Feasibility of the Embedded Calculation in Pin Power Reconstruction

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1. Introduction

Conventional two-step nodal analysis based on the simplified equivalence theory [1] has been widely used in modern reactor analysis. Although the nodal method is good enough to obtain fuel assembly (FA) level results, such as FA-wise power distribution, for reactor safety analysis, the pin level results are additionally needed for safety analyses. In general, the pin power reconstruction (PPR) method based on the form functions (FF) [2] is widely used to estimate the pin power distribution. Concretely, the key idea of the FF-based PPR is that the normalized homogeneous FA-wise power obtained from two-step nodal analysis is multiplied by heterogeneous pin level FFs pre-calculated from single FA lattice calculations. In this regards, this method has inevitable error in realistic reactor core because the FF are generated by all reflective boundary condition (BC) in unphysical lattice calculation.

In this study, we adopt other PPR method, named embedded calculation based PPR [3]. The pin power distribution of the target FA is calculated by solving extended color-set model with the net current boundary condition obtained from two-step nodal analysis. In the embedded calculation, the pin-wise homogenized group constants (HGCs) including cross sections (XSs) and discontinuity factors (PDFs) are used to take into account geometrical effect of FA. Even if this embedded PPR needs additional calculations, it can consider neighboring effect by expanding domain with appropriate net current boundary condition at the outer surface. In this paper, DeCART2D [4] was used for the lattice and reference calculation. Embedded PPRs were performed by in-house NEM based pin-wise nodal code.

2. Embedded Calculation

Embedded calculation is a local fixed boundary problem as shown in Fig. 1. Unlike the FF-based PPR, which modulate the smooth nodal flux shapes with the detailed assembly flux shapes [1], the flux distribution is directly determined by embedded calculation with given boundary condition from nodal calculation and pin-wise HGCs from lattice calculation.

For example, an expanded color-set model in Fig 1 is dealt to estimate the pin-power distribution of target FA (UOX-1 type) 'FA1' by constructing local fixed boundary problem using the eigenvalue and net currents obtained from nodal calculation. In this embedded calculation, pin-wise HGCs from single FA lattice calculation of each FA type are used in the all regions of expanded color-set domain.

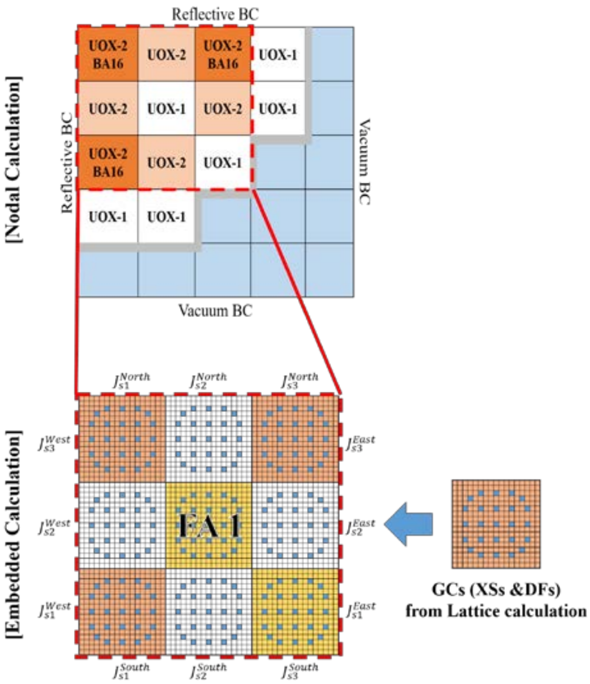


Fig. 1 Configure of embedded calculation

In the embedded PPR calculation, the pin-wise neutron balance is governed by following fixed boundary net current equation in Eq. (1). Equation (1) is solved by BiCGstab method with the conventional pin-size CMFD formula.

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

where

$(\nabla \cdot \vec{J}_g)_{\text{boundary}}$ = Given net current at the boundary surfaces

$(\nabla \cdot \vec{J}_g)_{\text{internal}}$ = Net current at the internal surfaces

$$(\nabla \cdot \vec{J}_g)_{\text{internal}} = -D_g \nabla^2 \phi_g$$

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

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

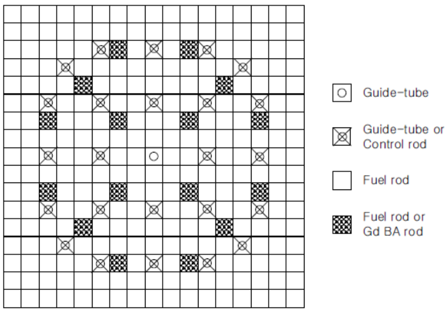
Other notations are standard.

For a two-group and 3x3 FA color-set problem, it takes 2.0~3.5 seconds in a personal computer. With the optimization of color-set size, which reduces half of FA, and parallel computing, it is expected that the additional computing cost of embedded PPR is acceptable compared with pin-wise nodal analysis.

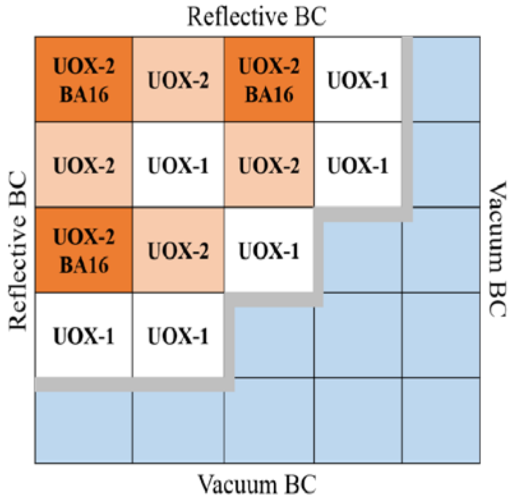
3. Numerical Results

3.1 SMR initial core

To test the feasibility of embedded PPR calculation, a small PWR [5] in Fig. 2 was considered. This 2-D small PWR is a modified core from the well-known KAIST 1A benchmark [5]. There are three typical 17x17 fuel assembles (UOX-1: 2.0 w/o, UOX-2: 3.3 w/o UOX-2 with 16 BA fuel pins). For the consistency, the baffle-reflector regions are also treated with pin-wise HGCs.



1) Configuration of UOX FA



2) Core layout of the small PWR

Fig. 2 Core configuration of a small PWR

Table 1 shows numerical results of two-step nodal analysis. Figure 3 shows the reference normalized FA power and corresponding FA power %error of two-step nodal analysis. These results are quite typical values in conventional two-step nodal analysis.

Table. 1 Numerical results of two-step nodal analysis

Condition	keff	$\Delta\rho$ [pcm]	FA power Max. %error
Ref. DeCART2D	1.112455	-	-
Two-step nodal	1.112052	-32.61	-2.94

1.582	**1.935**	**1.005**	**0.414**
-0.12	1.26	-1.15	0.17
	1.331	**1.116**	**0.332**
	0.67	-0.29	-2.04
		0.480	
		-2.96	

Ref. FA power
FA power %error

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

3.2 Embedded PPR

Based on results of above two-step nodal analysis, embedded PPR calculation is performed as mentioned in section 2. Figure 4 shows maximum and RMS %error between reconstructed pin power and reference pin power. Figure 5 shows description of pin position on FA. It is noted that embedded PPR calculation provides more accurate pin power distribution compared with the conventional FF-based PPR, which has typically 7~10% pin power error [6]. It is because embedded PPR calculation can consider the neighboring effect through the non-zero net current at the boundary surface and the geometrical effect via pin-wise HGCs.

Max	1.27 %	1.61 %	-2.79 %	2.86 %
RMS	0.50 %	1.30 %	1.42 %	0.78 %
Position	(13,13)	(5,4)	(17,11)	(1,17)
		2.73 %	-2.92 %	-4.09 %
		1.06 %	0.81 %	2.45 %
		(17,1)	(17,17)	(16,1)
			-3.83 %	
			3.02 %	
			(6,5)	

Fig. 4 Reconstructed pin power %error between embedded PPR and reference (octant core)

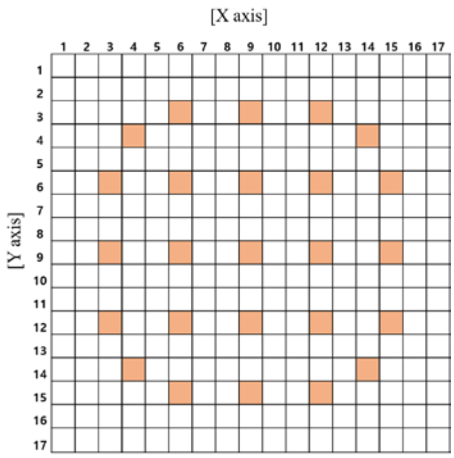


Fig. 5 Pin positions of FA

Figure 6 shows the reconstructed pin power %error distribution. Similar with inevitable pin-wise HGCs error of conventional two-step nodal analysis [7], the embedded PPR solution has same limitation since the pin-wise HGCs of embedded PPR were obtained from the single FA lattice calculation. As shown in Fig. 6, it causes relatively large error for pin power profile in the interface between different FAs and the peripheral pins near the baffle-reflector region. The maximum pin power error, -4.09%, occurs at the 2nd outmost fuel pin in the core (because of application of pin-wise DF), where the normalized pin power is relatively low, i.e. 0.202. The maximum normalized pin power is about 2.40 and corresponding pin has about 1.53% pin power error. Based on results, it is demonstrated the embedded PPR calculation can provide acceptable accuracy.

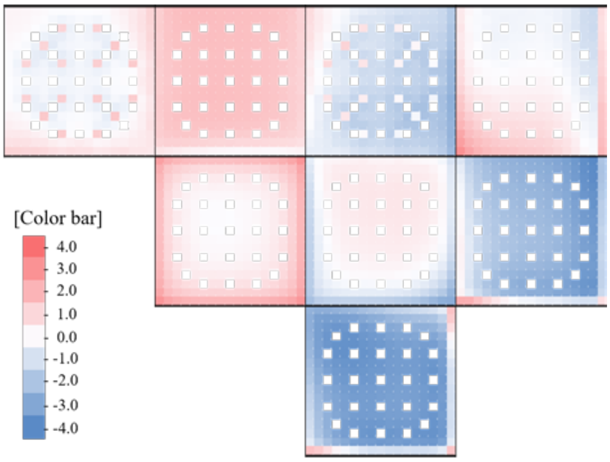


Fig. 6 Reconstructed pin-power %error distribution (octant core)

It is noted that FA-wise RMS %error of the embedded PPR calculation has similar trend with the FA power %error of two-step nodal analysis. As the embedded PPR calculation is performed based on the results of two-step nodal analysis, this trend is understandable. It is expected that if the nodal equivalence is enhanced, the accuracy of the embedded PPR calculation could be improved.

3.3 Embedded PPR with Ref. nodal solution

To investigate the expected improvement of the embedded PPR calculation when the nodal equivalence is enhanced, the perfect nodal equivalence condition is assumed. Figure 7 shows maximum and RMS %error of reconstructed pin power with Ref. nodal solution. Figure 8 shows the reconstructed pin power %error distribution with Ref. nodal solution.

As expected, compared with ‘two-step PPR’ (embedded PPR results of two-step nodal analysis), maximum RMS %error is reduced (almost ~ 1%) in the ‘Ref PPR’ (embedded PPR results of Ref. nodal solution). However, Ref PPR has similar maximum %error with two-step PPR since the pin-wise HGCs used in embedded calculation cannot reflect neighbor effect.

As shown in Fig. 8, there is still relatively large pin power error in the interface between different conditions, it becomes more white. The maximum pin power error, 4.17%, occurs at the outmost fuel pin in the core (because of application of pin-wise DF), where the normalized pin power is relatively low, i.e. 0.355.

Max	1.43 %	-1.33 %	-2.17 %	2.79%
RMS	0.52 %	0.37 %	0.94 %	0.90 %
Position	(13,13)	(14,17)	(17,11)	(1,17)
		2.81 %	-2.67 %	4.17 %
		0.83 %	0.70 %	1.11 %
		(17,17)	(17,17)	(1,17)
			3.50 %	
			1.00 %	
			(17,1)	

Fig. 7 Reconstructed pin power %error of embedded PPR with Ref. nodal solution (octant core)

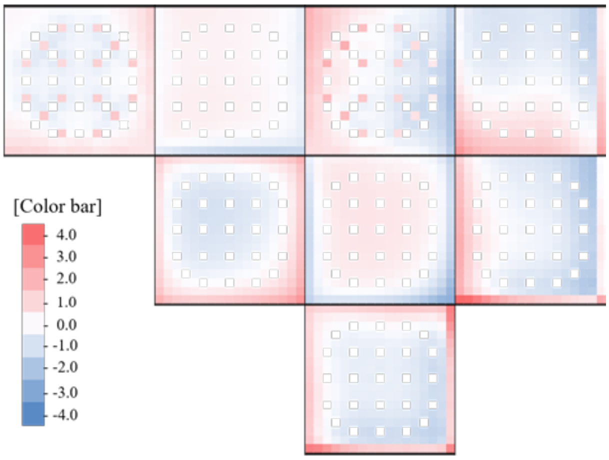


Fig. 8 Reconstructed pin-power %error distribution of embedded PPR with Ref. nodal solution (octant core)

3. Conclusions

In this study, pin power reconstruction has been performed by an embedded calculation with fixed net current boundary condition from the nodal analysis. To consider the geometrical effect of FA, pin-wise HGCs obtained from lattice calculation were used in the embedded PPR calculation. Based on the numerical results, it can be concluded that embedded PPR provides acceptable accuracy. In addition, it is demonstrated that the accuracy of embedded PPR is improved when the nodal equivalence is enhanced. For the further work, a leakage correction method, APEC [8] will be applied to enhance the nodal equivalence.

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