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Computational Fluid Dynamics Applied to Study Coolant Loss Regimes in Very High Temperature Reactors

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ABSTRACT

The nuclear energy is a good alternative to meet the continuous increase in world energy demand. In this perspective, VHTRs (Very High Temperature Reactors) are serious candidates for energy generation due to its inherently safe performance, low power density and high conversion efficiency. However, the viability of these reactors depends on an efficient safety system in the operation of nuclear plants. The HTR (High Temperature Reactor)-10 model, an experimental reactor of the pebble bed type, is used as a case study in this work to perform the thermohydraulic simulation. Due to the complex patterns flow that appear in the pebble bed reactor core CFD (Computational Fluid Dynamics) techniques are used to simulate these reactors. A realistic approach is adopted to simulate the central annular column of the reactor core. As geometrical model of the fuel elements was selected the BCC (Body Centered Cubic) arrangement. Parameters considered for reactor design are available in the technical report of benchmark issues by IAEA (TECDOC-1694). We obtain the temperature

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profile distribution in the core for regimes where the coolant flow rate is smaller than recommended in a normal operation. In general, the temperature distributions calculated are consistent with phenomenological behavior. Even without considering the reactivity changes to reduce the reactor power or other safety mechanisms, the maximum temperatures do not exceed the recommended limits for TRISO fuel elements.

Keywords: **VHTR, HTR-10, Pebble Bed Reactor, CFD.**

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1. INTRODUCTION

In the current scenario of continuous increase of world energy demand and the global warming problem, the Very High Temperature Reactors (VHTR) are an attractive candidate for energy generation in the near future. In addition, VHTRs present inherently safe performance and are high temperature source for industrial applications. This is a nuclear reactor of thermal neutron spectrum, moderated with graphite and cooled by helium gas, it was selected as one of six conceptual nuclear systems with potential to meet the performance and operating criteria proposed by the Generation IV International Forum [1].

The VHTR uses fuel particles known as TRISO (Tristructural Isotropic) particles composed of a kernel of fissile material coated with refractory layers responsible for the retention of all fission products inside the fuel, even under accident conditions. In a promising concept studied for the reactor core, the TRISO particles are inserted in a graphite matrix in spherical format, which fill the central space of the reactor randomly, resulting in the core of pebble bed with the format of annular or cylindrical column enclosed by graphite blocks. In the PBR (Pebble Bed Reactor) the coolant Helium circulates through of the interstitial spaces between fuel pebbles distributed at the core.

As part of a Coordinated Research Program of the International Atomic Energy Agency (IAEA) on VHTR reactor fuel technology, a set of benchmarking activities was developed to compare fuel performance codes under normal operation and operational transients [2]. On occurrence of a loss of coolant accident (LOCA), coolant loss could result in the uncontrolled increase of the fuel temperature up to levels that cause release of fission products.

From the safety point of view for design and engineering applications, it is important and recommended to simulate the flow and heat transfer processes in packed pebble beds. In particular, it is essential for the design and operation of a VHTR to investigate the temperatures reached by fuel in the occurrence of a LOCA. In this perspective, this work aims to perform thermohydraulic simulations in coolant loss regimes to investigate TRISO fuel behavior. In particular, if TRISO particles temperature remains in the safety margins with coolant flow smaller than projected for nominal operation. Besides, we disregarding reactivity changes, the reactor safety mechanisms and the air intake.

The HTR-10 (High Temperature Reactor) was used as a case study in this work. This reactor was projected and built by the Institute of Nuclear and New Energy Technology in China. The HTR-10 project was developed for feasibility study of pebble bed VHTRs, and to prove the safety performance of this technology [2]. The HTR-10's thermohydraulic calculations must prove that the heat transport capability is sufficient to extract the core generated heat. In addition, it must provide a set of termohydraulic parameters of the primary circuit, including the fuel temperature distribution [3].

Theoretically, the flow pattern inside the packed pebble beds is complex, so to an appropriate core safety analysis of the HTR-10 can be performed using Computational Fluid Dynamics (CFD) techniques. To simulation with CFD techniques, a realistic approach was adopted using ANSYS CFX code version 14.0. Results obtained by [4] indicate that the anisotropic thermohydraulic characteristics presents inside of the closely packed pebble geometry can be simulated more satisfactorily with this approach. The works of [5], [6] and [7] report the BCC (body centering cubic) arrangement as the configuration that obtains higher fuel temperatures inside the core. For that reason, we selected this arrangement with the average height of the core as geometric configuration. In a BCC unit cubic cell, a fuel sphere is positioned at the cell center and it is enclosed by eight 1/8-spheres at each corner of the same cell.

Numerous researches have been developed over the years to better understand and predict TRISO fuel behavior in normal operation and accident conditions. The results presented in [5] described the thermohydraulic steady state simulation of the HTR-10 core in normal operation using realistic CFD approach. In the works [8], [9] and [10] was investigated the air ingress accident for a high temperature gas cooled reactor, simulating the thermohydraulics characteristics and graphite corrosion oxidation. In [11], the authors considered changes in mass flow rate to simulate the heat transfer in packed pebble beds to study the heat transfer process by radiation.

The next section presents the model description, including the discretization scheme and mathematical models. The numerical results and discussion are offered in the section 3, where was used experimental data of the first benchmark issue at the TECDOC-1694 [2] to analyze the core temperature profiles in cases of coolant flow reduction. Finally, in the section 4, we offer the final comments and suggestions for future works.

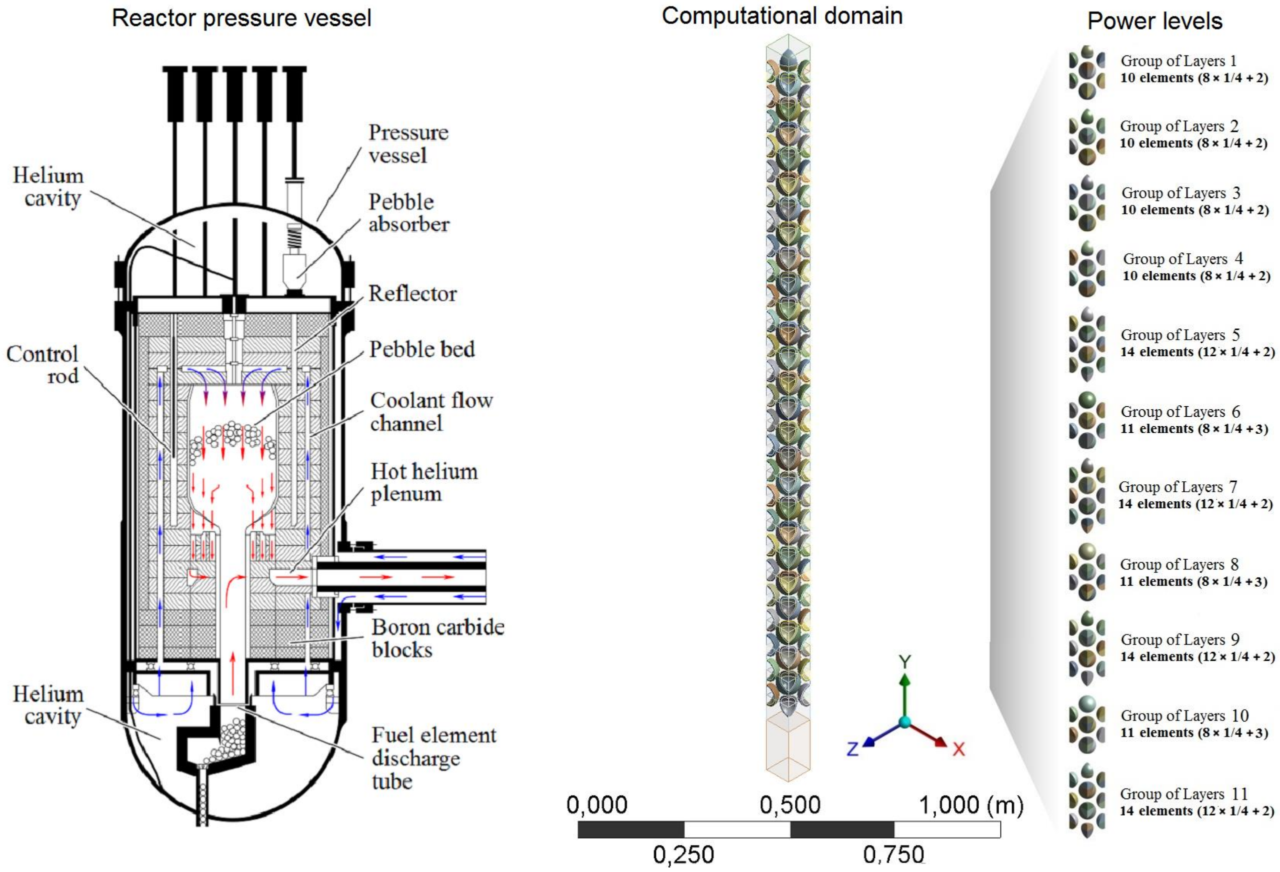
2. COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

The HTR-10 is a thermal neutron spectrum modular reactor moderated with graphite and cooled by helium gas. The core of this reactor, designed for a thermal power of 10^7 W, is a packed pebble bed of random and dense distribution consisting of the spherical pebbles same size. Each fuel sphere is composed of an inner fuel zone of 5×10^{-2} m diameter (where the TRISO particles are inserted) and an outer layer graphite fuel free shell of 5×10^{-3} m. The revestiment of the TRISO particle is 650-850$\times10^{-6}$ m diameter encompassing three layers of pyrolitic carbon PyC (buffer, inner pyrolitic carbon and outer pyrolitic carbon) and one of silicon carbide (SiC). Reactors that use TRISO particles are designed in such a way that the fuel temperature does not exceed 1873 K [12].

The coolant flow passages within the pressure vessel are shown in Figure 1. The cold gas, once pumped into the reactor vessel, flows through the annular space inside the core containment barrier. Part of the coolant helium bypasses the main flow path, only 87% of the total coolant flow rate effectively cools the fuel elements in the core. In normal operation, the gas pressure and the mass flow in the primary circuit are 3×10^6 Pa and 4.32 Kg/s, respectively; the gas inlet temperature is 523 K and the gas outlet mean temperature is 973 K.

Due to the high computational cost required for the full core simulation of the HTR-10 reactor, the computational domain used in this work is constituted by replication, in vertical direction, of BCC cubic cells of same dimension to represent the central column of the reactor core. The proposed geometry has a height of 1.94 m containing 27 BCC cells, with 25 full pebbles and 104 quarter pebbles divided in 11 power groups. At the bottom of the geometry, a 0.1438 m extension is added to ensure that the flow development conditions at the outlet are achieved. The computational domain and the power groups considered are shown in Figure 1. The values used for power generation in each group of layers were defined considering geometric parameters, as the packing fraction of the pebble bed, and based on the powers reported in [2] for the core central section.

Figure 1: *Coolant flow passages within the pressure vessel (left) and Computational domain of central column of the HTR-10 core with distribution of power levels (right).*



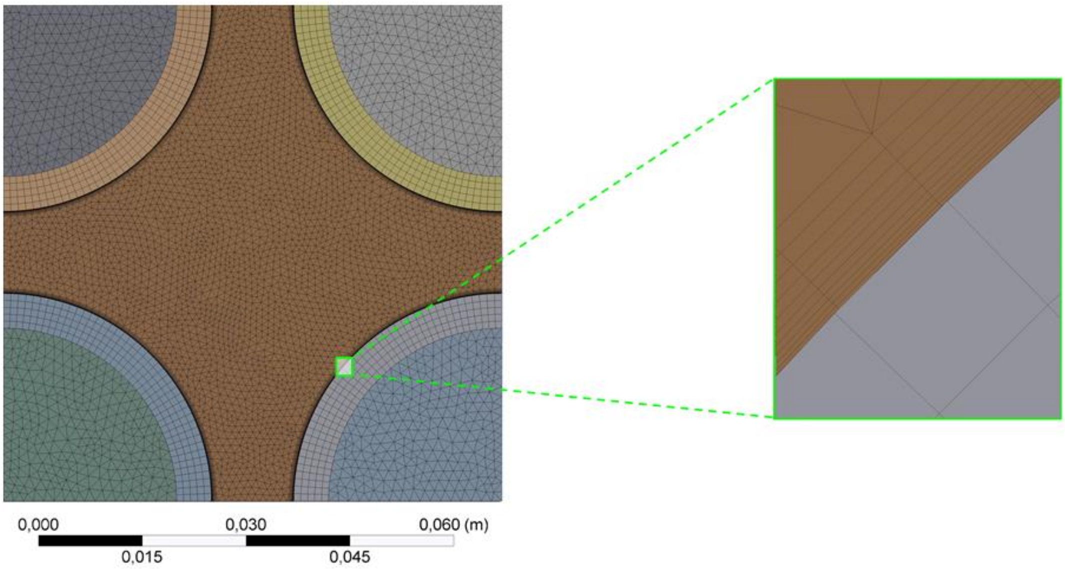
To describe properly the convective phenomenon, structured grids finer are applied at the interface between the coolant gas and the external graphite coating of fuel spheres (10 layers were defined); the thickness of the layers increase by a ratio of 20% of the previous layer to the next layer. With this configuration, the results were obtained in simulations with the use of three different meshes. The number of elements and nodes of the meshes are displayed on the Table 1, and the general mesh configuration on the external face of the BCC pebble structure is shown in Figure 2.

According [13], the Ansys CFX software applies the finite volume method to accomplish the discretization process.

Table 1: General characteristics of meshes.

Mesh	1	2	3
Inflation total thickness (m)	7×10^{-4}	6×10^{-4}	7×10^{-4}
Elements (millions)	39.49	39.98	75.21
Nodes (millions)	12.55	12.64	20.25
Elements size of solid domains (m)	2×10^{-3}	2×10^{-3}	1×10^{-3}

Figure 2: *Mesh used in simulation of BCC pebble structure.*



In the present work, we considered symmetric boundary conditions for inlet, outlet, and wall contours. In relation to the flow regime, it is assumed that the velocity is subsonic, and that the direction of the flow is normal to the inlet plane. Regarding turbulence intensity uncertainty in the domain region, a recommendation from [14] is adopted, with the definition of 5% intensity and the viscosity rate equivalent to 10. Considering the percentage of the Helium that effectively cools the fuel elements, and the area ratio between the core coolant inlet section and the BCC column inlet section, the mass flow rate at domain inlet was defined as 7.647×10^{-3} Kg/s. In the outlet region, the pressure profile chosen is associated with a mean pressure statically defined at 0 Pa.

In the simulation of the thermohydraulic characteristics of HTR-10 core, partial differential equations known as governance equations are used for the physical characterization of the flow of fluids [15]. The mathematical model includes also the standard k-ε turbulence model and considers the helium compressibility. The definition of the materials physical properties followed the recommendations of the benchmark [2] and the German Safety Guide [16].

The simulation of fluid turbulence in pebble bed is performed with the resolution of the equations of Reynolds-Averaged Navier–Stokes (RANS) and k-ε standard model which has good results for this problem in [6]. For the turbulence numeric treatment, the First Order High-Resolution scheme was used. The criteria of convergence for governing equations were defined in such a way that the RSM (Root Mean Square) value of the residues was inferior to 10^{-4}.

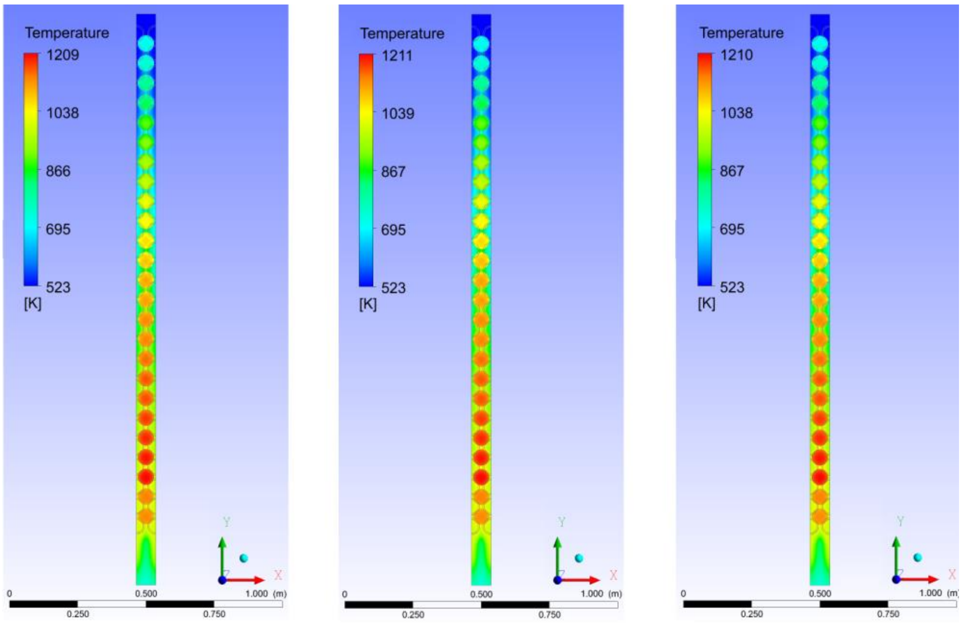
3. RESULTS AND DISCUSSION

To meet the proposed study, reductions in the mass flow rate of the coolant with a ratio of 10% were considered in relation to the quantity recommended for the nominal reactor operation. The values obtained for the flow rate were used in different sequential simulations. The flow rate reductions occurred until the maximum temperature reached by the fuel elements is very close to the recommended safety limit. Specifically, we simulate for 100%, 90%, 80%, 70%, 60% and 50% nominal flow rate. In the Figure 3, we present the temperature profile at the orthogonal axial central plane of the BCC column for the considered meshes with nominal flow rate and a 50 % reduction.

The numerical results behavior is consistent with the physical phenomenon: the fuel temperature increases along the axial direction, and the fuel temperature rises with the reduction of the mass flow rate. In the performed simulations, the fuel elements temperature doesn't exceed or even reach, the safety limit established for TRISO nuclear fuel with a reduction of up to 50% in the coolant flow rate. The temperatures obtained with different mesh configurations are very close. The relative deviation between the values obtained with the used meshes is less than 0.5%. For that reason, the results can be considered mesh independent.

The discrete graphs shown in the Figure 4 gives the calculated temperatures for different mass flow rate with respect to column height in the three considered meshes. The highest temperature along the column is located approximately at 1.7 m height for all tested flow rate values. This temperature is smaller than 1873 K (safety limit indicate in graphs by the red dotted line).

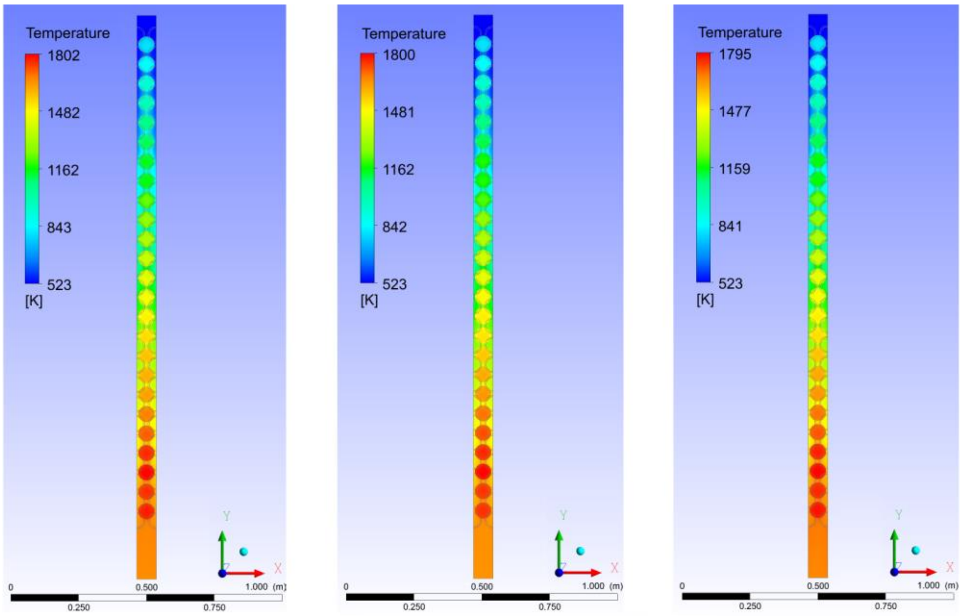
Figure 3: *Temperature distribution in the center plane of BCC column of the HTR-10 reactor core with 100% and 50% nominal flow rate.*



(a) Mesh 1 and 100% of mass flow rate.

(b) Mesh 2 and 100% of mass flow rate.

(c) Mesh 3 and 100% of mass flow rate.

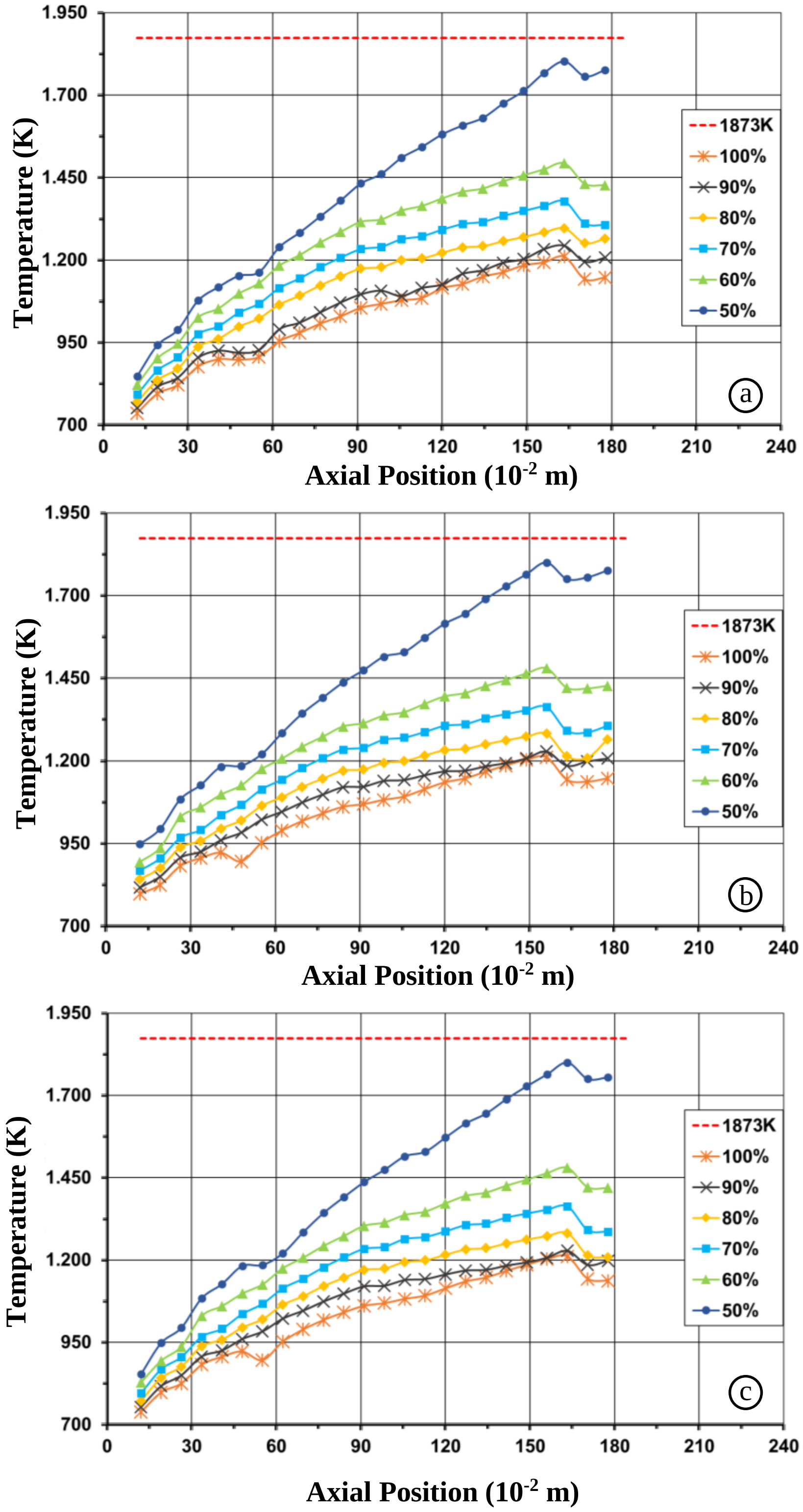


(d) Mesh 1 and 50% of mass flow rate.

(e) Mesh 2 and 50% of mass flow rate.

(f) Mesh 3 and 50% of mass flow rate.

Figure 4: *Fuel elements temperature for different mass flow rates using mesh 1 in (a), mesh 2 in (b) and mesh 3 in (c).*



From this point, we noted a temperature decrease toward the flow outlet region. The results suggest that the temperature drop is associated with the lower generated power in the core bottom section. According to Figure 4, the differences between the temperatures reached becomes more significant in the reduction of 60% to 50% in the coolant flow rate. Although they presented close values in the initial core section, the results begin to move away from the 0.8 m axial position due to the increase of the power generated in the core.

The simulations with finer meshes can present more details of the heat transfer process and, consequently, more accurate results. On the other hand, the coarse meshes uses imply a lower computational cost. The three meshes used in this work to generate similar results. Then, considering the computational cost, we suggest the mesh with a smaller elements number (mesh 1) more appropriate for future simulations.

4. CONCLUSIONS

The pebble bed reactor must passively remove the core generated heat under any designed accident conditions, keeping the maximum fuel temperature below 1873 K to retain all fission products inside the layers of TRISO coated fuel. A Helium loss accident has been simulated to verify the temperature reached by fuel elements on the core central column. To simulate discrete states under coolant loss condition were considered reductions in the coolant mass flow rate.

The obtained fuel temperature profiles shown a good agreement for different meshes and are consistent with the physical phenomenon. The temperature peak is located close to 1.7 m from the inlet, and a temperature drop is observed from this point.

The maximum fuel temperature reached in our simulations was 1802 K. This occurs in the regime with a reduction of 50% in the nominal flow coolant rate. Note that, this value is smaller than the maximum temperature supported by TRISO fuel. Then, disregarding reactivity changes or other safety mechanism, the HTR-10 core, supports a significant reduction on the helium flow rate without reaching temperature values that damage the TRISO particle integrity.

The next step in this research involves the study of the influence of the amount of inflation layers and to use the data of the second benchmark issue of the TECDOC-1694 with the problem of primary flow loss without scram.

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