Measurement of keff with an improved neutron source multiplication method based on numerical analysis Postprint

Authors: YE Bin, ZENG Li-Na, YIN Yan-Peng, YANG Chao-Wen, ZHENG Chun

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Abstract

In this work, we developed a numerical analysis-associated experiment method to determine the effective multiplication factor keff, which is difficult to obtain directly from conventional neutron source multiplication (NSM) method. The method is based on the relationship between keff, subcritical multiplication factor ks and external neutron source efficiency Φ∗ in the subcritical system. On basis of the theoretical analysis, the dependence of ks and Φ∗ on subcriticality and source position was investigated at the Chinese Fast Burst Reactor-II (CFBR-II). A series of ks were measured by NSM experiments at four subcritical states (keff = 0.996; 0.994; 0.991; 0.986) with the 252Cf neutron source located at different positions (from the system center to outside) at each subcritical states. The Φ∗ was obtained by Monte-Carlo simulation for each condition. With the measured ks and calculated Φ∗, keff of the subcritical system was evaluated with a relative difference of <1% between values obtained by the improved method and by positive period method. Especially, the relative difference of <0.18% with the source located at the system center.

Full Text

Preamble

Measurement of keff with an improved neutron source multiplication method based on numerical analysis

YE Bin, ZENG Li-Na, YIN Yan-Peng, YANG Chao-Wen, and ZHENG Chun

Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, Mianyang 621900, China

College of Physical Science and Technology, Sichuan University, Chengdu 610064, China

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In this work, we developed a numerical analysis-associated experiment method to determine the effective multiplication factor keff, which is difficult to obtain directly from conventional neutron source multiplication (NSM) methods. The method is based on the relationship between keff, subcritical multiplication factor ks, and external neutron source efficiency $\Phi*$ in subcritical systems. Through theoretical analysis, we investigated the dependence of ks and $\Phi*$ on subcriticality and source position at the Chinese Fast Burst Reactor-II (CFBR-II).

A series of ks measurements were performed via NSM experiments at four subcritical states (keff = 0.996, 0.994, 0.991, and 0.986) with the 252Cf neutron source located at different positions (from the system center to outside) for each state. The $\Phi*$ values were obtained by Monte-Carlo simulation for each condition. Using the measured ks and calculated $\Phi*$, keff of the subcritical system was evaluated with a relative difference of $< 1\%$ between values obtained by the improved method and by the positive period method. Notably, the relative difference was $< 0.18\%$ when the source was located at the system center.

Keywords: keff, Neutron source multiplication, Monte-Carlo; Fast critical system

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Introduction

Neutron source multiplication (NSM) method, a simple measurement technique that uses an external neutron source and an ordinary neutron detector, is suitable for real-time measurement. With the recent development of accelerator-driven systems (ADS) [1], increasing attention has been paid to NSM experiments associated with various subcritical systems [2, 3]. Such experiments can acquire subcritical multiplication factor ks and external neutron source efficiency $\Phi*$, which can be used to design ADS systems and analyze their neutron multiplication characteristics [4, 5]. The subcritical multiplication factor ks is related to the neutron multiplication M [6] by ks = $1 - 1/M$, but in practice one needs to know the effective multiplication factor keff.

In this paper, to overcome the difficulties of obtaining keff directly from conventional neutron source multiplication methods, we propose a numerically associated experiment method. In Sec. II, the NSM method and the relationship between effective multiplication factor keff, subcritical multiplication factor ks, and neutron source efficiency $\Phi*$ are reviewed briefly. The experimental apparatus is described in Sec. III. In Sec. IV, to verify the proposed NSM method, numerical analysis and a series of NSM experiments were carried out at the Chinese Fast Burst Reactor-II (CFBR-II) at various subcritical states with a 252Cf neutron source located at different positions in each subcritical state (from the center of the system to outside).

II. Theoretical Basis

For critical systems composed of fissile materials and other materials, the neutron balance equation in fundamental mode is expressed as:

$$L\phi_0(r,E) = P\phi_0(r,E)$$

where $\phi_0(r,E)$ is the neutron flux distribution at position $r(x,y,z)$ at energy E, L is the destruction operator, and P is the production operator. By taking the inner product $< ... >$ of Eq. (1), which indicates integration over space and energy variables, keff can be expressed as:

$$k_{eff} = \frac{< P\phi_0(r,E) >}{< L\phi_0(r,E) >}$$

For subcritical systems with an external source at steady state, the neutron balance equation is:

$$L\phi_s(r,E) = P\phi_s(r,E) + s(r,E)$$

Similarly, the subcritical multiplication factor ks can be expressed as:

$$k_s = \frac{< P\phi_s(r,E) >}{< L\phi_s(r,E) >}$$

where $\phi_s(r,E)$ is the neutron flux in the subcritical system with the external neutron source $s(r,E)$.

The external source efficiency, Φ^*, is the ratio of average importance between the source neutron and fission neutron. The Φ^* implies that a neutron emitted from the source, with a certain position and energy distribution, will produce certain "important" neutrons that can lead to higher or lower neutron multiplication for a given fissile system.

Deduced from properties of the operator and Eqs. (1)-(4), we have Eq. (5):

$$\frac{k_s - 1}{k_{eff} - 1} = \Phi^* \Rightarrow k_{eff} = k_s - \Phi^*(k_s - 1)$$

Thus, the multiplication factors ks and keff can be theoretically correlated with the neutron source efficiency Φ^*.

Obtaining keff of the system through Eq. (5) requires knowledge of ks and Φ^*. As mentioned above, ks can be measured by neutron multiplication experiments, but the neutron source efficiency Φ^* cannot be obtained from experiments directly. In the following sections, we acquired Φ^* from numerical analysis and successfully evaluated keff.

III. Experiment Apparatus Review

Experiments were carried out at the Chinese Fast Burst Reactor-II (CFBR-II) [7], an ellipsoidal assembly consisting of, from inside to outside, enriched-uranium spherical shells, inner brass reflector, depleted uranium reflector, and outer brass reflector. The reactor can be divided into upper, middle, and lower parts [Figure 1: see original paper]. The middle part is a 5.2 cm thick stainless steel plate with three horizontal holes for three control rods to pass through: an auto-adjustment rod, a composition rod, and a pulse rod.

The three rods are made of cast enriched uranium. A 10 cm × 4.2 cm × 14.5 cm (w × h × d) irradiation chamber and two horizontal experimental holes are located in the plate. The neutron source can be placed at any position in the horizontal holes by a neutron source transmission device. Reactivity of the assembly can be controlled by adjusting the insertion depth of the three control rods. The assembly can operate at subcritical, delayed critical, or super-prompt critical states.

A 252Cf spontaneous fission neutron source (with activity of 1.41 × 10ˆ5 sˆ−1) sealed in an aluminum box of Φ7.8 mm × 11 mm can be sent into a horizontal hole of the stainless steel plate by the transmission device when the system is in a deep subcritical state. The control rods are then inserted to different depths to operate the reactor at different subcritical power states.

Two BF3 proportional counters of the SZJ-1 type, produced by Beijing Nuclear Instrument Factory, are used to record neutrons (which is proportional to the neutron density in the system). They consist of a paraffin barrel (Hanson long counter), preamplifier, HV power supply, main amplifier, and multi-scalar. The detectors are positioned 180 cm away from the system center.

IV. Numerical Analysis and Experiments

A. Numerical Calculations

Before carrying out experiments, the Monte-Carlo numerical method [8] was used to build a subcritical system model identical to CFBR-II [Figure 1: see original paper]. Four subcritical states with keff = 0.996, 0.994, 0.991, and 0.986 were selected as conditions for our multiplication experiments. The source positions were varied along the r-axis at each subcritical state (i.e., 0 mm, 20 mm, 40 mm, 60 mm, 80 mm, 100 mm, 120 mm, and 150 mm). The spontaneous 252Cf neutron source, described by the Watt fission spectrum [9], was positioned the same way as in the planned experiments.

The ks values for all experimental conditions were calculated by MCNP5 with statistical uncertainty $< 0.7\%$. The neutron source efficiency Φ^* is closely connected with neutron importance, which is proportional to the detector response to a unit source. In other words, neutron importance measures the "importance" of a neutron in contributing to the detector response, or the expected counts per neutron at a certain position, direction, and energy. Using MCNP code, the detector counting rates for the system with the 252Cf neutron source in the core could be obtained, and the counting rate for the eigen neutron source distributed in the system could also be recorded. The ratio of these two counting rates gives the external neutron source-related average efficiency Φ^* [10, 11].

For eigen-distribution neutron source acquisition, we used the KCODE and SSW cards in MCNP5 critical calculation to achieve this goal. Thus, we tallied Φ^* in MCNP5 calculation following specific regulations according to MCNP rules.

By calculating ks, Φ^*, and keff inside and outside the neutron source, we were able to investigate the effect of system subcriticality and source position.

For the subcritical state (keff = 0.994), the effect of source positions along the r-axis is demonstrated by the calculation results in [Figure 2: see original paper]. The source efficiency Φ^* and subcritical multiplication factor ks at different source positions indicate that the smallest discrepancy between ks and keff is achieved when the source is at the center of the core.

shows the subcriticality effect on ks and Φ^* at keff = 0.996, 0.994, 0.991, and 0.986. For the four subcritical states, when the source is at the core center, ks is very close to keff, with a relative difference $< 0.8\%$, and Φ^* was greater than 0.91. The results indicate that as the system approaches the critical state, the relative values of ϕ_s and ϕ_0 become more equal, as do the values of ks and keff. Conversely, placing the source outside the core makes the discrepancy between ks and keff much larger, with the maximum relative difference being 22.1340% at keff = 0.986 and the source positioned 150 mm away from the core center.

To check the source position effects on neutron leakage rate, we performed additional numerical analysis to investigate the detector response to non-collided neutrons emitted from the source and to total neutrons. The results in [Figure 3: see original paper] show that the relative difference is below 0.25%. Placing the neutron source closer to the system edge increases the counting rate for non-collided neutrons from the source while decreasing the total neutron counts. In other words, the detector counting rate decreases for eigen-distribution neutrons (fission neutrons inside the system). This explains why the discrepancy between ks and keff becomes large when moving the 252Cf neutron source away from the system center.

B. Experimental Results and Discussion

Based on the numerical investigation in Sec. IV.A, NSM experiments were carried out at CFBR-II to measure ks and evaluate Φ^*. The subcritical states were experimentally achieved by adjusting the insertion depth of the control rods. All experimental apparatus and conditions were completely identical to the numerical ones. The results are shown in [Figure 4: see original paper]. The ks values decreased with increasing distance of the source from the core center and with deepening subcriticality, which is identical to the calculation results in [Figure 2: see original paper].

To test the feasibility of this improved NSM method, we considered four subcritical states (keff = 0.996, 0.994, 0.991, and 0.986) and eight neutron source positions for each subcritical state. Using the calculated source efficiency Φ^* and measured ks, we obtained the effective multiplication factor keff according to Eq. (5) for 32 studied conditions. For comparison, we used the positive period method to measure reactivity as the reference method. Specifically, we measured reactivity in super-criticality and extrapolated to subcriticality using a calibrated reactivity curve of the control rods.

As shown in , comparison between the reference method and our results at the four subcritical conditions with the source located at the core center revealed fairly good agreement with a maximum relative difference of 0.18%. For a certain subcriticality (keff = 0.991), the discrepancy between keff measured by the positive period method and the evaluated values in this work is the smallest of all. When keff $>$ 0.9910, the evaluated keff values are slightly larger than experimentally measured ones. However, at very deep subcriticality (e.g., keff = 0.9860), the evaluated keff is slightly less than the measured value because source neutrons cannot propagate efficiently in deep subcriticality. These results demonstrate the good precision of this improved method and validate the Monte-Carlo calculation model.

In general, keff of the system for all studied cases was well approximated, as shown in [Figure 5: see original paper].

Results

The comparison between keff from references (positive period method, marked as keff-exp) and our method (keff-eva) is given by $\Delta(\epsilon) = [(k_{eff-eva} - k_{eff-exp})/k_{eff-exp}] \times 100\%$. As shown in [Figure 6: see original paper], the spatial effect on keff can be seen across a large range of neutron positions. Generally, when the neutron source is inside the subcritical system, the relative difference is small compared to when the source is outside the system, and the relative difference increases rapidly with distance of the neutron source from the system center, becoming irregularly large at distances $>$ 85 cm. This occurs because the brass and depleted uranium reflectors are located at these positions, causing uncertainty related to complicated neutron behavior.

Therefore, to reduce the relative difference in experimental implementations, the neutron source should be placed inside the subcritical system.

V. Conclusion

A methodology to evaluate the effective multiplication factor keff from measured ks and numerically analyzed Φ^* was investigated via NSM experiments on CFBR-II. The evaluated results were approximately equal to those from the reference method (positive period method).

Based on theoretical and numerical preparations, ks was measured through a series of NSM experiments with a 252Cf spontaneous fission neutron source located at different positions in four subcritical states of CFBR-II. The effective neutron multiplication factor keff obtained in all subcritical states when the neutron source was located inside the subcritical system showed a relative difference $< 0.2\%$ between values obtained by the improved NSM method and the positive period method. Therefore, to reduce relative differences in experimental implementations, the neutron source should be placed inside the system. The numerical analysis-associated NSM method we proposed is feasible for simple subcritical apparatus such as CFBR-II.

[Figure 6: see original paper] Relative difference at four subcritical states between calculated and measured values.

References

[1] Chen G H, Chen J F, Wan T M. Nucl Sci Tech, 2012, 23: 267–

[2] Tsuji M, Suzuki N, Shimazu Y, et al. J Nucl Sci Technol, 2003, 40: 158–169.

[3] Pyeon C H, Morgan H, Tsuyoshi M, et al. J Nucl Sci Technol, 2008, 45: 1171–1182.

[4] Endo T, Yamamoto A, Yamane Y. Ann Nucl Energy, 2011, 38: 237–264.

[5] Shahbunder H, Pyeon C H, Misawa T, et al. Ann Nucl Energy, 2010, 37: 1214–1222.

[6] Shi Y Q, Zhu Q F, Xia P, et al. J Nucl Sci Eng, 2005, 149: 122–177. (in Chinese)

[7] Yang C D, Gong S L, Den M C. Tren Nucl Phys, 1995, 4: 58–

[8] Los Alamos National Laboratory, MCNP-A General Monte Carlo N-Particle Transport Code, Version 5. LA-UR-03-1987,

[9] Gregory D S, Robert D B, Takeshi S, et al. A Nucl Energ, 1999,

[10] Feng P, Liu S, Wei B J, et al. Nucl Sci Tech, 2011, 22: 379–

[11] Bell G I and Glasstone S. Nuclear Reactor Theory. New York: Litton Educational Publishing, 1970: 257–258.

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