Application of Modified 2D/1D Decoupling Method in the Pin-wise Core Analysis

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1. Introduction

Conventional two-step code systems developed to exploit limited computing resources are at a disadvantage in fully utilizing modern computer systems. On the contrary, the advanced code systems are being developed in a way that actively utilizes high-performance computers. This is to drastically improve the accuracy of nuclear design codes in the current situation where innovative reactors such as SMR are emerging and the need to respond to various operating scenarios such as load-follow operation is raised. In line with the trend, KEPCO NF (KNF) has also been working on the development of pin-wise two-step core analysis code [1].

In this study, a feasibility of the new 2D/1D decoupling method was evaluated. In the existing 2D/1D method, a core is calculated by dividing it into dozens of 2D planes and tens of thousands of 1D pins; in the new decoupling method, 1D calculation is performed in units of homogenized boxes of dozens of pins.

The 2D/1D calculations of the two methods presented in the following sections were performed with an in-house code [1]. The pinwise 4-group constants generated by the lattice transport code KARMA [2] were used for all calculations.

2. Methodologies of Decoupling Method

2.1 2D/1D decoupling method (2D1D)

The 2D/1D decoupling scheme illustrated in Fig. 1 is intended to improve the parallelism on multicore system. In each radial plane, the axial leakage term is treated as a source term as in Eq. (1). Similar to the 2D problem, the radial leakage term in each 1D problem is treated as a source term as in Eq. (2).

$$\sum_{u=x,y}\frac{1}{h_u}(J^R_{gu}-J^L_{gu})+\Sigma_{rg}\bar{\phi}_g = \frac{\chi_g}{k_{eff}}\sum_{g'=1}^{G}\nu\Sigma_{fg'}\bar{\phi}_{g'}+\sum_{\substack{g'=1\\g'\neq g}}^{G}\Sigma_{g'g}\bar{\phi}_{g'}-\frac{1}{h_z}(J^R_{gz}-J^L_{gz}) \quad (1)$$

$$\frac{1}{h_z}(J^R_{gz}-J^L_{gz})+\Sigma_{rg}\bar{\phi}_g = \frac{\chi_g}{k_{eff}}\sum_{g'=1}^{G}\nu\Sigma_{fg'}\bar{\phi}_{g'}+\sum_{\substack{g'=1\\g'\neq g}}^{G}\Sigma_{g'g}\bar{\phi}_{g'}-\sum_{u=x,y}\frac{1}{h_u}(J^R_{gu}-J^L_{gu}) \quad (2)$$

The calculation of Eq. (1) and (2) are performed alternately to update each other's leakage source term. The flux solver employs the finite difference method (FDM), and errors due to the use of pin-cell size meshes are compensated by the SPH method [3]. Hereinafter, this 2D/1D decoupling method is also called as '2D1D'.

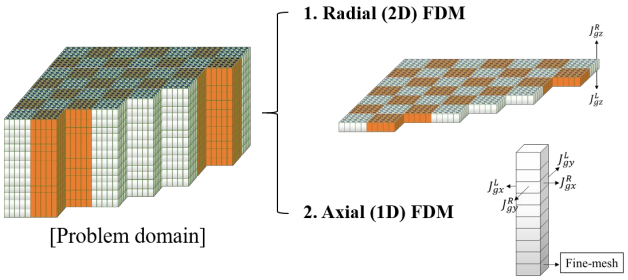

Fig. 1. 2D/1D domain decomposition scheme

2.2 Modified 2D/1D decoupling method (2D1DBOX)

Although the 2D1D method showed satisfactory results in terms of the accuracy and computing time, it was still burdensome to perform large amount of 1D calculations. For example, in the OPR1000 quarter core problem, the number of 1D fuel pins reaches 13,312.

In this regard, a modified 2D/1D decoupling method based on the observation that the neighboring pins have similar degree of the axial leakage was suggested. Hereinafter, it is also called '2D1DBOX'. In the 2D1DBOX method, the axial 1D pin problem is replaced with axial 1D box-level FDM problem as shown in Fig. 2. This introduces additional box-level homogenization in Eq. (3) and surface leakage aggregation in Eq. (4). This can significantly reduce the number of 1D calculations. In the case of the OPR1000 quarter core problem, using 4 boxes per assembly reduces the number from 13,312 to 208.

$$\bar{\Sigma}^i_{xg}=\frac{\sum_{k\in i}V_k\Sigma^k_{xg}\phi^k_g}{\bar{\varphi}^i_g V_i} \quad (3)$$

$$J^{box}_{s,g}=\sum\nolimits_{k\in box}J^{pin}_{s,g} \quad (4)$$

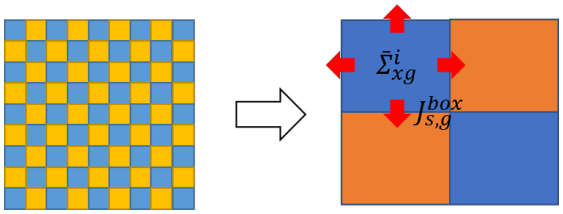

Fig. 2. Axial 1D problem change in 2D1DBOX

3. Numerical Results

In order to demonstrate the feasibility of 2D1DBOX method, a steady-state calculation without T/H feedback and cycle 1 depletion calculation were performed for the OPR1000 initial core problem. All calculations have been performed in a personal PC equipped with intel i9-12900K CPU and 128 GB RAM.

3.1 BOC clean core with fixed condition

Table I shows the problem descriptions of first test problem. First one has a problem setup to minimize the non-linear update from TH feedback, updating the number density of Xe/Sm, boron concentration, and etc.

With single thread, the 2D1D takes 26.71 secs and the 2D1DBOX takes 13.78 secs. The 2D1DBOX method has almost double speed-up. With 8 threads OpenMP platform, the 2D1D takes ~6.20 secs and the 2D1DBOX takes ~4.39 secs.

The Calc. module-wise required time of each method are tabulated in Table II and III. Since the 2D1DBOX method significantly reduces # of 1D FDM problem, it can save lot of computing time of 1D FDM which is the biggest portion (62.71%) in the 2D1D method.

Table I. Problem description of OPR1000 initial core

Item	Condition
Part	Quarter
Mode	Steady-state
Search	K-eff
Boron Concentration	700 ppm
Feedback	Fixed temperature
Xe/Sm Option	No Xe, No Sm

Table II. Require time for 2D1D calc. module

Item	Computing time [sec]	Portion [%]
1D FDM	13.03	62.71
2D FDM	7.67	36.93
3D CMFD	0.08	0.36
Total	20.77	100.00

Table III. Require time for 2D1DBOX calc. module

Item	Computing time [sec]	Portion [%]
1D FDM	0.34	3.75
2D FDM	8.59	92.57
3D CMFD	0.06	0.68
Total	8.99	100.00

Table IV shows the discrepancies of the major design parameters between two methods. It is noted that the difference is negligible.

Table IV. Discrepancy of design parameters

Item	2D1D	2D1DBOX	Diff
K-eff	1.03524	1.03526	2 pcm
Fr	1.6035	1.6030	-0.0005
Fxy	1.6066	1.6062	-0.0004
Fq	2.3419	2.3399	-0.002
Max FA Pow	1.4117	1.4111	-0.0006
RMS value of relative pin-power error (%)*			0.326

where RMS* is defined as follow;

$$\mathrm{RMS} = \sqrt{\frac{\Sigma(Err_{pow})^2}{N}},$$

$$Err_{pow} = \frac{pow_{2d1dbox} - pow_{2d1d}}{pow_{2d1d}} \times 100.$$

3.2 Core depletion results

The core depletion calculations were performed with two methods. Contrary to the previous section, the calc. conditions of depletion case follow the more realistic conditions as listed in Table V. With 8 threads OpenMP platform, the 2D1D takes about 707.28 secs and the 2D1DBOX takes about 442.76 secs. The 2D1DBOX method has around 38% speed-up.

Table V. Problem description of depletion calculation

Item	Condition
Part	Quarter
Mode	Steady-state
Search	Boron
Feedback	On
Xe/Sm Option	EQ Xe, TR Sm
Burunp step	17 steps (~13000 MWd)

Figure 3 to 6 show the discrepancy of CBC, ASI, peaking factors between two methods. Similar with previous section, the discrepancy between two methods are ignorable in terms of reactor design.

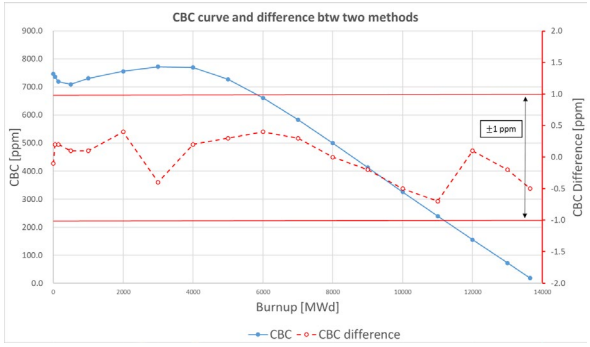

Fig. 3. CBC and difference between two methods

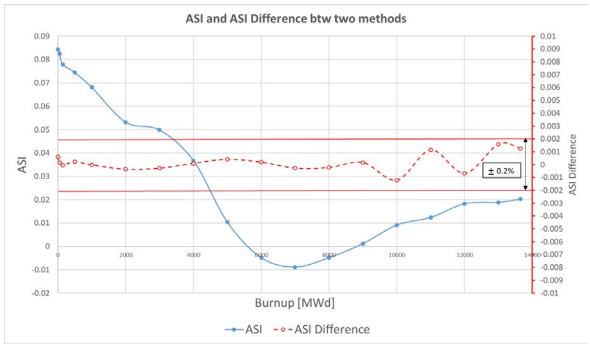

Fig. 4. ASI and difference between two methods

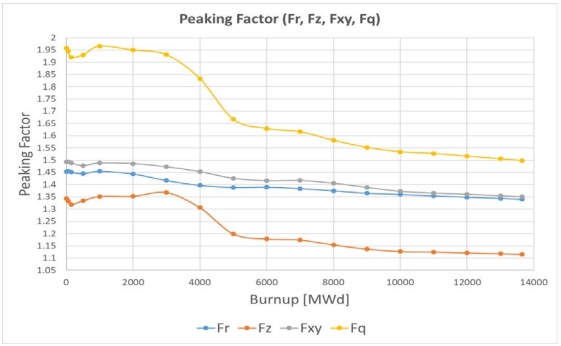

Fig. 5. Peaking factors behavior during depletion calculation

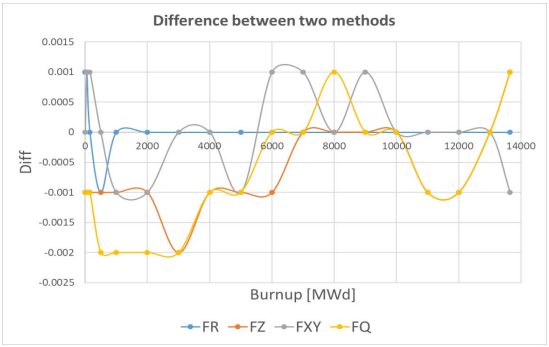

Fig. 6. Peaking factors difference between two methods

4. Conclusions

In this paper, the new 2D/1D decoupling method was suggested and its feasibility was shown. The new 2D1DBOX method is intended to reduce the computing time by homogenizing 1D pins into boxes. The computing expense for the additional homogenization process is marginal, and it was demonstrated by the reduced computing time. Compared with the existing 2D1D method, the 2D1DBOX method can save around 40% of the computing time. The numerical results did not show any noticeable discrepancies introduced by the new method. In the future work, comparisons between the two methods will be performed for a wider range of problems involving heavily rodded cores.

5. Acknowledgements

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