Two-Step Diffusion Solutions to the IAEA CRP5 Pebble Box Benchmark Problem

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1. Introduction

Recently, the IAEA CRP-5 Pebble Box benchmark problem was proposed for a code-to-code comparison [1]. To investigate the effect of the core/reflector spectral interaction and the effect of heterogeneity, the problem defines seven cases depending on the presence of a reflector and the level of heterogeneity.

We presented a preliminary MCNP [2] solution to this problem by using definitions of the problem in reference 3. In this study, the two-step diffusion solutions as well as the MCNP solutions to the problem by using the final specifications of the problem are presented. The results are compared with those from MCNP calculations. Since the problem size is very small when compared to that of a power reactor, a transverse leakage (TL) correction was needed for the infinite slab spectral geometry for the equivalent homogenization that was proposed for the analysis of large power reactors. Analysis results show that the errors can be reduced by using the transverse-leakage-correction.

2. Methods

The core in the benchmark problem consists of a box with dimensions of 1m × 1m × 1m. In case 1, the core is filled with homogeneous mixture of UO_2 fuel and graphite matrix. In case 2 and case 3, the core is filled with singly heterogeneous and doubly heterogeneous pebbles, respectively, with packing fraction of 0.61. In case 4, case 5, and case 6, there is a graphite reflector with a thickness of 1m around the core of case 1, case 2, and case 3, respectively, and the resultant dimension of the problem becomes 3m × 3m × 3m in those cases. In case 7, an impurity of 10 ppm B-10 was added to the reflector of case 6.

A two-step procedure [4] was adopted for the diffusion analysis. In the first step, cross-sections are generated by solving a spectral geometry problem with the HELIOS code [5]. In the second step, the diffusion calculation is performed over the whole core by using the cross-sections generated in the first step. For case 1, two-group cross-sections were generated from a homogeneous single cell calculation with the HELIOS code. For case 2, the Equivalent Cylinder Model (ECM) [5] was used to transform a spherical pebble into an equivalent cylindrical fuel. The geometrical transformation using ECM enables 2-dimensional lattice physics codes such as HELIOS to model a spherical pebble. For case 3, the Reactivity-equivalent Physical Transformation (RPT) [6] was used together with ECM to transform the doubly heterogeneous spherical pebble fuel to an equivalent singly heterogeneous cylindrical fuel. Figure 1 shows the HELIOS models for case 2, and 3. The RPT radius was determined so that the k_{eff} from the HELIOS calculation should be the k_{eff} from the MCNP calculation.

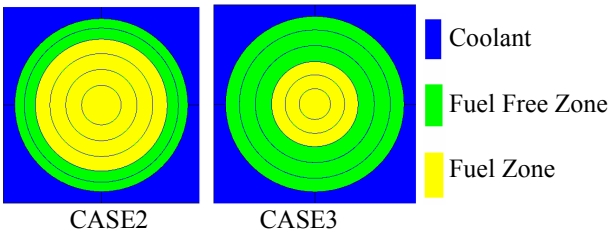

Figure 1. Equivalent Cylinder Fuel Modes for HELIOS

For the graphite-reflected cases (case 4, 5, 6, and 7), infinite slab spectral geometries were used to generate cross-sections. Space-dependent two-group cross-sections were generated from the spectral geometry problems with the help of the Equivalence Theory (ET) [7]. Figure 2 shows the spectral geometries for the graphite-reflected cases. The HELIOS models in Figure 2 are consistent with model A in reference 3. The packing fraction distribution of model A was incorporated into the macroscopic cross section distributions in the fuel region.

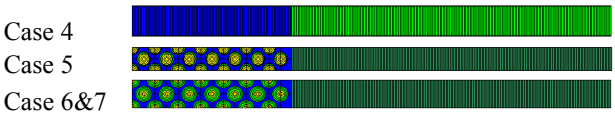

Figure 2. Infinite Slab Spectral Geometries for HELIOS

The first step by using an infinite slab core of our two-step procedure relies on an assumption that the leakage in one direction is dominant and the transverse leakage is negligible, which is the case in a large power reactor. For example, it is evident that the radial leakage dominates the azimuthal or axial leakage in the PBMR-400 power reactor. However, this assumption is not valid in this small cubic core and it may cause a large error in our analysis. To resolve this problem, a transverse leakage correction technique was adopted, in which the transverse leakage was simulated in the HELIOS model by using an albedo boundary conditions at the surfaces faced in y-direction in the core region. The group-wise albedo values were updated iteratively by using group-wise fluxes and group-wise currents at the interface between the core and the reflector until a convergence.

A FDM solver was used to perform the whole core diffusion calculation in the second step of our two step procedure. 1.25*cm* was used as the mesh size for $0cm<x,y,z<100cm$ and 2.5*cm* was used for other parts.

3. Results and Conclusions

Table 1 summarizes the effective multiplication factors for the cases. Relatively large errors in the homogeneous and singly heterogeneous cases (Case 1, 2, 4, and 5) are ascribed to the fact that the resonance integral table of heavy nuclides in the HELIOS cross-section library was generated for heterogeneous configurations. Table 1 also shows that the errors in the graphite-reflected cases can be reduced by using the transverse leakage correction described in the previous chapter. Table 2 shows the RMS errors of the relative power density profile along the x-axis for the graphite-reflected cases, in which the MC results with model A were taken as the reference solution. Figure 3 shows the relative power density profile for the cases. From Figure 3, we can see that the power density profile of model A and that of model B are quite different from each other although the effective multiplication factors of the two models in Table 1 are very similar. The k_{eff} errors and the RMS power errors of the two-step diffusion calculation with TL correction for the realistic doubly heterogeneous cases (case 6 and case 7) were less than 500pcm and 6%, respectively. Considering the facts that the core of the problem is very small compared to that of a power reactor and that a small problem is much more difficult than large one to predict accurately in general, the accuracies of the two-step procedure for the doubly heterogeneous cases of this problem are acceptable.

Table 1. Effective multiplication factors and errors (pcm)

T[K]	Method		CASE						
			1	2	3	4	5	6	7
300	MC	A	1.38333	1.41888	1.52234	0.98037	0.99154	1.02618	0.68306
		B		-58	+39		+29	-66	-
	Diff.	No	+852	+505	+29	+2578	+1259	+913	+1536
		TL				+1618	+780	+259	-31
800	MC	A	1.29901	1.3353	1.44939	0.92196	0.93388	0.97190	0.65089
	Diff.	No	+864	+680	+7	+2296	+1081	+726	+1224
		TL				+1485	+641	+72	-185
1200	MC	A	1.25859	1.29848	1.40965	0.88480	0.89608	0.93421	0.62909
	Diff.	No	+891	+374	+8	+2543	+1388	+1018	+1351
		TL				+1990	+1040	+446	+49
800 1200	MC	A	-	-	1.41670	-	-	0.96100	0.64190
	Diff.	No	-	-	+7	-	-	+531	+1040
		TL.				-	-	-66	-303

Table 2. Relative Power Density Errors (RMS,%)

Temp. [K]	Method	CASE			
		4	5	6	7
300	No	5.7	5.0	6.2	2.9
	TL	4.2	4.4	5.6	2.3
800	No	4.3	5.0	5.3	2.4
	TL	2.8	4.4	4.7	1.9
1200	No	3.8	4.5	4.7	2.4
	TL	2.6	3.9	4.0	1.8
800 1200	No	-	-	5.5	2.5
	TL	-	-	4.9	2.0

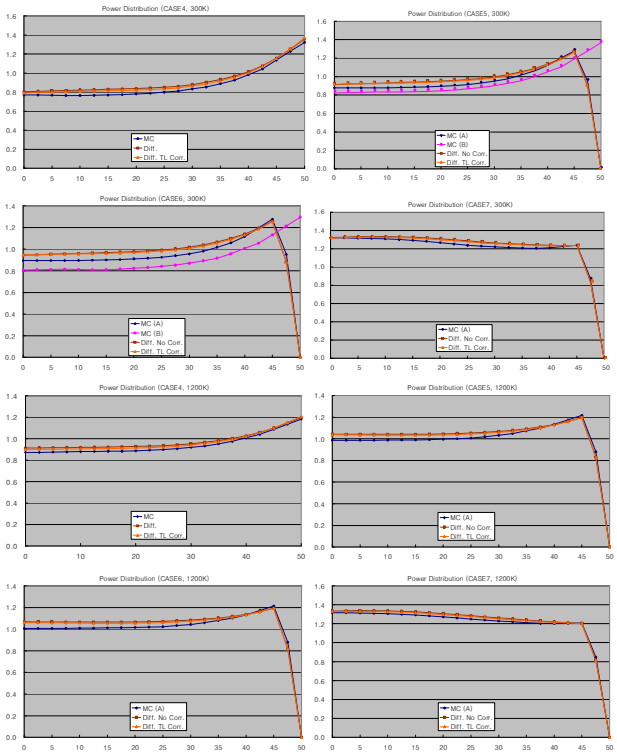

Figure 3. Power Distribution along the x-axis

Acknowledgement

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