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A neutron-leakage spectrum model for on-the-fly rehomogenization of nodal cross sections

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ABSTRACT

Modeling spectral effects due to core heterogeneity is one of the major challenges for current nodal analysis tools, whose accuracy is often deteriorated by cross-section homogenization errors. AREVA NP recently developed a spectral rehomogenization method that estimates the variation of the assembly-averaged neutron flux spectrum between environmental and infinite-lattice conditions using a modal synthesis. The effectiveness of this approach is tied to the evaluation of the spectrum of the neutron leakage from or into the assembly in the environment.

In this paper, we propose a method for the leakage spectral distribution building upon Fick's diffusion law. The neutron-exchange spectrum at a nodal interface is computed as a function of the gradient of the environmental flux spectrum, which is determined by the rehomogenization algorithm. This diffusive approach is applied to PWR benchmark problems exhibiting strong interassembly heterogeneity. We show that the method accurately reproduces the energy dependence of streaming effects, and that significant improvements in the input nodal cross sections, fission power and multiplication factor estimates are achieved at a low computational cost. The proposed model is compared with an alternative approach, that uses the fundamental-mode leakage spectrum obtained from the solution of the B_1 equations. This second strategy is generally less accurate, and can only provide an adequate approximation of the environmental leakage in weakly heterogeneous systems.

1. Introduction

Routine calculations for reactor core design, monitoring and safety analyses are commonly performed with advanced nodal-diffusion methods on coarse meshes (Lawrence, 1986; Stacey, 2007). Fuel-assembly homogenization for the generation of few-group constants (nodal cross sections and discontinuity factors) is performed via heterogeneous transport calculations under the assumption of reflective boundary conditions at the assembly outer edges (Smith, 1986). However, this approximation can lose its validity when the assembly is simulated within the real environment (i.e., the reactor core). Here, streaming effects induced by internodal heterogeneity can cause significant deviations of the actual neutron flux distribution from the infinite-medium one used for spatial homogenization and energy collapsing of cross sections. Common examples in which the homogenization error can be highly penalizing are configurations with strong burnable absorbers and control rods; mixed oxide (MOX) assemblies surrounded by uranium oxide (UOX) assemblies; fresh-fuel assemblies facing depleted regions; and fuel bundles bordering reflector nodes. With these diverse layouts, the equivalence between the homogeneous nodal representation and the heterogeneous fine-mesh transport solution is only ensured if environmental (spatial and spectral) effects are modeled.

Several methods can be found in the reactor physics literature to correct single-assembly cross sections for spectral effects. Among them, we mention: empirical correlations taking into account local spectral interactions (Palmtag, 1997; Ban and Joo, 2016; Smith, 2017); the parameterization of nodal cross sections and discontinuity factors versus the current-to-flux ratio (and/or other albedo parameters) at the node outer surfaces (Rahnema and Nichita, 1997; Kim et al., 2017); high-order cross-section homogenization (Rahnema and McKinley, 2002); a spatial superposition technique of typical four-assembly configurations (Clarno and Adams, 2005); a *recondensation* method based on the Discrete Generalized Multigroup (DGM) energy expansion theory (Zhu and Forget, 2011); and a semi-heterogeneous transport-embedded approach (Groenewald et al., 2017).

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The present work builds upon the spectral rehomogenization method developed at AREVA NP (Dall'Osso et al., 2010; Gamarino et al., 2017, 2018). In this approach, the variation of the neutron flux spectrum in the homogenized assembly between the environmental and infinite-medium conditions is estimated during the core nodal calculation via modal synthesis. The energy-condensation defects are computed on-the-fly and added to the few-group nodal cross sections interpolated from the standard parameterized tables. The performance of the method depends on two paramount points: (*i*) the set of basis and weighting functions employed for the modal expansion of the spectrum perturbation, and (*ii*) the definition of an accurate spectral distribution of the neutron leakage in the real environment. The former topic has been extensively treated in previous work (Gamarino et al., 2017, 2018). In Gamarino et al. (2018), two modal approaches have been investigated. The first strategy uses analytical basis functions (Chebyshev polynomials of the first kind) and a physical mode in the fast group (i.e., the neutron fission-emission spectrum). The second approach is based on the Proper Orthogonal Decomposition (POD). It computes the optimal (in a least-squares sense) orthonormal basis functions for the space spanned by a set of snapshots of the reference spectrum perturbation. The two methods have been compared in terms of accuracy and computational efficiency. Several aspects of the rehomogenization method have been discussed, such as the implementation features, the impact of the approximations in the derivation of the algorithm, and the complementarity with other kinds of cross-section corrections (i.e., spatial rehomogenization and the critical-buckling spectrum correction).

In this paper, the methodology for the leakage spectral distribution is described. The leakage rate in a fuel assembly is dominated by two factors (Hebert, 2009): scattering anisotropy and interassembly neutron exchange. The former has an important effect in Pressurized Water Reactors (PWRs) due to the presence of hydrogen in the moderator, and is usually taken into account via transport corrections (such as the consistent B_1 and P_1 approximations) performed at the lattice-calculation level. The latter is inherently dependent on the core environment. The inaccurate results achieved with a flat-leakage approximation (i.e., considering the leakage spectral distribution uniform and equal to the coarse-group nodal estimate) highlighted the importance of finding a realistic energy shape for streaming effects (Gamarino et al., 2018). Hence, the aim of this work is to develop a model for the leakage spectrum. Two approaches are proposed and investigated. The first one is based on the application of Fick's diffusion law to the node-averaged environmental spectra estimated by the rehomogenization algorithm. We refer to it as *diffusive-leakage* model. The second one uses the homogenized-assembly critical-leakage spectrum from the fundamental-mode (B_1) calculation. The two strategies are tested on PWR assembly layouts characterized by significant heterogeneity. Both isothermal fresh-fuel conditions and configurations with depletion feedbacks are considered. Focus is given to the more promising diffusive-leakage approach.

This paper is structured as follows. In Section 2 the diffusive and fundamental-mode leakage methods are described. Section 3 shows numerical results for several PWR benchmark problems. In Section 4 we address various features of interest of the diffusive model. Concluding remarks and suggestions for future work follow in Section 5.

2. Description of the method

In this Section, the spectral rehomogenization method is briefly reviewed for the sake of completeness. The description of the two models for the leakage spectrum follows.

2.1. Review of spectral rehomogenization

The details about the derivation and the implementation features of the method can be found in Gamarino et al. (2018a).

For a generic homogenized node, the neutron continuous-energy balance equation in the environmental conditions can be written, within the coarse group G, as

$$\Sigma_{t,G}(u)\Phi_{\mathrm{env},G}(u) + L_{\mathrm{env},G}(u) = \sum_{G'=1}^{N_G}\left(\frac{\chi_G(u)}{k_{\mathrm{eff}}}\int_0^1 du'\nu\Sigma_{f,G'}(u')\Phi_{\mathrm{env},G'}(u') + \int_0^1 du'\Sigma_{s,G'\to G}(u'\to u)\Phi_{\mathrm{env},G'}(u')\right). \quad (1)$$

The lethargy-like quantity u, bounded between 0 and 1, is defined as

$$u = \frac{\ln\left(\frac{E}{E_G^-}\right)}{\ln\left(\frac{E_G^+}{E_G^-}\right)}, \quad (2)$$

where E_G^+ and E_G^- denote the G-th group upper and lower energy boundaries. In Eq. (1), $\Phi_{\mathrm{env},G}(u)$ and $L_{\mathrm{env},G}(u)$ represent the neutron spectrum and the leakage energy distribution, respectively. The remaining symbols have the conventional meaning (Stacey, 2007). The assumption is made that the cross-section distributions depend only weakly on the environment (namely, $\Sigma_{x,G}(u) \approx \Sigma_{x,G}^{\infty}(u)$ for reaction type x). From now on, when referring to spectral functions we omit the argument u for the sake of lightness of the notation (i.e., $f_G = f_G(u)$).

In each of the N_G coarse groups, the environmental spectrum is formulated as the sum of the reference distribution in the infinite-medium conditions ($\varphi_{\infty,G}$) and of the spectrum variation in the real environment ($\delta\Phi_G$):

$$\Phi_{\mathrm{env},G}(u) = \bar{\Phi}_G\varphi_{\infty,G}(u) + \delta\Phi_G(u). \quad (3)$$

In Eq. (3), $\bar{\Phi}_G$ denotes the few-group node-averaged flux. The single-assembly spectrum $\varphi_{\infty,G}$ is normalized to unity, and $\delta\Phi_G$ has zero average within G. The spectrum perturbation is expanded in terms of N_{Q_G} zero-averaged modal components $Q_{G,i}$:

$$\delta\Phi_G(u) = \sum_{i=1}^{N_{Q_G}}\alpha_{G,i}Q_{G,i}(u). \quad (4)$$

Eqs. (1), (3) and (4) define the spectral rehomogenization problem. The coefficients $\alpha_{G,i}$ are solved for with a weighted-residual technique: after substitution of Eqs. (3) and (4), Eq. (1) is projected over a set of weighting functions $W_{G,j}$ (with $j = 1,\ldots,N_{Q_G}$) and integrated over u. The following $N_GN_{Q_G} \times N_GN_{Q_G}$ linear system is obtained:

$$\bar{\Phi}_G h_{R,t,G,j} + \sum_{i=1}^{N_{Q_G}}\alpha_{G,i}h_{V,t,G,i,j} + c_{G,j} = \sum_{G'=1}^{N_G}\bar{\Phi}_{G'}\left(h_{R,s,G'\to G,j} + \frac{\chi_{G,j}}{k_{\mathrm{eff}}}h_{R,f,G'}\right) + \sum_{G'=1}^{N_G}\sum_{i=1}^{N_{Q_{G'}}}\alpha_{G',i}\left(h_{V,s,G'\to G,i,j} + \frac{\chi_{G,j}}{k_{\mathrm{eff}}}h_{V,f,G',i}\right). \quad (5)$$

In Eq. (5), the leakage projection coefficient $c_{G,j}$ is defined as

$$c_{G,j} = \int_0^1 du W_{G,j}(u)L_{\mathrm{env},G}(u), \quad (6)$$

whereas the remaining variables read as

$$\chi_{G,j} = \int_0^1 du W_{G,j}(u)\chi_G(u), \quad (7a)$$

$$h_{R,t,G,j} = \int_0^1 du W_{G,j}(u)\Sigma_{t,G}(u)\varphi_{\infty,G}(u), \quad (7b)$$