Enhanced Resonance Self-shielding Method in Lattice Physics Code STREAM

Sooyoung Choi [a], Changho Lee [b], Deokjung Lee [a*]
[a] *School of Mechanical and Nuclear Engineering, Ulsan National Institute of Science and Technology, UNIST-gil 50, Ulsan, Korea*
[b] *Nuclear Engineering Division, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL, USA*
[*]Corresponding author: deokjung@unist.ac.kr

1. Introduction

A new resonance self-shielding method has been developed to enhance performance of lattice physics code STREAM. Equivalence theory is widely used in many lattice physics codes to generate the effective cross-section (XS) [1]. However, there are several drawbacks in the conventional equivalence theory. First, intermediate resonance approximation cannot model the resonance scattering source accurately [2]. Second, a crude resonance interference model causes significant error. Third, constant XS within fuel pellet is assumed.

In this paper, the pin-based slowing-down method (PSM) has been developed to solve a spatially dependent pointwise energy slowing-down equation for the problem of sub-divided fuel pellet. The multi-group cross sections determined with pointwise flux solutions. Using light water reactor pin-cell problems, it was demonstrated that the new resonance self-shielding method showed good agreement with MCNP6 [3] solutions in eigenvalues and XS.

2. Methodology

In this section, the pin-based pointwise energy slowing down equation is derived. A transport equation with collision probabilities is written for submesh *i* of fuel pellet as follows:

$$\Sigma_{t,i}(u)\phi_i(u)V_i = \sum_{j\in F} P_{ji}(u)V_j Q_{s,j}(u) + P_{Mi}(u)V_M Q_{s,M}(u) \quad , \tag{1}$$

where $\Sigma_{t,i}(u)$ is the total XS of region *i* and energy *u*; $\phi_i(u)$ is the flux of region *i*; V_i is the volume; $P_{ji}(u)$ is the first flight collision probability from region *j* to *i*; $Q_{s,j}(u)$ is the slowing-down scattering source of region *j*; and, M is index of non-fuel region.

A pseudo moderator is made for each unit pin-cell by homogenizing non-fuel regions of each pin-cell and assuming that the pseudo moderator has only potential XS. Further using reciprocity relation, the fluxes of region *i* and non-fuel region are written as

$$\begin{cases} \phi_i(u) = \sum_{j\in F} \dfrac{P_{ij}(u)}{\Sigma_{t,j}(u)} Q_{s,j}(u) + \dfrac{P_{iM}(u)}{\Sigma_{p,M}} Q_{s,M}(u) \\ \phi_M(u) = \sum_{i\in F} \dfrac{P_{Mi}(u)}{\Sigma_{t,i}(u)} Q_{s,i}(u) + \dfrac{P_{MM}(u)}{\Sigma_{p,M}} Q_{s,M}(u) \end{cases} . \tag{2}$$

If the collision probabilities P_{ij}, P_{iM}, P_{Mi} and P_{MM} are known, the fluxes and scattering sources can be calculated by solving a fixed source problem. However, it is costly to calculate the collision probabilities for all energy points and large geometries (*i.e.* fuel assembly and full-core) because of significant computing resource requirements. Therefore, the PSM uses a two-step strategy. In the first step, the collision probability is computed as a function of total XS of isolated fuel pin. In the calculation, fuel pellet is subdivided into multi regions. In the second step, an effect of neighboring fuel pellet and structure material (so called the shadowing effect) is corrected by using an adjustment factor. A whole problem-wise fixed source transport problem is solved to calculates the Dancoff factor, and then used in computing the multi-term rational approximation for the fuel escape probability which is used in the equivalence theory. The shadowing effect correction factor is calculated as a ratio of the multi-term rational approximations for an isolated pin and pin in lattice. The correction factor is used in considering the shadowing effect which is not considered in the first step. With the two-step method, collision probabilities in Eq. (2) are calculated efficiently.

Once the pointwise energy fluxes of submeshes are calculated, isotopic pointwise XSs in the fuel material are straight-forwardly condensed to multi-group XSs as

$$\sigma^r_{x,i,g} = \frac{\int_{\Delta u_g} \sigma^r_x(u)\phi_i(u)du}{\int_{\Delta u_g} \phi_i(u)du} \quad . \tag{3}$$

In this method, the resonance interference effect is considered inherently because the pointwise slowing-down calculation is performed with all nuclides included in a fuel.

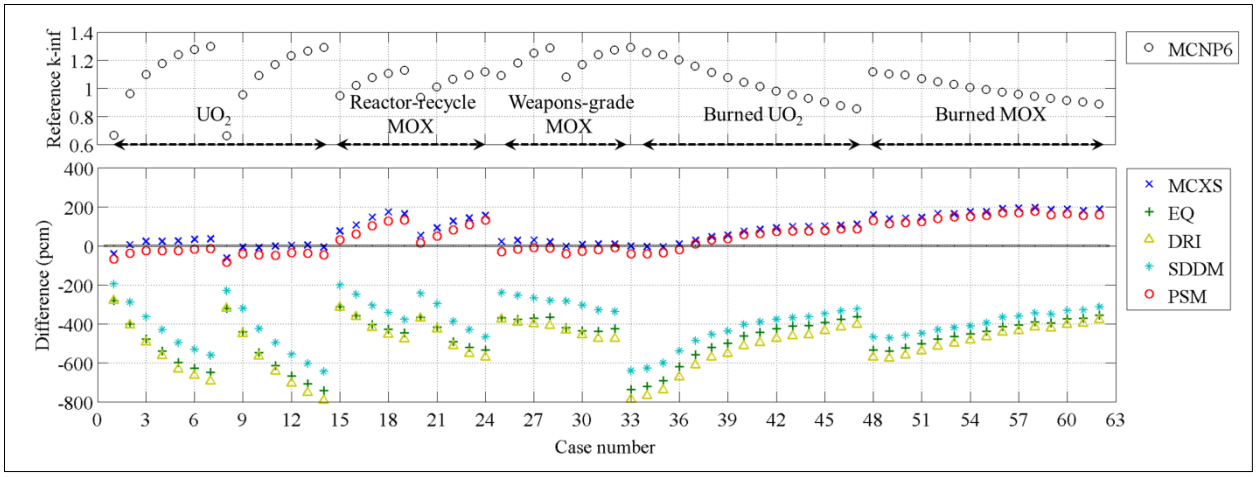

Fig. 1. Pin-cell comparison results.

3. Verification

PSM is tested against to 62 infinite pin-cell problems as shown in Fig. 1. The case numbers 1 to 32 are problems in well-known Mosteller benchmark. The case numbers 33 to 47 are burned UO_2 fuel problem, and the case numbers 48 to 62 are burned MOX fuel problems. 5 wt% enriched UO_2 fuel at hot full power (Case number 14) and 8 wt.% Pu content reactor-recycle MOX fuel at hot full power (Case number 24) are burned up to 60 MWd/kgU burnup. The depletion calculations are performed with MCNP6, and the material compositions of each burnup step are extracted in order to make STREAM code inputs. More than 120 burnup steps are used in the depletion calculation. However, the 15 steps are selected in order to reduce the number of test models.

PSM is compared to contemporary resonance self-shielding methods. Following methods are implemented in the STREAM code, and compared in Fig. 1.

1) MCXS: multi-group XS of resonance energy range (0.3 eV to 24 keV) from MCNP6.
2) EQ: Conventional equivalence theory [1].
3) DRI: Distributed resonance integral method with 15 submeshes in the fuel [4].
4) SDDM: Spatially dependent Dancoff method with 15 submeshes [5].

The equivalence theory based methods (EQ, DRI and SDDM) show similar results each other. The eigenvalues from the three methods are underestimated about 200 ~ 800 pcm. There are various error sources in the equivalence theory such as the resonance scattering source [2] and resonance interference treatment [6]. On the other hand, PSM shows significant improvement in eigenvalue calculations. PSM has less than 100 pcm differences for the UO_2 fuel problems and less than 200 pcm difference for the MOX fuel problems. There are less than 50 pcm difference between PSM and MCXS. In other word, the error from the resonance treatment of PSM is less than 50 pcm. The first purpose of the resonance treatment is to calculate accurate multi-group XS compared to the continuous energy Monte Carlo result. There are many error sources in multi-group calculations (*i.e.* discrepancy in the reaction rates from continuous energy calculation and multi-group calculation; errors in thermal and fast energy range). The error from other sources except the resonance multi-group XS is out of scope of the resonance treatment.

4. Conclusions

The pin-based slowing-down method (PSM) has been developed to enhance the performance of the lattice physics code STREAM. In the PSM, the spatially dependent pointwise energy slowing-down equation is solved for pin-cell and then the effective multi-group XS is condensed with the pointwise energy flux. Through various pin-cell problem analyses, it is verified that the STREAM code with PSM gives order of 100 pcm accuracy.

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