A Cross-Section Adjustment Method for Double Heterogeneity Problem in VHTGR Analysis

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1. Introduction

Very High Temperature Gas-Cooled Reactors (VHTGRs) draw strong interest as candidates for a Gen-IV reactor concept, in which TRISO (tristructural-isotropic) fuel is employed to enhance the fuel performance. However, randomly dispersed TRISO fuel particles in a graphite matrix induce the so-called double heterogeneity problem.

For design and analysis of such reactors with the double heterogeneity problem, the Monte Carlo method is widely used due to its complex geometry and continuous-energy capabilities [1, 2]. However, its huge computational burden, even in the modern high computing power, is still problematic to perform whole-core analysis in reactor design procedure.

To address the double heterogeneity problem using conventional lattice codes, the RPT (Reactivity-equivalent Physical Transformation) method considers a homogenized fuel region that is geometrically transformed to provide equivalent self-shielding effect [3]. Another method is the coupled Monte Carlo/Collision Probability method, in which the absorption and nu-fission resonance cross-section libraries in the deterministic CPM3 lattice code are modified group-wise by the double heterogeneity factors determined by Monte Carlo results [4].

In this paper, a new two-step Monte Carlo homogenization method is described as an alternative to those methods above. In the new method, a single cross-section adjustment factor is introduced to provide self-shielding effect equivalent to the self-shielding in heterogeneous geometry for a unit cell of compact fuel. Then, the homogenized fuel compact material with the equivalent cross-section adjustment factor is used in continuous-energy Monte Carlo calculation for various types of fuel blocks (or assemblies). The procedure of cross-section adjustment is implemented in the MCNP5 code [5].

2. Two-Step Calculation with Cross-Section Adjustment

The fuel block is homogenized by Monte Carlo calculations in two steps. Step 1 calculation geometry in the GTMHR (Gas Turbine Modular Helium Reactor) is composed of fuel compact region embedded in graphite matrix and coolant channel regions, as shown in Fig. 1.

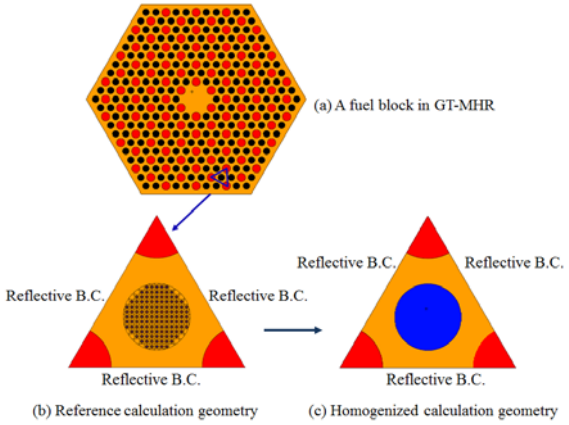

Fig. 1. Unit cell for a compact fuel in Step 1 calculation

The key idea is to homogenize fuel compact volumetrically (and no change of the radius) by adjusting capture cross sections of the nuclides to preserve the k_{eff} of the heterogeneous geometry. In the Step 1 calculation, the MCNP5 code is wrapped around by the secant method. Thus, the MCNP code solves the following continuous-energy neutron transport equation for eigenvalue $k_{eff}^{(i)}$, with given cross-section adjustment factor $\beta^{(i)}$:

$$\begin{aligned}&\vec{\Omega}\cdot\nabla\psi\left(\vec{r},\vec{\Omega},E\right)+\sigma_t\left(\vec{r},E\right)\psi\left(\vec{r},\vec{\Omega},E\right)\\&=\int d\vec{\Omega}'\int dE'\hat{\sigma}_s\left(\vec{r},E'\to E,\vec{\Omega}'\cdot\vec{\Omega}\right)\psi\left(\vec{r},\vec{\Omega}',E'\right)\\&+\frac{1}{k_{eff}^{(i)}}\frac{\chi\left(E\right)}{4\pi}\int d\vec{\Omega}'\int dE'\nu\sigma_f\left(\vec{r},E'\right)\psi\left(\vec{r},\vec{\Omega}',E'\right),\end{aligned}\tag{1}$$

where

$$\hat{\sigma}_s\left(\vec{r},E'\to E,\vec{\Omega}'\cdot\vec{\Omega}\right)\equiv\sigma_s\left(\vec{r},E'\to E,\vec{\Omega}'\cdot\vec{\Omega}\right)\times\frac{\sigma_t\left(\vec{r},E'\right)-\beta^{(i)}\sigma_{n,\gamma}\left(\vec{r},E'\right)-\sigma_f\left(\vec{r},E'\right)}{\int d\vec{\Omega}\int dE\sigma_s\left(\vec{r},E'\to E,\vec{\Omega}'\cdot\vec{\Omega}\right)},\tag{2}$$

for nuclides in homogenized region, and

$$\hat{\sigma}_s\left(\vec{r},E'\to E,\vec{\Omega}'\cdot\vec{\Omega}\right)=\sigma_s\left(\vec{r},E'\to E,\vec{\Omega}'\cdot\vec{\Omega}\right),\tag{3}$$

for nuclides in other regions.

Here i is the iteration index of the secant method and $\beta^{(i)}$ is updated till $k_{eff}^{(i)}$ becomes k_{eff}^{ref}. The volumetrically homogenized fuel compact material with converged cross-section adjustment factor is then used in Step 2 fuel block (or assembly) Monte Carlo calculation as shown in Fig. 2. The results of Step 2

calculation can be used to homogenize the block according to the equivalence theory in nodal diffusion methodology. Alternatively, these two steps can be combined into a single step, and implementation of this alternative approach is in progress.

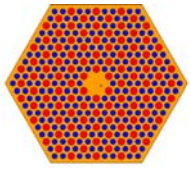

Fig. 2. Fuel block in Step 2 calculation

3. Numerical Results

A representative GTMHR fuel block problem [6] with 3.3 w/o UO_2 fuel is considered for a test of the new method. The results of the Step 1 calculation are shown in Table I, while the results of fuel block calculation are shown in Table II. It is seen that the homogenized fuel compact material with cross-section adjustment provides good agreement in k_{eff} with speedup factor of about 3.5 even in the same Monte Carlo calculation.

Table I: Comparison of k_{eff} in fuel compact calculation

	β	k_{eff}	1 σ [pcm]	$\Delta k_{eff}/k_{eff}$ [pcm]
Reference heterogeneous fuel compact	-	1.02875	9.3	-
Volumetric homogenized fuel compact	-	0.99093	9.9	-3676.3
Homogenized fuel compact with X-section adjustment (0.1~300 eV)	0.880182	1.02854	8.2	-20.3
Homogenized fuel compact with X-section adjustment (whole energy range)	0.919854	1.02879	9.3	3.9

Table II: Comparison of k_{eff} and computing time in fuel block calculation

	k_{eff}	1 σ [pcm]	$\Delta k_{eff}/k_{eff}$ [pcm]	Computing Time* [min]
Reference heterogeneous fuel block	1.00146	9.0		5361
Volumetric homogenized fuel block	0.96736	8.7	-3405.0	1597
Homogenized fuel block with X-section adjustment (0.1~300 eV)	1.00172	9.0	26.0	1214
Homogenized fuel block with X-section adjustment (whole energy range)	1.00237	9.0	90.9	1570

*: on 14 Core 2 Duo Dual-Core Processor E8400 CPUs

The tallied neutron spectra of the fuel block calculation are shown in Fig. 3. Unlike the conventional volumetric homogenized case, the neutron spectra resulting from cross-section adjustment show very good agreement with the reference heterogeneous fuel block spectrum.

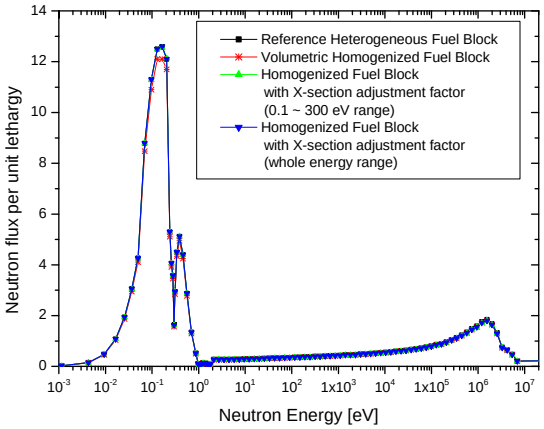

Fig. 3. Comparison of neutron spectra in fuel block calculation

4. Concluding Remarks

A two-step Monte Carlo homogenization method based on cross-section adjustment was introduced in this paper and implemented in the MCNP5 code. Numerical results on a representative GTMHR fuel block problem showed good agreement in eigenvalues and neutron spectra compared to the results of the reference heterogeneous fuel block calculation.

Although the method was applied to compact fuel in this study, application to pebble fuel is straightforward.

Since the cross-section adjustment method does not change the boundary of the fuel region, it would encounter no mismatch complications with thermal analysis component in the multi-physics computational framework.

If desired, the results of Step 1 calculation could be post-processed and used in the conventional lattice physics (deterministic) codes for two-dimensional problems.

References

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