A Feasibility Study of in-situ 2-Group Cross-sections Correction in Pin-by-Pin Core Analysis

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1. Introduction

Recently, high-fidelity multi-dimensional reactor analysis tools are gaining more attention because of their accurate prediction of local parameters for core design and safety assessment. The accuracy of direct whole-core transport is quite promising, however, it is very costly in terms of the computing time and memory requirements. Another possible solution is the pin-by-pin core analysis in which only few fuel pins are homogenized and the 3-D core analysis is performed using a low-order operator such as the diffusion theory.

In the pin-by-pin core analysis, the multi-group constants can be produced using the well-known generalized equivalence theory (GET) [1,2,3] and these group constants can be corrected by the super homogenization method (SPH) [4,5]. Moreover, both cross-sections and discontinuity factors (DFs) must be corrected based on the leakage information in order to obtain an accurate solution for pin-by-pin core analysis [6].

In a recent work by W. Kim and Y. Kim [7], the albedo-corrected parameterized equivalence constants (APEC) method was proposed. In this method fuel assembly two-group cross-sections are parameterized as a function of an assembly-wise current-to-flux ratio (CFR) and spectral index (SI). In this study, we have investigated feasibility of APEC-like correction of two-group constants for homogenized pins in PWR cores, which is called APEC for Pin-cell or APECp. Similar to the APEC method, both CFR and SI in pin-cell are used for functionalization of pin cross-sections. The pin-wise two-group parameters are evaluated using a 2-D method of characteristics (MOC)-based lattice code, DeCART2D [8] and a pin-by-pin core analysis is considered using the HCMFD method [9]. HCMFD is a new global-local iteration method that has been developed for efficient parallel calculation of pin-by-pin heterogeneous core analysis.

2. Albedo-corrected Parameterized Equivalence Constant Pin-cell (APECp) method

Conventional flux-weighted constants (FWCs) are the starting point of generating equivalent group constants. As the FWCs are determined in all reflective boundary condition, they have quite significant discrepancy from the reference values which are obtained from whole-core heterogeneous calculation.

Therefore, if pin-wise equivalent group constants are functionalized with node interface condition and are updated using the actual leakage information during the iterative core calculation, it is expected that more accurate equivalent group constants are obtained. Consequently, resulting nodal equivalence will be improved.

2.1 Position-wise Functionalization of pin-cell

Compared with the fuel assembly, pin-wise group constants are more sensitive based on its location such as near the baffle, guide thimble and burnable absorber. To consider this pin location-dependency, the position-wise functionalization is adopted. In this study, total 39 positions are considered based on the 1/8 symmetry typical PWR fuel assembly as shown in Fig. 1.

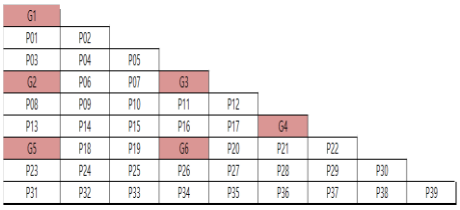


Fig. 1. Symmetry 39 position in typical 17x17 fuel assembly.

Previous studies [9] showed that two-group pin homogenized cross-section have a strong relationship with the node-average CFR and SI, defined as below;

$$CFR = \frac{\sum_s J_g^s}{\sum_s \phi_g^s} \qquad SI = \frac{\phi_F}{\phi_T} \tag{1}$$

The position-wise changes in cross-sections from their initial position-wise pin cross-section values are functionalized by change of both node-average CFR and SI as follows;

$$\Delta\Sigma_F = a_1 dCFR_{1st} + a_2 dCFR_{2nd} + a_3 \tag{2a}$$

$$\Delta\Sigma_T = b_1 dCFR_{2nd} + b_2 dSI + b_3 \tag{2b}$$

$$\Sigma_g = \Delta\Sigma_T + \Sigma_g^{initial} \tag{2c}$$

where the initial position-wise cross-section and node-average CFR and SI are calculated from the single fuel assembly calculation

$$dCFR_g = CFR_g - CFR_g^{initial} \tag{3a}$$

$$dSI = SI - SI_g^{initial} \tag{3b}$$

As the pin near the baffle-reflector region has different behavior, the position-wise pin cross-sections near the baffle-reflector are functionalized separately.

2.2 Fuel assembly pin cross-section Functionalization

In order to determine proper coefficients, a few additional color-set calculations are needed as shown in Fig. 2. In this study, three additional color-set calculations are considered to functionalize position-wise pin cross-section of FA type 1. To consider proper range of CFR and SI, FA type 2 has been selected with different FA type or enrichment perturbation.

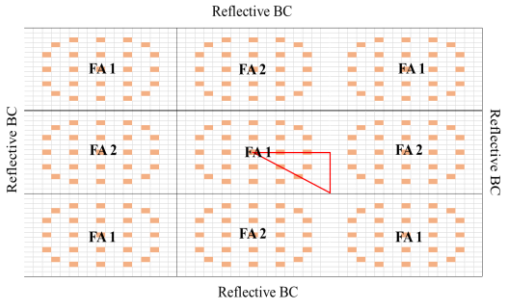
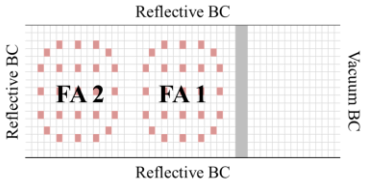


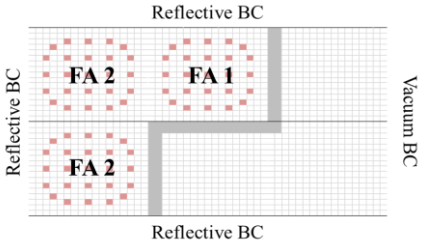
Fig. 2. Simple Color-Set calculation for fuel assembly cross section functionalization

2.3 Pin Cross-section Functionalization near the Baffle-Reflector

For the functionalization of pin near the baffle-reflector, typical two spectral geometry calculations are considered; flat baffle-reflector and L-shape baffle-reflector geometry as shown in Fig. 3. To handle different characteristics, two different functions are considered for L-shape and flat baffle. In this study, three additional spectral geometry calculations for each baffle-reflector are considered to fit position-wise pin cross-section of target FA type 1.



3-1 Flat baffle-reflector



3-2 L-shape baffle-reflector

Fig. 3. Two Baffle-Reflector Color-Set calculations of fuel pin near the baffle-reflector

3. Results and Discussions

The feasibility of APECp method was studied by functionalized position-wise cross-section using Eq. (2). Simple small UOX core was chosen as the test problem as shown in Fig. 4. In the test UOX core, there is three typical 17x17 fuel assemblies (UOX-1 : 2.0 w/o, UOX-2 : 3.3 w/o, and UOX-3 : 4.5 w/o). For the accurate pin-by-pin core analysis, the baffle-reflector region are also treated as pin-wise.

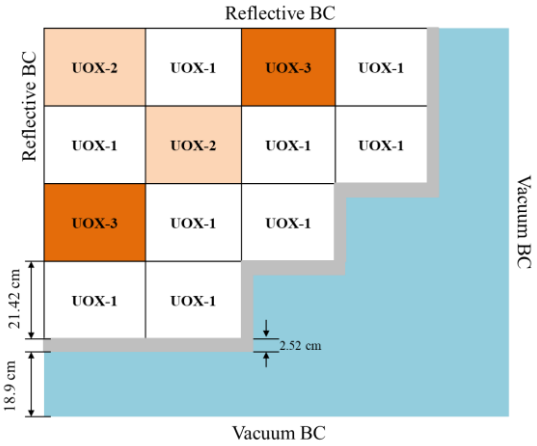


Fig. 4. Quarter core configuration of UOX test core.

In APECp method, it initially starts with pin-wise cross-section and discontinuity factor from single FA calculation. With functionalized position-wise pin cross-section, the position-wise pin cross-sections are updated during the power iteration.

For the APECp correction, the FA pin cross-section functions are used. The pins (half of FA) located near the baffle-reflector are corrected by the pin cross-section function near baffle-reflector.

As this is first preliminary study, the APECp correction mode is ‘On’ when initially given solution is converged and pin cross-sections are updated every global outer iteration. Therefore, it requires additional computational cost. Based on the cross-section behavior by APECpS as shown in Fig. 5 and 6 which is major cross-section in PWR core, a few iterations are needed to converge pin cross-section. In result, the corrected pin cross-section become much closer than initial pin cross-section as expected. The pin location of Fig. 5 and 6 is FA corner position between two different FAs where initial cross-section has significant discrepancy.

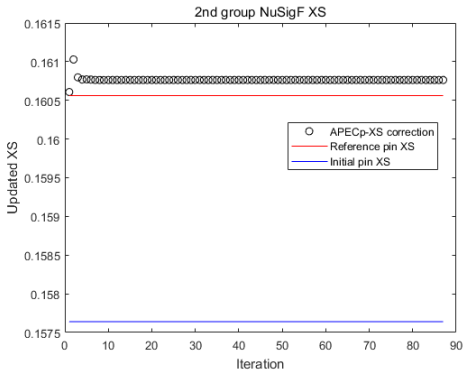


Fig. 5. 2nd group NuSigF XS behavior by APECp correction

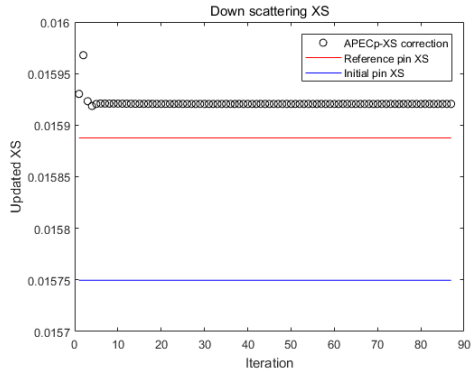


Fig. 6. Down scattering XS behavior by APECp correction

Table 1 shows several sets of HCMFD solutions which are different condition in FA's group constants. As small size test problem, the reference pin-wise group constants are used in the baffle-reflector region. It is to be noted that the k-eff of the APEC correction approaches the targeted k-eff (Ref XS and SA DF) from initial k-eff (SA XS and DF) even if absolute k-eff error is increased.

Table. 1. Results of Test UOX core problem.

FA Group Constants		k-eff	k-eff difference [pcm]	pin power %error Max (RMS)
XS	DF			
Ref	SA	1.155639	-58.5	-1.24 (0.62)
SA	SA	1.156833	60.8	-2.49 (0.79)
APECp	SA	1.155503	-72.1	-1.92 (0.69)
Ref. DeCARD2D		1.156224	Ref	Ref

* SA: single fuel Assembly calculation

Figure 7 shows the comparison of assembly-wise maximum and RMS normalized pin power %error distributions of cross-section from the reference solution, single fuel assembly calculation and APECp correction. In these calculation, the SA DF is used for comparison. The maximum pin power %error is reduced by application of APECp correction.

Max	RMS						
-0.62	0.40	-0.87	0.43	-1.24	0.79	1.14	0.79
-1.44	0.39	1.80	0.65	-2.23	0.91	2.40	0.79
-0.86	0.47	-0.95	0.45	-1.92	0.99	1.18	0.67
-0.87	0.43	1.00	0.26	0.79	0.55	1.11	0.70
1.80	0.65	-1.60	0.53	1.98	0.77	-2.11	0.86
-0.96	0.45	1.49	0.40	1.03	0.64	-1.60	0.79
-1.24	0.79	0.79	0.55	0.78	0.53		
-2.23	0.91	1.98	0.77	-2.49	1.14		
-1.92	0.98	1.03	0.65	-1.77	0.73		
1.14	0.79	1.11	0.70				
2.40	0.79	-2.11	0.86				
1.19	0.68	-1.60	0.79				

Ref XS
SA XS
APECp-XS

Fig. 7. Assembly-wise Maximum and RMS Pin Power %error distribution of test UOX core.

Figure 8 and 9 show the assembly-wise maximum and RMS pin cross-section % error of initial SA cross-section and APECp corrected cross-section. As expected, the maximum and RMS %error of pin cross-section are pretty reduced by application of APECp correction. In the high enriched UOX-3 fuel assembly, the decrease in maximum down scattering error is quite lower than other position in terms of RMS values.

SA DF	APECp						
-0.51	0.44	0.54	0.39	-0.92	0.62	2.18	0.69
1.29	-0.21	-1.62	0.19	2.88	-0.46	-2.17	0.21
1.08	-0.63	1.23	-0.50	1.89	-1.12	-6.92	-2.58
-1.75	0.28	2.25	-0.30	-3.79	0.61	3.05	-0.33
-0.69	0.32	1.57	0.15	-1.52	-0.74	1.82	-0.86
-1.82	0.29	2.37	-0.32	-3.90	0.63	3.12	-0.36
1.83	-1.77	3.30	-0.79	3.26	-3.14	-4.76	-2.82
10.33	-1.29	-12.96	1.32	22.58	-2.41	-14.12	1.36
0.54	0.39	-0.60	0.26	1.33	0.94	3.14	0.87
-1.62	0.19	1.65	-0.15	-1.67	0.14	-3.37	-0.48
1.23	-0.50	1.10	-0.40	-2.73	-1.64	-10.68	-4.94
2.25	-0.30	-2.19	0.23	2.34	-0.19	4.96	0.75
1.57	0.15	-1.02	0.22	1.70	-0.34	-1.60	-1.71
2.37	-0.32	-2.27	0.24	2.47	-0.20	5.02	0.72
3.30	-0.81	1.93	-0.97	3.61	-2.46	-6.42	-3.90
-12.96	1.32	13.57	-1.01	-13.39	1.15	-16.54	1.15
-0.92	0.62	1.33	0.94	3.07	1.08		
2.88	-0.47	-1.67	0.14	-3.33	-0.51		
1.89	-1.04	-2.73	-1.64	-10.75	-5.08		
-3.79	0.62	2.34	-0.19	4.90	0.79		
-1.52	-0.72	1.70	-0.34	-1.43	-1.41		
-3.90	0.63	2.47	-0.20	4.95	0.76		
3.26	-3.10	3.61	-2.46	-6.53	-4.04		
22.58	-2.41	-13.39	1.15	-16.17	0.91		
2.18	0.69	3.14	0.87				
-2.17	0.21	-3.37	-0.48				
-6.92	-2.58	-10.68	-4.94				
3.05	-0.33	4.96	0.75				
1.82	-0.86	-1.60	-1.71				
3.12	-0.36	5.02	0.72				
-4.76	-2.82	-6.42	-3.90				
-14.12	1.35	-16.54	1.11				

Dif	1st
	2nd
Abs	1st
	2nd
NuSigF	1st
	2nd
Scat	Down
	Up

Fig. 8. Assembly-wise Maximum Pin cross-section error change in the test UOX core.

SA DF	APECp						
0.31	0.21	0.35	0.12	0.61	0.31	0.67	0.24
0.39	0.11	0.55	0.04	0.87	0.23	0.72	0.06
0.87	0.29	0.58	0.14	1.54	0.50	1.97	0.78
0.52	0.14	0.74	0.06	1.15	0.31	0.99	0.08
0.47	0.13	0.57	0.04	0.91	0.30	0.61	0.30
0.57	0.15	0.81	0.06	1.24	0.32	1.07	0.08
1.50	0.78	1.22	0.37	2.51	1.29	2.21	1.07
3.26	0.67	4.91	0.44	6.70	1.35	5.32	0.45
0.35	0.12	0.37	0.15	0.34	0.14	0.96	0.25
0.55	0.04	0.56	0.09	0.52	0.05	0.80	0.08
0.58	0.14	0.84	0.19	0.65	0.23	2.72	0.90
0.74	0.06	0.74	0.12	0.69	0.06	1.13	0.11
0.57	0.04	0.41	0.08	0.56	0.08	0.55	0.55
0.81	0.06	0.80	0.12	0.76	0.06	1.21	0.11
1.22	0.37	1.34	0.46	1.32	0.49	2.68	1.08
4.91	0.43	4.64	0.62	4.57	0.43	4.97	0.49
0.61	0.31	0.34	0.14	1.04	0.23		
0.87	0.23	0.52	0.05	0.81	0.08		
1.54	0.50	0.65	0.23	2.69	0.89		
1.15	0.31	0.69	0.06	1.14	0.11		
0.91	0.30	0.56	0.08	0.49	0.44		
1.24	0.32	0.76	0.06	1.22	0.11		
2.51	1.29	1.32	0.49	2.65	1.07		
6.70	1.35	4.57	0.43	5.06	0.45		
0.67	0.24	0.96	0.25				
0.72	0.06	0.80	0.08				
1.97	0.78	2.72	0.90				
0.99	0.08	1.13	0.11				
0.61	0.30	0.55	0.55				
1.07	0.08	1.21	0.11				
2.21	1.07	2.68	1.08				
5.32	0.44	4.97	0.48				

Dif	1st
	2nd
Abs	1st
	2nd
NuSigF	1st
	2nd
Scat	Down
	Up

Fig. 9. Assembly-wise RMS Pin cross-section error change in the test UOX core.

4. Conclusions

The two-group pin group constants for PWR pin-by-pin core analysis are functionalized as function of pin leakage information. For the better pin cross-section correction, the position-wise pin cross-section near baffle-reflector are functionalized separately. The HCMFD pin-by-pin core simulation result for UOX test problem with APECp correction. The k-eff of APECp approaches to the k-eff of targeted one which use reference cross-section and initial single fuel assembly discontinuity factor. The maximum and RMS pin power %error are pretty reduced. The pin cross-section %error are also quite reduced by application of APECp correction. Currently, application of APECp method in the typical BA-loaded UOX core is ongoing.

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