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On the use of the SPH method in nodal diffusion analyses of SFR cores

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ABSTRACT

A number of recent studies successfully demonstrated the feasibility of using Monte Carlo code Serpent to generate few-group cross sections (XS) for full core nodal diffusion analyses of SFR cores. The current study investigated the potential of the SPH method, applied to correct the few-group XS produced by Serpent, to further improve the accuracy of the nodal diffusion solutions. The procedure for the generation of SPH-corrected few-group XS is presented in the paper. The performance of the SPH method was tested on a large oxide SFR core from the OECD/NEA SFR benchmark. The reference SFR core was modeled with the DYN3D and PARCS nodal diffusion codes using the SPH-corrected few-group XS generated by Serpent. The nodal diffusion results obtained with and without SPH correction were compared to the reference full-core Serpent MC solution. It was demonstrated that the application of the SPH method improves the accuracy of the nodal diffusion solutions, particularly for the rodded core state.

1. Introduction

Several recent studies investigated the capability of Monte Carlo (MC) code Serpent (Leppänen et al., 2015) to produce few-group homogenized cross sections (XS) for the 3D nodal diffusion analyses of Sodium cooled Fast Reactor (SFR) cores (Fridman and Shwageraus, 2013; Rachamin et al., 2013; Nikitin et al., 2015). In these studies the few-group XS generation methodology was established and tested on various simplified 2D and more realistic 3D SFR core configurations. The nodal diffusion results obtained with the Serpent generated few-group XS showed generally good agreement with the reference full core MC solutions. However, it was observed that for the rodded cores the quality of the nodal diffusion results (e.g. k-eff, power distribution) somewhat deteriorates as compared to the unrodded cases.

Several methods have been applied to improve the accuracy of the control rod few-group cross sections. For example, in the ERANOS code, the transport–transport reactivity equivalence method is routinely used for the treatment of regions containing control rods (Rimpault et al., 2002). More recently, the nodal equivalence theory was applied to produce discontinuity factors for the interfaces between a control assembly and surrounding fuel assemblies (Heo and Kim, 2014). The method, however, requires the conversion of heterogeneous *X–Y* control rod geometry into a simplified multi-ring R–Z model. The goal of the current study is to assess the potential of Superhomogenization (SPH) method (Kavenoky, 1978; Hebert, 1993), particularly applied to the control rod regions, to further improve the accuracy of the nodal diffusion solutions.

In this paper the approach to the generation of SPH-corrected few-group XS is described and the performance of the SPH method is tested on a large SFR core design adopted from the OECD/NEA SFR benchmark (Blanchet et al., 2011). The reference core is modeled with DYN3D (Grundmann et al., 2000, 2005) and PARCS (Downar et al., 2010) multi-group nodal diffusion codes using SPH-corrected few-group XS generated by Serpent. The current results are compared with the previous Serpent-DYN3D and Serpent-PARCS solutions obtained without applying the SPH correction (Nikitin et al., 2015). The nodal diffusion results obtained with and without SPH correction are verified against the reference full-core Serpent MC solution.

This paper has the following structure. The reference SFR core is briefly described in Section 2. The approach to the generation of few-group XS and application of the SPH method are described in Section 3. Section 4 presents the results of the verification calculations. Section 5 summarizes the paper.

2. Description of the reference SFR core

A large 3600MWth SFR U-Pu mixed oxide (MOX) core specified by the SFR Benchmark Task Force of OECD/NEA (Blanchet et al., 2011) was selected as a reference core design. It should be noted

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that the selected reference core is fully identical to that used in our previous study (Nikitin et al., 2015).

The reference core consists of 225 inner and 228 outer MOX fuel sub-assemblies with variable Pu content and surrounded by 330 radial reflector sub-assemblies. The fuel sub-assemblies have 271 helium bonded fuel rods with Oxide Dispersion Strengthened (ODS) steel cladding and surrounded by a hexagonal EM10 steel duct. The fuel rods are subdivided into 5 axial zones including lower gas plenum, EM10 steel lower reflector, fuel, upper gas plenum, and EM10 steel upper reflector. The axial and radial fuel rod description including the distribution of the Pu content is presented in Fig. 1. The actual dimensions of the fuel sub-assembly components are summarized in Table 1. The radial layout of the fuel sub-assembly is shown in Fig. 2a. According to the benchmark specifications, the radial reflector sub-assemblies are modeled as a homogeneous mixture of sodium and EM10 steel.

The core is controlled by two independent reactivity control systems. The primary reactivity control system consists of the 24 control and shutdown devises (CSD), each of which has 37 sodium bonded natural B_4C pins (Fig. 2b). The secondary reactivity control system comprises of the 9 Diverse Shutdown Devises (DSD) with 55 sodium bonded enriched B_4C (90.0 w% of B-10) pins (Fig. 2c.). The main design parameters of the CSD and DSD sub-assemblies are summarized in Table 2. For the nominal case, the CSD and DSD sub-assemblies remain at the parking position that is the bottom of the CR pins is located at the top of the active core.

Fig. 3 presents the radial core layout including the location of the control sub-assemblies. In order to simplify the modeling, two uniform temperatures are considered namely 1500 K for the fuel and 743 K for all structural materials, coolant, and CRs. A detailed description of the material compositions can be found in the benchmark specifications (Blanchet et al., 2011).

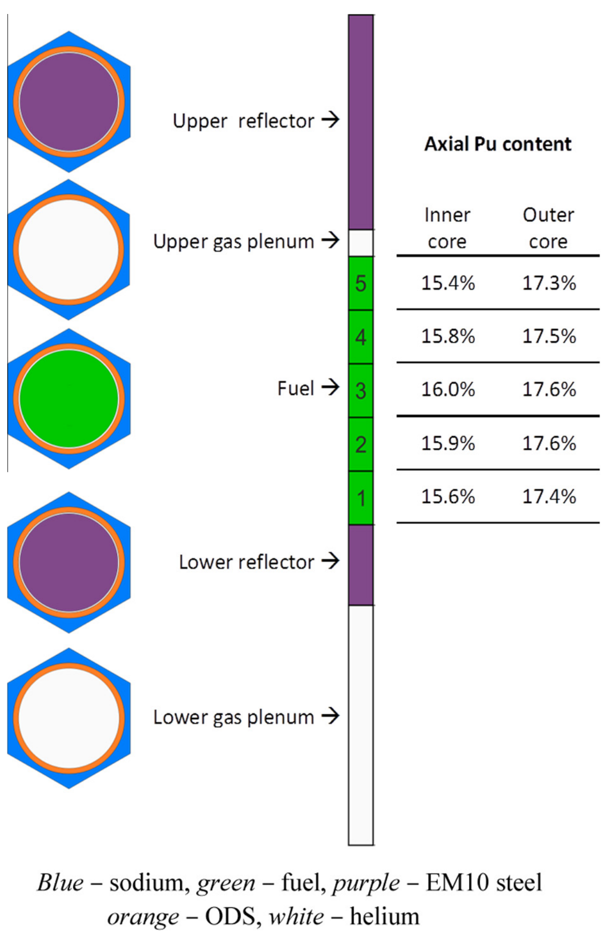

Fig. 1. Radial and axial fuel rod description.

Table 1
Fuel sub-assembly: summary of the main design parameters.

Total sub-assembly heigth, cm	311.16
Lower gas plenum heigth, cm	89.92
Lower axial reflector heigth, cm	30.17
Active core height, cm	100.56
Upper gas plenum heigth, cm	10.06
Upper axial reflector heigth, cm	80.45
Sub-assembly pitch, cm	21.22
Outer duct width (flat-to-flat), cm	20.7468
Inner duct width (flat-to-flat), cm	19.8418
Number of fuel pins	271
Outer cladding radius, cm	0.5419
Inner cladding radius, cm	0.4893
Fuel pellet radius, cm	0.4742
Pellet material	$(U, Pu)O_2$
Central hole radius, cm	0.1257
Pin pitch, cm	1.1897

3. Generation of the few-group XS and application of the SPH method

3.1. A general approach to the few-group XS generation

The general approach to the few-group XS generation is similar to that adopted in our previous study (Nikitin et al., 2015). Therefore only a brief description of the XS generation methodology is given. In this study the Serpent code was used to generate few-group XS data for all core components according to the following procedure:

- The few-group XS for the fuel sub-assemblies not facing radial reflector were calculated using a 3D single sub-assemblies model with reflective radial and black axial boundary conditions (BC).
- The few-group XS for the outermost fuel assemblies facing the radial reflector were generated using 3D fuel-reflector models depicted in Fig. 4. The group constants were homogenized over the peripheral fuel sub-assemblies facing the radial reflector only.
- The few-group XS for all non-multiplying regions (i.e. axial and radial reflectors, gas plenums, empty CR channels, CSD and DSD sub-assemblies) were prepared using 2D super-cell models depicted in Fig. 5. All super-cells were constructed as central

Table 2
Control sub-assemblies: summary of the main design parameters.

	CSD (primary control)	DSD (secondary control)
External duct:		
- Outer width (flat-to-flat), cm	20.7468	20.7468
- Inner width (flat-to-flat), cm	19.8418	19.8418
Internal duct:		
- Outer width (flat-to-flat or diameter), cm	15.6883	14.8838
- Inner width (flat-to-flat or diameter), cm	15.2860	14.4815
Number of pins cm	37	55
Outer cladding radius, cm	1.1476	0.8222
Inner cladding radius, cm	1.0474	0.7709
Pellet radius, cm	0.9202	0.7039
Pellet material	B_4C (19.9 w% B-10)	B_4C (90.0 w% B-10)
Pin pitch, cm	2.4438	1.7519