Application Research of Dynamic Control Rod Worth Measurement Method in Tianwan VVER

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Abstract

Accurate measurement of control rod worth in physics experiments is of great significance for the safe operation of reactors. Research has been conducted on multi-group space-time kinetics calculation methods based on hexagonal geometry. Based on this, research on an advanced dynamic rod worth measurement method suitable for hexagonal geometry has been carried out. This method features a wide range of application, high measurement accuracy, and a fast measurement process. The method was validated using dynamic rod worth measurement test data from the Tianwan VVER reactor. The results show that the control rod worth measured by this method deviates from the theoretical value by less than 10%, indicating high computational accuracy. Additionally, the method features short computation times and high computational efficiency.

Full Text

Preamble

Title: Research on the Application of Dynamic Rod Worth Measurement Method to Tianwan VVER Reactors

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Abstract

Accurate measurement of control rod worth in physical startup tests is of paramount importance for the safe operation of nuclear reactors. This study develops a multi-group space-time neutron kinetics calculation methodology based on hexagonal geometry and proposes an advanced dynamic rod worth measurement method suitable for hexagonal cores. This method offers broad applicability, high measurement accuracy, and rapid measurement capabilities. Validation was performed using dynamic rod worth test data from the Tianwan VVER reactor. The results demonstrate that the deviation between the measured control rod worth and theoretical values remains within 10%, indicating high computational accuracy. Furthermore, the method exhibits short computation times and high computational efficiency.

Keywords: dynamic rod worth measurement; control rod worth; hexagonal geometry; space-time neutron kinetics

Introduction

Control rod worth measurement constitutes a critical component of physical startup tests for nuclear power plants and research reactors, providing essential validation of core performance against design predictions. The dynamic rod worth measurement method [1-3], pioneered by Dr. Rongan Zhao of Westinghouse, represents a rapid approach for control rod worth evaluation. Its primary advantage lies in reducing overhaul cycles by approximately 15 hours per outage while maintaining safety standards. This method has gained widespread adoption in China, the United States, and France. However, current research on dynamic rod worth measurement has primarily focused on square-lattice cores, with limited application to hexagonal-lattice cores.

This study employs the self-developed HEXNK program [4] to simulate the test process, calculating both static spatial factors (SSF) and dynamic spatial factors (DSF), and completes dynamic rod worth measurement tests on the Tianwan VVER reactor.

1. Principle of Dynamic Rod Worth Measurement

The complete computational workflow for dynamic rod worth measurement comprises three sequential steps: static spatial factor correction, transient simulation of rod insertion, and point-reactor inverse kinetics. Static spatial factors account for the influence of control rod position on assembly power distribution and ex-core detector response. The transient simulation of rod insertion determines the variation in detector current during the withdrawal process. Point-reactor inverse kinetics solves for the reactivity introduced during control rod insertion, termed dynamic reactivity, which differs from static reactivity because the transient power distribution does not coincide with the static power distribution even at identical rod positions. During actual experiments, dynamic reactivity can be derived from measured current data. The critical aspect of the dynamic rod worth method lies in accurately simulating the transient rod insertion process to obtain precise power variations in each node.

1.1 Static Spatial Factor Correction

The relationship between detector current signals and the three-dimensional core power distribution is established through Equation (1):

$$R = C \times \sum_k W_k P_k V_k$$

where R represents the detector signal, n denotes core power, P_k is the normalized power density of node k, W_k is the detector response factor, V_k is the node volume, C is a constant, and the subscript k indicates the node index.

To account for power distribution differences at various rod positions, the static spatial correction factor (SSF) is defined as:

$$\mathrm{SSF} = \frac{\sum_k W_k P_k V_k}{\sum_k W_k P_k^{\mathrm{ARO}} V_k}$$

where ARO denotes the all-rods-out condition.

To calculate static spatial factors, the detector response factors must first be determined, typically using MCNP or deterministic shielding software. Subsequently, the power distribution at different rod positions is computed using the program, and the static spatial correction factor is obtained through Equation (2). Note that the static response factor is a function of rod group and position.

1.2 Dynamic Spatial Correction Factor

The dynamic spatial correction factor is defined as the ratio of reactivity obtained from inverse dynamics calculations to static reactivity, as expressed in Equation (3):

$$\mathrm{DSF} = \frac{\rho_{\mathrm{dyn}}}{\rho_{\mathrm{static}}}$$

where ρ_{static} represents static reactivity and ρ_{dyn} represents dynamic reactivity. The dynamic spatial correction factor highlights the distinction between static and dynamic reactivity.

2. Hexagonal Node Flux Expansion Methodology

2.1 Hexagonal Node Flux Expansion

The neutron fixed-source problem based on the diffusion equation can be expressed as:

$$\nabla \cdot D(\mathbf{r},t)\nabla\phi(\mathbf{r},t) - \Sigma_a(\mathbf{r},t)\phi(\mathbf{r},t) + \frac{1}{k_{\text{eff}}}\chi(\mathbf{r},t)\nu\Sigma_f(\mathbf{r},t)\phi(\mathbf{r},t) = S(\mathbf{r},t)$$

Each node is hexagonal in the radial direction, with uniform material properties assumed within a single node. The node is first transformed through linear mapping into a reference node with a face-to-face distance of 2 cm and a height of 2 cm, as illustrated in [Figure 1: see original paper]. The mapping is represented by Equation (5):

$$\xi = \frac{x}{H}, \quad \eta = \frac{y}{H}, \quad \zeta = \frac{z}{h_z}$$

where H and h_z are the face-to-face distance and axial height of the original node, respectively.

The original fixed-source problem (4) transforms to:

$$\nabla \cdot D(\xi,t)\nabla\phi(\xi,t) - \Sigma_a(\xi,t)\phi(\xi,t) + \frac{1}{k_{\text{eff}}}\chi(\xi,t)\nu\Sigma_f(\xi,t)\phi(\xi,t) = S(\xi,t)$$

The neutron flux for each energy group is decomposed into two components: a homogeneous term and a particular term. The homogeneous term ϕ_h satisfies the homogeneous form of Equation (6) (with zero source term) and adopts solutions in the form of hyperbolic cosine and hyperbolic sine functions. The particular term ϕ_p is expanded using second-order orthogonal polynomials to satisfy Equation (6) with source terms in a weighted sense. Since the flux expression form is similar for each energy group, the energy group subscript is omitted in the following formulas for simplicity unless otherwise specified. Thus, the neutron flux is expressed as the sum of homogeneous and particular terms, as shown in Equation (7):

$$\phi(\xi,t) = \sum_{k=1}^{N}\left[a_k\cosh(B_k u) + b_k\sinh(B_k u)\right] + \sum_{i=1}^{M} d_i w_i(\xi)$$

where a_k, b_k, and d_i are expansion coefficients to be determined, N is the number of homogeneous terms, and w_i are orthogonal polynomials.

The expansion coefficients are determined based on coupling conditions between nodes and Equation (6). Following the fixed-source solution, the precursor density is calculated.

2.2 Backward Euler Method

The space-time neutron kinetics equations can be written in the following form:

$$\frac{1}{v}\frac{\partial\phi(\mathbf{r},t)}{\partial t}=\nabla\cdot D(\mathbf{r},t)\nabla\phi(\mathbf{r},t)-\Sigma_a(\mathbf{r},t)\phi(\mathbf{r},t)+(1-\beta)\chi_p\nu\Sigma_f(\mathbf{r},t)\phi(\mathbf{r},t)+\sum_{m=1}^{M}\lambda_m C_m(\mathbf{r},t)$$

$$\frac{\partial C_m(\mathbf{r},t)}{\partial t}=\beta_m\nu\Sigma_f(\mathbf{r},t)\phi(\mathbf{r},t)-\lambda_m C_m(\mathbf{r},t),\quad m=1,2,\dots,M$$

The time derivative terms in these equations are approximated using backward difference:

$$\frac{\partial f(t)}{\partial t}\approx\frac{f(t)-f(t-\Delta t)}{\Delta t}$$

Discretization yields the following fixed-source form equation system:

$$\left[\frac{1}{v\Delta t}+\Sigma_a(\mathbf{r},t)-(1-\beta)\chi_p\nu\Sigma_f(\mathbf{r},t)\right]\phi(\mathbf{r},t)-\nabla\cdot D(\mathbf{r},t)\nabla\phi(\mathbf{r},t)=\frac{1}{v\Delta t}\phi(\mathbf{r},t-\Delta t)+\sum_{m=1}^{M}\lambda_m C_m(\mathbf{r},t)$$

$$\left[\frac{1}{\Delta t}+\lambda_m\right]C_m(\mathbf{r},t)=\frac{1}{\Delta t}C_m(\mathbf{r},t-\Delta t)+\beta_m\nu\Sigma_f(\mathbf{r},t)\phi(\mathbf{r},t),\quad m=1,2,\dots,M$$

This system can be solved using the nodal method described above.

2.3 Backward Differentiation Formula

The Backward Differentiation Formula (BDF) is a class of implicit linear multistep methods suitable for solving stiff problems. The computational cost per step for implicit linear multistep methods is typically comparable to that of the backward Euler method, while offering higher accuracy. This study employs second-order BDF for solving space-time neutron kinetics equations. For constant step sizes, the second-order BDF formula is given by:

$$y_{n+1}=\frac{4}{3}y_n-\frac{1}{3}y_{n-1}+\frac{2}{3}\Delta t f(t_{n+1},y_{n+1})$$

where y represents the solution vector and n denotes the time step index.

3. Validation and Application

3.1 Program Verification

The benchmark problem involves a control rod ejection accident in a VVER-440 reactor [5]. The core material layout is symmetric about the x-axis in the horizontal plane, as shown in [Figure 2: see original paper], with the axial layout illustrated in [Figure 3: see original paper]. Components numbered 1, 2, and 3 represent fuel assemblies, while components numbered 21, 23, 25, and 26 are control rod assemblies.

This case simulates an asymmetric control rod ejection accident without feedback effects. The ejected control rod has a worth of approximately 0.7β. Initially, control rods numbered 23 and 25 are fully withdrawn from the core, while rods numbered 26 and 21 are inserted, with positions shown in [Figure 3: see original paper]. At the initial moment, control rod number 26 is ejected from the core at a velocity of 2500 cm/s. After 1 second, the reactor scrams, and all control rods except number 26 (including rod 21) begin dropping to the core bottom at a constant velocity of 25 cm/s. The entire transient lasts 6 seconds.

[Figure 4: see original paper] shows the relative power variation over time.

3.2 Tianwan VVER Dynamic Rod Worth Validation

Based on actual current data from three operating cycles of the Tianwan VVER reactor, dynamic spatial correction factors were calculated using the constant-step BDF kinetics simulation. Control rod group worths were then determined from measured currents. The relative deviations between measured and theoretical rod worths are presented in . The results indicate that the maximum error for any rod group does not exceed 10%, with most rod groups showing excellent agreement.

Simulating the entire transient process for a single rod group insertion requires approximately 8 minutes on a personal computer. This computational efficiency enables completion of the entire dynamic rod worth simulation within a reasonably short timeframe.

Conclusion

This study presents the theoretical framework of second-order backward differentiation formula combined with functional expansion nodal methods for solving hexagonal multi-group space-time neutron kinetics, and integrates it with the dynamic rod worth measurement methodology to develop a corresponding computational program. Validation using dynamic rod worth test data from multiple operating cycles of the Tianwan VVER reactor demonstrates that the errors between measured and theoretical control rod worths based on the developed program are all less than 10%, confirming the program' s high computational accuracy. Additionally, the method exhibits high computational efficiency, with calculation time for dynamic correction factors of a single rod group being approximately 8 minutes.

Author Contributions

Cai Yun: Developed space-time kinetics models and program, performed data analysis and paper writing. Zhao Wenbo: Developed dynamic rod worth measurement models. Jiang Zhumin: Conducted result evaluation and paper revision. Liu Tongxian: Performed result evaluation and guided paper writing and revision. Li Tianya: Conducted result evaluation. Li Qing: Reviewed and supervised the paper.

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Note: Figure translations are in progress. See original paper for figures.