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Application of the 3-D Nodal Equivalence Theory to the CANDU Reactor

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1. Introduction

The CANDU6 (CANada Deuterium Uranium) reactor is a heavy water cooled reactor, four of which are being operated in Korea. Currently, the core calculation of the CANDU6 totally relies on the Canadian AECL's coarse-mesh FDM code, RFSP [1]. However, the RFSP code is found to be subject to inconsistency issue mainly due to the lack of nodal equivalence [2]. In Ref. 2, it has been shown that nodal equivalence theory can be effective for the 2-D CANDU core analysis. In this work, the 3-D nodal equivalence theory was applied to see its effectiveness in a 3-dimensional CANDU reactor analysis.

2. Flux Discontinuity Factors

In the standard nodal equivalence theory [3], the flux discontinuity factor (DF) on a node surface *s* is defined as:

$$f_{g,s} = \phi_{g,s}^{het} / \phi_{g,s}^{\hom}, \quad (1)$$

where $\phi_{g,s}^{het}$ is the g^{th} group heterogeneous flux on surface *s* and $\phi_{g,s}^{\hom}$ is the g^{th} group homogeneous flux on surface *s*. In order to calculate the DF for 3-D equivalence theory, both standard fuel lattice and supercell lattice are modeled including the endplate at the end of the fuel bundle. Figs. 1 and 2 show the standard fuel lattice and a supercell lattice with mechanical control absorber (MCA) rod, respectively.

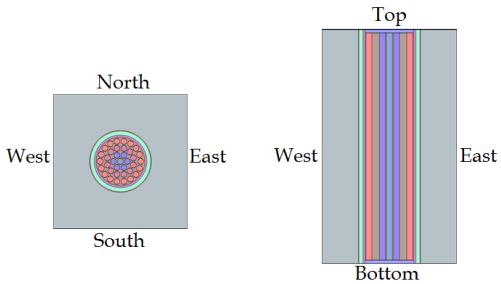

Fig. 1. Standard lattice model (left: front view, right: top view)

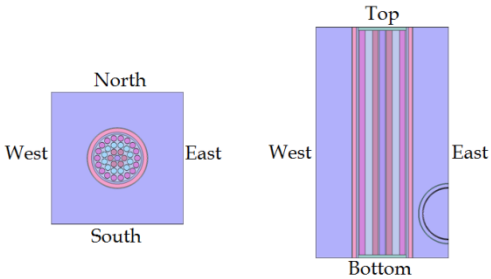

Fig. 2. Supercell lattice model (left: front view, right: top view)

Figure 3 shows the radial reflector model used to generate 2-group parameters. In this study, two types of radial reflectors are modeled: a) two layers of heavy water reflector, and b) a heavy water reflector near fuel and a light water reflector near the boundary. The axial reflector is modeled in a similar way, but the complicated refueling mechanism and the reflector are simply homogenized into one homogeneous medium for simplicity.

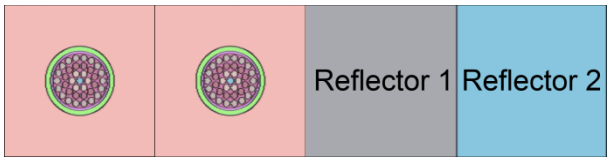

Fig. 3. Radial reflector model

3. Numerical Results

In this study, a clean CANDU6 core is used. To reach a critical state using fresh fuels, 9 ppm of soluble boron is mixed into the moderator and 1 out of 4 MCA rods is inserted into the center of the core. The top view of the whole core model which is used in the MCNP5 [5] reference calculation is shown in Fig. 4. The half-inserted MCA rod is marked with a square.

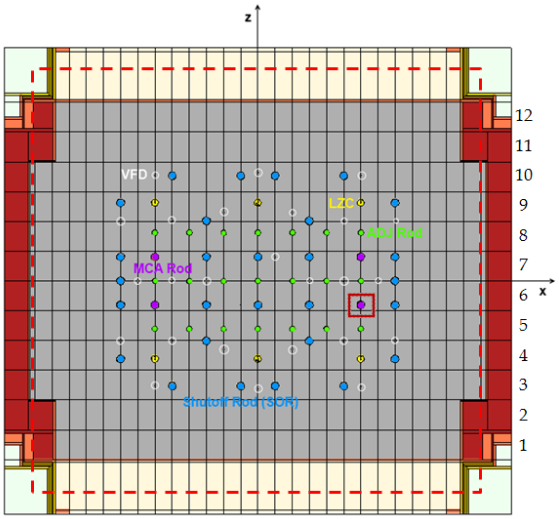

Fig. 4. Top view of reference whole-core model.

The DFs of fuel lattices are obtained by using the Monte Carlo code, Serpent2 [4]. For the standard lattice, the DF of the four surfaces is identical and axial DFs should be the same for both top and bottom. In Table I to III, the DF results of standard fuel lattice, supercell lattice with MCA rod, and reflectors are listed, respectively.

Table I. DF values of standard fuel lattice

Enrichment	Surface	Fast	Thermal
Natural Uranium (0.711 wt% ^{235}U)	Radial	0.7606	1.1572
	Axial	0.9668	1.0165
Depleted Uranium (0.513 wt% ^{235}U)	Radial	0.7579	1.1416
	Axial	0.9645	1.0154

Table II. DF values of supercell lattice with MCA (Natural Uranium fuel)

	Surface	Fast	Thermal
Radial	North	0.7610	1.1616
	South	0.7610	1.1616
	West	0.7723	1.3357
	East	0.7456	0.8912
Axial	Top	0.6908	0.6162
	Bottom	1.2234	1.4106

Table III. DF value of reflector model

Reflector model	Fast	Thermal
Radial (D_2O + D_2O)	1.0203	0.9701
Radial (D_2O + H_2O)	1.0176	1.3794
Axial	0.9019	0.9724

In addition, DF of the fuel lattices are calculated for all 19 lattice types in the initial core model considering different reactivity devices and fuel enrichments.

For the whole core calculation, COREDAX [6], a diffusion nodal code developed at KAIST, was chosen due to its ability to handle 3-D nodal equivalence. The core model in the COREDAX calculation ignored the region outside the dashed line in Fig. 4. In the COREDAX code, the discontinuity factors can be considered for both the radial and the axial directions. To see the effect of the discontinuity factors, the results are compared with the reference MCNP5 results for three cases: a) without any DF, b) with only radial DF, and c) with both radial and axial DFs. The standard deviation of the reference k_{eff} result is 1 pcm.

Table IV. Multiplication factor results

Method	k-eff	error
MCNP5 reference	0.99490	σ=±1 pcm
COREDAX (w/o DF)	0.99737	247 pcm
COREDAX (radial DF)	0.99680	190 pcm
COREDAX (all DF)	0.99675	185 pcm

As shown in Table IV, when equivalence theory is applied, the accuracy in terms of multiplication factor is improved. The application of the 3-D nodal equivalence theory shows a little additional improvement.

The radial power distribution is also compared for the axially integrated fuel channel power. The RMS and maximum relative error of the radial power distribution between the MCNP5 reference and COREDAX results are shown in Table V.

It is shown that the application of the DF gives more accurate power distributions in terms of both the RMS and maximum relative error. This enhancement of the radial power distribution mostly came from the correction of large errors near the fuel-reflector interface. The RMS error of the outermost fuel channel is shown in Table VI. As in the k-eff case, it is observed that implementation of the axial DF leads to a marginal improvement in the power distributions, too.

Table V. RMS error of radial power distribution

Method	RMS error	Max. error
COREDAX (w/o DF)	3.238 %	10.363
COREDAX (radial DF)	2.096 %	6.981
COREDAX (all DF)	2.064 %	6.981

Table VI. RMS error of radial power distribution of the outermost fuel boundary

Method	RMS error
COREDAX (w/o DF)	6.601 %
COREDAX (radial DF)	3.197 %
COREDAX (all DF)	3.227 %

4. Conclusion

The 3-D nodal equivalence is applied to the whole core analysis of a clean CANDU6 core. Both the radial and the axial DFs are quite different for different reactivity devices inside the fuel lattice. It has been demonstrated that the application of the conventional 2-D nodal equivalence theory gives better accuracy in terms of the k-eff and power profiles, while the 3-D equivalence theory only results in marginal improvements. The relative ineffectiveness of the axial discontinuity factor may be ascribed to simplifications of the very complicated core geometry and some assumptions in modeling both radial and axial reflectors of the CANDU reactor. For a more accurate evaluation of the 3-D equivalence theory, more realistic reflector models are currently under development.

REFERENCES

[1] W. Shen and B. Phelps, “Assessment of the Coarse-Mesh Finite-Difference Method with the Multicell Methodology in RFSP for ACR-1000,” Proceedings of 30th CNS Annual Conference, Calgary, June, 2009

[2] Y. Kim, W. Kim, D. Hartanto, and B.H. Cho, "Effectiveness of the Nodal Equivalence Theory in CANDU Reactor," Transactions of the American Nuclear Society vol. 107, San Diego, CA, USA, November 11-15, 2012

[3] K. S. Smith, “Assembly Homogenization Techniques for Light Water Reactor Analysis”, Progress in Nuclear Energy, 17, 303, 1986

[4] J. Leppanen. "PSG2 / Serpent - a Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code," VTT Technical Research Centre of Finland, Jun. 13, 2012

[5] X-5 Monte Carlo Team, “MCNP A General MonteCarlo N-Particle Transport Code, Version 5,” Los Alamos National Laboratory, 2003

[6] “A User’s Manual for the Rectangular Three-Dimensional Diffusion Nodal Code COREDAX – Version 1R,” NURAPT-2010-01, KAIST/KINS, 2010