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A New Approach to Treating Baffle/Reflector Heterogeneity in AFEN Methodology

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Abstract

In this paper, an effective method for resolving difficulty resulting from the heterogeneity of the PWR baffle/reflector region is developed on the basis of the AFEN method. The essential difference of the new method from the conventional approach based on the equivalence theory is that the heterogeneous baffle/reflector is directly, without homogenization, considered as a node in nodal calculation. Numerical results show that AFEN method with the new method can accurately predict both the multiplication factor and the power distribution of thermal reactors with baffle explicitly modeled.

I. Introduction

Advanced nodal methods have been successfully applied to the analysis of the thermal reactors with aid of the equivalence theory. However, it is well known that accuracy of nodal methods highly depends on how to treat baffle/reflector region of the PWR core. Especially, the bundle power in peripheral region of the core can have a large error if the baffle/reflector region is not treated properly. The simplest treatment of the baffle/reflector region is to model the baffle and reflector regions independently. However, this direct modeling requires much longer computing time and furthermore the nodal algorithm may suffer from the numerical instability caused by the highly irregular mesh system.

To surmount this difficulty, two approaches have been popularly used: one is the albedo method[1], and the other is based on the equivalence theory[2]. The albedo approach replacing the baffle/reflector region by the albedo boundary condition has been used with limited success. In the latter approach, an equivalent homogeneous node with discontinuity factors substitutes the heterogeneous baffle/reflector region. This approach requires several extended assembly calculations to obtain accurate equivalent homogenized parameters for the baffle/reflector region. Consequently, extra computational efforts in addition to the nodal calculation are needed, computation time of which is not negligible in the analysis of large practical cores. Therefore, in practice, a single set of equivalent parameters obtained with one-dimensional calculation is usually used, to save the computing time, with fudging factors to take

into account the various states of cores including jagged baffle/reflector and burnup effects.

In this paper, a new approach to treating the heterogeneity of the PWR reflector is suggested within the framework of AFEN[3,4,5] method. The new method, which is quite different from the above two approaches, has been successfully applied to AFEN nodal calculations.

II. Methodology

II.1 Nodal Equations

The derivation of the nodal coupling equations for a homogeneous assembly, we use the same procedure used in the original AFEN methodology, which is not repeated here. For the baffle/reflector nodes, we starts from the two-group two-dimensional diffusion equations :

$$-\nabla \cdot D^n \nabla \phi^n(x,y) + \Sigma^n \phi^n(x,y) = \frac{1}{k_{eff}} Q^n \phi^n(x,y), \tag{1}$$

where the notations are standard.

In this work, we allow the heterogeneity of cross sections in the baffle/reflector nodes. Similarly to the AFEN calculation with burnup gradient[5], the solution of the equation is expanded in terms of analytic basis functions and additional polynomial correction terms, that is,

$$\phi^n(x,y) = \phi^{n,a}(x,y) + \phi^{n,p}(x,y), \tag{2}$$

where $\phi^{n,a}(x,y)$ is analytic expansion function, which can be obtained with AFEN method, and $\phi^{n,p}(x,y)$ refers to polynomial function.

For the polynomial basis functions, Legendre polynomials are used :

$$\phi^{n,p}(x,y) = \sum_{ij} E_{ij}^n P_i(\frac{x}{h}) P_j(\frac{y}{h}), \tag{3}$$

where P_i denotes i'th order Legendre polynomial. In the present work, five polynomial functions are used and they are composed of linear and quadratic Legendre polynomials.

To determine the coefficients of the flux expansion given in Eq.(2), we need 14 nodal conditions. We can find nine coefficients by requiring the flux expansion to reproduce the nine nodal quantities. Five more constraints are obtained by forcing the flux expansion to obey the diffusion Eq.(1) in a weighted residual sense:

$$\int_{-h}^{h}\int_{-h}^{h} w(x,y)[\ -\nabla \cdot D^n(x,y)\nabla\phi^n(x,y) + \Sigma_E^n(x,y)\phi^n(x,y)]\,dxdy = 0, \tag{4}$$

where

$$\Sigma_E^n(x,y) = \Sigma^n(x,y) - Q^n(x,y).$$

In this way, all the expansion coefficients can be expressed in terms of nine nodal quantities. Once all the coefficients in the flux expansion are expressed in terms of

the nodal unknowns, we must build as many solvable nodal coupling equations as the number of nodal unknowns. The nodal coupling equations are derived similarly as in the homogeneous AFEN calculation: neutron balance equation, current continuity equations, and corner-point leakage balance equations are used to derive the required nodal equations.

II.2 Analytic Expansion Functions in the Baffle/Reflector Region

As described in the previous section, the intranodal flux in the baffle/reflector region is expanded with both analytic functions and polynomial terms. To obtain the analytic part, we have to determine x_g, which requires representative cross sections of the heterogeneous baffle/reflector node. In this paper, the representative group constants are determined in the following way :

$$\bar{\Sigma}_a = w\Sigma_a^{baffle} + (1-w)\Sigma_a^{reflector}$$

In the above formula, the weighting factor w is obtained using a simple two-dimensional calculation in a spectral geometry shown in Fig. 1.

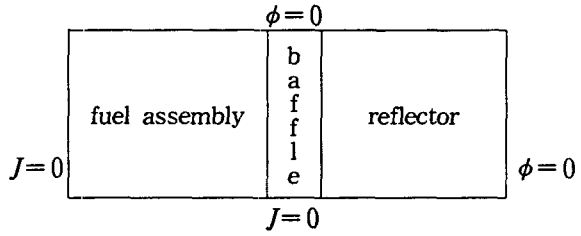

Fig. 1 Spectral geometry to determine w

To determine the optimal value of w, an iterative procedure is needed :

Step 1 : Find the heterogeneous solution (k_{eff}^{het}) for the spectral geometry.

Step 2 : Let $w=0.5$ (initial guess).

Step 3 : Find the nodal solution (k_{eff}^{nodal}) with current w.

Step 4 : If $|100(k_{eff}^{het}-k_{eff}^{nodal})/k_{eff}^{het}| \leq 0.001$, stop.

Otherwise, adjust w and go to Step 3.

This iteration converges very rapidly (a few iterations) and the optimal w is usually in the range $0.45 \leq w \leq 0.6$ in most cases.

It is worthwhile to note that, in the present approach, a single value of w is used for all baffle/reflector nodes. Therefore, the spectral geometry calculation is performed only once for a core under investigation.

III. Application to Benchmark Problems

To test accuracy and applicability of the new method, several benchmark problems were analyzed. The first benchmark problem is a small PWR core with explicit baffle

of 2.8 cm thickness. Geometrical layout of problem I is shown in Fig. 2 and group constants of the problems are given in Table I. Assembly side-length is 21 cm and zero current boundary conditions are imposed on left and top surfaces and the outer boundary conditions are flux-zero condition.

For this problem, spectral geometry calculations with fuel type 1 give the optimal weighting factor $w=0.52$. In Fig. 2, numerical results of the new method are compared with those of the conventional homogenization approach. The equivalent homogenized parameters of the baffle/reflector node are obtained using one-dimensional extended assembly calculation for fuel type 1 adjoining the baffle/reflector node. From the results, one can see that both the new method and conventional method provide accurate solutions in both k_{eff} and nodal power for this problem.

Table I. Material properties of benchmark problems

TYPE	Group	D	Σ_a	$\nu\Sigma_f$	$\Sigma_{1\to2}$
1	fast	1.51334E+00	1.21010E-02	6.01302E-03	2.11238E-02
	thermal	3.94854E-01	1.68140E-01	2.18104E-01	
2	fast	1.51333E+00	9.32598E-03	4.62554E-03	2.11234E-02
	thermal	3.95012E-01	1.41160E-01	1.64089E-01	
3	fast	1.46576E+00	1.47702E-02	4.63361E-03	1.89548E-02
	thermal	3.85034E-01	1.75467E-01	1.72962E-01	
4(MOX)	fast	1.20000E+00	1.37912E-02	6.85245E-03	1.58634E-02
	thermal	4.00000E-01	2.31576E-01	3.44398E-01	
baffle	fast	1.020	0.0032		0.000
	thermal	0.335	0.1460		
water	fast	1.700	0.0010		0.035
	thermal	0.350	0.0500		

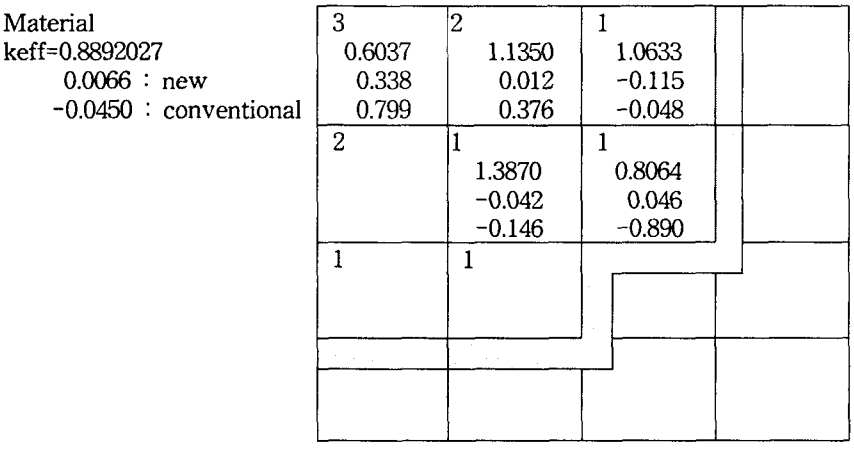

Fig. 2. Error distribution of new and conventional methods in benchmark problem I

Considering the practical design procedures of reactor cores, a modeling of baffle /reflector should have two properties: first, the solution should be close to the reference one as much as possible and secondly, power distribution should be

accurately predicted even when the reactor is at some state other than the reference state for which the baffle/reflector node is characterized. To model such a situation, benchmark problem II is introduced, where we put the MOX assemblies in the jagged baffle region of benchmark problem I and interchanged fuel type 1 and 2 as shown in Fig. 3.

In Fig. 3, errors of new and conventional methods are compared. It should be noted that equivalent parameters for the baffle/reflector nodes are the same as in problem I and the same weighting factor in the new method is also used. As shown in Fig. 3, the new method provides more accurate k_{eff} and nodal powers than the conventional approach although the core state is quite different from the reference state.

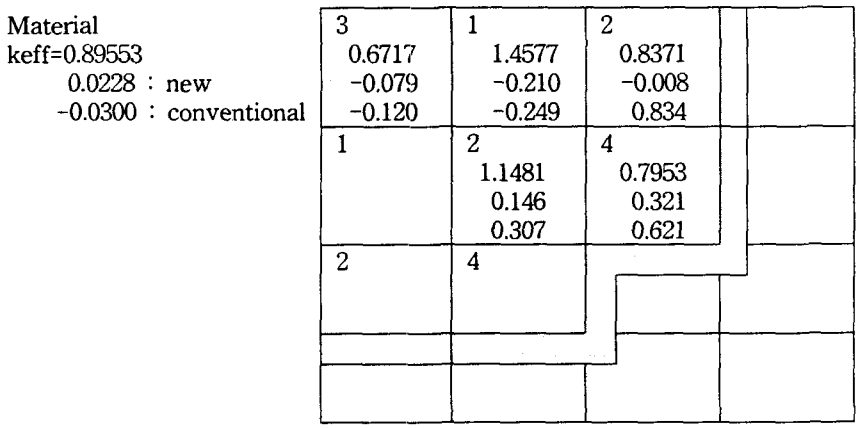

Fig. 3 Error distribution of new and conventional methods in benchmark problem II

The third benchmark problem is the well-known two-dimensional Zion core[6] composed of 4 types of fuel assemblies and baffle/reflector. Geometry and group constants of the Zion core can be found in Ref. 6. Group constants of the baffle are very similar to those of problem I, but there are significant differences in cross sections of water reflector.

For the baffle/reflector node of the Zion core, the optimal weighting factor was found to be 0.555. Calculational results for this problem are summarized in Table II. In the Zion core, it can be observed that the new method provides much better solution than the conventional one-dimensional homogenization approach. The maximum error of the present work in nodal power is only about 0.5%, while it is as much as 2.4% in the conventional approach.

Table II. Results for the Zion core

method	k_{eff}	k_{eff} error(%)	node power error(%)	
			max.	avg.
reference	1.27489	--	--	--
new	1.27493	0.003	-0.490	0.160
conventional	1.27409	-0.063	2.472	0.820

IV. Conclusions

We have shown that the long-standing problem in nodal methods caused by baffle/reflector heterogeneity in PWR cores can be effectively resolved in AFEN method. In the new method, unlike the conventional approaches, the heterogeneous baffle/reflector node is directly treated and simple nodal calculations in a spectral geometry are required. From various benchmark calculations, we can draw the following conclusions :

- The new method can provide more accurate solutions than the conventional one-dimensional homogenization technique.
- Accuracy of the present approach is insensitive to changes of core configuration. Therefore, once the spectral geometry calculations are done, the resulting parameters can be faithfully used for any core configuration.

Considering the fact that the present approach can hardly be realized in the conventional nodal methods, it can be said that the present work reveals another advantage of the AFEN method over the conventional ones.

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