A Method Development for Dancoff Factor Calculation Based on Monte Carlo Method

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1. Introduction

The Monte Carlo method is a computational algorithm that is based on the random sampling to simulate the physical phenomenon. All geometries in the mediums should be described for the accurate Monte Carlo particle transport. There are numerous fuel kernels randomly distributed in the pebble bed core. Therefore, it is complicate to model all geometries and takes a long computation time. To avoid these problems, some techniques and assumptions are used for that kind of the Monte Carlo simulation.

In this study, an evaluation method of the Dancoff factor based on the Monte Carlo method was developed and the calculation results were analyzed. The method proposed uses the random sampling of the kernel and pebble. In the calculation of the Monte Carlo transport, only the three surfaces, which are the fuel region, pebble and kernel, are used. Therefore, this method includes the random distributions of the geometries as well as the short computation time. Especially, the wall effect, which affects the kernel geometry modeling in the wall boundary, is reflected in this method.

2. Method

The key ideas of the method proposed are the random sampling of the kernels and pebbles, application of realistic kernel number densities, and random selection of fuel and moderator pebbles. Each method is described in section 2.1, 2.2 and 2.3.

2.1 Random sampling and rejection of kernel and pebble

At first, a center of a source kernel is sampled. The center of the source kernel is randomly chosen in R_f -r_k in the fuel region of the initial source pebble. R_f is the radius of the fuel region and r_k is the kernel radius. Then, a starting point and direction of the neutron for Monte Carlo simulation is sampled. After the initial conditions are decided, the neutron transport calculation is performed.

The sampling of the kernel and pebble are performed by random sense. For the sampling of the kernel or pebble, the cross section of the kernel or pebble is used in this study. An analytical evaluation method by using cross section was developed by Lane et al. in 1962 [1]. The kernel and pebble have spherical shapes; therefore, the microscopic and macroscopic cross sections of the kernel or pebble are given by Equations (1) and (2).

$$\sigma = \pi \cdot r^2 \quad (1)$$

$$\Sigma = \rho \cdot \sigma \quad (2)$$

Where, r is the radius of the kernel or pebble and ρ is the number density of the kernel or pebble. For the application of the wall effect, the rejection of the geometry sampled is performed. The number density, which is explained in section 2.2, is used for the geometry sampling of the kernel. And, the experimental data is used for the calculation of the pebble number density.

Using the macroscopic cross section, the sampling of the geometry is performed with the following steps:

a. A distance sampled by using the macroscopic cross section is decided by Equation (3).

$$d = -\frac{\ln(\varsigma)}{\Sigma} \quad (3)$$

Where, ς is a random number.

b. The location of the kernel or pebble is randomly sampled. The center of the kernel or pebble is on a surface which is at right angle to the neutron path. And, the center sampled must be located within r from an intersection of the neutron path and the surface.

c. If the center of the fuel kernel or pebble is in a region which cannot be located by the wall, the geometry sampled is rejected. Hence, the number density in the wall region is naturally reduced by the wall boundary.

2.2 Number density calculation of fuel kernels

Center region is defined as a region which does not take the wall effect. And, wall region is defined as a region which takes the wall effect. Any points in center region have probabilistically a maximum number density because it does not take the wall effect. A number density at a position in the fuel region is proportional to a volume ratio of Reg_1 to Reg_2. Reg_1 is a region which is non-affected by wall effect in Reg_2, and the Reg_2 is a region which influences the number density at the position. Because of the spherical shape of the kernel, the Reg_2 is spherical with having the kernel radius.

The fuel density at a radial position in the fuel region is given as following:

$$\rho(r) = \rho_m \qquad 0 \le r \le R_f - 2r_k \quad (4\text{-}1)$$

$$\rho(r) = \frac{V_{p,p}(r)}{V_{T,p}}\rho_m \qquad R_f - 2r_k \le r \le R_f \quad (4\text{-}2)$$

Where, $V_{p,p}(r)$ is the volume of Reg_1, $V_{T,p}$ is the volume of Reg_2, and ρ_m is the number density in the

center region. The $V_{p,p}(r)$ is the sum of the two partial volumes as the followings:

$$V_{p,p}(r) = V_{p,R_f}(r) + V_{p,r_f}(r) \quad (5)$$

$$V_{p,Rf}(r) = \int_{p(r)}^{R'} \pi(\sqrt{R'^2 - r'^2})^2 dr' \quad (6)$$

$$V_{p,rk}(r) = \int_{r-p(r)}^{r_k} \pi(\sqrt{r_k^2 - r'^2})^2 dr' \quad (7)$$

$$p(r) = \frac{R'^2 - r_k^2 + r^2}{2r} \quad (8)$$

Where, R' is $(R_f - r_k)$, $p(r)$ is the boundary of two partial regions, and r is an arbitrary position in the fuel region.

The average number density of the center region is a constant because it does not take the wall effect. The average number density of the wall region is given as the followings:

$$\bar{\rho}_w = \frac{\int_{R_f - 2r_k}^{R_f} \rho(r) \cdot 4\pi r^2 dr}{V_w} \quad (9)$$

Where, $\bar{\rho}_w$ is the average number density of the wall region, and V_w is the volume of the wall region.

In this study, the average number density of the center region is used for the sampling of the fuel kernels. The average number density of fuel kernels is given in equation (10). Using the equation (7), the number density of the center region is given in Equation (11).

$$\bar{\rho}_a = \frac{n}{V_F} = \frac{\bar{\rho}_c V_c + \bar{\rho}_w V_w}{V_F} \quad (10)$$

$$\bar{\rho}_c = \frac{\bar{\rho}_a V_F - \bar{\rho}_w V_w}{V_c} \quad (11)$$

Where, $\bar{\rho}_a$ is the average number density of fuel kernels, n is the number of fuel kernels in a fuel region, V_F is the volume of the fuel region, $\bar{\rho}_c$ is the average number density of the center region, and V_c is the volume of the center region.

2.3 Random selection of the pebble kinds

The specific pebble proposed in this study is used for the average inter-pebble Dancoff factor calculation when the fuel and moderator pebbles are randomly mixed in the pebble-bed core. The specific pebble is that it can be fuel or moderator pebbles. When a neutron enters into the specific pebble, the random selection procedure is performed. The detail of the specific pebble is explained in reference [2].

3. Results

By using the method proposed in this study, the Dancoff factor was evaluated. The calculations were pursued with the MATLAB program. The radius of the fuel region is 2.5cm and the fuel kernel diameter is 0.05cm. The macroscopic cross section of the graphite is 0.4097/cm [1] for the 0.661keV neutron. F/M pebble ratio is 1:1. The neutron history is 10^8 for the relative standard deviation <<1%.

In the case of the 15,000 fuel kernels, the average Dancoff factor reaches 0.3940. In the case of the 30,000 fuel kernels, the average Dancoff factor reaches 0.5680. The results of the intra-pebble Dancoff factors agree well within 1% with the result of the previous study [3], which used the random sampling of the all kernel positions.

4. Conclusions

In this study, an evaluation method based on the Monte Carlo simulation was proposed to evaluate the Dancoff factor. The results of the intra-pebble Dancoff factors agree well within 1% with the result of the other study [3]. The method proposed in this study can be easily utilized to calculate the Dancoff factor for the various geometries because the simple modeling of the pebbles and kernels is possible as well as good accuracy. This method can use for the investigation of the wall effect in specific cases because the realistic distribution of the number density is applied. Also, this method can be applied to the inter-pebble Dancoff factor for the various mixture ratios of the fuel and moderator pebbles by using the specific pebble. Hence, this is helpful to analyze the resonance absorption effect when the various pebble-bed reactors are designed.

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