Optimum Detector Position Search for Pulsed-Neutron-Source Alpha Measurement Using Time-dependent Monte Carlo Simulation at AGN-201K

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1. Introduction

The prompt neutron decay constant, alpha, is one of the essential neutronics parameters that can be measured directly from the experiments utilizing the pulsed-neutron-source (PNS) method, the noise method, or the exponential method. The PNS method is a simple but effective method for measuring alpha because one can estimate it from the exponential time-decaying neutron behavior independent of position and energy characteristic of detector and neutron source. However, it has been reported [1-2] that the convergence to its fundamental mode depends largely on the detector and source position due to the remaining higher mode effects.

There have been studies to reduce the higher mode effect and measure the proper fundamental mode alpha. Taninaka [3] proposed a masking technique that temporally excludes the initial higher mode parts of the PNS histogram in the exponential fitting method. Katano [4] suggested an estimation method to reduce higher mode by a linear combination of multiple detector responses. Although these methods give clever ways for removing higher mode effects, it is still difficult to determine when and where to get high-fidelity detector signals adequate to estimate proper alpha. For this purpose, Jang [5] devised a practical method to determine optimum detector position for PNS alpha measurement using time-dependent Monte Carlo(TDMC) simulation and applied it to the Pb-Bi-zoned ADS experimental benchmark at KUCA.

The purpose of this study is to extend the applicability of the time-dependent Monte Carlo simulation to search an optimum detector position for PNS alpha measurement. The AGN-201K, a research and educational reactor currently conducting subcriticality measurements at Kyung Hee University, is selected for the application. To check the spatial effect of source on alpha measurement, the optimum detector position is searched varying the initial source location.

2. Optimum detector position search using TDMC simulation

2.1. TDMC simulation of PNS alpha measurement

For a sustainable simulation of pulsed-neutron-source alpha measurement, the time-dependent Monte Carlo method is required due to the initial burst and exponential decrease of the neutron population, especially when the system is far from the critical state. In TDMC simulation, the neutron population is controlled by the combing method or Russian roulette/splitting at the end of each time step. The neutron time is updated with the sampled track length until it crosses the next time boundary as

$$t_k^{i,j} = t_{k-1}^{i,j} + \frac{l_k^{i,j}}{\sqrt{2E_k^{i,j}/m_n}} \qquad (1)$$

where i, j and k are time bin, history, and track index respectively. E and m_n denote energy and neutron mass. When a neutron track is sampled greater than the upper time boundary of i-th time bin (T_{i+1}), the neutron is stopped at T_{i+1} and stored as a survival neutron. After all neutrons are simulated, the survival neutrons are uniformly discarded or split to maintain the number of neutrons while preserving the total weights. In McCARD, an analog MC branch scheme with the combing method is used for TDMC simulation.

Through the TDMC simulation with population control, one can track the asymptotic behavior of the prompt neutrons after they are injected as pulsed neutron sources. Then alpha corresponds to arbitrary detector position can be measured by the exponential fitting method using time-dependent detector responses. The time-dependent detector response at i-th time bin is expressed as

$$R_D(\mathbf{r}, \bar{t}_i) = \sum_m \sum_r \int_{V_D} \int_E \int_{\bar{t}_i - \Delta t/2}^{\bar{t}_i + \Delta t/2} \Sigma_r^m(\mathbf{r}, E)\phi_p(\mathbf{r}, E, t)\, d\mathbf{r}\, dE\, dt \qquad (2)$$

where m and r denote the isotope and reaction type. $\bar{t}_i$ and Δt are the center time of i-th time bin and the time interval. Since the estimate of alpha changes according to data points used for exponential fitting, it can be defined with respect to the start time of fitting t_s as below.

$$R_D(\mathbf{r}, t) = C_1 \cdot \exp\left[-\tilde{\alpha}_0(\mathbf{r} \mid t_s) \cdot (t - t_s)\right] + C_2 \qquad (3)$$

In the above equation, $\tilde{\alpha}_0(\mathbf{r} \mid t_s)$ is the estimate of alpha at position $\mathbf{r}$ with the detector responses within a fixed time interval from t_s. C_1 and C_2 are the fitting constants.

2.2. Determination of an optimum detector position

An optimum detector position for PNS alpha measurement should satisfy the relatively high count rate after neutron behavior at the position converges to its fundamental mode. Since the detector counting process follows the Poisson distribution, the high count rate means high reliability. The convergence of alpha estimate can be determined by comparing its relative error for the reference with the prescribed convergence criterion. The onset time of convergence is determined as

$$t_0(\mathbf{r}) = \min\left\{ t_s ; \left| \frac{\bar{\alpha}_0(\mathbf{r}\,|\,t_s) - \alpha_{\text{ref}}}{\alpha_{\text{ref}}} \right| < \varepsilon \right\} \tag{4}$$

$$\bar{\alpha}_0(\mathbf{r}\,|\,t_s) = \frac{1}{N}\sum_{n=1}^{N} \tilde{\alpha}_{0,n}(\mathbf{r}\,|\,t_s) \tag{5}$$

where $\bar{\alpha}_0(\mathbf{r}\,|\,t_s)$ is the mean of alpha estimates from replica calculations and N is the number of replica calculation. α_{ref} is the reference fundamental alpha and it is calculated by MC α-iteration method which solves the alpha mode eigenvalue equation with the MC power method. ε is the prescribed convergence criterion.

When the onset time of convergence is determined, the amplitude of detector response or count rate is calculated for the fitting time interval, ΔT , as follows.

$$\bar{R}_D(\mathbf{r}) = \sum_m \sum_r \int_{V_D} \int_E \int_{t_0(\mathbf{r})}^{t_0(\mathbf{r})+\Delta T} \Sigma_r^m(\mathbf{r},E)\phi_p(\mathbf{r},E,t)\,d\mathbf{r}\,dE\,dt \tag{6}$$

By comparing the relative amplitude of detector response at each position, an optimum detector position for PNS alpha measurement can be obtained.

3. Application results

3.1. AGN-201K model

The proposed method is applied to the AGN-201K reactor to determine the optimum detector position for PNS alpha measurement. AGN-201K consists of 9 fuel disks, which are homogenized with 19.5 w/o UO_2 and polyethylene moderator. The 9 stacked fuel disks are surrounded by graphite reflector and lead shielding in a water tank. The reactor has 2 safety rods and 1 coarse rod and 1 fine rod as control rods. All rods are comprised of fuel material and inserted axially from the bottom of the core. In addition, there is a glory hole that penetrates the center of the core and 4 beam ports in a graphite reflector region. Figure 1 and 2 shows the configuration of AGN-201K McCARD model. For geometry information and material composition, [6] and [7] are referred.

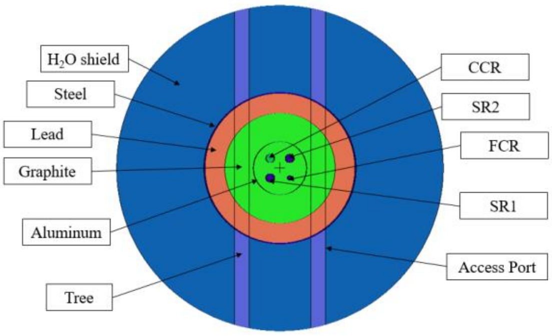

Figure 1. Cross-sectional View of AGN-201K

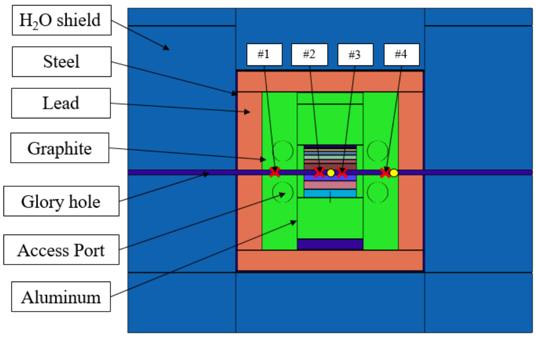

Figure 2. Vertical View of AGN-201K

3.2. Searching optimum detector positions

The PNS alpha measurement experiment is postulated in the deepest subcritical core configuration, where all control rods and safety rods are fully ejected from the core. The effective multiplication factor calculated at all rods out condition was 0.97906±0.00009 with ENDF/B-VII.1 cross section libraries. Since there is no accelerator driven system to make intense pulsed neutron sources in the facility, a Cf-252 source is assumed to be inserted as a pulsed neutron source for numerical experiments. The numerical PNS experiment is conducted for two cases varying the initial Cf-252 source location. The initial source positions are set to be the center and 30cm away from the center in the glory hole respectively, which are marked as yellow points in figure 2.

McCARD TDMC simulations are conducted with 1,000,000 neutron histories until 5 ms with 0.1 ms time interval. The mean of alpha estimates at each detector position are estimated with 10 replica calculations. The convergence criterion is set to 2%. The reference alpha is calculated by MC α-iteration method with 10,000 neutron histories and 3000 active iterations. ENDF/B-VII.1 cross section libraries are used for all cases.

Figure 3 shows the convergence trends of $\bar{\alpha}_0(\mathbf{r}\,|\,t_s)$ at several candidate detector positions with the initial source located at 30cm away from the center in the glory hole. The candidate detector positions are marked as red cross in figure 2. The reference alpha value is estimated to be 333±10 from the MC α-iteration method. The result shows all estimated alpha values converge to the reference value with different trends. The detector position #4 which is the nearest position to the initial source shows slower convergence than the others due to its remaining higher mode effect, whereas the detector position #2 gives the fastest convergence among the candidates. Figure 4 shows the corresponding trends of detector signals in different positions.

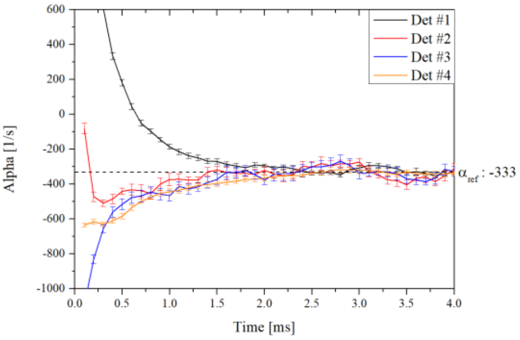

Figure 3. Convergence Trends of $\bar{\alpha}_0(\mathbf{r}\,|\,t_s)$

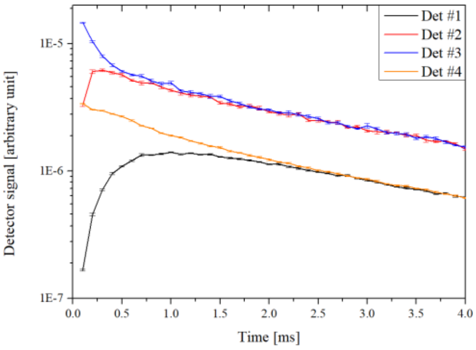

Figure 4. Trends of Detector Signals

Figure 5 and 6 show the maps of the convergence time and amplitude of detector response with the initial source located at the center and 30cm from the center in glory hole respectively. When the initial source is located in the center, it shows symmetric results that the regions near the center of the core converge faster and give higher detector signals than other regions. On the other hand, when the initial source is moved to 30cm right from the center, the results show somewhat skewed maps that the right parts of the core converge slower and give lower detector signals than other symmetric locations due to the initial source effect.

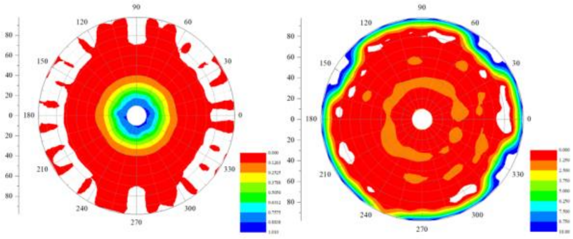

Figure 5. Amplitude of detector signal (left) and convergence time (right) maps with source at center

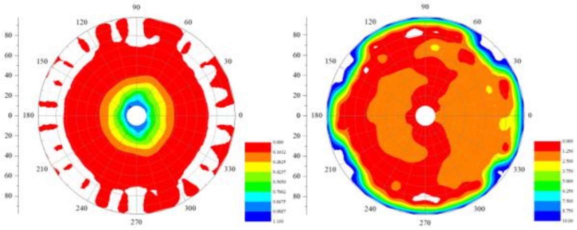

Figure 6. Amplitude of detector signal (left) and convergence time (right) maps with source at 30cm

4. Conclusion

For extending applicability of the time-dependent Monte Carlo simulation to subcritical reactor experiments, the optimum detector positions for PNS alpha measurement are searched by the numerical simulation on AGN-201K reactor. Though the intense pulsed neutron source is assumed to be a Cf-252 source in the simulation, the trend or the relative amplitude of detector responses for measuring alpha can give insights and information for selecting better detector positions. In addition, the effect of initial source position on PNS alpha measurement is examined.

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