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Pin Power Reconstruction with Leakage-corrected Embedded Calculation in PWRs

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1. Introduction

In modern reactor analysis, simplified equivalence theory (SET) [1] based two-step nodal analysis has been widely used for light water reactor (LWR). Although this nodal analysis has acceptable results in terms of fuel assembly (FA) level, such as FA power distribution, the pin level results are essential for reactor safety analysis. To estimate the pin power distribution, the pin power reconstruction (PPR) method based on form function (FF) [2] is a common way. In this FF-based PPR, the homogeneous FA power obtained from two-step nodal analysis is multiplied by predetermined heterogeneous pin level FFs from the lattice calculations.

In our previous study [3], we adopted the PPR based on embedded calculation [4], named 'embedded PPR' to consider neighboring effect. In this work, we apply two leakage correction methods, APEC (albedo-corrected parameterized equivalence constants) method [5] and GPS (GET Plus SPH) method [6] to improve accuracy of embedded PPR. In this study, DeCART2D code [7] was used for the lattice and reference core calculation. Embedded PPRs were calculated by in-house NEM based pin-wise nodal code.

2. Embedded PPR and Leakage Correction Method

2.1 Embedded Calc. based PPR

Embedded calculation is a local fixed boundary problem as shown in Fig. 1. Unlike the FF-based PPRs, which modulate the smooth nodal flux shapes with the detailed assembly flux shapes [1], the flux (or power) distribution is directly determined by embedded calculations with given boundary conditions (BCs) from nodal calculation and pin-wise homogenized group constants (HGCs), such as pin-wise cross-sections (XSs) and discontinuity factors (DFs), from lattice calculation. In other words, to obtain pin-level information at target 'FA' in Fig. 1, we solve an extended color-set model using both pin-wise HGCs of each FA type and FA-wise boundary information.

Due to the nature of embedded PPR, additional computing cost is inevitable. However, each (two-group 3x3 color-set model) takes less than ~1 second in a personal computer. With the optimization of color-set size and code itself, it is expected that the additional computing cost is acceptable compared with pin-wise nodal analysis.

It is noted that, compared with net current BC in previous work [3], the incoming partial current BCs were considered in this work. As Neumann BC, the net current boundary problem has some convergence issues.

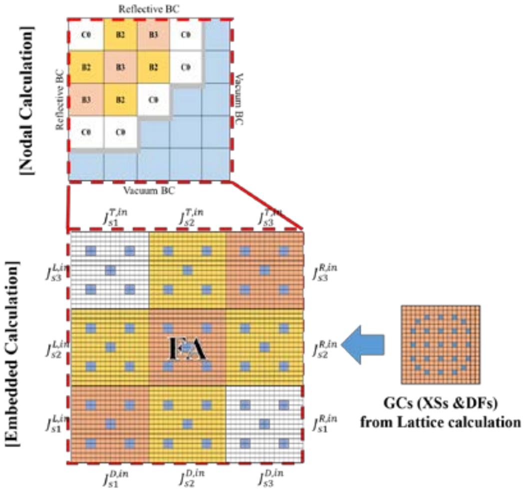


Fig. 1 Configuration of embedded calculation

The pin-wise neutron balance is governed by following fixed boundary incoming partial current equation in Eq. (1). Equation (1) is solved by BiCGstab method with the conventional pin-size CMFD formula.

$$\nabla \cdot \vec{J}_g + \Sigma_{r,g}\phi_g - S_{fiss\&scat} = 0 \qquad (1)$$

where

$$\vec{J}_g^{in} = \frac{\phi_g}{4} - \frac{\vec{J}_g}{2} = f(r), \qquad r \in \Gamma$$

$\vec{J}_g^{in}$ = 'Given' incoming partial current at boundary

$S_{fiss\&scat}$ = Neutron source from fission and scattering

$$S_{fiss\&scat} = \frac{\chi_g}{k}\sum_{g=1}^{G} \nu\Sigma_{f,g}\phi_g + \sum_{g=1}^{G}\Sigma_{s,g'\to g}\phi_{g'}$$

Other notations are standard.

2.2 Leakage correction method

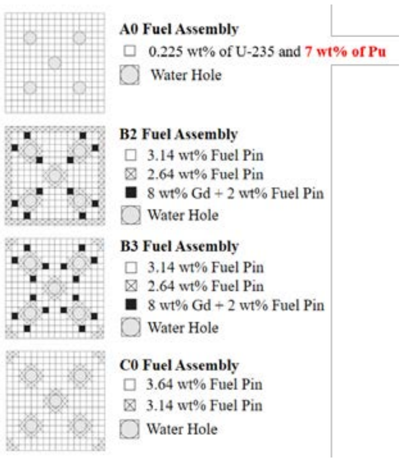
In the previous study, it was demonstrated that the accuracy of embedded PPR is improved when the nodal equivalence is enhanced. To complete our two-step nodal with embedded PPR, we adopt two leakage correction methods, APEC and GPS method. The APEC correction improves the nodal equivalence of two-step nodal analysis and the GPS correction enhance accuracy of pin-wise reaction rate at embedded PPR.

In this work, we use the same APEC functions from Ref. 8. The GPS functions are functionalized with a fitting data-set from the same color-set model from Ref. 8.

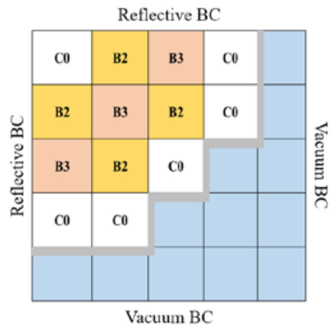
3. Numerical Results

3.1 SMR benchmark core

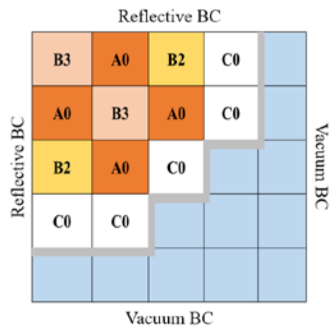
To test the performance of embedded PPR with leakage correction method, two small PWRs were selected as shown in Fig. 2. One of them is partially MOX-loaded SMR which is the most difficult benchmark problem in LWR.



1) Configuration of FAs



2) Core layout of UOX-loaded SMR



3) Core layout of partial MOX-loaded SMR

Fig. 2 Core configuration of two SMR cores

Table 1 shows numerical results of nodal analyses. Figure 3 shows the reference normalized FA power and corresponding FA power % error of nodal analyses. The results of two-step nodal are quite typical and APEC correction improved the nodal equivalence as expected.

Table. 1 Numerical results of two-step nodal analysis

Condition	keff	$\Delta\rho$ [pcm]	FA pow %error Max. (RMS)
UOX-loaded SMR			
Ref. DeCART2D	1.07492		
Two-step Nodal	1.07657	142.40	1.58 (1.04)
APEC-corrected Nodal	1.07481	-10.03	0.79 (0.52)
Partially MOX-loaded SMR			
Ref. DeCART2D	1.05380		
Two-step Nodal	1.05774	352.89	2.52 (1.13)
APEC-corrected Nodal	1.05389	7.43	0.82 (0.44)

3.311	**1.565**	**0.814**	**0.608**
0.29	-0.68	-1.17	1.06
-0.37	0.19	0.05	-0.71
	1.036	**0.661**	**0.432**
	-1.15	0.93	1.09
	0.60	0.79	-0.50
		0.493	
		1.58	
		0.37	

Ref. FA power
%Error of Two-step
%Error of APEC

a) UOX-loaded SMR

1.090	**1.324**	**1.061**	**0.961**
-0.92	-1.61	0.09	0.07
-0.50	-0.09	-0.07	0.65
	0.991	**1.064**	**0.682**
	1.28	0.15	1.11
	0.37	0.52	0.08
		0.737	
		2.52	
		0.82	

Ref. FA power
%Error of Two-step
%Error of APEC

b) Partially MOX-loaded SMR

Fig. 3 Reference FA power and %error of nodal analysis (octant core)

3.2 Numerical results of PPR

Two conventional PPRs, FF-based and embedded PPRs, were performed based on results of nodal analyses. Figure 4 shows maximum and RMS %error between reference pin-power and reconstructed pin-power distribution of FF-based PPR. Figure 5 shows %error for embedded PPR. It is noted that the embedded PPR provides more accurate pin-power distribution compared with the FF-based PPR since the embedded PPR can take into account the neighborhood effects by extended problem domain.

Max	-3.25	3.13	-2.74	7.18
RMS	0.97	1.28	1.31	1.77
		-2.31	8.52	-34.48
		1.29	1.38	8.35
			-24.68	
			7.14	

a) UOX-loaded SMR

Max	-7.24	-8.36	-7.22	6.74
RMS	2.37	2.40	2.30	1.71
		8.11	-7.89	-36.62
		2.66	1.93	8.63
			-53.78	
			9.55	

b) Partially MOX-loaded SMR

Fig. 4 Reconstructed pin power %error of FF-based PPR

Max	0.58	-1.34	-1.95	2.45
RMS	0.33	0.70	1.17	1.23
		-1.93	2.61	2.81
		1.15	1.15	1.21
			2.59	
			1.61	

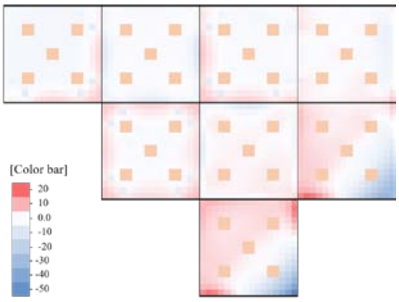
a) UOX-loaded SMR

Max	3.15	-3.91	3.96	-2.03
RMS	1.57	1.77	1.30	0.74
		6.00	-2.94	4.56
		1.93	0.96	1.58
			5.42	
			2.70	

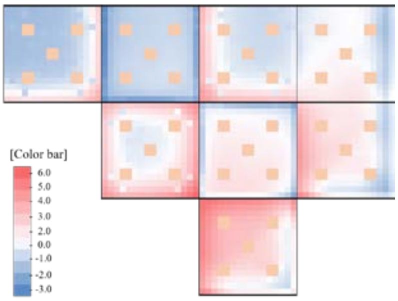
b) Partially MOX-loaded SMR

Fig. 5 Reconstructed pin-power %error of embedded PPR

Figure 6 shows the reconstructed pin-power %error distribution of partially MOX-loaded SMR. Similar to the inevitable error of pin-wise HGCs in conventional two-step nodal analysis [6], both FF-based and embedded PPRs have the same limitation. It causes relatively large pin-power %error at the interface between different FAs and peripheral pins near baffle-reflector regions as shown in Fig. 6.



a) FF-based PPR



b) Embedded PPR

Fig. 6 Reconstructed pin-power %error distribution of partially MOX-loaded SMR (octant core)

In the case of the embedded PPR of partially MOX-loaded SMR, the maximum pin-power error, 6.00%, occurs at the corner pin which faces two MOX FAs, where normalized pin-power is 0.711. At the same location, however, FF-based PPR has a higher pin-power error, 8.11%.

The maximum normalized pin-power is around 1.542, and corresponding pin has about -0.63% (FF-based PPR) and -1.09% (embedded PPR) pin-power error. Although corresponding pin-power error of embedded PPR is slightly higher than that of FF-based PPR, it has acceptable accuracy. Furthermore, embedded PPR has less maximum and RMS pin-power %error at corresponding FA.

As mentioned above, the FF-based PPR solution also has the same limitation that caused by FF. In addition, the homogeneous flux distribution of FF-based PPR is determined by FA-wise information, which also has the inevitable error. In these regards, the embedded PPR solution has better accuracy.

3.3 Embedded PPR with APEC correction

To investigate the improvement of embedded PPR by leakage correction method, APEC correction is firstly analyzed. Figure 7 shows FA-wise maximum and RMS reconstructed pin-power %error of embedded PPR of APEC-corrected nodal calculation. According to our previous study [3], FA-wise RMS %error of embedded PPR has a similar trend with FA power %error of two-step nodal analysis. In this regard, it is expected that the accuracy could be improved if the nodal equivalence is enhanced. Figure 7 demonstrates it, especially in terms of RMS %error. As shown in Fig. 8, however, similar level of maximum %error is occurred at peripheral pins of FA. This means that it is caused by error of pin-wise HGCs. It is expected that the accuracy of embedded PPR could be improved in terms of FA-wise maximum pin-power error as long as GPS function corrects the pin-wise reaction rate

Max	-1.36	1.11	1.64	-2.44
RMS	0.51	0.33	0.55	1.00
		2.01	2.32	-2.93
		0.78	1.01	0.98
			-1.95	
			0.85	

a) UOX-loaded SMR

Max	2.97	-2.40	2.91	-2.38
RMS	1.20	0.87	1.03	0.94
		3.59	-2.30	-3.07
		1.28	1.09	1.16
			3.40	
			1.51	

b) Partially MOX-loaded SMR

Fig. 7 Reconstructed pin power %error with APEC correction

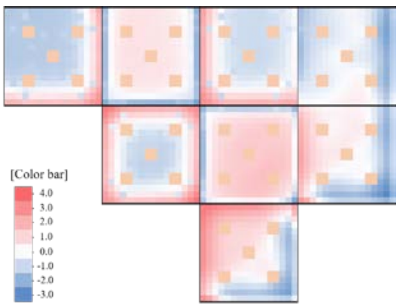


Fig. 8 Reconstructed pin-power %error distribution of partially MOX-loaded SMR with APEC correction

3.4 Embedded PPR with two leakage correction

In this section, both APEC and GPS correction are applied in embedded PPR. In other words, GPS-corrected embedded PPR of APEC-corrected nodal analysis will be investigated. Figure 9 shows FA-wise maximum and RMS reconstructed pin-power %error with two leakage correction methods. Figure 10 shows the corresponding reconstructed pin-power %error distribution of partially MOX-loaded SMR.

As expected, compared to the 'uncorrected' embedded PPR (embedded PPR results of two-step nodal analysis), maximum and RMS %error are reduced in the case of 'corrected embedded PPR'. It is noted that FA-wise RMS %error is almost ~1. The range of FA-wise maximum pin-power error is also significantly reduced (as absolute value, 2.03 ~ 6.00 to 0.62 ~ 1.84 for partially MOX-loaded SMR).

Max	-1.01	0.64	-0.95	-1.81
RMS	0.53	0.28	0.30	0.86
		1.18	1.82	-1.32
		0.63	0.96	0.59
			0.96	
			0.44	

c) UOX-loaded SMR

Max	-1.17	0.62	0.59	-1.84
RMS	0.55	0.19	0.22	0.83
		0.74	0.87	-0.69
		0.40	0.55	0.22
			1.79	
			0.82	

d) Partially MOX-loaded SMR

Fig. 9 Reconstructed pin power %error with two leakage corrections

Compared with Figs 6 and 8, the pin-power error at FA peripheral pins is clearly reduced with GPS method. For partially MOX-loaded SMR, the maximum pin-power error, -1.84%, occurs at the outmost fuel pin, where normalized pin-power is 0.462. The pin where the highest pin-power is occurred has relatively small pin-power error, -0.46%. Based on results, it is expected that suggested embedded PPR can provide substantially improved accurate solution compared with other existing PPR.

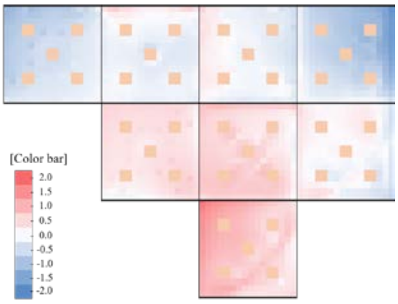


Fig. 10 Reconstructed pin-power %error distribution of partially MOX-loaded SMR with two leakage corrections

4. Conclusions

In this study, pin-power reconstruction (PPR) has been performed by a new embedded calculation with incoming partial current boundary conditions from the nodal analysis. As the embedded PPR considers neighborhood effects by the extended problem domain, and the pinwise discontinuity factors are taken into account, the new method provides much better accuracy than the conventional form-function schemes at the cost of small increase in computing time. In addition, it was confirmed that the accuracy of embedded PPR is noticeably improved with the APEC-GPS two-step leakage corrections. With the APEC method, the nodal equivalence of conventional two-step reactor analysis is significantly improved. Moreover, additional GPS correction in the embedded PPR with the APEC-corrected nodal calculation also results in a noticeable improvement in the reconstructed pin-power distribution.

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