SIMULATION OF CEFR NEUTRONIC START-UP TESTS WITH FENNECS AND COUPLED PIN-BY-PIN MODEL OF A CEFR SUBASSEMBLY

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ABSTRACT

Within the frame of the IAEA Coordinated Research Program I31032, FENNECS was used to simulate Neutronic Start-up Tests, performed at the China Experimental Fast Reactor (CEFR). The FENNECS simulations showed a good agreement with the measurements as well as with the results obtained by Serpent. In addition, a high-fidelity coupled FENNECS/ATHLET model of a single CEFR fuel assembly using pin cell-homogenized and parameterized cross section libraries was developed for first test calculations.

CEFR NEUTRONIC START-UP TESTS

The China Experimental Fast Reactor CEFR is a pool-type sodium cooled fast reactor with a thermal power of 65 MW and UO_2 as fuel. The first core loading consisted of up to 79 fuel subassemblies (SA), 8 control SAs, one neutron source SA, 394 stainless steel (SS) SAs, and 230 boron shielding SAs. The control SAs comprehend two regulating rods (RE-1 and RE-2) and three shim rods (SH-1, SH-2, SH-3), which form the first shut down system, as well as three safety rods (SA-1, SA-2, SA-3), constituting the second shut down system. In the shim and safety rods, the enrichment of ^{10}B in the B_4C absorber is 90% and 20% in the regulating rods.

During the CEFR physical start-up in 2010, the obtained measurements of several experiments (e.g., net criticality, control rod integral and differential worth, void reactivity effects and subassembly exchange reactivity effects [1]) were provided in the frame of an IAEA CRP for benchmark analysis.

THE NEUTRON KINETICS CODE FENNECS

The Finite ElemeNt NEutroniCS code FENNECS is a steady-state and time-dependent 3-d few-group finite element-based diffusion code [2][3]. It applies the continuous Galerkin weighted residual approach using upright triangular prisms with linear basis functions as spatial elements. FENNECS provides a high geometrical flexibility that allows to model complex and irregular geometries. For the spatial meshing of the problem geometry, the Python Enhanced Meshing Tool with Yaml input PEMTY is developed [4]. PEMTY can also provide the mesh with pin cell-wise resolution for high-fidelity coupled simulations of cartesian and hexagonal lattices, as well as of e.g., control drums.

FENNECS requires macroscopic cross sections libraries in a NEMTAB-like format that may be parameterized with respect to thermal hydraulic feedback parameters with linear cross section interpolation. Thermal-hydraulic feedback is considered by a coupling with the GRS thermal-hydraulic system code ATHLET [5].

MONTE CARLO MODELS IN SERPENT

Two types of Monte Carlo models were built to provide a comparison for FENNECS and to generate the cross sections. For both, the Serpent version 2.1.31 with ENDF/B-VII.0 nuclear basis data was used. To compare the FENNECS results of the start-up tests, full core Monte Carlo calculations were performed. Here, the geometry was reproduced in detail. The thermal expansion was considered in the geometric dimensions as well as in the mass and nuclide densities using linear thermal expansion correlations. This effect was included in the Monte Carlo simulations using an extended Serpent version [6] based on version 2.1.31. For the cross sections generation, a single full-scale fuel assembly was modelled in a radial infinite lattice. Assemblies containing non-fissile materials were simulated using supercell models (according to the approach described in [7]): the model includes a non-fuel assembly surrounded by six fuel SAs halves. The macroscopic cross sections are generated in 10 energy groups.

DETERMINISTIC MODELS IN FENNECS

In the FENNECS model of the CEFR, each hexagonal assembly is composed radially by at least six triangular prismatic finite elements. The axial mesh size ranges between 0.006 cm and 7 cm, leading to 58 layers. Consequently, the geometry comprehends 247776 elements, represented by 131924 nodes.

The nuclear data generated by Serpent were directly used as input for FENNECS, except the absorption cross sections of strong neutron absorbers, hence the highly enriched B_4C axial section, located in shim and safety rods. A suited correction must be applied to these cross sections to avoid that the reactivity of the control rods is overestimated. Therefore, the absorption cross sections of the highly enriched B_4C axial section were multiplied by an iteratively determined factor of 0.9158333 (applied to all energy groups) such that FENNECS exactly reproduces the Serpent multiplication factor of k_{eff} = 1.01427.

SIMULATION RESULTS OBTAINED BY FENNECS

FUEL LOADING AND CRITICALITY

Before the start-up, the fuel positions were loaded with mock-up fuel SAs. Criticality was reached by substituting them stepwise with fuel SAs. Actually, during the experiment at the CEFR, when the core was loaded with 71 fuel SAs, this was subcritical, as foreshown by the calculation. FENNECS predicted supercriticality with 72 fuel SAs. Accordingly, the final criticality state was reached with 72 fuel rods at a measured temperature of 245 °C and with RE2 positioned at 70 mm, as shown in Table 1.

Table 1: Core states and criticality obtained for various fuel loading with 7 control rods out of the core.

Number of fuel SAs loaded	Position of RE2	Core state	keff FENNECS	keff Serpent	Reactivity difference w.r.t. Serpent (pcm)
70	Out-of-core	Subcritical	0.99296	0.99533	-240
71	Out-of-core	End of subcritical process	0.99751	0.99936	-186
72	190	Supercritical	1.00146	1.00301	-154
72	70	Critical (Predicted)	1.00100	1.00260	-159

CONTROL ROD WORTH

During the control rod worth experiments, the core uniform temperature was 250°C and it contained 79 fuel assemblies and two additional SS SAs. The control rod worth is derived from the reactivity difference arising from the insertion of one or multiple rods. 14 scenarios were simulated and their description, together with the obtained results, can be found in Figure 1. The FENNECS results agree with the experiments within the measurement errors and slightly overestimate the rod worths, except for RE1 and RE2. For RE2, SA3 and the first shutdown system with SH1 stuck, the highest discrepancies (up to 14 %) were observed. In the other cases, the difference was below 4.2%.

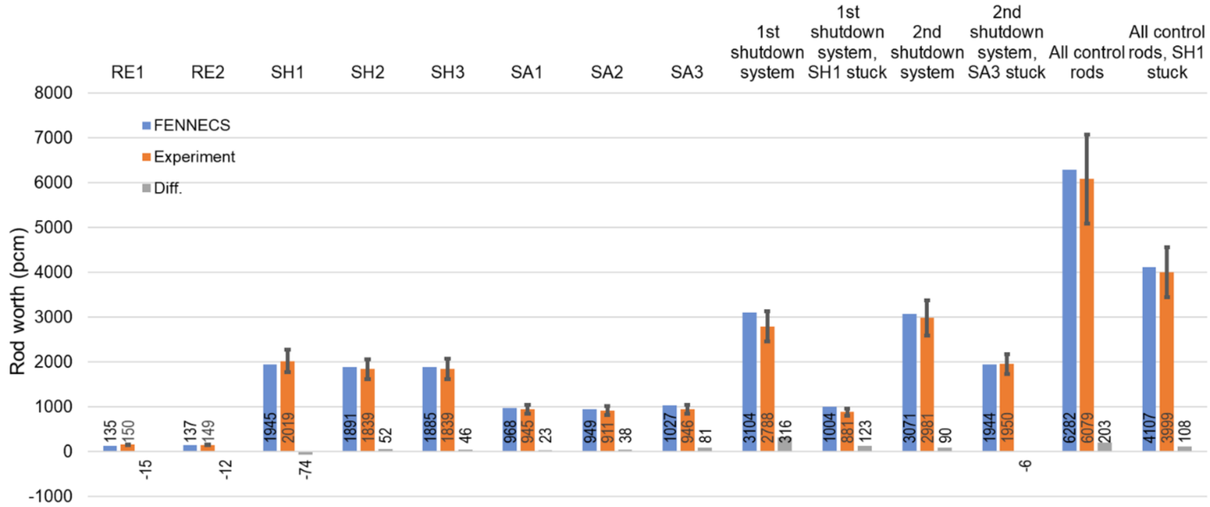

Figure 1: Control rod worth simulations obtained with FENNECS (blue) in comparison with measurements (orange). Differences are shown in grey bars. Error bars denote measurement errors.

Additionally, integral and differential control rod worth curves were determined with FENNECS as well as with Serpent. From both graphs, depicted in Figure 2, the different characteristics of the SAs are clearly visible: regulating rods, containing natural ^{10}B abundance, show flatter curves compared to rods made of enriched ^{10}B. For all rods, the FENNECS results satisfactory match the Serpent simulations.

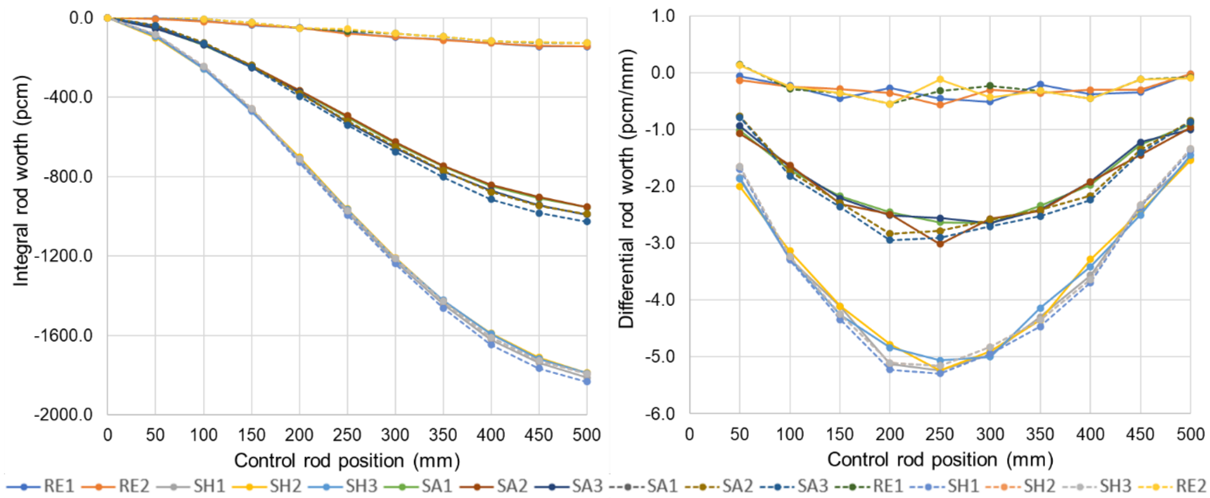

Figure 2: Integral (left) and differential (right) control rod worth curves for the eight control rods obtained by FENNECS (solid lines) and compared with Serpent (dashed) lines.

SODIUM VOID REACTIVITY

The sodium void reactivity is measured by replacing a fuel rod with a voided one in combination with the measurement of the change in the critical control rod position. The replaced SA are marked with blue labels in the right panel of Figure 3.

As shown in the left panel of Figure 3, the void reactivity is negative for all measurement positions. This can be attributed to the small size of the CEFR. Therefore, the (negative) neutron leakage contribution dominates over the positive spectrum hardening effect due to the voiding. Even though, the measurements are slightly overestimated, the FENNECS results are within the measurement errors.

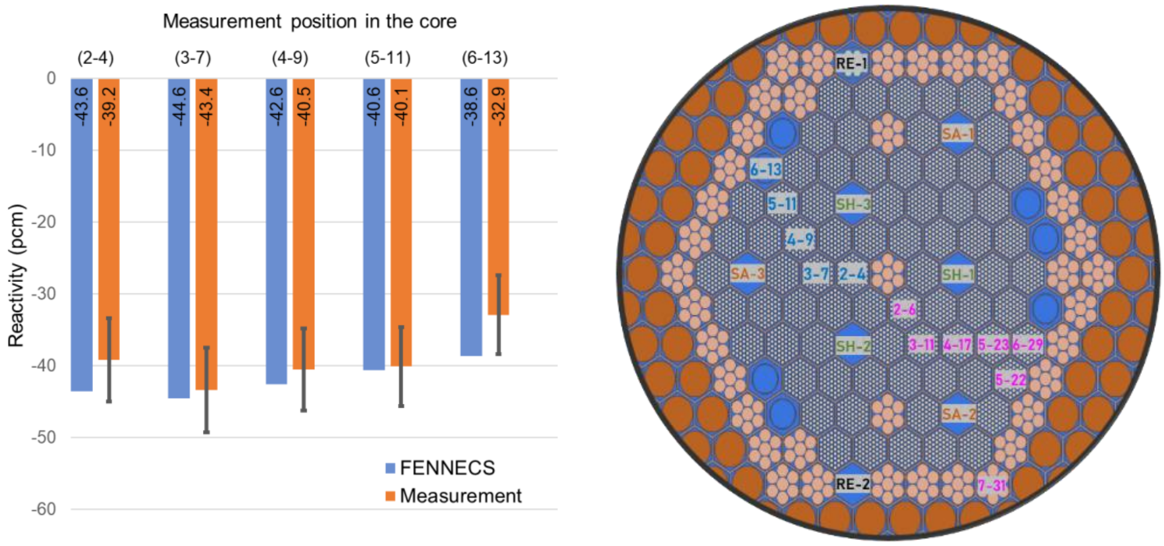

Figure 3: Left: Sodium void reactivity calculated by FENNECS (blue) in comparison with measurements (orange). Error bars denote measurement errors. **Right:** Active core region with assembly labels.

SUBASSEMBLY SWAP REACTIVITY

To simulate the consequences of fuel loading errors, the swap reactivities were measured for 6 fuel rods and 2 SS SAs that are indicated with pink labels in the right panel of Figure 3. In this experiment, the positions of single control rods as well as multiple rods were adjusted and the results can be seen in the left and right panel of Figure 4, respectively. FENNECS slightly underestimates the measured swap reactivities, with deviations between 27 pcm and 118 pcm. However, all calculation results are still within the measurement uncertainties.

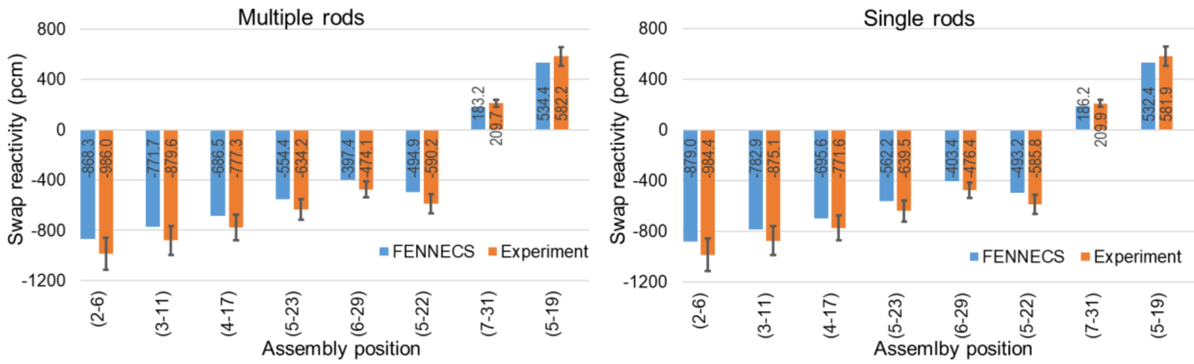

Figure 4: FENNECS results (blue) for the control rod swap reactivities obtained by multiple (left) and single control rods (right) in comparison with measurements (orange). Error bars denote measurement errors.

COUPLED PIN-BY-PIN FENNECS/ATHLET MODEL OF A CEFR SUBASSEMBLY

In the scope of this work, coupled pin-by-pin FENNECS/ATHLET models of the active axial section of a single CEFR fuel assembly and a minicore using pin cell-homogenized and parameterized cross section libraries were developed. This extends the coupled high-fidelity multiphysics simulation methods already available for LWR [8][9][10] to Generation IV and other innovative systems.

Although there are considerable efforts in extending the subchannel code CTF to simulate sodium [11], a release of CTF for sodium is not yet available. Therefore, fluid dynamic and heat transfer are simulated by the thermal hydraulic system code ATHLET [12] in a subchannel-like approach [13]. In this model, the parallel subchannels of the sodium flow around pins, which included 37 inner, 18 edge and 6 corner ones (see left panel of Figure 5), were simulated by individual thermo-fluid-dynamic objects (TFO). The heat transfer between pin and sodium was treated by the heat-conduction objects (HCO). It should be noted that simulation limitations arise from the restriction of the current rod model of ATHLET, where a HCO can be coupled to only one TFO. In FENNECS, a pin cell-resolved neutron kinetics model of both a single CEFR assembly and a minicore consisting of seven assemblies has been developed (see right panel of Figure 5). The pin cell-homogenized cross section libraries have been calculated by Serpent based on the models described above and are parameterized with respect to fuel temperature, sodium density, cladding temperature and pin lattice pitch to capture thermal hydraulic feedback. For the fuel temperature, six support points have been set between 518 K and 2100 K. For each of the remaining feedback parameters, three support points have been chosen, for the sodium density between 0.74 g/cm^3 and 0.927 g/cm^3, for the cladding temperature between 518 K and 1200 K, and for the pin lattice pitch between 6.124 cm and 6.1996 cm.

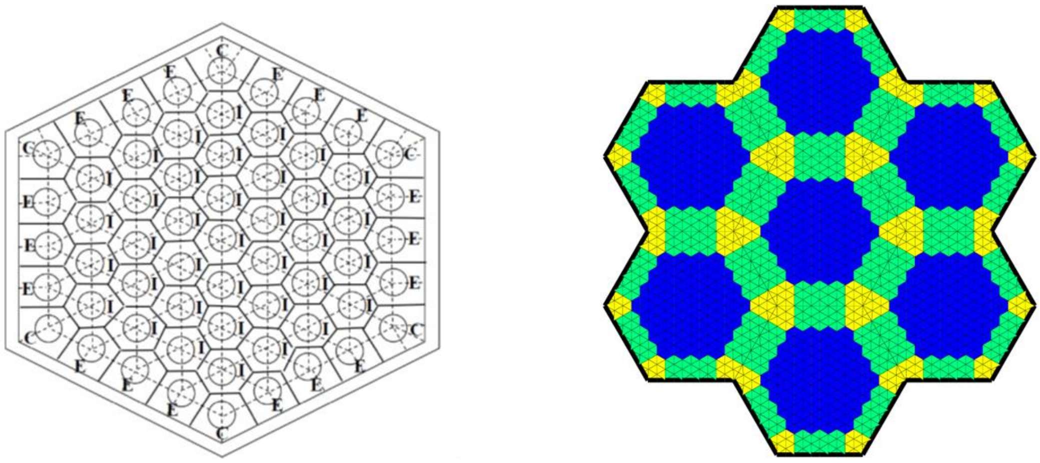

Figure 5: Left: Schematic description and ATHLET mesh setup of the CEFR fuel assembly with inner (I), edge (E) and corner (C) channels. **Right:** Material (cross section library) distribution in inner (blue), edge (green) and corner (yellow) pin cells of a minicore model in FENNECS.

Both for the single CEFR fuel assembly and the minicore, a 1-by-1 feedback mapping between FENNECS and ATHLET is applied, i.e. one pin cell of FENNECS is coupled to only one parallel subchannel in ATHLET. The left panel of Figure 6 shows the steady state fuel temperature distribution in the minicore axial midplane. The temporal evolutions of the minicore power as well as the average and maximum fuel temperature obtained by FENNECS/ATHLET for a transient initiated by a temporary 200 K inlet temperature decrease is shown in the right panel of Figure 6. Although the applicability of ATHLET is questionable for such modeling requirements, the results appear physically plausible and demonstrate the basic applicability of FENNECS to coupled SFR multiphysics simulations including transients. In the future, ATHLET is expected to be replaced by the subchannel code CTF to simulate sodium flow and heat transfer.

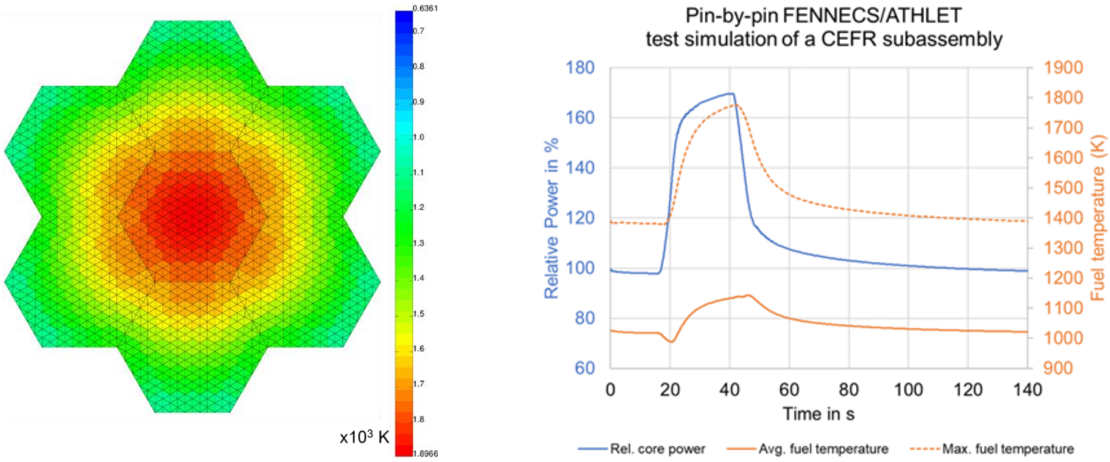

Figure 6: Left: Steady state fuel temperature distribution at the core midplane of the CEFR minicore obtained by FENNECS/ATHLET. **Right:** FENNECS/ATHLET simulation of a transient in a CEFR fuel assembly.

SUMMARY AND CONCLUSION

In this paper, CEFR start-up tests were simulated with the deterministic neutron kinetics code FENNECS in the frame of an IAEA coordinated research project. The criticality, control rod worth, as well as sodium void and subassembly swap reactivities were simulated with FENECCS. Satisfactory agreements were obtained between FENNECS and measurements as well as with Serpent Monte Carlo simulations, thus contributing to the validation of FENNECS. Finally, coupled pin-by-pin steady state and transient simulations were performed for a CEFR single fuel assembly as well as for a minicore using FENNECS/ATHLET. The obtained results demonstrate the basic applicability of FENNECS to coupled SFR multiphysics simulations including transients.

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