APPLICATION AND ANALYSIS OF THE REVISED ACCURATE WEIGHT METHOD FOR FUSION FACILITIES

Do Hyun Kim, Hyoseong Gwon, and Mu-Young Ahn
Korea Institute of Fusion Energy (KFE), Daejeon, Republic of Korea

Email: dhkim@kfe.re.kr

1. INTRODUCTION

Monte Carlo (MC) methods are widely used for nuclear analysis in fusion-related facilities such as ITER Test Blanket Module (TBM). However, due to the complex geometries of these facilities, it is well known that the computational cost for MC simulations is significantly high. Various variance reduction techniques have been developed to enhance computational efficiency. One of the most widely used approaches in recent years is the hybrid MC method, which utilizes deterministic methods to determine the parameters required for variance reduction, followed by MC simulations for accurate calculations. Among these methods, CADIS [1] and FW-CADIS [2] have been successfully applied. CADIS method is proposed to accelerate calculations for a single tally, such as a detector. In contrast, FW-CADIS is applied to multiple tallies, such as dose maps. These methods are implemented in the ADVANTG [3] code. In previous our study, the Revising Accurate Weight (RAW) [4] method was proposed to refine variance reduction parameters using relative errors (RE) for problems involving multiple tallies. In this study, the RAW method was applied to a fusion experimental facility in the conceptual design phase to identify potential issues.

2. METHOD

In particle transport of MC simulations, interactions such as absorption and scattering can be impeded particles from reaching a distant region of interest. To ensure particle presence in a specific location, the number of particles in that space needs to be increased. This is achieved through variance reduction techniques, which adjust particle weights by either splitting or reducing the particle in the desired region. In the hybrid MC method, a deterministic approach is used to rapidly obtain information about global system and then determine the weight values. The closer the information from the deterministic method matches that of the MC calculation, the more reliable the MC simulation becomes. However, when using the deterministic method, assumptions regarding spatial, angular, and energy discretization, as well as the hybrid MC methodology itself, can lead to regions with increased relative error. In these regions with high relative error, more precise calculations are required to improve accuracy. To achieve this, the RAW method utilizes the following equation:

$$\bar{w}_{RAW}(\vec{r},E) = \bar{w}_{hy}(\vec{r},E) \times Min[RE]^2/RE^2(\vec{r}), \quad (1)$$

where, $Min[RE]$ represents the minimum relative error in the system, and $\bar{w}_{RAW}$ and $\bar{w}_{hy}$ denote the average weights of the RAW method and the hybrid MC method, respectively. In Eq. (1), the squared ratio of RE is used; however, this can lead to excessively low source sampling. Therefore, in this study, the results of using $Min[RE]^2/RE^2(\vec{r})$ and $Min[RE]/RE(\vec{r})$ are compared, along with the results obtained using the FW-CADIS method. The process for applying the RAW method is as follows:

1. Determine the weight values using the hybrid MC method.
2. Perform an MC simulation using MCNP [5] using the determined weight values, ensuring that the mesh size is the same as the one used to obtain the weights.
3. Update the weights by incorporating the obtained relative error into Eq. (1).

3. APPLICATION AND COMPARISON

The model used for application and comparison is the test cell model of the Integrated Breeding Test Facility (IBTF) [6], which is in the pre-conceptual design stage, as shown in Figure 1. At the center, a tritium breeding unit is located, surrounded by concrete structures. Cooling pipes penetrate through the concrete, and on the right side, an accelerator tube is positioned for the incoming deuteron beam. The relative error maps obtained using the RAW method with $Min[RE]^2/RE^2(\vec{r})$ and $Min[RE]/RE(\vec{r})$, as well as the FW-CADIS method, are shown in Figure 2. The high relative error observed inside the white-lined corner regions when using the FW-CADIS method was improved with the application of the RAW method. However, a common increase in error was observed in the region containing the gas pipes. The quantitative results of the calculations are summarized in Table 1. $\mathrm{FOM_{ave}}$ represents the overall efficiency, which improved when using the RAW method compared to the FW-CADIS method. Among the tested approaches, the RAW method with $Min[RE]/RE(\vec{r})$ showed the highest efficiency, achieving a 10.7-fold increase in overall efficiency ($\mathrm{FOM_{ave}}$) and a 4.74-fold improvement in maximum error regions ($\mathrm{FOM_{max}}$) compared to the FW-CADIS method as shown in Table 1. The decrease in efficiency observed with the RAW method using $Min[RE]^2/RE^2(\vec{r})$is expected to be due to the significant influence of low-reliability information from the initial calculation used to evaluate RE. The RAW method with $Min[RE]/RE(\vec{r})$ is expected to improve computational efficiency not only for thick shielding materials but also for penetrations and gaps in complex facilities such as ITER TBM.

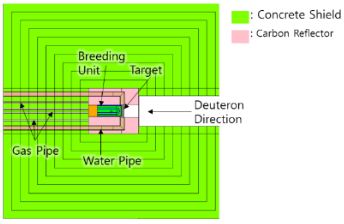
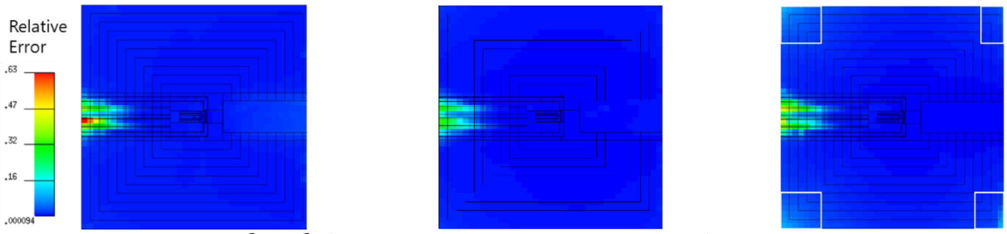


Figure 1. Nuclear analysis model for application and comparison



(a) RAW with $Min[RE]^2/RE^2(\vec{r})$ (b) RAW with $Min[RE]/RE(\vec{r})$ (c) FW-CADIS

Figure 2. Relative error maps with RAW and FW-CADIS methods

Table 1. Results from RAW and FW-CADIS methods

Method	Total MC time [Min]	$\mathrm{FOM_{ave}}$*	$\mathrm{FOM_{max}}$**
RAW with $Min[RE]^2/RE^2(\vec{r})$	32634	0.565	4.48×10^{-5}
RAW with $Min[RE]/RE(\vec{r})$	29992	1.74	3.27×10^{-4}
FW-CADIS	29985	0.163	6.90×10^{-5}

*: average figure of merit (overall efficiency) = $1/(\overline{RE}^2 \times Total\ \ MC\ \ time)$
**: maximum figure of merit (minimum efficiency) = $1/(Max[RE]^2 \times Total\ \ MC\ \ time)$

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