In-situ APEC Leakage Correction for Homogenized Group Constants of Baffle-Reflector Region

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1. Introduction

A two-step method based on the generalized equivalence theory (GET) is a foundation of modern reactor physics analysis for the thermal reactor [1]. Recently, the albedo-corrected parameterized equivalence constants (APEC) method was introduced to improve the equivalence of the two-step method that utilizes the simplified equivalence theory (SET) [2, 3, 4]. It was proven that the in-situ correction by APEC method for homogenized group constants (HGCs), cross-sections (XSs) and discontinuous factors (DFs), of fuel assemblies (FAs) could substantially improve the nodal equivalence by taking into account the actual leakage during the nodal analysis [5, 6]. In this study, the conditional necessity of the APEC correction for HGCs baffle-reflector (BR) region, depending on the circumstances, is discussed by solving the partially MOX-loaded core and its variants.

2. APEC Modeling for Baffle-Reflector Region

The main principle of the APEC leakage correction is to update HGCs during the nodal iteration through predetermined APEC functions. The APEC XS and DF modeling introduced in Ref. [6] were used for FAs. In the case of BR region, the APEC modeling should be appropriately modified mainly due to the way to obtain standard HGCs of BR.

In general, approximated HGCs of BR can be easily obtained by spectral geometry or color-set model. However, they may not be favorable since their error could not be negligible when the neutron spectrum is changed by neighborhood effect. One of the effective ways to set up the HGCs is to conduct whole core calculation by transport analysis at the beginning of the cycle (BOC), and then they are used for variant core analysis or even depletion calculation.

Unlike the HGCs of FAs, those of BR obtained by whole core calculation are position-dependent, so the representative HGCs of BR such as flux-weighted constant (FWC) or assembly-wise DF (ADF) do not exist. In this respect, it is necessary to define standard HGCs only in the BR region as reference HGCs obtained by whole core calculation to introduce the APEC modeling for BR region.

The APEC XS and DF functions were defined in terms of differences of the normalized leakage parameters such as current-to-flux ratio (CFR), and flux-ratio (FR) as below.

$$\Sigma_{x,g}^{BR} = \Sigma_{x,g}^{\text{Standard}} + \Delta\Sigma_{x,g}^{BR} \quad (1),$$

$$\Delta\Sigma_{x,F}^{BR} = a_{x,F}\Delta CFR_F^N + b_{x,F}\Delta CFR_T^N \quad (2),$$

$$\Delta\Sigma_{x,T}^{BR} = a_{x,T}\Delta CFR_T^N + b_{x,T}(\Delta CFR_T^N)^2 \quad (3),$$

$$DF_g^{BR} = DF_g^{\text{Standard}} + \Delta DF_g^{BR} \quad (4),$$

$$\Delta DF_g^{BR} = a_{g,1}\Delta FR_g^S + a_{g,2}\Delta CFR_g^S + a_{g,3}\Delta CFR_g^N \quad (5),$$

where,

Σ^{Standard} : Standard *XS of the BRs*,

F : fast group, T : thermal group,

$\overline{J}^s$: surface current, $\hat{\phi}^s$: surface flux, $\overline{\phi}^{avg}$: average flux,

$$\Delta\text{CFR}_g^N = \frac{\sum \overline{J}_g^s}{\sum \hat{\phi}_g^s} - \frac{\sum \overline{J}_g^{s,\text{Standard}}}{\sum \hat{\phi}_g^{s,\text{Standard}}},$$

$$\Delta\text{CFR}_g^S = \frac{\overline{J}_g^s}{\hat{\phi}_g^s} - \frac{\overline{J}_g^{s,\text{Standard}}}{\hat{\phi}_g^{s,\text{Standard}}},$$

$$\Delta FR_g^S = \frac{\overline{\phi}_g^{avg}}{\hat{\phi}_g^s} - \frac{\overline{\phi}_g^{avg,\text{Standard}}}{\hat{\phi}_g^{s,\text{Standard}}}.$$

3. Numerical Results

3.1 Partially MOX-loaded SMR Benchmark Problem

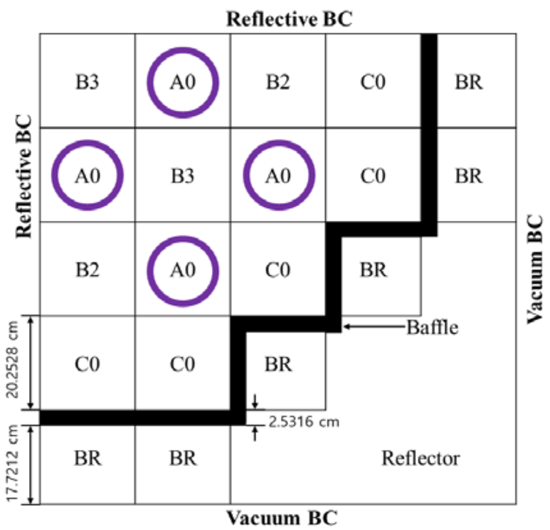

Fig. 1. Core configuration of partially MOX-loaded SMR.

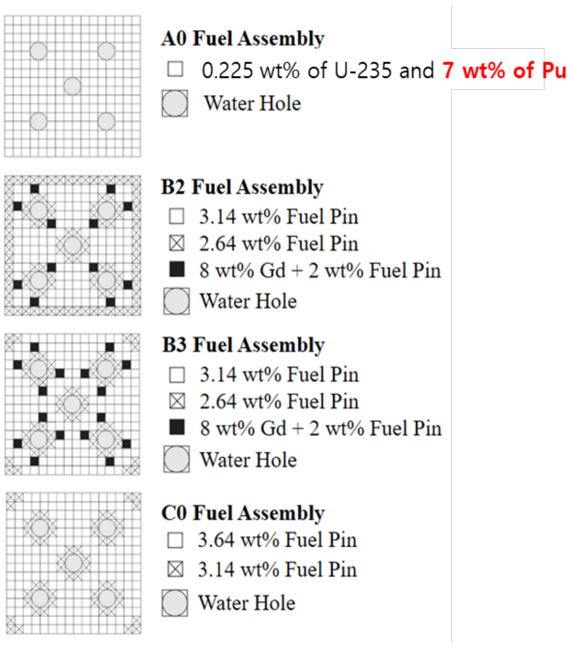

Fig. 2. Types of fuel assemblies loaded in SMR.

The most complex SMR model, partially MOX-loaded SMR, was set up as a benchmark problem to analyze the impact of the APEC correction for BR region. The reference solution and HGCs of FAs and BR were calculated by DeCART2D code [7]. The APEC correction for FAs and BR was applied in the in-house NEM nodal code.

The APEC XS and DF functions of the FAs and BR were predetermined by setting up the color-set model, as shown in Fig. 3 and Table I. Based on the color-set for UOX-loaded SMR, which were listed by random, some of the color-set calculations highlighted by red color in the table were added to reflect the change of the neutron spectrum occurred by MOX-loaded FA. The APEC functions of BR region were constructed by using the HGCs data marked in green color in the color-set, as shown in Fig. 3 and were only applied to XSs and DFs of the BR region, as shown in Fig.1.

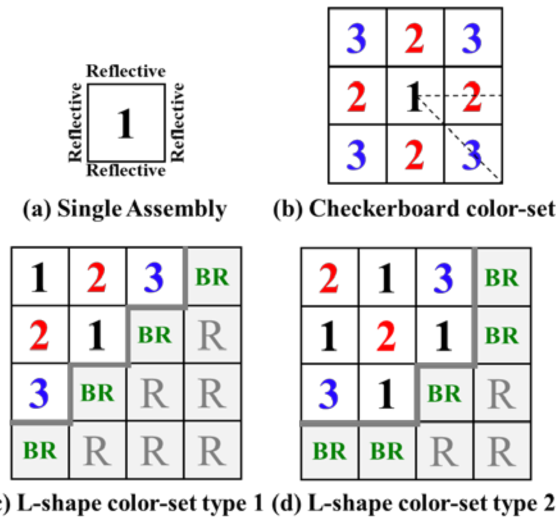

Fig. 3. Color-set models for constructing APEC functions.

Table I: List of Color-set models

Color-set Model	Combination of FAs
Checkerboard	(B2,B3,C0), (B3,C0,B2), (C0,B3,B2), (A0,B2,B3), (B3,C0,A0), (C0,A0,B2)
L-Shape Type1	(B2,B3,C0), (B2,C0,B3), (B3,C0,B2), (B3,B2,C0), (C0,B2,B3), (C0,B3,B2) (A0,B2,C0), (A0,C0,B3), (B2,A0,C0), (B2, B3, A0)
L-Shape Type2	(B2,B3,C0), (B2,C0,B3), (B3,C0,B2), (B3,B2,C0), (C0,B2,B3), (C0,B3,B2) (B2,B3,B2), (C0,B2,C0), (B3,C0,B3), (C0,B2,A0), (A0,B3,C0), (B2,A0,B3), (B3,B2,A0),(A0,C0,A0), (C0,A0,C0), (B3,A0,B3)

The results showed that the APEC correction of FAs could substantially improve the nodal solution, as shown in Table II and Fig. 4. The accuracy of both the multiplication factor and power distribution are improved through in-situ leakage correction in the nodal analysis. It is reasonable that the impact of the APEC correction of BR region is neglected since the differences of the normalized leakage parameters are close to zero when the standard HGCs of BR region are used.

Table II: Results of Partially MOX-loaded SMR

FA	BR	k_{eff}	$\Delta\rho$ (pcm)	RRMS[a] (%)	Max.[b] (%)
DeCART2D		1.053803			
HGC[c]	SHGC[d]	1.057638	344.06	0.980	1.859
APEC[e]	SHGC[d]	1.053974	-9.18	0.337	0.728
APEC[e]	APEC[e]	1.053645	-14.26	0.361	0.718

a: Relative Root Mean Square Error (%),
b: Maximum Absolute Relative Error in Assembly power (%),
c: HGCs generated by Lattice (FWC | ADF),
d: Standard HGCs of the SMR benchmark problem,
e: APEC correction for HGCs (APEC XS | APEC DF).

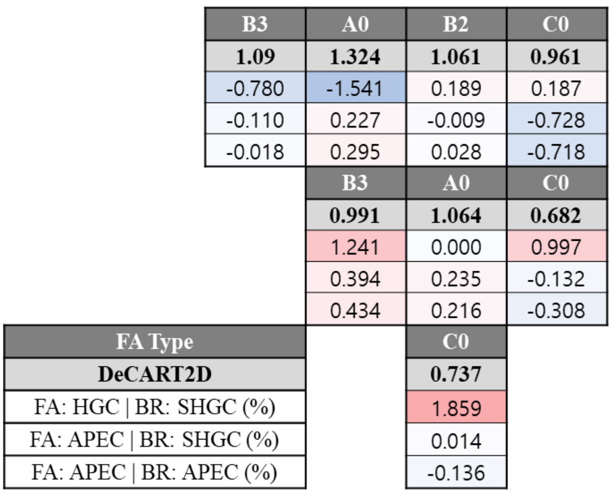

Fig. 4. Power distribution and relative power error of partially MOX-loaded SMR.

3.2 APEC Leakage Correction for Variant Cores

By introducing several variants generated by random, the suitability of the APEC correction of BR region was analyzed. The results showed that the tendency of the improvement by APEC correction of BR region is obviously observed when the MOX-loaded FA, A0 type, is located at the peripheral region, as shown in Table III, Fig 5, 6, 7 and 8. It is observed that the standard HGCs of BR region are good enough to correct HGCs in FAs by APEC method when the UOX-loaded FA is loaded nearby BR region,

The relative RMS errors (%) of the converged HGCs of partially MOX-loaded SMR and its variants were tabulated in Table IV. The results showed that the accuracy of the HGCs in the case of the A0 type FA and BR region are significantly improved when APEC correction is applied to both FAs and BR region. It implies that the MOX-loaded FA can change the neutron spectrum in the BR region so that HGCs of BR region are quite different from those of standard. Therefore, the APEC correction of the HGCs at the BR region could be conditionally necessary when the MOX-loaded FAs are located in the peripheral region.

Table III: Results of Variant SMR Cores

FA	BR	keff	$\Delta\rho$ (pcm)	RRMS[a] (%)	Max.[b] (%)
DeCART2D		*1.138768*	*Variant 1*		
HGC[c]	SHGC[d]	1.141329	197.08	0.895	1.072
APEC[e]	SHGC[d]	1.139281	39.53	0.527	0.962
APEC[e]	APEC[e]	1.139196	33.03	0.484	0.833
DeCART2D		*1.035491*	*Variant 2*		
HGC[c]	SHGC[d]	1.038042	237.34	0.752	1.520
APEC[e]	SHGC[d]	1.035533	3.95	0.663	1.052
APEC[e]	APEC[e]	1.053645	3.82	0.673	1.054
DeCART2D		*1.049439*	*Variant 3*		
HGC[c]	SHGC[d]	1.052795	303.78	1.636	3.317
APEC[e]	SHGC[d]	1.049892	41.12	1.063	2.438
APEC[e]	APEC[e]	1.049334	-9.58	0.509	0.844
DeCART2D		*1.062324*	*Variant 4*		
HGC[c]	SHGC[d]	1.065042	240.21	0.818	1.325
APEC[e]	SHGC[d]	1.062192	-11.69	0.813	2.341
APEC[e]	APEC[e]	1.062068	-22.68	0.521	0.918
DeCART2D		*1.111130*	*Variant 5*		
HGC[c]	SHGC[d]	1.113556	196.09	0.942	1.506
APEC[e]	SHGC[d]	1.111501	30.01	0.560	0.944
APEC[e]	APEC[e]	1.111404	22.17	0.651	0.890

C0	A0	C0	A0
2.506	1.669	1.212	0.499
0.156	-1.072	0.899	0.521
0.024	0.276	-0.446	0.962
0.219	0.431	-0.413	-0.100
	C0	B3	C0
	1.411	0.654	0.360
	0.957	-0.933	1.056
	0.142	-0.291	-0.528
	0.269	-0.260	-0.833
		B3	
		0.294	
		-1.020	
		-0.680	
		-0.816	

FA Type
DeCART2D
FA: HGC | BR: SHGC (%)
FA: APEC | BR: SHGC (%)
FA: APEC | BR: APEC (%)

Fig. 5. Power distribution and relative power error of variant 1.

A0	B3	A0	C0
1.806	1.285	1.307	0.962
-0.880	0.117	-0.191	1.372
1.052	0.342	0.191	-0.977
1.047	0.335	0.191	-0.904
	B2	B2	B2
	1.147	0.822	0.444
	-0.445	0.231	-0.225
	0.096	-0.292	-0.833
	0.087	-0.316	-0.878
		B3	
		0.408	
		-1.520	
		-0.907	
		-1.054	

FA Type
DeCART2D
FA: HGC | BR: SHGC (%)
FA: APEC | BR: SHGC (%)
FA: APEC | BR: APEC (%)

Fig. 6. Power distribution and relative power error of variant 2.

B3	B2	B3	A0
1.004	1.103	0.966	0.685
-3.317	-1.342	-0.994	0.847
-1.215	-0.698	-0.673	1.591
-0.458	-0.100	-0.383	0.453
	A0	C0	C0
	1.437	1.382	0.723
	-1.308	1.889	1.660
	0.404	-0.130	-0.263
	0.828	-0.022	-0.719
		A0	
		0.841	
		1.558	
		2.438	
		0.844	

FA Type
DeCART2D
FA: HGC | BR: SHGC (%)
FA: APEC | BR: SHGC (%)
FA: APEC | BR: APEC (%)

Fig. 7. Power distribution and relative power error of variant 3.

A0	B3	C0	B3
1.566	1.240	1.525	0.586
-0.760	0.210	0.098	-1.177
0.613	0.056	-1.036	-0.017
0.830	0.234	-0.918	0.085
	A0	B2	C0
	1.313	0.869	0.564
	-0.990	1.013	0.479
	0.381	0.357	-0.301
	0.465	0.299	-0.479
		A0	
		0.551	
		1.325	
		2.341	
		0.417	

FA Type
DeCART2D
FA: HGC | BR: SHGC (%)
FA: APEC | BR: SHGC (%)
FA: APEC | BR: APEC (%)

Fig. 8. Power distribution and relative power error of variant 4.

	C0	**A0**	**B2**	**C0**
	2.783	**1.654**	**0.881**	**0.589**
	0.007	-1.506	0.488	1.104
	0.158	0.351	-0.250	-0.611
	0.438	0.581	-0.182	-0.815
		B3	**C0**	**A0**
		1.031	**0.911**	**0.371**
		0.854	0.922	0.701
		0.252	-0.724	0.944
		0.408	-0.779	-0.890
FA Type			**B3**	
DeCART2D			**0.375**	
FA: HGC | BR: SHGC (%)			-0.828	
FA: APEC | BR: SHGC (%)			-0.214	
FA: APEC | BR: APEC (%)			-0.534	

Fig. 9. Power distribution and relative power error of variant 5.

4. Conclusions

The APEC model for HGCs of BR region has been proposed to reflect the change of HGCs of BR region by the change of neutron spectrum. It is concluded that the APEC correction for HGCs of BR region is conditionally necessary when the FAs that can change the neutron spectrum of BR region are located in the peripheral region. It is expected that the BR HGCs corrections by APEC method based on the standard HGCs calculated at BOC might be significant in the depletion analysis since it can reflect the change of the neutron spectrum appropriately.

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Table IV: Results of Relative RMS Error (%) of the HGCs

	D_1	Σ_{a1}	$\nu\Sigma_{f1}$	$\Sigma_{s1\to2}$	DF_1	D_2	Σ_{a2}	$\nu\Sigma_{f2}$	$\Sigma_{s2\to1}$	DF_2
A0 Type FA										
Case 1[a]	0.273	0.552	0.370	0.690	0.973	0.558	1.418	1.620	5.233	6.235
Case 2[b]	0.092	0.196	0.121	0.231	0.558	0.035	0.146	0.166	0.283	2.568
Case 3[c]	0.090	0.193	0.121	0.228	0.553	0.024	0.121	0.138	0.148	1.837
B2 Type FA										
Case 1	0.129	0.313	0.191	0.690	0.814	0.165	0.385	0.642	2.541	1.848
Case 2	0.048	0.198	0.070	0.087	0.795	0.062	0.136	0.243	0.973	1.422
Case 3	0.030	0.063	0.074	0.107	0.731	0.008	0.072	0.089	0.160	1.193
B3 Type FA										
Case 1	0.380	0.962	0.330	1.253	0.854	0.148	0.329	0.815	2.457	2.105
Case 2	0.067	0.176	0.152	0.258	0.761	0.023	0.069	0.055	0.112	1.275
Case 3	0.067	0.175	0.152	0.258	0.761	0.023	0.069	0.054	0.110	1.275
C0 Type FA										
Case 1	0.532	1.285	0.828	2.882	1.249	0.191	0.831	0.983	2.854	2.946
Case 2	0.115	0.184	0.120	0.279	0.958	0.042	0.066	0.075	0.203	2.356
Case 3	0.116	0.184	0.120	0.282	0.958	0.042	0.065	0.074	0.205	2.337
Baffle-Reflector										
Case 1	0.751	1.636	0.000	0.743	0.876	0.218	2.377	0.000	0.563	18.163
Case 2	0.751	1.636	0.000	0.743	0.876	0.218	2.377	0.000	0.563	18.163
Case 3	0.663	0.667	0.000	0.629	0.496	0.054	0.488	0.000	0.421	1.666

a: FA: HGC | BR: SHGC, b: FA: APEC | BR: SHGC, c: FA: APEC | BR: APEC