2015 International Nuclear Atlantic Conference - INAC 2015
São Paulo, SP, Brazil, October 4-9, 2015
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: 978-85-99141-06-9

NEW STAGE IN THE DESIGN OF A TRANSMUTATION ADVANCED DEVICE FOR SUSTAINABLE ENERGY APPLICATIONS (TADSEA)

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ABSTRACT

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 obtaining heat at very high temperatures to produce hydrogen. In this new stage in the design of TADSEA, it was proposed and modelled a new burn-up strategy, simulating a multi-pass scheme of the pebbles through the core. In order to obtain the axial density power distribution more uniform, for more realistic thermal-hydraulic calculations. In the neutronic calculations it was considered the double heterogeneity of the fuel, by means of a detailed geometry modelling. In previous thermal-hydraulic studies of the TADSEA using CFD code, the pebble-bed nuclear core was considered as a porous medium. In this paper, the heat transfer from the fuel elements to the coolant was analysed using a realistic approach in ANSYS CFX 14. The maximum heat transfer inside the spherical fuel elements with a body centered cubic (BCC) cell and the entire height of core was studied. During the steady state, critical elements don't reached the limit temperature value for this type of fuel.

1. INTRODUCTION

The innovative projects that were chosen to form part of the Generation IV of nuclear reactors respond to eight main objectives which covers the areas: sustainability, economics, safety, proliferation resistance and physical protection [1].

Sustainability of nuclear energy will depend on the capability of reducing the inventory of nuclear waste and its long-term radiotoxicity, mainly dominated by the transuranic isotopes remaining in the spent fuel. Fast critical reactors and Accelerator Driven Systems (ADS) are the two main options to reduce the nuclear waste inventory and the final requirements for their deep geological disposal facility. In a ADS, neutron cascades, initiated by spallation on heavy materials by medium energy (few hundred MeV) protons, are used in a subcritical assembly to transmute the unwanted wastes into less harmful species. Critical reactors applied to

transmutation of nuclear wastes have the safety problem to handle fuel isotopes based on transuranic isotopes with a small delay neutron parameter (β). The reactor operation is simpler in subcritical reactors as is the case of ADS, providing a safe subcriticality margin [2]. In this context, ADSs designed as Very High Temperature Reactors (VHTR) can solve the mentioned problems, and also, to obtain high temperatures in the coolant, gives the possibility to produce hydrogen through heat and water by means of the I-S thermochemical process or high temperature electrolysis, with low emission of greenhouse gases [3].

In previous studies [2], the design of a Pebble-Bed Transmuter (PBT) was done. It is a subcritical system cooled by helium and moderated by graphite that uses as fuel small amounts of transuranic elements in the form of TRISO particles, confined in 3 cm radius graphite pebbles, forming a pebble bed configuration. The PBT is a device designed for the transmutation of nuclear wastes from the existing Light Water Reactors (LWR). With the goal of producing hydrogen from water and heat in view of the big amounts of hydrogen that would be required in a future energy scenario, the PBT's thermal power was increased as much as possible, maintaining the transmutation capabilities of the system and the shape of the power density profiles. The maximum power density value permitted for this type of systems is around 7 W/cm^3 [4], which represents a thermal power of 100 MWth for this device. In [5], the conceptual design of the new device with 100 MWth, called Transmutation Advanced Device for Sustainable Energy Applications (TADSEA), was presented. The proton accelerator technological choice is based on a linear accelerator (LINAC), instead of the cyclotron technology used for the previous few-MW experimental pebble-bed concept [2]. Following the directives of projects as the European PDS-XADS [6], that required increase in beam energy and current, we suggests a 1 GeV – 10 mA particle accelerator for subcritical core with a neutron multiplication factor Kef < 0.95. The gas coolant is Helium, with an outlet mean temperature of 950 ^{0}C, as required for a hydrogen production scheme based on the I-S thermo-chemical process in cogeneration mode with electricity production by a Brayton cycle. The Table 1 shows the basic parameters of the previous TADSEA design.

The pebble distribution inside the core of PBT and TADSEA in their original conceptual designs they presented a packing fraction of 0.74 which corresponds with a hexagonal compact configuration in an infinite medium. In [7] is calculated the real packing fraction of the TADSEA (0.64) and it was developed a methodology allowing calculating the real porosity on a finite medium. Previous PBT and TADSEA simulations were made with a homogeneous description of the fuel zone, where the materials that form the fuel zone (TRISO particles, graphite matrix) where homogenized using the adequate mass fraction of graphite, silicon and fuel. This approach has a significant influence on the calculation of the multiplicative properties of the core, underestimating the values of Kef and the neutron flux [8].

A very important topic 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. Theoretical temperature limit of TRISO particles, which is the fuel type of the TADSEA, is fixed at 1600 ^{o}C according to different reasons [9]–[12].

There are two main approaches for the CFD simulation of the close packed pebble geometry: the porous approach and the realistic approach. In the porous approach, an averaged concept

of porosity is applied to simulate the close packed geometry. In the realistic approach the real pebble bed geometry is simulated.

Table 1: Basic parameters of the previous TADSEA design

Parameter	Unit	Value
Internal radius	cm	15.5
External radius	cm	125.75
Reactor thermal power	MW	100
Height	cm	293.94
Total volume	cm^3	14.38
Reflector thickness	cm	60
Number of pebbles	-	94092
Core inlet temperature	^0C	590
Core outlet temperature	^0C	950
Coolant	-	Helium
Pebble diameter	cm	6
Diameter of fuel zone in a pebble	cm	5
Density of graphite in matrix and outer shell	g/cm^3	1.73
TRU mass loading per fuel element	g	1.5
Accelerator parameters		
Beam current	mA	3.41
Beam energy	MeV	1000
Beam power	MW	3.41
Electricity consumption	MW	6.82

In previous thermal-hydraulic studies [7], TADSEA's nuclear core was considered as a porous medium using the packing fraction calculated in that work, in order to guarantee core's outlet temperatures high enough for hydrogen production. The coolant temperature profiles were obtained from the power density distributions previously calculated.

In [13], it was carried out the realistic CFD simulation of a small core section, with the conditions established for the a analytical homogeneous model to three critical sections of the core. The maximum temperatures were superior that for the analytical homogeneous model.

In this work, a new neutronic simulation of TADSEA's core was made, considering a more exact model to describe the double heterogeneity of fuel and realler burn up conditions. A more accurate core power distribution was obtained. In the thermal-hydraulic studies, the maximum heat transfer inside the spherical fuel elements with a Body-Centered Cubic (BCC) cell and the entire height of core was performed.

2. CORE NEUTRONIC SIMULATION

In the reactors pebble-bed type there is a double heterogeneity given by the random distribution of all the pebbles in the core and the random distribution of all the TRISO particles with all the

composing layers fully considered. The generation of models that allow the random distribution of the pebbles and the TRISO particles is very hard to simulate using MCNPX code [14]. Due to this limitation fixed arrangements for both, pebbles and TRISO particles were used. It was used a MCNPX card called repetitive structures, that allows the generation of many surfaces through the simulation of one or a surface set (unit cells), where exist a high level of symmetry. The use of unit cells introduces two main approximations: the non-randomness even in the pebbles as the TRISO particles and the cut effect given by the intersection of the generated surfaces with the container surface (the pebble surface with the TRISO particles and the cylinder surface who delimits the core with the pebble bed). To simulate the double heterogeneity, the simulation was divided in two stages: the simulations of the pebbles inside the core and the simulation of the TRISO particles inside the pebbles.

2.1. Simulation of TRISO particles inside the pebbles

In previous study [15] was evaluated the influence of the cut effect in the multiplicative properties of the HTR-10 core, by means of the use of several models of distribution of the TRISO particles inside the pebbles, and it was demonstrated that there is no significant differences in the multiplicative properties of the cut effect at reactor scale. Besides, it was demonstrated that the uniform model of distribution that represents better the TRISO particles inside the pebbles, and the smallest cut effect is obtained with the uniform cubic model [15].

For this new stage of design of the core was chosen the uniform cubic model to distribute, in a heterogeneous way, the TRISO particles inside the TADSEA fuel elements. To generate a uniform cubic distribution of the particles inside the pebble, knowing the fuel mass and density, it is calculate the needed fuel volume. The fuel volume consider in the pebble is divided by the kernel volume of the TRISO particle and it is obtained the total number of TRISO particles needed for the established mass. Once calculated the total number of particles, the volume of the fuel zone is divided by the total number of particles to obtain the volume of one cubic unit cell that will be uniformly repeated inside the fuel zone of the pebble. In the center of the cubic nit cell is located one particle. Fig. 1 shows a cross-section of the pebble at Z=0 for the uniform cubic distribution for 1.5g of fuel mass per pebble and a density of 10.33 g/cm^3 (TADSEA characteristics).

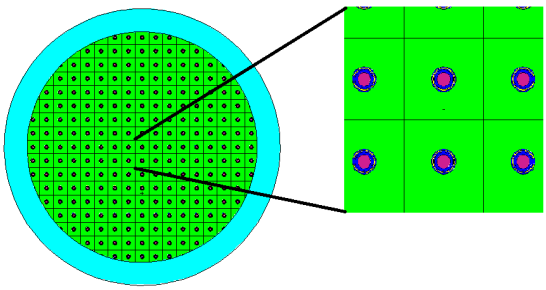


Figure 1: Uniform cubic model for TRISO particles inside the TADSEA fuel elements.

2.2. Simulation of the pebbles inside the core

In previous studies of TADSEA [5], [16], the geometrical description of the pebbles inside the core was obtained by means of repetitive structures using a Faced-Centered Cubic

configuration (FCC). Initially the pebbles were simulated for a packing fraction of 0.74, and later, in [7], the pebbles were spaced conveniently to simulate the pebble-bed using the real packing fraction (0.64). In [15] was evaluated the influence of the use of FCC and BCC (Body-Centered Cubic) unit cells in the spectrum for several fuel-to-moderator relationship in the multiplicative properties for HTR-10, where it was demonstrated that the use of both cells is equivalent. Based in those results, it was chosen BCC unit cell to describe the distribution of the pebbles inside the core of the TADSEA. The BCC unit cell (Fig. 2) is composed by eight octants of pebbles in the corners and one pebble located at the center of cell. The packing fraction is considered spacing conveniently the pebbles and the octants inside the cube. Both, the central pebble and the octants are filled with TRISO particles using the uniform cubic model presented previously. In this way is considered the double heterogeneity in the simulation of the TADSEA's core.

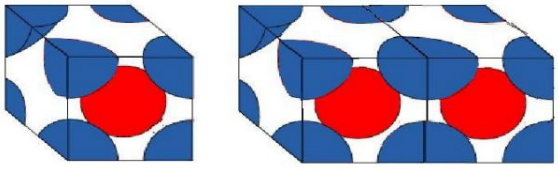


Figure 2: Body-Centered Cubic (BCC) array used for simulation of pebbles inside the core.

3. NEW PARAMETERS OF DESIGN

Using the proposed models mentioned previously is possible to simulate the pebble-bed in the core, considering the double heterogeneity of fuel. Employing repetitive structures for the pebble distribution, there is a cut effect in axial and radial directions. To keep the defined packing fraction of the bed, the height of the original TADSEA was diminished of 293.94 cm to 282.81 cm, in a way that the unit cells were not cut by the top surface that delimits the core. In this simulation of the TADSEA is also considered the entry of the pebbles in the core, by the simulation of the cavity of 41 cm of height at the top of the core (like the cavity of the test reactor HTR-10). Another element of design added to the model, which they were not consider in previous simulations of the TADSEA are the cone and the tube of discharge of the pebbles. These elements were designed in a similar way to the HTR-10, but were dimensioned in such a way that the tube reached the bottom surface of the core [17].

Although the control of the ADSs is simple due to the subcritical character of the core, it was added to the conceptual project of the TADSEA a new safety element: ten absorbers rods, which were inserted in the radial reflector, in emergency cases, to guaranty a deep core subcriticality. In operation stationary state, those rods must remain retired. The rods were simulated in the reflector, at 30 cm of the cylindrical surface who delimits the core. The geometry, materials and composition are the same of those used in the HTR-10 [17]. The top reflector thickness was considered equal to the original project of the TADSEA (100 cm), as well as the characteristics of the spallation target, the energy and the current of the proton beam. Fig. 3 shows the sketch of the TADSEA redesign.

Taking into account the results in [15], it was used for the redesign the particle of 250 μm of kernel radius. Table 2 shows the main parameters: geometrical, materials and operational for the redesigned TADSEA.

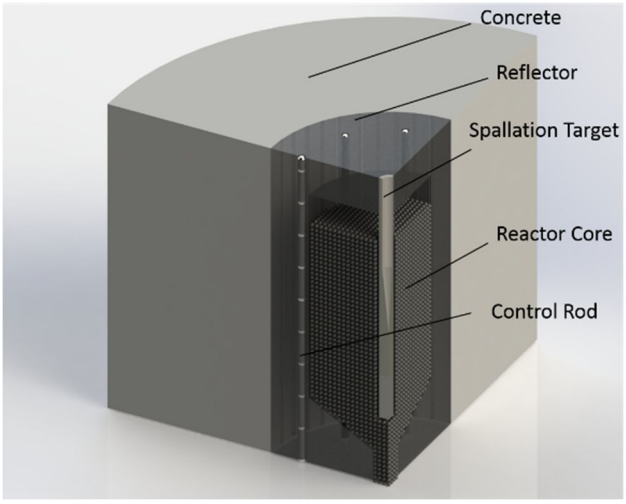


Figure 3: Sketch of the TADSEA redesigned.

Table 2: Geometrical and materials parameters of the TADSEA redesigned.

Parameter	Unit	Value
Thermal power	MW	100
Beam intensity	MeV	1000
Core radius	cm	125.75
Core heigth	cm	282.81
Top core cavity height	cm	41
Beam current	mA	10
Radial reflector thickness	cm	60
Axial reflector thickness	cm	100
BCC unit cell size	cm	7.07
Coolant	Hélio	
Number of control rods	-	10
TRISO kernel parameters		
Radius	cm	0.025
Fuel density	g/cm^3	10.33
TRISO particles parameters		
Materials of the layers		PyC/PyC/SiC/PyC
Layers thickness	cm	0.009/0.004/0.0035/0.004
Layers density	g/cm^3	1/1.9/3.18/1.9

4. CFD MODEL DESCRIPTIONS

It was carried out the realistic simulation of a section of the core for the previous design (Table 1) [7] and the current design (Table 2). The first simulation domain consists in a FCC cell

arrangement with 290.8 cm of height (Fig. 4). This geometry has 65 layers of pebbles with 33 full pebbles, 128 half pebbles and 132 quarter pebbles, with a total of 130 pebbles. The second simulation consist in a BCC cell arrangement with 282.8 cm of height (Fig. 5). This geometry has 81 layers of pebbles with 40 full pebbles and 164 quarter pebbles, with a total of 81 pebbles. The pebbles are stationary in the core. There is a spacing between pebbles to simulate the packing fraction, the value calculated in [7] was assumed. The fuel was considered as a homogeneous sphere.

4.1. Computational domain and boundary conditions

For the simulations of the flow field and convective heat transfer ANSYS CFX 14 [18] was used. To resolve the phenomena in three dimensions, the Reynolds-averaged equations for compressible flows were solved. For modeled turbulence the k − ε model is used and in the advection term of the RANS simulation, the High Resolution scheme was used. For the calculation of the turbulence quantities, the first-order upwind scheme was used.

Helium gas is set to be injected from the top of pebbles and an extra flow length is added to the last layer of pebbles in order to conserve the fully developed flow condition at the outlet. It was applied a symmetry boundaries conditions on the four side surfaces. Mass flow input for this simulation is calculated proportionally to the total coolant's mass flow in the core (53.3 kg/s) and it is 0.08622 kg/s for the FCC arrangement and 0.05441 kg/s for the BCC arrangement. Pebbles emit an uniform volumetric heat flux, depending on the position in the core. The power distribution used for this simulation corresponds to the section with the highest power of the core.

Properties of helium surrounding the pebbles were calculated according to the German Safety Guide. Where d is the pebble's diameter, k_{Helium} is helium thermal conductivity and the dynamic viscosity η_{Helium}, which can be calculated as:

$$k_{Helium} = 2.682 \cdot 10^{-3}\left(1 + 1.123 \cdot 10^{-3} \cdot P\right) \cdot T^{0.71\left(1 - 2 \cdot 10^{-4} \cdot P\right)}, \quad (1)$$

$$\eta_{Helium} = 3.674 \cdot 10^{-7} \cdot T^{0.7}, \quad (2)$$

where P is the pressure, T the temperature, and Cp_{Helium} = 5195 J/kg K are the heat capacity. The density of fuel was ρ_{fuel} = 1773.62 kg/m^3, the conductivity and specific heat of fuel was assumed a constant average as, k_{fuel} = 24.7 W/m·K and Cp_{fuel} = 1692.93 J/kg K [13].

Unstructured grids are used in the whole geometry due to the model complexity. Mesh independence calculations are also performed to verify that the simulation results presented below are mesh independent. Two final cases with 59 831 948 and 69 710 223 of elements for first problem and with 40 422 816 and 55 952 147 for second problem were compared. The maximum deviations in the maximum temperature are less than 1.0% for the cases with different mesh sizes.

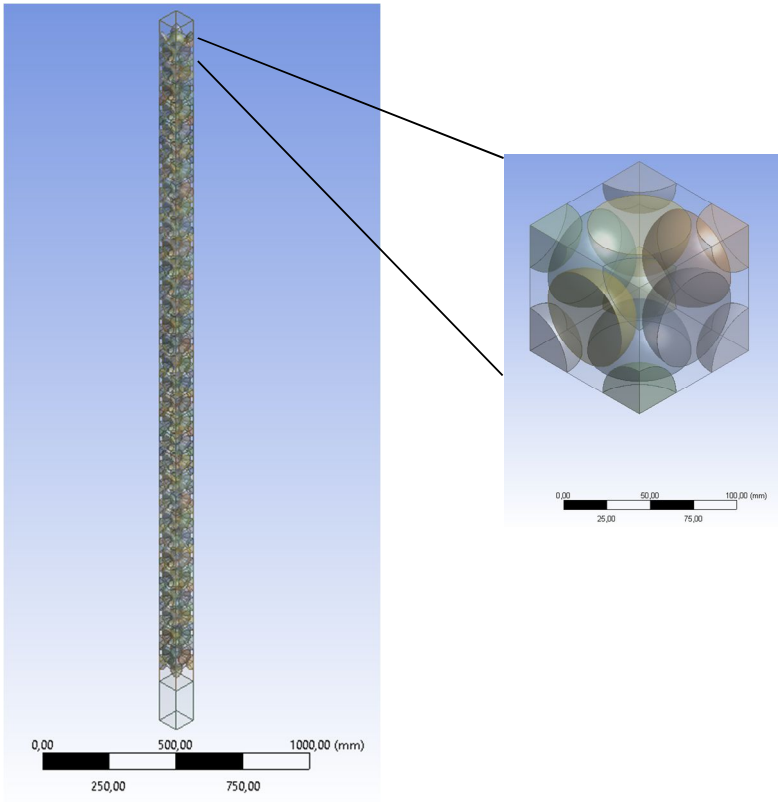


Figure 4: Geometry of computational model in previous design.

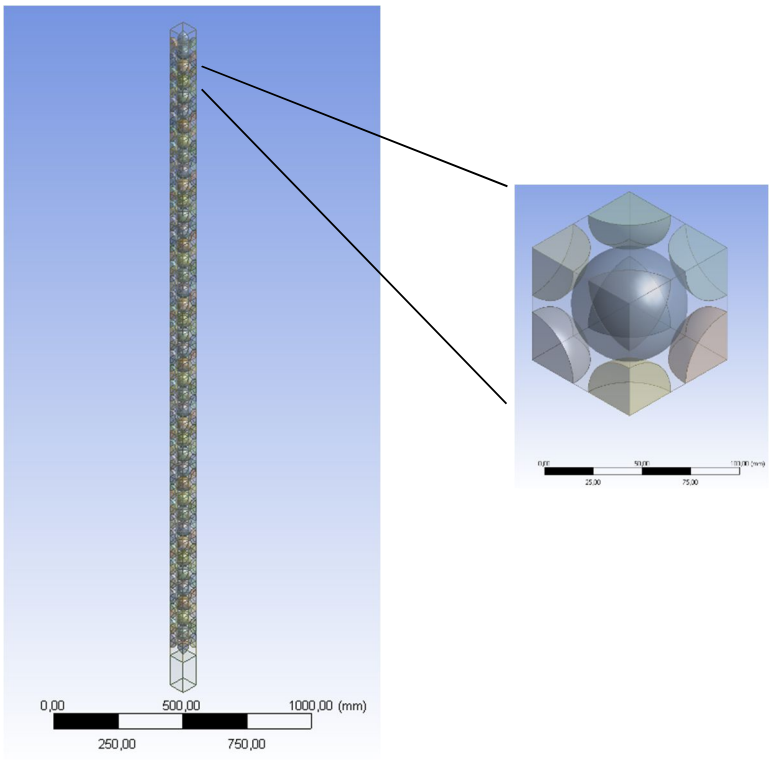


Figure 5: Geometry of computational model in current design.

5. RESULTS AND DISCUSSION

5.1. Calculation of the neutronic parameters of the core of the redesigned TADSEA

The TADSEA uses as fuel plutonium and minor actinides isotopes in a proportion similar to the existing in the typical spent fuel from a LWR power plant with a burnup of 40 GWd/Ton and after 15 years of radioactive decay [16]. For the new geometrical and materials characteristics of the TADSEA, it was calculated the effective multiplication factor as function of the fuel mass in the pebble, in order to determine the mass fuel value in the pebble to guaranty the desire subcriticality in the core near to the established value in the original conceptual design. Fig. 6 shows the Kef variation as function of the fuel mass in the pebble, with the absorber rods retired. As it was expected, in the calculation using a detailed simulation of the core considering the double heterogeneity, larger values were obtained for the multiplicative properties in the core for fresh fuel in comparison with the obtained results for the previous TADSEA conceptual design. In Figure 6, it is observed a major value of Kef for 1.5 g of fuel mass in the pebble, in comparison with the obtained value of Kef for the TADSEA using a homogeneous description of the fuel, which decrease with the increasing fuel mass in the pebble. For the fuel mass in the pebble of 4.5 g, was obtained a value of Kef of 0.95930, subcritical value near to the required value, besides a major mass of spent fuel guaranty a higher burn up level, which is one of the main goals of the conceptual design.

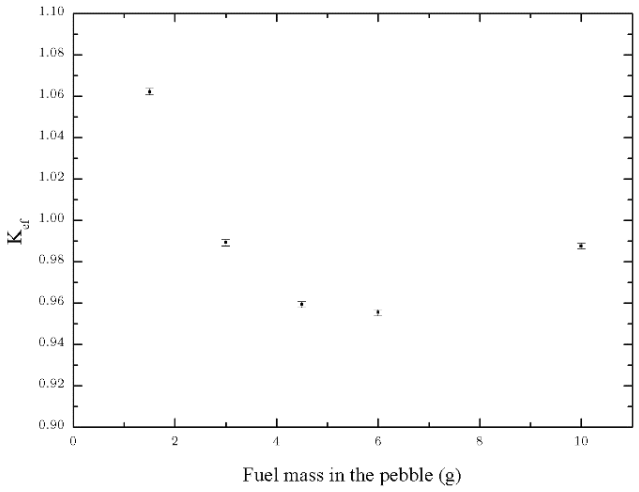


Figure 6: Kef value as function of the fuel mass in the pebble for the redesigned TADSEA.

For the core configuration of 4.5 g of fuel mass in the pebble, it was calculated the axial distribution of power density in the TADSEA core for the initial load. Fig. 7 shows the axial distribution of power density for the TADSEA. The core was divided in ten zones of equal height and it was calculated de average power density in each zone. Power density was normalized to 100 MWt, value permitted by the facility, and that parameter can be controlled by the accelerator current. It was obtained a maximum peak factor equal to 1.24. The average power density of the facility was 7.22 W/cm^3, which is very close to the recommended value.

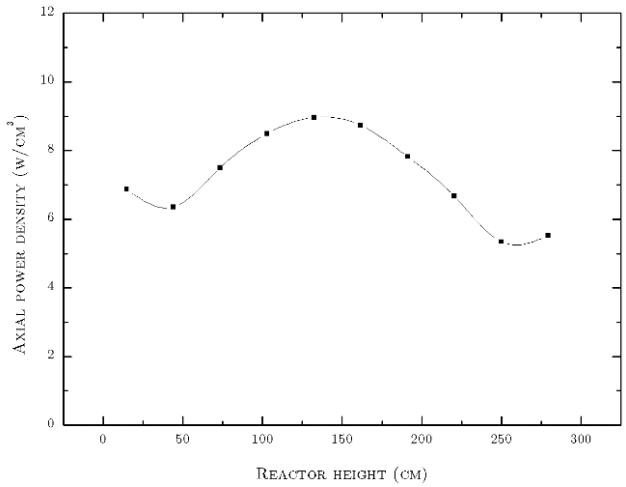


Figure 7: Axial power density of redesigned TADSEA for 4.5 g of fuel in the pebble.

5.2. Study of the isotopic variation of the fuel

The real procedure of continuous reload is impossible to simulate, and when a detailed simulation of the TRISO particles is done the problem is much more complicated. Also, the repetitive structure do not allow to describe the burn up of the pebbles separately. In this study, in order to obtain an equilibrium composition of the fuel simulating a multi-pass reload sketch with a detailed simulation of the fuel, a new strategy to manage the fuel is presented.

1. The core is divided in ten materials zones in the axial direction and each zone is initially loaded with fresh fuel.
2. The variation of the isotopic composition was calculated for the reactor core divided in ten zones, with a burn up step of 100 days, with the reactor working at full power until 2000 days (We will call this as burn up calculation). At this time, the fuel achieved an average burn up level of 632.2 GWd/Ton HM. This time is, as average, the time spent by one pebble in the core.
3. To simulate a representative composition of the core in the stationary state, considering a multi-pass sketch of fuel reload (ten times), 3 average compositions were taken for the ten zones, describes as follow, to be representative of the ten zones with pebbles of different number of times through the core.
4. The first three zones in the axial direction (counting up to down) were loaded with the obtained composition for the zone 2 at 900 working days in the burn up calculation. Here the burn up level was 284.5 GWd/Ton HM.
5. The following 4 zones were loaded with the composition obtained for the zone 5 at 1000 working days in the burn up calculation of 316.2 GWd/Ton HM.
6. Finally, the composition of the last 3 zones and the discharge cone were set like the composition obtained for the zone 9 at 1100 working days, with a average burn up level of 347.7 GWd/Ton HM.

With this composition in the core, is considered that the pebble remains as average 2000 working days and reach a burn up level of 632.2 GWd/Ton HM and travel through the core 10 times. Considering a linear dependence between the irradiation time and burn up level in the stationary state, the mixture of the pebbles have a burn up level equal to the half of the total

burn up level. The first 3 upper zones have an average burn up level 10 % lower than the burn up level reached in the central zones, meanwhile the 3 lower zones have a burn up level 10 % greater. Using the calculated composition for the stationary state was obtained the axial distribution of power density for the TADSEA, equally normalized for the 100 MW of power density and shows in Fig. 8.

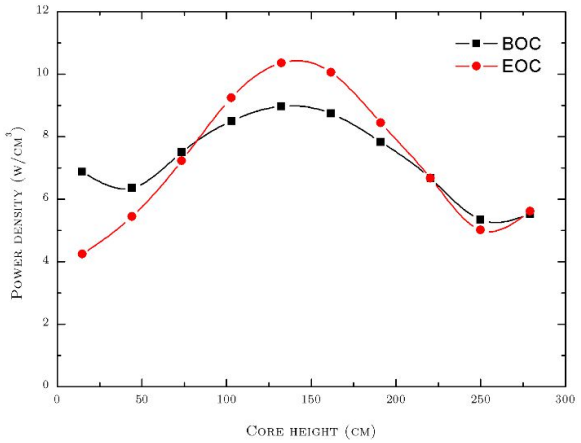


Figure 8: Comparison between the axial distribution of power density for the initial load (BOC, Begin of Cycle) and stationary state (EOC, End of Cycle).

In comparison with the power density distribution obtained for the initial load, it is observed an increment in the power density in the central zone and a decrease in the lower zone given by the fuel burn up. In the stationary state, a peak factor of 1.43 at the central zone was obtained. Comparing these results with the results obtained for the original TADSEA, is achieved a better uniformity in the axial power distribution. The peak factor obtained for the original TADSEA in stationary state (End of cycle) was 1.69 [19]. The possible total maximal power obtained in the stationary state was 159 MWt which allows to produce the design power values (100 MWt).

5.3. Thermo-hydraulics studies using CFD

Regarding safety, temperature of the fuel elements during normal operation and transients is a very important issue that should be studied in a nuclear reactor to assure the integrity of materials composing the fuel element and avoid the release of fission products. Leakage of gaseous fission products is produced through the fuel element by means of diffusion processes; when temperatures raise the diffusion increases. If temperature is very high the integrity of TRISO particles would be damaged due to manufacturing defects, internal pressure of fission gases, etc. The limit temperature at which the TRISO particles begin releasing the gaseous fission products was estimated as 1873 K (1600 ºC) [9]–[12], [20].

Fig. 9 and 10 gives the axial temperature contours on the center plane of the core including the pebbles and helium for the previous and current design, respectively. At right side of Fig. 9 and 10 a zoomed view of the pebbles with the maximum temperatures. The calculations show that the core temperature increases along the axial direction achieving a maximum value of 1742 K in the fuel and an average temperature at outlet of 1230 K for the previous design It was achieved a maximum value of 1711 K in the fuel and an average temperature at outlet of 1512

K for the current design. This means an improvement with this small decrease in the maximum temperature of the fuel and a great increase in coolant outlet temperature.

It can be seen in Fig. 9 and 10 the difference that the maximum temperatures reached in the previous design were close the middle of the core, meanwhile in the current design were in exit of the pebbled bed. This results are more close to the real heat released, like the previous realistic studies in the test reactor HTR-10 [21].

In Fig. 11 and 12 is shown the surface temperature at the front and rear of the pebble with the maximum temperature of the pebble bed for the two designs. It shows that the gas flows onto the front of the pebble, causing the higher heat transfer and the lower surface temperature. On the rear of a pebble, the flow detachment would result in the inferior heat transfer and simultaneously the higher surface temperature, as clearly shown in Fig. 10 and 11. We obtained a higher temperature difference (~133 K) between the front and the rear locations for the pebble at the previous design, and a minor difference (~61 K) for the current design. This result implies another improvement in the homogenization of heat released in this new model.

The maximum temperatures reached by the fuel are more than 131 K below the limit for this fuel in the realistic simulation of both designs for the steady state.

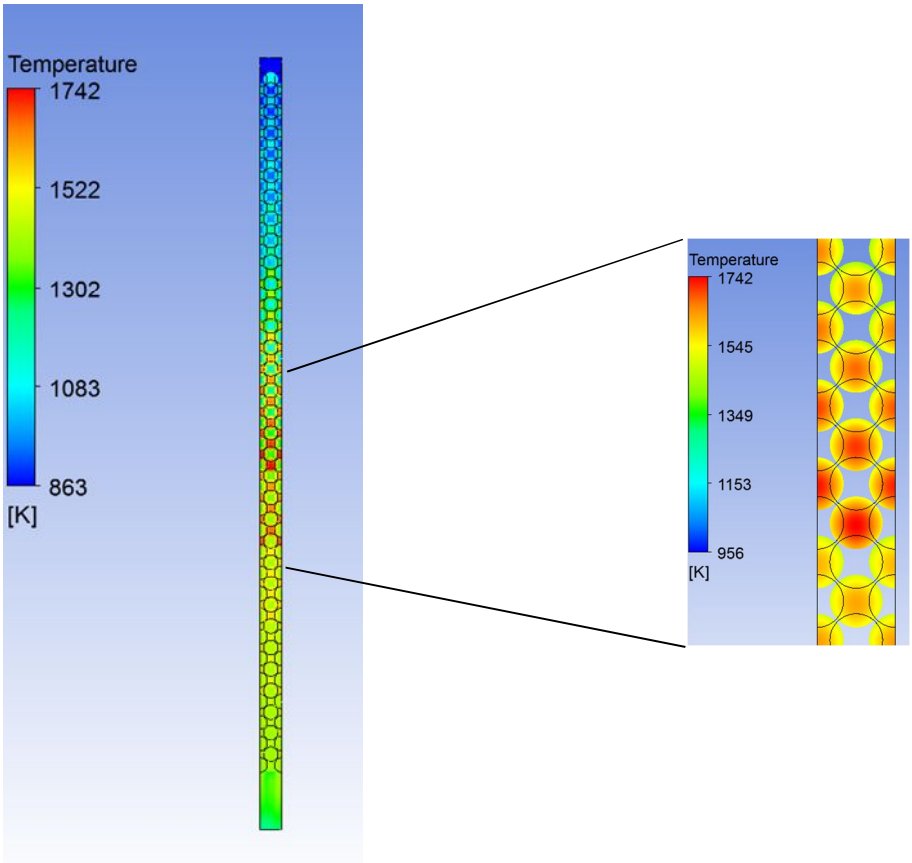


Figure 9: Helium and fuel temperatures at centerline plane for previous design.

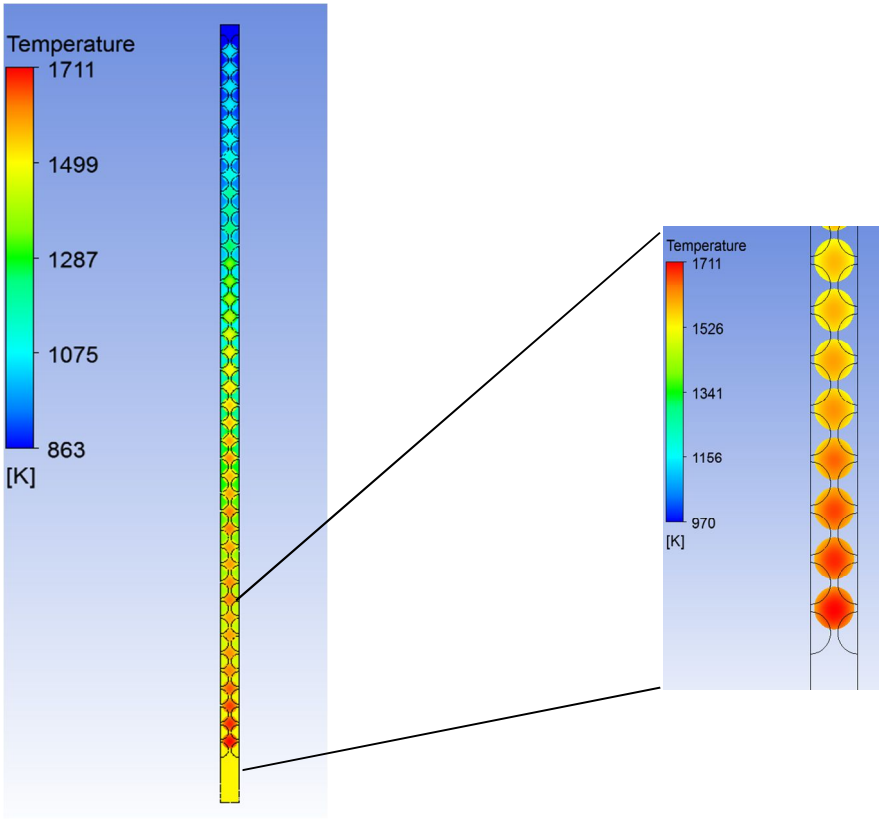
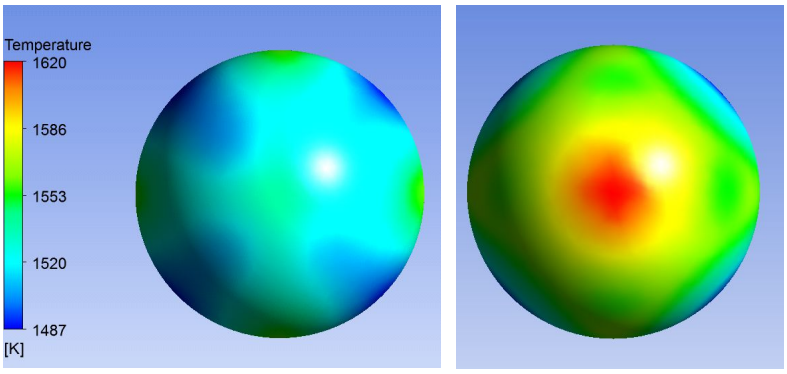
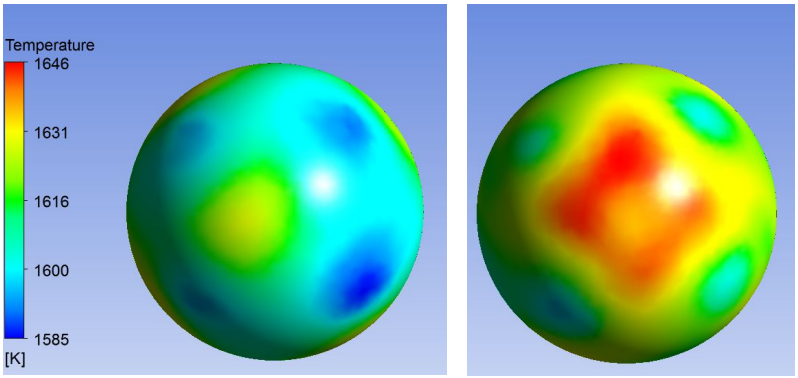


Figure 10: Helium and fuel temperatures at centerline plane current design.



(a) (b)

Figure 11: Maximum fuel surface temperatures in previous design (a) front, (b) rear



(a) (b)

Figure 12: Maximum fuel surface temperatures in current design (a) front, (b) rear.

6. CONCLUSIONS

In this work is proposed new advances in the conceptual design of TADSEA, an ADS pebble bed type which uses TRISO fuel. It was designed for the transmutation of long life nuclear waste, from the light water reactors, as well as the production of electricity. It was redesigned the core of TADSEA taking based on the simulations results obtained to model accurately the double heterogeneity of pebble bed.

Due to the impossibility to simulate the real continuous reload of the fuel and a pebble multi-pass scheme, a new fuel burn up strategy was defined. It was recalculated the distributions of axial power density, for the initial load and stationary-state. A better uniformity in the axial distribution was achieved.

It was carried out realistic CFD simulations of compressible flow considering a FCC cell for the previous design and a BCC cell the current design, in both cases, with the height of the entire core of the pebble bed reactor. The steady-state temperature distribution of the TADSEA at section of the core with the highest power density were obtained. The maximum temperatures reached by the fuel of 1742 K are much lower than the limit value for TRISO fuel 1873 K. The complexity of the flow results in a significant temperature difference at pebble surface, in this case, was reached a maximum of 133 K for previous design and 61 K for current design.

Nevertheless, this realistic CFD model of the whole height of TADSEA has many advantages, some assumptions made has to be improve. In future works will be use a model of the fuel with the graphite shell. Another improvement will be consider situations with the loss of coolant.

ACKNOWLEDGMENTS

This work has been carried out in the framework of the MES-CAPES 114/11 project titled “Study of Advanced Nuclear Systems pebble bed type with TRISO fuel for the transmutation of long-lived waste and hydrogen production with high temperature technologies”. Also, the authors thank to CAPES (Higher Education Co-ordination Agency of Education Ministry of Brazil) and to NBCGIB (Núcleo de Biologia Computacional e Gestão de Informações Biotecnológicas), of the Universidade Estadual de Santa Cruz (UESC), by the availability of high-performance computing platform for the realization of this work.

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