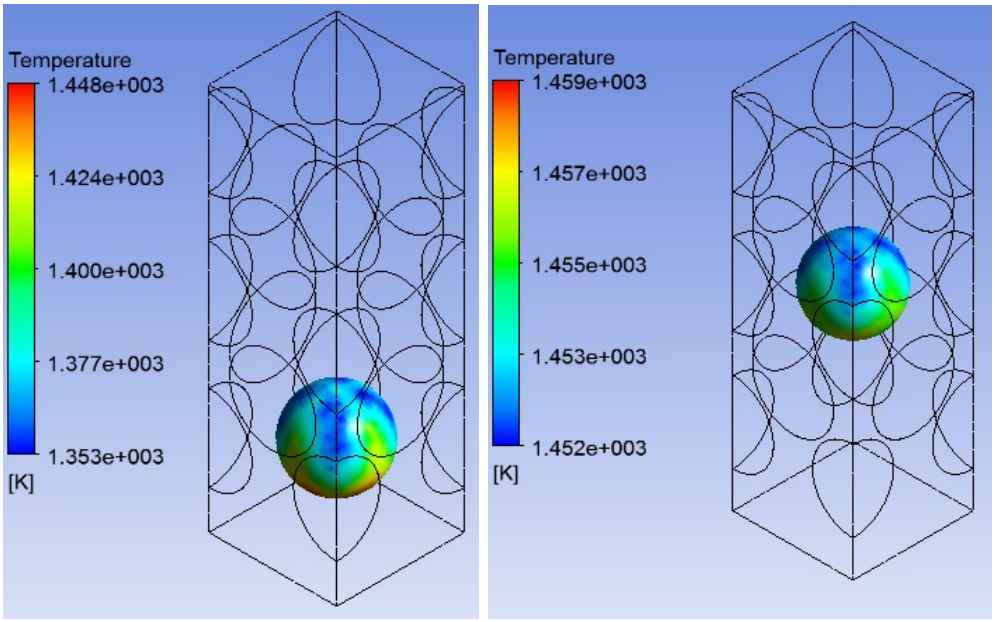
(a) Pebble 1 (b) Pebble 2

Figure 7: Temperature inside the pebbles.

The temperature distribution on the central plane of the section considered for pebbles 1 and 2 is shown in Fig. 7. The maximum temperature values obtained with the more realistic CFD model are higher than those obtained with the mathematical homogeneous model, but are very close to those from the mathematical non-homogeneous model. There

is a large temperature variation inside pebble 1, reaching 1595 K in its centre, very similar to the value obtained with the non-homogeneous model (1613 K), while the temperature profile in pebble 2 is rather flat (except for the pebble in the bottom) and the maximum temperature value at the centre is 1469 K, same as that of the non-homogeneous model (1469 K).

In Fig. 8 is shown the temperature distribution on the surface of the pebble of the section where the maximum surface temperature value is obtained, for both cases. In the case 1, it is the pebble in the last layer, but for the case 2 it is in the third layer. The maximun temperature values obtained for case 1 (1448 K) are superior to the 1276 K obtained by the analitical models, and for the case 2 (1459 K), this is slightly superior to the 1447 K by the analitical models.



(a) Pebble 1 (b) Pebble 2

Figure 8: Surface temperature of the pebbles.

6. CONCLUSIONS

With the objetive to obtain the temperature distribution at critical pebbles of TADSEA and to assure their integrity during normal operation were applied two mathematical models: a homogeneous model that consider the pebbles of fuel like spheres composed by a homogeneous mixture of all materials of TRISO particles and the graphite of the matrix and moderator, and a non-homogeneous model that consider the pebbles composed by an internal sphere composed by an homogeneous mixture of all materials of TRISO particles and the graphite of the matrix, surrounded by layer of graphite as moderator.

For each physical model was developed a mathematical model to obtain the temperature distribution inside of the three types of fuel elements considered as critical due to their location at reactor core: the region where more power is generated by volume unit, the

region where the helium is hottest and the region where power by volume unit and the helium temperature are relatively high.

Results of both models were compared and it is shown that the maximun temperature that reach the pebbles through the steady state is inferior that the limit temperature for this type of fuel for two models studied. The pebble that is located in the region with highest power density reach the highest temperature in the pebble center. With the non-homogeneous model were obtained temperatures in the pebble center highest than with the homogeneous model.

Additionally, it was carried out the realistic CFD simulation of a small core section, with the conditions stablished for the homogeneous model to "pebble 1" and "pebble 2". The maximun temperatures were superior that for the mathematical homogeneous model, but similar to the analitical non-homogeneous model.

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