Depletion Analysis of Fuel Assembly with the iDTMC method

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1. Introduction

For a practical application of the Monte Carlo (MC) method in commercial reactor problems, a whole core depletion calculation should be economical in terms of the memory and time requirement. Although the performance of the computer has been steadily increased, the large-scale whole core burnup calculation on an intra-pin level is still demanding and unfeasible.

Many research groups have studied to decrease the numerical cost of the depletion calculation in MC method. The Chebyshev rational approximation method has been developed to enhance the computational accuracy and efficiency in solving the burnup matrix by examining characteristics of the matrix [1]. The predictor-corrector method has been widely used in the depletion calculation [2], which can improve the stability of the established MC burnup calculation. Both studies showed improvements over other methods, but challenges to be solved still remained.

In the meantime, the iDTMC method has been previously developed to decrease the computing time and stochastic uncertainties for the steady-state MC eigenvalue analysis [3][4]. This study showed that the iDTMC method can noticeably improve the accuracy and reliability of the pin-wise power and flux profiles compared to the conventional MC method. Moreover, it is demonstrated that the iDTMC method can produce the accurate and reliable intra-pin power distribution with the reconstruction scheme [5]. Since the power and flux distributions are essential parameters in the depletion calculation, it would be plausible for the improved burnup calculation with the iDTMC solutions applied.

In this study, the iDTMC method is applied to the depletion calculation in a single fuel assembly of the APR1400 problem. The concept of the iDTMC method in the depletion calculation is briefly introduced. In the assembly problem, the burnup dependent criticality and intra-pin power distribution are estimated and the computing time is compared between the standard MC and iDTMC methods.

2. Methodology

2.1. iDTMC method

The improved deterministic truncation of the Monte Carlo solution (iDTMC) method has been developed to improve the numerical performance and efficiency in nuclear reactor analyses [3][4]. The iDTMC method strategically adopts the assembly-wise coupled partial current based coarse mesh finite difference (p-CMFD) method to accelerate the convergence of the fission source distribution during the inactive cycles and the pin-wise decoupled p-CMFD method to produce the reactor solutions during the active cycles [6] as shown in Fig. 1.

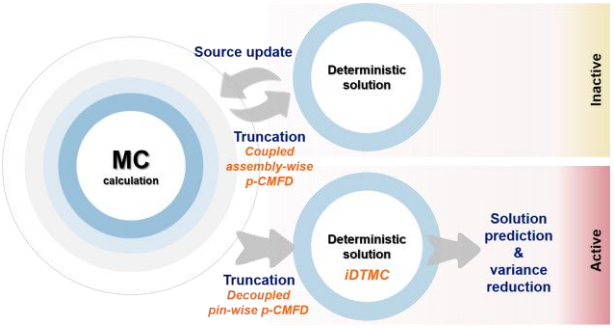

Figure 1. Concept of the iDTMC method

The p-CMFD method solves the one-group diffusion-like neutron balance equation.

$$\sum_{s,n=i,j,k} \frac{A_s}{V_{i,j,k}} (J_{s1} - J_{s0}) + \Sigma_a^{i,j,k} \phi_{i,j,k} = \frac{1}{k_{eff}} \nu\Sigma_f^{i,j,k} \phi_{i,j,k} \quad (1)$$

where V is the node volume, A is the surface area, s is the surface index, ϕ and J are the flux and current, respectively, and Σ is the cross section. The CMFD parameters are calculated from the MC simulation, and the surface currents can be preserved by the correction factors.

$$J_{s1}^{+} = \mp \frac{1}{2} \tilde{D}_{s1} (\phi_{n+1} - \phi_n) + \hat{D}_{s1}^{\pm} \phi_{n+1/2\mp1/2} \quad (2)$$

where $\hat{D}_{s1}^{\pm}$ is the correction factor.

$$\hat{D}_{s1}^{\pm} = \frac{J_{s1}^{\pm MC} \pm 0.5 \cdot \tilde{D}_{s1} (\phi_{n+1}^{MC} - \phi_n^{MC})}{\phi_{n+1/2\mp1/2}^{MC}}$$

2.2. Depletion with the iDTMC method

Depletion calculation in nuclear reactor problems is a repeated process between the steady-state neutronic calculations and material composition calculations as shown in Figure 2, and the numerical cost is mostly consumed in the neutronic calculation in the MC method. In the meantime, it has been verified that the

iDTMC method can effectively reduce the computing time of the neutronic calculation. Therefore, total numerical cost for the depletion calculation can be significantly decreased by applying the iDTMC method.

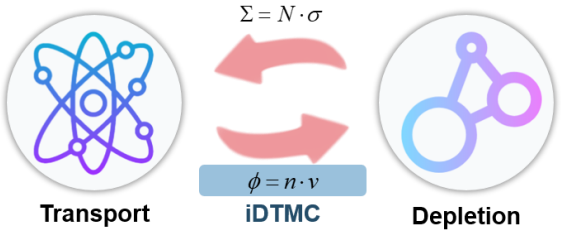

Figure 2. Diagram of iDTMC method in depletion analyses

Since the iDTMC method only can produce the node-wise homogenized solution, the intra-pin reconstruction scheme is applied with the pin-wise form function generated by the MC calculation to generate the intra-pin power and flux distributions.

$$\phi_{i,r} = ff_{i,r} \times \phi_i^{iDTMC} \quad (3)$$

where r is the region index included in the node i. The form function is calculated in the MC simulation.

$$ff_{i,r} = \frac{\phi_{i,r}^{MC}}{\sum_{r=1}^{N_r} \phi_{i,r}^{MC} / N_r} \quad (4)$$

In this way, material- and zone-wise depletion is available with the iDTMC method in the arbitrary geometry [5].

3. Numerical Results

The calculation is done with the iMC code which has been developed in KAIST for nuclear reactor core analyses. The B1 type single fuel assembly of the APR1400 problem with the all reflective boundary condition is tested as shown in Figure 3. The standard UO_2 fuel rods are divided into 3 rings and the fuel rods with a Gadolinia burnable absorber (BA) are divided into 7 rings to take into account the strong spatial self-shielding as shown in Figure 4. The linear power density is 30 kW/cm.

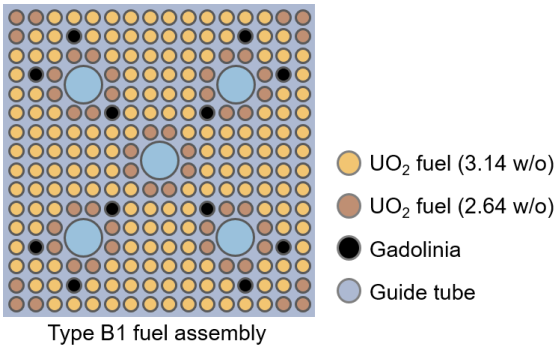

Figure 3. B1 type fuel assembly of APR1400 problem

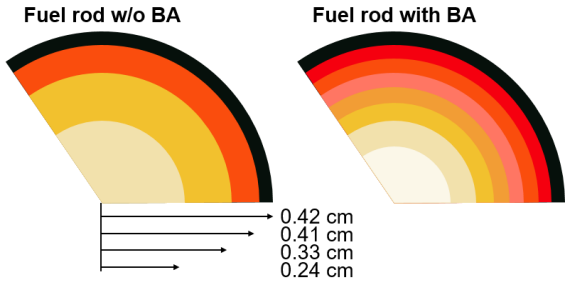

Figure 4. Geometry of fuel rods for fuel depletion

The number of inactive cycles is determined by the strategies for CMFD-accelerated inactive cycle (SCI) [6], the average number of inactive cycles is presented in Table I, and 10,000 histories per cycle are simulated. For both methods, more than 15 inactive cycles were needed to obtain the converged FSD at the first depletion step, but after the first eigenvalue calculation, only around 8 cycles were needed because the flux distribution was already converged and was almost invariant on the adjacent depletion steps.

Table I. Calculation condition

	MC	iDTMC
No. of inactive cycles	8.2	8.4
No. of active cycles	10	5
No. of histories	10,000	

Total 10 active cycles are used in the standard MC calculation, but 5 active cycles are used in the iDTMC calculation. For the reference solution, 25 inactive cycles and 500 active cycles are used for each steady-state calculation. All the calculations are carried out with a total of 112 cores of Xeon E5-2697 with 2.60GHz clock speed.

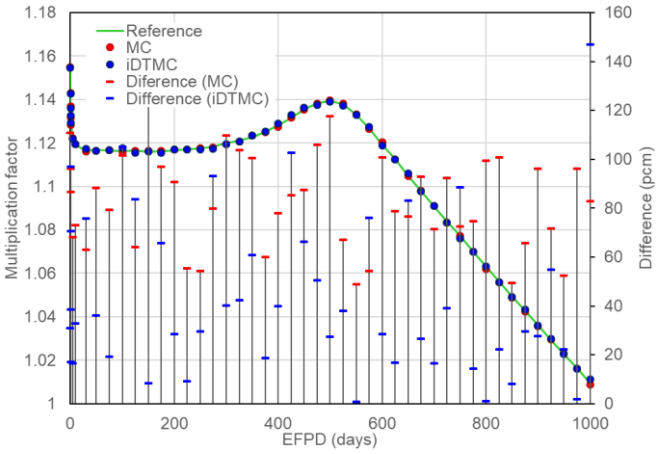

Figure 4. Burnup dependent criticality and its difference

Figure 4 shows the burnup dependent multiplication factors and the discrepancies with the reference solution. Although the iDTMC method used less number of

cycles, it showed better agreement with the reference solution within the 50 pcm difference on the average. The average differences is estimated to 84 pcm for the standard MC and 44 pcm for the iDTMC method.

Figure 5 describes the stochastic uncertainties of the multiplication factors. Due to the attributes of the each method and limits of the computing resource, only apparent standard deviation is presented for the standard MC, and the real standard deviation is estimated by the correlated sampling scheme [6] for the iDTMC method. The real standard deviation of the iDTMC method is shown to be smaller than the apparent standard deviation of the standard MC method on the average. The larger uncertainties of the iDTMC method in the early cycle seems considered by the effect of the Xenon buildup.

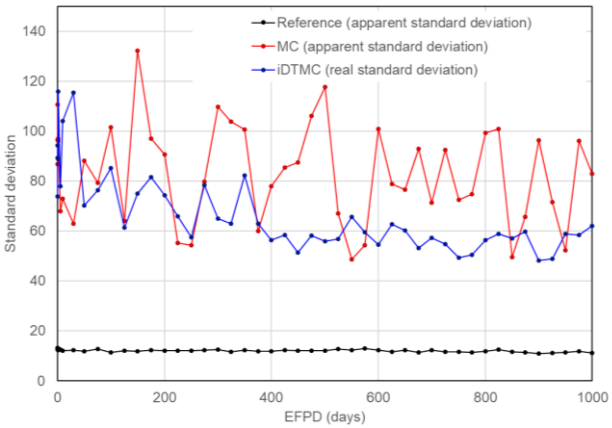

Figure 5. Standard deviation of the multiplication factor

Figure 6 and 7 describe the intra pin power distribution, and Figure 8 and 9 show the relative error distribution of the intra pin power distribution at the first time step (i.e. 0 EFPD) for the standard MC and the iDTMC method, respectively. The intra pin power distribution looks similar each other, but the standard MC method showed smaller relative errors than the iDTMC method compared to the reference solution.

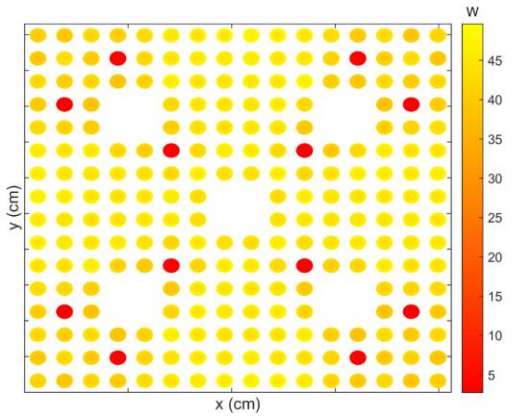

Figure 6. Intra pin power distribution at 0 EFPD (MC)

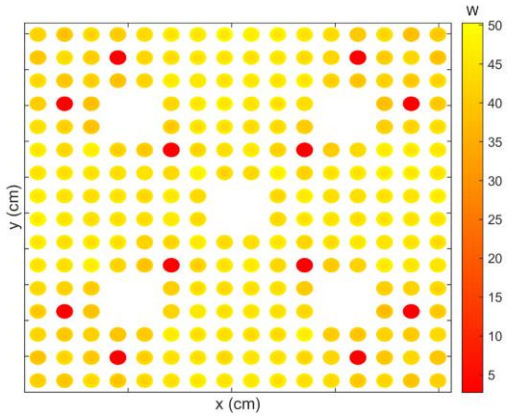

Figure 7. Intra pin power distribution at 0 EFPD (iDTMC)

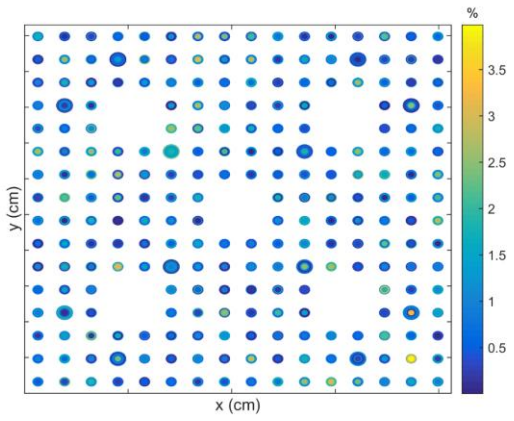

Figure 8. Relative error distribution at 0 EFPD (MC)

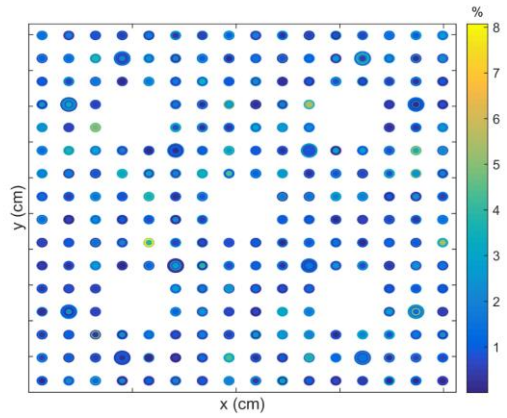

Figure 9. Error distribution at 0 EFPD (iDTMC)

Figure 10 displays the average of relative errors for the intra pin power distribution along with the depletion. Contrary to the criticality, the iDTMC showed larger average relative errors for the intra pin power distribution than that of the standard MC method.

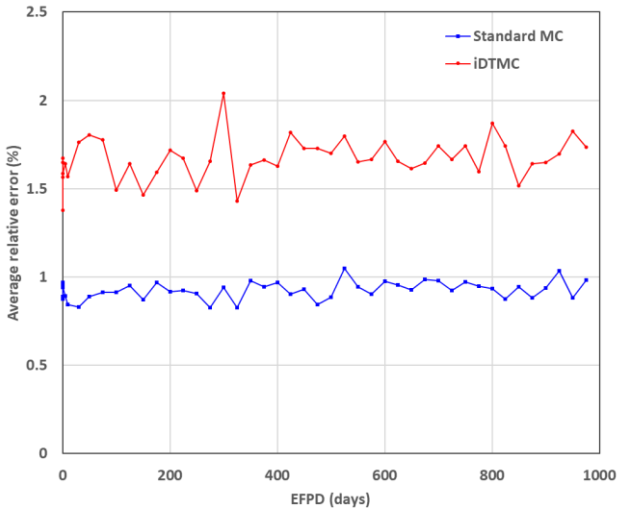

Figure 10. Average relative errors of intra pin power

Table II presents the computing time for the whole depletion calculation. Since the iDTMC method used less number of cycles, the computing time should be proportionally lower in the iDTMC calculation than in the standard MC. Nevertheless, it is verified that the iDTMC method can provide accurate and reliable solutions over the standard MC method with the reduced numerical cost.

Table II. Total computing time

	MC	iDTMC
Time (hr.)	3.3	2.9

4. Conclusions

An improved deterministic truncation of Monte Carlo solution (iDTMC) method has been applied to neutronic depletion calculation in a single fuel assembly of the commercial APR1400. Although the iDTMC method used less number cycles to produce the steady state eigenvalue, the iDTMC method still showed better agreement with the reference solutions for the eigenvalue. It showed lower discrepancy with the reference solution and smaller standard deviations, while took shorter computing time. On the contrary, the iDTMC method showed larger errors in the intra pin power distribution. In the future, the inconsistent outcome between the criticality and power distribution will be examined. Moreover, the real standard deviation of the standard MC results should be evaluated by the multi-batch simulations.

ACKNOWLEDEGEMENT

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