In-Core Power Distribution Monitoring of PWR by STREAM/RAST-K

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1. Introduction

This paper presents the three-dimensional (3D) power distribution of pressurized water reactor (PWR) with in-core detector signal to improve core protection calculation. Core protection calculation is important to prevent the several accidents in reactor power plant. Reactor Protection System (RPS) sends the signal to the Reactor Trip Switch Gear (RTSG) and Engineering Safety Features Actuation Signal (ESFAS) by collapsing the Ex-Core detector system and core protection system (CPCS) [1][2]. One of trip signals occurs when the detector senses the abnormal axial power distribution [1][2]. Therefore, in this paper, prediction of axial power distribution is calculated by in-core detector signals. The OPR-1000 reactor is used for validation against with measured data. The OPR-1000 reactor has totally 45 number of detector assemblies in whole core pattern. Each detector assemblies have fixed structure and located in central instrument tube. The axially five box signals are calibrated by CECOR code with precalculated coupling coefficients (CCs) and five-mode Fourier series [3][4].

In previous studies of 3D core power monitoring, YGN-3 of South Korea reactor was used based on the least-square method adopted in ACOPS (Advanced Core power Surveillance) [3]. In the reference [3], preconditioned conjugated gradient normal residual (CGNR) method are used to solve the matrix generated by the least-square method. In case of boiling water reactor, the reference [5] calculates the power distribution by using the least-square method. In this paper, least-square method, CGNR and incomplete Cholesky Factorization are used for 3D core power calculation by STREAM/RAST-K.

2. Method

The two-step calculation is performed with lattice physics code STREAM and nodal diffusion code RAST-K. The cross-section for 3D core calculation and heterogeneous form function for pin power calculation are generated by transport code STREAM [6]. RAST-K uses unified nodal method (UNM) with coarse mesh finite difference (CMFD) method and performs micro depletion calculation [6]. STREAM/RAST-K two step method has been validated and verified in several commercial reactor types as shown in reference [6].

To adjust core condition, least-square method is used with nodal coupling coefficients. Nodal balance equation is shown in Equation (1) to solve [3].

$$\mathbf{A}\phi = \mathbf{M}\phi - \frac{1}{k_{eff}}\mathbf{F}\phi = \mathbf{b}\,, \tag{1}$$

where matrix **M** contains leakage, absorption, and inter group transfer of neutrons [3]. **F** contains the fission reaction. The size of **A**, **M** and **F** is number of groups multiplied by number of nodes ($N_{group} \times N_{nodes}$). Matrix **b** is external source vector. Detector response equation based on two-group diffusion theory is set as Equation (2) [3].

$$\mathbf{D}\phi = \mathbf{s}\,, \tag{2}$$

where **D** is a matrix of kappa (energy released per fission) multiplied by fission cross section as shown in Equation (3) and matrix **s** is detector signals (power of detector assemblies). The size of matrix is number of detector signals multiplied by number of nodes ($N_{detectors} \times N_{nodes}$). In this study, node-wise power is used to calculation. OPR-1000 reactor has 45 number of detector assemblies and axially five detectors in one detector assembly. Totally, 225 number of detector signals are generated in whole core model and this number is used in this study.

$$\mathbf{D} = \begin{pmatrix} \kappa\Sigma_f^{i,1} & \cdots & \kappa\Sigma_f^{i,N_{node}} \\ \vdots & \ddots & \vdots \\ \kappa\Sigma_f^{N_{detector},1} & \cdots & \kappa\Sigma_f^{N_{detector},N_{node}} \end{pmatrix}. \tag{3}$$

To solve the diffusion equation with considering the detector signal, over-determined problem can be governed based on the nodal balance equation (Eq. 1) and detector response equation (Eq. 2) as written in Equation (4) [3]. To find best estimated solution, the least-square method is used following previous work as shown in reference [3]. Equation (6) shows the best estimated equation by using least-square method [3].

$$\begin{pmatrix} \mathbf{A} \\ \mathbf{D} \end{pmatrix}\phi = \begin{pmatrix} \mathbf{b} \\ \mathbf{s} \end{pmatrix}, \tag{4}$$

$$\mathbf{R}\phi = \begin{pmatrix}\mathbf{A} & \mathbf{D}\end{pmatrix}\begin{pmatrix}\mathbf{A} \\ \mathbf{D}\end{pmatrix}\phi \simeq \mathbf{A}^{\mathrm{T}}\mathbf{A}\phi = \mathbf{c}\,, \qquad (5)$$

where **R** is the best estimated matrix by using least-square method and **c** is matrix defined as detector power and nodal diffusion coefficient ($\mathbf{c} = \mathbf{A}^{\mathrm{T}}\mathbf{b}$) [3]. Equation (5) uses to find the solution of flux. In this paper, the linear solver calculation is performed by CGNR with incomplete Cholesky Factorization [3][7][8]. Dynamic drop box (0.02 boundary) is used for calculation [3][7][8].

Algorithm 1 presents the incomplete Cholesky factorization adopted in RAST-K [7][8].

Algorithm 1. Incomplete Cholesky Factorization

1. $L(1,1) = \sqrt{R(1,1)}$
2. $do\ k = 2, n$
3. $\quad L(k,1) = R(k,1)/L(1,1) \qquad (k,1) \notin P$
4. $\quad do\ i = 2,(k-1)$
5. $\quad L(k,i) = \dfrac{R(k,i) - L(i,1:(i-1)) * L^{T}(1:(i-1),k)}{L(1,1)}$
   $(k,i) \notin P\ and\ (i,k) \notin P$
6. $\quad enddo$
7. $\quad L(k,k) = \sqrt{R(k,k) - L(k,j) * L^{T}(j,k)}$
8. $enddo$

where P is dynamic drop box. Equation (6) presents the assumption of incomplete Cholesky factorization to solve Equation (5)

$$LL^{T} = R\,. \qquad (6)$$

Figure 1 presents the non-zero matrix of incomplete Cholesky factorization. Left-side graph is matrix **L** and right-side graph is matrix **R** generated by Equation (6). Matrix size is N x N (N is N_{group} x $N_{\text{radial node}}$ x $N_{\text{axial node}}$). Figure 2 shows the matrix **R** calculated by Equation (5). Figure 3 presents the calculation progress.

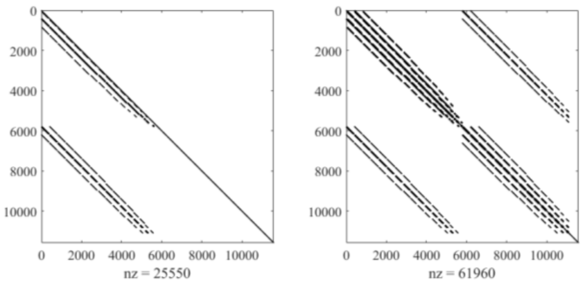


Figure 1 Non-zero matrix of incomplete Cholesky factorization

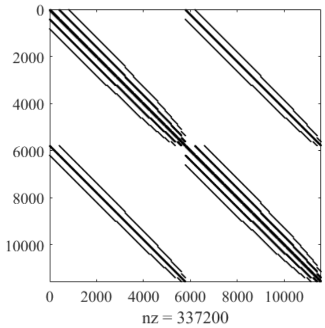


Figure 2 Non-zero matrix of **R**

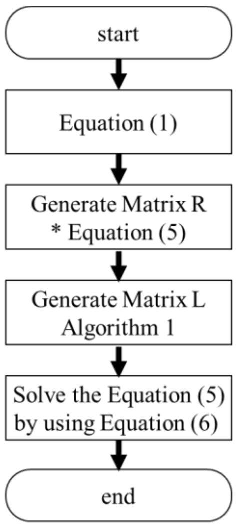
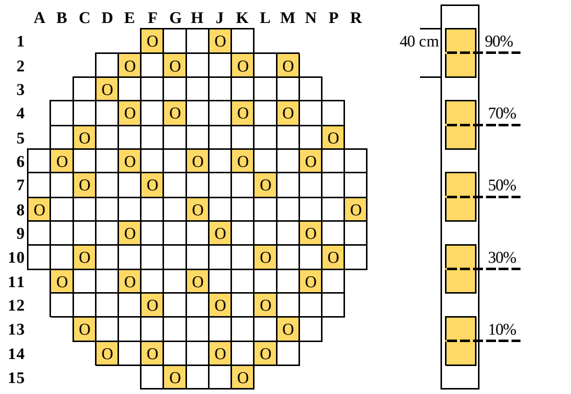


Figure 3 Calculation flow of flux

3. Results and discussions

This section presents the comparison results with measured data. The calculated values are generated by STREAM/RAST-K two step method with detector signals (used signal information ranging is from 5 GWd/MTU to 10 GWd/MTU). The calculation is performed with whole core model as shown in Figure 4. Yellow box indicates radial detector positions in the core and totally 225 (45 x 5) detector signals are used: number of 45 is radial positions of detector in layout of whole core; five is number of axial detectors in one radial detector position. Also, the axial detector positions of one radial detector position is presented in red box. The height of one detector is 40 cm. Fuel material is uranium dioxide and burnable absorber is gadolinia. Figure 4 presents the detector position in OPR-1000 reactor and Figure 5 presents loading pattern of OPR-1000. Enrichment of UO_2 and number of gadolinia in each fuel assembly are illustrated Figure 5: letter A to letter F are fuel assembly types.



(a) Radial layout of detector (b) Axial location of detector

Figure 4 Detector position in OPR-1000

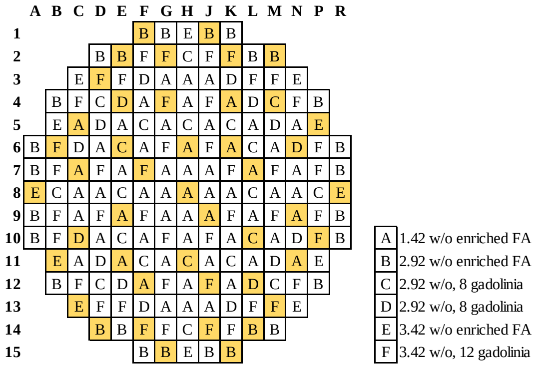


Figure 5 Layout of OPR-1000

Figure 6 presents the radial power distribution calculated by CGNR with incomplete Cholesky factorization (IC) at 5 GWd/MT and Figure 7 is at 10 GWd/MTU. Table I presents the summary of radial power comparison results. Maximum, minimum and root mean square (RMS) differences are listed in this table. Reference is measurement data from CECOR. Column of CGNR+IC is the result calculated by conjugated gradient normal residual method with IC. Methodology is referred by reference [3]. The column of RAST-K means the stand-alone calculation without using any detector signals. To compared RMS values, CGNR+IC has smaller relative errors compared with RAST-K results.

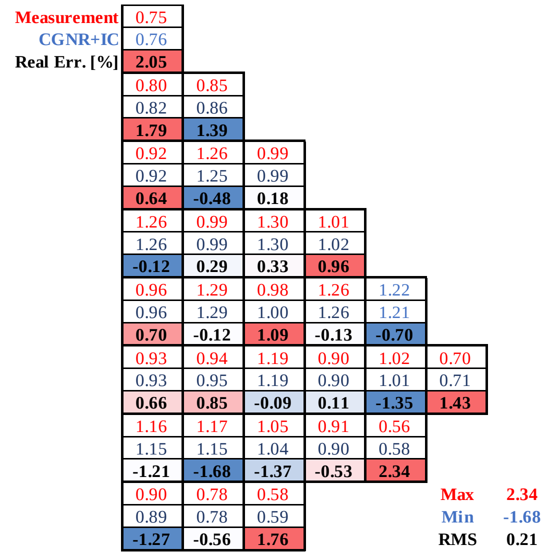


Figure 6 Radial power shape [5 GWd/MTU]

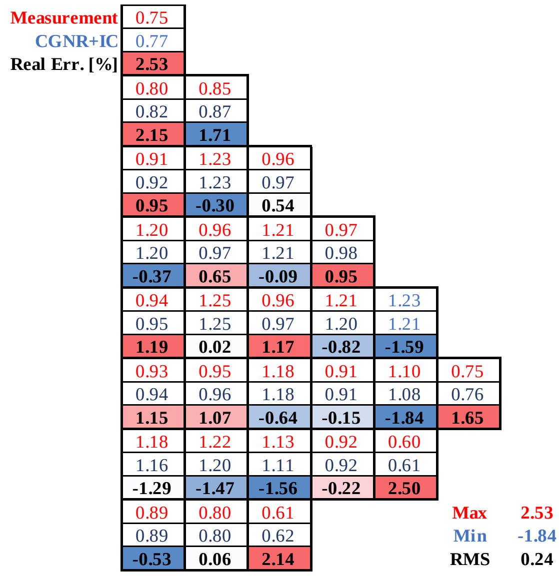


Figure 7 Radial power shape [10 GWd/MTU]

Table I: Relative error compared with measurement

5 GWd/MTU		
	CGNR+IC	RAST-K
Max	2.34	2.36
Min	-1.68	-1.68
RMS*	0.21	0.22
10 GWd/MTU		
	CGNR+IC	RAST-K
Max	2.53	2.54
Min	-1.84	-1.81
RMS*	0.24	0.25

*RMS (root mean square): $\sqrt{\frac{\sum_{i=1}^{N} err_i}{N}}$, N is number of radial nodes

Figure 8 presents the axial shape index, Figure 9 shows the Fxy values and Figure 10 contains the Fq. Definition of axial shape index, Fxy and Fq are described in reference [9]. Reference is measurement data. In case of axial shape index and Fq, three values calculated by each method have similar trend. CGNR+IC calculation has smaller error than RAST-K in ASI comparison.

Reference [7] describes the weakness of IC method as the IC method has less conversion ratio compared with other orthogonal factorization preconditioner method. However, in this calculation, all results with IC method have conversed value.

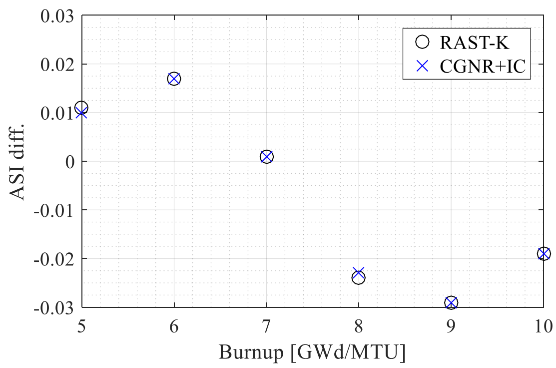


Figure 8 Comparison of Axial Shape Index

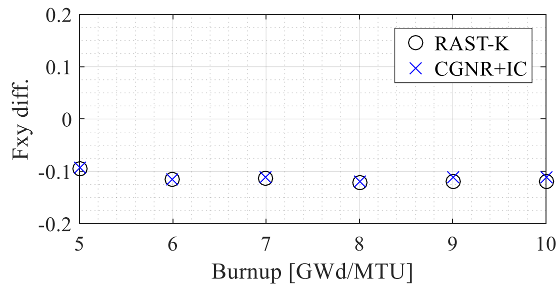


Figure 9 Comparison of Fxy

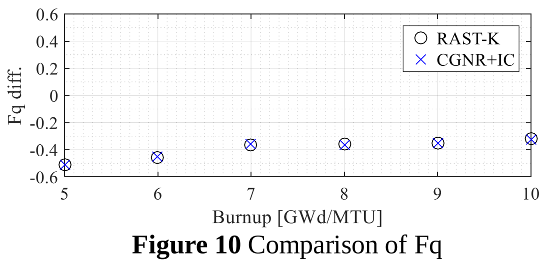


Figure 10 Comparison of Fq

4. Conclusion

The 3D core power calculation method is presented by using least-square method with detector signal. The over-determined system of nodal balance equation with detector signals, is solved by conjugated gradient normal residual (CGNR) method with incomplete Cholesky factorization (IC). OPR-1000 reactor and CECOR measurement are used for comparison. The calculation with IC and CGNR method has smaller relative errors in ASI, Fxy and Fq, compared with RAST-K calculation without considering detector signals.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (No. NRF-2019M2D2A1A03058371).

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