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A Preliminary Study of Monte Carlo Code Development for Pebble Bed Reactor: A New Approach on Judgment of Fission Source Convergence

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1. Introduction

The core of the pebble bed reactor has random and double heterogeneous structure. Due to the geometrical configuration, some specific and difficult techniques are essentially required for Monte Carlo simulation. A development project of a user friendly Monte Carlo code for pebble bed reactor has been being pursued by this research team. The purpose of the project is that the core geometry modeling [1], source option, and tally option are automatically determined and calculated by the code itself. As a part of the project, a decision method of the inactive cycle is proposed in this study.

It is noted that if fission source positions in Monte Carlo calculation are not converged enough, the calculation bias is occurred. Therefore, the inactive cycle is used for the skip of the calculation until the fission source positions are converged. Some methods [2-4] for the decision of the inactive cycle were known, however, the applicability of the methods into the Monte Carlo code is not sufficiently secured. In this study, a new approach for checking the fission source convergence is proposed for the enhancement of the applicability. For the verification, the inactive cycles of pebble bed core problems are estimated by using the proposed method and compared with the result of the Shannon entropy method [2].

2. Methods and Results

2.1 Overview of Fission Source Convergence

In the Monte Carlo eigenvalue calculation, fission source iterations are given as the following equations:

$$S^t(r) = \frac{1}{k^{t-1}} \int_{V_R} H(r' \to r) S^{t-1}(r') d^3 r' \tag{1}$$

$$k^t = \int_{V_R} S^{t-1}(r) d^3 r \Big/ \left\{ \frac{1}{k^{t-1}} \int_{V_R} S^{t-1}(r) d^3 r \right\} \tag{2}$$

where, $S^t(r)$ is neutron source number density at location r of t cycle, $H(r' \to r)$ is number of first-generation fission neutrons per unit volume about r caused by the parent neutron generation at r', V_R is the fissionable fuel region, and k is a multiplication factor. By using the definition of the multiplication factor, the integral of $S^t(r)$ can be normalized by k^t as the following:

$$\frac{1}{k^t} \int_{V_R} S^t(r) d^3 r = 1 \tag{3}$$

In the initial cycle $t = 0$, $S^0(r)$ is defined by user. After the enough iteration of the inactive cycle, $S^t(r)$ is converged into a specific source distribution. $S^t(r)$ is a continue function with variable r; hence, the check of the fission source convergence should be performed at r position. However, Eq. (3) cannot be directly used for the source convergence check because the Monte Carlo calculation has only finite number of particle history. In practice, the region V_R is divided into the sub-regions V_m, and cell-wise fission source density is given as the follows:

$$S_m^t = \int_{V_m} S^t(r) d^3 r \tag{4}$$

where, m is bin number of sub-regions. There are three kinds of the methods to check the source convergence, which are relative entropy method [2], posterior method [3], and anterior method [4]. The criterion and check method are different in each other; however, the cell-wise source density is used in the previous studies. The problem in using Eq. (4) is low applicability into the Monte Carlo code because sub-region m should be properly divided with considering core configuration.

2.2 Checking Method of the Fission Source Convergence

In this study, a check method of the fission source convergence is proposed by using the averages and standard deviations of the source positions. Thus, the process of dividing sub-regions is not required in this method. The source number density $S^t(r)$ is expressed as shown in Equation (5).

$$S^t(\underline{r}) \equiv S^t(x) \cdot \hat{e}_x + S^t(y) \cdot \hat{e}_y + S^t(z) \cdot \hat{e}_z \tag{5}$$

where, $S^t(x)$, $S^t(y)$, and $S^t(z)$ are the source number densities on directions x, y, and z of t cycle. If the source number densities are converged at cycles P, the averages and standard deviations of source positions x, y, z have specific values as shown in Eqs. (6) and (7).

$$\begin{aligned} &E[xS^P(x)/k^P] = \mu_x \\ &E[yS^P(y)/k^P] = \mu_y \\ &E[zS^P(z)/k^P] = \mu_z \end{aligned} \tag{6}$$

$$\begin{aligned} &S[xS^P(x)/k^P] = \sigma_x \\ &S[yS^P(y)/k^P] = \sigma_y \\ &S[zS^P(z)/k^P] = \sigma_z \end{aligned} \tag{7}$$

where, (μ_x, μ_y, μ_z) and $(\sigma_x, \sigma_y, \sigma_z)$ are population averages and standard deviations of fission source positions (x, y, z) at the converged source cycle P. Monte Carlo simulation uses a finite number of fission source, therefore, the average and standard deviation within 95 % confidence interval can be expressed as the following:

$$E[x_i^P] = \mu_x \pm 2\sigma_{\mu x}$$
$$E[y_i^P] = \mu_y \pm 2\sigma_{\mu y}$$
$$E[z_i^P] = \mu_z \pm 2\sigma_{\mu z} \qquad (8)$$

$$S[x_i^P] = \sigma_x \pm 2\sigma_{\sigma x}$$
$$S[y_i^P] = \sigma_y \pm 2\sigma_{\sigma y}$$
$$S[z_i^P] = \sigma_z \pm 2\sigma_{\sigma z} \qquad (9)$$

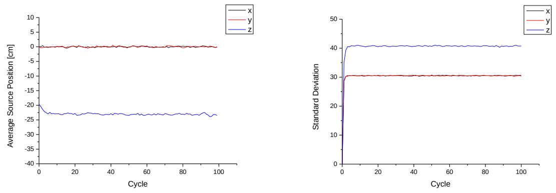
where, (x_i^P, y_i^P, y_i^P) are i'th source positions at cycle P, ($\sigma_{\mu x}$, $\sigma_{\mu x}$, $\sigma_{\mu x}$) are standard deviations of (μ_x, μ_y, μ_z), and ($\sigma_{\sigma x}$, $\sigma_{\sigma y}$, $\sigma_{\sigma z}$) are standard deviations of (σ_x, σ_y, σ_z). It is noted that if the number of samples is over 30, the variance of the samples can be used instead of the population variance. In this study, it is assumed that the population averages and standard deviations given in Eqs. (8) and (9) are replaced to those of 50 samples between P+1 and P+50 cycles. After 51th cycle, the convergence judgment of the source distribution is started with the Eqs. (8) and (9) for every cycles excepting last 50 cycles.

2.3 Results of the Inactive Cycle Calculation

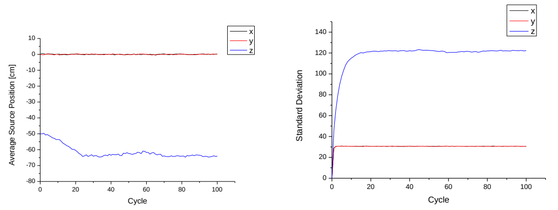
Cores I-III were assumed as shown in Table I. The initial source positions are located at the center of active core. The Monte Carlo simulations were performed by using the method proposed in the previous study [1]. The results of the averages and the standard deviations at each cycle were evaluated as shown in Figure 1.

Table I. Description of the Pebble Bed Core Assumed

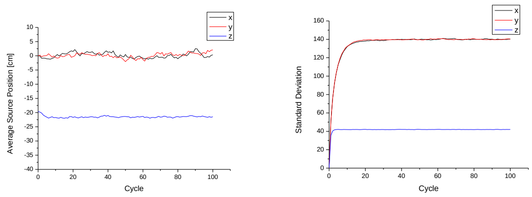
	Core I	Core II	Core III
TRISO and Pebble	HTR-PROTEUS Core 4.2 [5]		
Core Inner Radius	62.5 cm	62.5 cm	300 cm
Core Outer Radius	163.1 cm	163.1 cm	400 cm
Active Core Height	150 cm	500 cm	150 cm
Core Height	189.3 cm	600 cm	189.3 cm
Reactor Height	330.4 cm	800 cm	330.4 cm



(a) Position AVGs of Core I (b) Position STDs of Core I



(c) Position AVGs of Core II (d) Position STDs of Core II



(e) Position AVGs of Core III (f) Position STDs of Core III

Fig. 1. Averages and Standard Deviations of the Source Positions for the Cores I, II, and III

The inactive cycles for the Cores I-III were evaluated by the proposed method. The results were calculated to 5, 20, and 31, respectively. Also, the inactive cycles was estimated with Shannon entropy method [2]. The results were 5, 15, and 26, respectively. The results show that the inactive cycle with the proposed method is conservatively evaluated.

3. Conclusions

As a part of the Monte Carlo code development project for pebble bed reactor, a new approach for the check of the source convergence is proposed. To enhance the Monte Carlo code applicability of the method, the averages and standard deviations of the fission source points were used for the check of the source convergence. The inactive cycles with three cases were evaluated and compared with the results of Shannon entropy method. The results show that the proposed method can properly calculate the inactive cycle. It is expected that the method can directly apply to the Monte Carlo codes with high applicability.

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