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Analysis of the X2 VVER-1000 benchmark with FENNECS

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ABSTRACT

The X2 VVER-1000 benchmark contains operational data from the Khmelnitsky (X2) Nuclear Power Plant and offers the opportunity to validate nuclear simulation codes in hexagonal geometry. The first part to the benchmark is dedicated to the fresh core at hot zero power (HZP) state. During the start-up experiments, several quantities have been evaluated such as the worth of the control rod banks and the isothermal temperature reactivity coefficient. As there is no thermal-hydraulic feedback, this benchmark is ideal for the validation of stand-alone neutronics methods and codes.

In this paper, the HZP state is reproduced with the FENNECS code and with the Monte-Carlo (MC) code SERPENT. The modelling with SERPENT is twofold: generation of few-group cross sections for FENNECS and generation of a reference solution in terms of power distribution since there is no experimental data available for it. Prediction of FENNECS for the HZP are in fair agreement with the reference MC solution, both multiplication factor and radial power distribution discrepancies are within common acceptance margins. FENNECS results are also in good agreement with experimental values such as the isothermal temperature reactivity coefficient. Some weakness in the prediction of control rod worth has been identified. To mitigate shortcomings resulting from the cross-section energy condensation, the superhomogeneisation method has been applied. It results on a better agreement between FENNECS and the reported measured worth.

1 INTRODUCTION

In the last few years, a growing interest has been observed in small modular reactors (SMR). They are often characterized by a complex geometry that classical nodal method cannot describe and, whereas MC methods are standard to describe the steady-state of such system, transient application at a reasonable computing ‘cost’ are not yet available. In order to perform multi-physics transient safety assessment for these new concepts, the Finite ElemeNt NeutroniCS (FENNECS) code [1] which is also coupled with the system code ATHLET [2] is currently under development at GRS. After a preliminary phase of verification, FENNECS is mature enough to enter the validation phase. This phase will be split in two groups of exercises: The first one aims at assessing the performance of FENNECS on regular geometry problems and the second one on irregular geometries.

Within this framework, the X2 benchmark [3] offers an opportunity to contribute to the validation of FENNECS in hexagonal geometry. The benchmark is separated into three parts:

- Fresh core hot zero power experiment,
- Operational history of four fuel cycles,
- Transient scenario.

After a description of the FENNECS code, the benchmark model of the HZP state is described for both SERPENT [4] and FENNECS. Insight to the few-group cross sections generation is given. In the final part of the paper, an analysis of the result with thoughtfully comparison between codes predictions and measured values is performed. Finally, conclusions are drawn, and future development are presented.

2 FENNECS

2.1 Finite element method approach for the few-group diffusion equation

The finite element method implemented in the code FENNECS solves the three-dimensional few-energy group steady-state and time-dependent diffusion equation. The method can be summarised as follows:

1. The geometry is split into triangular prisms containing six nodes.
2. Using the Galerkin weighted residual approach, the diffusion equation for each energy group is represented by a linear system of equations.
3. Evaluation of the coefficients of the equation system is obtained by an iso-parametric coordinate transformation of each element to an upright triangular prism in the reference frame.
4. The system is resolved with an inner-outer iteration scheme
   a. the inner iteration uses an ILU (Incomplete Lower Upper factorization) preconditioned conjugate gradient method,
   b. the outer iteration is either a power iteration or a Wielandt inverse power iteration;
5. Fully implicit time integration is used for transient problem.

More detailed description of the code features and capabilities can be found in [1, 5].

2.2 Control rod model

The modelling of the control rod is a recent development of FENNECS that required validation. Position of the control bank is an input value that can be changed during a time-dependant simulation. From this position FENNECS determines if a fuel assembly is in a rodded state or not. It also determines which rodded state is to be associated to the element. Indeed, FENNECS is able to model axial heterogeneity of the control bank, as it is the case for the X2 benchmark: The first 30 cm of the absorber part is composed of dysprosium titanate Dy_2TiO_5 while the remaining upper part (320 cm) is composed of boron carbide B_4C.

During the control rod movement, it may take place that the interface between two materials (cross section) does not correspond exactly with the mesh resulting in what is usually called a partially rodded (finite) element. Such element required the definition of a mixed cross-section. In order to mitigate the cusping effect a flux weighting model is used to evaluate the mixed cross section in order to conserve the reaction rates. This model gives satisfactory results as it will be shown in section 4.3.

3 BENCHMARK

3.1 Models

The VVER-1000 core model was built with the state-of-the-art MC code SERPENT and with the newly developed finite element code FENNECS of GRS. It is based on the X2 benchmark specification [3]. The core is arranged in a hexagonal lattice with a nominal pitch of 23.6 cm surrounded by the baffle which is pierced at several positions (Figure 1). Vacuum boundary conditions are imposed for both models.

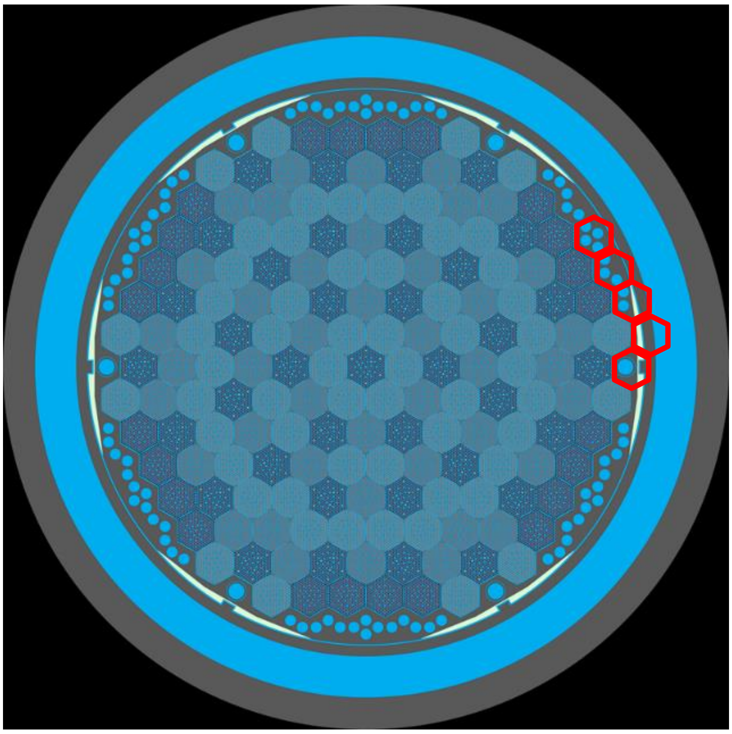

Figure 1: Top view of the SERPENT core model with radial reflector domain (in red).

The core contains five different fresh fuel assemblies (FA):

- 48 FA with U^{235}-enrichment of 1.3 %
- 42 FA with U^{235}-enrichment of 2.2 %
- 37 FA with average U^{235}-enrichment of 2.98 % (fuel rod with gadolinium)
- 24 FA with average U^{235}-enrichment of 3.99 % (fuel rod with gadolinium)
- 12 FA with average U^{235}-enrichment of 3.96 % (fuel rod with gadolinium)

Every FA is modelled accurately, meaning that heterogeneous axial and radial structures are explicitly modelled. All dimensions and material compositions are presented in the benchmark specification [3].

SERPENT criticality calculations are performed with the nuclear data library ENDF/B-VII.0. In order to ensure a standard deviation smaller than 1 pcm for multiplication factors, 1000 cycles of 10^7 neutron histories each have been simulated where the first 100 batches were discarded.

FENNECS criticality calculations used a mesh of in total 243,072 elements (48 axial layers of 5064 triangular prisms, Figure 2 left). This mesh was found to provide the desired accuracy at an acceptable computational cost. Results are presented in the section 4.

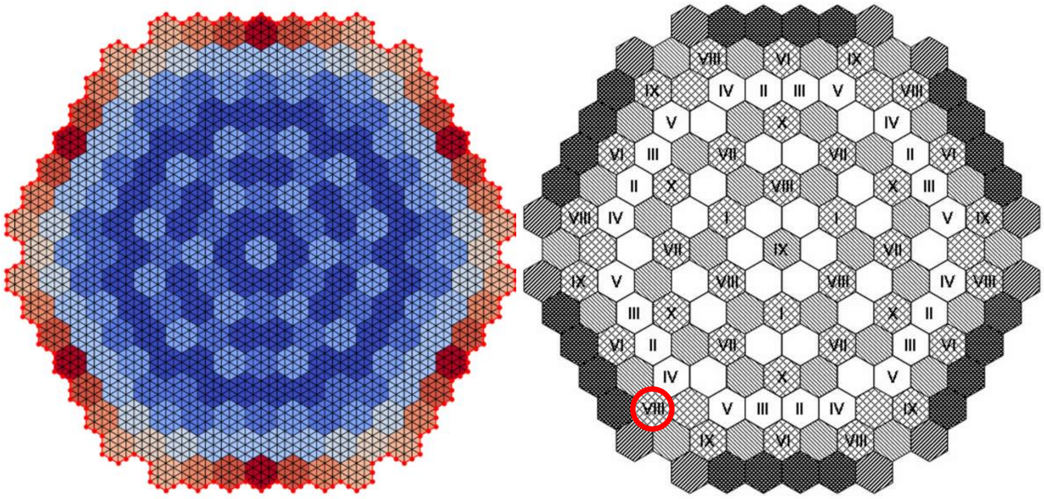

Figure 2: Top view of the FENNECS core model (left) and control bank positions (right).

3.2 Cross sections generation

Besides providing a reference solution to the problem, SERPENT modelling allows for generation of the different group constants required to solve the neutron diffusion equation. This task is commonly used to be done by deterministic (2D) lattice codes, but in the past few years SERPENT has shown its ability to generate accurate few-group homogenized cross sections without approximations to the geometry. The main drawback of the Monte-Carlo method remains the large computational resources required. This is why different smaller models are considered for this task:

- For the fuel cross sections, a single 2D FA (Figure 3, left) is considered with periodic boundary conditions. Group constants are obtained with the P1 leakage model.
- For radial reflector, the simulation domain is a 2D model of the core from which five hexagonal domains (Figure 1) are used for the homogenisation process.
- For the top and bottom reflectors, a mini 3D core model (Figure 3, centre and right) is considered with reflective radial and vacuum axial boundary conditions.

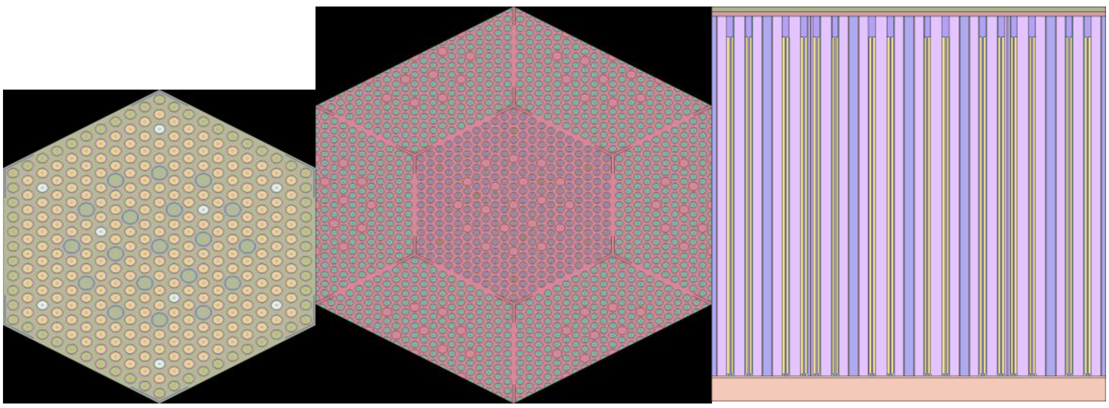

Figure 3: SERPENT models used for cross sections generation

Different states (fuel temperature, water density and boron concentration) were modelled to produce parametrized few-group cross-section libraries: One for the HZP (section 4.1), two for each reactivity coefficient measurement (section 4.2) and one for the control rod worth (section 4.3).

3.3 Superhomogeneisation method

The superhomogeneisation (SPH) procedure is a cross-section correction method that aims to preserve the total average reaction rates, leakage and eigenvalue within macro regions obtained through a homogeneous calculation with respect to a reference, heterogeneous problem [6]. The correction is applied to reduce the error that stems from spatial homogenization which modifies the physics of the problem.

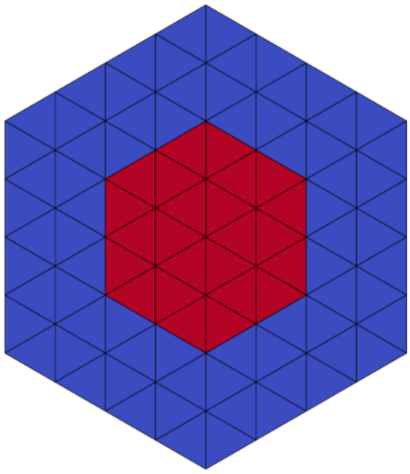

Figure 4: SPH model :2D, controlled FA (red) surrounded by six halves FA (blue) with reflective boundary conditions.

The method is an iterative process where the cross-section (and diffusion coefficient) are adjusted by the SPH factors (Eq. 1) defined for each energy group as described in Eq. 2, with φ being the scalar flux, N a normalisation factor to ensure the uniqueness of the solution and r the macro region (depicted in red and blue in the Figure 4).

$$\Sigma_r^i = \mu_r^i * \Sigma_r^{ref};\ \ \mathrm{D} = \mu_r^i * \mathrm{D}_r^{ref} \tag{1}$$

$$\mu_r^i = N * \frac{\iiint_r \varphi^{SERPENT}\, dV}{\iiint_r \varphi^{FENNECS}\, dV}; \qquad N = \frac{\sum_r \iiint_r \varphi^{FENNECS}\, dV}{\sum_r \iiint_r \varphi^{SERPENT}\, dV} \tag{2}$$

For each iteration i, a FENNECS calculation is performed with the updated cross-section data set until convergence is reached, typically when the relative difference between SPH factors from the current and the previous iteration is lower than 10^{-6}. Improved results obtained with this method are discussed in section 4.3.

4 RESULTS

4.1 Hot zero power

The HZP state was obtained with the following conditions: Material temperatures are set to 281 °C and the control rod bank 10 is 76 % withdrawn; the critical boron concentration was measured to be 1207 ppm. At this given state, the multiplication factor predicted by SERPENT is 1.00018 ± 1 pcm. FENNECS predicts a value of 1.00156 which represents a discrepancy of 138 pcm. Additionally, a relative comparison of the assembly power distribution in a 60° section is shown in Figure 5, the maximum deviation observed is 3.6 %. Altogether, satisfactory agreement is obtained between the two solutions.

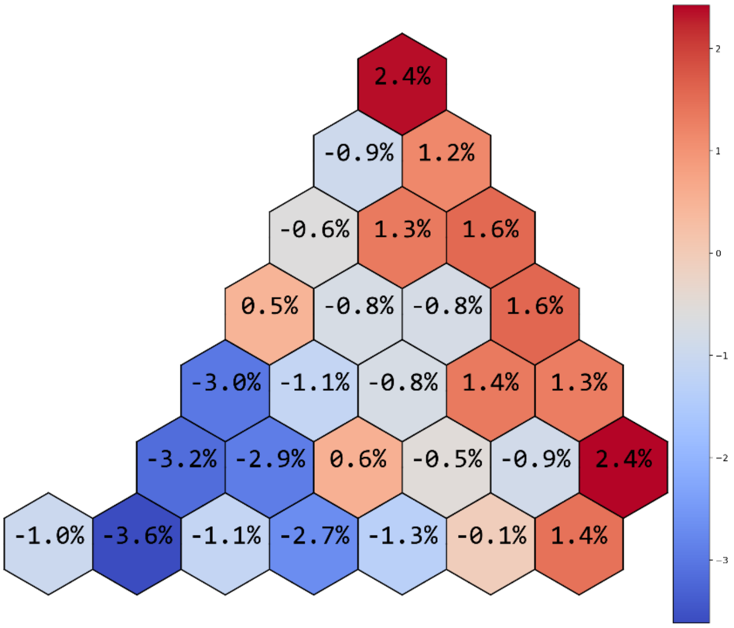

Figure 5: Relative difference (in %) of the assembly power distribution between FENNECS and SERPENT

4.2 Isothermal reactivity coefficient

The fresh zero power state HZP was also used to evaluate the isothermal reactivity coefficient for two different configurations of the control bank. Measured value as well as FENNECS results are reported in Table 1.

Table 1: Measured and calculated isothermal temperature reactivity coefficient.

	CB (ppm)	Isothermal Temperature change (°C)	isothermal reactivity coefficient (pcm/°C) experiment	isothermal reactivity coefficient (pcm/°C) FENNECS
First measurement, all bank out but bank 10 76 % withdrawn	1233	280.7 –> 276.0	−4.88 ± 0.50	-4.77
		276.4 –> 280.6	−5.39 ± 0.54	
Second measurement, same as previously but bank 7, 8 and 9 fully inserted	997	280.3 –> 275.7	−13.58 ± 0.14	-13.30
		275.7 –> 280.2	−14.67 ± 0.15	

The first one is very similar to the HZP configuration meaning that only the bank 10 is slightly inserted. The second one considered is a case where banks 7, 8 and 9 are fully inserted. For each experiment, the measurement was repeated twice for results that differ by almost 10%. This variation can be partially attributed to uncertainty on reported operating conditions. Taking this uncertainty into account, it can be observed that FENNECS predictions are in good agreement with the measured value during the start-up test.

4.3 Control rod worth

Finally, the SCRAM worth was evaluated during the start-up test. Two worth's were evaluated, one considering the simultaneous drop of each control bank position but one (circle in red in Figure 2, right) followed by this last one to obtain the total SCRAM worth. Thermal-hydraulics conditions remained unchanged during the SCRAM test. The worth predicted by

FENNECS was obtained with two criticality calculations where only the control bank positions were changed. Two sets of control rod cross sections were used, the one obtained directly with SERPENT and the other obtained with the SPH method (denoted as SPH in the Table 2). Considerable improvement is obtained with the second set with predicted values within the uncertainty of the measurement. It should be noted that these large uncertainties are a known issue discussed in the specification [3]. Hence, due to limitation of the measurement technique, measured worth's are underestimated by almost 10 %. In the light of this information, FENNECS using the SPH corrected cross section set appears to perform fairly well.

Table 2: Measured and calculated SCRAM worth.

	worth (pcm)		
	Experiment	FENNECS	FENNECS+SPH
SCRAM with rod 17 stuck	5230 ± 310	6034	5643
SCRAM	7000 ± 430	8011	7402

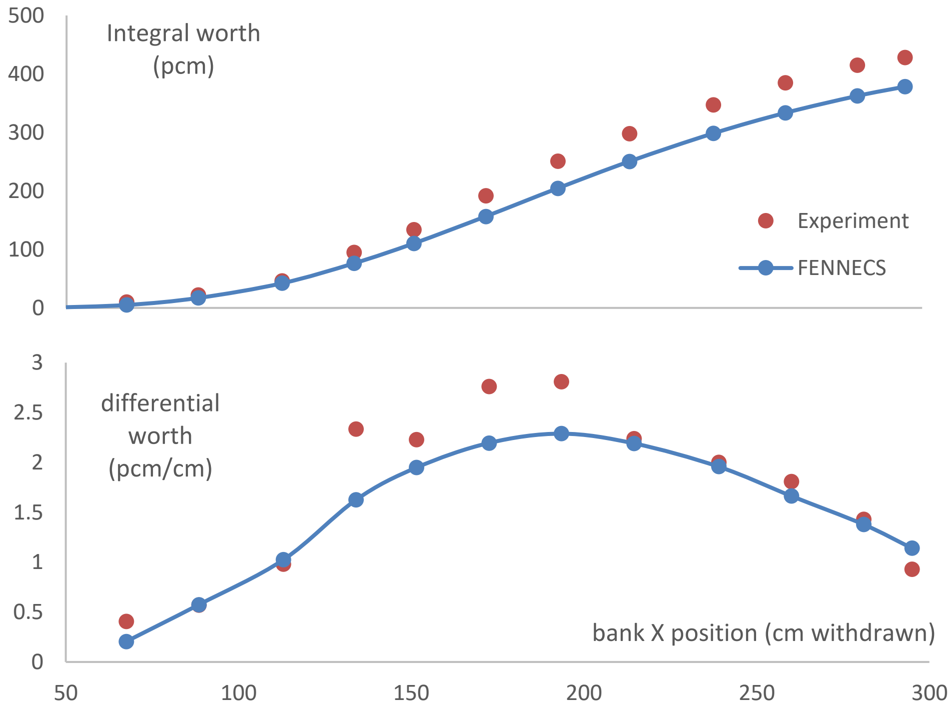

Figure 6: Integral (up) and differential (down) control bank 10 worth.

The last measurement of the start-up test concerned the integral and differential worth of the bank 10. During the experiment, the boron concentration was increased while withdrawing the bank 10, initially fully inserted while other banks were totally withdrawn, step by step from the core. Once more, calculated curves were obtained with several criticality calculations and are displayed in Figure 6 together with the experimental results. It can be seen that FENNECS underestimates the integral worth by almost 10 %. This is explained by a slight underestimation of the differential worth in the middle part of the core. Nonetheless, it should be noted that the experimental differential curve does not have the expected smooth behaviour indicating large uncertainties in the measurement (no values reported in the benchmark). As a last point in the validation purposes, it should be noted that no cusping effect is observed demonstrating that the control rod model was appropriately implemented.

5 CONCLUSION

The HZP of the X2 benchmark was reproduced with FENNECS. In order to produce few-group cross-section, suitable SERPENT models have been built. Furthermore, SERPENT was also used to produce a high-fidelity reference solution of the problem in terms of power distribution. Comparison of the two solutions was performed and demonstrates good agreement.

Moreover, FENNECS results were compared to experimental data. Good agreement has been obtained for isothermal temperature reactivity coefficient. Nevertheless, discrepancies in the prediction of the control rod worth have been identified. The use of the SPH method was applied to successfully mitigate some of these discrepancies.

Altogether, FENNECS was proven to be a reliable tool to model this LWR in hexagonal geometry for steady-state conditions. In the future, time dependent problems will be considered for both standalone and multi-physics scenarios.

ACKNOWLEDGMENTS

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