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基于聚乙烯的中子能谱探测组件研究设计

摘要

自给能中子探测器（Self-Powered Neutron Detector, SPND）作为反应堆堆芯探测系统的核心设备，凭借其不需要外加电源、体积小等优势，长期承担堆芯中子通量监测任务。本研究针对现有 SPND 技术在中子能谱探测领域的局限性，提出一种基于慢化层结构的中子能谱探测方法。研究通过理论建模与数值模拟相结合的方法，系统阐述了自给能中子能谱探测组件的物理机制。设计了一种基于聚乙烯慢化层的中子能谱探测组件，其核心结构包含四个不同厚度慢化层的 SPND。采用蒙特卡洛模拟方法建立三维几何模型，计算能谱探测组件在中子能量 1×10-9 -10 MeV 范围内的响应函数矩阵，数值结果表明不同慢化层厚度探测器对特定能区中子具有显著选择性响应。为验证组件的能谱求解可行性，研究提出基于响应矩阵逆运算的能谱解析算法，并通过输入三类典型中子能谱（热中子谱、压水堆能谱、混合能谱）作为测试基准。结果显示：通过四通道电流信号反演计算获得的能谱分量占比与预设值最大相对偏差小于 3.5%，验证了探测组件结构设计及解谱算法的有效性。误差分析表明，误差主要来源于慢化层厚度优化不足及探测单元数量限制。本研究建立的 SPND 能谱探测方法为堆内实时能谱监测提供了新的技术路径。在后续工作中，可增加探测器的数量、使用耐高温慢化层材料，使用最小二乘算法等解谱方法，提高反演计算稳定性，实现更精准、分群更详细的能谱探测工作。

关键词

中子探测；能谱探测；反应堆探测；蒙特卡洛方法；自给能中子探测器；

Abstract

The Self-Powered Neutron Detector (SPND), as a core component of reactor core monitoring systems, has long been utilized for neutron flux measurement due to its advantages of requiring no external power supply and compact size. However, existing SPND technologies exhibit limitations in neutron spectrum detection. To address this, this study proposes a novel neutron spectrum detection method based on a moderated-layer structure. Combining theoretical modeling and numerical simulation, the physical mechanism of the self-powered neutron spectrum detection assembly was systematically analyzed. A polyethylene-moderated neutron spectrum detection module was designed, comprising four SPNDs with varying moderator thicknesses (0 cm, 2 cm, 5 cm, and 8 cm). A three-dimensional geometric model was established using the Monte Carlo simulation method to calculate the response function matrix of the detection assembly across the neutron energy range of 1×10^{-9}–10 MeV. Numerical results demonstrated that detectors with different moderator thicknesses exhibited selective sensitivity to neutrons in specific energy regions. To validate the feasibility of spectrum unfolding, an inversion algorithm based on the response matrix was developed and tested using three typical neutron spectra: a thermal neutron spectrum, a pressurized water reactor (PWR) spectrum, and a mixed spectrum. Simulation results showed that the maximum relative deviation between the unfolded spectrum components and preset values was less than 3.5%, confirming the effectiveness of both the detector design and the unfolding algorithm. Error analysis indicated that deviations primarily originated from suboptimal moderator thickness configurations and insufficient detector units. The proposed SPND-based spectrum detection method provides a new technical pathway for real-time in-core neutron spectrum monitoring. Future work should focus on increasing the number of detectors, employing high-temperature-resistant moderator materials, and implementing advanced unfolding algorithms to enhance computational stability and achieve higher-resolution spectrum detection.

Keywords

neutron detection; spectrum measurement; reactor monitoring; Monte Carlo method; self-powered neutron detector (SPND)

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